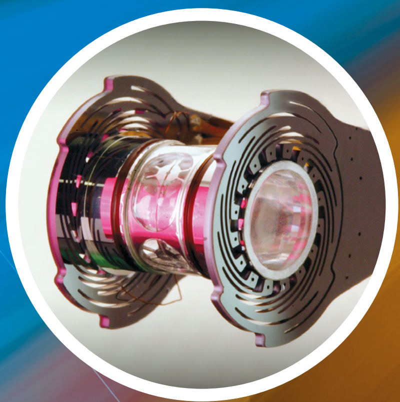
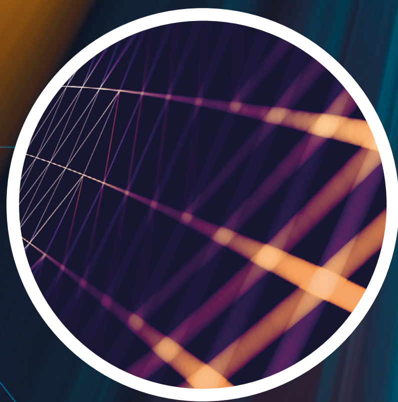
Memorandum

Laser Inertial Fusion Energy



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Executive Summary

Deutsch

Fusion ist der Prozess, bei dem zwei leichte Atome unter Freisetzung einer großen Menge Energie zu einem schwereren Atom verschmelzen. Dieser Prozess ist die Hauptenergiequelle unserer Sonne. Wenn es uns gelingen würde, diese Reaktionen auf der Erde kontrolliert zu replizieren, könnte dies auch eine bedeutende Quelle für erneuerbare Energie sein. In den letzten Jahren haben Fusionsforscher:innen und Unternehmen auf der ganzen Welt bedeutende Fortschritte bei der Entwicklung von Möglichkeiten zur Nutzung dieser Energiequelle erzielt. Im Dezember 2022 gelang ein bahnbrechender wissenschaftlichen Meilenstein an der National Ignition Facility (NIF) am Lawrence Livermore National Laboratory in den USA: Erstmals wurde aus einer lasergesteuerten Fusionsreaktion mehr Energie gewonnen, als durch die Laser zur Auslösung der Reaktion in die Brennstoffkapsel eingebracht wurde. Dass dies zum ersten Mal unter kontrollierten Laborbedingungen erreicht werden konnte, ist das Ergebnis von mehr als 60 Jahren wissenschaftlicher Forschung und Entwicklung. Sie umfassen eine Reihe von Bereichen, einschließlich der Fusion- und Plasmaphysik, Materialwissenschaften, Lasertechnologie und Technologie-Fortschritten. Für diesen Erfolg waren Ausdauer, öffentliche Investitionen und die Zusammenarbeit brillanter Köpfe aus der ganzen Welt ausschlaggebend.

In der Fusionsforschung werden mehrere technische Ansätze verfolgt. Bei der Trägheitsfusion (Inertial Confinement Fusion, IFE), auf die sich dieses Memorandum konzentriert, werden gepulste Treiber wie etwa starke Laser oder elektrische Ströme verwendet, um die Implosion einer brennstoffgefüllten Kapsel auszulösen. Dabei entstehen für kurze Zeit Bedingungen, die sogar die im Zentrum der Sonne übertreffen. Der Brennstoff brennt dann für einige zig Billionstel Sekunden, wobei er währenddessen durch seine eigene Trägheit an der Expansion gehindert wird. Der Ansatz, der an der NIF gewählt wurde, ist derzeit der einzige, bei dem die Zündung eines Plasmas gelang. Von Zündung spricht man, wenn sich das zunächst erzeugte Plasma durch die einsetzenden Fusionsreaktionen ohne weitere Energiezufuhr von außen selbst weiter aufheizt und die dabei entstehende Energie nicht nur die zunächst eingesetzte Energie zur Erzeugung des Fusionsplasmas einschließlich aller Leistungsverluste aufgewogen hat, sondern auch noch darüberhinausgehend Energie freigesetzt hat. Neben der Demonstration der wissenschaftlichen Machbarkeit bietet die Trägheitsfusion auch andere technologische Vorteile und Vielfalt in einem Bereich mit immensem kommerziellem Potenzial.

Ausgelöst durch die jüngsten Fortschritte hat das Bundesministerium für Bildung und Forschung (BMBF) seit 2022 eine Reihe von Aktivitäten initiiert, um den Bedarf und das Potenzial für IFE zu bewerten. Für die Erlangung eines umfassenden Verständnisses, beauftragte es eine Gruppe von weltweit, in verschiedenen für die Fusionsenergie relevanten Technologiebereichen führenden Experten, die Möglichkeiten und Chancen für Deutschland auf dem Gebiet der Trägheitsfusionsenergie zu evaluieren. Nach einer umfassenden Bewertung des aktuellen Standes der Technik kam das Gremium zu dem Schluss, dass die Fusion ein großes Potenzial für die zukünftige Energieversorgung der Welt bietet und für die deutsche Industrie und Gesellschaft eine hervorragende Chance darstellt, die notwendigen Hightech-Entwicklungen zu einer sauberen, robusten und nachhaltigen Energieversorgung voranzutreiben. Auch wenn es noch einige wissenschaftliche Hürden zu überwinden gibt, wurde nun die Realisierbarkeit der Zündung durch Laser gezeigt. Deshalb sollte der Fokus jetzt darauf liegen, die Forschungs- und Entwicklungsanstrengungen auf Konzept, Technologie, Konstruktion und Betrieb eines Fusionskraftwerks, sowie die Entwicklung des Geschäftskonzepts, der Lieferketten und des Produktionsingenieurwesens dafür auszuweiten.

Die jüngsten Fortschritte in der Fusionstechnologie haben auch den Wettlauf um die Kommerzialisierung der Fusionsenergie weltweit angeheizt: Mit einer Gesamtinvestition von über 5 Milliarden US-Dollar verfolgen mehr als 38 Start-ups, darunter vier in Deutschland, Forschung und Entwicklung für die Nutzung von Fusionsenergie. Doch trotz des schnellen Fortschritts sind noch erhebliche Fortschritte erforderlich, bevor Fusion zu einer wirtschaftlich tragfähigen Energiequelle werden kann. Eine wesentliche Herausforderung besteht darin, den technischen Break-Even nachzuweisen und den sogenannten "Balance of Plant" zu realisieren, der die Gesamteffizienz eines Kraftwerks beschreibt. Die Fusionsenergie muss also zeigen, dass sie mehr Energie erzeugen kann, als das Fusions-Kraftwerk für seinen eigenen Betrieb verbraucht.

Die Forschung im Bereich der Fusionsenergie ist ein kritisches und risikoreiches Unterfangen, das die Verfolgung eines breiten Spektrums von Ansätzen und Technologien erfordert, um die Erfolgsaussichten zu erhöhen. Magnetische (Einschluss-)Fusionsenergie (MFE) und Inertiale (Einschluss-)Fusionsenergie (IFE) sind zwei vielversprechende Technologien, die dazu beitragen können, das Ziel einer nachhaltigen Energieversorgung zu erreichen. Angesichts der Vielzahl und Größe der Herausforderungen, die noch in beiden Ansätzen zu bewältigen sind, wäre es verfrüht, sich auf eine endgültige Siegertechnologie festzulegen. Indem wir in Forschung und Entwicklung sowohl für MFE als auch für IFE investieren, erhöhen wir die Wahrscheinlichkeit, unsere Ziele für eine nachhaltige Energieversorgung zu erreichen. Unser Expertengremium hat sorgfältig Berichte der Nationalen Akademie der Wissenschaften der USA und des US-Energieministeriums sowie die wissenschaftliche Fachliteratur geprüft. In diesem Memorandum haben wir uns speziell auf die Verwendung von Lasern als Treiber für IFE konzentriert, da klar wurde, dass nicht-laserbasierte Ansätze für IFE viele der Schlüsselvorteile von Lasern nicht aufweisen und nicht so weit in ihrem Technologiereifegrad fortgeschritten sind. Zudem besitzt Deutschland weltweit führende Expertise im Bereich Lasertechnologie.

Das Gremium ist der Ansicht, dass mit einem zielgerichteten IFE-Programm und starken internationalen Partnerschaften die Schlüsseltechnologien für das Design eines ersten IFE-basierten Fusionskraftwerks innerhalb von zehn bis zwanzig Jahre entwickelt werden könnten. Mit einem ehrgeizigen und gut finanzierten Forschungs- und Entwicklungsplan ist es Stand heute unter Berücksichtigung typischer Entwicklungs- und Bereitstellungshorizonte denkbar, dass eine betriebsfähige Demonstrationsanlage für die Trägheitsfusion bis etwa 2045 in Betrieb sein könnte. Folglich geht das Gremium davon aus, dass die Fusionsenergie voraussichtlich nicht zur laufenden Energiewende beitragen wird, die bis 2045 abgeschlossen sein soll.

Dies unterstreicht die Dringlichkeit für Deutschland, in die IFE zu investieren und einen Rahmen zu schaffen, der ein lebendiges Fusionsenergie-Ökosystem aufbaut und fördert, welches auf vier Eckpunkten basiert:

1. einem starken wissenschaftlichen Programm, um die nächste Generation von Wissenschaftlern:innen auszubilden und zu trainieren, während gleichzeitig vorwettbewerblich wissenschaftliche Fragestellungen gelöst werden,
2. einer offenen Forschungsinfrastruktur für sowohl Wissenschaft als auch Industrie,
3. einer kompetenten Industrie, die sich an Innovationen beteiligt und einen Technologietransfer befähigt, und
4. der internationalen Zusammenarbeit zwischen Regierungen, um Ressourcen und Fördergelder zu bündeln und Überschneidungen dabei zu vermeiden.

Letztendlich erfordert die erfolgreiche Kommerzialisierung der Fusionsenergie eine starke Zusammenarbeit und die Partnerschaft zwischen Industrie, Regierungen und Wissenschaft. Nur mit umfangreichen, risikotoleranten öffentlich-privaten Partnerschaften kann die Ausrichtung an Marktanforderungen erzielt, Risiken und Kosten für Steuerzahler gesenkt, die Stärken sowohl des öffentlichen als auch des privaten Sektors genutzt, Arbeitsplätze in neuen Branchen geschaffen und

Deutschlands Führung bei der kommerziellen Nutzung der Fusionsenergie durch wissenschaftliche und technische Innovationen gesichert werden.

Eine entscheidende und maßgebliche Voraussetzung für die Kommerzialisierung der Fusionsenergie ist ein starkes Bekenntnis und Engagement der politischen Führung. Um den Aufbau eines erfolgreichen Innovationsökosystems zu erleichtern, ist es entscheidend, einen technologieoffenen regulatorischen Rahmen zu schaffen, der Sicherheitsbedenken berücksichtigt, Innovationen fördert, Technologieexportvorschriften harmonisiert, wirksame Exportkontrollen implementiert, Lieferketten unterstützt und die Öffentlichkeit einbezieht. Hierzu ist anzumerken, dass die Dual-Use-Bedenken hinsichtlich IFE auf bestimmte Design-Technologien beschränkt sind und nicht auf IFE-Anlagen im Allgemeinen zutreffen. Die Schaffung eines präzisen, technologieoffenen Fusionsregulierungssystems wird Investoren anziehen, die fundamentale Analysen und Due Diligence priorisieren und sich langfristig engagieren möchten.

Um dies zu unterstreichen, hat die US-Regierung unter Biden beispielsweise angekündigt, im Jahr 2024 für die Fusionsforschung 1,01 Milliarden US-Dollar bereitstellen zu wollen, was den jüngsten bahnbrechenden Erfolg und den parteiübergreifenden Konsens im Kongress widerspiegelt. Hiervon sind 135 Millionen US-Dollar für ein öffentlich-privates Partnerschaftsprogramm reserviert, das im Herbst 2022 angelaufen ist. Auf dem White House Fusion Summit 2022 wurde ein Programm angekündigt, das das Ziel verfolgt, kommerzielle Fusionsenergieinitiativen zu beschleunigen, um dem ganzen Land zu nutzen. Die im Rahmen des Programms bereitgestellten Fördergelder sollen die Entwicklung innovativer Technologien für saubere Energielösungen beschleunigen und die Kommerzialisierung der Fusion als eine vielversprechende Quelle sauberer Energie fördern. Darüber hinaus legte im Jahr 2020 das Fusion Energy Sciences Advisory Committee (FESAC), welches das US-Energieministerium (Department of Energy, DOE) berät, Prioritäten für die Fusionsforschung unter verschiedenen Budget-Szenarien dar. Der im Jahr 2021 erschienene Bericht “Strategic Plan for U.S. Burning Plasma Research”, erstellt von der Nationalen Akademie der Wissenschaften, Technik und Medizin (NASEM), war einer von mehreren Berichten, die eine vergleichbare Bewertung für die Fortschritte in der Fusionswissenschaft und der Entwicklung der Fusionsenergie in den USA boten. Der Bericht über grundlegende Forschungsanforderungen (Basic Research Needs, BRN), erschienen Anfang 2023, der von einem großen wissenschaftlichen Gremium zusammengestellt wurde, das auch einige Mitglieder der Fachkommission dieses Memorandums umfasst, enthält einen Leitfaden zur Forschungsförderung für die US-Regierung, die Wissenschaft und die Industrie. Er identifiziert die wissenschaftlichen und technologischen Herausforderungen, die überwunden werden müssen, und bietet Empfehlungen zur Förderung von Wissenschaft und Technologie hin zu einem Demonstrator für ein Fusionskraftwerk. Der Bericht bietet eine aktuelle und umfassende Übersicht über IFE und ist eine wertvolle Ressource für dieses Memorandum.

Auf dem Weg zu einer kommerziellen Anwendung der lasergetriebenen IFE sind mehrere Herausforderungen zu bewältigen. Dazu gehören das Verständnis brennender Plasmen, die Entwicklung von Laserquellen und geeigneter Targets, die Herstellung von Materialien, die Fusionsbedingungen standhalten können, und die Lösung komplexer technischer Probleme. Da das weltweite Programm nun stark in Richtung Energiegewinnung aus Trägheitsfusion drängt, müssen IFE-spezifische Technologien deutlich weiterentwickelt werden, da es in der Vergangenheit nur sehr begrenzte Anstrengungen in diese Richtung gegeben hat. Und obwohl sich die FuE in der Plasmaphysik und dem Design der Reaktionskammer zwischen MFE unterscheidet, gibt es wesentliche Synergien bei spezifischen Komponenten, speziell jenen, die vom Fusionsplasma weiter weg entfernt sind. Insbesondere in diesen Bereichen sollte Deutschland seine vorhandenen Stärken aus der MFE-Fusionstechnologie zukunftsweisend nutzen. Um den Erfolg sicherzustellen, müssen die IFE-Akteure in Deutschland eine technologische Führungsposition erreichen und ihre Fähigkeiten weiterentwickeln.

Die Forschungsarbeiten im Bereich der Fusionstechnologie müssen Technologie- und Konstruktionsentwicklungen für ein Fusionskraftwerk einschließen, nicht nur Grundlagenforschung zur Plasmaphysik. Der Schwerpunkt sollte zunächst auf Konstruktionsstudien für ein IFE-Kraftwerk gelegt werden, um eine umfassende FuE-Strategie zu entwickeln. Auf diese Weise werden die Ressourcen auf relevante technologische Fortschritte konzentriert und künftige Risiken im Zusammenhang mit IFE-Konzepten vermindert. Um das Wachstum entscheidender und renditestarker Technologien für Deutschland zu fördern, wird empfohlen, die Entwicklung von Schlüsseltechnologien, Kompetenzen und Fähigkeiten in Innovationshubs zu organisieren. Prinzipien offener Innovation sollten ermutigt werden, um rasche Fortschritte in der Fusionsforschung und deren Kommerzialisierung zu ermöglichen. Die Hubs könnten in der Reihenfolge ihrer Dringlichkeit auf die folgenden Bereiche ausgerichtet sein:

Deutschlands weltweit führendes Know-how in der Lasertechnologie und forschung stellt einen entscheidenden Vorteil bei der Entwicklung der Trägheitsfusionsenergie (IFE) dar. Indem sich Deutschland auf die Entwicklung geeigneter Treiberkonzepte für einen IFE-Demonstrator konzentriert und die Fähigkeiten von Laser-Treibern und Multigigashot-Lasern verbessert, kann es seine Position als führender Akteur in der Laserindustrie nutzen, um eine solide Grundlage für die wettbewerbsfähige Produktion von fortschrittlichen Hochleistungslasern für IFE zu schaffen. Dies wird Deutschlands Wettbewerbsvorteil auf dem internationalen Markt stärken und zu neuen, einzigartigen Alleinstellungsmerkmalen führen. Wenn es nicht gelingt, hier unverzüglich zu handeln, könnte der Wettbewerbsvorteil auf dem Lasermarkt langfristig verloren gehen.

Für IFE sind kostengünstige, massenproduzierte Fusionstargets erforderlich. Derzeit gibt es jedoch weltweit keinen Lieferanten, der die erforderliche Menge und Qualität liefern könnte. Deutschland verfügt bereits über umfangreiche Expertise und Fähigkeiten bei den Fertigungstechnologien von Targets. Somit hat Deutschland aufgrund der bestehenden Kompetenzen bei der Herstellung von kugelförmigen Kapseln mit Schaumstoffauskleidung, bei der Metallbearbeitung und bei den entsprechenden Prüftechniken die Chance, auf dem Gebiet der Targetentwicklung führend zu werden. Wenn nicht in die Zielentwicklung investiert wird, könnte dies bedeuten, dass ein bedeutender Energiemarkt verpasst wird und Deutschland bzw. Europa für eine kritische Komponente für IFE-Reaktoren auf ausländische Hersteller angewiesen ist, wodurch wirtschaftliche Unsicherheit und Energieversorgungsrisiken geschaffen werden. Das Expertengremium empfiehlt ein engagiertes Entwicklungsprogramm zur Massenproduktion von IFE-Targets und Injektorsystemen anzulegen, dass auch die Demonstration genauer Zielerfassungssysteme einschließt.

Nach der Zündung des Plasmas und der Freisetzung seiner Energie sind die Werkstoffe für Struktur, Funktion und Abschirmung die größten Herausforderungen für ein zukünftiges Fusionskraftwerk und bestimmen die Anforderungen an das technische Design der Reaktionskammer des Kraftwerks. Dies umfasst auch optische Materialien, die einem Bombardement von Neutronen, Röntgenstrahlen und kleinen Trümmern ausgesetzt sind. Auf all diesen Gebieten verfügt Deutschland über beträchtliche Erfahrungen und hat Forschungslabors für Materialcharakterisierung eingerichtet, ergänzt durch beträchtliche Bemühungen bei der Modellierung und Simulation von Materialien, ohne die kein Kraftwerk gebaut werden kann. Hier gibt es viele Überschneidungen mit dem deutschen MFE-Programm; eine Zusammenarbeit wäre ein Katalysator für einen beschleunigten Fortschritt. Sollten sich deutsche Institutionen hier nicht engagieren, würde eine einzigartige Gelegenheit für den öffentlichen und privaten Sektor Deutschlands verloren gehen, eine Schlüsselrolle in der zukünftigen Entwicklung zu spielen.

Das Blanket ist für die Energiegewinnung und den Brennstoffkreislauf notwendig und somit *ein entscheidender Bestandteil eines Fusionskraftwerks. Ein konsistentes Blanketdesign ist für ein wirtschaftlich rentables Kraftwerk mit langer Lebensdauer und einfacher Fernkontrolle unerlässlich. Weltweit sind bisher nur wenig Bemühungen zum Blanketdesign erfolgt, und der private Sektor erwartet vom öffentlichen Sektor, dass dieser diese komplexe Komponente entwickelt. Deutschlands Erfahrungen in der Entwicklung von Fertigungs- und Fügeverfahren sowohl im öffentlichen als auch im privaten Sektor sind weltweit führend. Mit einer erfolgreichen Beteiligung an diesem noch nicht sehr weit entwickelten Element könnte Deutschland seine Führungsrolle ebenfalls in der Fusion sichern. Zur Erzeugung von Energie in einem Fusionskraftwerk ist darüber hinaus die Trennung und Wiederaufbereitung der Wasserstoffisotope (Tritium, Deuterium) aus dem Abgas oder dem Blanket notwendig. Deutschland führt weltweit bei der Prozesssteuerung, Diagnostik und der Entwicklung neuer Technologien für Tritium-Forschung und Einrichtungen wie Tritium-Labors. Mit zunehmender Bedeutung der Wasserstofftechnologie ist der Ausbau der deutschen Kompetenzen und Fähigkeiten in diesem Bereich sowohl für die Fusion als auch für Wasserstoffanwendungen von entscheidender Bedeutung.*

Im Bereich der Hochdichten und heißen Plasmen (Fusionsplasmen) verfügt Deutschland auf der einen Seite nur über wenig Kompetenzen, auf der anderen Seite verfügt Deutschland aber über umfangreiche Kompetenzen in den Bereichen künstliche Intelligenz (KI) und High-Performance-Computing (HPC). Diese können genutzt werden, um IFE-Simulationscodes zu entwickeln, die verschiedene Bereiche wie Multiphysik, Multi-Fidelity und Multisystemmodelle integrieren. Auf diese Weise können Experimente und Simulationen effektiv ausgewertet werden und es können Experimente mit hohen Wiederholungsraten (>10 Hz) durchgeführt und analysiert werden. Diese sind notwendig für die Entwicklung vollständiger Systemmodelle und IFE-Kraftwerken. KI und HPC werden in Zukunft voraussichtlich auch erforderlich sein, um ein IFE-Kraftwerk automatisiert zu betreiben. KI und HPC sind Querschnittsthemen, die für die IFE-Forschung absolut notwendig sind, und ohne Investitionen in IFE-spezifische Anwendungen wird Deutschland keine Spitzenposition aufbauen können.

Obwohl die Reaktionskammer eine kritische Komponente jedes zukünftigen IFE-Kraftwerks ist, wurden bisher erstaunlich wenige Konzeptstudien dazu durchgeführt. Die Schnittstellen zwischen der Reaktionskammer und dem Rest des Kraftwerks erfordern einen integrierten Entwurfsprozess, um Kompromisse abzuwägen und Informationen über die Auslegungsbedingungen für den Rest des Kraftwerks zu erhalten. Es ist daher wichtig, den technischen Einsatzreifegrad zu steigern und mit den Ländern zusammen zu arbeiten, die bereits Studien durchgeführt haben, insbesondere mit den Vereinigten Staaten und dem Vereinigten Königreich.

Der deutsche Privatsektor entwickelt derzeit ein Konzept und ein Betriebsmodell für ein IFE-Kraftwerk. Ein Instrument für integrierte Konzeptstudien für IFE-Kraftwerke fehlt jedoch in der IFE-Gemeinschaft. Ein solches Instrument ist für Scoping-Studien unerlässlich, um die optimale Kombination verschiedener Elemente in einem IFE-Kraftwerk zu ermitteln und die Anforderungen an die Komponenten in integrierter Weise festzulegen. Wir schlagen vor, dass Deutschland dringend mit der internationalen Gemeinschaft zusammenarbeitet, um einen umfassenden Systemcode zu entwickeln und dafür seine eigene Expertise auf diesem Gebiet zu nutzen.

Hochspezialisierte Diagnostik ist erforderlich, um die extremen Bedingungen von ICF-Plasmen zu untersuchen, während sie komprimiert, geheizt und gezündet werden. Darüber hinaus muss die Diagnostik Informationen über die Lasertreiber und die das Plasma umgebenden Systeme liefern. Die gewonnenen Daten dienen der Validierung und Überprüfung von Theorien, Modellen und Codes, die für die Auslegung und Vorhersage verwendet werden. In einem voll funktionsfähigen kommerziellen Fusionskraftwerk wird die Diagnostik voraussichtlich minimal sein, aber in den zwischengeschalteten Test- und Pilotanlagen, die zu diesem Punkt führen, wird die Diagnostik eine *entscheidende Rolle bei der Förderung des Gesamtverständnisses spielen. Zwar verfügt Deutschland derzeit nicht über besonders einzigartige oder fortschrittliche ICF-Diagnosekapazitäten, aber die Entwicklung von Diagnosen und die Fähigkeit, Behauptungen und experimentelle Ergebnisse zu validieren und zu verifizieren, müssen für jede neue Fusionsanlage (einschließlich Test- oder Zwischenanlagen) und für Fortschritte Deutschlands in allen anderen, in diesem Bericht erörterten Bereichen, geschaffen werden.*

Die Entwicklung eines soliden Fusionsenergieprogramms in Deutschland kann als attraktiver Anziehungspunkt für Talente aus der ganzen Welt dienen. Dies unterstreicht die Bedeutung und den Wert von Hightech-Entwicklungen, insbesondere inmitten des internationalen Wettlaufs um die Fusionsenergie. Eine echte Herausforderung für Deutschland ist jedoch die begrenzte Verfügbarkeit erfahrener Arbeitskräfte in den Bereichen Plasmaphysik mit hoher Energiedichte bzw. der damit verbundenen Technologieentwicklung, Kerntechnik und Energielaserentwicklung. Um den wachsenden Personalbedarf des privaten Sektors zu decken und gleichzeitig die Exzellenz der öffentlich finanzierten Forschung und Entwicklung aufrechtzuerhalten, ist es von entscheidender Bedeutung, in die Entwicklung einer umfassenden und modernen Ausbildung an Universitäten und Hochschulen schnell zu investieren. Spezialisierung und praxisorientierte Ausbildung sind wichtige Komponenten und erfordern experimentelle Einrichtungen und moderne Entwicklungsfinanzierung. Universitäten und Hochschulen sollten in Zusammenarbeit mit Partnern aus der Industrie Programme entwickeln, die praktische Ausbildungsmöglichkeiten in Versuchsanlagen bieten.

Im Vergleich zu den Vereinigten Staaten, Großbritannien, Japan, Italien oder Frankreich hat sich Deutschland noch nicht als ein wesentlicher Akteur auf dem Gebiet der ICF oder IFE etabliert. China und Russland haben noch keine IFE-Ambitionen bekannt gegeben, aber sie haben bereits mit dem Bau von großer ICF-Anlagen begonnen, die der NIF ähnlich sind. Dennoch sind die Herausforderungen, die diese Technologie mit sich bringt, enorm und Deutschland hat jetzt die einmalige Chance, mit seinen vorhandenen Kompetenzen einen wesentlichen Beitrag zu leisten und sich als wichtiger Partner in diesem Bereich zu etablieren. Um dieses Ziel zu erreichen, muss Deutschland internationale Partnerschaften mit strategischen Verbündeten und führenden IFE-Technologien aufbauen und stärken.

Zur Ausschöpfung des Potenzials der Fusionsenergie ist in Deutschland ein umfassendes und gut koordiniertes Programm mit langfristigen Investitionen erforderlich. Durch die Etablierung an der Spitze dieser vielversprechenden Technologie könnte Deutschland von den wirtschaftlichen, ökologischen und strategischen Vorteilen der Fusionsenergie profitieren und gleichzeitig eine führende Rolle bei der Weiterentwicklung dieses Bereichs auf europäischer und globaler Ebene spielen. Es besteht dringender Investitionsbedarf. Es muss schnell gehandelt werden, um in diesem Bereich eine Vorreiterrolle einzunehmen. Die Nutzung der Fusionsenergie würde zweifelsohne den Lauf der Menschheitsgeschichte verändern. Sie hätte das Potenzial, die Art und Weise, wie wir diese lebenswichtige Ressource nutzen, zu verändern und Energieresilienz und Energiesouveränität zu gewährleisten.

English

Fusion is the process by which two light atoms combine to form a heavier atom. This creates a large amount of energy. This process is the primary source of energy in the sun. If we were able to replicate these reactions on Earth, it would serve as a significant source of renewable energy as well. In recent years, fusion researchers and companies around the world have made significant progress in developing ways to harness this energy source. In December 2022, the U.S.'s Lawrence Livermore National Laboratory's National Ignition Facility achieved a groundbreaking scientific milestone: generating more energy from a laser-driven fusion reaction than delivered by the lasers to start it. This was the first time this has been achieved in a controlled laboratory environment and is the result of over 60 years of scientific research and development. It spans multiple fields, including fusion and plasma physics, materials science, laser technology, and engineering advances. It has taken dedication, perseverance, public investment, and collaboration among brilliant minds from around the world.

There are various technical approaches to fusion being pursued. Inertial confinement fusion (IFE), on which this report is centered, uses a pulsed driver, such as massive lasers or electric currents, to induce an implosion of a fusion fuel capsule, creating conditions that surpass those at the center of the sun. The fuel then burns for tens of trillionths of seconds, confined by its own inertia. The approach demonstrated at the NIF is currently the only one to have achieved burning plasma, where fusion reactions are strong enough to allow the plasma to self-heat, and then beyond that to ignition, where the reaction produces more energy than it consumes. Besides the essential demonstration of scientific viability, inertial fusion also offers technological advantages and diversity in a field with immense commercial potential.

Inspired by recent progress, the Federal Ministry of Education and Research (BMBF) initiated a series of activities starting in 2022 to assess the need and potential for IFE. To gain a comprehensive understanding, it charged a group of world-leading experts in various technology fields relevant to fusion energy to evaluate the opportunities for Germany to engage in the field of inertial fusion energy. After a comprehensive assessment of the current state of the art, the panel concluded that fusion holds great promise for the world's future energy supply and represents an outstanding opportunity for German industry and society to pursue high-tech development towards achieving a clean, resilient, and sustainable energy source. Although there are still scientific hurdles to overcome, the feasibility of ignition has already been demonstrated with lasers. Therefore, the focus should now shift towards expanding research and development (R&D) efforts on concept, technology, construction, and operation of a fusion power plant, as well as the development of the business case for it, including supply chains and production engineering.

The recent advancements in fusion technology have also fueled the race for commercializing fusion energy worldwide: with a total private investment of over $5 billion, more than 38 start-ups, including four in Germany, are pursuing R&D for the use of fusion energy. However, even with the rapid progress, significant advancements are still needed before fusion can become an economically viable energy source. One of the most critical challenges is the balance of plant, or overall efficiency of a fusion energy system and the need to demonstrate engineering gain. Fusion energy will need to show that it can create more power than the power plant consumes for its own operation.

Fusion energy research is a critical and high-stakes endeavor that requires the pursuit of a diverse range of approaches and technologies to increase the chances of success. Magnetic (confinement) fusion energy (MFE) and inertial (confinement) fusion energy (IFE) are two promising technologies that can help achieve the goal of sustainable energy. Given the magnitude and large quantity of challenges still to be overcome in both approaches, it would be premature to declare a definitive winning technology at this stage. By investing in research and development (R&D) for both MFE and IFE, we increase the likelihood of success in achieving our sustainable energy goals. The panel carefully reviewed reports from the U.S. National Academy of Sciences, the Department of Energy and peer-reviewed science literature. In this memorandum we focused specifically on using lasers as a driver for IFE because it became clear that non-laser approaches to IFE lack a lot of the key advantages of lasers and were not as advanced in their technology readiness level, and furthermore Germany possesses world leading expertise in lasers.

The panel believes that with an aggressive IFE program and strong international partnerships, the enabling technologies for a first-of-a-kind IFE based fusion power plant design could be developed within the next decade or two. With an ambitious and well-funded research and development roadmap, it is conceivable that an operational inertial fusion energy (IFE) demonstration power plant could be achievable by approximately 2045, following typical development and deployment schedules. Consequently, the panel believes that fusion energy is not anticipated to contribute to the ongoing energy transition that is slated to be completed by 2045.

This underscores the urgency for Germany to invest in IFE and establish a framework that builds and promotes a vibrant fusion energy ecosystem based on four main pillars:

1. a strong science program to educate and train the next generation while solving precompetitive science questions,
2. an open research infrastructure for both academia and industry,
3. a competent industry that participates in innovation and facilitates technology transfer, and
4. international collaboration between governments to leverage resources and funding while reducing duplication of efforts.

Ultimately, the successful commercialization of fusion energy will require strong collaboration and partnership between industry, government, and academia. Comprehensive, risk-tolerant public-private partnerships are needed to ensure alignment with market requirements, reduce risks and costs for taxpayers, leverage the strengths of both public and private sectors and stakeholders, create jobs in new industries, and ensure that scientific and technical innovations lead to Germany's leadership in commercial fusion energy and enabling technologies.

A strong backing and commitment from political leadership to fusion energy is an essential and paramount prerequisite for facilitating the commercialization of fusion energy. To facilitate building a successful innovation ecosystem, it is crucial to establish a technology-open regulatory framework that addresses safety and security concerns and fosters innovations, harmonizes technology export regulations, implements effective export controls, supports supply chains, and engages the public. It should be noted that the dual-use concerns regarding IFE are limited to certain design technologies and not applicable to IFE plants in general. Establishing a concise, technology-open fusion regulatory framework will help attract investors who prioritize fundamental analysis and due diligence, and who are committed to investing for the long term.

To put this into perspective, the U.S.'s Biden Administration has issued its intent to fund fusion research with $1.01 billion in 2024, reflecting the recent breakthrough potential of fusion energy and bipartisan consensus in Congress. $135 million are reserved for the private-public partnership program that launched in fall 2022. At the 2022 White House fusion summit, a program was announced with the objective of expediting commercial fusion energy initiatives to benefit the entire country. The funding provided by the program seeks to hasten the development of innovative technologies for clean energy solutions and facilitate the commercialization of fusion as a promising source of clean energy. Furthermore, the Fusion Energy Sciences Advisory Committee (FESAC), which advises the U.S. Department of Energy (DOE), laid out research priorities under different budget scenarios in 2020. The 2021 "Strategic Plan for U.S. Burning Plasma Research" report by the National Academies of Sciences, Engineering, and Medicine (NASEM) was one of several reports that offered a comparable evaluation for the progression of burning plasma science and fusion energy development in the United States. The 2023 Basic Research Needs (BRN) report, compiled by a large scientific panel that includes some members of this memorandum's expert panel, provides guidance for research funding by the US government, academia, and industry. It identifies the scientific and technological challenges that must be overcome and offers recommendations for advancing science and technology towards a fusion power plant demonstrator. The report provides a recent and comprehensive overview of IFE and forms a valuable resource for this memorandum.

To achieve commercial laser driven IFE, several challenges need to be addressed, including understanding burning plasmas, developing efficient laser drivers and suitable targets, creating materials that can withstand fusion conditions, and solving complex engineering problems. As the worldwide program now starts to strongly push towards inertial fusion energy, IFE-specific technology will have to be developed substantially, since there has only been very limited dedicated effort in the past. Although the R&D involved in plasma physics and reaction chamber is distinct for IFE and MFE, some significant synergies exist in specific elements, particularly those further from the fusion-generating plasma. Germany should leverage its strength in MFE fusion technology in these areas while planning the way forward. To ensure success, IFE stakeholders in Germany must attain technological leadership and enhance their capabilities.

The fusion energy research portfolio must include technology and engineering research for a fusion power plant, not just basic plasma science. Initial emphasis should be placed on design studies for an IFE power plant to inform a comprehensive R&D strategy. This will concentrate resources on pertinent technology advancements and diminish future risks related to IFE concepts. To promote the growth of crucial and high-return-on-investment technologies for Germany, it is recommended to organize the development of enabling technologies, competencies, and capabilities in hubs. Open innovation principles should be encouraged to facilitate rapid progress in fusion research and commercialization. The hubs could be based on the following areas in order of urgency:

Germany's world-leading expertise in laser technology and research is a key advantage in developing Inertial Fusion Energy (IFE). By focusing on developing capable driver concepts for an IFE demonstrator and improving laser driver and multi-gigashot laser capabilities, Germany can leverage its position as a leader in the laser industry to lay a solid foundation for competitive production of advanced high-power lasers for IFE. This will strengthen Germany's competitive edge in the international marketplace and lead to new distinctive unique selling points (USP). Failure to act promptly could result in the long-term in losing the competitive advantage in the laser market.

IFE requires cost-effective, mass-produced fusion targets, but there are currently no suppliers in the world that can meet the required quantity and quality. Germany has already vast expertise and capability in target manufacturing technologies. Thus, the country has an opportunity to lead the way in target development due to the expertise in fabricating spherical capsules lined with foam, metalworking, and verification techniques. Failure to invest in target development could mean missing out on a significant energy market and relying on foreign nations for a critical component for IFE reactors, creating economic uncertainty and energy security risks. The expert panel recommends establishing strong program for mass-producing IFE targets and injectors, as well as demonstrating accurate targeting.

Once the plasma has ignited and released its energy, the structural, functional, and armor materials present the greatest challenges for a future fusion power plant and set the constraints for the engineering design of the power plant's reaction chamber. This includes optical materials exposed to neutrons, x-rays, and debris. In all these areas, Germany has considerable experience and has established research labs for material characterization, complemented by considerable material modelling and simulation efforts, without no power plant can be built. There is quite a bit of overlap with the German MFE program, and accession would be a catalyst for accelerated progress. If German institutions do not participate in this area, a unique opportunity for Germany's public & private sector to play a key role in future development will be lost.

The blanket is necessary for energy recovery and the fuel cycle, and as such a crucial component of a fusion power plant. A consistent blanket design is essential for an economically viable power plant, with long service life and easy remote handling. Globally, efforts have been very limited in blanket design and the private sector is looking to the public sector to develop this challenging component. Germany's experience, both in the public and private sector are leading the way in developing its manufacturing and joining processes. Germany's successful participation in this underdeveloped element could secure its leadership. Furthermore, to produce energy in a fusion power plant, hydrogen isotopes (tritium, deuterium) must be separated and reprocessed from the exhaust gas or the blanket. Germany leads the way globally in process control, diagnostics, and developing new technologies for tritium research and facilities, such as tritium laboratories. As hydrogen technology grows in importance, expanding Germany's expertise and capabilities in this area is crucial for both fusion and hydrogen.

While Germany has no strong IFE physics capability, it can leverage its existing substantial expertise in Artificial Intelligence (AI) and High-Performance Computing (HPC) to develop IFE simulation codes bridging multi-physics, multi-fidelity, and multi-systems, to extract experimental and modeling insights, to execute experiments at the high repetition rates (>10 Hz) that will be required of IFE power plants and develop full systems models. In the future, AI and HPC will be required to run an IFE power plant in an automated fashion. AI and HPC are cross-cutting areas that will be required for IFE research across the board, and without investment in this area for IFE-specific applications, Germany will not be able to establish a leadership position.

Although the reaction chamber is a critical component of any future IFE power plant, surprisingly few conceptual design studies have been conducted. Its interfaces require an integrated design process to balance trade-offs and inform design constraints for the rest of the power plant. It is important to increase the level of technical readiness and to collaborate with countries that have already conducted studies, principally the US and UK.

Germany's private sector is currently involved in developing an understanding and operations model for an IFE power plant. However, there is a notable absence of a tool for integrated conceptual studies of IFE fusion power plants in the community. Such a tool is essential for scoping studies to guide the optimal combination of various elements in an IFE power plant and to set component requirements in an integrated fashion. We strongly suggest that Germany collaborates with the international community to create a comprehensive system code, leveraging its own expertise in the field.

Highly specialized diagnostics are required to study the extreme conditions of ICF plasmas while being compressed, heated and ignite. Furthermore, diagnostics must provide information on the drivers and systems surrounding the plasma. Data obtained are used to validate and verify theories, models, and codes used for design and prediction. In a fully operational commercial fusion power plant, diagnostics are expected to be minimal, but on the intermediate test facilities and pilot plants leading up to that point, diagnostics will play a critical role in advancing overall understanding. While

Germany does not currently have a particularly unique or advanced ICF diagnostic capability, the development of diagnostics and the ability to validate and verify claims and experimental results must be established for any new fusion facility (including test or intermediate facilities) and for Germany to make progress in any of the other areas discussed in this report.

Establishing a robust fusion energy program in Germany can serve as a compelling draw for global talent and reinforce the significance and worth of high-tech advancements, especially in the midst of the international race to fusion energy. However, it is indeed a challenge for Germany to address the limited availability of experienced workforce in the areas of IFE plasma science and engineering, nuclear engineering, and energetic laser development. To meet the growing demands of the private sector while maintaining the excellence of publicly funded research and development, it is crucial to invest in building up a comprehensive and modern curriculum at universities and colleges. Specialization and hands-on training are important components and require experimental facilities and cutting-edge development funding. Universities and colleges should work with industry partners to develop programs that offer practical training opportunities in experimental facilities.

Germany has not yet established itself as a significant contributor to the field of ICF or IFE when compared to the United States, United Kingdom, Japan, Italy, or France. While China and Russia have yet to declare IFE ambitions, they have already embarked on building large-scale ICF lasers that resemble the NIF. Nevertheless, the challenges posed by this technology are vast, and Germany has a unique opportunity to utilize its capabilities to make a significant impact and establish itself as a crucial partner in this area. To achieve this goal, Germany must establish and strengthen international partnerships with strategic allies and IFE technology leaders.

We are in a pivotal decade, and it's important to take ambitious action towards addressing the climate crisis by utilizing existing technologies and establishing Germany and Europe as a clean energy innovation hub. Fusion holds promise as a long-term solution to the climate crisis while providing economic, sovereignty, and national security benefits. However, to be successful, IFE must compete with other clean energy sources such as solar, wind, advanced nuclear reactors, and fossil fuels with carbon capture and storage. To realize the potential of IFE, Germany must launch a significant, well-coordinated program with long-term investments. By establishing itself at the forefront in this promising technology, Germany could reap the economic, environmental, and strategic benefits of fusion energy while playing a leading role in advancing the field on a European and global scale. The need to invest is urgent and swift action is required to lead rather than follow in this area. Harnessing fusion energy would undoubtedly change the course of human history, with the potential to transform how we use this vital resource and provide for energy resilience and energy sovereignty.

02

Conclusion and High-Level Recommendations

Energy is at the heart of modern economies, and recent global events point to the importance of energy security and sovereignty for Germany. While a diversified portfolio of energy sources is likely needed to fulfill future needs, fusion offers a potential long-term energy source that is not only clean, but virtually limitless, and does not produce long-lived radioactive waste.

With the recent demonstration of fusion ignition on the NIF; the growing scientific basis of fusion ignition, burn, and energy gain; significant growth from the private sector and new public-private partnerships; and a number of exciting emerging technologies making progress, we are at a pivotal juncture in IFE research. It is an opportune time for Germany to get involved in inertial fusion energy.

The main findings and recommendations of the IFE Expert Panel are set out below and are further explained and substantiated in the main body of this report. IFE-specific science and IFE technology elements are each described in separate chapters, along with their role in IFE, existing capabilities and competencies, challenges and technical gaps, and specific priority research opportunities.

2.1 Fusion Energy is in the National Interest: Pursuing Both an IFE and an MFE Program is Essential

Finding Fusion energy is of national interest. It can provide for energy sovereignty, resilience, and contribute to a diverse energy portfolio. While Germany does not currently have an IFE program, it would be in its interest to pursue one. IFE represents a viable path towards achieving fusion energy, presenting distinct technical advantages, disadvantages, risks, and benefits when compared to MFE. Both fusion technologies need cutting-edge science and sophisticated engineering and as such will spur innovation, attract talent, strengthen international competitiveness, contribute to a modern society and foster economic growth.

Recommendation Germany should pursue both a strong MFE and IFE program. Where appropriate, the two programs should work closely together to accelerate progress on their technological commonalities, build a brand such as Fusion Lighthouse Germany, and strengthen Germany's position in international competition for resources and intellectual property.

Fusion energy research is a critical and high-stakes endeavor that requires the pursuit of a diverse range of technologies to increase the chances of success. Both magnetic confinement fusion (MFE) and inertial confinement fusion (IFE) are promising technologies that can contribute to achieving this goal. While a winning technology cannot be identified at this stage, pursuing both MFE and IFE research and development can increase the chances of success.

A society that is committed to finding sustainable and environmentally friendly solutions to meet its energy needs must invest in fusion energy R&D and demonstrate openness to various technologies. By doing so, it can position itself as a leader in the transition to a more sustainable future.

In Germany, building an IFE program alongside the ongoing and strong MFE program could lead to advanced innovation and programmatic pace, ultimately moving the country forward. While the plasma physics and reaction chamber of the two approaches are quite different, synergies exist in the elements further away from the plasma and should be explored. leading to a collaborative effort to advance fusion energy research and development, build a vital program with the ultimate goal of achieving sustainable, clean, and limitless energy.

While magnetic and inertial fusion use very different physics approaches and there power plants are vastly different in their core engineering design, there are some commonalities that could apply to both types of power plants, such as in developing a regulatory framework for commissioning, operation and decommissioning, power plant balancing, fuel cycle, thermoelectric conversion and turbines, cooling mechanisms, blanket materials development and design, waste stream management, safety, etc. Government should incentivize the building of joint working groups to foster solutions to these problems and initiate collaboration.

2.2 Urgency to Move Now

FINDING	IFE is a burgeoning field, has enormous potential, and is essential to a future diversified energy portfolio. It promotes high-tech innovations in areas in which Germany has unique competencies. Numerous countries worldwide are taking action to develop IFE technology and claim the intellectual property essential to serving the growing global energy market.
RECOMMENDATION	Germany needs a robust, aggressive IFE program with a sustained and critical mass of funding to enable the country to get a foothold in the field. The pursuit of both an applied research and technology program and a supporting basic science program is of the utmost importance as the race for fusion energy unfolds worldwide. Germany should strive to be a leader in laser fusion energy and enabling technologies and a strategic partner for its allies in these fields.

The fusion experiment at Lawrence Livermore National Laboratory‘s National Ignition Facility on 12/5/2022 has provided evidence that scientific inertial confinement fusion with lasers is feasible, demonstrating the viability of laser fusion. Among others, the 2013 report from the United States National Academy of Sciences, Engineering, and Medicine (NASEM) recommended the establishment of a comprehensive program to explore inertial fusion energy once ignition had been demonstrated. As such, the time has come to take action, as the world has already begun to make progress in this area.

It is, however, such a large challenge to achieve this that no one country can do it alone. It is therefore essential that countries work together and pool their resources to advance fusion energy. IFE technologies are currently at different Technology Readiness Levels (TRLs), ranging from 1 to 5, as indicated in this report and in [BRN2022], with Germany leading in some of the higher TRL IFE-enabling-technologies. This implies that a robust basic and applied research program is necessary to develop these technologies. Given the complex scientific and engineering challenges involved, substantial (initial >€150Million/yr), sustained long-term (horizon 10 yrs minimum) public funding is essential to attract talent and establish the workforce, commitment, passion, capabilities, and competencies needed to advance the field. The facilities required to support IFE development in Germany may take several years to construct and bring online, and are essential prerequisites for successful technology transfer. Additionally, sustained public funding is necessary to create a stable environment that encourages private industry to invest in long-term projects and enter into public-private partnerships in Germany that may have significant payoffs in the future.

By developing a robust IFE ecosystem in Germany, the country can not only reap the benefits of IFE developments worldwide but also bolster its economy in areas where it already excels while simultaneously creating new areas of growth. The country may need to undertake concurrent efforts and take on more risks, which could result in higher costs, to increase the chances of success and acceleate the development timeline. It is imperative that Germany moves quickly to capitalize on this opportunity and leverage its strengths to become a leader in IFE. Failure to do so may result in missed opportunities for the country and will leave it lagging behind other countries in the IFE space.

The urgent prioritization of IFE R&D is crucial to make it technically and economically viable within a reasonable timeframe that aligns with the projected increase in global energy demand. It is therefore imperative that both an applied research and technology program and a supporting basic research program be implemented simultaneously and on an expedited schedule to provide the technological basis for planning a fusion power plant in the near future.

2.3 Building Trust for Fusion Energy

Finding	The success of fusion energy hinges on a supportive social and political environment that accelerates research, development, and deployment efforts. The timeline for achieving fusion energy depends on the level of investment, commitment, and determination.
Recommendation	The German government needs to foster an ecosystem that enables fusion, builds trust, and engages the public to build support for IFE development and deployment.

As with many emerging technologies, the government can spur the development and adoption of fusion by setting up the conditions that promote innovation and provide the incentives to accelerate. This includes

- **public policy**, e.g. promote trust by implementing transparent and open communication with the public about the country's commitment, progress, benefits, and risks associated with IFE development,
- **creating markets**, e.g. Implementing policies that encourage innovation, providing financial support through grants and funding programs, reducing regulatory barriers, promoting entrepreneurship and a start-up culture, and creating networks and partnerships with industry and academia to facilitate knowledge sharing and collaboration,
- **a welcoming regulatory environment**, e.g. providing a planning base for investors and private industry, as well as assuring the public that the technology is being developed responsibly,
- **vigorous funding opportunities**, including cooperative programs with other countries, and providing funding and support for education and outreach programs to promote scientific literacy and public understanding of IFE,
- **and investment in signature** IFE technology testbed and training facilities.

Throughout the expert panel hearings, representatives from startups and private industry emphasized the crucial importance of government commitment and trust-building.

For example, the current "Atomgesetz" primarily regulates nuclear fission and the handling of (fissile) radioactive materials, so it does not specifically address fusion energy. However, it does regulate the licensing and operation of nuclear facilities, and new regulations or amendments may be necessary to address the safety and licensing of fusion facilities in Germany. This is because fusion is fundamentally different from fission and carries no risk of runaway or long-lasting radioactive waste streams, nor is it associated with nuclear weapon development or proliferation risks. Therefore, it is crucial that the German government assist and guide the development of a regulatory framework that supports fusion power (both IFE and MFE) and R&D, rather than obstructing it, and that clearly distinguishes fusion from fission. The United Kingdom has already done this, and the United States is poised to follow. Establishing an international agreement on this issue would be beneficial. Without a suitable policy and regulatory framework, startup companies, industry, and investors may look to other countries with more favorable opportunities.

To accelerate the transition from fundamental science to practical application in fusion energy, it is essential to establish specialized facilities that can enable accelerated learning and experimentation with new technologies. Given the limited required IFE technology capabilities, there is an opportunity for Germany to establish signature facilities with cutting-edge technology in various IFE-relevant areas and become a leader in this field. These may include energetic high-power lasers; accelerated testing of optical materials; target manufacturing; target injection, tracking and laser engagement; blanket development; and reaction chamber (first wall) materials development and testing.

By establishing such facilities, Germany can become a strong partner to its strategic allies in IFE, providing the necessary resources and expertise to advance the development and implementation of this critical technology. The functional requirements and primary criteria for these facilities should be developed in an open dialogue with stakeholders, such as private fusion companies pursuing a distinct and credible approach to fusion energy, national laboratories, and relevant government agencies.

By fostering collaboration with stakeholders and investing in these facilities, Germany can accelerate the transition to the practical application of fusion energy, benefiting both its own energy security and the global community.

Finally, well-designed public-private partnerships should be used to leverage the capabilities and resources of both sides while creating competition through appropriate Request for Proposals (RFP). Funding mechanisms that offer greater predictability and accountability, such as milestone-based programs, can be used, while international partnerships can be leveraged to increase access to facilities that are unavailable in Germany.

2.4 Need for Establishing Competency-Based Fusion Hubs

FINDING	Germany already harbors many areas of unique competence and expertise of relevance to IFE.
RECOMMENDATION	Organize "hubs" or "centers of excellence" around competencies and capabilities that can grow the most crucial and highest return-on-investment science and technologies for Germany. Principles of open innova-

tion should be promoted so that fusion research and commercialization can move as fast as possible.

Creating hubs or centers of excellence that combine expertise and resources from various regions of Germany is a swift and impactful way to tackle shared challenges encountered by different approaches to IFE, and thus also shared by multiple private and public ventures. These hubs should be established on existing German strengths and expand their areas of competence by pooling resources, generating new skills, knowledge, techniques, and technologies. Such hubs must involve universities, national labs, and private industry to ensure comprehensive and robust solutions to complex problems.

By organizing around community needs, the development and integration of technologies through the hubs can help demonstrate the required performance is possible and provides a community technology development testbed. Advancements that can solve the highest number of common problems should be targeted, with the efforts within the hubs aligned to ongoing overall systems efforts to further inform requirements and ensure consistency. The private sector should be strongly engaged to both help set the needs and requirements, but to also partner and provide joint funding.

Several areas identified by this expert panel with high potential include:

1. High power optics and laser systems
2. Target manufacturing
3. Fusion materials
4. Nuclear process engineering
5. Nuclear/safety engineering
6. Simulations and modeling (as a crosscut supporting the other hubs)

Applying open innovation principles enables access to a broader range of expertise and resources, tapping into a larger network of researchers, entrepreneurs, and startups. This can reduce costs and risks while accelerating development, fostering a wider range of ideas and approaches, ultimately promoting greater creativity and innovation, and spin-outs along the way. We also note that bullet points 3, 4 and 5 present excellent opportunities for synergy with existing or to be developed MFE programs in this area.

2.5 Focus Needed for Establishing Successful Leadership in IFE

Finding	Several private fusion companies have recently been established in Germany. Each is pursuing a different fusion engine (fusion-driver) approach, and their R&D is solely focused on that one design.
Recommendation	A significant government-led effort in IFE is required to coordinate and focus the overall IFE effort in Germany, and to establish leadership for the country.

Recently, several private fusion companies have been established in Germany. In addition to securing investment and developing innovative concepts for fusion energy, these private fusion companies also play a vivacious role in promoting the acceptance of IFE by industry and the public. In addition, fusion companies and the established private sector that provide enabling technologies are driving the commercialization of fusion energy, and public-private partnerships could greatly accelerate the development of a healthy ecosystem for fusion technology innovation and grow new markets.

During our discussions with MFE and IFE startups, we were impressed by their impressive levels of motivation, despite facing highly ambitious goals and resource limitations. Although many have made good progress in hiring skilled personnel to develop their concepts, it is clear that a fully-fledged development effort is necessary to bring IFE to fruition and construct a functioning power plant. In the previous statement, we noted that the scale of technological development required to achieve these goals is too great for any one country to undertake, given the unavailability of manpower and the limited infrastructure and test capabilities that are absolutely necessary to develop a FOAK IFE demonstrator.

In the IFE sector specifically, German startups Marvel Fusion and Focused Energy are focused on developing a First-Of-A-Kind power plant. This involves research and development of enabling technologies as well as the development of plasma physics and target concepts. Each of these areas has tremendous opportunity but must also be developed in close collaboration and integration with the larger project to develop an IFE demonstrator. Addressing this challenging task may be possible if either a national laboratory that provides integrity and confidence and has extensive expertise in systems engineering, or a professional systems integration firm with comparable capabilities, assumes responsibility for managing and communicating performance and risk budgets on behalf of a wider IFE program.

Another large challenge is, that significant infrastructure is needed to test the approaches touted by these companies and to establish both scientific and commercial viability. This infrastructure includes experimental facilities, production capabilities, theory, computation, and modeling expertise, and workforce. Developing the necessary infrastructure for IFE cannot be accomplished solely by single private companies in the near or long term. It necessitates the participation of public sector organizations that have expertise in constructing and operating large-scale facilities and user facilities, such as the Helmholtz-Association, Fraunhofer Gesellschaft, Max-Planck-Society and universities. These institutions have abundant knowledge and resources that can be utilized.

Consideration should be given to engaging in collaborative efforts between private industry and the research organizations for the development of these facilities, as it can stimulate technology innovation and facilitate technology transfer. Therefore, the development of IFE will require collaboration and coordination among diverse fields and public sector organizations. In fact, growing a healthy IFE ecosystem will require some assistance through partnerships with leading universities.

To best steward public funds, and ensure that Germany is on the best path, coordination should programmatically be managed and occur at the central level. Periodic re-assessment is also recommended to assure agility as new knowledge is gained.

2.6 Evaluating and Prioritization of IFE concepts

Finding	There are many IFE concepts. It is difficult to make measurable progress if the efforts are too diffuse.
Recommendation	Maximize the return on investment (ROI) for public funding by targeting high-potential concepts and technologies via scoping studies with thorough physics review to inform a careful selection process that allocates resources to have the greatest impact and drive innovation in key areas of research.

To ensure that public funding for research and development initiatives in Germany generates the highest possible return on investment, it is important to prioritize concepts and technologies with the greatest potential for success. A careful selection process should be undertaken to identify the most promising concepts and allocate resources where they will have the greatest impact. Comprehensive scoping studies, with input from stakeholders such as the power generation industry and experts in fusion science and technology, should be conducted to pre-select and provide direction for technology development. Independent peer review, milestone-based programs, market creation (buying products and services from start-ups or private industry rather than providing subsidies to fund their R&D), and other methods are best suited to manage risk, stimulate the economy and create demand, incentivize short time-to-market, and ensure cost-effectiveness. Each IFE effort should also allow support for open technology, high risk, high reward approaches if their idea is scientifically feasible.

By adopting a targeted approach to public funding, Germany can effectively support innovative and high-impact initiatives, drive progress in key areas of research, and position itself as a global leader in science and technology.

2.7 Develop an Integrated System

Finding	Globally, there is a gap and need for integrated systems models for IFE, which are necessary for evaluating risk and tradeoffs.
Recommendation	Germany should build up a capability to model full integrated fusion power plant systems.

While there have been several notable full system IFE studies in the past (HAPL, LIFE, HYLIFE, SOMBREO, etc.), there currently does not exist a fully integrated systems modeling (systems engineering) capability anywhere globally. Such systems models are required to manage the complexity of a fusion plant concept, identify areas for development, understand challenges and risks, and determine performance or engineering tradeoffs between subsystems. Such an integrated systems model is necessary to help define the roadmap of science and technology development.

Furthermore, an integrated systems model that can evaluate design choices is crucial to help Germany determine the viability of different approaches and compare and contrast their advantages and disadvantages. This type of appraisal is necessary to guide the government and the field in making the best decisions on how to invest their limited resources and workforce.

The expert panel finds that this may be a particularly good place for international collaboration. While Germany has strong systems engineering expertise to bring to the table, the historical IFE system knowledge-base still sits outside the country, and collaboration may bring both to bear.

Systems modeling is also a need in workforce and training.

2.8 Establish Public Private Partnerships

Finding	As investments in both the private and public sector for fusion are ramping up, significant opportunity exists to create appropriate and well-thought-out public-private partnerships (PPP) that are mutually beneficial and can accelerate the development and commercialization of IFE.

Recommendation	Germany should facilitate PPP structures and programs that enable an environment where both public and private ventures can support each other, and enable both to be competitive with the global ecosystem.

Germany should help facilitate public-private IFE partnerships that serve the needs of both the public and private sector and can help accelerate the development of IFE. The public sector possesses considerable expertise in a range of R&D areas relevant to IFE, and these capabilities can and should be appropriately leveraged via PPP's to help grow the fusion sector. By planning appropriate programs, resources, facilities, and streamlined community access, PPP's can be thoughtfully developed to help advance both individual company concepts while sustaining and growing foundational capabilities that serve the entire community. The hubs described in Recommendation 4 are one such mechanism that would allow for joint development of common technologies, where subsequent knowledge and intellectual property could then be shared.

Such PPP's could be used to address foundational research and development, next-generation test and support facilities, licensing and regulatory issues, and workforce development. Appropriate joint planning and road-mapping activities facilitated by PPP's would be useful to guide investments for both the public and private sectors. PPP's may also play an essential role in developing the necessary workforce for the future. Initiatives where the public and private sector are working together can enlarge the available workforce and widen the training opportunities, while providing increased vitality and flexibility to the overall fusion ecosystem.

2.9 Establish International Collaborations

Finding	Challenges in fusion energy are significant and multifaceted, and Germany need not try to solve all of them on its own.
Recommendation	Use international collaborations to reduce the risk and cost of a German fusion program while protecting German intellectual property and competitive advantages.

In IFE, there are numerous technical and scientific challenges that must be addressed to develop a viable and sustainable fusion energy source. Some of these challenges include achieving high target gains, improving the efficiency of laser systems, developing target fabrication methods capable of producing high quality fuel capsules in large quantities. Moreover, solutions are still needed for first wall materials and breeding blankets in fusion reaction chambers in general.

Given the breadth and complexity of the challenges facing IFE, it is unrealistic and impractical for any one country or organization to attempt to solve all of them on their own. Instead, it is important for countries like Germany to focus their resources and efforts on specific areas of expertise and where they can make the most meaningful contributions and not replicate efforts other strategic allies are already pursuing. While the challenges facing IFE are significant and multifaceted, it is important for Germany to focus its efforts and expertise on specific areas where it can make the greatest impact and collaborate with others to collectively advance the field.

2.10 Strategize on IFE Implosion Facility

Finding	There are limited experiments available on existing implosion facilities, worldwide, to rapidly advance IFE ignition and gain, and technology development.
Recommendation	Germany should develop a strategic plan for testing target concepts on IFE implosion facility, including considering building a next generation IFE implosion facility with international partners as appropriate, to accerate the pace of IFE research and development.

Compression and fuel assembly are key requirements for achieving a self-sustaining burning plasma that can ignite. Specifically lower adiabat, high gain targets have proven tricky when scaling from subscale experimental results, requiring full-scale testing and tuning. Currently, only the NIF at LLNL in the US is a full-scale fusion facility capable of conducting implosion experiments and generating a burning plasma. Three other facilities, LMJ in France, OMEGA at LLE, and SG-III in China can study sub-scale spherical implosions, but do not have the drive energy to achieve fusion burn or burn propagation.

To accelerate progress, it is imperative to conduct more experiments to test different designs – this is true not only for Germany but globally. Hence, Germany should develop a strategic plan for the next ten years on where and how testing of target concepts on an IFE implosion facility can be accomplished and consider building the next generation IFE implosion facility with international partners as appropriate. Consideration should be given to scale, phasing, access to testing, concept variety, etc. and build on the Key Enabling Technology program (lasers, targets, first wall and reaction chamber etc.) that has been assembled prior. Such a facility could facilitate research on implosion physics in direct or indirect drive configuration, target injection, and tracking, debris removal, materials and component testing. Strategy and scoping is needed within the next two years to inform Germany's overall IFE program and prepare accordingly.

2.11 Maintain IFE Approaches until Assessment Studies are Done

Finding	The optimal target-drive-configuration for high gain is still to be determined. Both the direct and indirect drive approaches, have potential, but with risks and unknowns. Other alternate schemes such as fast ignition or shock ignition could potentially achieve higher gain; however, their physics and technologies are at even lower technical readiness levels (TRL).
Recommendation	It would be prudent to keep both potential pathways open, as well as exploring alternate, viable concepts.

There are pros and cons to both direct drive and indirect drive. Our analysis shows that there is not yet a winner for either concept due to unknowns or scaling that has not been validated on a full-scale ignition target. While current indirect drive concepts may be limited in maximum gain, the advantages of direct drive may also be outweighed by increased system and laser complexity, including less laser efficiency. Therefore, it would be prudent to keep both avenues open and explore alternative concepts that are viable at the same time. Here is why:

For a fixed laser, direct drive has greater energy coupling to the capsule by avoiding the intermediate hohlraum laser-to-x-ray energy conversion step of indirect-drive. This can be an energy advantage of 7-10x. Some of this energy advantage may be offset by cross-beam energy transfer (CBET) which can redirect inward coming energy outward. While the ablation pressures for direct and indirect-drive are similar, the mass ablation-rate for indirect-drive is larger, because of the deeper penetration into the ablator of x-rays. This leads to a higher hydrodynamic efficiency (ratio of implosion kinetic energy to energy absorbed) in the case of indirect-drive. Taken together (the two bullets above) the overall laser energy to implosion kinetic energy conversion of direct-drive is ~5% while for indirect-drive it's ~1.5%.

Due to the energy advantage of direct-drive, the stagnation pressure requirement for ignition of a direct-drive implosion is approximately half that of indirect-drive. This leads to lower implosion convergence requirements for ignition. This then leads to larger capsules allowable for direct drive, which can provide larger fusion yields (~4x) for a given implosion velocity.

However, the direct-drive advantage in energy coupling is offset by the higher adiabat (lower fuel compression) requirements of direct-drive that are needed for hydrodynamic stability control. This increased sensitivity of direct-drive implosions is essentially due to the steeper ablation density profile associated with the electron-conduction as opposed to the less steep profile in x-ray driven ablation. Direct-drive implosions have an additional seed for high-mode (>30) hydrodynamic instability, laser "imprinting," that indirect-drive avoids by use of a hohlraum. Because of the laser directly impinging upon a direct-drive capsule and because of the relatively thin ablators used in the direct-drive, electron preheating of direct-drive capsules is correspondingly more difficult of an issue than for indirect-drive.

Indirect drive has demonstrated ignition. Direct drive has not yet, and it is to be seen if the issues described above are surmountable and whether direct drive can indeed provide the ~3x improvement in energy coupling. See Sec. 5.2 for more detail.

On the engineering of the fusion reaction chamber and fuel injection, the indirect drive approach to convert laser energy to x-rays through the hohlraum leads to a more complex target, but also protects the fragile ID capsule and DT fuel within when entering the hot reaction chamber. The target could be rapidly spun around its cylindrical axis to provide stability during its flight phase to the point of engagement with the lasers. For direct drive (DD) capsules, a solution[1] is required to protect them during injection into the chamber environment and to prevent them from heating[2] or deforming during their transition to the point of engagement. Reducing the chamber buffer gas, as compared to indirect drive configurations, to protect the DD target will increase the risk of damage to the first wall. A sabot (a casing that protects the capsule in flight phase and opens before laser engagement) has been proposed to encase the DD capsule.

[1] Two methods have been proposed and one demonstrated. Mechanical deflection of the sabot (after leaving barrel and before entering chamber) into a collector. Sabots would then be recycled by regrinding and remolding. This method was demonstrated. The other method is electromagnetic deflection and recirculation of the sabot (after leaving the barrel and before entering the chamber). This is still in the concept stage.

[2] Heating would cause increase in entropy and asymmetry. Protection could be by IR reflective layer, working with liquid fuel, injection at much higher speed, reduced chamber buffer gas work to protect target, however that would increase the heat load and damage effects on the chamber walls.

2.12 Assess IFE Programs for Accountability

Finding	Defined metrics and milestones are necessary in programmatic initiative to assess and measure progress.
Recommendation	Government-initiated IFE programs should include performance metrics and milestones.

A fusion working group should be established to establish meaningful metrics and milestones for the particular IFE program and its associated R&D that can measure progress and serve as markers of success. Entities receiving government funding must participate in time-bound reporting and meet deliverables to continue to have access to the grant or loan. Metrics should be inclusive of different approaches and allow for risk-taking and innovation, while remaining technically rigorous. Key performance indicators and project milestones with associated completion criteria are an example of how program progress can be measured.

2.13 Build and Maintain German Competencies

Finding	Inertial Fusion Energy is a multi-disciplinary field that requires a diverse range of expertise from various fields, including physics, engineering, materials science, optics, and computer science. As a potential carbon-free, abundant energy source, IFE is a great motivating goal to attract new talent and inspire the next generation.
Recommendation	IFE can and should be used to attract diverse talent to MINT: Conduct a study of the fields, skills, and career types that are required to develop IFE and operate a fusion plant in the future. Promote study results to MINT and STEM audiences through appropriate advertising material. Demonstrate commitment to fusion by providing programs for fusion development and education (see Sec. 2.14).

IFE is an emerging field with the potential to revolutionize the way we generate energy and solve the global energy crisis. This potential for impact can attract a wide range of people who are passionate about making a difference in the world. By highlighting the opportunities for innovation and collaboration in this field, new talent can be encouraged to pursue careers in STEM. However, there has always been a lack of diversity in STEM fields, particularly in terms of gender and race. Using IFE as a means to attract diverse talent can help close this gap and create more opportunities for underrepresented groups in STEM fields.

In order to attract diverse talent to the STEM fields (Mathematics, Computer Science, Natural Sciences, and Technology), it is important to promote the exciting career opportunities that exist in the development of IFE (Inertial Fusion Energy) and the operation of a fusion power plant in the future. A study of the fields, skills, and career types required to develop IFE and operate a fusion facility can be an effective way to showcase these opportunities and attract diverse talent.

The fields involved in IFE development and operation include physics, engineering, materials science, computer science, and mathematics. Skills required include experimental and theoretical physics, both in the area of materials, lasers, nanoengineering, production engineering and so on, engineering design and analysis; high performance computing, materials science, data analysis and visualization, and project management. Career types in this field include research scientists, engineers, technicians, project managers, and administrative personnel.

To attract diverse talent to this field, it is important to

- demonstrate a commitment to fusion by providing programs for related education. This may include international and domestic scholarships, internships, financial aid for underrepresented groups, and training programs for students and early career professionals from diverse backgrounds. It may also include partnerships with universities and research institutions to advance fusion research and development,
- Recruit and retain diverse faculty and staff at universities,
- Support student organizations and initiatives
- Partner with organizations that promote diversity
- Enable defined and simple routes for students to engage in hands-on experiences and connect with potential employers.

Appropriate promotional materials, such as brochures, websites, social media campaigns, and outreach events, can be developed to promote the study results and career opportunities to STEM audiences. It is important to highlight the potential impact of fusion on society and the environment, as well as the exciting research and development opportunities in the field.

2.14 Development of an IFE Curriculum is needed

Finding	Germany (and the world) is currently lacking and IFE curriculum at the universities and schools.
Recommendation	A concerted effort to develop an IFE curriculum is crucial to building up the necessary IFE workforce of the future.

University level curricula are the most urgent since IFE in a research and development phase. Then high school curricula as high schools are a pipeline of students to universities. When IFE nears or reaches a deployment stage, technical school curricula will be needed.

An IFE curriculum is needed to train and build up the workforce of the future that will be capable of taking on the challenges of developing IFE. The curriculum can be designed for undergraduate and graduate students, as well as for professionals. Such a curriculum should:

- Develop a core competency framework: This framework should outline the key competencies needed to work in IFE. It should include technical skills as well as non-technical skills such as communication, teamwork, and problem solving. This framework can be used to guide the development of IFE-related programs and workshops.
- Establish IFE-relevant programs: Universities can establish or expand programs that focus on IFE-related topics such as plasma physics, ICF/IFE, materials science, nuclear engineering, high-energy laser engineering, and power plant systems engineering. These programs can be designed to meet the needs of students and industry professionals.
- Organize workshops and conferences: These events can bring together experts from academia, industry, and government to discuss the latest developments in IFE research and technology. They can also provide opportunities for networking and learning about career opportunities in the field.
- Promote education in the MINT fields:

MINT stands for mathematics, computing, science, and technology. Universities can promote MINT education by offering scholarships, mentoring programs, and outreach activities to encourage students to pursue careers in these fields.

- Connect with IFE research centers: Universities can connect with IFE centers of excellence and research to provide students and professionals with first-hand, hands-on expertise. This can be done through internships, joint research projects, and collaboration on workshops and conferences.
- Develop international partnerships: International collaborations can help expand the scope of IFE research and development. Universities can partner with institutions that have expertise in IFE and work together on joint research projects, exchange programs, and international conferences.
- Build an IFE community: Universities can create a community of IFE professionals and students by establishing student groups and organizing events such as seminars, guest lectures, and social gatherings. This community can help foster collaboration, knowledge sharing, and career development.
- Attract new talent: Universities can attract new talent by promoting the excellence and opportunities available in IFE. This can be done through marketing campaigns, outreach activities, and partnerships with industry and government organizations.

2.15 Need for a High Brilliance, Pulsed Fusion Neutron Source

Finding A pulsed neutron source prototypical of an IFE reaction chamber does not exist and is needed to fully develop and qualify IFE reaction chamber first walls and blankets. Germany already possesses key competencies in blanket and first wall design and structural engineering, but this pulsed neutron source for testing materials is missing.

Recommendation Germany must advance the research and development of the blanket and first wall by working with its partners to construct a pulsed fusion neutron source. This facility, which does not exist anywhere in the world, is urgently needed and will allow for the study of fusion materials damage and lifetime. By leveraging its competencies, Germany can play a significant role in advancing the IFE sector here.

The blanket is a critical component of a fusion power plant, performing multiple functions such as power extraction, fuel growth, and shielding the reaction chamber from the environment. However, the current technology readiness level (TRL) of the blanket for IFE devices is still rudimentary due to limitations and constraints on the blanket material resulting from the unique conditions and goals of the fusion power plant. As a result, the fuel cycle boundary conditions are also at a low TRL level.

To achieve optimal performance, it is essential to conduct extensive studies on the limitations and capabilities of different classes of materials. Scaled experiments under fusion-typical conditions are necessary, and experimental data obtained by IFMIF DONES should be used for structural materials. In addition, there are synergies between magnetic fusion R&D and ICF/IFE in the areas of blanket breeding, heat extraction, shielding, and fuel cycle processing modes and sequences.

Germany has unique expertise in the fuel cycle, materials research on irradiated structural and functional materials, and integrated blanket design, and its involvement in fusion energy research includes several industrial partners. However, activities and expertise have focused primarily on magnetic fusion, and a comprehensive approach is needed to consider all fusion options.

To test and validate material damage, degradation and survivability, a scaled pulsed neutron source capable of generating relevant fluxes with energy spectra as seen in a full-scale IFE power plant will be required. This neutron source could build on the expertise developed with the high-energy, high-rep-rate laser beamline, and it is essential to maximize the synergistic expertise in both the U.S. and Germany. The near-term focus should be on those aspects that are unique to ICF/IFE, such as pulsed operation and different first wall loads, which require investment in experimental facilities.

2.16 Support German Industry

Finding	Currently, several industries lack the capacity to support the construction of multiple laser-driven IFE power plants. These industries include the production of large laser amplifier glass, manufacturing of pump laser diodes, and fabrication of large aperture precision optics. Additionally, certain industries such as IFE target manufacturing do not exist yet.
Recommendation	Establish a robust supply chain and skilled workforce to facilitate the delivery of fusion technology and enable German industry to thrive in a future global fusion market. Create a fusion industry that sets global standards and can export fusion technology worldwide in the coming decades.

03

Overview

3.1 Overarching Introduction

3.1.1 The enormous potential of fusion makes it Hard to Ignore

Energy has driven innovation and economic growth, increased life expectancy and health, and enabled the accelerated growth of the world's population by tenfold over the last 300 years. Fossil fuels, which store the sun's energy over millions of years, have powered industrial revolutions and sustained our lifestyles with mankind learning to convert heat into mechanical power. Today, energy is not only used to sustain our lifestyles, but abundant, reliable energy is also the key to raising the standard of living for developing nations. However, as global temperatures rise and energy demands increase, transitioning to clean energy sources becomes imperative.

The pursuit of fusion energy, the process that powers the sun, as an inexhaustible source of power has been an enduring aspiration for humanity for over seven decades. If this energy source could be tapped for controlled power generation on Earth, humanity would have access to a weather-, and location-independent, greenhouse gas-free, inexhaustible, and ubiquitous energy source. Furthermore, the energy density in fusion fuels is 100 million times higher than in fossil fuels and the highest overall in the universe. In a decentralized energy grid, there will always be a need for small-footprint, high energy density power sources that can provide 24/7 baseload energy located next to large consumers such as chemical plants, metropolitan regions, seawater desalination plants, or carbon capture and sequestration plants. Even though constructing a fusion power plant is a formidable undertaking, its vast potential makes it a necessary attempt, a moonshot, that can aid in addressing both the energy and climate predicaments.

The effort to achieve the extraordinary conditions where fusion occurs with net energy gain is technologically very challenging. In fact, the performance of a fusion device is determined by three parameters: density, temperature, and "confinement" time in which these conditions can be maintained in a plasma. There are mainly two credible approaches to generate these conditions:

» Inertial confinement fusion (ICF): The concept of laser-driven ICF was originally described in the initially classified work of John Nuckolls and Nikolay Basov. To achieve the extreme temperatures (>100 Million Degree Celsius) and densities (>1000 times solid density) necessary, typically pulsed high-power lasers are used for imploding a hollow spherical shell a few millimeters in diameter containing the fusion fuel. To achieve energy gain, a considerable portion of the fuel must undergo burn before the internal pressure breaks apart the fusion conditions. The fuel's inertia confines it for a brief moment, which is why it is called Inertial Fusion. Using lasers as the driver is the most extensively researched type of inertial fusion, followed by magnetically driven inertial fusion concepts. Inertial Fusion Energy (IFE) uses the principles of ICF in the development of a practical power plant design. Typically, it will run ICF reactions at repetition rates around 15 times per second. There are mainly two ways to drive the fuel capsule:
  - "Indirect drive" is a technique in which the fuel capsule is not irradiated directly by the laser beams, but by X-rays generated by the interaction of the laser with a high-Z material, such as gold or lead, surrounding the capsule ("hohlraum"). The X-rays heat and compress the capsule, causing the fuel to ignite and undergo fusion reactions. Indirect drive has a crucial benefit of smoothing the light used to drive the implosion. This technique also reliefs

requirements on the drive laser.
  - The “direct drive approach” to laser fusion, where the laser beams impinge directly on the implosion shell. Direct drive is expected to be more efficient than indirect drive. However, laser driver technology is more challenging and complex.

» Magnetic Confinement Fusion (MCF): A large volume (~1000 cubic meters) of hot (>100 Million Degree Celsius), low density (approximately 100 billion times less dense than in ICF) deuterium-tritium (DT) plasma is confined in a stationary manner by strong magnetic fields. Heating up to burn temperature occurs through electrical currents, radio wave, and particle beam injection. MCF has not yet demonstrated self-sustaining fusion burn as there is no full-scale facility existent till now (the maximum ratio of fusion power divided by heating power deposited in the plasma was 0.67 in D-T experiments in the JET tokamak). The first facility capable of demonstrating fusion burn in an experimental setting (no net power generation) is the International Thermonuclear Experimental Reactor (ITER) currently under construction in France, with a planned start of DT fusion gain experiments in 2035. The term “magnetic fusion energy,” or MFE, refers to the application of magnetic confinement fusion principles to energy production.

On December 5th, 2022 the National Ignition Facility (NIF), a large laser fusion facility at Lawrence Livermore National Lab (LLNL) in the United States, conducted a successful fusion experiment, where the energy produced from a fusion reaction of a mixture of Hydrogen isotopes Deuterium and Tritium released 3.15 Megajoule in energy surpassing the laser energy of 2.05 Megajoule that was used to initiate it. This is the first time in human history such a feat has been achieved in the laboratory. The experiment demonstrated a self-burning plasma with a target gain of 1.5, a capsule gain of ~12, and a fuel gain of ~120. This means that after the laser ignited the DT-fuel, the energy released from the first fusion contributed to further heating the fusion fuel, triggering more fusion reactions, and thus releasing more energy. This took roughly 80 trillionth (10-12) of a second.

The breakthrough at the NIF ended the long-standing debate about whether fusion ignition was possible in the laboratory. It provided scientific proof of laser-driven inertial confinement fusion and now forms the basis of a possible path toward inertial fusion energy. This exciting result by NIF spurred significant government, private industry, and investor interest.

An IFE plant would encompass a substantial number of components and subsystems, where technologies will need to be researched and developed, production engineered and scaled to mass-production and transported to various construction sites across the globe. One of the key subsystems of an IFE power plant is the laser driver system, comprising hundreds of 100kW-class high energy laser system modules. Production of these and servicing them and other components for plants could bring significant economic benefits to communities and regions both in Germany and internationally.

To date, the main fusion approach pursued by Germany has been Magnetic Fusion Energy (MFE). The basic science mission is funded by the German Federal Ministry of Education and Research (BMBF) with €149 million per year (2023) and includes smaller efforts for materials studies and development efforts for the first wall in the reaction chamber, fuel cycle or blanket development. As such, Germany is a world leader in plasma science and technology for the Tokamak, and especially the Stellarator line. Germany is the largest contributor to the EUROfusion consortium that strongly supports ITER and aims to develop the physics and technology basis for a European MFE demonstration plant (DEMO). Germany contributes to ITER via the EU domestic agency F4E (for development of diagnostics and heating and current drive systems) and other international programs in the US, UK or China. While reactor concepts and associated technological developments are more advanced in

MFE, the studies of burning plasma physics in IFE have already progressed into the burning plasma regime. Investing in the R&D of both approaches hence increases our chances of achieving sustainable energy goals.

Triggered by the advancements in laser inertial fusion, the BMBF initiated a process in September 2022 to explore the potential of laser inertial fusion and to outline the path to a possible power plant, with the participation of recognized experts from German science and industry that led to organizing this expert panel to take a deeper look at Germany's competencies and capabilities, and how to best align them.

Extensive research is still necessary in the field of plasma science and fusion in order to realize a fusion power plant. However, even at this stage, such a power plant should be designed with a focus on feasibility and economic viability. As the technology readiness levels of the key technologies are matured, it is expected that there will be many spin-out technologies and opportunities. A few examples include: laser-driven secondary sources for medical and semiconductor technology, future analysis of defense components, nuclear radiation effects testing, target production, sensor technology and diagnostics, simulation and modeling, and material development, among others.

Generating power from any type of fusion technology presents significant scientific and technological difficulties. There are many ways to make fusion and today there are a plethora of concepts that have been tried. Each concept has its own pros and cons, there is no magic shortcut – in the fusion plasma, sufficient density and temperature must be achieved over a long enough timescale to generate enough burn and overcome the numerous loss mechanisms, and the various subsystems must be compatible and together form an integrated power plant solution that is economically viable. Due to the many remaining unknowns, but also the significant potential benefits, it is crucial to maximize the chance of success, on as fast a timescale as possible, by exploring multiple avenues in the pursuit of fusion energy. To achieve power generation from fusion energy by the middle of the century, it is essential to commence the development of enabling technologies and underlying engineering for IFE without delay, even though there are still obstacles to overcome in ICF science. Although the plasma physics and reaction chamber of IFE and MFE differ significantly, there are commonalities in the technological elements further away from the plasma that can be leveraged. Therefore, conducting a joint program to study these aspects will lead to synergies, particularly in areas such as the outer fuel cycle and material questions.

3.1.2 Fusion is Inherently Safe

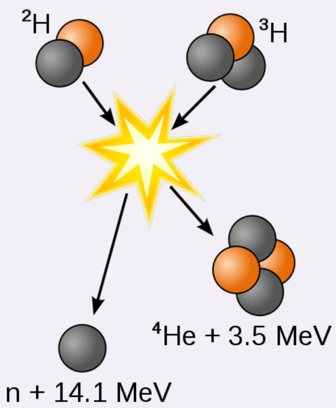
Understanding the distinction between nuclear fission and fusion is crucial. Fusion works by releasing energy by forcing together light atoms such as hydrogen, which requires a very precise balance of temperature, pressure and fuel density. The reaction is self-limiting because in any event of a malfunction, the reaction will automatically stop – defined by the underlying physics. The fusion reaction that is easiest to initiate in conditions we can achieve on earth, is between the two hydrogen isotopes, Deuterium and Tritium, resulting in the production of one Helium nucleus (an alpha particle) and one energetic neutron. This process will also produce some very energetic x-rays and particles, but any activation of the reaction chamber walls is expected and well-understood, and can be safely accommodated. By the choice of appropriate materials in a fusion reaction chamber, the radioactive waste produced will decay on the order of ~80 years vs. 100,000's of years for fission, hence no long-lived radioactive waste is generated.

In contrast, the current conventional nuclear power stations are based on nuclear fission that rely on splitting heavy atomic nuclei through fission reactions. Nuclear fission entails the division of a heavy atomic nucleus into two or more smaller nuclei, resulting in the release of energy. This process can become chain-reactive and lead to an uncontrolled release of energy, potentially causing melt-down and catastrophic destruction. This cannot happen with fusion. Additionally, the by-products of nuclear fission are highly radioactive and can remain hazardous for thousands of years, posing significant risks to human health and the environment.

Another very significant concern with nuclear fission plants is the proliferation of fissile nuclear material that may be used in a nuclear weapon. In contrast, Fusion enhances non-proliferation efforts. Fusion does not produce plutonium and would not involve enrichment, reprocessing, or other technologies with greater proliferation potential. This will allow for the confident sharing of fusion technology and construction of fusion power plants worldwide, even in countries that may be geopolitically less stable.

What is Fusion?

Fusion, the power that drives the sun and stars, combines light elements in the form of plasma - the hot, charged state of matter composed of free electrons and atomic nuclei - that generates massive amounts of energy. Scientists are seeking to replicate fusion of Earth for a virtually inexhaustible supply of power to generate electricity.



3.1.3 Proliferation

Nuclear proliferation concerns for ICF typically center around the spread of nuclear weapons technology, knowledge, and materials to countries or organizations that did not previously have access to these capabilities. Furthermore, there is worry about the ability to enrich uranium or plutonium into fissile materials which can then be used for nuclear weapons, or tritium diversion. The proliferation risks associated with IFE and ICF R&D have previously been assessed ([NASEM2013]: Assessment of Inertial Confinement Fusion Targets), with the high-level findings being:

1. While it is technically possible to utilize the large neutron fluxes generated in a fusion reaction chamber to enrich U or Pu, to do so covertly would be incredibly difficult and current IAEA monitoring would be sufficient to safeguard against this scenario as transfer of the material into and out of the fusion power plant would likely be detectable, and reprocessing facilities would also need to be constructed – an activity that is not easily hidden.
2. Tritium is an essential fuel for a fusion power plant and can also be used to fuel modern nuclear weapons. It is conceivable that tritium could be diverted from the power plant, however, tritium can be produced in several ways in sufficient amount, and with current technologies tritium alone is not useful for building a nuclear weapon.
3. Much of the information related to ICF targets is already declassified. Only some aspects of computer codes and certain target designs remain classified. The pursuit of ICF does not directly provide insight into that classified information, and furthermore, that information is primarily useful only in the presence of the large database of historical underground tests.

4. Fusion research facilities can provide insight into fusion physics; however, this is not the same as information about weapons design. Fusion power plants will likely be engineered for economics and efficiency, with minimal diagnostics, so would provide only limited information about the physics itself.

It has been assessed that the risk of proliferation from nuclear fusion power plants is far less than fission power plants and the authors of this Memorandum are in full support of the above findings.

3.1.4 Why Inertial Fusion Energy?

When considering power generation from fusion energy, laser driven IFE offers several advantages [BRN2022] over other approaches:

» IFE is highly modular and uses separable components, providing flexibility in developing subsystems and future commercial fusion reaction chamber.
» IFE has multiple target concepts that can be tested with the same driver, reducing risk and allowing for varied testing with the same facility.
» IFE targets typically require approximately 0.3 milligrams of DT, which aligns with the anticipated burn-up fraction for IFE with a gain of 100, estimated to be around 30%.
» IFE offers a development path that enables methodical progress on systematically more complex facilities.
» The modular technology of IFE is furthermore expected to generate technology and science spin-offs that will provide early return on investment (EROI).

Researching and developing fusion energy is a major scientific and technical challenge that requires different approaches and paths to maximize the probability of success. Against the backdrop of significant progress in the last two years, several countries are launching new initiatives and investments to accelerate technology development for energy production from IFE and to build innovation ecosystems with industry and position themselves in international competition. Known countries include USA, the United Kingdom, Japan, France and China.

3.1.5 International Research of Inertial Fusion Energy

There are several laser fusion schemes, including indirectly or directly driven with hot spot ignition, and advanced schemes such as shock ignition, electron fast ignition, and proton fast ignition. The latter approaches are less explored and vastly more complex, but theoretically have the potential for higher fusion energy gains (>100) suitable for power generation. The two main ICF programs in the US are carried out at the National Ignition Facility (NIF) at Lawrence Livermore National Laboratory (LLNL) in California and the OMEGA Laser Facility at the University of Rochester in New York. The ICF program within the Department of Energy's (DOE) National Nuclear Security Administration funds both entities, which have a combined funding of around USD 420 million and employ about a thousand individuals. NIF is the largest and most energetic laser system in the world, and it is used to study a range of scientific phenomena, including high-energy-density physics, astrophysics, and materials science. The Laboratory for Laser Energetics (LLE) in the USA leads direct drive research using the OMEGA laser facility (approximately 60x smaller than the NIF), yet still the fourth largest laser system in the world. While ignition is not possible on OMEGA due to the insufficient laser energy, it is possible to study, on this downscaled platform, hydrodynamics and material science relevant to fusion ignition.

At the time of this writing, there are no coordinated IFE programs anywhere in the world that are publicly funded by governments. However, there are ongoing efforts to develop IFE programs in various regions such as the United States, Asia, and Europe.

The confluence of steady progress in NNSA's ICF program in the United States, the endorsement by the DOE's Fusion Energy Sciences Advisory Committee (FESAC) to create an IFE initiative, robust backing from U.S. Congress, and significant private investment in emerging fusion startups creates a distinct and stimulating moment for the advancement of Inertial Fusion Energy research and development (R&D). This has grown significant political interest to launch an inertial fusion energy research program. The U.S. White House's Office of Science and Technology Policy (OSTP) announced in March 2022 a decadal push for commercialization of fusion. The INFUSE program, which provides public funding and seeks private investment, was initiated by the DOE several years ago to foster collaborative research and technology ventures among national laboratories, private industry, and universities. The ultimate objective was to facilitate technology transfer to the private sector by minimizing obstacles to cooperation and leveraging the expertise and distinctive resources offered by DOE laboratories and universities. Similarly, ARPA-E has developed several programs to support high-risk, high-reward, innovative research in alternative fusion energy concepts, and the CHIPS-Act passed in 2022 provides funding to the private-public-partnership program (PPP) of DOE, launched in fall of 2022, that aims for at least a 50/50 cost share in developing concepts for fusion power plants within ten years. Last but not least, the Fusion Energy Sciences Program within the Department of Energy gathered the community to develop an IFE Basic Research Needs report published in January 2023 that developed a set of priority research opportunities for a U.S. inertial fusion energy research program. Thus, build-up of a strong IFE program in the United States is underway, including the establishment of new Professorships at universities in the area of fusion energy and High Energy Density HED science, attracting new talent.

From 2000 to 2008, the US had an internal program for high average power lasers (HAPL) for IFE that also developed elements of an IFE power plant based on direct drive. From 2007 until 2013, LLNL carried out an extensive internal program called Laser Inertial Fusion Energy (LIFE) which delivered a conceptual design for a fusion power plant based on indirect drive ICF. It is one of the most comprehensive studies performed worldwide and is contributing strongly to establishing confidence in the transition from ICF to IFE while there are still unresolved physics challenges. An evaluation of the potential of IFE was conducted by the US National Research Council and published in 2014 [NASEM2014]. The recently published Basic Research Needs report emphasizes strongly that a US IFE program should be reinstated due to recent advancements.

Similar to NIF, the French Laser Megajoule (LMJ) near Bordeaux, France, is a facility with similar size and mission (although only 174 laser beams to NIF's 192), and also configured for indirect drive approach. Research efforts for academic purposes in laser fusion in France primarily concentrate on shock-ignition and fast ignition.

China is investing heavily in both indirect and direct drive inertial fusion, even though their current lasers are below ignition-scale. Its SG-III facility operates at 180 kJ in the UV [Zhe2016]. A full-scale ignition laser facility SG-IV was proposed several years ago with an initial design goal of achieving 1.5 MJ or greater energy. Specific information about the construction progress of this facility is limited.

Russia has a similar program to that of NIF or LMJ and operates already their first 64 beams of its UFL-2M laser in Sarov that is designed to deliver 2.8 MJ at 527 nm from 192 beams [Sci2022] when complete. The longer wavelength at the second harmonic of Nd:Glass distinguishes it from NIF and LMJ, both of which operate at 351 nm.

Japan's research is centered on electron fast-ignition, which is conducted using the 12 kJ GEKKO XII/FIREX laser facility.

In Europe (including in France, the UK, Germany, and the Czech Republic) several high energy (kilojoule-class) facilities exist. These provide some capabilities of studying laser-plasma interaction processes but are not suitable for conducting implosion and integrated fusion experiments. Funding is very limited and comes from various national programs and to a small degree from EUROfusion, accounting for only ~€1 Million across all of Europe.

From 2008 to 2011, the European ESFRI Roadmap program was used to prepare for exploring a European fusion facility (HiPER). European scientists are now working on a plan to revive the HiPER project. Various academic institutions in several European countries, including Germany, Italy, Spain, the Czech Republic, Hungary, Greece, and France are still conducting research on laser fusion.

3.1.6 German Research in Laser Inertial Fusion

The expert panel spoke to representatives from German research organizations and national labs to develop a better picture of the German ICF/IFE scientific research landscape. In addition, a whitepaper was initiated by German attendees of the 43rd Workshop on High-Energy-Density Physics with laser and Ion beams in Hirschegg, coordinated by Prof. M. Zepf from University of Jena.

German research groups have a wide range of skills and expertise directly relevant to laser fusion research. Currently they are conducting experiments on national and European laser facilities, in the United States, Japan and occasionally also in China. Several key groups have expertise in plasma and HED science (in both the experimental and theoretical realms) on laser matter injections, instrumentation, and target diagnostics. Indeed, the U.S. ICF community has recruited repeatedly from this pool of talent in Germany. Universities such as TU Darmstadt, TU Dresden, University of Düsseldorf, University of Jena, LMU Munich, the University of Rostock are directly active in plasma science, high power laser research and/or computation and therefore already have many of the relevant skill-sets required to contribute to an ICF/IFE program and training of young researchers.

GSI Darmstadt, Helmholtz Zentrum Dresden Rossendorf (HZDR), XFEL/DESY Hamburg, Helmholtz Institute Jena (HIJ), and Forschungszentrum Jülich conduct experiments in the field of high energy density science, laser matter interaction and shock physics. GSI operates PHELIX, Germany's highest energy laser experimental facility with short pulse and nanosecond pulse capability approaching 1kJ. HZDR has a short pulse laser program and operates the ultrafast Petawatt laser DRACO suitable for training students. PENELOPE, another more energetic diode pumped laser (DPSSL) Petawatt laser is under construction and will address similar high intensity laser physics. Similar to PENELOPE, HIJ operates POLARIS, another multi-hundred-Terawatt laser system. There is also a dedicated HED beamline on DESY's XFEL (HIBEF) suited for basic HED-plasma and shock physics experiments using the ultrabright beam from X-FEL as a high resolution plasma probe. Within this facility there are several modern medium-energetic lasers, such as the DiPOLE laser from the UK with ~100Joules energy per pulse. Plans exist to co-locate a multi-kJ laser, making it ideally suited for ICF/IFE related science and code benchmarking. Access to HIBEF is high in demand and thus very competitive. CALA (TU Munich) is Germany's highest peak power facility, delivering 2 Petawatt with 60J. While not suited for compression or implosion experiments, fast ignitor science can be explored.

Although these facilities offer exceptional experimental capabilities for high-intensity laser matter interaction, secondary-source science, and some ability to study shock physics or warm-dense-matter science, their capacities for ICF or IFE physics are significantly limited.

Research efforts in current high-power laser and capability development are insufficiently coordinated, resulting in suboptimal national capability. Marvel Fusion and Focused Energy, the two IFE startups in Germany, plan to construct their own experimental capabilities to explore and validate their concepts. However, their and any other private fusion company's growth is constrained by the available workforce, and the projected need in S&T capability of the private sector cannot be met by talent from the national or European professional ICF or high power laser community without negatively impacting other critical experimental programs. The Hirschegg group recommends investing in expanding the curriculum and constructing dedicated facilities in Germany that combine multiple ICF laser driver beams with multi-kJ capability per beam. Additionally, establishing a robust science and engineering program in the fields of plasma and HED science, high-power laser physics, engineering, material science and engineering is necessary to establish a comprehensive research and development program aimed at initiating and sustaining a robust IFE program in Germany.

The Laser Inertial Fusion Expert Panel agrees with these overall recommendations We have discovered that Germany's ICF efforts are nascent but have enormous potential, and are currently driven by a small, but motivated group of individuals. The concept of clean, abundant energy from fusion science is very appealing to new talent, but the current number of competent individuals, funding and capabilities cannot support it. We also learned that the field suffers from the stigma that IFE is a type of nuclear energy or is associated with nuclear weapons research. This has accelerated brain drain from these areas.

3.1.7 Approach by the Fusion Expert Panel to this Effort

Fusion energy research and development is a major scientific and technical challenge that requires multiple approaches and pathways to maximize the likelihood of success. NIF demonstrated exceeding the Generalized Lawson Criterion on August 8th, 2021. Given the significant acceleration in inertial confinement fusion including the creation of several startups worldwide with significant funding in this field, several countries are currently launching new initiatives and investments to accelerate the development of fusion energy technologies and to establish innovation ecosystems with industry, thus positioning themselves in the international competition. These countries include China, France, the United Kingdom and the United States.

Hence, the BMBF convened in May of 2022 a round of stakeholders from private industry, specifically from the energy sector, heavy (energy demanding) industry, high-tech technology firms and Germany's fusion startups. The meeting concluded that the stakes are high, and a scientific expert panel should be convened to explore the prospects of fusion energy for Germany. In November 2022, a group of seven renowned international experts in the fields of laser-driven inertial confinement fusion, power plant and reactor physics, and magnetic fusion energy were convened for the first time at BMBF. They were tasked by Minister Bettina Stark-Watzinger to assess and provide recommendations in various areas, including:

- Approaches to inertial fusion and their specific physics case
- International players and programs in ICF/IFE
- Status and gaps in competencies and capabilities, and enabling technologies, both in Germany and internationally
- Training and workforce development in Germany to support ICF/IFE
- Role of industry
- Framing of an ICF/IFE program

The panel conducted a thorough examination of the BRN report [BRN2022], as well as other relevant technical literature and similar reports, to gather information in these areas. Over the course of three months, the panel convened for multi-day in-person meetings at BMBF and Lawrence Livermore National Lab, in addition to holding seven online meetings. During these meetings, the panel explored, reviewed, discussed and drew conclusions to achieve their objectives.

The panel interviewed German fusion start-ups (incl. MFE), energy industry professionals, and other experts to form recommendations.

In assessing competencies and capabilities the panel followed a logical structure outward from the heat generating plasma, similar like to peeling an onion. The group termed this "plasma onion" and it is the approach that was also followed in this memorandum. Going from inside to the outside: The core of the IFE system is the burning plasma, which is generated by means of a Laser Driver. The target for ICF/IFE is injected through a target injector into the center of the reaction chamber and then hit by lasers. The target injector must launch a target with the pulse repetition rate of the power plant, typically between 10 to 15 Hz. It must also collect the remains or shrapnel. The reaction chamber's innermost layer, facing the target, is known as the first wall and blanket, which collects the neutrons and sees – dependent on the plant design-x-rays and fast ions emitted from the target. Outside the reaction chambers are the drive lasers which deliver the energy to the target in order to ignite it and the fuel cycle that recovers unspent fuel and delivers new fuel to the targets. Finally, the outermost shell of the Fusion power plant is responsible for converting the high-grade heat generated by fusion processes into heat/steam to drive the thermoelectrical converters.

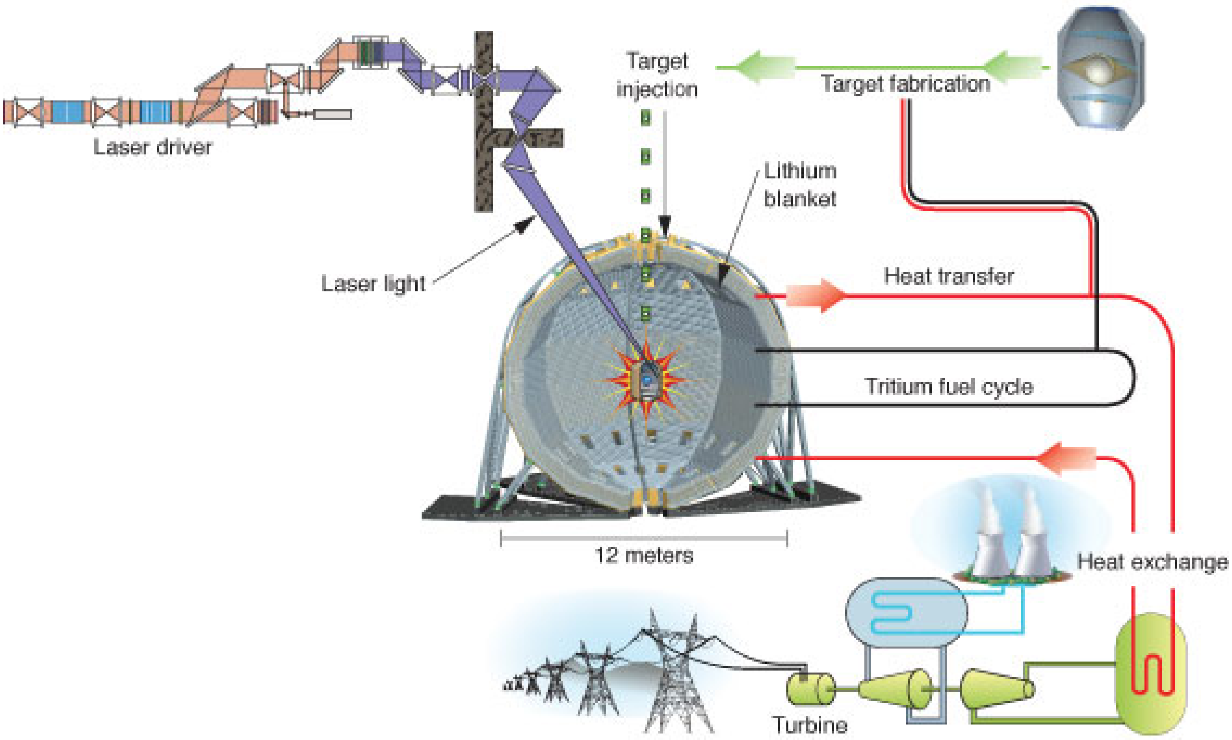


Fig. 1: Fusion Power Plant concept. Courtesy of LLNL

Technical Element	Scientific fields
Plasma	Physics and modelling
Target	» Capsule » Cavity (LID) » Coupling, Ignition and gain » Production scaling » Insertion and removal
Reaction chamber	Radiation & Debris mitigation
1st Wall and Blanket	» Radiation mitigation, materials » Fuel cycle » Cooling and heat removal
Laser Driver	» Final optics » Beam transport » Laser system » Laser support systems
Fusion Power Plant	Electrical conversion

Fig. 2: Elements of the "Plasma Onion".

04

Potential Role of Nuclear Fusion for Global Energy System

The fusion expert panel reviewed current literature [Mas2018], [IEA2022] and spoke to Prof. Henning, Head of the Expert Council for Climate Issues of the German Federal Government and to Siemens Energy about the World Energy Outlook and the role of Fusion in a global energy market. The following represents our takeaway:

In 2019, Europe adopted the Fit for 55 Pact as an interim step in its commitment to become the world's first climate neutral continent by 2050. This pact requires the European Union to reduce greenhouse gas emissions by at least 55% compared to 1990 levels. As a result of burden-sharing agreements within the EU, Germany has also adjusted its climate targets, committing to become climate neutral by 2045 and to reduce emissions by 65% by 2035 compared to 1990.

At present, 72% of the Germany's primary energy is imported, mainly from fossil fuels. Energy forecasting studies suggest that global energy demand is predicted to increase by up to 30 percent until 2050, with electricity becoming a dominant primary energy source globally. When compared to 2020, electricity demand is expected to grow by a factor of two or three globally as well as in Germany. Thus, different energy sources (e.g. electricity, hydrogen, heat) are required for an integrated future energy system It is expected that at least one-third of Germany's energy needs will still have to be met by imports, although it is predicted that two-thirds of Germany's energy needs could be met by domestic renewables by 2045 [Mas2018].

Models of the future energy system indicate higher dynamics of the energy market demanding increased flexibility. The daily demand for electricity is expected to fluctuate considerably. Power plants will need to be quickly ramped to supplement power generation; a function that is covered by storage power plants and gas plants. However, representatives of German heavy industry state, that future baseload requirements will be at least 25 percent, requiring secure supply 365 24/7. Furthermore, industry stresses, that industrial competitiveness of Germany's industry is directly linked to the affordability, stating that the cost of energy must not rise further, specifically in comparison to Germany's neighboring countries. In this context and in view of the continuously growing demand for electrical energy, industry states, that fusion-generated electricity is an attractive and highly interesting power source, even after 2045 but not much later as industry might move out of the country to more energy-economic locations.

However, given the amount of technology development ahead of making IFE a viable power source, fusion energy won't contribute to Germany's energy transition to net-zero in 2045 but present a very attractive opportunity to maintain net-zero in ever growing electrical demand not only in Germany but globally. Due to its high technical complexity and required investment into a power station, fusion energy will need to be source that runs 24/7, providing base load capacity. However, electricity generated by fusion -specifically in periods of low consumption- could be used for affordable production of energy carriers (e.g. hydrogen or ammoniac), which will be needed in areas where direct electrification is either too expensive or not feasible. Electrolytically produced hydrogen will play a crucial role here, either as a final energy carrier or as an intermediate for producing larger molecules. Both processes generate significant power demand that could be met by fusion power stations. Another increasingly important challenge in many regions of the world is the lack of access to potable water. Desalination is a very energy-intensive process for the removal of salt and other impurities from seawater. Demand for such techniques is expected to increase sharply in the future - fusion energy could provide a clean and efficient power source to drive the process, underscoring the need for energy equity. Furthermore, fusion power can be directly used to operate air capture systems for negative emission technologies.

There is more than net-zero goals and efficiency, which is energy diversity and resilience. In its analysis of the current energy crisis in Europe, the IEA stated in 2022 [IEA2022]: "Russia's invasion of Ukraine triggered a global energy crisis, impacting households, businesses, and economies. Europe is the main stage for the crisis and high energy prices are transferring wealth from consumers to producers. Fuel prices are responsible for over 90% of the increase in global electricity generation costs (data from 12/2022), with renewables and carbon dioxide playing a minimal role. "The costs of renewables and carbon dioxide have played only a marginal role, underscoring that this is a crisis where energy transitions are the solution, rather than the problem." Energy resilience can be gained by energy sovereignty, reducing dependencies specifically from countries with an unstable geopolitical setting. Developing a power source that is available 24/7 and independent of weather and energy imports provides a strong incentive to move the Fusion technology development forward.

The panel drew the conclusion, that meeting the likely increase in electricity demand after mid-century, especially to produce non-fossil energy and raw materials, requires considering additional new technologies and advancing their development through dedicated research programs. In the post-energy transition period, fusion-generated electricity could be a reliable and very attractive option for securing Germany's energy sovereignty.

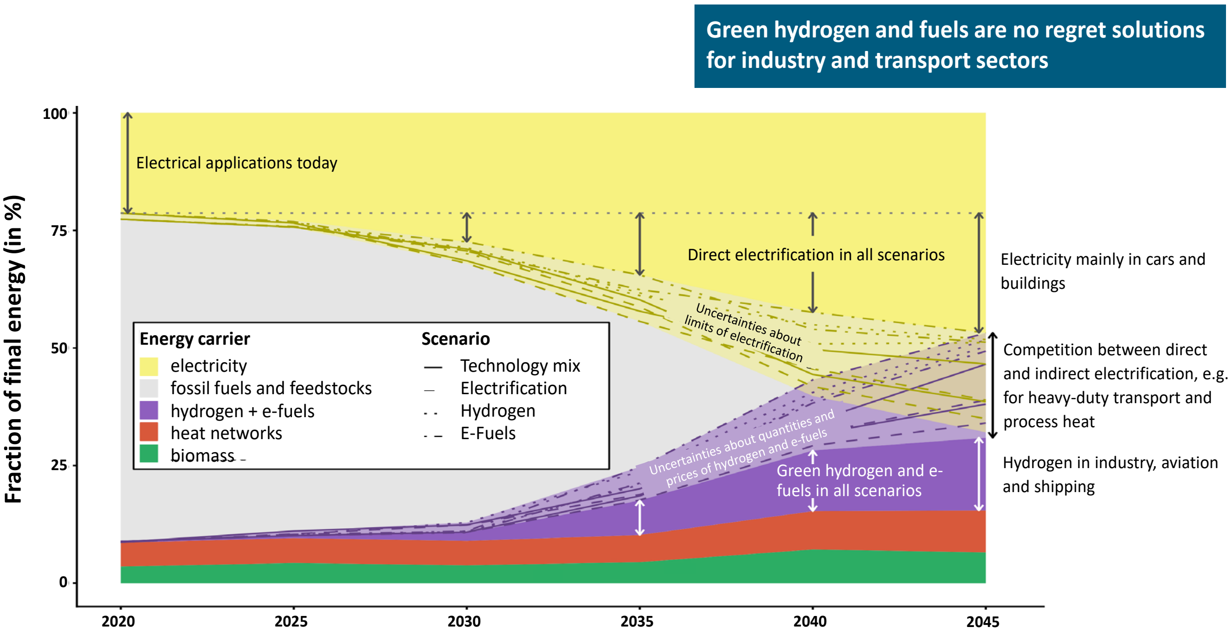


Fig. 3: Final energy mix in the scenarios of the ARIADNE project for the overall energy system [Uec2021].

05

Science and Technology of Inertial Fusion Energy (IFE)

5.1 Scientific Introduction of IFE

In the 1920's it was conjectured that all elements in the periodic table are constituted out of hydrogen atoms bound together and by the 1930's it was fully understood that stars, like our Sun, made their energy by fusing hydrogen nuclei together thus creating all elements via a chain of fusion processes termed "stellar nucleosynthesis."

The potential usefulness of fusion for terrestrial energy production comes from noting that the mass of fusion products do not quite add up the mass of the reactants in a fusion reaction; there is instead a small difference called the "mass deficit" that, because of Einstein's energy (E) to mass (m) equivalency formula ($E=mc^2$, where c is the speed of light), corresponds to a "binding energy" that is liberated during fusion. For example, the mass difference between one helium-4 atom and four hydrogen atoms is 4.87×10^{-29} kilograms which is equivalent to 4.4×10^{-12} Joules. Thus 1 kilogram of hydrogen undergoing fusion could yield 7×10^{14} Joules of energy – enough energy to supply 20,000-30,000 German households for a year.

All hot fusion schemes involve a "plasma" (a highly ionized gas) because high inter-atom kinetic energy is needed to overcome the electrical repulsion between positively charged nuclei thus forcing the reactants close enough to each other to have a nuclear fusion reaction. The probability of overcoming the inter-atom electric repulsion increases with temperature, but raising the temperature of any material, gas, or plasma, costs energy. The energy cost of electric repulsion is why practical fusion favors isotopes of hydrogen, rather than atoms higher up on the periodic table (i.e. elements with higher atomic number, Z).

Stellar fusion reactions are far too slow for terrestrial energy use, so fusion scientists mainly concentrate on reactions that involve heavy isotopes of hydrogen which have higher reactivity. The most reactive terrestrial fusion reaction involves the fusion of deuterium (D) and tritium (T) into a fast "14 MeV" neutron (which carries 80% of the produced energy) and a helium-4 nuclei, also termed an alpha-particle (which carries 20% of the produced energy). Very occasionally, a tiny 4×10^{-5} fraction of D+T fusion reactions generate a gamma ray and helium-5 nuclei.

The advantages of D+T fusion, as compared to other terrestrial fusion reactions, is that the reaction-rate peaks at the lowest temperature of any other fusion reaction (see Fig. 4) the tipping-point where fusion power just balances cooling by bremsstrahlung x-ray emission also occurs at the lowest temperature of any other fusion reaction (see Table 1), the theoretical ratio of energy output over energy input (Gain) is significantly higher than any other reaction, and the D isotope is plentiful in seawater. The Gain advantage of D+T comes about from its reaction-rate advantage and ignition temperature advantages, but also because the heat capacity, which is a measure of the energy required to bring a mass to a given temperature is significantly lower than that of non-hydrogen isotope fuels (for exam-

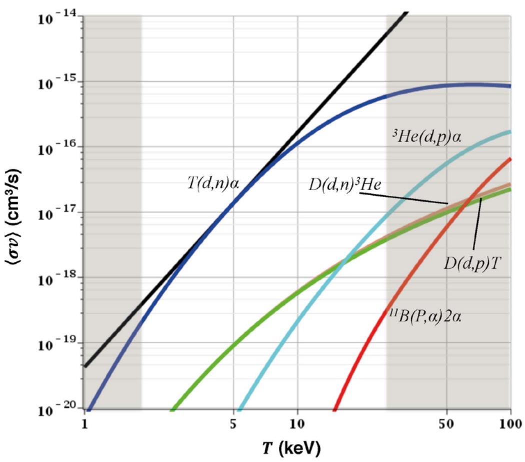


Fig. 4: The reaction-rates of select reactions are plotted based versus thermal temperature. The temperature region, 2 keV < T < 20 keV of practical interest to D+T based ICF is highlighted. The top curve is the DT reaction rate, while the tangent line is the power-law.

Fusion Reaction	$k_B T_{crit}$ (keV)	Q (MeV/reaction)
$D + T \rightarrow n + {}^4He$	4.3	17.6
$D + {}^3He \rightarrow {}^4He + p$	28	18.3
$p + {}^{11}B \rightarrow 3 \times {}^4He$	300	8.7

Table 1: The "critical temperature" T_{crit} [Pos1956], where fusion energy production just balances x-ray energy losses, is shown for some commonly discussed fusion reactions assuming thermal equilibrium in energy units (kB being the Boltzmann constant). Temperatures greater than T_{crit} are generally required for ignition. Q is the total fusion energy liberated per reaction. The T_{crit} value for pB11 comes from a modern revaluation [Put2019].

ple, DT heat capacity is 115 MJ/g/keV whereas pB11 heat capacity is 555 MJ/g/keV). The disadvantages of D+T fusion is that the T isotope is radioactive (a beta emitter) with a 12-year half-life, so T must be made to fuel the D+T reaction, and the neutron product of the reaction (which is the primary mechanism for extracting heat) damages materials of the reaction chamber. Nevertheless, it is the consensus scientific view that D+T fusion is the most practical fusion fuel in the short term.

Since it takes energy to heat a fusion plasma to the state where a significant number of reactions occur, fusion becomes a lot more attractive if one can engineer a situation where the some of the energy produced by fusion can be retained in the fusing region, thus heating itself. The principal way to get the plasma to be self-heating is to create conditions where there are sufficient inter-atomic collisions between the fusion products and the fusion reactants. For DT fusion, self-heating relies upon alpha-particles generated by DT fusion colliding with electrons in the DT plasma to "stop" the alpha-particle, which then adds heat to the DT plasma (stopping the 14 MeV fusion neutrons in the fusion plasma is not practical for inertial confinement fusion [ICF] systems). If the plasma self-heating heating is sufficiently intense, such that the self-heating overtakes all the processes that cool the plasma, the plasma has "ignited" and a thermodynamic instability is generated resulting a rapid increase in fusion energy production. The plasma conditions needed for ignition are determined by the Lawson Criterion [Law1957], which is a numerical threshold involving the fusion plasma density (or pressure), thermal temperature, and confinement-time. The Lawson Criterion for ignition in magnetic fusion energy (MFE) systems is numerically different and generally less restrictive than the generalized Lawson Criterion (GLC) appropriate for inertial confinement fusion (ICF) plasmas [Bet2010], the principal difference coming about from the impulsive nature of ICF/IFE fusion systems.

A low-density DT plasma of small spatial size has a very low probability of stopping alpha-particles. To increase the chance of stopping the alpha-particle fusion products one must either engineer the fusion volume to be large, add strong magnetic fields to force alpha-particles into a helical trajectory that traps the alpha-particles inside the plasma volume, or greatly increase the density of the plasma via a compression scheme (or a combination of these three tactics). Since compressing and heating a large mass of fusion fuel is energetically costly, ICF/IFE systems focus upon heating small masses of fuel, on the order of 10's to 100's of micrograms, in their operation.

At fusion relevant temperatures (> 10 keV, where 1 eV = 11,600 Kelvin), DT plasmas have significant pressure, for example a DT plasma of 0.001 g/cc density at 10 keV has 7.7 Mbar of pressure (where atmospheric pressure at sea level is about one bar). Stainless steel yields at 2 kbar and in general no material can contain Mbar's of pressure. Thus, magnetic fusion approaches that use confining pressure vessels work with large volume very low-density plasmas with pressures of a 3-7 bar in a quasi-stead-state. Whereas ICF plasmas impulsively create microscopic scale high density plasmas via an "implosion" that compresses the fusion fuel to the conditions needed for ignition, holding the fuel together ***inertially*** but for a moment (about 100 picoseconds) as fusion power is generated, then becoming a micro-explosion due to the ultra-high pressures (100's of Gbar) that are generated.

Fusion power integrated over sufficiently long times can result in energy gain. Since ICF/IFE systems are energy density concentrators that have elements of successively smaller components of decreasing size nested inside each other, an "energy gain" can be defined for each layer of the system. The central element of physical interest in an IFE system is the fusion fuel, thus one can define a "fuel gain" (G_{fuel}), which is the ratio of fusion energy produced over the net energy that was externally delivered into the fusion fuel. $G_{fuel}>1$ was achieved in the laboratory in 2014 [Hur2014]. The fusion fuel in an IFE system that involves an implosion is carried inside a shell of material, the capsule, thus "capsule gain" ($G_{capsule}$) defines the ratio of fusion energy produced over the net energy absorbed by the capsule. $G_{capsule}>1$ was achieved in the laboratory in 2021 [Abu2021]. In the case of x-ray driven ICF designs (see Section 2.2), a metallic outer structure, a "hohlraum", surrounds the capsule, completing the ICF target, and thus one can define a "target gain" (G_{target}, or sometimes simply G) which is the ratio fusion energy produced as compared to the energy delivered into the hohlraum. For ICF schemes not involving a hohlraum, capsule gain and target gain are the same thing. $G_{target}>1$ was achieved in the laboratory in 2022 [LLN2022], by generating 3.15 MJ of total fusion energy from 2.05 MJ of laser energy input into the target (as a practical reference point, note that 1 kWh = 3.6 MJ and the average German household energy use is 15-30 kWh per day).

None of these gain definitions account for the energy expended by the facility (usually orders of magnitude greater than the energy than what is delivered to an ICF target). Thus, fuel gain, capsule gain, or target gain greater than unity do not imply net energy production. "Engineering gain" ($G_{engineering}$) is usually defined to include the energy used by the facility, thus $G_{engineering} > 1$, would imply net energy gain in the practical sense of interest for IFE. *No manmade laboratory fusion system in existence has yet achieved* $G_{engineering} > 1$.

In addition to the plasma condition differences between MFE and IFE, IFE systems require expendable targets that contain the fusion fuel which are injected into a target chamber, "shot" with an intense source of concentrated energy (e.g. lasers), and the target then operates as a power and energy-density amplifier bringing the fusion fuel to ignition conditions thus generating fusion energy impulsively. For quasi-continuous power generation, IFE systems require a continuous stream of targets entering the target chamber which are then shot one-after-another at a rapid rate (many times per second), which is a significant engineering challenge.

5.2 Approaches to Laser Driven Nuclear Fusion

There are principally four experimental target concepts in laser driven IFE that are at various levels of development: Indirect-drive (TRL 3), Direct-drive (TRL 2), Fast-ignition (TRL 1), and Shock-ignition (TRL 1) [Shc1983]. The noted TRL levels reflect the maturity of each approach based upon experimentally demonstrated levels of performance, where indirect-drive has demonstrated ignition on the U.S. National Ignition Facility (NIF), direct-drive is projected to ignite at NIF-scale levels of laser energy based upon experimental work on the Omega laser

[Gop2019], while fast-ignition and shock-ignition approaches are further behind in testing with conceptual and experimental work ongoing [Bet2016].

In typical cases for these four target concepts, a (usually) spherical capsule is prepared with a layer of DT fuel on its inside surface (see Fig. 5). In the case of the indirect-drive (IDD) approach, the capsule is suspended inside a high atomic number (high-Z) volume that coverts laser energy into a nearly Planckian bath of x-rays that ablate the capsule surface generating ablation pressures of 100-200 Mbar (depending upon ablator material). In the case of direct-drive (DD) a hohlraum is not used, and instead the capsule surface is directly illuminated by laser beams in as uniform a fashion as possible. Fast-ignition and shock-ignition targets can be designed to either use IDD or DD illumination to compress their fusion fuel payload.

In all cases, as the capsule surface absorbs energy and ablates, ablation pressure accelerates the shell of remaining ablator and DT fuel inwards; the implosion stage of operation. By the time the shell is at approximately one-fifth of its initial radius it is imploding at a speed of many hundreds of kilometers per second – generally slower for fast-ignition/shock-ignition schemes and faster for direct-drive schemes. For the indirect-drive and direct-drive approaches by the time the implosion reaches minimum volume, a hotspot of DT has formed in the center of the capsule, surrounded by colder and denser DT fuel and if the conditions satisfy the Lawson Criterion, ignition starts in the hotspot and then propagates into the surrounding cold fuel over a short duration of time. In the case of fast-ignition and shock-ignition, a hotspot is not generated by the implosion. For fast-ignition, ignition is triggered by an auxiliary short-pulse laser that is directed into a conical section of the target geometry (see Fig. 5). For shock-ig-

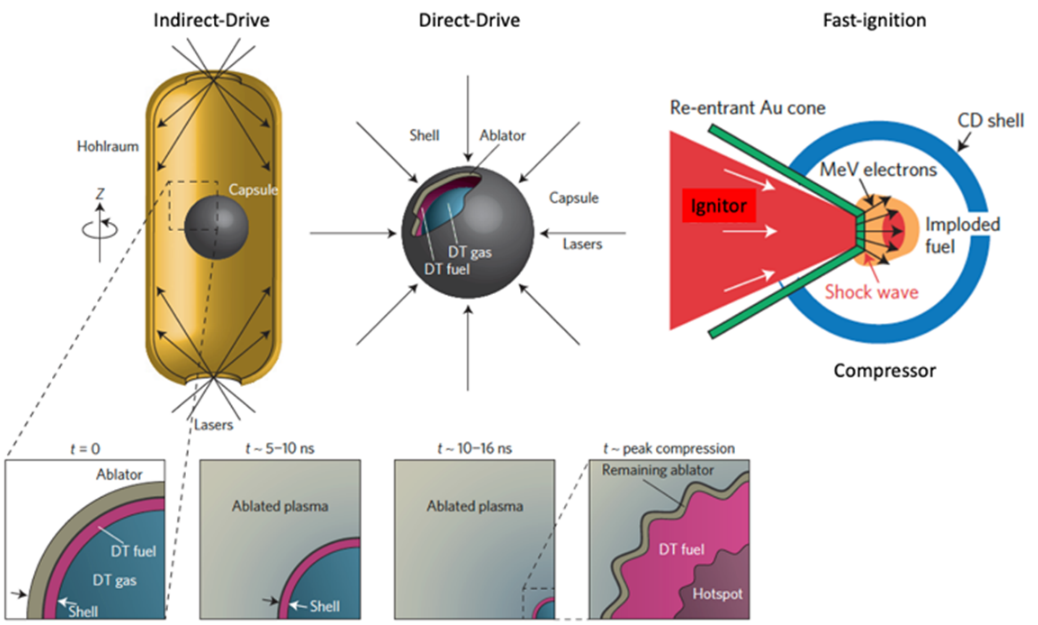


Fig. 5: (Left) IDD target configurations use a hohlraum as a converter of laser energy into x-rays, where the x-rays surround and implode a smaller fuel carrying capsule. (Middle) DD targets are capsules of fusion fuel directly illuminated by laser beams. (Bottom) In both the IDD and DD cases, ablation of the capsule surface generates pressure that accelerates a layer of fusion fuel to high velocity. At peak compression, kinetic energy is transformed into internal energy heating a central hotspot. (Right) Fast ignition (FI) targets split the compression of fusion fuel and ignition into two steps.(Adapted from [Bet2016]).

nition the target configuration can appear similar to either IDD or DD, but generally with a thicker capsule, and the operation emulates fast-ignition in the separation of the compression and ignition stages. At the end of the compression stage of the shock-ignition implosion an “ignitor shock” is launched into the implosion by spike in laser-power.

Key differences between indirect and direct drive are listed below:

» For a fixed laser energy, direct drive has greater energy coupling to the capsule by avoiding the intermediate hohlraum laser-to-x-ray energy conversion step of indirect-drive. This can be an input energy advantage of 7-10x. Some of this energy advantage may be offset by cross-beam energy transfer (CBET) which can redirect inward coming energy flux outward.
» While the ablation pressures for direct and indirect-drive are similar, the mass ablation-rate for indirect-drive is larger, because of the deeper penetration into the ablator of x-rays. This leads to a higher hydrodynamic efficiency (ratio of implosion kinetic energy to ablator energy absorbed) in the case of indirect-drive.
» Taken together (the two bullets above) the overall laser energy to implosion kinetic energy conversion of direct-drive is ~5% while for indirect-drive it’s ~1.5%.
» Due to the energy advantage of direct-drive, the stagnation pressure requirement for ignition of a direct-drive implosion is about ½ that of indirect-drive. This leads to lower implosion convergence requirements for ignition. Higher degrees of convergence require more physics and engineering control of the laser drive and targets.
» The energy advantage of direct-drive leads to larger capsules, which can provide larger fusion yields (~4x) for a given implosion velocity simply due to their increased volume.
» The direct-drive advantage in energy coupling is offset by the higher adiabat (lower fuel compression) requirements of direct-drive that are needed for hydrodynamic stability control. This increased sensitivity of direct-drive implosions is essentially due to the steeper ablation density profile associated with the electron-conduction as opposed to the less steep profile in x-ray driven ablation.
» Direct-drive implosions have an additional seed for high-mode (>30) hydrodynamic instability, laser “imprinting,” that indirect-drive avoids by use of a hohlraum.
» Because of the laser directly impinging upon a direct-drive capsule and because of the relatively thin ablators used in the direct-drive, electron preheating of direct-drive capsules is correspondingly more difficult of an issue than for indirect-drive.
» Direct-drive would greatly benefit from broadband lasers, since high bandwidth can suppress imprinting, CBET, and other LPI.

While the U.S. Department of Energy (DOE) ICF Program on the NIF has been a nuclear weapons program with the objective of achieving thermonuclear ignition to support the stockpile stewardship program (SSP) and study high-energy-density (HED) regimes at the extreme temperature, pressure, and density, the indirect-drive advantages of higher hydrodynamic efficiency and hydrodynamic stability control, mention above, were the principal reasons for indirect-drive being chosen over direct-drive for the NIF. As a result, it is a mistake to discount IDD as a potential path for IFE because of its choice for the DOE SSP mission. Instead, the above physics comparison implies there is no clear winner for IFE applications at this time.

Key differences between conventional ICF using IDD or DD and more advanced, but less developed concepts of FI and SI are:

» The two-step nature of FI and SI allows the use of relatively slow implosions that are less susceptible to the detrimental effects of hydrodynamic instabilities.
» Lower laser intensities can be used for the compression stage of FI and SI schemes making them less prone to exciting laser-plasma instabilities.
» Ignitor physics is less well developed than hotspot ignition. Ignition using an ignitor

pulse is yet unproven albeit the principals are sound, whereas hotspot ignition is proven. Uncertainties surround the very high laser intensity laser-plasma interaction needed for the ignitor.

The FI and SI alternatives to the conventional DD and IDD approaches, that are at the core of the US national program, are being investigated at the university level in the US, Europe, Japan, and China.

06

Expertise, competence, and capabilities organized by modular technologies/Research Areas

6.1 Fusion Plasma and Ignition

6.1.1 Role of Fusion Plasma and Ignition in IFE

A high-energy-density igniting fusion plasma is at the heart of any IFE system, yet the physics of ICF/IFE is extremely specialized and outside the experience of people trained in physics or even magnetic fusion plas-mas, where most of Germany's fusion plasma expertise resides.

6.1.2 R&D Status Worldwide

The worldwide expertise in ICF/IFE is limited to a few thousand people worldwide. Most R&D has been focused upon fundamental studies and getting to an ignited plasma in the laboratory, with little consideration given to IFE applications or practicality. The number of people worldwide who have investigated IFE concepts with any seriousness is less than a hundred, at best.

The US has led research in DD and IDD, where the ideas originated. IDD R&D has been the focus of Lawrence Livermore National Laboratory (LLNL) home to the NIF, Los Alamos National Laboratory (LANL), and to a lesser extent Sandia National Lab (SNL). Due to their national security mission, these US labs house most of the US expertise in the physics of IDD implosions, radiation-hydrodynamics, nuclear and x-ray diagnostics, multi-physics super-computer simulations, and research facility operations such as the NIF at LLNL and the Z-machine at SNL. The NIF is a 192-laser beam long-pulse facility that can deliver a maximum of 2.05 MJ of 351 nm laser light at a maximum of 500 TW of power into the target chamber. Experiments on the NIF are divided into the three general areas of ICF, HED, and national security. ICF work on the NIF has been focused on achieving robust and repeatable ignition and maximizing the fusion Gain. Technically, no IFE specific work has taken place on the NIF. IFE research at LLNL has been limited to reaction chamber design studies, laser technology development and more recently an integrated study of an IFE power plant called LIFE (Laser Inertial Fusion Energy) [Mos2009]. The LIFE project ended in 2013 and LLNL has not been directly involved in IFE research activities since then. While mostly devoted to IDD, some polar-DD studies have taken place on the NIF (see Sec. 2.4).

Most DD R&D in the US has been concentrated at the University of Rochester's Laboratory for Laser Energetics (LLE), which operates the OMEGA laser facility (a 60 beam 40 kJ long-pulse system plus EP, a two-beam short-pulse system with two-additional long pulse beams), and at the Naval Research Laboratory (NRL).Though smaller in size, the NRL effort has been effective in developing the applications of excimer lasers for IFE through the NIKE laser, a 56-beam krypton fluoride laser producing 3-kJ deep-UV (248 nm) light. In addition, the NRL Electra laser is capable of 5Hz repetition rates and 90,000 shots of continuous operation. Primary areas of study for DD include the fundamentals of laser driven fusion, DT-layered implosions, target design, laser-matter interactions, laser development, and target fabrication [LLE2021].

University or laboratories worldwide that have programs that touch upon IFE relevant R&D programs are given in Table 2:

Institution	Location	R&D Topic
CALA/LMU	Germany	Laser-matter interactions, computational plasma physics
CEA	France	Target fabrication, ICF, laser facilities

Institution	Location	R&D Topic
Centre Lasers Intenses et Applications, U. Bordeaux	France	Laser-matter interactions
ELI	Czech Republic	Laser-matter interactions
ENEA	Italy	HED/Laser-matter interactions/ICF
General Atomics	US	Target fabrication
GSI	Germany	Laser-matter interactions, target laboratory
HIJ/University of Jena	Germany	Laser-matter interjection
HZDR/ TU Dresden	Germany	Laser-matter interactions
Imperial College	UK	ICF/Radiation-hydrodynamics codes
Institute of Laser Engineering, Osaka University	Japan	Laser-matter interactions
Institute of Physics, Chinese Academy of Sciences	China	Laser matter interactions
Institution of Russian Academy of Sciences	Russia	IFE Reaction chamber
LANL	US	ICF/Plasma Diagnostics/IDD
LLNL	US	ICF/Plasma Diagnostics/Laser facilities/ IDD/laser-matter interactions
LULI	France	Laser-matter interactions
Massachusetts Institute of Technology	US	ICF/Plasma Diagnostics
National Institute for Fusion Science	Japan	IFE Reaction Chamber
Rutherford Appleton Laboratory, Oxford	UK	ICF/Laser-matter interactions
SLAC-MEC	US	Laser-matter interactions
SNL	US	ICF/Plasma Diagnostics
U. of California	US (Berkeley, Davis, Los Angeles, San Diego)	Laser-matter interactions
U. of Madrid	Spain	HED/Radiation-hydrodynamics codes
U. of Michigan	US	HED/Laser-matter interactions
U. of Nevada, Reno	US	HED
U. of Rochester/LLE	US	ICF/Plasma Diagnostics/Laser facilities/DD/ laser-matter interactions
University of Rostock	Germany	Laser-matter interaction

Table 2: Universities and Research Institutions with IFE relevant R&D programs worldwide.

6.1.3 Capabilities and Competencies in Germany

Radiation hydroydynamic codes are an essential component of the simulation capability for studying implosion physics and predicting implosion performance of IFE targets. There are only few rad-hydro codes connected to German developers. MULTI is a 1D and 2D rad-hydro code originally developed at Max-Planck-Institute for Quantum Optics in 1988 by Ramis, Schmalz and Meyertervehn as a 1D planar code [Ram1988]. It was extended to spherical geometry and 2D at the Universidad Politecnica de Madrid, Spain [Ram2009].

To study fusion schemes based on electron or proton fast ignition, PIC and Hybrid-PIC codes are required. PIC codes can simulate the particle acceleration from the interaction of a preformed plasma with a high-intensity short picosecond laser pulse. Using PIC codes to simulate the transport of energetic particles in overdense plasma is computationally too expensive. Hybrid-PIC codes can simulate both particle acceleration in underdense plasmas and energetic particle transport in overdense plasmas. However, Hybrid-PIC codes are less developed and only few versions are available. Dr. Javier Honrubia, currently with Focused Energy developed hybrid codes for fast ignition [Hon2009] Whereas, PIC codes are widely available at Max-Plank-Institute and at German universities. For example, VSPL by A. Pukhov [Puk1999] at the University of Dusseldorf. A widely used open-access PIC code is ORISIS, developed at UCLA (USA) and Instituto Superior Tecnico in Lisbon (Portugal).

Below is a comprehensive list of radiation hydrodynamic codes, PIC codes and other special-use codes of interest to IFE studies.

Code	Maintainer/Company	Description
CHICAGO/LSP	Voss Scientific	Radiation/ Hydrodynamics/ Magnetohydrodynamics/3D PIC
EPOCH	University of Warwick	3D PIC for LPI studies
FLASH	Flash Center Code Group/University of Rochester/Petros Tzaferacos	3D Radiation /Hydrodynamics/ Magnetohydrodynamics
FLYCHK	NIST	Atomic level populations and charge state distributions
HELIOS	Prism Comp Sci	1D Radiation/Hydrodynamics
HYDRA	Marty Marinak/LLNL	3D Radiation/Hydrodynamics/Magnetohydrodynamics
OSIRIS	Warren Mori/UCLA	3D PIC code for LPI studies
PICLS	Yasuhiko Sentoku	3D PIC code for LPI studies
PROPACEOS	Prism Comp Sci	Equation of State and Opacity
SPECT3D/ PrismSPECT	Prism Comp Sci	Collisional-radiative spectral analysis codes
VISRAD	Prism Comp Sci	Viewfact/Experimental Design
Vorpal	TechX	3D PIC code for LPI studies
VPIC	R. F. Bird/ LANL	3D PIC code for LPI studies
WarpX	Jean-Luc Vay/LBNL	3D PIC code for LPI studies
MULTI	Meyer-Ter-Vehn (Germany)	Rad hydro/PIC on GPU
DUED	Atzeni	2D rad hydro
HYADES H2D	Cascade Applied Science	1D and 2D rad hydro

Table 3: Overview of Open Codes.

6.1.4 Findings and Recommendations

To enhance its involvement in the IFE field, Germany should establish international partnerships with prominent IFE facilities, given its current lack of intense research in IFE plasmas. This collaboration would enable German scientists to have a more active role and contribute to the IFE community. Furthermore, Germany should collaborate with European and global partners to improve its physics understanding through enhancement of open codes.

6.1.4.1 Research Opportunity in the 1-3 Year Timescale

Finding	Insufficient data is available concerning the performance of wetted foam targets for laser direct and indirect drive implosions.
Recommendation	Codes with adaptive mesh capabilities or ad-hoc turbulent models with appropriate closure and validated equation-of-state are required to simulate wetted foam target implosions. Theory regarding physics models of equation of state and turbulent dynamics suitable for wetted foam targets as well as direct numerical simulations resolving relevant small scale flow should be impactful if validated against experiments.

Since the implosion of a solid sphere of fusion fuel is energetically unfavorable as compared to the implosion of a hollow shell of cryogenic temperature fusion fuel (a "DT layer"), most present-day IFE concepts focus upon implosions involving a frozen fusion fuel layer surrounded by a spherical shell of ablator material, as shown in Fig. 6. The preparation involved in preparing a fuel layer inside an ICF target for present-day experiments is considerable and impractical for IFE applications. Wetted foam targets (where a foam wicks cryogenic liquid fusion fuel into a hollow shell form) offer a potential solution to bypass the complications of a cryogenic layering process.

However, there is little data on the fusion performance of wetted foam targets. Some IDD implosion tests with wetted foams have been performed on the NIF, with some mixed success [Zyl2018], but no relevant wetted foam implosion data yet exists for DD. Questions remain about the non-uniformities seeded by the foam structure than can contribute to seed hydrodynamic instability and about the turbulence ensuing after the first shock passes through foam. When compressed, turbulence can channel energy away from internal energy into small scale kinetic energy. To directly simulate the effects on implosions of small scale turbulence, it requires codes with adaptive mesh capabilities or ad-hoc turbulent models with appropriate closure. Questions also remain about the equation-of-state (EOS) of wetted foams, limiting the capability of simulations to correctly model wetted foam implosions. Theory and computations work on wetted foams, validated against experiments, could be impactful for all potential IFE schemes.

Finding	Few radiation-hydrodynamics codes suitable for laser driven implosions are available with open access. None of them include all the physics relevant to the different IFE concepts.
Recommendation	Develop a rad-hydro code with open access to the IFE community. Carry out an assessment of the currently available open-access radiation-hydrodynamic codes and evaluate the best path forward to developing a comprehensive community code.

Few radiation-hydrodynamics codes suitable for laser driven implosions are available to the broader IFE community (e.g. MULTI1D/2D, DEUD, and HYADES). None of these codes have undergone extensive validation with implosion experiments or against the codes used at the American national laboratories. Additionally, none of the above accessible codes include all the relevant physics (e.g. cross-beam-energy-transfer (CBET), and non-local energy transport are not yet available in these codes). There is a need to develop a radiation-hydrodynamics code that is open to the IFE community, with all the relevant physics included and with adequate experimental testing. There are other state-of-the-art open-access radiation hydrodynamic codes that are not yet capable of simulating laser-driven implosions but are widely used in the HEDP community to simulate HEDP experiments at laser facilities. For instance, the code FLASH is a capable AMR rad-hydro code with laser ray-tracing, SESAME tables and multi-fluid hydrodynamics, widely used around the world.

The capabilities of FLASH can be extended to simulate laser-driven spherical implosions though some important physics (CBET and non-local transport) are absent in the current version of that code. Possible collaborations with the FLASH team at the University of Rochester can be established to further develop FLASH and extend its capabilities.

FINDING	Despite advances in numerical simulations, even the state-of-the-art radiation hydrodynamics codes at the US national laboratories are not capable of accurately predicting experimental outcomes and guiding the design of implosion experiments. Recently, machine learning algorithms have been successfully applied to laser fusion implosions leading to improved experimental predictions.
RECOMMENDATION	Explore the latest advances in machine learning to develop algorithms to bridge the gap between experiments and simulations thereby improving the predictive capability of implosion experiments.

Even the American national laboratory simulations have shown deficiencies in capability. Having limited laser-plasma instability (LPI) predictive capability (important for energy coupling and laser safety) and poor hohlraum predictive capability (need laser power energy ad-hoc multipliers to match observed energetics and symmetry). Questions remain about the accuracy of the material equation-of-state (EOS) and opacity properties that ICF/IFE simulations use. Reliable simulations reduce the empiricism needed for IFE development.

There are exciting recent opportunities for developing a machine learning framework to bridge the gap between simulations and experiments. Recent efforts at LLNL have been successful in improving the predictive capability by first training Deep Neural Networks on large simulation databases and then re-retraining them (“transfer learning”) on the limited available experiments ([Spe2018], [Hum2021], [Gaf2019]). Another approach developed at University of Rochester, uses Bayesian inference and dimensional analysis to map experimental observables onto simulated observable [Gop2019], [Lee2021]. The Rochester approach provides a predictive capability for the fusion yield within a 10% error and it was used to improve the target design and laser pulse shape to increase the fusion yield by over 5-fold.

Applications of Machine Learning to improve the predictive capability of the radiation hydrodynamic codes used to simulate ICF implosions is a fertile new area of research. Furthermore, many other applications of ML can be envisioned in all the disciplines relevant to IFE development.

6.1.4.2 Research Opportunity on the 3-6 Year Timescale

Finding High target gains in excess of 100x are required for an IFE power plant using laser drivers. For hot spot ignition, such high gains require highly convergent implosions with convergence ratio well above 20x. To date, implosion experiments designed with radiation hydrodynamic codes to produce high convergence and high target gains have underperformed expectations. Performance degradation at high convergence is common to both direct and indirect drive.

Recommendation Collaborate with target design and experimental groups at the major implosion facilities to develop a robust physics understanding of the causes limiting implosion performance at high convergence and develop mitigation strategies.

Fusion fuel compression is essential for burn efficiency, but theory generally overpredicts DT fuel compression. In 1D implosion theory, high convergence leads to high compression, high areal densities and high fusion yield. However, when high convergence is achieved in experiments, the fusion yield and core pressure are much lower than predicted and even below those of equivalent lower-convergence implosions. In DD, high convergence (CR>20) has been out of reach thus far regardless of the fusion performance. DD implosions designed to achieve highest convergence led instead to the lowest measured convergence in experiments. This fuel compression problem is a priority for the US ICF program since it is the key path to higher Gain.

Finding Hotspot ignition has been demonstrated at the NIF with indirect drive leading to a target gain of 1.5x. Laser direct drive experiments on the 30kJ OMEGA laser scale to about one megajoule of fusion yield at 2MJ of laser energy. Other ignition schemes require major R&D for proof of principle experiments demonstrating target gains above unity.

Recommendation Other approaches using different ignition schemes, such as fast ignition, should be evaluated to assess their requirements for an ignition-scale proof-of-principle demonstration necessitating new large laser facilities.

While hotspot ignition has been demonstrated on the NIF using a low compression design [Kri2022], [Zyl2022], other ignition schemes (e.g. fast-ignition, shock-ignition, or ignition using fuels other than DT) require major R&D for proof-of-principle. New facilities are required to advance the physics of fast-ignition, since fast-ignition requires an integration of a compression laser plus ignitor laser. The NIF and OMEGA facilities could provide some valuable data, but they are presently oversubscribed. Both fast and shock ignition require a fuel assembly that achieves high densities and areal densities. Shock ignition makes use of a single laser type to assemble the fuel and to shock it right before peak convergence. The high intensities required to launch a strong shock near the end of the implosion are of concern due to the excitation of laser plasma instabilities. There is very little data on laser-plasma instabilities at the UV intensities of ~10^{16} W/cm^2 relevant to shock ignition.

6.1.4.3 Research Opportunity on the 6-9 Year Timescale

Finding	ICF targets that are proven to ignite are complicated, expensive, fragile (see Fig. 6) thus making them inappropriate for direct application in IFE.
Recommendation	The community needs to leverage the physics understanding of what ignites into developing target concepts that are ignition/Gain capable, but that make much more sense from an engineering practicality perspective. Economically viable IFE is not possible without this step.

Additional target engineering challenges are addressed in Sec. 6.2.

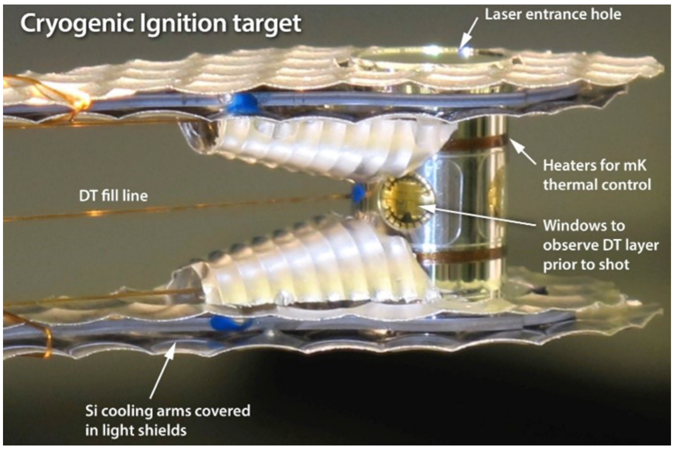


Fig. 6: An example IDD target used in ignition experiments on the NIF facility at LLNL, key components are labeled, Courtesy of LLNL.

6.2 Targets

6.2.1 Role of Targets in IFE

Targets form the central nexus of activity in an IFE power plant. The targets contain small quantities of fusion fuel that are carefully shaped to allow successful implosion and ignition when shot by the laser driver beams. A target injector shoots the target into the center of the reaction chamber, where the laser driver beam must precisely hit the target. Upon ignition and burn, the fused fuel and target parts emit neutrons, gamma rays, and ions (helium and target element ions), that are collected by the reaction chamber first wall and blanket. The high energy and intensity of the emissions from the target are a severe threat to the lifetime of the blanket and first wall.

6.2.1.1 Target Design

As discussed in Sec. 6.1, there are many types of target designs. Fig. 7 shows a number of typical laser-driven target types. Most target designs contain a spherical capsule The selection of material for ICF targets is determined by various physical properties necessary for fusion, but the ultimate and most crucial factor is the total effort required to produce the final energy output per capsule. This factor often leads to the selection of polymer materials as the best choice. Currently, solid or solid composite materials, such as diamond and diamond film sequences, are used as ICF targets. The capsule is often lined inside with a uniform layer of low-density foam (<~50 mg/cm^3). Capsule diameters typically of interest are in the range of 3 – 8 mm. Capsule wall and foam layer wall thicknesses typically of interest are in the range of a few microns to a few hundred microns. The tolerance of capsule and foam layer diameter, thickness, sphericity is typically a few microns to a few 10's of microns. Capsule surface smoothness in today's science targets is less than a few 10's of nm. Additionally, pit, voids, and high-density inclusions in the capsule wall must be kept to a minimum. In today's targets only a few of these defects larger than a micron or two are allowed. Dimension and tolerances thereof are still being determined and will ultimately need experimental verification. IFE targets being larger than today's targets (in the ignition target at NIF the capsule diameter was 2 mm) may end up with somewhat relaxed tolerances. Some target designs have additional parts such as a hohlraum (an open ended can), a cone, and membranes.

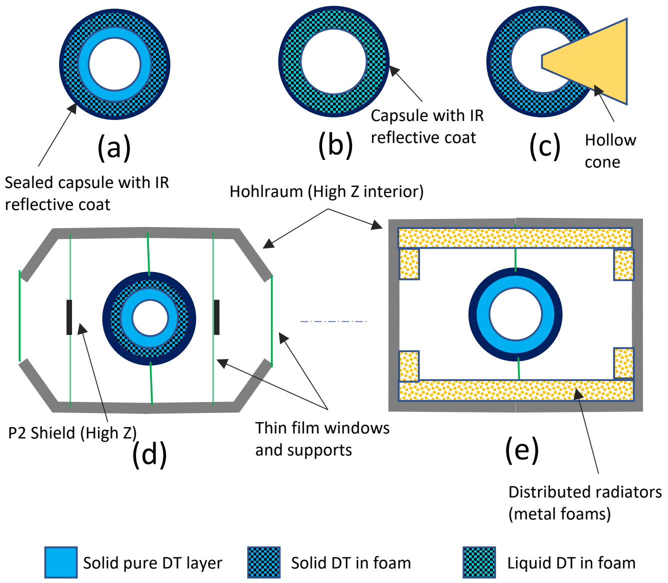


Fig. 7: Some abstracted typical target types, others exist [Set2010]. (a) a laser direct drive, HAPL like configuration [Ols2021]. (b) a laser direct drive liquid DT wetted foam configuration. (c) a cone-in-shell fast ignition configuration [Sha2012], [Bet2016], [Norimatsu2017], [Dit2021]. (d) a laser indirect drive, LIFE like configuration [Mil2014]. (e) a heavy ion indirect drive distributed radiator configuration [Cal1999]. Courtesy of General Atomics.

6.2.1.2 Target Supply, Filling and Injection

Typical IFE reaction chamber concepts are designed for shooting targets at rates between 1 and 15 targets per second (Hz). Thus, each reaction chamber requires a supply of targets (unfueled) of between 86 thousand and 1,3 million targets per day. At each reaction chamber there will be a cryogenic filling and layering station to fill the target with fuel (typically DT) and create a uniform thickness fuel layer within the target. Also, at each reaction chamber there will be a target injector. Both filling and layering station, and injector must operate at the reaction chamber shot rate. Developing mass production manufacturing methods for targets, especially given the expected tolerances, is a challenging endeavor. Similarly challenging are the cryogenic fill and layering station, and the target injector. To add to the challenge, fueled targets, delivered to reaction chamber center, will likely need to cost less than between 20 cents and 1 euro to allow the reaction chamber to function economically. Studies of concepts to produce, fuel, and inject targets indicated this may be feasible [Goo2004], [Mil2009].

The fusion fuel typically used in targets is DT due to its high reactivity. Cryogenic temperatures, approximately 20 K, are required to condense DT gas; liquid or solid DT depending on target design. The reaction chamber temperature will be high, which will lead to a high thermal radiation heat load being placed on the target during injection into the reaction chamber. This can be compounded by methods to protect the chamber first wall from the threat of the target emission, for instance adding gas into the chamber to slow and or spread out in time the ions and photons. A balance must be carefully struck between protecting the target from thermal damage in the chamber and protecting the chamber first wall when implementing chamber protection schemes. Target injectors are typically designed to launch the targets at 50 – 200 m/s to limit exposure time in the reaction chamber, and with the acceleration limited to less than 1000g to prevent damage to the target or its DT fuel layer.

After targets are shot, the target and its fuel become the waste "ash" of the IFE reaction chamber. When shot, the target becomes a plasma and its ionized elements blown all around the chamber. Careful materials selection must be done to insure that, once cooled, these target materials can be removed from the reaction chamber. The target elements will recombine to form various chemical compounds or remain elemental in some cases. The target's materials will become activated and not all fuel will be burnt. Thus, the target materials should be selected to minimize nuclear activity in times scales appropriate for reaction chamber maintenance, to minimize waste disposal ratings at end-of-life decommissioning time scales, and to minimize production of tritiated compounds (e.g. tritiated hydrocarbons) that complicate the tritium processing and purification systems of the reaction chamber.

6.2.2 R&D Status Worldwide

6.2.2.1 Target production in general

Currently no one can produce IFE targets in the quantities needed for an IFE reaction. Targets are currently made individually for science experiments in small quantities and with substantial efforts in characterization. Most target fabrication methods utilized for science targets are chosen for flexibility of changing target dimensions, since scientists continually change the target design to be able to learn new information about the target physics and performance. Current targets are also extensively measured and characterized, so that simulations can be checked against as-built dimensions. Target injectors have been or are in development. Single shot, room temperature prototypes have been built and tested for accuracy. Cryogenic injectors with automatic target loading are in the planning stages at most. Research and development efforts in mass production of targets for IFE and development of IFE target injectors has or is going on at several locations.

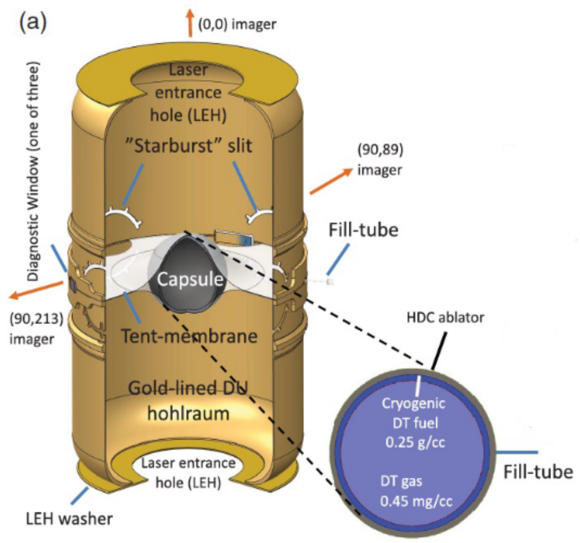


Fig. 8: Parts of an IDD Target, Courtesy of LLNL.

6.2.2.2 Capsule

IFE relevant, spherical capsule fabrication methods include overcoating a spherical mandrel followed mandrel removal; drop-tower blowing; and micro-encapsulation. Overcoating a spherical mandrel has been used to form capsules of HDC (a nano-crystalline diamond material), DLC, beryllium, and an amorphic plastic referred to as GDP. It is notable that the first laboratory fusion ignition with gain greater than 1, occurred at the NIF at LLNL on 5 December 2022, using a capsule made of HDC (high density carbon). This coating was done by Diamond Materials GmbH in Germany on a silicon sphere. The silicon sphere was removed at General Atomics (GA) in USA by laser drilling a small hole through the HDC coating and dissolving the silicon with acid. Typically, PE-CVD (for HDC, DLC, and GDP) and sputtering (for Be) are used for coatings. Capsules are fabricated this way at GA (GDP, Be, DLC), LLNL (GDP, HDC), CEA-Val Duc (GDP), and Diamond Materials. The LIFE reaction chamber project of LLNL considered both GDP and HDC capsules (foam lined). HDC coating equipment would need to be modified for mass production. During the HAPL project GA built a prototype mass production GDP coater based on a "rotary kiln" configuration [Ver2007], with solenoid coils extending over the length of a rotating tube to inductively couple to the plasma. In

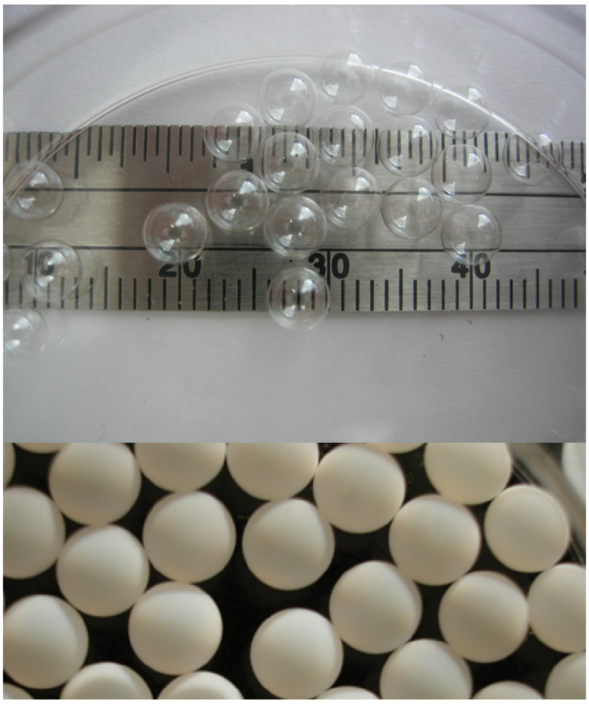


Fig. 9: Spherical IFE capsules (left) and foam shells (right) of IFE size (~4-5 mm diameter) made by General Atomics using micro-encapsulation. Lower scale at left has minimum divisions of mm. Courtesy of General Atomics.

drop tower capsule production, granules containing a blowing agent (e.g. a polystyrene granule saturated with an organic solvent) are dropped through a vertical oven/furnace. The oven heats the granule past the melting point, and the blowing agent is vaporized. In the zero g fall through the oven, the vapor blows the melted granule into a spherical capsule. For thicker wall capsules, wall uniformity can be an issue since the blowing agent vapor bubble may be first nucleated anywhere within granule. Polystyrene capsules are/were fabricated this way at the Lebedev Physical Institute [Mer1994], [Coo1994] where they uniquely shoot the granules up into the drop tower and then let them fall out of the tower. Glass capsules were formerly made at LLNL and GA by dropping glass frit down drop tower ovens. Micro-encapsulation can create solid wall capsules or spherical foam shells. In micro-encapsulation, compound droplets are formed and suspended in solution to cure the layer of the compound droplet that has polymer dissolved in it. The solutions that form the compound droplet and the suspension fluid are immiscible in each other. This is effectively blowing liquid bubbles in solution. Surface tension and energy minimization naturally want to make the droplet spherical and smooth. The major technical difficulties occur during curing: maintaining smoothness and homogeneity of the capsule wall and maintaining concentricity between the inner and outer wall since there is not a centering force for a static compound drop. Methods for making compound drops of IFE size (several mm in diameter) include concentric nozzles, T-junction, micro-fluidic droplet combination. Micro-encapsulation in an ICF or IFE context has/is done at GA, LLE, LLNL [Coo1994], ILE, CEA Val Duc, Hamamatsu, Cardiff University under aegis of CLF (Prof. David Barrow's research group [Li2021]). LLE has studied using dielectrophoretic force (applying AC electric fields) to deterministically force the inner and outer walls of capsules to be concentric during curing [Wan2011], [Cho2016]. It should be noted that micro-encapsulation at smaller scales and more relaxed tolerances is a highly used industrial process. For instance, fertilizers, perfume, medicines, nutrients, and epoxies are just a few of the items that are micro-encapsulated into commercial products.

IFE target designs often call for a spherical capsule lined with a uniform layer of foam. There are three generic ways to accomplish this: coat a foam shell with a solid layer, coat the inside of a solid capsule with a foam layer, and create both solid wall and the foam layer at the same time. For the first method, during the HAPL program, GA utilized interfacial condensation chemical reaction [Schr2007] to coat foam shells, and the rotary GDP coater; also see [Schro1995]. For the second method, during the LIFE program, LLNL studied surface catalyzed ROMP to grow the foam layer from the inner surface and studied random rotation to uniformly coat the capsule interior with foam forming solutions. For the third method, additive manufacturing could be used, although considerable development is needed to increase the production rate. The two photon polymerization (2PP) additive manufacture method has the submicron resolution desired to form smooth capsules and low density small pore foams. Currently, for ICF targets, 2PP is being pursued by LLNL, LANL, GA, LLE, and University of Nebraska [Coo2020],[Ols2021]. Many other institutions and companies develop 2PP additive manufacturing in a general context.

6.2.2.3 Hohlraum

More complex targets include additional parts besides capsules, such as hohlraums or cones. Currently, these are typically made by electroforming on a precision machined mandrel (used at AWE, CEA Val Duc, CLF, GA, ILE, LANL, LLE, LLNL, TU Darmstadt, and Scitech Precision). Rapid production of precision mandrels to electro-plate onto would make this technique applicable to IFE. Stamping of cone mandrels, and injection molding of cone mandrels followed by sputtering for a conductive layer have been investigated at GA. Stamping and deep drawing were also looked at for cone mass production by GA. Potential hohlraum mass production methods include stamping, swaging (cold forging), deep drawing, die casting, injection molding. Applicability will depend on hohlraum material choice. Note that only the interior few tens of microns of needs to be of a high Z material. So, a plastic hohlraum lined with lead may be acceptable, although this much carbon and protium may prove expensive for a tritium processing system to handle. Swaging, deep drawing, and die casting were investigated for LIFE hohl-

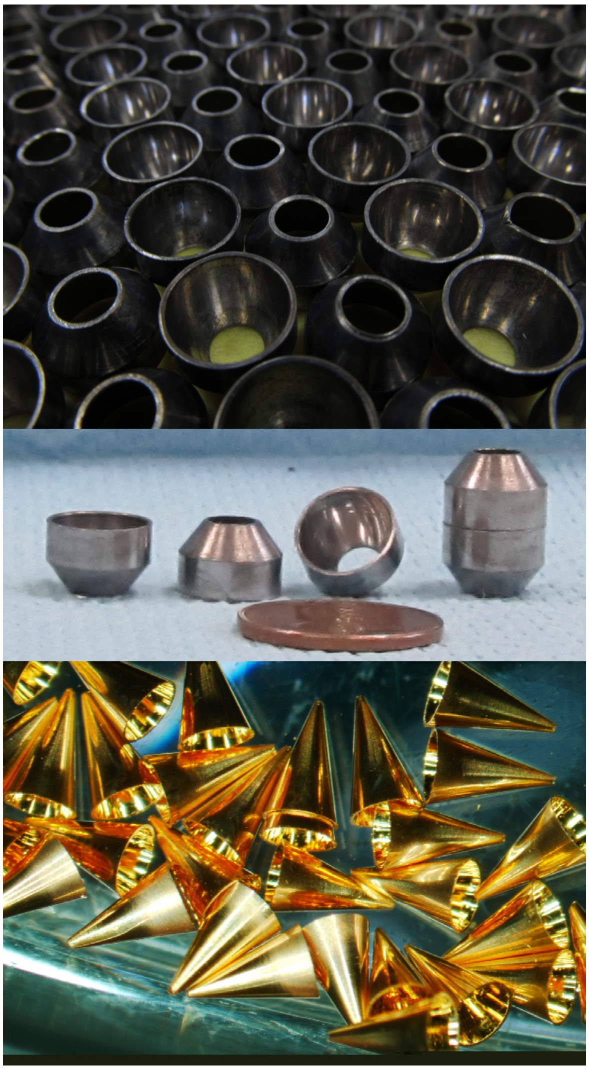


Fig. 10: above - Lead hohlraums produced by swaging at General Atomics. Coin is a USA penny. below– gold cones produced by electro-forming using a stamped mandrel at General Atomics. Courtesy of General Atomics.

raum production using lead by LLNL and GA. Swaging for instance is used to produce air rifle pellets, where competition grade pellets have dimensional variance of less than 10 micron and hohlraum production investigated [Alex2013].

6.2.2.4 Nanostructured Targets

Flat targets, especially with a laser facing surface with engineered micro or nano engineered structures have applicability to fast ignition and non-thermal ion targets. In fast ignition a surface in the cone when hit by a short pulse laser generates an electron or ion beam which then impinges on a compressed core to ignite the core. In a non-thermal ion target, ions generated in nano structures intersect inculcating fuel and the nanostructure to effect burning of the fuel. Processes for fabricating micro and nanostructures on surfaces include lithography, MEMS, LIGA, 2PP printing, laser patterning and etching, catalyzed growth of nano fibers, and AAO templating. One or more of these techniques is employed by all the previously mentioned institutions, and many more as well. This includes but is not limited to ENEA, HZDR, LMU, and UPM.

6.2.2.5 Assembly of Targets

Complex targets required assembly. Today for ICF targets this is most typically done on optical coordinate measuring machines in conjunction with custom fixtures and manual or motorized precision stages. Automated robotic assembly will be required for IFE targets with more than one part. Robotic assembly development for targets is being developed at LLNL and GA[Lee2011], [Car2016], [Boe2017] but is currently at assembly rates much lower than required for IFE.

Fig. 11: Robots set up and programmed to assemble cone-in-shell targets at General Atomics. Cone tips centered to capsule center to within +/- 10 microns. Courtesy of General Atomics.

6.2.2.6 Filling of Target with Fuel

After the structure of the target is complete it must be filled with fusion fuel. The typical fuel is DT which is a gas at room temperature. The DT must be cooled to cryogenic temperature, ~20K to condense to a liquid, and a bit colder to solidify into ice. Additionally, the condensed DT must be reshaped into a uniform layer on the inside of the capsule of the target. Filling may be accomplished by permeation (diffusion) through polymer capsules walls at room temperature in a pressure cell capable of holding high pressure. The pressure must be ramped up slowly, or the capsule will be crushed, and 100's of atmospheres of gas pressure are required to get the necessary amount of gas into the capsule to form a thick ice layer once the gas is condensed at cryogenic temperature. Permeation filling takes many hours to complete. An alternative is wicking liquid DT into the capsule through a fill tube (ICF target) or hole in the capsule wall (IFE target). If the capsule has a foam layer, the capillary action will wick the liquid to fill the foam and thus create a uniform layer as it is being filled. Only sub-atmospheric pressures are required for wicking liquid DT into foam, so this is a safety advantage relative to permeation filling. Over filling may be a challenge that requires precision dosing or draining to get the correct amount of liquid into the capsule to just fill the foam. This so called "wetted foam target" [Ols2021] is a design that the USA program is just starting efforts to field on the OMEGA and NIF lasers. The filling and layering of a wetted foam target is expected to be fast, on the order of about 10 seconds. Layering of a solid DT layer can be done by beta-layering [Mar1988], [Hof1988] as is done by the ICF programs in the USA (LLNL, LANL, LLE, and GA) and France (LMJ. CEA-Val Duc and CEA-SBT), or by rolling the capsule down a spiral cryogenic temperature tube as is done by the Lebedev Institute (referred to as FST layering) [Alek 2020]. FST is a fast layering technique which is helpful for IFE. However, FST cannot make uniform layers if the layer is too thick, placing some limits on target design. Beta-layering uses the volumetric heating of the DT ice (caused by the tritium beta decay radiation) to sublimate and recondense the solid DT until the entire DT ice inner surface is at a uniform temperature. Holding the capsule in a spherical temperature field will cause the DT to move to a uniform spherical layer. Many e-folding times, 26 minutes each, are required to reach the uniformity of the layer required, so many hours are required to layer a capsule. During the HAPL program, GA developed a prototype of a cryogenic fluidized bed [Boe2011] for beta-layering large batches of capsules simultaneously. Here the fast agitation and random rotation in the bed was expected to provide the needed spherical isotherm at each capsule on a time averaged basis (rotation rates >> layering e-fold time). This long layering time is a drawback for IFE, since slow filling and layering lead to large batches of capsules being required to be processed together, which leads to large tritium inventory. A HAPL like target fill and layering station was calculated to need, at bare minimum, an inventory of 500 to 1000 g of tritium in an IFE filling and layering station [Schw2003]. In contrast, wetted foam filling and layering times are expected to be about 10 seconds, which would only need less than about 10 g of tritium for the filling and layering system. The wetted foam target has the disadvantage of mixing foam into the fuel which makes the fuel harder to ignite. Other fuel layering systems may be possible, including dynamically forming the fuel layer during the laser shot as was proposed by Goncharov [Gon2020].

6.2.2.7 Target Injector

Target injectors are also required to shoot the target into the chamber. Gas-guns, electro-static and various electro-magnetic propulsion methods can be used for injecting targets. A full size and speed gas gun prototype was developed at GA for the HAPL program [Fre2005]; speeds up to 400 m/s. Direct drive targets were protected with a two-piece sabot. During the LIFE program LLNL was working on a gas gun for indirect drive targets. In Japan IFE, Gifu University, and Hiroshima University were working on a hybrid gas-gun with electro-magnetic speed trim and sabot removal for cone-in-shell targets. This injector was capable of ~100 m/s. During the HAPL program, GA developed a low-speed prototype of an electro-static injector with target steering. For the LIFE reaction chamber, GA developed a prototype of a linear induction accelerator [Pet2015] which could inject indirect drive targets with electrically conductive hohlraums, or direct drive targets using a conductive sabot. This injector featured electro-magnetic steering post barrel to improve accuracy. It reached ~60 m/s with surrogate targets, and target placement consistency of 0.14 mrad radially. the Lebedev Institute is developing an injector based on an HTSC sabot [Alek 2020], [Alek2022] that is electro-magnetically driven, and have demonstrated initial propulsion of the HTSC sabot. For HiPER, CEA-SBT proposed a laser ablation driven sabot followed by and magnetic Halbach array for a non-contact barrel [Per2011]Ex-Fusion in Japan has development of IFE target injectors as part of their business plan. All of the above prototypes were only operated at room-temperature (or liquid nitrogen temperature in the Lebedev Institute case) and single shots at a time. IFE injector development needs to continue to include continuous auto-loading of targets, and full cryogenic operation.

The IFE reaction chamber commercial companies (Focused Energy, First Light Fusion, HB11, Innoven, Laser Fusion X, Longview Energy Systems, Marvel Fusion, and Xcimer Energy) with their partners likely are starting the development or are planning the development of target manufacture and target injectors. HB11 has received a $20M (Australian) grant for target/ hydrogen boron fuel development. Also of note is that the ICF program in China, is actively working to duplicate the target capabilities of the USA program [Liu2016] [Du2018].

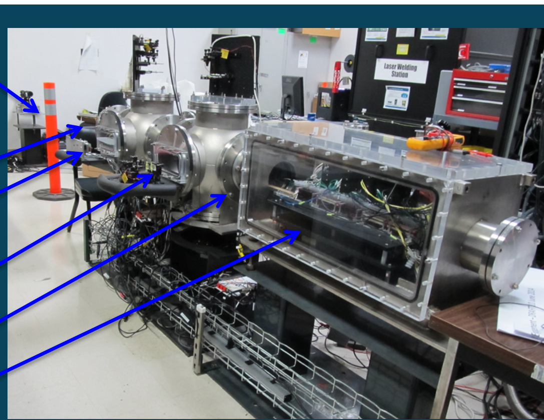


Fig. 12: Target injector room temperature prototype based linear induction accelerator built at General Atomics. The prototype shot surrogate targets at ~57 m/s with a placement repeatability of 0.14 mrad. Courtesy of General Atomics.

6.2.3 Capabilities and Competencies in Germany

Germany has expertise that can be applied in this area targets. Germany has long been known for extensive expertise and capability in chemistry particularly organic, polymer, resin, photo-initiator, and dye chemistry, which can be applied to polymer capsule and foam shells fabrication via micro-encapsulation or additive manufacturing. Deuteration of the precursor chemicals will be beneficial for tritium purification systems. Germany produced about 2% of the world supply of deuterium. In the field of micro-encapsulation, several members of the editorial board of the Journal of Microencapsulation are from German Universities. Microencapsulation is a specialty of Fraunhofer ICT (Fraunhofer Institute for Chemical Technology) and IAP (Fraunhofer Institute for Applied Polymer Research). German companies involved in microencapsulation include BRACE, Follmann, BASF SE, Symrise, Koehler

Innovation Solutions, and Evonik. Germany has made major investments in additive manufacturing including the very high resolution 2PP method. Capability and competence in 2PP exist at Fraunhofer IPT (Fraunhofer Institute for Production Technology), Fraunhofer ILT (Fraunhofer Institute for Laser Technology), Fraunhofer ISC/CESMA (Fraunhofer Institute for Silicate Research), Fraunhofer IPMS (Fraunhofer Institute for Photonic Microsystems), KIT (Karlsruher Institute for Technology)/EDMM2O, TU Darmstadt and others. The first commercial 2PP printer was introduced by NanoScribe, and others have followed (e.g. Multi-Photon Optics). The strong competence and capability in Germany in the fields of optics, optomechanics, and lasers are ideal to apply to faster 2PP printing. Spherical diamond coating, layer sequencing, and processing for HDC capsules was pioneered by Fraunhofer IAF and was successfully commercialized by its spin-off Diamond Materials. Diamond Materials spherical coatings were used in the first successful laboratory ignition of a laser target done at the NIF.

High resolution/accuracy metrology, inspection, and characterization are essential for developing targets. Germany is renown for expertise in optical and x-ray metrology and inspection. Commercial companies of equipment in this area include Bruker, Leica Microsystems, and Zeiss. Research institutions for x-ray inspection include Development Center X-ray EZRT of Fraunhofer IIS (Fraunhofer Institute for Integrated Circuits), Nuernberg.

Expertise and capability in laser target fabrication exist at the Target Laboratory of the Institute of Nuclear Physics of TU Darmstadt, Institute for Nano- and Microfluidics of TU Darmstadt, the Integrated Micro- and Nanosystems Laboratory of TU Darmstadt, the Technology Laboratory of LMU (Ludwig-Maximilians-Universität Munich), and at HZDR (Helmholtz-Zentrum Dresden Rossendorf). Focused Energy is hosting and expanding the TU Darmstadt Target Laboratory and is developing fabrication for their cone-in-shell target. Marvel Fusion and its partners are developing expertise and capability for nano-structured target fabrication.

Micro and nano structuring of surfaces can be accomplished via lithography, MEMS (Micro-Electronic-Mechanical-Systems), and LIGA (Lithographie). These techniques are available a numerous German universities, companies, and research institutions. There is experience applying nano structuring to laser targets at Fraunhofer IOF (Fraunhofer Institute for Applied Optics and Precision Engineering) Jena.

The KIT Karlsruhe Tritium Laboratory (TLK) has expertise in tritium and cryogenics which could be applied to filling wetted foam capsules with liquid DT. Cryogenic and vacuum industries will likely be drawn from for building such a device. Initial development can be done with liquid deuterium, but ultimately liquid DT will be needed to verify such issues as handling and movement of DT filled targets which will self-charge due to tritium beta decay. This will lead to electro-static charging of targets not present in liquid deuterium filled targets.

6.2.4 Industry Led R&D for IFE

IFE targets will be a mass-produced product that ultimately will likely be fabricated by industry. Industry provides much of the expertise in mass production of components and assemblies so it would be valuable to involve industry in the development of fabrication methods for targets. However, the commercial market for IFE targets is decades away and there are no obvious alternative markets for IFE targets. Although some manufacturing techniques developed for IFE targets could prove useful in other arenas (e.g. ultra fast, high resolution additive manufacturing, and fast micro-assembly robotic automation). This leaves existing industry unlikely to develop IFE target mass-production techniques unless provided funding to do so from the public sector or from private IFE reaction chamber companies. Further industry will be most efficiently involved if clear target design specifications and tolerances are provided and iterated upon, from either or both of national laboratories or IFE reaction chamber companies

There are numerous industries that could be drawn into the development of IFE targets. For capsules these include chemical, polymer (deuterated polymers), micro-encapsulation, and instrumentation companies for characterization especially optical and x-ray techniques. For fast additive manufacturing industries of chemical resins, polymers, optics, optical mechanics, and short pulse lasers. For hohlraum and cone type target parts industries could include machine tool makers, tool and die makers, press, stamping, deep drawing, and injection molding machines. Assembly could involve automation and robotics industries. In fuel production, the deuterium and lithium extraction industries. In fueling and layering systems cryogenic and vacuum industries could be drawn upon. Injectors could involve electromagnetic systems providers.

6.2.5 Findings and Recommendations

The DOE BRN [Ma2022] identified the TRL for manufacturing and mass production of reaction compatible targets for laser driven IFE reaction chamber concepts as TRL 2. The TRL for target injection, tracking, and engagement at reaction chamber -compatible specifications was also identified as TRL 2. This means that a substantial technology development gap exists before these areas are ready for use in an IFE reaction chamber, even a pilot plant scale reaction chamber.

Finding	Large quantities of low-cost targets, continually injected into the IFE reaction chamber, are essential for an IFE reactor's operation and economic viability. Currently, the capability to mass manufacture IFE targets at the preci-sion and quantity required does not exist.
Recommendation	Germany should establish a program to develop economic mass manufacturing methods for IFE precision targets.

The program could be to, in particular, demonstrate high-volume and eventually low-cost techniques for spherical capsule or wetted foam capsule fabrication (DOE BRN PRO 5-1). This includes both the structure of the target and methods to fill and layer the target structure with fuel (e.g. DT). Additionally, this should include demonstrating that the cryogenic target survives a thermal exposure equivalent to that expected during injection of a target into the reaction chamber. This could be by modelling or experiment. An experiment could consist of a low-speed injection of a target through a short vacuum oven such that the time in the oven was the same as the flight time of a high-speed injection into a large chamber. Pulsed x-ray or optical imaging could be employed upon exit from the oven to inspect the target and its fuel. Additional information on development approaches is provided later in this section.

Finding	A key requirement in an IFE reaction chamber is to accurately hit the target with the laser beams while the tar-get is flying through the center of the reaction chamber.
Recommendation	Germany should establish a project to demonstrate the accurate engagement of a target shot at full reaction chamber relevant velocity with a laser beam of reaction chamber relevant diameter. An actual IFE target or suitable surrogate may be used in the demonstration.

Demonstrating accurate engagement on-the-fly of IFE targets by a driver beam was DOE BRN Report PRO 5-2. This is a key risk or believability issue for IFE reaction chamber, completion of which will provide higher confidence for public and private decision makers to invest in IFE. To date target engagement has only been demonstrated at low speed (~5 m/s) and with small diameter laser beams (~25mm) [Car2010]. The gap here is that tracking at high speed, to ~<10 µm accuracy from large distances away (~10 m) will be challenging. Also, rapidly (a few msec) slewing a large (~ 1 m diameter) laser beam several tenths of mrad will be a challenging development for beam steering optics. Surrogate targets and simplified target injectors may be used for this demonstration. The technologies must also be compatible with the laser and final optics design.

FINDING	An injector for shooting delicate cryogenic targets into an IFE reaction chamber is a key need of an operational IFE reactor. Full speed, continuously loaded (with targets), cryogenic target injectors have yet to be demonstrated.
RECOMMENDATION	Germany should establish a program to develop a full speed, continuously loaded, cryogenic target injector.

Developing an IFE target injector for cryogenic IFE targets capable of reaching reaction chamber-relevant velocity without damaging the target or its fuel layer is DOE BRN report PRO 5-3. The gap in injector development is that while room temperature, single shot injectors have been demonstrated, what is needed is a fully cryogenic injector, that is automatically and continuously loaded with cryogenic targets. For DT fueled targets, the injector will also have to be designed with tritium containment and safety in mind. Schemes to block neutrons, emanating from the ignited targets, from damaging the injector (aka dynamic neutron shielding) are also likely to be required. Potential international partners that could be considered for such a program include CEA-SBT, LLNL, and GA.

Additionally, target fabricability, survivability, compatibility with reduced activation allowing reaction chamber maintenance and waste disposal, tritium inventory implications from filling and layering, and implications on the tritium recovery and purification systems should be considered in system studies of IFE reaction chambers. Conducting such system studies is included in the High-Level Recommendation 2.7. This was also included in the DOE BRN report PRO's (4-1).

As noted in the first Finding/Recommendation of section 6.2.5, a critical gap for an IFE reactor is mass production of wetted foam capsules at an economically viable cost. This includes not only the wetted foam capsule structure, but also systems to fill and layer the capsule with liquid DT. The production rate needed is ~1-15 Hz/reactor, with reaction chambers requiring fueled targets 24/7. The cost of targets including DT fueling and injecting will likely need to be ≤~20% of the electricity value produced by the targets' implosion. The cost of just the target structure will likely need to be ≤~5% of the electricity value produced by the targets' implosion.

This is important because economic production of the targets is one of the key needs for IFE reactor to be economically viable. Without large numbers of low-cost targets, IFE reaction chambers are not viable. Germany should pursue this because targets, along with lithium and deuterium are the fuel for IFE reaction chambers. Germany or German companies involved in the ongoing production of fuel for future energy sources will provide Germany with long-term benefits. As a key enabling technology for IFE, helping to bring IFE power reactors will be of great economic and security benefit (domestic supply of base load electricity and or high temperature process heat).

Partners in wetted foam capsule mass production could include CLF/research group of Prof. David Barrow, Cardiff University; DOE laboratories LLNL, LANL, SRNL, and support contractor General Atomics, and ILE/Osaka University, Japan. An all-domestic program could also be considered.

Development of mass production of wetted foam capsules should start now because it is a difficult task. Roughly, for each reaction chamber, one million, high precision targets need to be made each day for a cost of a few tens of cents each. Tolerances of microns on dimensions, and tens of nanometers on surface finish are typical for capsules of a few millimeters in diameter. If taking on the liquid DT filling development, tritium systems go through extensive design, engineering, and review to ensure safety, which lengthens development time.

Three generic approaches to making the structure of the wetted foam capsule are: (1) create a solid wall spherical capsule, then coat the interior of the capsule with a uniform foam layer, (2) create a spherical foam shell, then coat the exterior with a solid wall, and (3) create both the solid exterior and foam interior layers at the same time. For (1) micro-encapsulation can be used to form the solid capsule. The inner foam layer could then be catalyzed of the inner surface by ROMP (ring opening metathesis polymerization) from injected solution, or injected foam forming solution can be injected into the capsule followed by random rotation to evenly coat the inner surface. For (2) micro-encapsulation can be used to form the foam shell. The outer solid layer can be formed with an interfacial condensation reaction. If needed, this thin (few micron) coating can be thickened via PE-CVD (e.g. GDP) of polymer while agitating the targets in the coating region. Note that for the micro-encapsulation in (1) and (2) maintaining concentricity between the inner and outer surfaces of the capsule is one of the key challenges. Surface tension of the encapsulated, liquid suspended, compound drop that when cured will form the capsule will naturally want to form a smooth spherical shape. For (3) additive manufacturing using two photon polymerization (2PP) is method that could fabricate the inner and outer layers of the capsule simultaneously. The key development in this case is to drastically increase the speed of this production method, currently ~1 day to make one capsule. Options include but are not limited to massive parallelization of optics of the AM system, faster/ lower power setting print resins, holographic projection, and resin chemistries naturally forming foam so that individual foam cells or ligaments do not have to be traced, but rather entire area cross-sections can be micro-projected into the resin. For wetted foam targets, it is assumed that liquid DT will be wicked into the foam of the capsule to simultaneously fill and layer the capsule with DT. Here the key development points are compatibility of the foam with liquid DT (surface tension collapsing the foam and holding up to beta radiation damage from the tritium), and precision filling to the correct DT layer thickness. Where the issue for the latter is that capillary action will cause an overfill of the capsule (meniscus forming inside the capsule). Options here include precision dosing the wetted foam capsule with liquid DT, and heating the capsule to drive would the extra liquid DT after the capsule has been removed from contact with the liquid DT filling reservoir.

A coarse notional timeline for target systems development could be as follows:

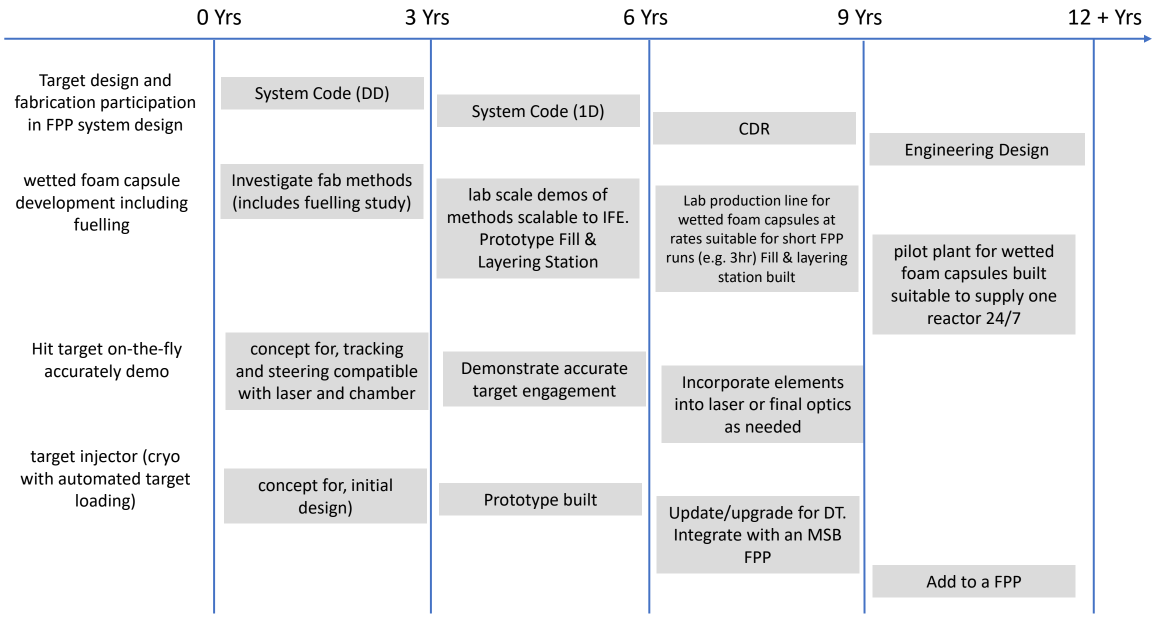


Fig. 13: National timeline for target system development.

The funding level to take these areas from the current TRL 2 level to a TRL 6 level (ready for installation on IFE reaction chamber pilot plant) is expected to be at the 200M€ level to within a factor of a few depending on the complexity of the target chosen for development. That is to say direct drive or shock ignition targets will be less costly to develop mass manufacturing for than indirect drive targets. This funding level is for developing one target concept in these areas. If additional target concepts are selected for development, then the funding level would rise commensurately.

6.3 Reaction Chamber

6.3.1 Role of Reaction Chamber in IFE

In the 'IFE onion model' used in this memorandum, the definition of the Reaction Chamber reads 'everything between the plasma and the wall'. This implies that there are critical interfaces to (at least) the target, the driver, the first wall and the fuel cycle (including removal of non-fuel elements). The Reaction Chamber itself then has to fulfill the following (sometimes conflicting) functions:

» First wall protection by mitigating the flux of particles and radiation originating from the imploding target
» Allow good coupling of the driver (access ports, beam propagation and absorption in the chamber)
» Protection of final optics from target debris
» Access for auxiliary systems (diagnostics, monitoring)
» Removal of fuel and ash (He and unspent D-T)
» Removal of impurities/debris from both target and first wall (anything that is not He and unspent D-T)

Most of these critical items arise from the high rep rate operation sustained over long time, and have not been a real issue so far (e.g. for NIF). It is important to note that the last two points must allow to re-establish identical conditions after each implosion, which will pose very strict limitations on the remaining non-removed fraction that can lead to large build-up over time.

The possible solutions to fulfill these functions are listed in the table below, taken form the IFE BRN report [Ma2022]:

Concept Wall/chamber	Advantages	Challenges
Solid Wall/vacuum	Simplest Chamber Easier Laser/Target Issues	Material survival
Magnetic Intervention/Vacuum	Smallest Chamber Mitigates first wall thermal Load	Ion Dumps
Replaceable Solid Wall/Vacuum	Easier Laser/Target Issues	Operational Complexity
Solid Wall/Gas in Chamber	Smaller Chamber	Laser/Target Issues (hot gas/ residual plasma
Thick Liquid Walls	Much Reduced Materials and Neutronics Issues	Chamber Recovery Droplet Formation Difficult to modify

Table 4: High level description of the advantages and challenges of IFE reaction chamber and wall concepts

6.3.2 R&D Status Worldwide

The R&D status in this area is in general quite low, as indicated in the TRL self-assessment from the BRN report[3]:

IFE concepts → Critical aspects for IFE development ↓	Laser Indirect Drive	Laser Direct Drive (Including Shock ignition)	Fast ignition	Heavy Ion Fusion	Magnetically Driven Fusion
Demonstration of ignition and reactor- level gain	4	3	2	1	3
Manufacturing and mass production of reactor compatible targets	2	2	2	2	1
Driver technology at reactor-compatible energy, efficiency, and repetition rate	4	4	3	2	3
Target injection, tracking, and engagement at reactor-compatible specifications	2	2	2	2	1
Chamber design and first wall materials	1	1	1	1	1
Maturity of Theory and Simulations	3	3	2	2	2

[3] While there are ongoing discussions about the absolute values of the TRLs in Fusion in general, we take the table as an indication of the relative TRL of the individual elements of the IFE onion.

IFE concepts → Critical aspects for IFE development ↓	Laser Indirect Drive	Laser Direct Drive (Including Shock ignition)	Fast ignition	Heavy Ion Fusion	Magnetically Driven Fusion
Availability of diagnostic capabilities for critical measurements	3	3	2	2	2

Table 5: TRL for five IFE concepts for the seven aspects critical for an IFE development path.

Studies of an integrated concept have only been conducted on a conceptual level on paper (for an overview see[Mei2010]. LIFE [Lat2010] proposed a Xe fill gas at about 1 mbar pressure at normal conditions. This would have the effect of converting all kinetic energy in charged particles into a flash of X-rays with a first peak and a retarded wave profile. The SOMBREO study [SOM1994] applied a similar principle (6 mbar at normal conditions). The start-ups which whom we discussed in the course of this assessment did not present a definition of a concept for a reaction chamber and hence did not give specific input to the assessment for the reaction chamber.

The studies found that the buffer gas does not affect laser beam propagation and absorption or the injection of indirectly driven targets. However, studies focused on directly driven targets revealed that the buffer gas can cause surface modifications, which would negatively impact symmetric coupling. [Goo2001].. Clearly, more detailed assessments are needed here.

For concepts that do not use a specific fill gas, these problems are not of concern, but the problem is transferred to the protection of the first wall, usually envisaged by liquids on the first wall.

Concerning the chamber clearing of debris from target, ablation of the first wall, and unspent fuel, studies are not very detailed and must be taken to a more concrete level. Since this is an optimization problem with many interfaces and boundary conditions, a systematic treatment in a 'systems code' approach is recommended. This is in line with BRN PRO 6-3 'develop synergistic target/fuel cycle co-design between the plasma physics community and the fuel cycle teams and chamber design teams. In such an activity, we recommend that adequate weight is given to the chamber clearing, noting that existing studies address in detail mostly the wall protection aspect.

Experimental verification of the individual elements of the technologies needed has so far only been performed on some individual points (e.g. mock-up of the Flibe spray), but will need a serious coordinated effort in any IFE development program. An important part of the strategy will be to separate items that can be done in a non-nuclear environment, to develop corresponding evaluation concepts and to work towards an integrated test that finally has to be transferred to the nuclear environment. While isolated aspects such as the interaction of the target with the fill gas, the formation of solid debris from first wall materials or the hydrodynamics of liquid wall materials can be studied individually, an integrated demonstration will finally have to prove the expected steady state conditions achievable in the chamber for long operation periods (with millions of targets imploded). This will require a dedicated facility generating representative debris at realistic rep rate to demonstrate the desired level of removal. Without any detail, the Expert Group discussed a possible timeline for such an approach which is given below.

YEAR	1	2	3	4	5	6	7	8	9	10	11	12	>>
integrated plant description	System code (0-D)			System Code (1-D)			CDR						
FPP design										Engineering design			
removal of material	Conceptual study 3 options												
				experiments on isolated aspects									
steady state demonstration							integrated non-nuclear						
steady state demonstration including specific first wall damage										integrated nuclear			
				1st strawman						Plant conceptual design			

Fig. 14: Timeline for reaction chamber design.

A very rough estimate for the resources indicates that the experiments on isolated aspects and the development of evaluation concepts might require several Mio € in total over the 3 years time span proposed, while an integrated nuclear test would need a larger dedicated facility. The integrated nuclear test requires a dedicated IFE facility to which costing is largely determined by other elements and hence not attempted here.

6.3.3 Capabilities and Competencies in Germany

The present level of capabilities is clearly insufficient and must be upgraded substantially for any serious IFE program. The existing capabilities (codes, simple mock-ups for individual elements exist mainly in the US. As pointed out above there is a serious lack of integrated testing facilities. The problem is very specific to IFE and does not have significant commonalities with R&D carried out in MFE. At present, Germany does not hold special capabilities or competencies in this field.

6.3.4 Industry Led R&D for IFE

This is at present a basic research activity that does not lend itself well to involving industry led R&D.

6.3.5 Findings and Recommendations

The gaps pointed out in Sec. 6.3.2 are

» Develop an integrated concept that takes into account all of the constraints and boundary conditions. For this, one or several 'strawman' IFE plant conceptual designs need to be established at systems code level.
» Demonstrate individual engineering solutions for all elements that can be separated. Establish which ones can be tested in a non-nuclear environment.
» Demonstrate integrated solution to validate that the requirements can be met over long periods of time (i.e. millions of implosions).

Since the problem has to be solved for any IFE FPP design (although with different solutions for the individual elements depending on the schemes chosen for the IFE FPP), it would be a very good field for international collaboration, especially if the systems code approach can be developed jointly in such an environment. The integrated test will need a large installation with high rep rate, also pointing to a large benefit of international collaboration since not many of these facilities will exist (there is none at present). Prime partners for collaborations are those who have conducted ICF/

IFE programs in the past, i.e. US, UK, France, Japan (China and Russia could in principle be partners as well, but that would need a stable political environment).

Finding	The reaction chamber concept has important interfaces to the concepts of target design and injection, coupling of the driver wall protection and removal of debris and unspent fuel. While so far, a lot of focus has been put on wall protection. The design choices in all these areas are interlinked and need to be optimized together.
Recommendation	Initiate an integrated study that takes into account the different interface aspects, at least on a systems code level.

Finding	There are only a few integrated studies on the reaction chamber concept, and especially no recent ones.
Recommendation	Initiate a thorough study on the reaction chamber concepts.

Finding	The concept studies on the reaction chamber are mostly theoretical and no clear path for an experimental validation exists.
Recommendation	Establish a path for experimental validation, first for individual aspects, then for an integrated non-nuclear test (if meaningful) and then in a nuclear environment.

6.4 First Wall and Blanket, Fuel Cycle

6.4.1 Role of First Wall, Blanket and Fuel Cycle in IFE

The first wall and the blanket are central elements of a future fusion power plant. Like the combustion chamber walls of a fossil fuel power plant, they enclose the power plant core in which the fusion reaction takes place, as illustrated in Fig. 15 of a generic fusion power plant design. The interface between the blanket and the plasma is the so-called first wall. In addition to the high temperatures of the fusion reaction and, above all, the high-energy particle stream (-particles) as well as the radiation from the reaction, the first wall is exposed to special stresses. In addition, it experiences time-dependent loading during inertial fusion, which places extreme demands on the material. Immediately adjacent to the first wall is the blanket, which, in addition to extracting the heat generated in the fusion reaction for conversion to a thermodynamic power cycle, must perform two other tasks that distinguish a fusion power plant from other types of power plants. First, the blankets shield the radiation generated during the fusion reaction so that no radiological hazard to the environment occurs outside the biological shield. More importantly, however, the blankets generate the fusion fuel, tritium, using an appropriate configuration of breeding and, if necessary, multiplier materials, so that a fusion power plant does not require an external fuel feed. The tritium produced in the blanket by means of a nuclear breeding reaction is extracted from it and fed to the fuel preparation of the internal fuel cycle, which processes the unburned fuel (exhaust processing), in the so-called external fuel cycle. The bred fuel is reinserted for combustion in the reaction chamber.

The first wall of a reaction chamber is exposed to extreme loads originating from the burning fusion targets. Extreme heat load includes x-rays and charged particles but also neutrons. The charged particle spectrum consists of alpha particles, carbon ions, protons, deuterons and tritons. Thermal reactions of materials leads to serious damage in a fusion reactor independent of how the fusion is achieved either by magnetic confinement or by means of a laser induced fusion process. Although the power level may differ between the fusion reactor concepts (laser or magnetic fusion) the principal damage features are more or less the same, but with a different emphasize of the individual damage types. In both confinement concepts the first wall is facing power densities of the order of MW/m^2, see e.g. [Lat2017], [Tak2015] or [Lin2011] and numerous other articles.

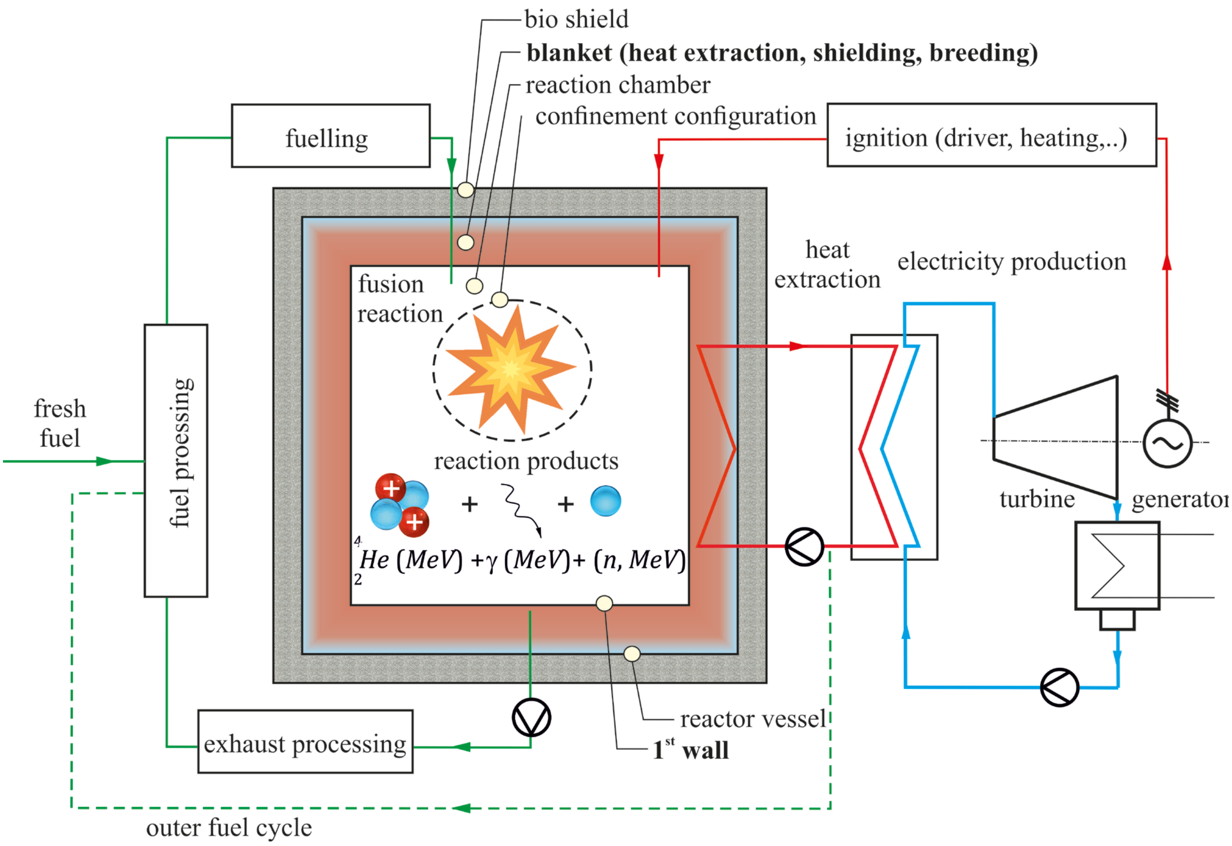


Fig. 15: Functional diagram of the reaction chamber of a fusion reactor, its interfaces and the associated power systems and process cycles.

Laser fusion offers a higher degree of freedom to design the in-vessel -components of the core than magnetic confinement fusion, due to the absence of forming a magnetic cage for the fusion plasma. Thus, in principle to in-vessel configurations are conceivable. But a closed fusion reactor concept has not yet been formulated. Such a concept is therefore indispensable in order to concretely formulate clear requirements for the first wall, the damage to the structural material, but also the requirements for the blanket (heat removal, burn rate) and the fuel cycle, so that a targeted development of a fusion reaction chamber and the components inside it can take place.

There are in principle two options to design the reaction chamber as outlined below.

1. Integral In-vessel Design
Provide a sufficiently thick liquid film on the reaction chamber walls that will not cause permanent damage to the armor material and will remove helium atoms and unburned fuel such as debris. This can be either liquid metal or a liquid salt compound. Such a design option limits laser access to the reaction chamber and also is challenging for required in-vessel remote handling operations. But it substantially reduces the thermal and neutron wall load on the solid reactor boundaries.

2. Solid State Design
Both the shield and the blanket are designed as solid structural units, which facilitates remote handling installation and removal operations while providing a high degree of wall coverage for successful tritium breeding, but also, reduces the lifetime of this component due to material degradation of the solid armor.

While option 1 has been explored up to now only in a concept form, the current power plant studies mainly rely on a solid-state design, in which the so-called in-vessel components (first wall plus attached blanket) are constructed in the form of an onion skin. The interface between the reaction chamber and the blanket is formed by the first wall composed of a so-called armor material, which consists of a low-activation high-melting temperature material. Behind this is then the composite of structural and functional material that forms the blanket. Both the first wall and the blanket must be replaced several times during the life of a fusion power plant due to high material degradation, typically in cycles of 3-5 years. Due to the high activation during operation, the replacement must be done remotely. At the same time, in order to keep the radiological load outside the power plant low, they should be designed to ensure good recyclability of functional and structural materials. Integral designs (option 1) seem to be simple at first glance, however, they exhibit several challenges, such as film instabilities, dissolution of fuel and debris in the liquid so that they are currently considered to be very advanced concepts.

6.4.1.1 Armor Materials

In case neutrons and charged particles irradiate and heat the first wall material with a high intensity directly, a series of competing effects take place damaging the material altering is thermophysical properties and then even more the material can be sputtered off or ablated. Once the wall is ablated, expanding gas or plasma can disturb the propagation of laser light irradiating the fuel target in case of inertial confinement fusion or to prevent ignition in case of magnetic confinement fusion devices.

There are many studies on laser fusion such as the LIFE-program (laser inertial fusion energy) in the US, the HiPER (high-power laser energy research), the HAPL program (High Average Power Laser (HAPL) and for magnetic fusion Studies in the US (ARIES) or Europe (EUROfusion) identifying potential first wall material candidates and potential failure and degradation aspects, because pre-mature failure of the plasma facing components (in-vessel-components) affects not only the safety performance of the plant but also comprises maintenance and thereby availability.

Irrespective of the fusion reaction principles tungsten is the primary candidate as first wall material for several reasons. Tungsten reveals not only a high thermal conductivity and a high melting point which makes it ideal as heat sink material. Moreover, tungsten exhibits a relatively high thermal shock resistance, low physical and chemical sputtering and reveals a relatively low tritium retention, which is favorable to safety of a nuclear installation. From the nuclear point tungsten creates some transmutation products and shows a rather large activation, however, this is decaying fast and only the transmutation products create challenges to the material's mechanical behavior.

The major challenges for the armor are

» neutron damage (dpa and He/dpa transmutation), and combined effect (see Sec. 6.4.1.2),
» damage to the first wall by the Helium ions, creating high close to surface heat fluxes by stopping of the Helium-atoms near to the surface (stopping in a boundary layer of only about 6µm depth).
» Helium-ions displacement damage in the tungsten or iron lattice leading to aging effects such as softening due to phase transformations.
» Helium implantation in the wall causing continuous cracking and permanent swelling.
» Spalling, sputtering of the wall.
» First wall hydrogen embrittlement

Some studies related to He-particle damage and its effects have been executed both in the US and in Europe, indicating a high susceptibility of the armor material to He-irradiation. Also, the effect of pulsed irradiation on armor due to permanent cycling and the associated modifications in the grain structure have been identified. Especially the high peak loads released in the armor yield power releases in the lattice structure being of orders of about 103 higher than the mean value causing likely grain and lattice structure modification impacting the material properties. For fusion reactor applications however, there is a lack of reliable data on limitations, in particular from the combined exposure to neutrons and gamma radiation.

6.4.1.2 Structural Materials

Helium-particles and gamma-irradiation challenge the armor material mainly in form of heat release. However, neutron damage and Helium transmutation pose a similarly high challenge for the structural material, since neutrons with a kinetic energy of 14.1 MeV are penetrating deep into the blanket material structure and are creating dislocations, vacancies etc., expressed by the quantity displacements per atom (dpa). Typical damage rates for fusion reactors are in the range of >10dpa per full power year. Moreover, their energy is high enough to cause a neutron induced transmutation reaction generating Helium atoms within the material. The mobility of the generated Helium-atoms, measured in appm in the structure material lattice is very low; limiting values for structure materials are of order of O(500-1000 appm). The uniqueness of simultaneous material damage by neutrons and transmutation expressed by the He/dpa ratio (on the order of 10 appm/dpa) is specific to fusion, and differs significantly, for example, from knowledge in nuclear lattice or accelerator science.

Although especially iron exhibits, for fast neutrons (>100 keV), still a high nuclear cross-section, there is basically no alternative to the use of steel as structural material, neither in terms of activation nor in terms of manufacturing, bonding/welding techniques and versatility of design.

Fusion reactor concepts all focus to use low activation ferritic martensitic (RAFM) steels such as EUROFER97 or F82H as structure material, in which the conventional steel alloying elements are replaced by lower activation elements. Only ferritic martensitic (FM) steels provide sufficiently high heat conductivity at low swelling rates at high material damage and thereby allow for the exchange of reaction chamber and first wall parts. There are promising attempts to develop so-called ODS steels (oxide dispersed strengthened), see [Zin2017], allowing for higher high temperatures (>600°C) and with potentially very high resistance to fusion neutron-induced property degradation. The currently available results show for the ODS steels higher temperature-dependent uniaxial yield strengths, higher tensile elongation, better high-temperature thermal creep, and lower ductile to brittle transition temperature (DBTT) as well as a superior fracture toughness behavior compared to conventional RAFM steels. However, they require a powder metallurgical production route and a nuclear qualification is similarly absent as well as qualified joining technologies in case of replacement. Thus, the focus in most research projects is directed towards RAFM steels and their qualification, see for laser fusion e.g. [Alv2011].

The challenges for structural materials integrally correspond in laser fusion to those also being present in magnetic fusion. Specific challenges arise from the pulsed operation of some Hz repetition rate, which may cause segregation processes that can further degrade the structural mechanical properties, especially aging effects such as creep and fatigue could lower the material limits. The fundamental challenges faced by laser fusion here correspond almost to those of the armor material except for the Helium implantation.

6.4.1.3 Functional Materials

One advantage of laser fusion is a potentially a higher wall coverage of the reaction chamber by blankets, since this fusion power plant concept does not require a large particle exhaust device and comparably smaller openings for driver systems than magnetic devices, in which several heating systems must be integrated. Thus, neutron multipliers such as beryllium/beryllides or lead are virtually not required if a wall coverage by blankets of more than 85% of the reaction chamber by a credible blanket design can be ensured using lithium or lithium salt mixtures simultaneously as breeder and coolant and keeping the steel fraction of the coolant confining structures considerably below 10% of the blanket volume, see [Saw2007] or [Mei2013].

Some principal computational studies on the suitability of breeder and neutron multiplier studies have been conducted in the context of the HAPL program. The functionality of the breeder and multiplier material itself is not affected by the pulsed operation of a laser fusion plant, since the time averaged fluxes are the same for laser fusion and magnetic confinement. But, the structural behavior and properties of solid breeder/multipliers, which in the prior studies were identified as reference solutions for a laser fusion plant, are strongly impacted by pulsed operation. For the breeder material in pulsed laser fusion plants this is associated to the exothermal reaction of lithium with the neutrons generating tritium. By pulsed operation the peak flux density and the temporal power release yields to temperatures causing segregation within the material also altering grain structure, which is challenging especially to the long term integrity of the breeder. Current assessment tools are not capable to depict these effects with sufficiently high local resolution in correlation with impact on the materials (both breeder and multiplier). However, at least conservative validated tools are mandatory to establish a closed substantiated blanket concept.

6.4.1.4 Blanket Development

The blanket is the key component of any fusion reaction and irrespective of the fusion power plant concept to be followed has three major functionalities.

» Breeding of tritium to an extent to allow for self-sufficiency of the plant (potentially further other fusion power plants-FPP).
» Heat removal of the energy released by the neutrons in the bulk and heat sink for the armor material.
» Radiation shielding of the reaction chamber vessel towards the ambient.

The evaluation of the power released on the wall and within the structures as well as on the interface by ion, photon, X-Ray and neutron radiation necessitates a coupling of plasma burn physics with radiation transport modelling to interface the different physics domains. The transport calculations of neutrons and photons is for fusion reactor types (inertial fusion and magnetic fusion) by now mostly based on a steady state Monte-Carlo simulations using fusion special IAEA certified nuclear fusion data libraries (JEFF – OECD, ENDF/B-VIII-USA, JENDL-Japan, CENDL-China, TENDL-CERN) which allows to calculate

» neutron wall load,
» material damage (through linear energy transfer models -),
» transmutation rate,
» activation of material (and thus shut down dose rate, nuclide vector as function of time, decay heat development at operation and for extraction,
» radiation release through ambient and most important,
» tritium breeding ratio (TBR), which specifies the amount of tritium generated by incident fusion born neutron as well as energy amplification through exothermal reaction of neutron with matter.

Since the blanket constitutes the major heat source in a future fusion reactor for electric energy production through a thermodynamic cycle process an efficient blanket design has not only to meet the component functionalities but also must match superior power plant objectives

» predictable sizeable electric power output,
» flexible integration in a variable electric grid architecture with,
» potential plant black-out start-up capability,
» at highest nuclear safety levels,
» with a high availability,

such as formulated in [Fed2017]. This requirement set-exceeds by far the aspect of functionality but intrinsically necessitates an integrated approach of the blanket design into the context of a closed balance of plant architecture (BoP), considering all three pillars of the nuclear safety (operational safety, plant safety, radiation waste handling) and finally logistics and maintenance in the view of the entire power plant. This holistic approach is reflected by a balance of plant (BoP) analysis, which interlinks the power production by the fusion reaction with the components and the required operational units such as the tritium plant, the laser, the vacuum systems, the diagnostics and potential electric/thermal buffer volumes. A simplified sketch is illustrated in Fig. 16, from which it becomes obvious that the only power source driving the plant is the blanket, which has to feed all other power consuming units.

The key elements of the blanket development are the structural materials confining the coolant, the coolant itself and the functional materials, such as the armor and in case of magnetic confinement fusion neutron multiplier and breeder material. Closely reviewing the BRN report [Ma2022], the formulated focused Priority Research Opportunities (PRO) for Power Systems Science, Engineering, & Technology addresses that closed requirements sets for a blanket design in the view of holistic power plant concept is one of the most urgent steps to be mastered. By now the blanket requirements are only indirect addressed via two priority formulations reading to

» Undertake a series of system-design studies to establish a suite of self-consistent, quantitative IFE plant models, and use these to guide each aspect of the R&D program (PRO 6-5);
» Develop a test facility with a neutron source to evaluate blanket technologies and to test fuel cycle components and systems at scale, including tritium extraction and transport, and the potential for direct internal recycle (DIR) (PRO 6-4).

Moreover, the reaction chamber (blanket, vacuum systems) associated technologies are still in a state of concept proof on the level of feasibility identification. This additionally requires a concept for the inner and outer fuel cycle layout (blanket, vacuum systems - unburned fuel) and the associated technologies.

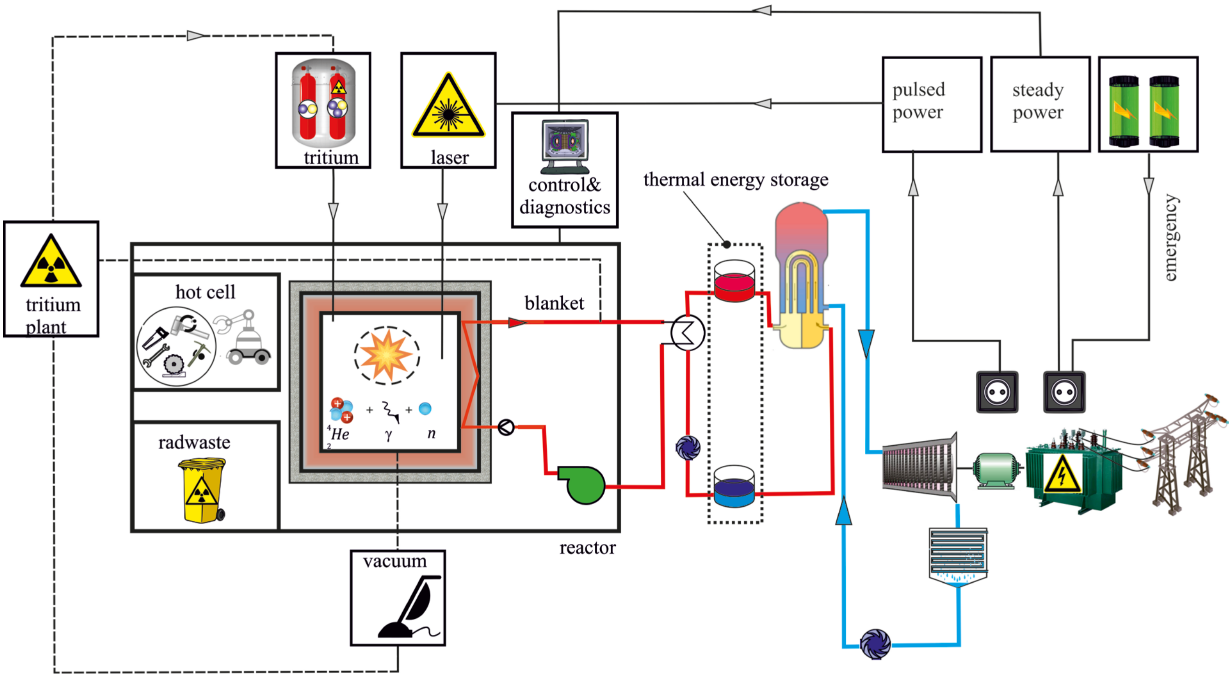


Fig. 16: Simplified sketch of the Balance of Plant (BoP) scheme for a Laser driven fusion power plant.

Without this synergetic functionality, however, a functioning power plant is inconceivable.

To summarize a closed blanket design requires as input some cornerstones of the plant architecture (logistics & maintenance, power train, fuel cycle, power requirements by auxiliaries) and is tightly linked to the fuel cycle and the material development and qualification. This has been identified stringently in magnetic confinement fusion about more than a decade ago at several sites (US, China, Japan, EuroFusion) and has been implemented in the fusion power plant development projects but still with a varying degree of stringency. The range of requirements management and the interaction between blanket development and the requirements for a power plant are described, for example, in [Cis2017]. The main systems impacted by the breeding blanket architecture and technology are:

» Primary heat transfer system not only delivering the heat to the power conversion systems but also confining the tritium within its barrier, a reliable tritium extraction, and in-line coolant control systems.
» The vacuum and shielding systems acting as static radiological barrier and life-time installation but allow for power installation lines (heating systems), safety monitors and diagnostics.
» Logistics systems providing access for remote maintenance, recovery & repair actions, ...

Thus, the blanket design always represents a compromise between the actual functional requirements (breeding, power extraction, shielding) and the requirements from the power plant context. Another important issue is the coolant selection for the blanket. The following points are particularly relevant in the context of the power plant:

» Tritium inventory and potential migration through power train (mainly for safety).
» Efficiency of the tritium extraction technology and development of a tritium fuel cycle.
» Coolant compatibility with structural materials, in-line coolant purification (affinity to

H, C, O, alloying element of structures, etc.) and coolant management through regular/ accidental plant operations,
» coolant limitations (temperature range, Magneto-hydrodynamic effects, heat extraction limits, dimensioning of ducts, ageing),
» thermal conversion efficiency,
» capability to integrate thermal storage systems

Finding Principal studies on the functionality of the blanket and its ingredients have been conducted in prior laser fusion programs. However, they´ve been not integrated in an overall plant concept. In turn no blanket design team composed of several expert profiles has been established.

Recommendation

» For a closed blanket design first a consistent closed plant design is mandatory, in which the high-level requirements of a power plant are formulated. This allows to establish a raw functional plant concept, for which different technical solutions can be analyzed in terms of feasibility and robustness on the plant level. Such a plant study should aim at identifying principal reference design options for different blanket concepts, armor and material options and elaborate potential fallback design options. Therefore, a plant design team is required, which consists of target and material experts as well as reaction chamber component and power conversion system designers.
» Set-up a blanket design team elaborating fundamental blanket concepts meeting the fundamental requirement such as breeding shielding matching to comply high level requirements. This team shall provide interfacing information to a plant design team.
» In a second step a system study needs to executed scoping a sensitivity and uncertainty study, which, on its part, enables the largest risk elements and systems to be registered and recorded in terms of their impact. Based on such an analysis research priority in terms of infrastructures and human capacity building to develop a roadmap containing milestones to reach that high-level goal can be extracted for development.

To speed the first two processes likely to be executed in parallel and potentially scoping a period of about 3 years, participants from prior studies such as HAPL or LIFE as well as experts for blankets and materials should be part of the studies. After the second step requiring approximately also 3 years a solidified basic and robust design should be existent allowing for larger scaled investment decisions on priority facilities required to substantiate a closed reaction chamber design.

Regarding purely the blanket functionality itself, the following competencies are required:

» coupled neutronics, thermomechanics and thermal hydraulics to extract a basic concept underpinned by expert know how in
» liquid metal engineering and coolant chemistry
» neutron – resistant material engineering
» fuel cycle and process engineering.
» system integration into the plant.
» Safety analyses.

With respect to blanket engineering, there is a broad synergy between magnetic and laser fusion not only for fusion specific expertise but also in neighboring science fields such as accelerator sciences, nuclear engineering and process engineering.

6.4.1.5 Fuel Cycle and Tritium Management

The fuel cycle of any fusion power plant is composed of an inner fuel cycle in which unburned fuel is extracted from the exhaust stream, processed in fuel plant to achieve an adequate 50:50 ratio of the fusion fuels deuterium and tritium and a fueling system to re-inject the matter into the reaction chamber. While deuterium is provided from outside the reaction chamber the tritium has to be bred in the blankets during plant operation and extracted from the blanket within the outer fuel cycle to be fed into the inner fuel cycle. Thus, the functionality of the inner fuel cycle covers:

- exhaust gas cleaning (removal of the Helium ash- alpha particles, cleaning of the exhaust gas from all other species than hydrogen and its isotopes),
- detritiation of the exhausts (steam, hydrocarbons),
- isotope rebalancing (to attain a favorable 50:50 mixture of fuel), and
- fuel storage.

The principal functionalities here are the same in magnetic fusion and in laser fusion, however, the inner fuel cycle design poses different challenges. The tasks of the inner fuel cycle are to:

- ensure a continuous removal of the ash and,
- removal of radiative gases injected to ensure armor (puffing, detached operation),
- diffusion losses of fuel evaporating from the pellet,
- detritiation of the exhaust constituents.

This requires dedicated vacuum systems such as diffusion and/or cryopumps and exhaust cleaning systems. Concerning the laser-based fusion, the fuel cycle design database is quite scarce. Most papers adopt a single cycle once through cycle as described e.g. in [Rey2013] and the literature cited therein. The fuel cycle itself and most of the components contain a functional description, however, a quantification of throughputs, process efficiencies and times as well as the inventories located therein is not provided. Additionally, as input a high tritium breeding ratio (TBR>>1.2) and highly efficient tritium extraction from lithium for the outer fuel cycle and a high burn-up fraction of the Deuterium-Tritium fuel by the reaction (assumed ~30%) are considered as inputs to achieve a viable architecture. To what extent this can be realized is not yet clear, but the technologies of the inner fuel cycle allow for cross-fertilization of magnetic fusion and laser fusion once a closed fuel cycle design for laser fusion is established. The synergetic effect is given that most of the processes are gas/solid or fluid/solid interfacial process with allow a transfer and a modular arrangement by up or downscaling.

Outer Fuel Cycle

The outer fuel cycle cannot be treated in a similar manner to the inner fuel cycle and strongly depends on the coolant breeder configuration of the blanket technology chosen. Regarding the functionality of the blanket interfacing the fuel cycle several tasks has continuously to manage:

- Tritium extraction from breeder (either solid or liquid),
- breeder fluid purification (only liquid breeder blankets),
- corrosion control of structures and
- permeation control of tritium.

For laser fusion liquid breeders seem to be an attractive design option, since large wall coverage of the reaction chamber by blankets seems to be feasible; discussed are even liquid lithium and lithium-based salts. Both, options allow a high tritium breeding ratio, however, also exhibit challenges in extraction of tritium and several technologies have been developed, such as permeation against vacuum (PAV), Gas Liquid Contactor (GLC) and Liquid Vacuum Contactor (LVC), however, the maturity level of all technologies still is insufficient for up-scaling.

Regarding laser fusion the extraction of hydrogen isotopes, mainly tritium from liquid lithium requires high purity liquid lithium. Due to the high reactivity with nitrogen, oxygen and carbon and their detrimental effect on material compatibility [Bor1987], [Cho1985] purification systems are necessarily needed. Cold traps (200°C) for oxygen, carbon and corrosion products and hot traps (600°C) for nitrogen with getter materials like titanium alloys or niobium are applied. The very high solubility of tritium in liquid lithium combined with the low partial pressure over the lithium even at 500°C($3.41*10^{-9}$Pa) prevents the recovery via the vapor phase as studied in detail in [Mor1995]. Different techniques are elaborated like the Maroni process based on molten salt extraction [PAT1976] and complementing research of [Mor1991] by gettering by yttrium or a combination of both, permeation windows, fraction distillation, cold traps and recently electrochemical extraction using solid lithium-ion conductors. Efficiency has also been studied by [Tep2019]. But all of these methods exhibit specific challenges associated with drawbacks which are mostly associated with insufficiently low efficiency of tritium recovery. The established Maroni process is very complex and suffers from considerable corrosion issues and potential impacts on the neutronics. The gettering process using yttrium suffers from the low dissociation pressure of the LiT, which results in low efficiency. Gettering combined with the molten salt process improves the efficiency of LiT dissociation and eliminates negative effects from the molten salts on the lithium but adversely increases complexity. Permeation windows like zirconium-palladium usually suffer from slow diffusion rates and surface contamination. Fraction distillation requires high temperatures (>900°C) with all associated material problems. All these aspects have been extensively studied in the context of the IFMIF-DONES facility since it produces the neutron fusion like spectrum by bombarding a free surface liquid lithium film with 40MeV deuterons (125 mA current) to produce a fusion like spectrum of neutrons for material irradiation and qualification studies.

More promising for the extraction of tritium are cold traps where protium is added to the lithium and by reducing the temperature (200°C). The dissolved hydrogen isotopes will, due to the large difference of the solubility, precipitate. These precipitations will be heated for tritium recovery and separated by a cryogenic distillation. Here, an efficient cold trap design and the extraction of the precipitates formulate the major challenges.

Electrochemical extraction using solid lithium-ion conductors as also discussed (Teprovich, et al., 2019, [Tep2019]) relies on the electrode development for lithium-ion batteries. Besides high ion conductivity chemical stability in contact with liquid lithium at around 500°C is as well required. Selection of the most suitable ion conductors, including scale-up and process optimization are the most challenging issues. Thus, the process design of the outer fuel cycle is still an open issue, which is also addressed in the BRN report in the context of Priority Research Opportunities (PRO) PRO 6-4 reading to:

“Develop a test facility with a neutron source to evaluate blanket technologies and to test fuel cycle components and systems at scale, including tritium extraction and transport, and the potential for direct internal recycle (DIR).”

Whether it makes sense to develop a fuel cycle in the context of a volumetric neutron source can be questioned, especially when the individual modules in the process chain are not yet validated and up-scalable, but the need for an infrastructure depicting the fuel cycle and the development of a verified and validated fuel cycle simulator are essential for a future fusion power plant and thus not debatable.

Finding	A rudimentary sketch of a fuel cycle facility has been developed in the prior US programs aiming to identify potential process engineering elements mainly with respect to their principal viability. In the absence of a reference target and blanket such an approach is justified. However, a closed concept has not been elaborated.
Recommendation	Once given a plant concept urgently all fuel process concepts developed in the past need to re-evaluated, the efficiency of the individual process elements need to be analyzed and interfaces have to be formulated targeting to develop fuel cycle simulator. This is mandatory not only to ensure the self-sufficiency of the power plant but also to develop an accountancy approach required for the licensing of a power plant.

6.4.2 R&D Status Worldwide

6.4.2.1 Materials

Laser and magnetic fusion experience simply bLaser and magnetic fusion experience simply by the fusion reaction itself the same fundamental material damage mechanisms for armor and structural materials. Laser fusion poses additional challenges for the reaction chamber wall by fast ion (mainly -particles) and hard-X-ray radiation even capable of causing gamma-neutron reactions and thus induces additional material damage. This type of damage mechanisms and its impact has been studied mainly in the context of accelerator sciences within the context of spallation sources such as spallation neutron sources in Europe e.g. the European Spallation Source (ESS, see https://europeanspallationsource.se/) and in the US at Oak Ridge (https://neutrons.ornl.gov/sns). Fundamental fusion studies devoted the Helium effect on armor materials such as tungsten are exploited in the US in collaboration with Oak Ridge e.g. at University of California San Diego [Wan2017], University of Wisconsin (Fusion Technology Institute, e.g. [Zen2010]). The European counterparts are Technical University Eindhoven, DIFFER (https://www.differ.nl/research/plasma-material-interactions), Forschungszentrum Jülich (FZJ) being also equipped with corresponding facilities such as MAGNUM-PSI at DIFFER or Jule-PSI at FZJ (https://www.fz-juelich.de/en/iek/iek-4) and the corresponding material analysis labs e.g. at Karlsruhe Institute of Technology (KIT) the Fusion material laboratory (FML- www.iam.kit.edu/mmi/Fusion_Materials_Laboratory.php). High heat flux simulation laboratories are available e.g. at IPP (Max Planck Gesellschaft, Gladys) or at KIT (Heloka-High pressure).

The main individual damage mechanisms such as dpa damage, helium transmutation within the material and the associated mechanistic and structure modifications have been identified more than 20 years ago. In a fusion reactor both damage types occur simultaneously and in the presence of hydrogen isotopes having a non-linear impact on the material properties, such as yield strength, increased hardening, altered creep and fatigue behavior. By now this cannot be predicted by numerical tools. Hence, a solid experimental data base and corresponding modelling and evaluation efforts for all types of materials exposed to neutrons at fusion relevant kinetic energies is indispensable if not even fundamental importance for the viability of any type of deuterium-tritium reactor based fusion power plant independent if it is laser based or relying on magnetic confinement. Neutron and Helium transmutation within the structural material is quite similar for laser and magnetic fusion requiring an irradiation facility providing neutron energies in the range of 14.1 MeV and a He/dpa ratio of the order of 10 appm/

dpa, especially to qualify structural materials. Such a neutron source for structural material qualification is developed currently in Europe in the context of EUROfusion under the label IFMIF-DONES (International Fusion Material Irradiation Facility- Demo Oriented Neutron Source, https://ifmif-dones.es/ [IFM2022], for technical details see [Iba2018] based on the preceding joint Japan-European project in the context of the Broader approach IFMIF-EVEDA demonstrating the viability of such a neutron source, for more information see https://www.ifmif.org/).

Observation

With respect to dpa damage and He/dpa effects synergies between both magnetic fusion and laser fusion are obvious although they´ve been not exploited visibly by now. Nonetheless, a single facility for the qualification of structural materials and the verification of low activation FM-based steels only without cross-referencing is a critical strategy in itself. But, apart from a structure materials qualification facility, there is a lack of infrastructure for armor materials, as well as for functional materials such as breeding materials and potential neutron multipliers. These need not be of the same order of magnitude as those for structural materials, but they must provide prototypical parameters in the energy spectrum, helium ions damage and neutron flux.

In addition to the determination of the damage to the different material classes and the verification and validation of corresponding calculation tools for the establishment of corresponding design tools, other parameters central to the design of a fusion power plant can thus be obtained. For example, for a future fusion power plant, technical quantities such as tritium breeding ratio (TBR), local power release, etc., are of relevance as a function of neutronic and thermal boundary conditions. Such quantities can be determined using high-performance computers within multiphysics and multiscale computational tools. However, the computations reveal a considerable sensitivity to boundary conditions, which is considerably increased by the propagation of uncertainties and therefore involves large uncertainties. A significant reduction can only be achieved by an experimental validation using a small-scale neutron source providing fusion-type neutron energies in a sufficient volume.

Finding

» For the structural materials of the in-vessel components there is practically no alternative to low activation ferritic martensitic steels (RAFM). And both laser and magnetic fusion have to rely on the material type furthest developed by now. Here, also laser fusion should synergistically make use of the data base being existent by now and incorporate all upcoming experimental findings to be obtained from IFMIF-DONES.

» For the armor materials inertial/laser fusion is facing substantially larger challenges than magnetic fusion. This is related not only by the pulsed operation leading to considerably higher heat loads through the armor than in magnetic fusion, but also through the helium implantation into the armor material.

» In order to achieve a sufficiently high tritium breeding ratio and simultaneous gut neutronic shielding of the reaction chamber, adequate functional materials such as breeder and neutron multiplier materials are necessary. Their qualification also necessitates an experimental validation at prototypical neutron energies and boundary conditions to ensure power plant functionality by up-scaling. Moreover, after validation fabrication qualification tests on scalable mock-up tests are in-dispensable for a fusion power plant at prototypical neutron energies, neutron flux and temperatures to enable a licensing procedure.

Recommendation

- » Maximize use of experimental data for structural materials from IFMIF-DONES to enable a closed consistent blanket program.
- » For the armor materials the specific impact of Helium and gamma-induced surface material degradation especially due to the pulsed operation in laser fusion should be internationally strength-ened, since there is no counterpart in magnetic fusion. Existing facilities both in US and Europe should be updated or if possible reactivated to provide a solid design basis.
- » Rapid development of a small scaled neutron source to allow for verification and validation of functional materials (breeder and neutron multiplier) scalable to a blanket program.

6.4.2.2 Blanket Engineering

The blanket is the most essential part of a fusion reactor due to this multi-functionality of heat extraction, fuel breeding and shielding and thus requires a multi-disciplinary interaction of different expertise incorporated in a design team. The bandwidth is from physics (neutronics), engineering (system integration, coolant technologies, thermal-hydraulics, thermal-mechanics), material sciences (fabrication & manufacturing, welding, corrosion) and process engineering (coolant chemistry, purification, selective extraction). This wide range of required expertise is available only in a few research institutions and/or large experiments and hardly to be found in universities. Major integrated expert groups in this fusion-specific field are to be found in the USA, Japan, Korea, China, India, Europe and ITER, which have elaborated more or less closed design concepts based on partial validation through single or some multi-effect studies.

Fuel Cycle

For the fuel cycle several technologies have been developed already in the context of nuclear engineering, such as detritiation of water or extraction of hydrogen from gas streams also on a large scale. However, fusion systems pose challenges currently not mastered on a larger scale and even not fully developed. Also, the modelling of some effects like diffusion through structures, super-permeation, fast and efficient isotope rebalancing are still in rudimentary state. The largest deficits arise here mainly for the outer fuel cycle. Thus, the depiction of a fully closed fuel inner and outer fuel cycle by all modules has not been realized in practise but also on model scale.

6.4.3 Capabilities and Competencies in Germany, Europe and Worldwide

6.4.3.1 Material Research

Most sites mentioned in the material context host single effect experiments, which are complemented by extensive computational efforts from atomistic (Molecular dynamics, MC and rate theory) to scale bridging modelling.

United States

Oak Ridge National Laboratory (ORNL), UT Battelle– radiation damage, (Spallation neutron source-SNS, HFIR reactor), Lawrence Livermore National Laboratory -neutron radiation, Fusion Technology Institute University Wisconsin Madison- Helium effects, University of California San Diego – pulsed irradiation (Laser)

Europe

DIFFER (Netherlands) - Plasma-wall interaction (Magnum-PSI, Ion Beam facility), CCFE (UKAEA- United Kingdom, Materials research Facility (MRF)- National nuclear user facility, hot cell- material characterization), CEA (West – Cadarache, France- structure materials- corrosion, erosion, manufacturing); ENEA (Italy- material damage, ion implantation), CIEMAT (Spain-electron accelerator, ion implanter, source – radiation shielding, insulator, breeding materials).

Germany

Institute for Plasma Physics (IPP-Garching- High heat flux materials, Gladys), Forschungszentrum Jülich (FZJ)- Plasma-wall interaction-High temperature material laboratory, JUDITH 1, JUDITH 2, PSI-2- Tungsten development, material damage; Karlsruhe Institute of Technology (KIT)- material development (Fusion material laboratory-FML, Heloka- high pressure) -low activation steels, breeder & multiplier materials, damage characterization, corrosion, high heat flux testing, Fraunhofer ILT (Fraunhofer Institute for Laser Technology), Fraunhofer IGCV (Fraunhofer Institute for Casting, Composite and Processing Technology), Fraunhofer IWM (Fraunhofer Institute for Mechanics of Materials) in additive manufacturing, other production technologies, material characterizations methods, materials modelling, and hydrogen isotope isolation (Fraunhofer IFAM-Fraunhofer Institute for Manufacturing Technology and Advanced Materials).

6.4.3.2 Blanket Design

Regarding Blanket design and its multidisciplinary nature only a few sites worldwide offer the capability and the resource to provide a closed design. Mainly the ITER contributors for the ITER test blanket such as Japan (NIFS), China (Chinese Academy of Sciences, China National Nuclear Corporation), Korea (KAERI), India (Institute for Plasma Research), the United States and Europe have developed these capabilities aside from the ITER team itself. The experimental infrastructures consist mostly of thermal-hydraulic loop systems (gas, water, liquid metal operated) connected high power heat flux simulators to mimic prototypical power densities at reduced scale (mock-ups) fusion typical operation conditions out of pile. However, none of the facilities worldwide has the scope of even a small-scale neutron source to simulate a fusion type load scenario.

United States

Integrated Blanket concepts: Princeton Plasma Power Laboratory (PPPL), University of California (UCLA)

But expert know how is present in different fields at: Fusion Technology Institute University Wisconsin Madison (neutronics, material), Oak Ridge National Laboratory (ORNL), Lawrence Livermore National Laboratory (LLNL), Argonne National Laboratory (ANL) & Idaho National Laboratory (INL) for multi-physics multiscale neutronics, thermomechanics, thermal-hydraulics.

Europe

Integrated Blanket concepts: CCFE (UKAEA-JET Culham, Unitewd Kingdom); ENEA (Italy-Frascati-Brasimone)

Expert know-how: CEA (Saclay, France), CIEMAT (Spain), CERN (Switzerland) University Polytecnica de Madrid (UPM)

Germany

Integrated Blanket concepts: Karlsruhe Institute of Technology (KIT)

6.4.3.3 Competence Holders Liquid Metal Engineering, Coolant Chemistry, Safety

United States
Argonne National Laboratory (ANL), University of California Los Angeles (UCLA), Idaho National Laboratory (liquid metals, salts), Oak Ridge national laboratory (salts)

Europe
CEA (Saclay & Cadarache , France), ENEA (Italy-Brasimone) with focus on also on Lithium

Germany
Karlsruhe Institute of Technology (KIT), Helholtz-Zentrum Dresden Rossendorf (HZDR)

6.4.3.4 Fuel Cycle

Similar as for the blanket engineering lots of worldwide research labs have special know how in singular process technologies relevant for a fusion fuel cycle, since they are essential for hydrogen process engineering or for nuclear safety (e.g. detritiation in CANDU reactors as in Darlington Canada). Currently, the world-wide first facility allowing for a full chain study of a fusion fuel cycle experimental facility with tritium is under erection in the United Kingdom (Hydrogen-3Advanced Technology-H3AT). All elements of a fuel cycle and a civil tritium laboratory is also present at Karlsruhe Institute of Technology (KIT)- Tritium laboratory Karlsruhe (TLK).

6.4.3.5 Competence Holders Fuel Cycle and Process Engineering

United States
Lawrence Livermore National Laboratory (LLNL- cryo engineering, tritium processing), Savannah River Site National Laboratory (SRNL), Los Alamos National Laboratory (LANL), Princeton Plasma Physics laboratory (PPPL), Argonne National Laboratory (ANL)

Europe
CEA (Valduc, France) -Military (aspects only-limited access), ENEA (Rome, Italy) – process technology

6.4.4 Industry Led R&D for IFE

The role of industry with respect to materials, blanket engineering and fuel processing is mainly governed by the economic market situations. For armor materials such as tungsten there is a vital interest of defense technology and space industry in e.g. robust shielding or for high heat flux applications. However, for functional materials as well as for fusion specific structure materials the development is focused on the national laboratories and only fabrication routes or dedicated material treatment aspects are developed in collaboration with the industry. In the absence of a business model for fusion by now the development risk for fusion specific products is considered high by industry so that most efforts are concentrated on niche markets with use cases like fusion.

A similar observation holds for blanket engineering. While for some multi-physics and multi-scale code systems developed in the context of fusion exist use cases such as for accelerator applications (e.g. pharmaceutical radioisotope production, neutron imaging, ion therapy) most of these applications are not in the core fusion applications and are often at the border of their applicability. Here, two measures would be helpful to stimulate indispensable industry engagement:

» development of a fusion market to encourage industry to collaborate by investments in experimental infrastructures.
» active marketing of fusion on public basis to profit from vast industry experiences in manufacturing processes, remote handling techniques, control diagnostics.

Regarding the fuel cycle technologies, some technologies have already gained interest by process industry, such as selective separation of hydrogen from gas streams, or detritiation of water in nuclear stations. However, some technologies such as isotope rebalancing, cryo-distillation and others are rather fusion specific nature. Nonetheless, promotion of fusion to industry via private public partnership projects could stimulate the development and validation of process simulators also to speed up fusion fuel cylce development.

6.4.5 Findings and Recommendations

6.4.5.1 Materials

Finding	Experimental platforms for the verification and validation of material research needed.
Recommendation	» Provision of fusion neutron energy typical source(s) complementary to IFMIF-DONES also accessible through universities & industry to execute research on structural, functional and armor materials. » Maximize utilization of experimental data to be gathered by IFMIF-DONES for structural material damage through fusion typical neutron operation for laser fusion by cooperation of both communities (laser and magnetic fusion). » Strengthening/reactivation of material research facility allowing to study effect of Helium implantation, especially with respect to pulsed power exposure of structural, armor and functional materials. » Enhancement of collaboration with material research laboratories allowing for post-test analysis of irradiated materials (PIE) requiring for in-pile specimens requiring hot-cells. In particular, the worldwide limited availability of material characterization equipment for irradiated samples (PIE) requires not only the joint use by laser and the magnetic fusion community, but also the development of international collaborations. » Establishment of research cooperation of national laboratories with universities on national and international level targeting at increased modelling as well as verification and validation of predictive numerical tool sets for all types of fusion typical materials.

In materials development, a number of research options arise for both structural materials and armor and functional materials. Single effects of material damage by neutrons or even helium formation by transmutation are well studied experimentally as well as numerically on the micro level using high resolution ab-initio models but also corresponding micro characterization experimentally, even if not always understood in full detail. The analysis of coupled phenomena like the dpa/He appm-ratio on the materials requires the synergetic interaction both on the model level not only on the micro-scale but also the transfer to the meso-scale and up to the macro-scale. This is only possible with the help of the cooperation of universities with research institutes in a national as well as international context, since both have the necessary expertise as well as the computer capacities, which make the solution of such questions possible.

Nevertheless, experimental platforms for the verification and validation of numerical results are indispensable. Even if IFMIF-DONES is projected to be a facility in which the fusion power plant-typical damage of structural materials at different temperatures will be possible for the first time, the spectrum of structural, functional and armor materials is so large that one facility cannot do this alone. In addition, validation of materials for diagnostics in a fusion reactor requires not only long-term experiments at a typical fusion neutron spectrum, but also short-term experiments to identify complementary damage mechanisms and to map them appropriately in models. IFMIF-DONES offers only limited flexibility here, focusing exclusively on structural materials at various boundary conditions. Here, at least one or better two/three flexible small-scale neutron sources are required to substantially accelerate the development of fusion-adapted components and diagnostic tools.

To mimic all kinds of material damage aspects and allow for material characterization for a quite large bandwidth of materials an accelerator type facility with a rather diverse spectrum is required. Only accelerator-based facilities allow for a high degree of flexibility (source: protons, deuteron, Helium), by using a dual beam facility set-up allow not only short-term proof of principle tests but also long-term performance testing can be executed with a high timely availability at relatively low cost compared to fusion based neutron source. (Moreover, the high neutron flux also allows the installation of an additional target station with a moderator to generate slow neutrons. The availability of cold neutrons enables material investigations e.g. by neutron reflectometry, small angle neutron scattering and neutron diffraction (e.g. for battery research or other diagnostics) and substantially increases the facility utilization).

Further, even if the structure, armor and functional material are fully characterized at fusion typical neutron energies and fluxes, still fabrication technologies to towards a blanket design need in-pile validation at least a down-scaled level to allow for demonstration for a licensing process.

6.4.5.2 Blanket

Finding

The same applies to blanket technology as to materials research, although the starting point is different. A credible blanket program first requires the definition of a reaction chamber concept and at least the cornerstones of a possible mode of operation in order to determine, for example, rudimentary dimensions of the reaction chamber and thus the power density on the first wall, the neutron flux and many other parameters.

Recommendation

» Therefore, first a fusion reactor study at the beginning of the program is mandatory to condense the solution space for a laser fusion power plant to a manageable number of options. This also requires at least a rudimentary description of the mode of operation. Such a study should include experts not only in fusion physics, but also in blankets, materials, fuel cycle, driver systems, and diagnostics to avoid dead ends that assign physically infeasible tasks to a system. The goal of the study should be a simplified 1-1.5-dimensional power plant model from which cornerstones for the blanket can be extracted such that a

closed-loop design activity can be incorporated. Ideally, national and international experts should be part of this activity.
» The second step is to build a design team for the blanket, with the goal of creating a feasible base design that would meet all functionalities. This should essentially be led by research laboratories, as only they have the sufficient range of expertise. However, industry participation is strongly advised, especially with respect to manufacturing, operations and exchange, to ensure design consistency.
» Verification and validation play a central role in the design consolidation phase. This requires two pillars
  - first, the use of the neutron source(s) already addressed in materials to optimize the design concept through scaled small mock-ups.
  - The second pillar is the use of industry expertise in highly scalable component manufacturing, coolant purity control, remotely manageable logistics concepts and interface management.

6.4.5.3 Fuel Cycle

Finding	Fuel cycle development needs a feasible power plant design.
Recommendation	Fuel cycle is modular, individual technologies can be built up, develped and analysed separately.

Fuel cycle development also needs a feasible power plant design (pulsed repetition rate, fuel burnup, …) as a basis to determine the amount of fuel, the possible amount of exhaust gas, debris, etc., and to match the inner and outer fuel cycle. Since the fuel cycle is modular, the individual technologies can be developed, built up and analyzed at different locations with the available expert know-how.

To verify and validate most modular systems, the availability of a tritium laboratory is not necessarily mandatory, for some specific processes and for the determination of material parameters small tritium test capabilities, however, are mandatory. Parallel to the development of the modular process modules, the corresponding models must be validated by means of the individual modules. This can be done at universities, research institutes or industry, so that at the end of the fuel cycle development a simulation model for the entire process chain is available.

However, validation and verification of the entire process chain is required by a scaled-down experimental process simulator. Whether this must necessarily be implemented in a tritium laboratory can only be demonstrated by a sensitivity study, where critical interactions between process modules occur.

6.4.6 Time Table and Investments

A rough time table for blanket, materials and fuel cycle is depicted below. It requires a closed program reflected on the plant level by a design team. Here, only current similar projects can be compared. The UK STEP program assigns a yearly effort of more than 50M€/year to the design team during the conceptual design phase (CDP) and engineering design phase (EDP), while the blanket, material research and fuel cycle are covered by own R&D projects.

The conceptual design of an IFE power plant needs to be advanced, which analyzes the requirements and limitations of each module required for a laser fusion power plant within the framework of a balance-of-plant model, taking into account sensitivities and uncertainties. To develop the tools and understanding concisely, a development program is needed that we estimate to a few million euros per year and, since Germany does not have sufficient expertise in all expertise areas, it must be carried out in the framework of international cooperation.

Assuming a full utilization of IFMIF-DONES and the access for the blanket team to existing US or European R&D facilities for thermal-hydraulics mock-up/prototype verification and qualification the major investments up to the blue print phase are associated with a combined neutron, alpha-particle (Helium implantation) and gamma radiation source providing at small scale numerical tool verification & validation and a downscaled fuel cycle demonstrator, each requiring an investment in the range of about 40-100M€ depending on the requirements requested by a design team.

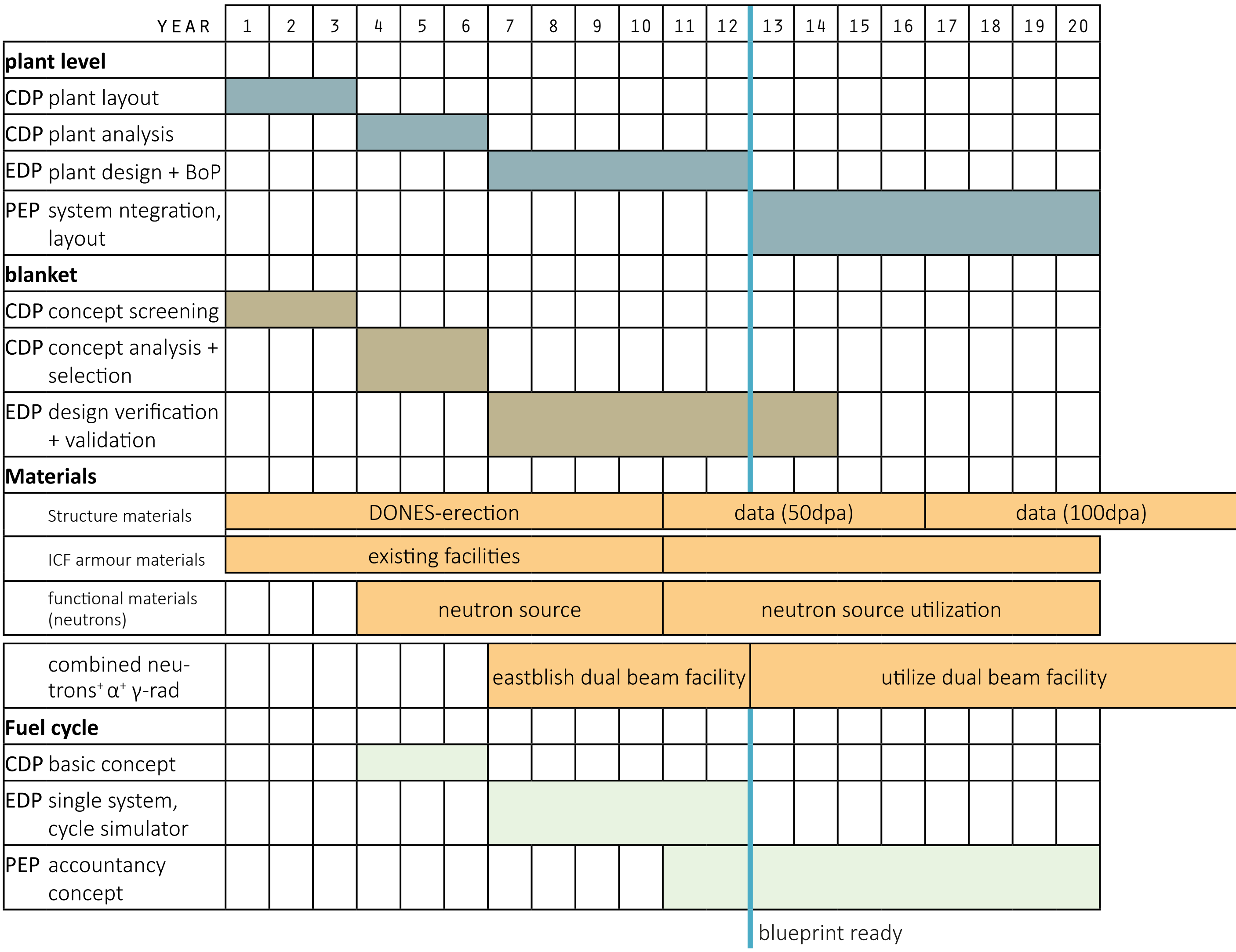


Fig. 17: Timetable for 1st Wall and Blanket design. Conceptional design phase = CDP, engineering design phase = EDP, project execution phase = PEP.

6.5 Laser Drive and Optics

6.5.1 Role of Drive Laser Technology in IFE

In the last six decades, lasers have evolved from being a solution in search of a problem to an integral part of our daily lives. Their impact has been felt in various fields such as fiber-based communication, medical procedures, materials processing, and fusion research. Laser fusion has played a crucial role in pushing laser technology to the limits of extremely high energies, posing unique challenges.

In inertial fusion energy (IFE), the driver is used to initiate and control the fusion reaction. The driver is responsible for delivering the energy required to compress and heat the fusion fuel to the necessary conditions for nuclear fusion to occur. High-power lasers are a suitable and elegant technology for achieving fusion plasma conditions. So far, most of the inertial confinement fusion (ICF) experiments have employed lasers as the primary energy source to compress and heat the fusion targets. While there have been other proposed "drivers" for ICF such as heavy ion particle accelerators, pulsed power, gas guns, or magnetic flux compression, lasers are currently the most advanced technology possessing the necessary combination of characteristics.

The use of laser beams allows the concentration of abundant energy (several MJ) in the form of light onto a small capsule of fusion fuel from a considerable distance, allowing a substantial distance between the walls of the fusion reactor and the ignited fusion plasma. IFE lasers must be pulsed, delivering pulses of concentrated energy in time and space to compress the fuel capsule. In addition to the pulsed laser operation, other factors such as laser energy, pulse duration, focusability, wavelength, bandwidth, and the often-overlooked power balance and laser pulse fidelity (its temporal pulse shape and temporal pulse structure) are critical parameters that must be optimized to create a uniform, spherically-symmetric implosion of the fuel target and achieve efficient and reliable ignition. Achieving the optimal combination of these parameters is a critical area of research, as it is essential to making fusion energy possible. Enabling a viable clean energy source for the future.

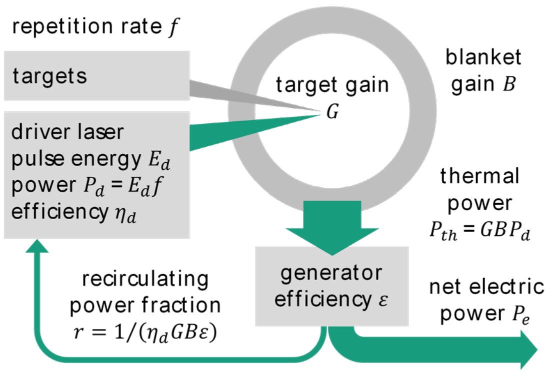
Some fusion schemes (e.g. "electron fast ignition", "ion fast ignition", "shock ignition") require energetic ignition lasers in addition to the compression laser drivers. These can generate bursts of electrons or ions for fast ignition schemes and typically require laser pulse durations 1000 times shorter than the compression drivers, i.e., on the order of picosecond-duration. For IFE, where the timescales on which fusion occurs and a burn wave propagates are on the order of several tens of picoseconds, pulse durations less than 1 ps are less likely to be relevant – an important consideration when developing laser architectures that can serve both as compression or after appropriate changes as a fast ignition or shock driver.

To compress the fusion fuel capsule to ignition conditions, target concepts with a target gain of >30 require a laser system capable of delivering a high-energy pulse of at least a few MJ at UV wavelengths, with precise control of the pulse shape, lasting a few nanoseconds, and with a peak power of approximately 500 TW. For a power plant with an electrical output of one GW, these pulses must be delivered at a repetition rate of 10-20 Hz. This corresponds to an average power of about 40 MW. As the energy is distributed across multiple beamlines, at least several hundred beamlines must be employed to ensure sufficiently symmetric illumination of the target. For a larger number of lasers the energy could be distributed over more apertures, thus reducing optics sizes and the cost per optic, respectively. However, an increasing number of beamlines growths the complexity of the overall system and a balance between cost and practicability must be found.

High wall-plug efficiency is a critical consideration in the design of laser architectures for fusion power plants. This metric measures the overall energy efficiency of a laser system by comparing the output optical power to the total electrical power input required to operate the laser, including cooling, power conditioning systems and laser control systems. Achieving high wall-plug efficiency simplifies heat removal from the laser and reduces the amount of recirculating power required in the power plant, Fig. 18. This results in more efficient and cost-effective operation, as well as higher overall power output. A general rule of thumb suggests that the product of laser wall-plug efficiency and target gain should be greater than 10, otherwise most of the power generated is consumed by the driver [Mei2008]. Thus, the recirculating power fraction must remain under 20%. The desired goals for an IFE powerplant are therefore a laser wall-plug efficiency of >10% and a target gain of 100. Considering the cost of electricity (COE), it can be shown that the cost of the laser driver is more heavily influenced by laser energy rather than its repetition rate [Mei2009]. However, it's worth noting that laser systems designed to maximize efficiency may have added complexity, reduced flexibility, and higher construction costs, and a power plant's cost model may dictate a different laser concept and architecture than what would be selected based solely on power and efficiency considerations. As such, cost modeling plays a crucial role in the design of laser systems for fusion power plants.

Besides the laser itself, a beam transport and delivery system are needed in a fusion power plant. It performs the critical task of transporting laser beams from the laser system to the target chamber and consists of a series of mirrors, lenses, and other optical components that are used to focus and steer the laser. The system must maintain the high quality and integrity of the laser beams, as any distortion or loss of beam quality can significantly reduce the effectiveness of the laser system and its capability to ignite the fusion fuel. Target tracking and fast beam steering are required to detect and hit the target in the reaction chamber with the precision of less than the width of a human hair. While the function of these systems may appear simple, the underlying technology required to meet the specifications for high performance, durability, and material compatibility with the target chamber environment is extremely challenging to develop and manufacture, requiring significant research and testing efforts.

There are different types of laser concepts considered for IFE, such as solid-state lasers and excimer lasers, which operate in different configurations (laser-indirect-drive or laser-direct-drive). Both solid state and excimer lasers are advanced and have their unique advantag-



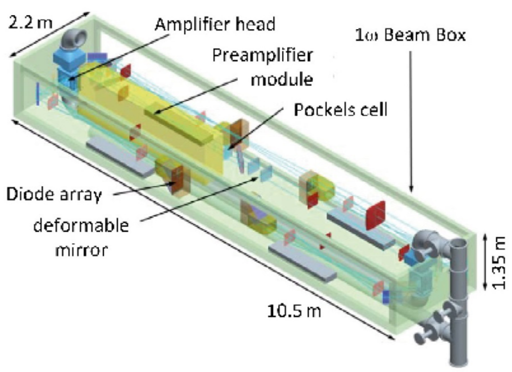


Fig. 18: Basic parameters of an IFE power plant (left). Illustration of a "1 ω beam box" providing 8.1 kJ at 1.05 µm (converted to 5.7 kJ at 0.35 µm close to the target chamber) as a modular component of an IFE laser system (right) [Bay2011].

es and limitations. Solid-state lasers and excimer lasers are fundamentally different in their construction, design, and operation.

Solid-state lasers employ a gain medium that is typically a crystal or glass containing rare earth or transition metal ions such as Neodymium or Ytterbium. These ions are excited by light emitted from either flashlamps or semiconductor diode lasers to produce laser light. Solid-state lasers can operate in continuous wave or pulsed modes and emit light mostly in the near-infrared wavelength regions. They can access UV wavelengths through nonlinear optical processes: harmonic generation and sum frequency generation. Harmonic generation involves the use of a crystal with nonlinear optical properties to which a highly intense beam of light passes, generating new wavelengths of light at integer times the original frequency, such as the third harmonic (ultraviolet) of a NIR laser. Harmonic generation is a special case of sum frequency generation, which works similar and where a new wavelength is generated by sum frequency generation of a pump and signal wave in a nonlinear crystal.

A subset of solid-state lasers are fiber lasers that are widely used in industry. While fiber lasers have become increasingly popular in many applications due to their high efficiency and compact size, they have not yet demonstrated to produce the high-energy pulses required for IFE. Despite this, some research has been conducted into the use of fiber lasers for IFE, as noted in several studies [Lab2008], [Mor2013], [Kle2018]. These investigations are still in the early stages, and it remains to be seen if they can be scaled up to the levels necessary for IFE. To explore this exciting approach, a full conceptual system design study with an associated cost model is required. This will help to determine the feasibility of using fiber lasers for IFE and to assess the potential benefits and drawbacks of this technology.

Excimer lasers, on the other hand, are a type of laser that use a gas mixture consisting of halogen gases (such as fluorine, chlorine, or bromine) and a noble gas (like argon, krypton, or xenon) as their gain media. The halogen gas utilized depends on the desired output wavelength and other factors pertinent to the laser design. An electrical discharge at a high voltage excites the gas mixture, causing the halogen and noble gas molecules to combine briefly and form an excited dimer or trimer molecule called an excimer. The excimer rapidly de-excites and emits a photon of laser light in the ultraviolet or deep-ultraviolet range. Excimer gain media have a lower energy storage capacity than typical solid-state laser materials. Despite their limited wall plug efficiency due to the intrinsic efficiency of the laser medium, they offer some distinct advantages over typical solid-state lasers for IFE drivers. They can deliver even shorter ultraviolet wavelengths without the need for frequency conversion and can operate within a frequency bandwidth of a few Terahertz, which reduces laser plasma effects such as Stimulated Brillouin Scattering (SBS) and Stimulated Raman Scattering (SRS) and improves therefore energy coupling to the fuel capsule in laser-direct-drive or to the hohlraum in laser-indirect-drive. Even though high-energy excimer lasers are not as technically advanced as DPSSL, they are still a promising option for achieving large bandwidth in the deep UV with high rep rates, high power, and wall-plug efficiencies ranging from 5-10%. Therefore, it is important to explore laser-plasma-interaction physics at ignition-relevant scale using existing facilities to derive needs and requirements for broadband UV architectures. Meanwhile, it is recommended to evaluate both excimer lasers and broadband DPSSL to determine their potential broadband performance and efficiencies. First estimates can be found in [BRN2022].

In comparison, solid-state lasers typically exhibit 2-3× higher wall plug efficiency, are easier to scale up to higher output energies than excimer lasers, which makes them more suitable for high-energy applications like inertial confinement fusion. Furthermore, solid-state lasers offer more precise control over pulse shape, duration, and energy than excimer lasers. This is particularly important in inertial confinement fusion, where precise timing and energy control are critical. DPSSL exhibit the highest technical readiness level [BRN2022] and are the most likely and common building block for IFE drive lasers. Therefore, we will not elaborate on other approaches in this discussion, and readers can refer to [BRN2022] for more information. However, it is important to conceptually explore various laser architectures that use different gain media to ensure that any emerging requirements from technological advancements in fusion plasma and LPI research are considered. In general, it is important to maintain technological openness to identify the best suited design.

It is noteworthy, that laser technologies have matured considerably, but all approaches require optimization of wall-plug efficiencies, scaling, materials, architecture, and technology to develop fusion power plant-ready devices. In addition to designing effective laser drivers, it is important to consider ways to reduce production costs and future maintenance and operation expenses, as well as establish and secure reliable supply chains. Target tracking and beam steering are also necessary for laser drivers. Additionally, development of standardized, integrated machine safety and performance control systems is needed.

6.5.2 R&D and Capability Status Worldwide

Laser-based ICF (implosion) facilities are designed in a configuration that supports a specific drive scheme, either the Laser-Driven Direct Drive (LDD) or Laser-Driven Indirect Drive (LID) target concept, defining the layout of the laser beam injection into the target chamber. The National Ignition Facility (NIF) where ignition was achieved in December 2022 is configured for polar indirect drive, Fig. 19. It is a unique laser facility with the size of

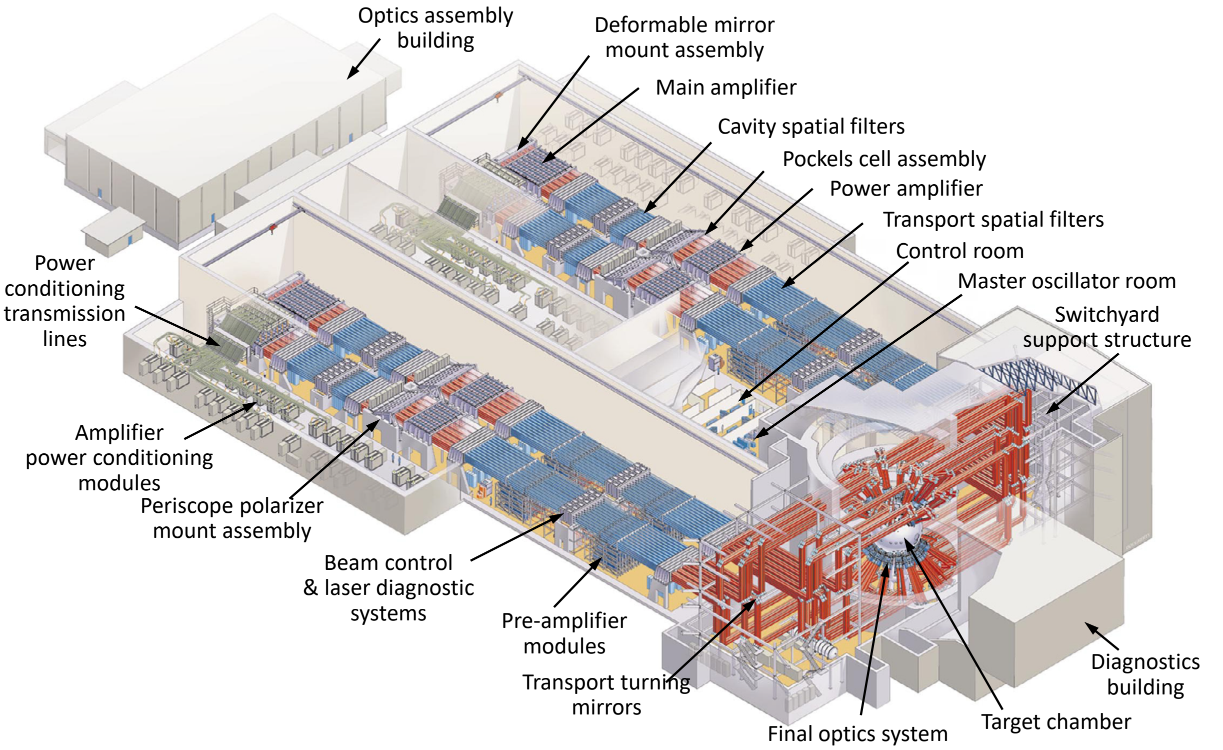


Fig. 19: Setup of the National Ignition Facility (NIF) [MOS2002].

three football fields located in Livermore, California, and operated by the Lawrence Livermore National Laboratory (LLNL). It is the largest and most powerful laser in the world and the only facility with the ability to ignite a deuterium-tritium (DT) plasma. Its focus is the research of high energy density plasmas, and specifically the scientific achievement of igniting a DT plasma on laboratory scale.

While the United States achieved ignition first, other countries are following a similar path:

» France has built the Laser MegaJoule (LMJ) that currently operates at 350 kJ and will reach 1.3 MJ when complete in 2026, a facility very similar to the NIF with some jointly developed laser and diagnostics technologies;
» Russia operates at 128 kJ from their first 64 beams of its UFL-2M laser in Sarov that is designed to deliver 2.8 MJ at 527 nm from 192 beams [Sci2022] when complete. The longer wavelength at the second harmonic of Nd:Glass distinguishes it from NIF and LMJ, which operate at 351 nm;
» China operates its SG-III facility at 180 kJ in the UV [Zhe2016] and has reported some years ago designing a full-scale ignition laser facility SG-IV with an initial design goal of achieving 1.5 MJ or greater energy.

Apart from the large-scale ICF implosion capable facilities discussed above, key research and development supporting fusion science is also being carried out at the OMEGA facility at LLE in Rochester, US and at several smaller facilities (5 kJ or less) such as in the UK at VULCAN [Dan2004] and ORION [Hop2015], in France at LULI 2000 [Zou2008], in the US the Excimer Facility NIKE [Obe2015], in Germany at the Phelix Laser at GSI Darmstadt [Bag2010] and the POLARIS Laser at the Helmholtz Center Jena [Hor2016].

To fully appreciate the daunting challenges facing an inertial fusion energy (IFE) driver, it is critical to gain a comprehensive understanding of the complexity and scale of today's inertial confinement fusion lasers. These sophisticated systems serve as the preeminent scientific test bed for high energy density (HED) and fusion science, and therefore provide a critical foundation for IFE driver development. The NIF is the result of LLNL's half-century-long development of increasingly powerful Neodymium-doped Glass (Nd:Glass) laser systems. In the early 1990s, the conceptual design for NIF was created, followed by its construction in 1997 and commissioning in 2009. The cost for the design and construction of NIF was $3.5B, with additional investments into diagnostics, targets and other facility improvements after. The laser system is configured with sixteen 3.4 cm thick Nd:Glass amplifier slabs in a single beamline. To reduce reflective losses in the laser beam, the slabs are arranged vertically on edge at Brewster's angle. The slabs are stacked four high and too wide to accommodate a bundle of eight laser beams and provide an unprecedented high beam packaging density. Beam transport between the amplifier sections is accomplished by two transport telescopes that are 82 meters long (Fig. 20 left). The required image depth for the Brewster-angled slabs and the intensity limitations in the pinhole plane of the telescopes are the main factors driving the length of the laser chain (105 m). However, with the transition to diode face pumping of the amplifier slabs, the length of the laser chain can be reduced to a fraction of the length of the amplifier cassette. NIF was the first ICF laser configured as a 4-pass amplifier instead of a linear Master Oscillator Power Amplifier (MOPA) chain [Spa2016]. This required the development of a large aperture (40×40 cm^2) active laser cavity electrooptical switch (plasma electrode Pockels cell - PEPC). Other main key technologies developed for NIF were large aperture, high energy adaptive optics; the development of the preamplifier module (PAM) amplifying the laser by ×1010 from nJ to 10 Joule, smoothing and precision-shaping the beam dynamically in time and space; a 320 MJ electrical Power Conditioning System (PCS), which consists of the highest energy array of electrical capacitors ever assembled; high damage threshold lenses and optical coatings for ultraviolet including a refurbishing and recycling loop; a control system that automatically aligns and controls the performance of the laser; and the

Advanced Radiographic Capability, the world's most energetic short pulse laser for backlighting dense targets including the development of many new optical elements to generate high intensity laser beams [Bar2004], [Hae2009], [DiN2015], [Ale2020].

NIF represents the largest optical system in the world and an IFE driver will be of similar scale though its footprint will/must be much smaller. Hence, the many optical components required represent a significant challenge for the supply chain.

To name the most significant, NIF developed with Schott and Hoya the continuous melt production of high-quality Nd:glass (Fig. 20 right) to provide the required amount of gain material for NIF (145 tons of laser slabs installed at NIF) and its French sister, the Laser MegaJoule; in-house (now outsourced) the rapid growth of potassium dihydrogen phosphate (KDP) for frequency conversion and PEPC; and many optical finishing and coating techniques used by industry today. Till today, NIF is sourcing critical optics from companies in the U.S., Germany (e.g. Schott, Heraeus, Laseroptik, Schott Lithotec), Japan (Nikon, AGC, Ohara, Inhabata, Hoya), the U.K. and others. Overall, the construction of NIF has significantly advanced the optics and laser industry in the United States, Germany and worldwide, enabling many advances that would not have been possible otherwise.

The High Repetition Rate Advanced Petawatt Laser System (HAPLS) [Hae2016], [Hae2017], a Helium-gas-cooled Nd:Glass laser is an aperture-downscaled fusion laser derived from LLNL's Laser inertial fusion energy study (LIFE) [Bay2011] developed until 2012, Fig. 20 left. The greatly increased repetition rate and efficiency over NIF required modifications to its architecture, including replacing flashlamps with laser diode arrays and pulsed power supplies to reduce heat load and increase overall efficiency. In addition, optical components, especially laser gain media and frequency conversion crystals, required active cooling. This system tested several critical components to an IFE driver laser. In the future, the substitution of Nd:Glass slabs with crystalline gain media, preferably with higher intrinsic efficiency [Erl2011], promises a path to high energy IFE drive lasers that do not require the bandwidth of Nd:Glass. Another laser, aka "DiPOLE", Fig. 20 right, developed by the Central Laser Facility in the United Kingdom also uses Helium-gas-cooling to remove the heat from its amplifier slabs made out of Yb:YAG. Due to its low gain at room temperature and high energy storage, the gain medium must be cryocooled to ~100 K to overcome this limitation, however reducing its spectral bandwidth significantly. Thus, it would not be suitable for a fast-ignition driver but may be suited for a DPSSL-fusion driver if the additional cooling effort is balanced by higher optical-optical efficiency than a material at room temperature. DiPOLE100 laser systems have been built for HILASE in the Czech Republic [Pilar018] and

Fig. 20: NIF laser facility (left), continuous strip of laser glass exciting the melter at NIF (right).

the HIBEF endstation on Germany's X-ray laser at DESY.

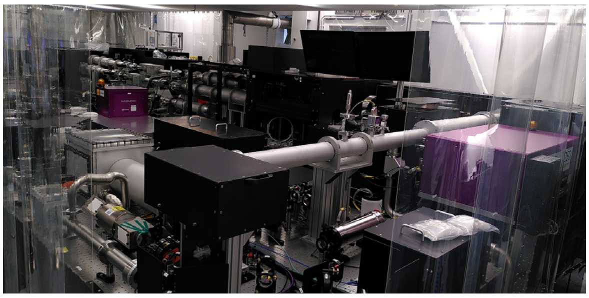


Fig. 21: High repetition rate, high energy lasers: HAPLS (left) comprising a Nd:Glass laser with 200 J at 10 Hz, and DiPOLE (right), a cryogenically cooled Yb:YAG laser with up to 150 J at 10 Hz (HiLASE).

6.5.3 The Development Path to High Repetition Rate, High Average Power IFE Drivers

Diode-pumped solid-state lasers (DPSSLs) or Energetic Excimer Lasers can be used for indirect and direct drive and fast ignition. The fundamental physics and technology were already developed for the National Ignition Facility [Spa2016]. To adapt these lasers for IFE, certain modifications are required, such as replacing flashlamps with semiconductor laser diode arrays and high-efficiency pulse-forming circuits [FUL2015] to reduce heat input and increase wall-plug efficiency. Active cooling of laser gain materials will replace convective cooling [Bay2011]. New passive and active components and approaches will be needed to compensate for large thermo-optical aberrations. Laser materials, such as ceramics or advanced glasses, with improved thermo-optical properties, longer storage time, or larger gain cross section will also be needed. Additional optical features such as large-aperture optical switches, gain isolation, frequency conversion [Bay2011], [Hae2016], spatial filtering, beam image relaying [Che2019] at high average power will also be required. Advanced surface finishes and dielectric coatings are needed to increase damage threshold and lifetime.

Some of these architectural changes and technological advances have been realized in the ns-pulse high-energy pump laser of the HAPLS laser delivered to ELI Beamlines, or the DiPOLE Laser. Currently DPSSL technology is estimated to be at TRL 5, but due to the high capital cost currently associated with diode arrays, the overall TRL is set at TRL 4. To put this in perspective, a diode pumped NIF-like laser would need ~$20B (!) worth of diodes to today's market price, plus its electrical drivers. The required transition with respect to pulse energy and average power from state-of-the-art lasers to an IFE beamline and a full-scale IFE laser drive is shown in Fig. 22. Each of the different technology gaps on this path is described in more detail below.

Excimer lasers could be well suited for direct drive in the deep UV and with large bandwidth (<10THz for ArF, <3THz for KrF), but complexities in multiplexing, pulse compression, beam shaping, and optical damage require a detailed model. The overall efficiency is estimated at 10% (ArF) and 7% (KrF) after accounting for various factors. The ASPEN KrF concept promises to be simpler but is at an early stage [Con2022].

German startups in the field of fusion energy are developing power plant architectures

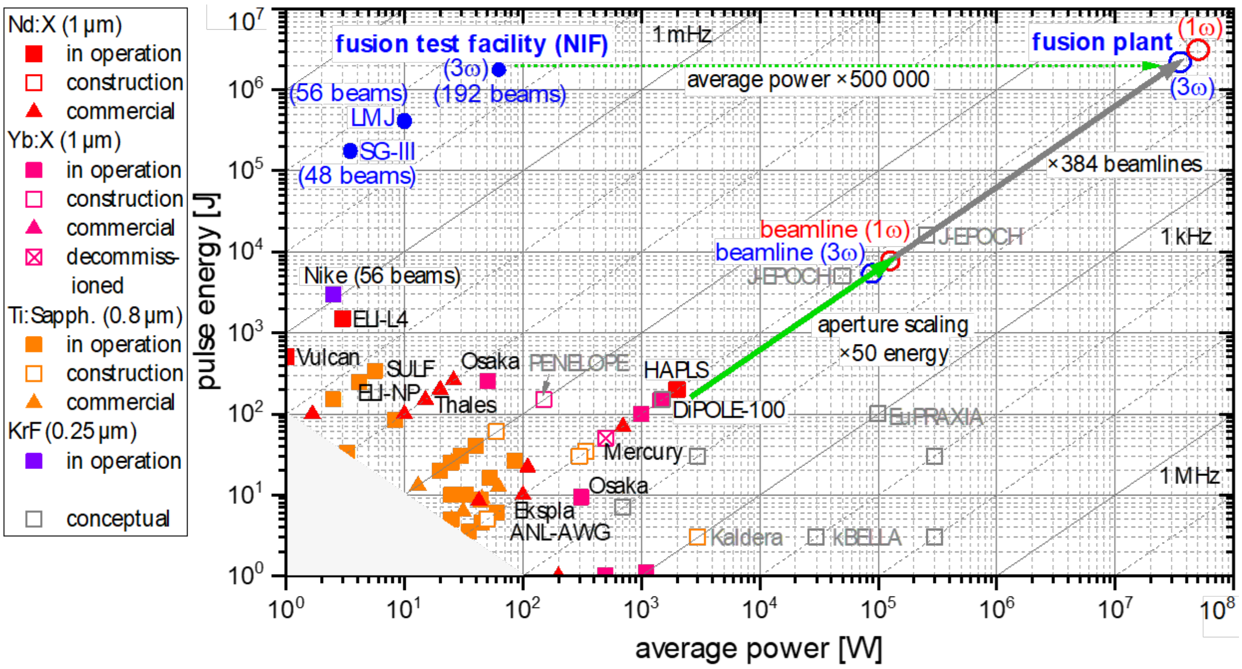


Fig. 22: Overview of high-energy laser systems and required scaling of pulse energy for an IFE laser driver (parameters of fusion plant according to the LIFE study). Scaling from the frontiers of DPSSL technology approximately x50 in performance improvement is needed, in addition to the necessary increase in wall-plug efficiency.

that require high peak power laser pulses to generate intensities exceeding 10^{19}W/cm^2 for secondary radiation source generation. Marvel Fusion GmbH requires laser pulses with durations less than 100 femtoseconds, while Focused Energy GmbH requires pulses with durations of a few picoseconds. Both require high energy (incoherent pulse pedestal) and high-power contrast (coherent pulse pedestal, 100dB or better). Estimates for the total energy, peak power, and other requirements are developed in ongoing target physics simulations. Integrated experiments at ignition scale have not yet been conducted. Both companies underpin the need for efficient DPSSL drive laser development that can be retrofitted with chirped pulse amplification. Gain media will have to support these very short pulses or adequate nonlinear pulse shortening methods must be employed.

In the following, areas of R&D and technology demonstrators are listed needed for developing today's laser technology jointly towards a fusion driver beamline.

An Integrated IFE Beamline Design is Needed

Understanding the target physics requires high precision, advanced lasers, diagnostics and simulation tools. Hence, the laser is a key technology that must advance in TRL faster to drive the other areas forward in capability, as it is one of the critical elements in driving a fuel capsule to ignition. To achieve the intended pulse energy of ~2 MJ for an inertial fusion power plant (energy requirement differs between direct drive and indirect drive approach), a minimum number of beam lines is required to ensure homogenous illumination of the target while maintaining symmetry. However, the maximum number of beam lines is limited by the acceptable number of apertures in the reaction chamber and the beam quality. Large aperture amplifiers can reduce the total number of components and system complexity, while smaller apertures ease laser-design, thermal management, and mass-production of optical components.

To demonstrate a credible path to an inertial confinement fusion power plant, an integrated design for an IFE laser beamline is needed to identify potential risks, opportunities, technology gaps, supply chain issues and necessary developments, overall schedule and cost estimates for realizing a first-of-a-kind plant, and an estimate of the economy of scale. Design studies must address not only the definition of critical components, but also the scaling of these components with respect to aperture and power. They would identify specific R&D topics and enable a focus on the most promising and urgent topics. Industry involvement at this fundamental stage is essential for long-term success.

Pulse Energy

Laser sources with even higher performance levels than the DIPOLE or HAPLS laser (>1 kJ and >10 kW for a single beamline) are required for an IFE power plant. These lasers have a significantly lower market readiness level and very long market horizons (7 years+). Challenges are aperture scaling of laser gain media, architectures for effective energy storage and extraction techniques, relay imaging and spatial filtering at very high intensities, gain isolation at large aperture and high fluence levels, and others. With adequate funding, technology readiness levels (TRL) of 3-4 can be achieved on an individual beamline level in a research environment. However, reaching TRL 5-6 and the production capability to mass-produce hundreds of beamlines for an IFE power plant requires significant involvement and investment from industry, which needs to be incentivized and subsidized to bridge these long market horizons. Developing a reliable and capable supply chain is another challenging task. Despite the long market horizon for an IFE power plant, a large-scale coordinated laser development effort holds enormous potential to drive spin-outs and uncover novel market opportunities.

Efficiency

Achieving greater than 10% wall-plug efficiency (see above for definition) has not been demonstrated for gas-cooled technology demonstrators like DiPOLE or HAPLS, both operate at lower fluencies (DiPOLE ~2.5 J/cm^2; HAPLS ~8 J/cm^2) than necessary to achieve high wall plug efficiencies. This achievement remains a critical research and development process that requires careful attention to design details. Efficiency is determined by the physical properties of the laser gain media, heat extraction method, heat exchange and recirculation of the coolant and the optical design. High laser fluencies and low saturation fluencies, as well as pump-pulse duration well below the upper-state lifetime, are ways to increase the extracted energy out of the active laser medium. However, these methods are limited by laser-diode costs, optical damage, threshold of optical materials and coatings used, amplifier cross-section, and choice of laser material. For the latter, a trade-off between emission cross-section, energy levels and upper-state lifetime, bandwidth, thermos-optical properties, laser diode suitability, and intrinsic efficiency must be found. The optical path can be optimized by a homogeneous top-hat beam profile, adapted imaging, and increasing the number of passes inside the active medium while lowering the single-pass gain at the same time. Beam transport and robust high average power spatial filtering have been addressed in HAPLS but scaling to full aperture for high energy still must be demonstrated.

Thermal Management

The cooling of high-energy (>1 kJ) and high average power (>>10 kW) lasers is a challenge due to the large amplifier cross-sections (>10 cm × 10 cm) and the limited ability to transport waste heat out of the optical aperture over distances >1 cm without inducing serious temperature gradients and thermo-optical aberrations. Face-cooling is the only possible solution for solid-state lasers, demonstrated with helium-cooled slabs at room-temperature (HAPLS) and cryogenic temperatures (DiPOLE). Liquid cooling has been demonstrated at low repetition rates [Rus2017]. However, scaling to very high average-power and energies requires increasing the mass flow of the coolant inducing increased perturbations and system complexity. Cooling outside the beam path in an active-mirror geometry and liquid-cooling could be an alternative approach, but mounting-induced strain and scaling to large apertures require new technical solutions. The same accounts for optically separating the dominating waste power by dumping fluorescent radiation and ASE of the amplifier from the heat generated by the laser process itself.

Gain Materials

DPSSL designs suitable for laser indirect drive offer a high level of technical readiness for the near-term construction of a fusion pilot plant. Currently, most designs rely on Nd:Glass as gain media, which is the only laser gain material produced at scale in large quantities and of sufficient optical quality. Nd:Glass is compatible with commercially available diode pumping. However, there are drawbacks such as the short gain lifetime, average power-induced phase distortions, and stress birefringence that affect beam quality. These issues are bypassed by cryo-cooled Yb:YAG in DiPOLE, however requiring a more complex amplifier cooling scheme to achieve cryo temperatures, affecting efficiency along with the need for mitigating power caused by parametric lasing. Another consideration for gain media is the need for mitigating laser-plasma instabilities requiring broadening the frequency spectrum of the laser pulse. Nd:Glass has a much larger gain-bandwidth than Yb:YAG. However, if a 100-200 GHz 3ω bandwidth would be sufficient for controlling plasma instabilities with increasing laser drive power and energy, it may be possible to replace Nd:Glass with alternative longer storage gain media. Increasing the storage lifetime of the gain medium allows for the use of lower diode pump power, significantly reducing the quantity of diode pumps and therefore the total diode cost. Additionally, increasing the gain cross-section allows for higher extraction efficiencies or lower intensities inside the amplifier, increasing lifetime. However, an "optimal" solution will be derived from target physics requirements.

Gain Isolation & Switching

Achieving active gain isolation, switching, and back reflection mitigation for 1ω short-pulse drivers using the Pockels and/or Faraday effects is critical for high efficiency laser architectures. However, the combination of high average power and large aperture required for DPSSLs presents a significant challenge. Currently, no gain isolation or polarization switching device or passive polarization control through half- and quarter waveplates is available that can accommodate aperture sizes >10 cm × 10 cm and operate at fluences >10 J/cm², and average power >100 W/cm². Therefore, there is a need to develop alternatives or advancements to current plasma Pockels cells.

Ultrashort Laser Pulse Generation for Fast Ignition Schemes

To achieve high intensities for fast ignition schemes, laser drivers require short pulses using chirped pulse amplification (CPA) mode. This amplifies broadband, chirped pulses and uses a grating pulse compressor to achieve intensities above 10^{19} W/cm². Nd:glass and Yb:CaF_2 are gain materials for these type of lasers due to their mature technology and broad bandwidth, while Yb:YAG at room temperature is also viable, but has not been demonstrated at diameters consistent for energy extraction of kilojoules and beyond. High wall-plug efficiency >5% for CPA lasers is difficult to achieve and inherently less than DPSSL driver lasers. Furthermore, the use of diffraction gratings to compress the pulse and focusing with reflective optics near-by the reaction chamber is needed, which poses challenges for optics survival and integration into blanket systems. Despite presenting lower LPI problems, isolating the laser against 1ω back reflections from a target remains a challenge that requires mitigation studies. It is recommended to develop conceptual system architectures and performance studies for high wall-plug efficiency CPA lasers that align with the requirements of Fast Ignition while experiments are ongoing to validate the expected physics concepts for the various FI-fusion concepts.

Cost & Mass Production

To achieve the most economic trade-off between pulse energy and number of beamlines, all system components must undergo cost optimization, and corresponding mass production technology must be developed. Additionally, a large number of beamlines can offer additional functionalities such as independently delivering wavelengths or higher fault tolerance despite an increased statistical failure rate. corresponding mass production technology must be developed. Additionally, a large number of beamlines can offer additional functionalities such as independently delivering wavelengths or higher fault tolerance despite an increased statistical failure rate.

6.5.4 Capabilities and Competencies in Germany

Germany has a strong research focus on photonics including high-energy laser technology, with several institutions and universities conducting research in applying these capabilities to supporting experiments on shock-physics, astrophysics, materials at extreme conditions, laser-particle acceleration, production engineering, EUV-generation, medicine and life science, and more. Some notable examples for institutions in Germany include:

- » GSI Helmholtz Centre for Heavy Ion Research in Germany and the Helmholtz-Institute Jena conduct research in laser development, particularly in the field of high-energy lasers for applications in high energy density science, warm dense matter research, laser-driven secondary sources and their applications in medicine.
- » Helmholtz-Zentrum Dresden-Rossendorf (HZDR): The Institute of Radiation Physics at HZDR conducts research on laser-driven ion acceleration, laser-plasma interactions, and the development of high-power laser systems.
- » Fraunhofer Institute for Laser Technology (ILT): ILT focuses on the development of high-power lasers and laser systems for industrial applications, laser systems engineering for aerospace, as well as research on laser material processing including laser-based additive manufacturing and laser-based optics manufacturing.
- » Fraunhofer Institute of fine mechanics (IOF): IOF focuses on the development of fiber-based high-power lasers for industrial applications, as well as research on precision optics development
- » Laser Zentrum Hannover (LZH): LZH conducts research on laser systems for industrial applications, as well as laser-based manufacturing technologies, laser material processing and high power coatings.
- » Ludwig Maximilian University LMU Munich and Center for Advanced Laser Applications (CALA): Research on high-energy and high-peak-power laser systems and the application to laser-particle acceleration, X-ray generation and high-field physics.
- » Max Planck Institute of Quantum Optics (MPQ): MPQ conducts research on high-intensity laser physics, including the development of high-power laser systems for particle acceleration, laser-driven fusion energy, and the study of extreme laser-matter interactions.
- » Technical University of Munich (TUM): TUM has a strong focus on research in high-peak power laser physics, including the development of laser systems for fusion energy, laser-driven particle acceleration, and the study of ultrafast laser interactions with matter.
- » Ferdinand Braun Institute Berlin (FBH): FBH's main research activities include design of high power laser diodes, manufacturing and packaging of laser diode bars and packaging of micro optics
- » Institut für Strahlwerkzeuge (IFSW) Stuttgart: IFSW conducts research in the area of high power solid state lasers with a focus on ThinDisk and fiber lasers.

On the industrial side, Germany is one of the leading optics and lasers manufacturer, integrator and system developer. Companies with key expertise in fields relevant to fusion lasers are:

- » TRUMPF: A leading global company in laser technology for industrial applications, with headquarters in Ditzingen, Germany.

TRUMPF offers a wide range of lasers for various industries, including manufacturing, aerospace, and electronics.

- Coherent: A global supplier of laser-based solutions for a wide range of industries, including semiconductor, microelectronics, and medical. Coherent is headquartered in Santa Clara, California, but has a significant presence in Germany, with various locations in Germany.
- Jenoptik: A German company with expertise in photonics and laser technology for industrial applications, healthcare, and defense. Jenoptik offers a range of lasers, including high-power diode lasers and ultrafast lasers.
- Laserline: A German manufacturer of high-power diode lasers for industrial applications, including welding, cutting, and additive manufacturing. Laserline is headquartered in Mülheim-Kärlich, Germany.
- Heraeus: Provides materials and components for lasers, such as laser crystals, fibers, and optics.
- Schott: Supplies glass materials for laser components, such as laser-glass, laser windows and lenses.
- ZEISS is a well-known company in the field of optical manufacturing. The company has a long history of innovation in optical technology and is considered a leading manufacturer of optical components, systems, and solutions, as well as an innovator in the design and construction of complex optical instruments and systems.
- OptoTech Optikmaschinen GmbH: a manufacturer of machines and systems for precision optics, including polishing and coating machines.
- Laser Components GmbH: a supplier of components for laser technology, including optics and coatings.
- Layertec is a German company that specializes in optical components and coatings, including high-precision thin-film coatings for laser optics. Layertec is considered a leading supplier of high-end optical coatings and has partnerships with several key players in the laser industry.
- Laseroptik is a manufacturer of high LIDT (laser induced damage threshold) laser optics and coatings from VUV to IR for industry, medical technology and scientific research.
- AMS OSRAM is a global leader in high power diode lasers with production capabilities for large numbers of single emitter diodes as well as diode lasers arrays
- IPG is a global leader in industrial fiber lasers providing the full value chain from diode laser emitters to industrial high power lasers up the multi-100 kW continuous output power

Both lists represent only a snapshot of private laser- and optics industry and is by no means considered complete.

These companies are leaders in the development and production of lasers and optics for various applications, including industrial manufacturing, scientific research, and medical applications. They have a significant impact on the German economy and the global laser market.

6.5.5 Industry Led R&D for IFE

Germany is already a major player in the global laser market with a market share of 40% in Europe. These companies, along with many more German companies leading in lasers, optical materials, optics manufacturing, production machines and other enabling technologies would benefit from an increased demand for high-power and high-energy lasers required for IFE. The significant and simultaneous improvement of quality and productivity of large, high quality optical components will boost the development of optical materials and coatings, automated production processes as well as sensing and inspection methods. The development of IFE laser drivers could further strengthen Germany's position in the market by driving the development of new and more advanced laser technologies, as well as fostering collaborations and partnerships between companies, research institutions, and government agencies. These activities can only be realized in close collaboration with industry and cannot be achieved by research institutions alone. This could spur further innovation and advancement in laser technology, leading to increased competitiveness in the global market. Additionally, the development of IFE technology could lead to new job opportunities within the laser industry in Germany, boosting the country's economy and contributing to its global leadership in the field of photonics.

Overall, the development of laser drivers for IFE will have a significant impact on the photonic and its supply chain industries, specifically in Germany, providing new opportunities for growth and innovation, while also addressing global energy and environmental challenges. It has the potential to position the country as a leader in high-power laser technology, in both academia and industry.

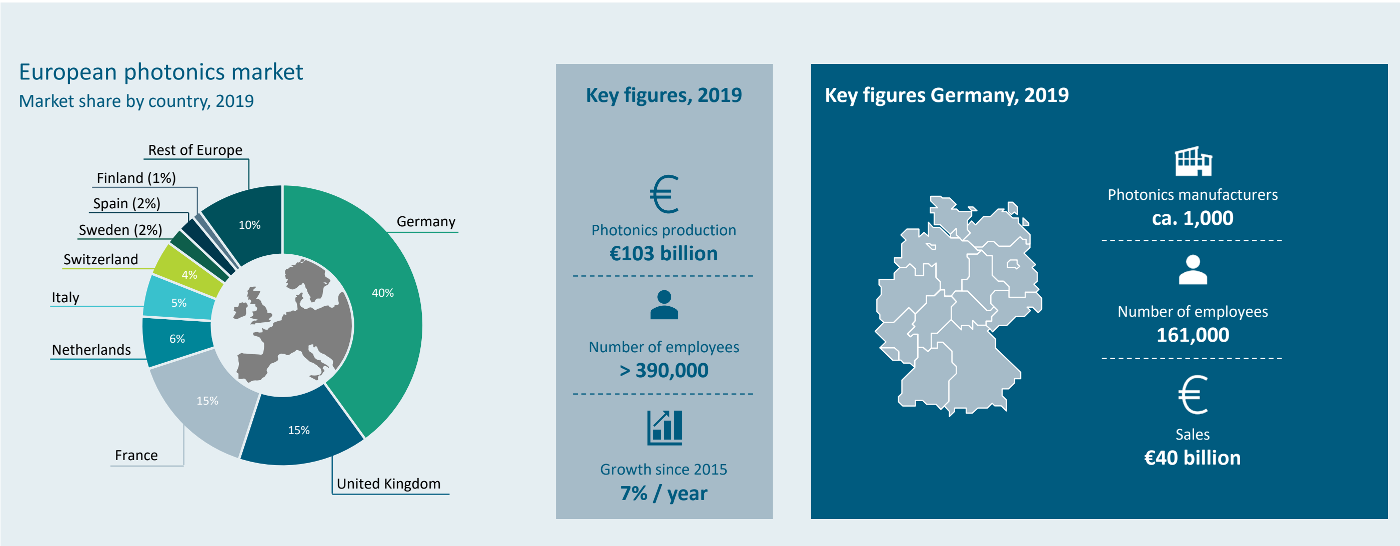


Fig. 23: European Photonics Market 2019 and numbers of German Photonic Industry [Spe2021].

6.5.6 Findings and Recommendations

Germany and the EU have a strong presence in the fields of optical component design, manufacturing, and high-precision, high average power laser sources for commercial material processing and metrology. While this provides a solid foundation for laser source development in laser-driven inertial fusion power plants, there is a need for a functional engineering ecosystem that specifically addresses the requirements of lasers that combine high energies (>100 J) and high average powers (>1 kW). However, the market for lasers with these parameters has only recently emerged, primarily in the field of laser-driven secondary sources, which generate high-energy photons, electrons, neutrons, or ions through the interaction of high-peak power lasers with matter. These sources are now experiencing successful commercial applications and expected to transition from basic research to applied technology in the coming years.

Developing IFE drive lasers requires advancements in various components and optical technologies, such as optical materials, nonlinear crystals, and coatings for reflectors and anti-reflection. To ensure their long-term performance and reliability, accelerated lifetime testing is necessary, which involves exposing the laser components to higher stress levels and operating conditions to identify any potential weaknesses or failures before deployment. This testing helps in reducing the risk of costly failures and downtime in the future. Therefore, it is recommended to develop an accelerated lifetime test laser facility that can scale from current high power laser architectures and known materials, without requiring high wall-plug efficiencies. This facility should complete within 4-5 years to support IFE beamline development.

To make a design decision for laser beamlines for an IFE power plant in ten to twelve years, we propose implementing two identical beamline demonstrators operating at similar output characteristics. These demonstrators should replicate the beamlines to be used in

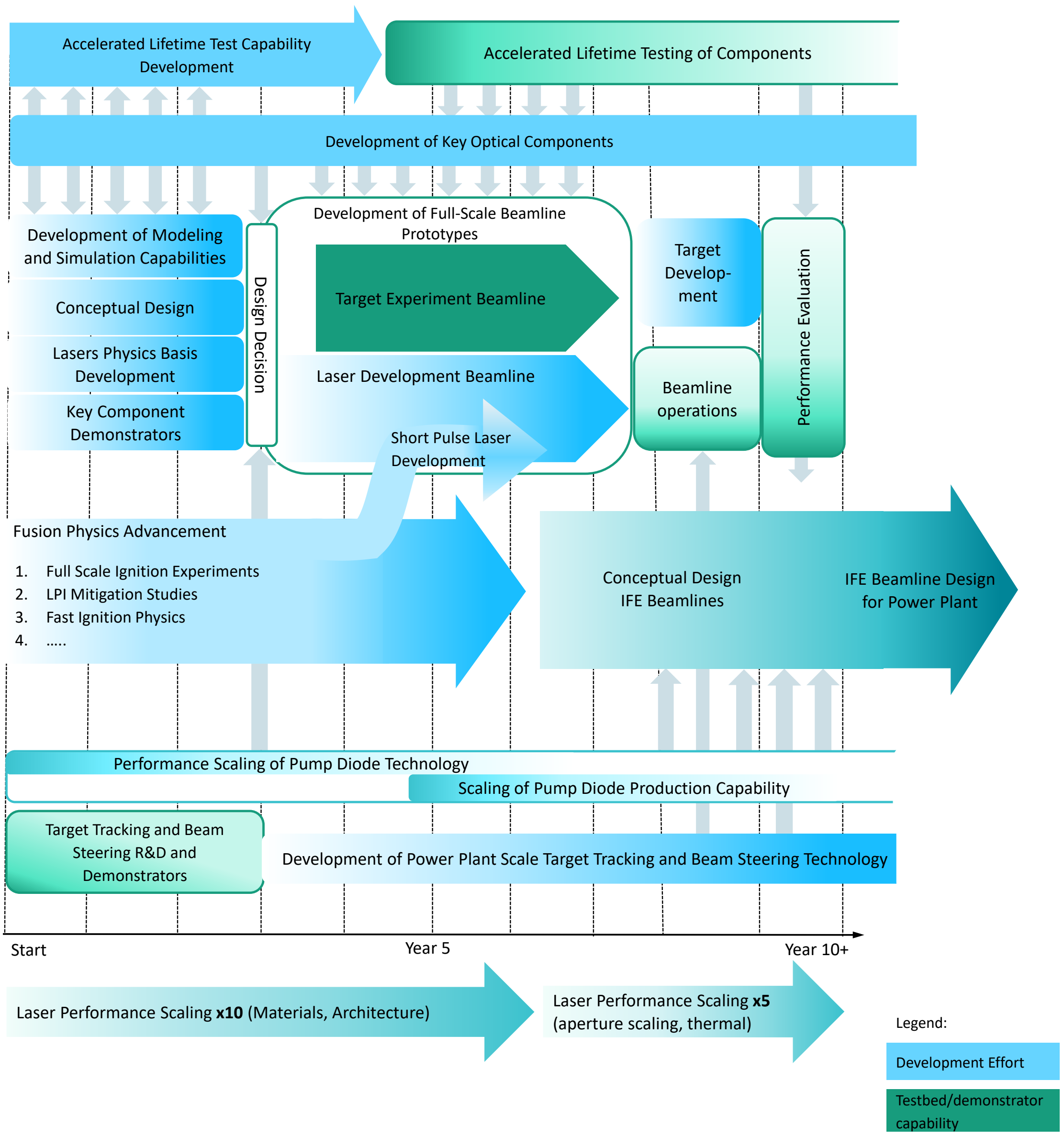


Fig. 24: Recommended course of action for developing an IFE beamline concept for fusion power plants, building on a multi-pronged approach of technology development, testbeds and phased performance scaling.

the IFE power plant, including output energy, repetition rate, and efficiency. Depending on diode prize development, a smaller aperture may be used to lower costs, but all technologies used on the beamline must be capable of being aperture scaled for use in an IFE beamline. Consequently, any new technologies must have a well-defined and practical development plan attached to them. The first beamline, called the "Laser development beamline," will evaluate laser architectures, allow for continued R&D, process development and optimizing laser performance, as well as test laser components. The second beamline, known as the "Target experiment beamline," will have a scaled target chamber and will serve as a testbed for target experiments and IFE diagnostics. The aim of this dual beamline approach is to create a testbed facility with two beamlines: one for laser research and development, and the other for target development and testing, which will be efficient and effective.

The demonstrator implementation (years 4-8) will be preceded by a design study (years 1-3) evaluating different laser architectures (gain material, active medium geometry, cooling architecture, pump architecture, amplifying beam path,...) with respect to the requirements for an IFE power plant laser source (energy, efficiency, beam quality, bandwidth,...). This could start from a re-evaluation of LLNL's LIFE study [Bay2011], [Erl2011] with respect to changing laser require¬ments due to recent findings in fusion research (e.g. larger bandwidth require¬ments) and advances in laser and component technology. Moreover, an experimental verification of the feasibility of the laser design proposed in the LIFE study (very high fluences to reach required efficiencies) with a reduced aperture prototype operating at similar fluence and efficiency is recommended. Implementation of the demonstrators will be followed by an experimental performance evaluation (years 8-9) succeeded by a design review (year 10) based on the findings of the evaluation phase, which allows for optimization of the beamline design prior to making a final design decision for beamlines for an IFE power plant. As similar development efforts are expected to occur globally, it is crucial to compete in terms of performance, reliability, availability, maintainability, and cost.

In the following we list the core findings and recommendations to achieve the final goal of delivering critical technologies is support of a cost competitive and industrially manufacturable IFE beamline:

6.5.6.1 Design Study

Finding	Worldwide, there hasn't been an integrated laser system design study for driving IFE conducted since the LIFE study in 2012, while in Germany an integrated study has never been carried out.
Recommendation	Develop a comprehensive conceptual design study for a laser system(s) capable of driving an IFE powerplant including the physics case and a cost model for the architecture. Identify risk centers and potential R&D to buy down risk.

The first step is to perform competitive system engineering concept studies for an IFE laser beamline, including transport and focusing systems. These studies should take the tremendous progress made over the last decade in high energy (>100 J), high repetition rate (>10 Hz) and high average power (>1 kW) lasers such as Mercury, DiPOLE in the UK or HAPLS in the US. High-level conceptual design studies are essential to identify and refine potential paths forward and the most promising IFE concepts.

The conceptual design study of the IFE driver architecture aims to achieve total cost-effectiveness. However, it is also important to review the different design prospects and limits, such as the supported bandwidth or control of other beam parameters. Versatility is critical for alternative approaches to fusion energy, such as direct drive and fast ignition, as well as for secondary applications in science and industry for high-speed processing and extreme states of matter.

For example, laser direct drive (LDD) with hot-spot ignition or shock ignition offers the potential for high-gain performance for commercial power production, indicating a ~5× higher laser energy coupling compared to indirect drive schemes (see Sec. 5.2). However, laser plasma instabilities pose a challenge to realizing the higher coupling efficiency potential. Broadband laser irradiation may mitigate these plasma instabilities and improve target irradiation uniformity. Besides new concepts like optical parametric amplification and sum frequency generation of a single aperture, a laser system consisting of more, but smaller aperture beamlines can deliver broadband irradiation by combining the output of lasers operating at many discrete wavelengths spanning the required spectrum. The modular approach provides scalability across a range of IFE facilities to enable complex pulse shapes, many wavelengths, and focal spot zooming to optimize LDD drive. The large number of lasers using off-the-shelf optical components could spur competitive commercial development leading to economies of scale with high-volume manufacturing that would benefit industrial and other applications for nanosecond lasers of this scale.

Furthermore, the impact on design architecture by laser packaging, reliability, availability, and maintainability must be considered. The conceptual design must account for the reliability and longevity demands of continuous operation in a power plant environment. Thus, the laser system must be highly modular – both on a beamline-level as well as on a subassembly-level. Each beamline must fit the standard maximum dimensions of transportation and need to be hot swappable with standardized interfaces. For fast service the beamlines of different suppliers should be interchangeable. Likewise, the beamlines should be composed of as many modular subcomponents as possible, easing off-line service at site and stock holding. The system design must avoid all causes of component deterioration such as sputtering or radiation exposure of optical components. Moreover, system design should minimize interlinkage of component failures and damage to assure for fast restoration in case of component damage.

6.5.6.2 Simulation and Modelling for Design, Evaluation, and Control of the Laser System

Finding	The proposed high energy laser is a very complex technical system – with respect to design of the individual components, data evaluation for the overall system, and control of the adaptive elements during operation (deformable mirrors, diode laser operation for adaptive pumping, …).
Recommendation	To design and operate such a complex cyber-physical system sophisticated simulation tools and models need to be employed and developed. The concept and design phase must be accompanied by modeling and numerical simulations. This includes the main components and processes: High-power diode pumps, laser amplification, laser beam propagation, cryogenic cooling, nonlinear frequency conversion.

Most of the numerical tools for the simulations are available but may need to be adapted and extended for the specific purpose. Computational Fluid Dynamics (CFD) codes

(OpenSource and commercial) can be used out of the box, but especially the modeling of turbulence requires experience. A special challenge for the simulation of optical propagation is the large apertures in the system. Besides software for multi-physics simulation of the laser operation, beam propagation, and fluid-dynamics (for the cooling concept), novel concepts from the field of data science including solutions based on artificial intelligence (AI) are used to evaluate and process the data stream from a variety of sensors and return control instructions, for example for the adaptive optics for wavefront correction. The overall system consisting of master oscillator, pump modules, amplifier, frequency conversion, focusing, etc. and many necessary sensors reaches a level of complexity that needs active control. A large amount of sensor data must be collected, evaluated in real time and fed back into the control system.

6.5.6.3 High-power Diode Pump Sources

Finding	The cost of semiconductor lasers for pumping an IFE powerplant size facility is prohibitive currently.
Recommendation	Establish an R&D program to reduce the production costs of semiconductor laser pump modules suitable for IFE-DPSSL technologies.

To achieve an economically feasible fusion powerplant, the diode laser technology needs to provide robust, high reliability and long performing high-power pump sources at affordable price points. Compared to the state of the art today (500 W/bar, lifetime of 2.2 Gshots in QCW mode [Kou2021], cost of 0.4 $/W, efficiency of 55%-60%), significant improvements are necessary, especially regarding lifetime (7× increase) and cost (50× decrease) [Hae2022]. To put this in perspective, a diode pumped, NIF scale implosion facility pumped with diodes instead of flashlamps would require diodes worth ~$20B at today's market price, plus the power forming network. To support the production of a single fusion powerplant, the annual global output of high-power bars must increase by 25 times. This would require significant automation of the entire chip production process, with a particular focus on the assembly and packaging steps, which currently account for the majority of the expenses (around 90%), Fig. 25 right. The whitepaper [Hae2022] jointly developed by public research and private industry concludes that it is possible to achieve high power laser diode manufacturing costs of <$0.05/W that rests on the following development areas:

- Improving electro-optical efficiency to values around 70% at high brightness through novel chip and epitaxial design and through enhanced thermal management technology. Modeling the complex interplay of electrical, optical, and thermal phenomena within the devices represents a key method to rapidly identify promising new design concepts.
- Advancing diode reliability and mean-time-to-failure (MTTF) assurance via improved crystal growth, advances in facet passivation technologies, optimized package development, and establishing of test facilities to validate the new designs.
- Reducing cost of diode production through the development of advanced manufacturing processes and technologies that improve fabrication yields.
- Developing a standardized industrial supply ecosystem that includes multiple sources of standardized pump diode components.

More information can be found in the aforementioned whitepaper.

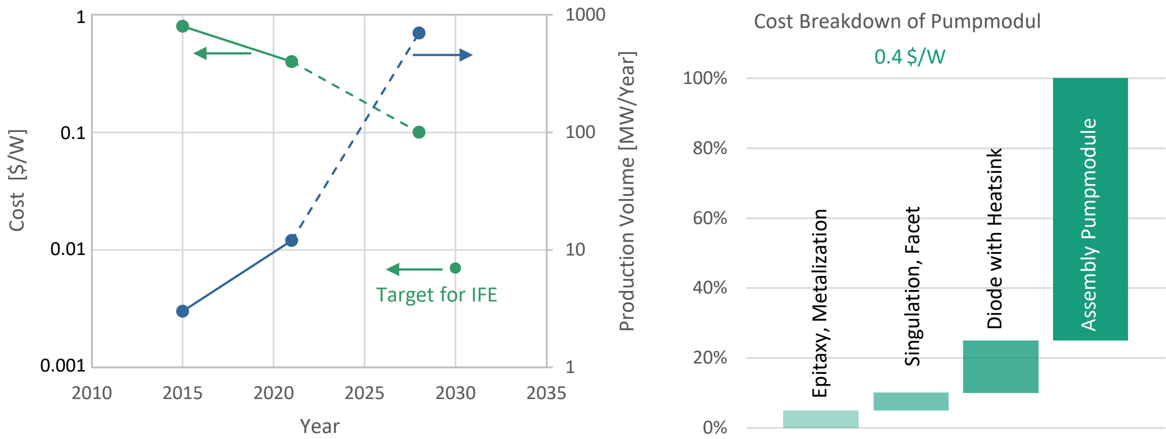


Fig. 25: Evolution of cost and production volume (left) and cost breakdown of high-power pump modules (right). Based on [Hae2022].

6.5.6.4 Optical Components

Finding A large number of optics and optical components are needed for an IFE laser system. Disruptive technologies for manufacturing those with high precision, high repeatability and consistent with high fluence laser operation or consistent with the aggressive environment around the fusion target chamber have to be developed, allowing economic and fast production of large optics in high volumes.

Recommendation Establish an R&D initiative that leverages Germany's extensive expertise in optics manufacturing to establish an IFE optics manufacturing center of excellence. The center will cultivate the skills and capacity to mass-produce optics for IFE power plants.

Disruptive technologies for manufacturing optical components have to be developed, allowing economic and fast production of large optics (diameter >200 mm and larger) in high volumes and consistent with IFE laser specifications. Approx. 10,000 optical components of this size are required per facility, in addition to ~30,000 small optics. Innovative manufacturing technologies like laser-based optics manufacturing or precision molding combined with state-of-the-art grinding, polishing, MRF and IBF processes have the potential to form new process chains and overcome the limits of today's optics manufacturing. For economical implementation and minimized down time during operation also novel packaging and alignment concepts need to be developed.

Besides the production process of the optical components their surfaces and coatings must fulfill high requirements in terms of absorption, optical damage thresholds and reliability. Low absorption of passively cooled components is critical due to the high average power. A damage threshold as high as possible is an absolute must have for high laser efficiency and small footprint. For reliable long-term operation, the density of defects must be as low as possible. Critical defects, which can grow during operation, must be avoided in the final optics. For mass production of the demanding surfaces and coatings on large aperture optics with high yield intensive development of process, manufacturing techniques, automation and material sourcing is necessary.

In terms of passive amorphous materials used for beam delivery, only a few rad-hard glasses like fused silica and cerium stabilized glasses are available. While fused silica is highly transmissive in the UV, stabilized glasses are available with high index of refraction. New optical materials need to be developed which combine these properties.

Neodymium doped phosphate glass is the active laser medium for most high energy lasers. The main benefits are comparably low cost and availability in large dimensions and repeatable optical quality. Laser crystals on the other hand have comparable high thermal conductivity and lower induced thermo-optical aberrations at the expense of time-consuming crystal growth and limited apertures if conventionally grown. Edge-defined film-fed growth (EFG) offers the possibility to grow crystal sheets with larger dimensions, but this technique was so far only demonstrated for limited materials. Laser ceramics are in between glass and monocrystalline materials, they can be produced in larger apertures with almost the same performance compared to the base material. Research also needs to focus on the reduction of scattering losses and aligning of crystallites. To date Nd:Glass and cryogenic cooled Yb:YAG/ceramic are the best possible choices in terms of economical respective performance reasons. Overall, a suitable aperture and production scalable gain material must be developed.

The frequency conversion of infrared laser radiation into the ultraviolet using energies >>10 J in combination with high repetition rates (about 10 Hz) and thus high average powers (>>100 W) is significantly limited by the availability of suitable nonlinear crystals. In recent years, nonlinear media such as deuterated KDP, YCOB, and LBO have been identified and tested as potentially suitable nonlinear media, although crystals made of these media have limitations in specific aspects in each case. For example, the maximum allowable fluence applied onto a crystal is limited by the laser-induced damage threshold of the material and optical coatings. Therefore, the maximum available aperture of the crystal determines the maximum achievable pulse energy in the UV. For use in an IFE laser facility, nonlinear crystals must be fabricated with volumes or apertures scaled up by an order of magnitude while reducing the residual linear absorption to keep the thermal load low. In the case of LBO, high quality crystals with apertures well beyond the state of the art of 100 cm^2 have to be produced to be able to apply the full energy of a beamline at a fluence consistent with the damage threshold. In addition, the current fabrication process must be refined, or a new process developed, so that the number (>1000) of large aperture, high quality nonlinear crystals required for an IFE laser facility is compatible with a production time of well under one year.

6.5.6.5 Final Optics

Finding	For reliable long-term operation of IFE power plants, final optics near the reaction chamber are needed that withstand high neutron and UV fluences. These components must be available in large size (approx. 500 to 1000 mm) and large volume.
Recommendation	Significant progress in the development of rad hard glasses is mandatory, e.g., developing of rad hard materials with high damage threshold, transmission and index of refraction. Economic mass production technologies of these materials and the optical components made of them shall be developed, including low absorptive optical coatings which can withstand both high UV fluences and intensive neutron irradiation.

To facilitate the advancement of high-energy laser (HEL) systems, significant focus is required in materials research for optics. This involves exploring novel materials such as ultralow absorbing glasses and developing mass production methods for molded or 3D-printed optics. Additionally, it is crucial to conduct research on self-healing optics, particularly for radiation resistance, to enhance the durability of HEL optics. Tailored optics and active media development also hold great potential in improving the performance of HEL systems.

Furthermore, it is essential to develop automated optical assembly and optomechanical fixture methods that align with automated optics placement and ensure consistency in precision, repeatability, cost reduction, cleanliness, and high RAMI of the systems. Hence, research and development in this area must be emphasized to advance the practicality and effectiveness of HEL.

6.5.6.6 Accelerated Lifetime Test Facility

Finding	A high repetition rate (minimum 10x of IFE pulse repetition rate) capability is needed to perform materials testing in IFE-powerplant-like conditions as well as establishing expertise and train talent. Germany operates only high energy laser systems that are low repetition rate and based on outdated technology not suitable for IFE.
Recommendation	A high power accelerated lifetime tester should be designed and built to explore, research, develop and gain experience in energetic high power laser operation as well as establishing essentially important science and technology testbed facilities: To provide accelerate lifetime testing capability as a user facility to industry, public research institutions, and international partners. This capability would establish a Unique Selling Point for a capability no one else in the world has. Furthermore, these facilities are urgently needed to test concepts of big-data machine learning tools and train talent.

In order to test the durability and reliability of the materials and components, an accelerated lifetime tester provides a faster and more efficient way to simulate years of wear and tear in a shorter period of time, ultimately improving their design and performance for the IFE power plant while saving time and costs associated with long-term testing.

This accelerated lifetime tester should be a beamline established to evaluate the optics degradation and estimate and validate the mean time between failures (MTTF) and mean time to resolve (MTTR) by the means of intense studies. The tester should be capable of delivering fluence equivalent to power plant beamline operation point, but in a reduced area compared to power plant beamline, typically around 0.5-5% (i.e., approximately 50-500 J). The deterioration effects can be accelerated by an increased repetition rate, which can be around 1 kHz. Thus, being much higher compared to the power plant operation point. This repetition rate should be increased by the same factor by which the pulse energy (and fluence) is reduced, yielding the same average power as the power plant beamline. Since cost is scaling with laser output energy strongly and with repetition rate only weakly, this laser will provide fundamental insights to high power laser development for IFE at reduced cost compared to an IFE beamline. Additionally, there is the potential for spinouts/spin-offs, as the prototype could serve as a high brilliance secondary source driver or be relevant to a driver for a much more efficient EUV source driver (compared to the only a few % efficient CO_2 lasers).

6.5.6.7 Full Scale Beamline Prototypes

Finding	An IFE laser testbed facility is needed to study and optimize single-beam laser technologies, performance, target design, and diagnostics at relevant energy and pulse repetition rate.
Recommendation	A two-pronged approach should be taken to explore, research, develop and gain experience in energetic high power laser operation, as well as establishing essentially important science and technology testbed facilities. Furthermore, these facilities are urgently needed to train talent.

To reduce risks associated with both the driver and target in the development of an IFE power plant, it is recommended that two demonstrator facilities be established using a dual beamline approach. These facilities will provide researchers with a test bed to study and optimize laser performance, target design, control systems, and diagnostics at scale, which is crucial for mitigating potential failure risks and increasing the likelihood of success.

The first facility will be a laser development beamline, designed at an IFE scale to demonstrate the viability of various laser architectures and components for a fusion power plant demonstrator. This facility will utilize a single beamline with scalable components to evaluate full packaged product (FPP) driver performance and optimize reliability, availability, maintainability, and inspectability (RAMI) models to ensure safe and efficient operation. Economic evaluations will also be conducted to determine cost-effectiveness and scalability.

The second demonstrator facility will focus on target and diagnostic experiments and serve as a specialized beamline dedicated to delivering a high-availability laser driver to the target. It will incorporate advanced technologies such as active target tracking and fast laser steering to enable precise targeting of high-velocity moving targets, facilitating the acquisition of highly accurate and reliable experimental data. Additionally, the facility will facilitate various target studies, including target design, code validation, and diagnostics.

6.5.7 Conclusion and Summary

Competitive R&D involving universities, research institutes, centers and industry focused on high energy and high-power lasers is essential to create an ecosystem for the development, production and supply chain of such lasers and beam delivery systems. Strengthening and complementing the optics and laser expertise in Germany through high-energy laser engineering and science programs at universities is a prerequisite. In addition, substantial and sustained development programs allocated by scientific societies in Germany are necessary.

Inertial fusion is increasingly programmatic in other countries like the USA, UK, France, Russia, and China, with growing investment from the public sector and private-public partnerships. To avoid falling behind in the field, particularly in inertial fusion, Germany needs to increase its commitment swiftly. Though needed for IFE research, creating in the short-term a NIF-scale implosion facility for inertial fusion is unrealistic due to the required resources and expertise. Instead, Germany should focus on its existing expertise in laser and optics technology to achieve ICF fusion research goals. To foster international partnerships and establish USPs for Germany, an R&D program for an IFE drive laser is needed with strong participation and engagement from the private sector, including a technology roadmap and the realization of two beamlines for IFE laser development and for target physics development. An accelerated lifetime test infrastructure must be built to enable materials and component testing, as well as providing training capability for next generation talent. The 10-year milestone is a beamline design for an IFE power plant.

Furthermore, the development of laser drivers for IFE expected to create new job opportunities in the laser industry in Germany, as well as increase the country's competitiveness in the global laser and optics market. This will spur innovation and further advancements in laser- and optics technology, which benefit not only the IFE industry but also other industries that rely on lasers, specifically in manufacturing, security, and healthcare.

6.6 Fusion Power Plant

6.6.1 Role of Fusion Power Plant in IFE

This topic has been approached from two perspectives:

- In the IFE onion, it is the outermost shell in which the high-grade heat generated by fusion processes is converted into a usable end product, sometimes also referred to as Balance of Plant (BoP). The standard assumption is that this will be electricity, but it was pointed out during several expert hearings that in the future energy market, other options like production of hydrogen fuels can be attractive.
- More generally, the term 'Fusion Power Plant' is used to describe the FPP holistically as an installation that converts fuels into usable energy. Such an overall picture of an (IFE) FPP is important to both guide the integrated design on a conceptual level as well as to characterize how the FPP will fit into the future energy market demands.

6.6.2 R&D Status Worldwide

Balance of plant: assuming that the primary product of the FPP 'engine' is high grade heat (i.e. neglecting direct conversion of charged particle energy into electricity), the balance of plant should have large similarities with that of a fission plant in that it converts the heat transported out of the reaction chamber in the form of a coolant into the final product (e.g. electricity). Thus, it is expected that the needed technology is readily available and does not need targeted development specific for IFE FPPs[4].

This statement is strictly only true for water as a coolant, which is standard in other large power plants. Assuming Helium cooling, one either has to assume that this technology will be developed for other customers (e.g. Gen IV fission), or start some dedicated research since Helium cooling is not standard for large plants today. This is even more pronounced for other coolants.

Holistic model: there is no standard 'systems code', i.e. a tool that combines in a consistent integrated way the physics and technology assumptions about the different shells of the onion. Individual studies (such as LIFE) have certainly had such an approach to some degree, but it is not available. Such codes exist for MFE (e.g. the PROCESS code [Kov2014] which is the standard tool used in the EU), and might, on a conceptual level, be used as a model for setting up an equivalent IFE code.

Also, no description of an IFE plant as a part of

[4] We note that this split of the onion means that all challenges of converting the fusion power into a heated coolant are dealt with by the blanket/reaction chamber section(s).

the energy system exists. Again, this is available for MFE [Ker2023] and the basic approach (Characterization about start-up, steady state power generation and shutdown in terms of timescales and energy flows) could serve as a model.

6.6.3 Capabilities and Competencies in Germany and Europe

Balance of plant: extensive infrastructure exists with the Balance of Plant described above in industry in Germany and worldwide. In a hearing of the Expert Group with one large German company, it was stressed that there is at present interest to engage in the Balance of plant part, but not in the building of a whole IFE FPP. It was also stressed that the present environment in Germany is not viewed as favorable to engage in a nuclear technology[5]. This goes together with a decline in educated (and educating) workforce in Germany in the nuclear sector, which will have to be reverted in case Germany enters as key player in any fusion technology.

Holistic model: the absence of such a model was already pointed out above. The German competence in Laser technology and target fabrication could be used to give input to the corresponding modules of a systems code. The same is true for elements that are common with MFE and for which expertise exists in Germany or the EU (MFE in Germany is well embedded in the EU fusion program), such as outer fuel cycle or, to some degree, the blanket.

6.6.4 Industry Led R&D for IFE

Balance of plant: for water cooled solutions, there is no specific need for industry led R&D. For He cooled concepts significant contributions could come from industry engaging in this area in the frame of other power plant studies, such as Gen IV fission. It could be useful to look for alliances in this area.

Holistic model: since the elements of balance of plant exist in industry (with the caveats about the coolant choice made above), industry can supply models to both the systems code as well as the description of an FPP in an energy system. This will however not require substantial R&D.

6.6.5 Findings and Recommendations

Balance of plant: as mentioned above, the gap for He cooled balance of plant could be addressed together with partners (industry or research) who have an interest there as well (e.g. Gen IV fission).

Holistic model: both the systems code and the description in the energy system would ideally be developed in international collaboration, involving the key players who have already engaged in IFE on a conceptual level (US, UK, Jp). This would ensure that existing expertise is used, and might lead to a unified standard tool that can be used by all involved parties. Such a systems code is a must for any systematic study of IFE FPP options. We strongly recommend that Germany is an active partner in such a collaboration and brings in its expertise outlined above.

This recommendation is consistent with BRN PRO 6-5 “undertake a series of system-design studies to establish a suite of self-consistent quantitative IFE plant models”.

For completeness, we list here the findings and recommendations of the section on “Power Plant”.

[5] For the supplier, this was a strong argument for the use of aneutronic fuels.

Finding	The readiness of the balance of plant depends crucially on the chosen coolant concept.
Recommendation	Establish a process for down-selection of the coolant concept and clarify the impact of the choice on the development needed for the Balance of Pant.

Finding	There is no openly available systems code for a description of the whole plant. This is needed to study various options and prepare their down-selection.
Recommendation	Establish a systems code, preferably in international collaboration with the aim to produce a standard that is used in studies worldwide.

Finding	There is no description of the characteristics of an IFE plant in the future energy system. This is needed in studies of how IFE plants would fit in there.
Recommendation	Establish a model of an IFE plant that can be used in energy systems studies.

6.7 Diagnostics, Data Acquisition and Interpretation

6.7.1 Role of Diagnostics in IFE

To examine the extreme conditions of ICF implosions, measure the subsequent output of energy and particles, and to understand and quantify the input parameters, exquisite and sophisticated measuring devices are required. Such diagnostics are highly specialized instruments, that must operate in timescales down to nanoseconds (billionths of a second) or shorter, detect interactions often below the submicron level (millionth of a meter), and be capable of withstanding bombardment by intense particle and electromagnetic radiation and debris. The more information obtained about the physical state of the plasmas produced, and the driver and systems surrounding the plasma, the more stringent the test of theories, models, and codes can be leading to predictive capability and understanding.

In order to develop target designs that achieve high gain for IFE, the physics knowledge gap in scaling to such high gains from the current state must be bridged. The NIF and other large scale laser facilities (such as Omega or LMJ) possess a suite of diagnostics that exquisitely measure x-rays, neutrons, gammas, optical light, and more, to infer plasma temperature, density, shape, stagnation time, hydrodynamic mix, pressure, hot spot velocity, uniformity, yield, etc. There are over 100 diagnostic instruments on the NIF, that played a pivotal role in providing the understanding required to achieve ignition.

Even higher fidelity (spectral, temporal, spaEven higher fidelity (spectral, temporal, spatial, energy resolution) are necessary to better understand the foundational physics in order to achieve the high gains (~50-100) required for IFE. As we learn more about the sensitivities of the fuel assembly and heating process, new measurements and diagnostics will be needed to probe and observe the impact of perturbations or imperfections on the fusion plasma.

Of note, measurements at interfaces are particularly needed – both within the fusion plasma itself and at places where the various subsystems of an IFE power plant join. For example, precise measurements are needed at the interface between the capsule shell and DT fuel as this is one of the key locations where hydrodynamic instability growth can lead to mix and reduce the area of the “clean” hot spot. Diagnostics that can provide information at the interfaces can furthermore help us understand the interplay between different components, technologies, and subsystems. One example is at the final optics before the laser is delivered into the target chamber – it is here that the laser optics will be exposed to the largest amounts of debris and the highest laser intensities, and continuous monitoring of damage and optics degradation will be crucial to ensuring good laser performance is maintained.

In a fusion power plant, there should be minimal diagnostics. It is envisioned that once things are up and running, at routine operations, only a small set of instrumentation will be needed for: monitoring of laser delivery, target tracking and engagement, reactor wall monitoring, neutron yield, and maintenance diagnostics. There may also need to be a number of other failure mode diagnostics to provide information in the case things go wrong.

Until that point, however, and to enable that point, the intermediate fusion pilot plant or test facilities will have a set of diagnostic and analysis requirements in-between. This will include:

- High repetition-rate (>Hz), radiation hardened diagnostics
- Automated analysis to keep pace with the shot rate, and preferably provide on-shot feedback
- Edge computing to enable rapid analysis
- On-shot metrology of the target (to make decisions about the suitability of a target for shot)
- On-shot characterization of the driver
- Measurement of target performance – this will probably require a set of diagnostics on par or greater in number and capability than the set of diagnostics on the NIF
- Measurements that allow for understanding of the tradeoffs between the various subsystems in a FPP (e.g., target imperfec-

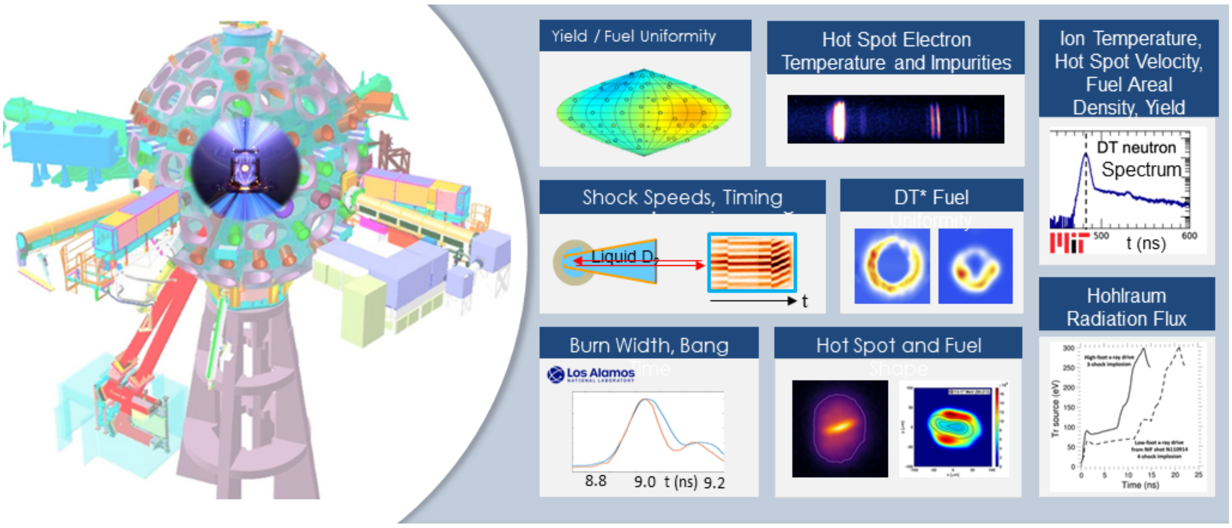


Fig. 26: There are over 100 diagnostic instruments on the NIF measuring a range of parameters related to the target physics. This diagnostic innovation has allowed for unparalleled view into the NIF implosion. Courtesy of LLNL.

tions can potentially be compensated for with laser adjustments)
» Measurement of laser delivery, target tracking, neutron yield, and wall monitoring
» Transition between plasma control to reactor control / machine protection

6.7.2 R&D and Capability Status Worldwide

In the U.S., ICF diagnostics are coordinated through the National Diagnostics Working Group which sets priorities for diagnostic development in ICF across multiple ICF facilities including NIF, Omega, and Z. This group pools resources and expertise from across multiple national laboratories and universities to develop and deploy increasingly sophisticated diagnostics for new and higher fidelity measurements. The group meets annually and also updates their plan to lay out how their mission space will be enhanced by new observables. Table 6 shows the ten transformational diagnostics identified by the group in 2021 that the Working Group will collectively develop over the next few years.

At the LMJ, the diagnostic set of mirrors the ones on NIF, but are currently more limited in number. It is reported that over 80 diagnostics have been installed at the 100 kJ level laser facility Shen Guang-II and Shen Guang-III prototypes [Wan2020].

Each short-pulse, high-intensity laser facility has its own set of target physics diagnostics, centered around the types of HED and other experiments carried out there. Depending on the operations model, users of the facility may often bring their own diagnostics for the experiment, then remove them afterwards. Each laser will also have a small set of laser characterization diagnostics, however, in most cases they are insufficient to provide full on-shot characterization.

Diagnostic modeling is an important capability that is typically tied to an individual diagnostic and can utilize a range of simulation and modeling tools ranging from PIC modeling to GEANT to provide synthetic data. Synthetic data can aid in diagnostic development, calibration, validation, and machine learning training. Another variation on diagnostic modeling is the modeling of laser performance, such as with the Laser Performance Operations Model (LPOM) at the NIF which uses diagnostic feedback from previous NIF shots to maintain accurate energetics models. The LPOM model also determines system setpoints required for requested shots and employs damage models to minimize the probability of damage to the system. Similar models will be necessary for IFE systems, but currently the NIF is the only laser to include such a comprehensive operations model.

6.7.3 Commonalities with Magnetic Fusion

There exist large discrepancies in parameter space between IFE and MFE: 12 orders of magnitude in confinement time, and 11 orders of magnitude in plasma density, but similar temperatures. Thus, in most cases, the diagnostics and measurements are quite different. However, conventional diagnostics such as spectroscopy and polarimetry (X-ray, optical, electron, neutron, and magnetic), scattering (Thomson and particle), fast ion diagnostics and their absolute calibrations are being developed in both IFE and MFE.

In IFE, the community has enormous expertise with fast measurements -- there may be some application in MFE to measure instability evolution or performance dynamics on nanosecond timescales. In MFE, the community has expertise with magnetic diagnostics – this could be applied to IFE for example with the use of externally applied magnetic fields in HED plasmas. High resolution X-ray spectroscopy for identifying and calibrating high-Z impurities in the plasma for MFE, may be another area that could be adapted to IFE, namely in the monitoring impurities and wastes.

In the realm of burning plasmas, there exists a need to understand and quantify self-heating from alpha particles. An already-established technique is measuring the signature alpha knock-on (AKN) tail in neutron spectra.

There are of course more commonalities between MFE and IFE as we move away from the plasma. This includes performance of materials in a fusion environment, tritium breeding blankets, tritium concerns including recovery, processing, accountability, and minimizing inventory

Finally, as IFE will be pulsed while MFE continuous in its generation of fusion plasmas and energy, there are different needs for irradiation and testing facilities.

Transformative Diagnostics	New Capability
Single LOS imaging (SLOS or DIXI-SLOS)	Multi-dimensional shape ad spectra with unprecedented time and space resolution for fusion, Pu strength, and radiation effects sources
Ultraviolet Thomson Scattering (UVTS)	Localized plasma conditions and turbulences in hohlraum and Laser Direct Drive ablation plasm. Additional uses include plasma conditions at low density for rad flow studies and many discovery science applications
3D n/gamma imaging (NIS)	3D shape and size of both burning and cold compressed fuel as well as remaining carbon ablator
Gamma spectroscopy (GCD)	Fusion burn history allowing inferred pressure with increased precision and measured truncation of burn from degradation mechanism such as mix and loss of confinement
Time resolved neutron spectrum (MRS-time)	Time evolution of the fusion burn temperature and areal density
Hard x-ray imaging (Wolter)	High energy source distribution and space-resolved plasma conditions in the hot plasma. Also enables high spatial and temporal resolution for radiography to infer material strength
Time resolved diffraction (XRDt)	Time evolution of material structure (including weapon materials) and compression at high pressure. Also enables more efficient facility use through multiple measurements on a single shot
High Resolution Velocimeter (HRV)	Higher accuracy (<1%) time evolution of material EOS at high pressure. Also enables more efficient facility use through multiple high-fidelity measurements on a single shot
>15 keV X-ray detection (DHEX)	Multiple-frame resolved detection of high energy (>15 keV) x-rays with high detection efficiency
hCMOS	Multi-frame, burst mode imaging sensor capable pf capturing images on the nanosecond timescale

Table 6: The ten transformational diagnostics identified by the National Diagnostics Working Group in 2021.

6.7.4 Capabilities and Competencies in Germany

Diagnostic capabilities in Germany and Europe are primarily tied to associated laser facilities. As the experimental facilities tend to be mid-scale and university facilities, the diagnostics developed have typically been targeted toward HED experiments and needs.

Fusion experimental diagnostics are not an area where Germany necessarily possesses unique expertise. However, it should be noted that diagnostics can be an avenue for relatively low investment for entry into partnership on a facility. Also, diagnostic development is a great tool for training of new experimental fusion scientists.

6.7.5 Industry Led R&D for IFE

Different ignition approaches will have slightly different requirements in the measurements of plasma conditions, interfaces, etc. For example, for the fast ignition approach, diagnostics for particle acceleration, as well as their stopping and heating effectiveness are required. Each test facility proposed by the private companies will be quite different, and thus will require its own set of bespoke diagnostics. Industry will need to define these requirements and necessary measurements. It is expected that industry will at least to some extent want to develop some of the needed diagnostics in-house, to ensure integration with the test facility and to ensure correct interpretation of data generated.

There are also many general diagnostic needs, with common diagnostic technologies that industry can play a role in providing. Technologies for high-repetition-rate (such as digital recording media and scintillators for signal amplification and transfer), radiation hardening, machine learning, and edge computing all require development. In the production of diagnostic components, advanced manufacturing or additive manufacturing of items such as novel materials for shielding or detection can be an area of exploration.

Industry may also play an important role in the calibration or diagnostics or diagnostic components. X-ray, neutron, or other radiation sources with stable and uniform properties are often needed to correlate the readings of the diagnostic instruments with a standard in order to check the instrument's accuracy.

Finally, while diagnostics for scientific discovery continue to be built in a bespoke fashion, as the IFE industry accelerates, there will be increased demand for diagnostic instruments in general. Industry may want to look for commercialization opportunities with respect to building, deploying, calibrating, and repairing diagnostics. This is accompanied by opportunities to support the data acquisition and handling.

6.7.6 Findings and Recommendations

In the area of diagnostics and data acquisition and interpretation, there are many gaps and subsequent research opportunities – until a full scale power plant is built that harnesses the energy from high-rep-rate high-gain targets, diagnostics are the key to understanding the physics and the IFE system.

New physics measurements are required to develop and test high gain target designs. These include:

- Laser plasma instabilities
- Fuel or plasma or ablator density/temp/conditions vs. space & time
- Opacity / opacity changes
- Imaging during explosive phase
- Mix
- Alpha heating/stopping, burn wave propagation

New technologies are required as well, these include:

» Target positioning determination/tracking
» Target quality (capsule voids and defects, microstructure, etc.)
» Chamber damage accumulation / materials monitoring

As the paradigm for data acquisition moves toward high-repetition-rate experiments, and thus high repetition rate diagnostics, very large data sets will become a reality. Big data and fast data handling and automation becomes a challenge, but also an opportunity. Standardization of data, controls, and system interfaces is a need to allow the different subsystems to interact with each other as necessary, while building a framework where feedback control can be used to optimize experiments in real-time. Some level of standardization will furthermore accelerate progress for the full field as each private company and public project centered around a "fusion engine" will likely run into similar issues. In order to make fast progress, there also needs to be coupling of diagnostics and the data they provide to codes and systems. Diagnostic data that can validate codes will enable the development of a predictive capability.

A major need is for diagnostics that can validate and verify claims and experimental results. There should be a set of common diagnostics that can be brought to different laser facilities, to verify both public and private approaches. Calibration facilities and capabilities are also needed.

Finding	Diagnostics are key to understanding the physics of IFE and developing a viable integrated FPP.
Recommendation	Germany should establish a program to develop target, laser, control, and systems diagnostics.

The diagnostic development program should be coordinated with and support the experimental program and facilities. This includes facilities to be built in Germany, as well as facilities outside of the country where collaboration is to occur. These diagnostics should build off of the extensive capability of instrumentation already developed for existing facilities (such as NIF), but should furthermore provide new insights into physics areas where there remain considerable uncertainties, and would benefit from improved temporal, spatial, and spectral resolution.

Finding	High repetition rate diagnostics are needed for new facilities coming online with high repetition rate lasers, and for future IFE demonstration facilities that will necessarily run at >Hz rates. There are currently only a limited set of relevant diagnostics worldwide capable of operating at these fast rates, capable of withstanding high fluence irradiation of radiation, EMP, and debris, and with automated analysis, and suitable data handling.
Recommendation	Germany should invest in high repetition rate diagnostic development.

Development of HRR diagnostics is seen to be an area of high return on investment, and a necessary step to make full use of the new high repetition rate laser facilities coming online around the world. This is an area that would necessarily also incorporate big data and machine learning approaches in order to process all the data effectively, so leans on another strong competency of Germany.

Finding	A major gap in assessing viability of various approaches is the lack of diagnostics that can validate and verify claims and experimental results.
Recommendation	There should be a set of common diagnostics that can be brought to different laser facilities, to verify both public and private approaches. Calibration facilities and capabilities are also needed.

6.8 Artificial Intelligence (AI) and High Performance Computing (HPC)

6.8.1 Role of AI and HPC in IFE

AI and HPC will play a pivotal role in both developing the fundamental understanding required to realize IFE, as well as transition technologies to application space. Specifically, HPC is required to run and develop simulation codes of increasing fidelity and complexity to fully capture the physics of the laser-target interaction (from the atomistic scale up to the hydro scale and beyond for the interaction with the reactor system), to interpret data while in the R&D stage, to develop full systems models of the IFE reactor, and later on to run the facility in an automated fashion and link an IFE-generated electricity source to a smart grid. AI is similarly needed to handle and utilize the large amounts of data generated through high-repetition-rate laser facilities. R&D and capability status worldwide (where, what).

There has been significant work worldwide in the development of AI and HPC capabilities. Use of both these tools for scientific computing and scientific discovery has advanced at a tremendous pace as new HPC machines come online around the world, and as researchers develop new techniques for harnessing AI for everything from automation to controls to feedback loops for self-driving optimization.

6.8.2 Capabilities and Competencies in Germany

Germany has substantial AI expertise spread across its many universities and research institutes. The HPC capability in Germany for the moment has been mostly sufficient for the scale of science being done, however, we expect demands will continue to grow for HPC resources, so this is an area that Germany must ensure it keeps up.

6.8.3 Industry Led R&D for IFE

Industry has a role in developing AI techniques for the range of needs in IFE – this can include the use of AI for modeling and simulation, efficiencies in large-scale or high-volume manufacturing, data handling, and more. It is unlikely that the fusion industry will be the center of HPC, as supercomputers are a significant investment (both in capital cost and operations), however, they can most surely drive demand and also provide hardware components that will be required in computational situations.

6.8.4 Findings and Recommendations

Continued needs as AI and HPC grow in importance include improved techniques for data analysis and interpretation, data standardization, data handling, development of algorithms for the design and optimization of IFE reactors or components, and overall computing resources to run simulations and models.

Finding	Germany possesses enormous expertise in AI and HPC across its many universities and research institutions.
Recommendation	German AI expertise should be fostered and brought to bear on the IFE problem by opening up AI funding opportunities to IFE.

Finding	As new experimental and research facilities are brought online, integration of AI and HPC will be necessary for full and optimal utilization of these facilities to provide new learning and knowledge acquisition.
Recommendation	Design and pursuit of new experimental capabilities should also consider AI and HPC.

Finding	Rapid and robust data analysis will be necessary for even a moderate repetition-rate facility. More data will require improved and automated data analysis, which can be enabled by AI and HPC.
Recommendation	Develop AI techniques to automate and improve data processing and analysis.

07

Education, Training, Outreach, Cooperation and Networking in Germany

7.1 Status & Needs for Education & Training

Germany has a broad research community in the areas of high-power laser and plasma science, high power laser development and other areas to develop a successful inertial confinement fusion/inertial fusion energy (ICF/IFE) strategy within the international context. The key groups located at universities, national research associations and industry have expertise in experimental and theoretical plasma science, laser target interactions, diagnostics and the know-how to run successful even high-power short-pulse laser experiments are rapidly transferable between high power laser and laser fusion communities. Thus, a whole chain of human resources with both practical and theoretical knowledge is ready to successfully establish and design a laser fusion project in cooperation with other leading countries. The already existing experimental facilities as well as the educational landscape enables the provision of appropriately trained talent in the long term. The corresponding resources in terms of high-performance computer capacities are also available. Major shortcomings are essentially that no laser/inertial fusion program has existed to support direct targeted cooperation with leading nations in the field, both monetarily and programmatically. Thus, the technology exchange was essentially focused on technical or methodological individual aspects, but a holistic systemic processing was absent.

This is also reflected in the low availability of experimental specific laser/inertial fusion facilities, even if the infrastructural prerequisites are given in Germany. Establishing laser fusion as a successful research field in Germany and also to mobilize successful industrial activity with respect to a future power plant requires building also some laser/inertial fusion activity at university level to complement the individual chairs.

Finding

Funding scheme for high power laser fusion research doesn't exist in Germany. There is vital high power laser community existent in Germany able to provide sufficiently large theoretical and experimental trained staff for a laser fusion power plant program. However an adequate funding scheme for laser fusion research is absent. A dedicated university education towards a laser fusion power plant is currently not existent.

Recommendation

Strengthen laser fusion specific education and funding program for education.

Provision of a specific laser/inertial fusion program with a funding to train future staff.

Strengthening laser fusion specific university education by provision of university chairs in:

- high power pulsed optical beam sources,
- beam shaping and guiding,
- efficient optical components and conversion as well as
- systems production technologies (from the optical systems to the target itself where the fusion reaction takes place) by establishing dedicated chairs.

Compared to the United States or the UK, Germany currently has a minimal presence in fusion technology and plasma physics at universities, with a primary focus on magnetic fusion. Furthermore, related fields such as nuclear technology, nuclear materials, and diagnostics have also been significantly impacted by the nuclear phase-out, resulting in discontinued chairs at universities and a poor starting position. Disciplines such as nuclear process engineering no longer exist in Germany.

Finding	Germany has a lack of nuclear-qualified staff.
Recommendation	Provision of chairs and corresponding infrastructures in Germany.

Regardless of which type of fusion power plant is realized, the provision of nuclear-qualified personnel for planning, construction, operation and decommissioning is necessary for both the licensor and the licensee, which requires the consistent development of corresponding expertise in training at universities and other institutions of applied science.

Provision of chairs with corresponding infrastructures at German universities to stimulate this type of education in the following disciplines

» Nuclear safety system engineering,
» Nuclear process engineering,
» Nuclear physics (nuclei interaction with matter),
» Nuclear instrumentation/diagnostics.

In the area of nuclear expertise can be used synergistically in other research fields not only fusion (laser and/or magnetic fusion), but the occupation of this competence fields with the output of educated and trained staff is essential for successful research and the construction of a fusion facility.

The research centers at Fraunhofer, Max-Planck and Helmholtz already host some large-scale infrastructures acting as a basis and seed for the development of future key technology development within Germany, which is not focused on inertial fusion but takes Laser Fusion (IFE) as the most challenging use case and driver. These already existing sites can act as hub to establish at nearby associated universities professorships, the educational basis to provide the personnel resources required to establish not only an internationally competitive scientific basis but also providing specialized staff for technology-oriented companies. Naturally, the professorships require a research infrastructure targeting fusion, but also being competitive and attractive for industry business to generate also an economic frame which require for each an equipment in the range of in average about two million Euros given that they can access the nearby infrastructures of the research centers. Since some of the identified topics are strongly interrelated it makes sense to cluster them at sites offering already pre-emptive know-how. The hub concept is so attractive because the established professorships can initially not only synergistically access the laboratories of the research centers until their own university infrastructures are established, but can also develop existing industry contacts of the centers to further develop their own expertise and thus achieve productive results after a relatively short time.

Finding	A laser fusion network doesn’t exist in Germany until now.In Germany there is currently no laser fusion network but rather individual centers of expertise (laser sciences, plasma physics, fusion engineering, materials research, manufacturing technologies). The same applies, albeit to a lesser extent, to magnetic fusion, since most of the projects on integration within the European framework are bundled there.

RECOMMENDATION Build a Laser Fusion network in Germany and strengthen the ecosystem for Laser technology development between industry and German Research Centers.

It should be considered whether a German laser fusion initiative jointly supported by the research centers (Fraunhofer, Max-Planck, Helmholtz), the universities and industry could represent laser fusion to the public. This in turn requires the establishment of a tangible laser fusion project that manifests the credible will to design and, if necessary, realize a fusion power plant.

FINDING Fusion research requires a wide range of expertise, infrastructure and organizational mechanism.

Any kind of fusion research requires the provision of a wide range of expertise, technical infrastructures (laser facilities, thermal-hydraulic test stands, process engineering plants, material characterization sites including hot-cell, dedicated manufacturing techniques) and organizational mechanisms (program and project structures) that are difficult to master by any state alone. At the same time, a duplication of large infrastructures does not make sense, but rather synergetic effects in accessing large infrastructures should be used.

RECOMMENDATION German Research institutions should collaborate with each other and with international experts in the field of IFE like LLNL (USA). Such collaboration could accelerate the time to market.

In a first step in a cooperation agreement between the competent bodies (e.g. LLNL, other US laboratories and Fraunhofer ILT, IPP Garching, KIT and possibly others from Germany) of the laser fusion in the context of a laser power plant study should be envisaged.

Such a measure would enable to pool all the expertise to identify a feasible power plant concept by mutual exchange of information and to develop the necessary interface mechanisms for a long-term cooperation and distribution of tasks. This cooperation allows for the exchange of experts at the specialist level, the mutual knowledge of the technical skills of the partners and generates for the future also the exchange of young scientists and students as well as practical training.

FINDING Germany has a great educational system in various fields which are needed for fusion technology.

RECOMMENDATION Keep the research capabilities in Germany and continuously invest in upgrades of laser facilities.

The mid-scale short-pulse, high-intensity scientific laser facilities (such as DRACO, PENELOPE, PHELIX, CALA, POLARIS) provide an excellent training ground for young scientists. As has been seen from the past three decades, besides being scientifically very productive, these facilities serve as spawning grounds for the necessary plasma physics, laser engineering, and high energy density science expertise needed for a growing IFE program. Furthermore, the nature of the training on these facilities sets up researchers well for translating to larger, more complex facilities, like what will be needed for IFE demonstration. Many of the current leaders in ICF around the world now were trained on these facilities and facilities like them.

Germany needs to ensure the sustainment and upgrade of existing mid-scale laser facilities, and furthermore pursue new high energy, ultra intense facilities. Such cutting edge facilities enable groundbreaking science, serve as an attractor of new talent to the field, and serve the very important mission of workforce development and training.

08

APPENDIX

8.1 References

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8.2 Abbreviations

1D	One-Dimensional
2D	Two-Dimensional
^{3}He	Helium-3 Isotope
2PP	Two photon polymerization; a high-resolution additive manufacturing method
AI	Artificial Intelligence
AM	Additive Manufacturing
appm	atomic parts per million
AWE	Atomic Weapons Establishment, United Kingdom
Be	Berylium
BMBF	Bundesministerium für Bildung und Forschung
BoP	Balance of Plant
BRN	Basic Research Needs
CALA	Center for Advanced Laser Application, München
CBET	Cross-Beam Energy Transfer
CEA	Commissariat à l'énergie atomique et aux énergies alternatives, France
CEA-SBT	Service des Basses Températures of CEA, Grenoble, France
CLF	Central Laser Facility of Science, Technology, and Facilities Council, United Kingdom
CR	Convergence Rate
D	Deuterium
DD	direct drive
DiPOLE	10 Hz Laser System at Rutherford Appleton Laboratory, Didcot
DIR	Direct internal recycle
DLC	Diamond Like carbon
DOE	Department of Energy

dpa	Displacements per Atom
DPSSL	Diode Pumped Solid State Laser
DRACO	Dresden laser acceleration source at HZDR
DT	Deuterium Tritium
ELI	Extreme Light Infrastructure
ENEA	Research Center in Frascati, of the Italian National Agency for New Technologies, Energy and Sustainable Economic Development
EOS	Equation of State
F4E	Fusion for Energy
FOAK	First of a Kind
FESAC	Fusion Energy Sciences Advisory Committee
FI	Fast Ignition
FPP	Fusion power plant
FZJ	Forschungszentrum Jülich
g	Acceleration of gravity, 9.8 m/s
G	Gain
GA	General Atomics, USA
GDP	an amorphic polymer plastic formed through **G**low **D**ischarge **P**olymerization in a plasma
GEKKO	Laser system at Institute for Laser Engineering, Osaka
GLC	Generalized Lawson Criterion
GSI	Helmholtz Zentrum – Gesellschaft für Schwerionenforschung mbH
HAPL	High Average Power Laser program; USA 2000 – 2008
HDC	High density carbon (a nano-crystalline diamond material)
HED	High Energy Density
High-Z	Material of high atomic number
HIJ	Helmholtz-Zentrum Jena

HIBEF	Helmholtz International Beamline for Extreme Fields, HZDR
HiPER	High Power Laser Research, EU project 2008-2013
HPC	High Performance Computing
HZDR	Helmholtz-Zentrum Dresden Rossendorf
ICF	Inertial confinement fusion
IDD	Indirect drive
IFE	Inertial Fusion Energy
ILE	Institute for Laser Engineering, Osaka
INFUSE	Innovation Network for Fusion Energy
J	Joule
JET	Joint European Torus
KIT	Karlsruhe Institute of Technology
kJ	KiloJoule
kWh	Kilowatt hour
LLE	Laboratory for Laser Energetics, Rochester
LMJ	Laser Megajoule, France
LMU	Ludwig-Maximillians-Universität München
LANL	Los Alamos National Laboratory, USA
LIFE	Laser Inertial Fusion Energy, LLNL reactor development effort, USA 2008 – 2013
LIGA	Lithographie, Galvanoformung, Abformung – lithography, electroplating, and molding
LLE	Laboratory for Laser Energetics of the University of Rochester, USA
LLNL	Lawrence Livermore National Laboratory, USA
LPI	Laser-Plasma-Instabilities
Nd	Neodym
MOPA	Master Oscillator Power Amplifier

MEMS	Microelectromechanical systems
MFE	Magnetic Fusion Energy
mg	Milligram
MINT	Mathematik Informatik Naturwissenschaft und Technik
MJ	MegaJoule
MPQ	Max-Planck Institut für Quantenoptik, Garching
mrad	Milli-radian
NIF	National Ignition Facility, USA
nm	Nanometer
NNSA	National Nuclear Security Administration
OMEGA	Laser System at Laboratory for Laser Energetics, Rochester
OSTP	Office of Science and Technology
PAM	Preamplifier Modul
PCS	Power Conditioning System
PE-CVD	Plasma enhanced chemical vapor deposition
PENELOPE	Petawatt ENergy-Efficient Laser for Optical Plasma Experiments, project at HZDR
PEPC	Plasma-electrode Pockel cepp
PHELIX	Petawatt High-Energy Laser for Ion eXperiments, GSI Darmsadt
PIC	Particle in Cell, Code
POLARIS	Multi-hundred Terawatt laser system, operated at HIJ
PPP	Public Private Partnership
PRO	Priority research opportunity
PW	PetaWatt
R&D	Research and Development
ROMP	Ring opening metathesis polymerization

SI	Shock ignition
T	Tritium
TBR	Tritium breeding ratio
TRL	Technical Readiness Level
TW	Terrawatt
TUD	Technical University Darmstadt
USP	Unique Selling Point
UPM	Universidad Politécnica de Madrid
YAG	Yttrium-Aluminum-Garnet-Laser
Yb	Ytterbium
Z	Atomic number of an element

8.3 Terms of Reference

Expert Group on Inertial Fusion: Terms Of Reference

The fusion of light atomic nuclei is the primary energy source of the universe. If we could develop this energy source for controlled energy generation on earth, humanity would have access to a climate-neutral, inexhaustible source of energy almost entirely independent of any location factors. The research and development of fusion energy is a grand scientific and technological challenge calling for different approaches and paths to max-imize the probability of success. In view of major progress made in the past two years, a number of countries, including the USA, France, the UK and China, are currently launching new initiatives and investment to accelerate technology development for fusion-based energy production, establish innovation ecosystems together with industry and thus position themselves favourably in international competition.

Germany is currently developing one of the most promising approaches, magnetic fusion, in the context of national and international partnerships. The ITER fusion research facility, which is currently being constructed in France, is intended to demonstrate positive net energy production on the basis of an MFE concept. It is expected to facilitate first research experiments with fusion plasmas of deuterium and tritium in 2035 at the earliest.

The National Ignition Facility at Lawrence Livermore National Laboratory in the USA pursues a different approach, known as laser-based inertial confinement fusion, and achieved an energy yield of 1.3 megajoules (MJ) in 2021. This groundbreaking achievement together with the successful follow-up experiments, the possibility of modular development of the necessary technologies and the US decision to once again launch an IFE program are all good reason to reassess the situation of inertial fusion in Germany and create an overview of possible research needs.

Tasks:

» **Summarized presentation and evaluation of the global state of the art of science and technology**
- of inertial fusion energy (IFE):
- Approaches to inertial fusion
- Consideration of the required modular technologies

» **Expertise, competence and capabilities**
- Who are the scientific players who play a key role in inertial fusion research worldwide?
- Which scientific centers in Germany contribute what kind of expertise to the research of inertial fusion?
- In which areas does Germany have outstanding scientific expertise, and where does it have any deficits?
- In which areas does German industry have outstanding know-how?
- What capabilities or experimental facilities in Germany contribute to or could be employed in the solving of questions on inertial fusion?
- In which technologies does Germany have unique advantages today?

» **Research needs**
- What are the biggest obstacles to industrial application of inertial fusion from a current perspective?
- What are the resulting research needs? Which German universities or research institutions could make relevant contributions to research based on existing expertise (such as experiments, theory and simulation, artificial intelligence and machine learning, diagnostics, drivers, targets, materials, integrated plant or system engineering)?

» **Scaling and implementation**
  - Germany's science and industry ecosystem has unique features in some technologies. Which of them could enable accelerated market access in a partnership with leading countries in inertial fusion?
  - What needs exist in terms of training and labor force development?

» **Evaluation of the role of industry, including the evaluation of public-private partnerships in an IFE program**
  - As far as is known, what is the status of technology development among the relevant enterprises in the field of inertial fusion?
  - What spin-out technologies can be expected as far as is predictable today?
  - In which fields can collaborations between enterprises and universities or research institutions accelerate development?

» **Timeframe**
  - In what timeframe can the above mentioned technological obstacles to the implementation of inertial fusion be overcome?
  - When can we expect an industrial use of inertial fusion (possibly broken down by different approaches)?

» **Recommendations**
  - To what extent does it make sense for Germany to be involved in inertial fusion from a scientific, technological or economic perspective?
  - How should Germany position itself in terms of science/technology to become a major partner in the international development of inertial fusion?
  - What strategic international partnerships should be envisaged, if any?

8.4 Expert Panel

Prof. Dr. Constantin Leon Haefner

- Head of the BMBF Inertial Fusion Energy Expert Panel
- Commissary for Fusion Energy, Fraunhofer Gesellschaft
- Head of Fraunhofer Institute for Laser Technology,
- Ordinarius, Chair for Laser Technology, RWTH Aachen

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- Chief Scientist, Laboratory for Laser Energetics
- RL McCrory Professor, Depts. Mechanical Engineering and Physics, University of Rochester, US

Omar Hurricane, PhD

- Chief scientist of the Inertial Confinement Fusion Program
- Distinguished Member of the Technical Staff, Design Physics (DP) Division
- Lawrence Livermore National Laboratory LLNL

Tammy Ma, PhD

- Program Element Leader for High-Intensity Laser HED Science, Advanced Photon Technologies
- Lead, Inertial Fusion Energy (IFE) Institutional Initiative
- Lawrence Livermore National Laboratory LLNL

Prof. Dr. Robert Stieglitz

- Head Institute for Neutron Physics and Reactor Technology (INR)
- Chair Institute for Applied Thermofluidics (IATF)
- Director Frederic Joliot-Otto Hahn School (CEA-KIT)
- Karlsruher Institute of Technology (KIT)

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Text
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Gestaltung
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Rest: VDI Technologiezentrum GmbH

Bildnachweise
Coverbild:
» Hintergrundgrafik: Tee_Photolive
» Target: LLNL
» Plasma: pixelparticle
» Stromleitungen: peterschreiber.media
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» Laser: Prof. Dr. Constantin Haefner
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