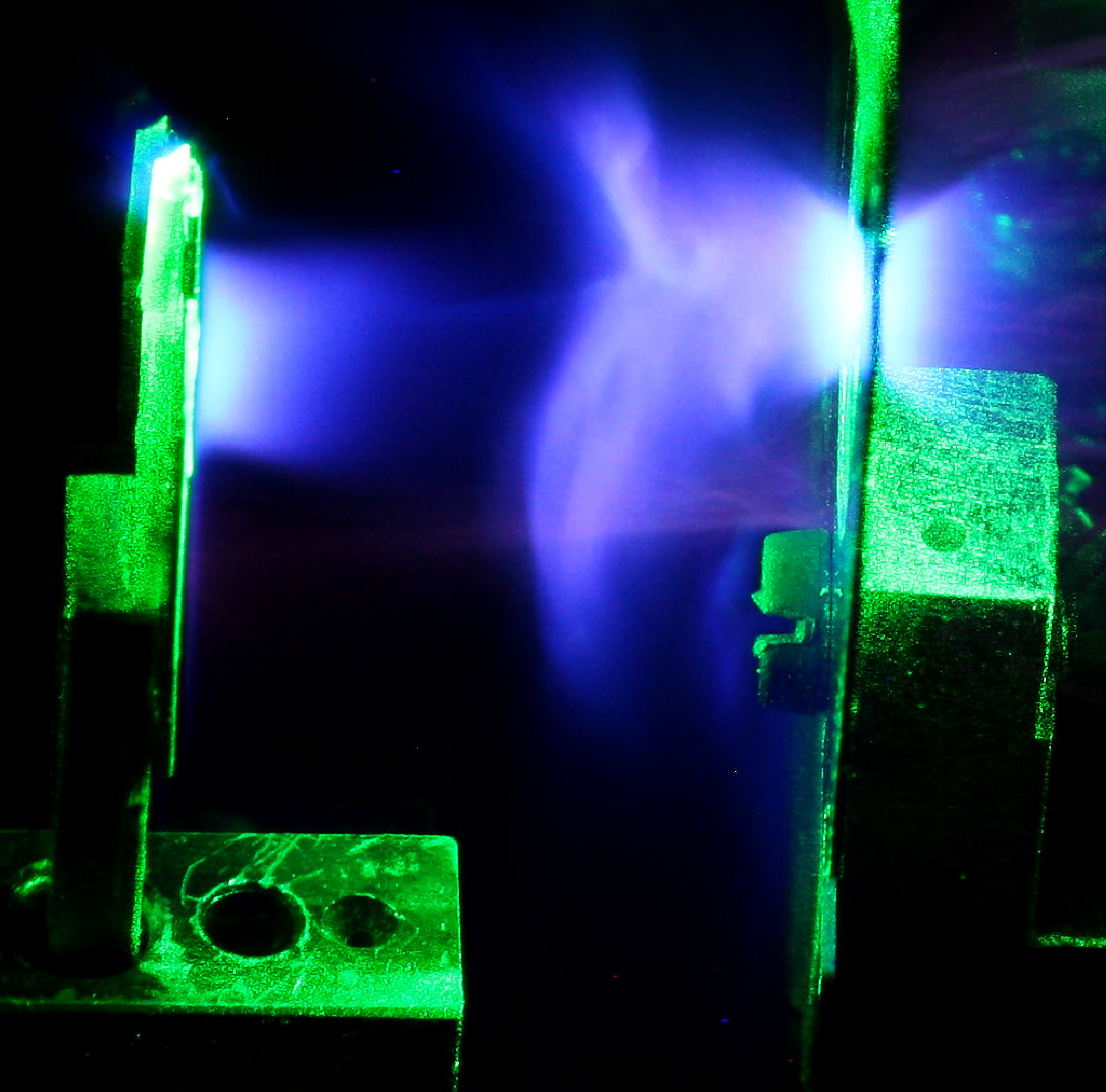
HELMHOLTZ

The Fusion Energy Options

Discussion paper of the Helmholtz Task Force „Laserbasierte Fusionsforschung“



Cover image: Helmholtz's expertise in high-energy lasers has brought insights to the basics of ICF physics: here, calcium ions from GSI's accelerator probe a laser-generated carbon plasma (in the middle) in ICF-relevant conditions (W. Cayzac et al., Nat. Commun. 2017).

Discussion paper of the Helmholtz "AG Laser" – Task Force „Laserbasierte Fusionsforschung"

Authors: W. Leemans (DESY, Chair), V. Bagnoud (GSI), I. Bohnet (HA-HQ), S. Günter (IPP), A. Lambrecht (FZJ), U. Schramm (HZDR), R. Stieglitz (KIT), T. Stöhlker (HI Jena/GSI)

Zusammenfassung (auf Deutsch)

Angesichts aktueller wissenschaftlicher Durchbrüche auf dem Gebiet der laserbasierten Fusionsforschung erfährt das Forschungsgebiet der Trägheitsfusion (Inertial Fusion Energy, IFE bzw. Inertial Confinement Fusion, ICF) auch in Deutschland große Aufmerksamkeit. Die Helmholtz-Gemeinschaft und das Institut für Plasmaphysik (IPP) bilden als strategische Partner einen international bedeutenden Akteur auf dem Gebiet der magnetbasierten Fusionsenergieforschung (Magnetic Fusion Energy, MFE bzw. Magnetic Confinement Fusion, MCF). Der folgende Bericht enthält eine Analyse des Status quo der Fusionsforschung in Deutschland und darüber hinaus, sowie eine Bewertung aktueller Positionspapiere und Memoranden des BMBF und seiner Arbeitsgruppen. Er beleuchtet dabei die Synergien von MFE und IFE, insbesondere im Bereich von Forschung & Entwicklung (FuE) für MCF und ICF, und skizziert mögliche bedeutsame Beiträge, die seitens der Helmholtz-Gemeinschaft zur ICF geleistet werden können, speziell auf dem Gebiet der Höchstleistungslaser. Schließlich spricht der Bericht eine Reihe von Empfehlungen zu möglichen Maßnahmen für FuE in den beiden unterschiedlichen Bereichen der Kernfusion aus, um Deutschland in der Fusionsforschung optimal zu positionieren[1].

Abstract

In view of current scientific breakthroughs in the field of laser-driven fusion research, the research area of ignition fusion energy (IFE) and inertial confinement fusion (ICF), respectively, is also receiving a great deal of attention in Germany. The Helmholtz Association (HA) and the Institute of Plasma Physics (IPP) as strategic partners form internationally a major player in the field of magnet-based fusion energy research (MFE) and magnetic confinement fusion (MCF), respectively. The following report contains an analysis of the status quo of fusion research in Germany and beyond, an assessment of current position papers and memoranda of the BMBF and its task forces, and highlights the synergies of MFE and IFE, in particular of MCF and ICF. Finally, the report outlines possible important contributions of the Helmholtz Association to ICF, in particular corresponding laser activities, and recommends possible additional measures for R&D in the areas of MCF and ICF in order to position Germany optimally in the field of fusion research.

[1] Wie die Zusammenfassung liegt auch die Kurzfassung des Berichts auf Deutsch vor.

Table of Contents

Kurzfassung (auf Deutsch)

Die Kernfusion wird in Deutschland und Europa als bedeutendes Element eines künftigen Portfolios der erneuerbaren Energieversorgung angesehen. Eine darauf basierende alltagstaugliche Kraftwerks-technologie kann voraussichtlich in den nächsten Jahrzehnten zur Verfügung stehen. Angesichts der Erfolge der letzten Jahre sowohl beim magnetischen Plasmaeinschluss (Magnetic Fusion Energy, MFE) wie auch bei der Laserfusion (Inertial Energy Fusion, IFE) wurde und wird weltweit zunehmend in die Fusionsforschung investiert. Entsprechend nimmt auch die öffentliche Wahrnehmung der Fusionsforschung, die auf einzigartige Weise eine Vielzahl von Hochtechnologiefeldern miteinander vereint, zu. Für Deutschland ist die Fusionsforschung sowohl für die Erreichung der Ziele der Energiewende als auch für die Sicherung als Hochtechnologiestandort von herausragender strategischer Bedeutung. Von fusionsbezogenen Technologieentwicklungen profitieren überdies andere wissenschaftliche und technische Bereiche, wie beispielsweise die beschleunigerbasierte Hochenergiephysik, die lasergetriebene Forschung und allgemein die Materialwissenschaften und sonstigen Technologieentwicklungen (darunter fallen unter anderem Hochstromtechnologien, Magnet- & Laser-Systeme und ihre Fernsteuerung, Diagnostiken, Werkstoffe sowie die Technikentwicklungen für nachhaltige Energielösungen zu Speichertechnologien). Für die Ausbildung und Vernetzung der dafür benötigten Akteure aus Industrie und Forschung und die Bereitstellung der entsprechenden Infrastrukturen ist eine umfängliche Förderung auf mehreren Ebenen erforderlich. Beginnend mit einer gezielten Förderung der Fusionsforschung an den Universitäten, die flankiert werden sollte durch große international sichtbare Leuchtturmprojekte, um volle Wirkung entfalten zu können.

In den letzten zehn Jahren wurde in der auf magnetischen Plasmaeinschluss basierenden Fusionsforschung (MFE) ein konkreter Fahrplan zur Realisierung eines Fusionskraftwerks entwickelt. Die MFE baut erfolgreich auf frühen physikalischen Demonstrationsexperimenten auf. Dabei konnten bedeutende wissenschaftliche Durchbrüche in der MFE erzielt werden, die eine verstärkte Investition in das erste kraftwerksrelevante Prototypsystem rechtfertigen, siehe dazu den Bericht „Auf dem Weg zum (deutschen) Fusionskraftwerk"[2]. Die darin dargelegten Forschungsthemen entsprechen denen des aktuell vom BMBF vorgestellten Positionspapiers zur Fusionsforschung[3]. Die erforderlichen Mittel auf dem Weg zu einem deutschen Stellarator-Kraftwerk liegen bei etwa 1 Mrd. € pro Jahr. Die Alternative, nämlich ein Engagement entlang der EUROfusion-Roadmap mit dem Ziel der Entwicklung eines Tokamak-Kraftwerks in Deutschland, würde die Investition in eine solche Anlage und damit ein entsprechend verstärktes Technologieprogramm erfordern.

Die lasergestützte IFE hat kürzlich erstmals die Zündung (Ignition) einer indirekt angetriebenen Trägheitsfusion demonstriert: In mindestens zwei separaten Versuchen am Lawrence Livermore National Laboratory (LLNL, USA) wurden hochenergetische Laserpulse (Multi-MJ) auf einen Hohlraum geschossen, die darin ein kleines schwebendes Kügelchen (Pellet) durch Umwandlung in Röntgenstrahlung zur Zündung gebracht haben. Obwohl dabei mehr Energie erzeugt als dem Pellet an Laserenergie zugeführt wurde, musste in die Laser-Anlage das Hundertfache an Energie gesteckt werden. Zudem handelte es sich bloß um jeweils einen Schuss am Tag, verglichen mit den erforderlichen Millionen von Schüssen pro Tag, wie sie ein Fusionskraftwerk vorhalten müsste. Damit liegt die lasergestützte Fusionsforschung auf ihrem Weg hin zu einem Kraftwerk deutlich hinter den Plänen der magnetbasierten zurück. Überdies müssen vor der eigentlichen Entwicklung eines kraftwerksreifen Konzepts erst noch wesentliche Zwischenziele verfolgt und erreicht werden, darunter die Leistungssteigerung wichtiger Teilsysteme um viele Größenordnungen, insbesondere bei der Wiederholrate und der Effizienz der Laser-Systeme, aber auch bei der Optimierung der Zielkonfigurationen der IFE. Daher muss der nächste Schritt zunächst darin bestehen, einen wissenschaftlich fundierten Konsens in der Fusionsforschung zu erarbeiten, wie der beste Weg für die

[2] Sibylle Günter (IPP): "Der Weg zu einem (deutschen) Fusionskraftwerk - erste Überlegungen aus wissenschaftlicher Perspektive", inkl. Eingaben des KIT, Februar 2023.
[3] BMBF (Referat 714): "Positionspapier Fusionsforschung: Auf dem Weg zur Energieversorgung von morgen", Juni 2023.

IFE in die Zukunft aussehen kann. Dies bedeutet auf jeden Fall ein langfristiges Engagement in der Grundlagenforschung der IFE mit entsprechenden zugrundeliegenden Technologieentwicklungen, was in der Helmholtz-Gemeinschaft am besten im Forschungsbereich Materie verortet und durchgeführt werden kann.

Einen wirksamen Beitrag zur Laserfusion kann der Forschungsbereich Materie zum Beispiel durch Aktivitäten zur Physik der hohen Energiedichte (High Energy Density Physics, HEDP) leisten, was dem grundlegenden Verständnis von Materie unter extremen Bedingungen dient und es erweitert. Auch die Physik der Laser-Plasma-Wechselwirkung, ein zentrales Thema in der Helmholtz-Gemeinschaft bei der Entwicklung kompakter plasmabasierter Beschleuniger, findet konkret Anwendungen bei der laserbasierten Fusionsforschung und der Zündung in Fusionsplasmen. Darüber hinaus können Kernkompetenzen der Helmholtz-Gemeinschaft im Bereich des multiskalierten Hochleistungsrechnens sowie der auf künstlicher Intelligenz basierenden Modellierungswerkzeuge (Maschine Learning) für die Plasmaphysik genutzt werden. Das trifft auch auf ein breites Spektrum der Materialforschung zu, die direkt an Aktivitäten zur Entwicklung von Konzepten der laserbasierten Fusionsforschung anknüpft.

Um die globale Wettbewerbsfähigkeit im Bereich der laserbasierten Fusion in Deutschland zu sichern, sind allerdings zusätzliche Ressourcen über die Programmorientierte Förderung der Helmholtz-Gemeinschaft (PoF) hinaus erforderlich. Diese sind unter anderem verbunden mit Investitionen in entsprechende Forschungsinfrastrukturen (z. B. Aufbau eines Lasers der sogenannten Multi-kJ-Klasse am European XFEL oder Aufrüstung des PHELIX-Lasers auf 2 bis 3 kJ sowie Kurzpuls-PW-Laser- zu Multi-PW-Laser-Anlagen usw.). Aber auch die Schaffung von Exzellenzzentren bzw. sogenannter Hubs im Bereich der Hochenergiedichteforschung ist erforderlich (ähnlich der vor kurzem vorgeschlagenen Gründung eines „Helmholtz-Institute High-Energy Density“, kurz HIHED an der Universität Rostock). Solche Zentren, Institute bzw. Hubs wären für die Weiterentwicklung der Wissenschaft im Bereich der Erforschung der Hohen Energiedichte in Deutschland von entscheidender Bedeutung, weil sie eine koordinierende Rolle bei der Beantwortung grundlegender Fragen zur laserbasierten Fusionsforschung spielen würden. Darüber hinaus basiert die angesprochene Institutsgründung in Rostock auf Kernkompetenzen im Bereich der modernen Laser- und Optiktechnologien, die sich auf umfangreiche Forschungsaktivitäten stützen. Hochleistungslaser sind in der Tat ein wesentliches Element bei der Entwicklung von Laser-Plasma-Beschleunigern, die erforderliche Leistung dieser Systeme muss allerdings erheblich verbessert werden, um die strategischen Zielmarken der Helmholtz-Gemeinschaft zu erreichen. Für die kurz-, mittel- und langfristige Entwicklung der Laserfusion wären entsprechend größere Investitionen in den Bereichen Laser und Photonik vorteilhaft. Diese Technologiebereiche sollten deshalb durch die Einrichtung von speziellen Förderkorridoren gestärkt werden, zusätzlich unterstützt durch gemeinsame Partnerschaften mit der Fraunhofer-Gesellschaft (FHG) und der Industrie, um die international unbestrittene Kompetenz der Helmholtz-Gemeinschaft in der Systemtechnik und beim Entwurf, Bau und Betrieb von Großanlagen bestmöglich zu nutzen.

Um sicherzustellen, dass der wissenschaftlich-technische Nachwuchs in diesem aufstrebenden Forschungsfeld auch in Zukunft zur Verfügung steht, sind überdies Investitionen in die Aus- und Weiterbildung erforderlich, und zwar durch den (Wieder-)Aufbau und Stärkung eines Lehrplans für Plasmaphysik und die Technologiebereiche, die den plasmagestützten Systemen zugrunde liegen. Diese sollten Synergien von IFE und MFE in Deutschland und Europa bestmöglich nutzen (z. B. durch Schaffung von thematisch ausgerichteten Nachwuchsgruppen und gemeinsamen Berufungen der außeruniversitären Einrichtungen mit den Universitäten, durch Einrichtung von Graduiertenschulen und Förderung der internationalen Zusammenarbeit).

Executive summary

Fusion is seen as an important element of the portfolio of a renewable energy supply in Germany/Europe with predicted availability of the technology in the next couple of decades. Building on the recent successes in both magnetic and inertial confinement-based plasma fusion in energy research (MFE and IFE, respectively), worldwide investments in fusion have increased dramatically in the past couple years and will continue to do so into the foreseeable future. Public visibility is growing. Fusion research uniquely combines a wide range of high-technology fields that are strategically important for achieving the goals of the energy transition as well as securing Germany as a high-tech location of the future. Fusion related technology developments benefit other fields such as accelerator based high-energy physics, laser-driven sciences and the general area of material sciences and engineering (e.g., high-current technologies, magnets, lasers, remote handling, diagnostics, materials, as well as engineering for sustainable energy solutions (e.g., storage technologies)). Therefore, funding on several levels, starting with an expansion of funding at universities, supplemented by targeted funding of large internationally visible lighthouse projects, which are outlined here, are required to provide the human resources and infrastructures of the future, and to interlink industry and research at an early stage.

During the past decade, building on early physics demonstrator experiments, MFE has developed a roadmap towards the development of a power plant and has reached significant breakthroughs that justify a continued and increased level of investment towards the first prototype power plant relevant system, as described in the paper “On the way to a (German) fusion power plant”[4]. The research topics match those outlined in the BMBF Positionspapier[5]. The resources required to proceed on the way to a German stellarator power plant are about €1 billion p.a. The alternative way to increase the engagement in the EUROfusion roadmap towards a tokamak power plant would require an investment for a new tokamak facility in Germany and an increased technology program.

Laser based IFE has recently demonstrated ignition of an indirectly driven implosion. In at least two separate experimental shots at LLNL (USA), high-energy (multi-MJ) laser pulses were directed at a Hohlraum and, through conversion into X-rays, drove a small pellet suspended in this Hohlraum to ignition. Although more energy was generated during the ignition compared to the supplied laser energy, more than 100 times larger energy was supplied to power the laser, and only a shot per day was achieved compared to the required millions of shots a day in a proposed power plant. As such, IFE is significantly behind MFE on the way to a power plant. Prior to the development of power plant ready concept, many basic science and technology steps still have to be demonstrated, including orders of magnitude increase in performance of several key subsystems, notably the repetition rate and efficiency of the laser, and optimized target configurations. Hence, obtaining a science-based consensus in the community on the best path forward is the next mandatory step, and will require a long-term commitment to advancing both the basic science and the underpinning technology that can best be served in the frame of the research field matter in the Helmholtz Association (HA) as follows.

Helmholtz can contribute effectively to the pursuit of laser fusion through continuing and expanding research areas that include, e.g., high energy density physics (HEDP) to understand matter under extreme conditions. Similarly, laser-plasma interaction physics, a central topic to the HA’s development of compact plasma-based accelerators, finds applications for the fast ignitor concept to fusion plasmas. In addition, HA’s core competencies in multiscale high-performance computing and artificial intelligence (machine learning) based modeling tools for plasma physics and in a broad range of other applications, such as fundamental materials research can be applied to ICF concept developments.

To ensure the global competitiveness in the area of laser-based fusion, additional funds from outside Helmholtz are required to invest into infrastructure (e.g., collocation of a multi-kJ class laser with the

[4] Sibylle Günter (IPP): „Der Weg zu einem (deutschen) Fusionskraftwerk – erste Überlegungen aus wissenschaftlicher Perspektive“, incl. input of KIT, February 2023.

[5] BMBF (Referat 714): „Positionspapier Fusionsforschung: Auf dem Weg zur Energieversorgung von morgen“, June 2023.

European XFEL, upgrading the PHELIX laser towards 2-3 kJ, and short pulse PW lasers to multi-PW) as well as the creation of one or more centers of Excellence/Hubs in high energy density science (e.g., similar to the previously proposed foundation of Helmholtz Institute at the university of Rostock). Such hubs would be instrumental for advancing high energy density science in Germany, and play a coordinating role towards addressing the back questions in ICF. In addition, Helmholtz has core competencies in advanced laser and optical technology as well as substantial research activities that rely on laser and optical technologies. High power lasers are indeed an essential element of the development of, e.g., laser-plasma based accelerators and the required performance of these systems must be improved to meet the strategic goals for Helmholtz. As such, increasing the investment into frontiers of lasers and photonics will both be beneficial to the Helmholtz mission in the short to medium term, and the pursuit of laser fusion in the long term. These technology areas should be further strengthened through the launch of funding corridors, supported in addition by joint partnerships with Fraunhofer (FHG) and industry, leveraging the world-renowned Helmholtz expertise in systems engineering and design/construction of large-scale facilities.

To ensure that the next generation of scientists, engineers and technicians is available, investments are needed in education and training, through the (re)building or strengthening of a curriculum in plasma physics and the technology areas that underpin plasma-based systems, synergistic with MFE, in Germany and Europe (e.g., creation of topically dedicated YIGs, joint appointments with universities, graduate schools, and by fostering international cooperation).

Section 1: Charge, committee membership, listing of input material, process summary

In response to the publication of the “Memorandum on Laser Inertial Fusion Energy” from the BMBF commissioned BMBF-“Expertenkommission zur laserbasierten Trägheitsfusion”, published late May 2023, Helmut Dosch as coordinator of the Helmholtz research field “matter” and the Executive Board of the Helmholtz Association, created a Helmholtz Working Group “Laser" to develop a draft of a position paper for the Helmholtz Association.

The Working Group’s membership included Wim Leemans (Chair, DESY), Vincent Bagnoud (GSI), Sibylle Günter (IPP), Astrid Lambrecht (FZJ), Ulrich Schramm (HZDR), Robert Stieglitz (KIT), Thomas Stöhlker (HI Jena/GSI), with support from Ilja Bohnet (HA-HQ) and observer Jolie Egbert (HA-HQ), as well as Sylvia Sibilak (HA-HQ) for administrative support.

The terms of reference to the “AG Laser”, presented by President Otmar Wiestler of the Helmholtz Association, on July 7, 2023, is as follows:

- Position Helmholtz as a major player in fusion research with a focus on magnetic fusion. Explore the option of a stellarator-based fusion power prototype.
- Summarize laser expertise at Helmholtz (DESY, HZDR, GSI, HI-Jena, FZJ, KIT, IPP and others) in terms of laser-based plasma acceleration, laser-based fusion and other application fields.
- Identify meaningful activities in particular in the area of laser R&D for collaboration with partners of FHG and industry in the field of inertial confinement fusion,
- Strengthen synergies with ongoing programs in the science areas of magnetic based fusion and plasma research.
- Write a draft of a position paper of the HA for the fall meeting of the General Assembly in September, which responds adequately to the requests of BMBF, with an outlook to PoF V.

The material on which our report is based, includes the “Memorandum on Laser Inertial Fusion Energy” (authored by Constantin Haefner (Head), Neil Alexander, Riccardo Betti, Omar Hurricane, Tammy Ma, Robert Stieglitz and Hartmut Zohm) from late May 2023, and the BMBF “Positionspapier Fusionsforschung”[5] from June 2023, as well as the “AG Laser” members expertise and know-how.

The “AG Laser” met on three separate occasions: the first (virtual) meeting (June 23, 2023) was focused on getting a process organized, the second (virtual) meeting (July 7, 2023) on discussing the charge with President Wiestler and an exchange with C. Haefner, lead author of the Memorandum, and the third (in-person) meeting (September 11-12, 2023) on finalizing our process culminating in the report writing.

The key charge elements are addressed next, starting in Section 2 with an assessment of magnetic fusion, followed by a discussion of capabilities and interests at the various relevant Helmholtz centers in Section 3. In Section 4, the research areas described in the BMBF Positionspapier are mapped on to current and future activities. In Section 5, a summary is presented of research topics in the context of fusion relevant to the mission of the Helmholtz Association.

Fusion power plants have the potential, in combination with renewable energies, to make a significant contribution to the energy supply. Interest in fusion has grown enormously, thanks to a number of recent successes (World fusion energy record in JET Deuterium-Tritium discharges, ignition reached in the National Ignition Facility, long-pulse operation in the W7-X stellarator, etc.) and the growing need for electricity. Private industries and investors are now part of the fusion effort and succeed in acquiring substantial funds.

Section 2: Assessment of magnetic fusion

Research in the field of magnetic fusion has advanced to the point where the design of a fusion power plant could begin in the near future. An international peer reviewed pre-conceptional design for a European tokamak demonstration power plant has been published recently with significant German contributions. In the physics and technology developments of optimized stellarators, Germany is even the world leader.

In view of the great success in the German magnetic fusion research, the Helmholtz fusion energy program in the research field “energy” will remain concentrated on magnetic fusion, supporting both lines of developments, the stellarator line with Germany’s unique expertise and the Wendelstein 7-X facility, as well as the tokamak line within the European coordinated approach.

The fastest way to a magnetic fusion power plant will take about 20-25 years if pursued consistently and should definitely be done with leading industry participation from the beginning. Significant investment in research, education, and technology development would be required in parallel with the design phase and construction of the power plant.

Germany should take the leading role in the realization of a fusion power plant and should chose the path to a stellarator power plant. With Wendelstein 7-X and the know-how developed during the construction and operation of this plant, Germany is the world leader in the field of stellarator research. The construction of such a power plant and the necessary research and development would require an investment of about €20 billion. In parallel with the design of the power plant, it is necessary to complete the stellarator concept and verify it with an appropriate pilot plant. At the same time, personnel in fusion physics and technology would need to be increased by a factor of about 2, and infrastructures for development, characterization, qualification, and ultimately certification of the materials, components, and technologies would need to be established and operated.

Although the stellarator is fundamentally the better concept (although not as well developed), an alternative path would be to provide greater support for the tokamak power plant path favored by the EU to date. Recently, the European roadmap to a tokamak power plant has been revised to move more quickly to a fusion power plant. The design and construction of a power plant should be started in parallel with the construction of ITER. In order to play an important role in this development and to build up appropriate know-how for the subsequent construction of fusion power plants in Germany, necessary investments and a strengthening of the German fusion program are required, in particular about €1 billion for a new tokamak experiment and about €200 million for the German contribution to the European research infrastructure IFMIF-Dones and the construction and operation of infrastructures for the development and characterization of the materials and technologies, as well as an increase in personnel by at least 20 %.

Although the physics part of a magnetic fusion power plant is significantly different from a laser fusion power plant, there are significant synergies between them in the area of technology, e.g., structural and functional materials, fuel cycle and processing, radiation hard instrumentation and power extraction technologies, where Helmholtz is in a worldwide leading position, although laser fusion has been up to now not in the focus of Helmholtz. Nuclear qualification of all technologies will also be an essential element, including radiation hard instrumentation as well as validation of functional materials such as breeding materials, neutron multipliers, or even low activated shielding materials. Furthermore, synergies exist, in particular in education and training. These synergies should be used to broaden the reach of plasma physics and related technologies research in Germany.

The efforts focused on magnetic fusion should be accompanied by a significant fundamental science-based program within the Helmholtz research field “matter”, concentrating on core physics questions that are relevant for laser fusion. Answering key conceptual and fundamental questions is a necessary pre-requisite to inform and guide future IFE power plant designs. This is discussed in the next section.

Section 3: Capabilities and interests at Helmholtz centers relevant to laser-driven fusion

Laser-driven fusion has achieved a major milestone in December 2022 where ignition was observed from an indirectly driven capsule in a Hohlraum resulting in 3 MJ energy output, using 2 MJ incoupled laser energy. A repeat of this success was recently announced. These amazing results provide renewed hope for a future fusion power plant based on the laser driven inertial confinement. However, many challenges remain that will require a systematic, multi-decadal commitment/investment to solving them, with both a fundamental science and a technology development component. For instance, the amount of energy needed to power the laser system was of the order of 300 MJ (excluding the energy required to power the facility), i.e., 100x more than was extracted. Net production of energy would require at least an order of magnitude higher output, mandating a 1000x improvement in system efficiency. Furthermore, whereas it is possible to fire, with today’s laser driver technology, one to maximum a couple shots per day, a future power plant would require 10-20 shots per second, i.e., roughly a million times more than currently possible. While laser technology has made tremendous progress for the last 30 years after NIF froze its laser design, the development of wall-plug-efficient high-energy high-average-power lasers still requires major investments in R&D. In addition, cryogenic targets would have to be produced and fired at, with an equally large scaling increase. Given the required precision of these targets, and especially the complexity in case Hohlraum based indirect drive targets, this is also highly challenging.

As a first step to address these formidable challenges, direct and indirect drive[6] approaches must be assessed through basic science experiments. Within the context of the German society and the challenges linked to the dual use thematic associated with indirect drive (including unavailability of classified data), direct drive would be the research area where the most significant contributions can be made in Germany. Actual research topics include, e.g., the understanding of laser plasma instabilities during the implosion, and the mitigation strategies that may be possible with advanced broadband laser technology. Similarly, laser beam smoothing techniques, essential to control the onset of hydrodynamical instabilities, must be reviewed and re-assessed in view of the most current possibilities offered by laser technology. In addition, material equation of states for conditions relevant to the

[6] Direct drive refers to laser beams being fired directly on a fuel pellet. In indirect drive laser beams are fired into a Hohlraum that converts the laser radiation in X-ray radiation that then in-turn irradiates a fuel pellet. Whereas indirect drive has succeeded in ignition, the intrinsic efficiency is lower than for direct drive as it is a two-step process. Direct drive has thus far not achieved ignition.

imploding plasma must be harvested in order to support the numerical code development necessary on the road to IFE. Finally, the fast ignitor concept that deals with the generation of an auxiliary particle beam must be investigated further. This topic finds a naturally large synergetic resonance in the HA, where particle acceleration in plasma is part of the Helmholtz portfolio, in particular within the Helmholtz program “matter and technologies” and its topic “accelerator research & development”.

Equally important will be the exploration and development of fundamentally different approaches to laser and target technology, where the output of the science experiments will guide the laser developers by providing requirements for those systems. Beside a broad experimental research program, essential will be the development of reliable, open-source tools for modeling and prediction of the laser-plasma interaction physics, aided by AI and HPC methods. Last but not least, a next generation of graduate students, postdocs and researchers needs to be trained in these exciting scientific and technological areas.

Despite the progress made in inertial confinement fusion (ICF) a closed power plant concept is still absent worldwide, i.e., blanket technologies, fuel cycle, heat extraction and tailored neutron and radiation resistant materials able to sustain ICF conditions are in their infancies. Here, the research centers of the HA have established considerable competencies and erected infrastructures in magnetic fusion research which can be transferred to ICF through international collaborations but could also serve to a seed of a future own German ICF power plant in the context of an IFE program. Profiting from the current know-how and human resource HA centers can maintain if not even expand their international position.

We next discuss how the HA is positioned to contribute to solving these challenges through an assessment of current capabilities and interests, and how it will benefit from the developments to advance the science mission of the HA.

Experimental capabilities at Helmholtz for ICF research

During the last decade, at various Helmholtz centers (HZDR, GSI, HI-Jena, DESY) as well as at European XFEL (where Germany is a 56% partner), prominent research infrastructures and facilities in the realm of relativistic and high-energy density plasmas have been developed and are now in routine operation. This unique portfolio of leading facilities has enabled excellent research opportunities for plasma and fusion relevant research and at the same time provides matching education and training grounds for the next generation of scientist.

Ultrashort-pulse lasers in the 100 Terawatt to Petawatt range have matured significantly over the last decade and today represent the workhorse for advanced accelerator research and respective applications. Moderate pulse energies in the few 10-J range at pulse durations of only 30 fs enable a wide range of applications at various HA centers with repetition rates of up to 10 Hz. The JETI200 laser (200 TW, HI-Jena), the dual beam DRACO-PW (200TW / PW, HZDR), ANGUS (200 TW, DESY), RELAX (400TW combined with European XFEL, HIBEF), and KALDERA (100 TW, working at kHz repetition rates, DESY) are internationally leading German representatives of this class of lasers, dominantly operated by the HA in Germany (exceptions are CALA at LMU and PHASER at the university of Hamburg). Aside of its peak power level, the laser beam quality proved to be essential for stable and controlled performance of laser-matter interaction studies. For this reason, HA centers invested significant efforts into both beam quality and real time diagnostics development over the last decade. These efforts have been rewarded by outstanding secondary beam performance: DESY pioneered machine-learning-assisted 24 hour performance of stable electron acceleration, while HZDR achieved record proton energies of 150 MeV protons as well as the first dose controlled in-vivo radiobiology study. Similarly, the first laser-accelerator-based FEL light was recently observed, raising hope for a dedicated pump-probe facility tailored to early-stage hydrogen compression physics. With the combination of ultra-intense laser light and European XFEL probes, recently established at HIBEF, first direct real-time observation of dynamics in hydro-dynamical plasma instability became possible opening unprecedented opportunities for HED plasma and fusion plasma research.

Helmholtz operates high-energy laser experimental facilities, like PHELIX at GSI or DIPOLE at HIBEF, that are relevant to nanosecond ICF driver studies. For example, seminal experiments to benchmark and correct alpha-heating models of ion-stopping power in plasma were done at GSI, using the unique combination of an ion-beam as probe and high-energy laser pulse as driver.

PHELIX (GSI), operating as a user facility, excels in this domain, yet only at a few pulses per hour. This significant limitation is circumvented by applying direct diode laser pumping of high energy short-pulse lasers (diode pumped solid state laser - DPSSL), as demonstrated with the ns-laser DIPOLE at HIBEF. For short laser pulses the technology pioneered at HI-Jena with POLARIS and within ATHENA at HZDR with PENELOPE, aiming for full PW operation at Hz level repetition rate. Such systems represent ideal candidates for the investigation of fast ignitor dynamics and will become operational in the next years.

Energy-efficient diode pumping of laser gain media is understood as key for any IFC driver laser concept. Prototype development of such systems provides benefits to the performance of ultra-short laser systems used in nearer term applications such as used in advanced accelerator research. Such systems, with application driven performance specifications, provide an ideal and currently unique testing ground for IFE optimized DPSSL amplifier concepts, jointly with industry.

To guide and complement experimental programs and facilities, Helmholtz entertains strong theory and computational physics groups. DESY, HI Jena, GSI, HZDR und Jülich have high intensity simulation groups using HPC powered, multi-parallel particle-in-cell codes on an internationally leading level (e.g. PIConGPU, HIPACE++), which have relevance to the plasma physics and HED. Hydrocodes, and in particular inherently multi-scale capable codes are being developed, and can be expanded to meet the requirements of ICF research. The available expertise can form the basis of a national and/or European effort to develop a dedicated fusion simulation suite.

By now HA centers (IPP, FZJ and KIT) host numerous infrastructures qualifying high heat flux materials mainly focusing on transient magnetic confinement plasma phenomena, prominent examples are Gladys, Heloka, etc.. ICF poses here additional challenges in terms of heat and particle loads on the plasma facing components, so called in-vessel components (IVC). In a first step, these facilities can be upgraded to execute preliminary tests in collaboration with the material research institutions already in place at universities, Fraunhofer and the Helmholtz centers. However, mastering ICF challenges will require new installations coping with the requirements to be formulated by a power plant design team to provide technical solutions for functional and structural materials to design breeding and power extraction components for a fusion power plant.

On the way to a ICF-based fusion power plant, on the long term, a reactor plant layout would need to be developed as is already being pursued in the MCF community.

Interest of Helmholtz in fusion research (ICF and MCF): Training and education

One of the challenges on the road to fusion power is to establish a sustainable ecosystem that has access to a qualified workforce. A coherent curriculum in fusion is absent in Germany both for MCF and ICF. Germany has a number of master programs that cover MCF or ICF relevant topics, such as plasma science, advanced plasma accelerators, materials, fusion technology, laser fundamentals and high power lasers. These programs are coupled to large RIs in Munich, Hamburg, Karlsruhe, Jena, Düsseldorf, Dresden and Darmstadt, where Helmholtz operates its facilities. Here, Helmholtz plays a significant additional federating role with its topical graduate schools, which offer additional training via summer schools, online seminars, soft skill development and mobility.

Bringing MCF and ICF research in Germany to the next level requires strengthening the effort in training and education. This should be done by developing the existing capabilities of the German universities through new faculty positions on fusion research and related themes, to which the HA could contribute by having joint appointments for the training of students and postdoctoral staff.

Frontiers of Laser Technology

Optical science and technology have become increasingly prevalent at the research centers of the HA, pushing the boundaries of our large-scale facilities and enabling significant advances in cutting-edge research in various research fields (matter, health, energy, information, transport). Of particular note, here are advances in laser technology and the development of high-energy, high-intensity and ultrafast laser systems operated at high repetition rate. Together with advances in optical components and materials, novel classes of research are enabled with applications in imaging and microscopy, ultra-wideband signal processing and photonic quantum technologies. At the Helmholtz Centers, however, this multitude of activities is currently spread across different research areas and topics, and a future overarching structure for optical sciences and technologies could further strengthen these challenging and disruptive developments. This should be considered for the next program period (PoF V). Such a structure, moreover, would substantially simplify the creation of additional synergies and progress through teaming up with leading partners at universities, non-university research institutions (Fraunhofer and Leibniz) and industry. In the context of ICF technology development, this structure would adequately federate all activities foreseen on ICF research within Helmholtz.

Section 4: BMBF Positionspapier recommendations & assessment of BMBF Memorandum

The summary of BMBF position recommendations can be divided into three categories: MFE, IFE and general, and are listed in the following three subsections, including a description of how current and future activities map to the recommendations.

BMBF Positionspapier -- Research topics (RT) relevant to MFE:

1. Research on Wendelstein 7-X as a model facility for the plasma physics and operational framework conditions of a stellarator-type fusion power plant.
2. Research on ASDEX Upgrade as a model facility for the tokamak type; here, above all, clarification of questions of plasma physics for the construction of ITER
3. High-field magnetic coils, possibly using high-temperature superconductors
4. Plasma-wall interaction and materials research for the first wall
5. Neutron resistant and low activation structural and functional materials for in-vessel components (blanket, diverters and limiters)
6. Fuel cycle (exhaust clean-up, tritium processing, storage and injection into reaction chamber) including concepts for tritium breeder blankets
7. Power extraction and balance of plant in conjunction with safety.
8. Fast and high-precision, radiation hard diagnostic systems for the operation of magnetic fusion plants. These include magnetic diagnostics, bolometric systems for plasma measurement, microwave diagnostics, interferometry and spectroscopy instrumentation for characterization of plasma core and edge regions, and infrared imaging systems.
9. Better understanding of fundamental plasma physics, also through improved simulation tools, in perspective possibly quantum computing, new simulation codes
10. Development of radiation resistant, robust remote handling systems for critical parts of a power plant, also for the complex geometry of stellarators.

Germany plays a leading role in the worldwide magnetic fusion research area, and covers all the crucial physics and technical areas mentioned in the position paper by the BMBF within the following three labs:

- The Max Planck Institute for Plasma Physics (IPP) operates two large-scale experiments: the ASDEX Upgrade tokamak at the Garching site near Munich and Wendelstein 7-X - the world's

largest stellarator-type fusion facility - at the Greifswald site. It thus covers the RTs 1, 2, 4, 5, 7, and 8.
- The Karlsruhe Institute of Technology (KIT)) focuses on fusion technology, fuel cycle (operation of a civil tritium laboratory), breeding blanket, safety and materials research and qualification, and covers the RTs 3, 5, 6, 9.
- The Forschungszentrum Jülich (FZJ) works on topics concerning plasma-wall interaction as well as material qualification under fusion-relevant conditions, and covers the RTs 1, 4, 7, 8.

Some of this work such as the development of neutron resistant materials and their qualification (jointly dealt with at FZJ and KIT) are cornerstones also relevant to ICF.

German fusion research is closely embedded in the activities coordinated at the European level and funded through EURATOM. The basis of this work is a long-term European roadmap on the way to a fusion power plant. The roadmap has recently been amended to accelerate the way to a magnetic fusion power plant in spite of the delay of ITER by parallelizing the research efforts and to take advantage of the increasing efforts by start-ups and industry.

BMBF Positionspapier -- Research topics (RT) relevant to IFE:

1. High-energy lasers (concepts and materials: cooling, decoupling, efficiency, diode-pumped solid-state sources, high bandwidth for "direct drive" investigations).
2. Target concepts (manufacturing, handling, cryogenics, and codes for target physics).
3. Optical components (large apertures, amplifier materials, glasses, coatings, electro-optical materials).
4. UV and radiation resistant components.
5. Diagnostics adapted to the needs of IFE, including radiation-resistant systems and refined diagnostics for validation of codes and models (e.g., target compression).
6. Neutron resistant functional and structural materials for in-vessel components (first wall, blanket) including fuel cycle technologies (exhaust cleaning, fuel processing, detritiation ...) with associated material characterization and material data.
7. Analysis of the advantages and disadvantages of direct and indirect drive.
8. Overall reactor concepts ("system codes", in close exchange with international partners with simultaneous development of common standards).

At many Helmholtz centers, lasers and laser development play an essential role in both the operations of the large-scale infrastructure and the science that is pursued. For example, high power lasers are drivers for new generations of particle accelerators (both electrons and ions) that are based on the use of plasma. Such accelerators require laser performances that are significantly less demanding than is needed for future laser-driven fusion power plants. Nevertheless, they need to operate at power levels that are several orders of magnitude beyond current state-of-the-art, and operate continuously (24/7) with high availability. In addition, to ensure sustainability, they must be power efficient requiring DPSSL based systems, similar to fusion drive lasers, and the cost of the systems should be reduced an order of magnitude. Hence, investments into technology that enables fusion relevant lasers (RT 1, 3 and 4) will be of great benefit to the development of lasers needed for accelerators.

The physics of such laser-driven accelerators is directly relevant to understanding laser-plasma hydro-dynamical instabilities and their mitigation, an area of research that is crucial to direct drive (RT 7). Regarding the IFE RTs 6 and 8, some synergies with magnetic fusion research can be exploited with the HA. Materials research, including blanket development with fusion relevant neutron irradiation (RT 6), is relevant for both approaches. The short high-energy pulses, however, represent specific challenges in case of ICF. Nevertheless, KIT and FZJ have some expertise to also deal with such research problems. In addition, KIT operates worldwide the only civil Tritium laboratory accessible to fusion research partners, relevant for MCF and IFE. Reactor concepts and associated systems codes (RT 8) do exist already for tokamaks. They need to be refined for the design of a power plant (IPP and KIT). For stellarators a first, still relatively premature version exists, needing further dedicated efforts (IPP and KIT). For IFE, no serious effort has been made so far for a corresponding system code.

Although some general experience from magnetic fusion research will be beneficial to support such an activity, dedicated efforts are required to proceed towards an IFE system code.

BMBF Positionspapier – General comments

The position paper highlights the importance of training the next generation work force, partnering with industry to enable innovation and technology transfer, building trust for plasma fusion within the general public, and the importance of international cooperation (most notably EuroFUSION and bilateral agreements with France, UK, USA in the area of laser-driven fusion). The important aforementioned topics are all incorporated in the recommendations made in this report for the positioning of the Helmholtz Association.

Section 5: Summary of recommendations

The following key findings and recommendations are the result of an analysis of the status quo in fusion, the Memorandum and BMBF Position paper, as well as the expertise and know-how of the “AG Laser” members.

Germany is a world leader in MFE and increased investments are needed towards the development of a fusion power plant, to both secure Germany’s role and advance this technology with urgency. This includes the pursuit of stellarator technology and participation in the international tokamak projects.

For MFE, the resources required to proceed on the way to a German stellarator power plant are about €1 billion p.a. The alternative way to increase the engagement in the EUROfusion roadmap towards a tokamak power plant would require an investment for a new tokamak facility in Germany and an increased technology program.

Given the current state of progress and maturity of ICF, new investments leveraging the HA core competencies in the following topics are urgently needed to support and to guide the strategic investments made by the German industry, which competes to establish Germany as a IFE leader worldwide. The research topics are:

- Laser-plasma interaction physics including the development of multiscale HPC based modeling tools, benchmarked against experimental results, and deployment of AI methods to expedite discovery.
- Material research including shock driven HED science experiments, as well as reactor wall relevant R&D, synergistic with MFE
- Technology areas such as laser and optical technology (joint with Fraunhofer and a broad range of industry)
- Assessment of system engineering and design of large-scale facilities

To ensure the global competitiveness in the area of laser based fusion, additional funds from outside Helmholtz are required in the following specific areas:

- Infrastructure:
  - Collocation of high-energy (multi-kJ class) lasers with the European XFEL. This capability will ensure that Europe/Germany maintains leadership with a successor to HIBEF as a world-class facility competitive with the $300M upgrade of the Materials under Extreme Conditions (MEC) upgrade at the LCLS facility at SLAC.
  - Upgrade of PHELIX towards 2-3 kJ. Combined with ion beams, essential data needed for high-fidelity modeling of targets interaction physics can be obtained at this facility.

  - Upgrade of HZDR's PW facilities to multi-PW for fast ignitor studies and a combination with a plasma accelerator powered VUV FEL for early stage studies of ablation / implosion physics.
- Excellence centers/hubs:
  - Launch of high energy density centera of excellence/hubs (e.g., as recently proposed as HI Rostock for the corresponding activities). These hubs would be instrumental for advancing high energy density and warm dense matter science in Germany, benefit from the leading large-scale infrastructure of the HA, and play a coordinating role towards addressing the back questions in ICF.

To accelerate the progress in technology development, it will be critical to launch joint programs with industry and Fraunhofer to advance laser technology towards high efficiency, high repetition rate, megajoule-class laser systems. Teaming of Helmholtz, Fraunhofer and industry, creates partnerships between the end-users with expertise in lasers and their application and operation in large-scale infrastructure settings, with teams that carry out R&D in plasma physics and laser technology, and with the German industrial muscle, renowned for its excellence in delivering quality. Such effort will be also a benefit for the HA's current mission to develop or acquire lasers systems of 10's of kW level with high wall-plug efficiency and reliable 24/7 operation.

To ensure that the next generation of scientists, engineers and technicians is available, investments are needed in education and training, through the (re)building of a curriculum in plasma physics both for MFE and ICF. This can be achieved through the creation of topically dedicated YIGs, joint appointments with universities, graduate schools, and by fostering international cooperation.

Outlook

This report is the basis for the discussion in the Helmholtz Association's General Assembly in September 2023 and subsequent discussions of the President and the Executive Board with the BMBF and the Strategic Partners.

Glossary

ANGUS	100 TW, 1 Hz repetition rate drive laser at DESY
ASDEX	Axially Symmetric Divertor Experiment
CALA	Center for Advanced Laser Applications at Garching
DIPOLE	DIPOLE 100-X at HIBEF
DPSSL	Diode pumped solid state laser
DRACO	Laser Dresden Laser Acceleration Source
EURATOM	European Atomic Energy Community
EUROfusion	Consortium of national fusion research institutes
European XFEL	European X-ray Free-Electron Laser Facility in Hamburg/Schenefeld
HED	High energy density
HEDP	High energy density physics
HIBEF	Helmholtz International Beamline Facility at the European XFEL
HIPACE++	Open-source GPU-capable 3D quasi-static particle-in-cell code
HPC	High performance computing
ICF	Inertial confinement fusion
IFE	Ignition fusion energy
IFMIF-Dones	International Fusion Materials Irradiation Facility – Demo Oriented NEutron Source
ITER	International Thermonuclear Experimental Reactor at Cadarache
JET	Joint European Torus in Oxfordshire (UK)
JETI200 laser	Jena's native 200 TW, Ti:Sapphire laser system
KALDERA	100 TW laser at DESY to operate at 1 kHz repetition rate
LLNL	Lawrence Livermore National Laboratory
MCF	Magnetic confinement fusion
MEC	Materials under extreme conditions
MFE	Magnet-based fusion energy
PHASER	Phase-stabilized Heine Laser
PHELIX	Petawatt High-Energy Laser for Heavy Ion EXperiments
PIConGPU	Particle-in-Cell code running on graphic processing units
PoF V	Fifth program funding period
RELAX	RELAX 400TW laser combined with European XFEL at HIBEF
W7-X	Wendelstein 7-X at the Greifswald branch of IPP
YIG	Young-Investigator Group funded by the HA

Example calculation to energy and electric power of Lasers in Joule and Watt multiplied by hours: 3.6 MJ is equivalent to 1 kWh. Laser pulse energy in Joule is determined from laser power times pulse duration. Correspondingly, a laser system with 1 PW power and pulse duration 10 fs has a pulse energy of 10 Ws or 10 J.