Laserlab-Europe AISBL

Europe’s IFE Strategic Direction

Report from the Expert Group in
Inertial Confinement Fusion / Inertial Fusion Energy (ICF/IFE)

Coordinator: Colin Danson

Published in April 2025

Content

Laserlab-Europe AISBL

Laserlab-Europe AISBL is an international not-for-profit association, bringing together 47 leading laser research infrastructures in 22 European countries. Jointly, they are committed to coordinate operation and R&D efforts in order to facilitate the development of advanced lasers and laser-based technologies, and to promote the efficient utilisation of advanced laser facilities by users from academia and industry. The majority of the members provide open access to their facilities to scientists from all over the world to perform experiments in a large variety of inter-disciplinary research, covering advanced laser science and applications in most domains of research and technology.

www.laserlab-europe.eu

Introduction

This report is the output of the Laserlab-Europe ICF/IFE Expert Group. It has been compiled and edited by all members of the expert group. It provides an overview of activities in Europe in the area of Inertial Confinement Fusion / Inertial Fusion Energy.

Laserlab-Europe ICF/IFE Expert Group Membership

Membership of the Expert Group is open to all relevant institutes across Europe. There are currently 16 Laserlab-Europe AISBL Member institutes participating in the Expert Group:

- CELIA, University of Bordeaux, France;
- Central Laser Facility, STFC Rutherford Appleton Laboratory, UK;
- Centre for Ultrafast Lasers, UCM, Spain;
- CESTA, CEA-DAM, Aquitaine, France;
- CLPU, University of Salamanca, Spain;
- ENEA, C. R. Frascati, Italy;
- GSI Helmholtz Centre for Heavy Ion Research, Darmstadt, Germany;
- HiLASE, Institute of Physics of the Czech Academy of Sciences, Dolni Brezany, Czechia;
- Institute of Plasma Physics and Laser Microfusion, Warsaw, Poland;
- Institute Superior Tecnico, Universidade de Lisboa,Portugal;
- Intense Laser Irradiation Laboratory, INO, CNR, Pisa, Italy;
- LULI, Ecole Polytechnique, France;
- Orion, AWE Nuclear Security Technologies, UK;
- PALS, Institute of Plasma Physics, Prague, Czechia;
- University of Strathclyde, UK;
- HUN-REN Wigner Research Centre for Physics, Hungary.

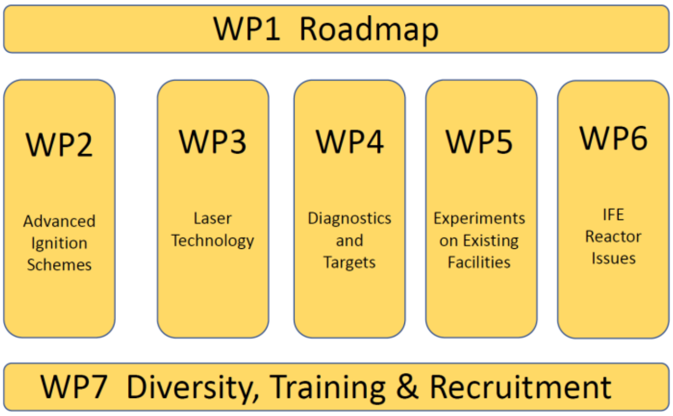
Much of the expertise in this area lies in Institutes without user facilities or not formally members of Laserlab-Europe, and hence are not Laserlab-Europe AISBL members. It is therefore appropriate to open the membership up to other European groups, with several invited to participate, including:

- ELI-Beamlines, Czechia;
- Fraunhofer ILT, Germany;
- Focused Energy GmbH, Germany;
- IFN-GV, Technical University of Madrid, Spain;
- Imperial College London, UK;
- Institute of Plasma Physics and Lasers, HMU, Greece;
- Queen’s University Belfast, UK;
- Technical University Darmstadt, Germany;
- Thales, LAS, France;
- University de Côte d'Azur, France;

- University de Las Palmas de Gran Canaria, Spain;
- University of Oxford, UK;
- University of Warwick, UK;
- York Plasma Institute, University of York, UK.

Aims and Activities of the Expert Group

The aims of the Expert Group are to strengthen the collaboration between research groups in Europe in ICF/IFE and to discuss potential future advances relevant to ICF/IFE. The activities for the Expert Group have been broken down into seven main Work Packages which will initiate focussed discussions and contribute to the strategy:



WP1. European IFE Roadmap

- ➢ Develop European roadmap for IFE.
- ➢ Develop strategy and lobby for a medium scale European IFE facility.

WP2. Advanced Ignition schemes

- ➢ Further develop advanced Direct Drive schemes for ICF.
- ➢ Modelling of ignition schemes.

WP3. Laser technologies for IFE platforms

- ➢ Working on high repetition rate laser technologies: including efficient diode pumping, high repetition rate and broad-band wavelength capabilities.
- ➢ Laser beamline modelling for optimum performance.

WP4. Related technology development (targets, diagnostics etc)

- ➢ Development of target technologies relevant to IFE (with strong synergies with the Laserlab-Europe Expert Group on Micro- and nano-structured materials for experiments with high-power lasers).

- Improving PW kJ-class diagnostic laser capabilities (ARC, PETAL, etc.) for ICF research (with strong synergies with the Laserlab-Europe Expert Group on Laser-generated EMPs).

WP5. Experiments on existing platforms

- Identify key experiments on current intermediate & large-scale international facilities to progress understanding of ICF/IFE.
- Coordinate the generation of collaborative proposals for accessing facilities.

WP6. IFE reactor issues (overlap with Tokamak technologies)

- Investigate reactor relevant issues.
- Study of IFE materials considerations.
- The threat of laser-generated EMPs (with strong synergies with the Laserlab-Europe Expert Group on EMPs)

WP7. Recruitment, training, diversity & inclusivity

- Opportunities for workshops, meetings & input to existing conferences.
- How can the community tackle diversity and inclusivity issues?

Background

The concept of laser-driven inertial confinement thermonuclear fusion (ICF) for energy production [1] was originally proposed in 1972 in seminal papers by Nuckolls and Basov [2, 3] that initiated a worldwide effort to demonstrate inertial fusion ignition in the laboratory. The Nuckolls abstract stated that '*Hydrogen may be compressed to more than 10,000 times liquid density by an implosion system energized by a high energy laser. This scheme makes possible efficient thermonuclear burn of small pellets of heavy hydrogen isotopes and makes feasible fusion power reactors using practical lasers.*' This began a global concerted effort, particularly in the US, for over 50 years to understand the physics behind ICF and finally demonstrate ignition. At the Lawrence Livermore National Laboratory (LLNL) a series of lasers were constructed from the mid-1970s with ever increasing energies and specifications: Janus and Cyclops in 1975; Argos in 1976; Shiva in 1977; Novette in 1983; Nova in 1984 and finally the National Ignition Facility (NIF). A progression of the development of lasers; their optical systems; diagnostics for both lasers and plasmas; targets; and computer architectures and codes for simulation and prediction was also undertaken – all critical to the delivery of the ICF programme.

A historic scientific achievement was realised on the 5th December 2022 on NIF at LLNL and announced at a press briefing on the 13th December 2022 by the US Department of Energy's National Nuclear Security Administration (NNSA). For the first time in any fusion experiment the team demonstrated getting more fusion energy out from the fusion reactions than was input, i.e. scientific breakeven. This was a major milestone and the culmination of decades of effort. NIF's implosion produced a total of 3.15 MJ of fusion energy, namely neutrons and alpha particles, with 2.05 MJ of laser energy, demonstrating that the process can produce more fusion energy than the laser energy delivered to the target [4]. This major milestone, showing a gain of 154%, follows a previous key achievement on NIF, demonstrating an igniting plasma and the world's first burning plasma on 8th August 2021. On that occasion the yield was estimated to be 72% of the laser input energy, with 1.35 MJ of fusion energy generated from 1.93 MJ of incident laser energy into the target [5]. The experiment performed on the 12th February 2024 produced an estimated 5.2 MJ of fusion energy employing 2.2 MJ of input laser energy, giving a gain of 236%, so more than doubling the lasers. [https://lasers.llnl.gov/news/fusion-ignition-and-the-path-to-inertial-fusion-energy]

Europe has played an important role on the journey to ignition with many researchers identified as co-authors in the key papers related to NIF energy-gain shots [6,7]. Unfortunately, strategic funding and investment in Inertial Fusion Energy (IFE) is lacking not only in Europe but globally, with support into Inertial Confinement Fusion (ICF) concepts primarily coming from governments possessing thermonuclear weapons. Despite its massive progress and significant breakthroughs, ICF has seen little support on the civilian side of research. Despite a few major investments (e.g. HIPER in the EU, HYLIFE and LIFE in the US) to harvest electrical energy from ICF, research activities in ICF are primarily financed through individual research grants, small investments by institutional funding, networking initiatives, and grassroots efforts. This stands in stark contrast to Magnetic Confinement Fusion (MCF), which enjoys significant backing from both EU and governmental research funding.

The HiPER (High Power Energy Research) initiative emerged in the early 2000s as Europe's response to advancing laser-driven inertial fusion energy research. Officially included in the

European Strategic Forum for Research Infrastructures (ESFRI) roadmap in 2006, HiPER aimed to explore high-gain laser-driven fusion schemes, particularly focusing on the shock ignition direct-drive approach, while establishing a sustainable, long-term basic science program across related fields.

In contrast, the United States has made significant strides with the National Ignition Facility (NIF), successfully demonstrating mega-joule scale energy yields from laser-driven inertial confinement fusion. While the NIF's strategic mission includes stockpile stewardship, Europe has lagged not only in defense-related objectives but also in acquiring knowledge and technological advancements in this highly promising field. This disparity highlights the substantial gap between the progress seen in the US and the ongoing challenges faced by ICF research in Europe, particularly in securing sufficient funding and support to develop inertial fusion energy as a viable pathway toward a Fusion Power Plant (FPP).

Given the current international activities and renewed interest in ICF as a viable option for fusion energy production, it is crucial for a Laserlab-Europe AISBL Expert Group to establish a comprehensive network of researchers across Europe. This initiative aims to enhance and align the efforts of each institution, fostering mutual collaborations and preparing for joint experimental campaigns

With the current international activities and renewed interest in ICF as a viable option for fusion energy production it is extremely timely therefore for a Laserlab-Europe AISBL Expert Group to develop a broad network of researchers across Europe, to promote and focus the activities of each institution to define mutual collaborations and prepare joint experimental campaigns.

European Initiatives

a) HiPER+

HiPER+ is a consortium of nine countries across Europe aiming to explore the feasibility of IFE whilst supporting a broad base of high-power laser interaction science [8,9,10]. A HiPER+ Collaboration Agreement has been written which sets out the framework in which members wish to cooperate in the future with the aim to build a high-gain Laser-Fusion European program following the experience of the previous HiPER project. In 2023 it published a roadmap for Inertial Fusion Energy in Europe [10]. In February 2024 it submitted an application, HiPER+RI, to the EU for a €3M grant for 'INFRA-DEV' funding. Unfortunately, it was not selected. Meanwhile, the HiPER+ consortium proposal “Innovative Education and Training in Laser Inertial Fusion Energy” was selected for funding within the Erasmus+ KA2 program. It is started in January 2025. The HiPER+ consortium also applied for an international doctoral network and for a COST Action.

b) German government strategy

Despite not having an ICF program for several decades, Germany has been a front-runner in developing various enabling technologies related to magnetic and laser fusion energy. Moreover, in response to the initial breakthrough results at NIF in 2021 and 2022, the German government made a strategic decision in December 2022 to initiate an international study aimed at investigating the potential, challenges, and opportunities related to ICF. Directed by Prof. Constantin Haefner, Director of the Fraunhofer ILT, a renowned group of international IFE and MFE experts delivered a comprehensive “Memorandum on Inertial Fusion Energy” in May 2023, which included a set of recommendations for the government. The experts advised the development and promotion of a thriving fusion energy ecosystem, emphasizing four key pillars: a robust science program, an inclusive research infrastructure for academia and industry, a competent industry, and international cooperation among governments to maximize resources and funding while minimizing duplication of efforts. The experts also emphasized the necessity of a clear regulatory framework surrounding these pillars, which they recommended as essential for the effective development of the fusion energy ecosystem

Responding just a month later, the Federal Ministry of Education and Research (BMBF) released its position paper, incorporating recommendations put forth in the Memorandum. The position paper also recommended the establishment of a dedicated Fusion Energy program in Germany. Subsequently, in September, the Secretary for BMBF announced to allocate a minimum of 1.2 billion Euro in funding for fusion over a period of five years. The BMBF quickly initiated the first projects to emphasize the need for urgent action and committed in March 2024 36 Million Euros pre-competitively over the next three years to three fusion initiatives: The PriFUSIO research project focuses on targeted component development and practical photonic techniques for laser-driven IFE. Led by the Fraunhofer ILT in Aachen, it brings together startups, medium-sized enterprises, large corporations, and research institutions such as the Laser Zentrum Hannover and the Fraunhofer Institutes. The Max Planck Institute for Plasma Physics (IPP) is coordinating a magnetic fusion project which includes collaboration with Proxima Fusion to address stellarator power plant concepts and optimization of related technologies. KIT is partnering with Gauss Fusion to develop dismantlable, superconducting coils for future fusion power plants, with IPP also involved in this effort. Shortly after, the program Fusion 2040 and the first call for proposals was launched. A second call was launched in July 2024 with a commitment of almost EUR 200 Mio that are matched in this PPP program by industry.

German start-ups Marvel Fusion and Focused Energy, along with other companies in the MFE arena, are actively working on developing an innovative power plant in the IFE sector. These initiatives receive support from the SPRIN-D agency (Federal Agency for Disruptive Innovations), which established Pulsed Light Technology GmbH (PLT). PLT is focused on addressing critical challenges in fusion energy, particularly in building essential infrastructure with an emphasis on laser systems. This includes research and development of enabling technologies, as well as advancements in plasma physics and target concepts.

Furthermore, supported by the German government, ELI-ERIC has launched the LIF (Laser Induced Fusion) initiative to aid the laser fusion community by providing access to experimental facilities and establishing a dedicated program through mission-oriented calls for users. One of the key activities of the LIF project was a general kick-off meeting held in November 2023 in Prague, bringing together major stakeholders from the EU and beyond [https://indico.eli-laser.eu/event/35/].

c) French government initiative

In response to the French government's funding call for "Investissements d'Avenir" (Investments for the Future), a consortium comprising Thales, the CEA, CNRS, and the French investment bank (BPI) has formed a new private entity called GenF. This consortium applied for funding of the TARANIS project, aiming to develop IFE as a commercial energy source. The project has secured an initial funding of 12 million euros for Phase 1, spanning 36 months from April 2024. Looking ahead, Phase 2 is projected to receive 200 million euros in 2027, followed by an additional 600 million euros to establish a demonstration plant.

d) UK government initiative

The UK primarily emphasises support for MFE (Magnetic Fusion Energy), as highlighted by established projects like STEP and robust participation in international MFE collaborations. The Department for Energy Security and Net Zero (DESNZ) is facilitating fusion development through a £650 million program over four years, managed by the UKAEA Culham Centre for Fusion Energy.

Since 2018 there has been a concerted effort to enhance coordination and collaboration in the UK inertial fusion community. This led to the creation of the UK Inertial Fusion Consortium (https://www.inertial-fusion.co.uk). Comprised of approximately 100 members from nine UK institutions (Imperial College London, Queens University Belfast, STFC Rutherford Appleton Laboratory, AWE, University of Lancaster, University of Oxford, University of Warwick, University of York, First Light Fusion). The UK Inertial Fusion Consortium published a UK Roadmap for Inertial Fusion Energy in 2021, shortly before NIF achieved ignition. This, combined with the breakthrough at the National Ignition Facility (NIF), has increased interest and investment in IFE (Inertial Fusion Energy).

The UPLiFT project (UK Project of Laser Inertial Fusion Technology for energy), is comprised of a consortium of seven UK institutions led by Robbie Scott at the STFC Rutherford Appleton Laboratory Central Laser Facility, exemplifies this trend. Phase 1 of UPLiFT has a budget of £10 million over four years, focusing on IFE laser design, prototype construction, implosion capsule target manufacturing, high gain physics, and extensive development of the hydrodynamic code ‘Odin’.

With respect to start-ups, First Light Fusion is a UK-based start-up focused on developing an ICF technology using a unique approach that involves compressing a fusion target with a high-speed projectile, with the aim of achieving a viable path to commercial fusion energy.

References

[1] S. Atzeni and J. Meyer-Ter-Vehn, ‘The Physics of Inertial Fusion: Beam Plasma Interaction, Hydrodynamics, Hot Dense Matter.’ Oxford University Press (2004)

[2] N.G. Basov, O.N. Krokhin and G.V. Sklizkov, ‘Heating of laser plasmas for thermonuclear fusion.’ In Laser Interaction and Related Plasma Phenomena vol 2 (New York: Springer) p.389 (1972)

[3] J. Nuckolls et al., ‘Laser Compression of Matter to Super-High Densities: Thermonuclear (CTR) Applications.’ Nature 239, 139–142 (1972) https://doi.org/10.1038/239139a0

[4] H. Abu-Shawareb et al., ‘Achievement of Target Gain Larger than Unity in an Inertial Fusion Experiment.’ Phys. Rev. Lett. 132, 065102 (2024)

[5] H. Abu-Shawareb et al., ‘Lawson Criterion for Ignition Exceeded in an Inertial Fusion Experiment.’ Phys. Rev. Lett. 129, 075001 (2022)

[6] A.L. Kritcher et al., ‘Design of inertial fusion implosions reaching the burning plasma regime.’ *Nat. Phys.* (2022) https://doi.org/10.1038/s41567-021-01485-9

[7] A.J. Crilly et al. “Measurements of dense fuel hydrodynamics in the NIF burning plasma experiments using backscattered neutron spectroscopy.” Phys. Plasmas (2024) doi: 10.1063/5.0203096

[8] S. Atzeni et al., ‘An evaluation of sustainability and societal impact of high power laser and fusion technologies: a case for a new European research infrastructure.’ *High Power Laser Science and Engineering, 9*, e52 (2021) https://doi.org/10.1017/hpl.2021.41

[9] S. Atzeni et al., ‘Breakthrough at the NIF Paves the way to Inertial Fusion Energy.’ EuroPhysics News 53/1 (2022) https://www.europhysicsnews.org/articles/epn/pdf/2022/01/epn2022531p18.pdf

[10] D. Batani et al., ‘Future for Inertial Fusion Energy in Europe: A roadmap.’ HPLSE Vol 11 e83 (2023)

Work Package 1: European IFE Roadmap

Contributors: Thomas Kuehl, GSI, Germany; Michael Tatarakis, IPPL, Hellenic Mediterranean University Research Centre, Greece; and Vladimir Tikhonchuk, CELIA, University of Bordeaux, France, with input from WP5.

Background

European scientists have made significant contributions to the study of laser-driven inertial confinement fusion by developing theoretical concepts, physics models, numerical simulation methods, and high-performance computing, as well as conducting experiments and designing diagnostics. Coordination among different countries is supported by the Eurofusion consortium through "keep-in-touch" activities with minimal funding compared to the investments into MFE research, and for a brief period from 2007 to 2013, by the ESFRI project HiPER, which developed its own roadmap for IFE. However, progress is hindered by the lack of an academic laser facility for conducting implosion experiments.

The success of NIF scientists in achieving implosion experiments with energy yield exceeding the input laser energy is the major breakthrough that motivated European scientists to initiate an active, coordinated, and goal-oriented approach to inertial fusion energy. An initiative group has been formed by several scientists from five European countries (Greece, France, Italy, Spain and the United Kingdom) and manifested with two publications advocating a better organisation and coordination of IFE research in Europe [1,2]. This group is growing in number and now includes German scientists strongly motivated by recent decisions of the German government concerning research on fusion energy [3].

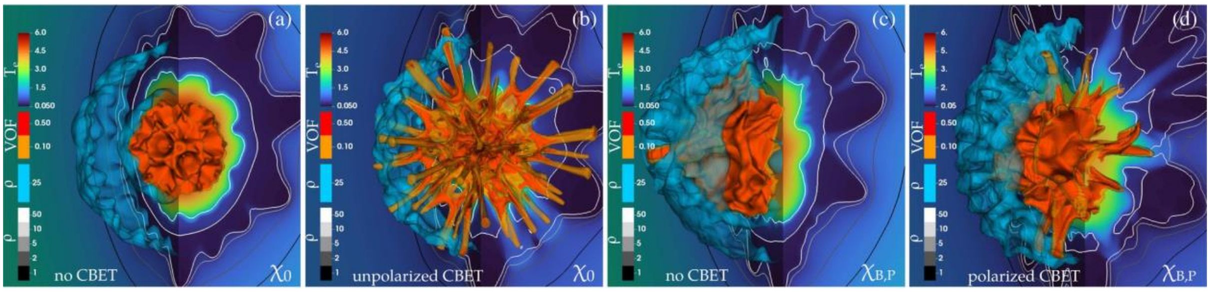


Figure is taken from the paper by Colaitis et al PRL 129,095001, 2022 on the effect of CBET on the symmetry of Omega implosions

Ongoing actions

WP1 operates along two axes:

1) development of a European road-map for IFE
2) development of strategy and lobby for a medium-scale European IFE facility.

Both axes have a common denominator of creating a landscape favourable for coordinated research in Europe in IFE science and technology and obtaining the support of several leading European countries for a joint project for the European Laser Fusion Facility.

The following actions have been conducted:

- Preparation of the HiPER+ project roadmap for IFE. A new roadmap was developed by a group of 14 scientists, and it is now published in the journal High Power Laser Science and Engineering [4]. It includes an executive summary outlining the research and development needed for commercialising inertial fusion energy, a description of the main achievements of European scientists in the domain of ICF, a general structure of the proposed project and a detailed description of short-term and long-term scientific and technological objectives. This document presents the basis for further developments and lobbying for the support of governmental and European organisations.
- A series of public seminars and conference presentations explaining the general features of the European IFE project has been conducted [5]. This action seeks increasing support from the international plasma physics community and creates a basis for future collaborations.
- Two Eurofusion seminars were organised in June 2022 and January 2024 with the goal of strengthening links with the magnetic fusion community in Europe, securing funding from the Eurofusion consortium and developing joint research in the domain of plasma diagnostics, material science and reactor technology.
- A memorandum of collaboration is developed and prepared for signing by organisations interested in participation in the project. This action aims to create a solid legal basis needed for the organisation of a large-scale international project.
- A training project “Innovative Education & Training in Laser Inertial Fusion Energy” (Acronym: LaserFusion) aiming to coordinate teaching and professional training in IFE science and technology was submitted and is accepted for funding by the Erasmus+ EU programme and operates since January 2025. The Kick-off meeting was held in Athens on January 24th. It includes eight universities from 6 European countries and one European organisation ELI ERIC. The project is strongly connected with the HiPER+ initiative (Coordinator: Hellenic Mediterranean University (HMU)/Institute of Plasma Physics & lasers (IPPL) I. Fitilis, M. Tatarakis).
- Two research projects are awarded by the Eurofusion consortium for a period 2024-2025. One aims to develop the shock ignition concept employing micro-structured materials (foams) (PI S. Le Pape), and another is dedicated to study the effects of spontaneous and external magnetic fields on energy transport in fusion plasmas (PI J. Santos). Both projects are successfully delivered mid-term results in February 2025.
- A project aiming at the preliminary conceptual design of a European Laser Fusion installation and research centre is under preparation (PI D. Batani). It was submitted to the ERC call INFRA-DEV in March 2024 but was not selected.
- Preparation of a request to enter the European IFE project into the ESFRI roadmap. Two meetings were organised with the management of the ESFRI program and Euratom in Brussels. Discussions are ongoing with the governmental organisations and ELI ERIC.
- Several proposals aiming to be submitted in the ELI-ERIC Mission-Based Access Program in Inertial Fusion Energy (IFE) are under preparation. The programme provides a unique opportunity to conduct extended experimental campaigns at ELI’s cutting-edge laser Facilities, addressing key scientific and technical challenges related to laser-powered IFE.

Way forward for Europe

We can define three temporal scales that we believe have to be considered for a future roadmap, capable to deal with the mentioned issues.

1. Short timescale:
    - Use of "single beam" academic facilities now in operation in Europe (Vulcan, LULI, Phelix, PALS, ELI…).
    - Use of multi-beam facilities (Omega, Gekko XII, Orion, SG II UP and SG III P in China).
    - Pushing to get programmatic access for IFE to LMJ.

2. Medium timescale
    - Build a facility like Omega (output of HiPER+ project), in terms of full energy. This requires a close collaboration and involvement of private companies working in laser fusion or related areas, as for example laser development (Thales, Amplitude, Trumpf), advanced materials, targetry, etc… Features of this facility:
        - Laser: Large bandwidth; High repetition rate; and High efficiency
        - Target configurations optimized for high repetition rates. That also requires the development of adequate capabilities for target production in Europe with dedicated laboratories and facilities.
        - Diagnostics operating at high repetition rates
        - Issues related to the laser-target interactions at high repetition rates and related chamber technology: activation; EMP etc.
        - Full energy experiments on DD schemes. Polar Drive in LMJ…

3. Longer timescale.
    - Build a facility for full energy experiments dedicated to academic access.

Where Europe could make a significant impact

- European scientists had a primary role in the development of IFE studies since the very beginning. Pioneering experiments were performed in Europe on inertial fusion, and these allowed to set the solid base on which building the current IFE knowledge and technology. Indeed, the basic book reference on IFE comes from European authors [1].
- This wide historical and current expertise on IFE is spread over many European Laboratories and Institutions. It is of primary importance to preserve this expertise with new investments, facilities and human resources.
- Broad collaborations within Europe exist, mainly through EUROfusion projects which however have very modest funding, for theoretical and experimental activities and related technological advances.
- In Europe the magnetic confinement fusion community has a recognized broad and strong activity. A closer collaboration between magnetic and inertial fusion communities can be an important step to help establishing synergies on common technological issues related to future reactors.

Ideas for potential ways forward

- According to what discussed, it is of primary importance for IFE researchers to get larger and programmatic access to laser facilities at all levels and within short time scales. For this it is necessary to create a legal and recognized Entity representing IFE

R&D in Europe and making the link among the European research groups. This may be as a consortium of participating laboratories or a similar structure.

- There is an increasing interest of private companies in IFE, and they have recently obtained very significant funding from the German government. Collaboration of public institutions with private companies has to be established. At the moment, four IFE companies are based in Europe: Focused Energy (FE); Marvel Fusion (MF); GenF; and First Light Fusion (FLF).
    - The current Focused Energy program is to build up to two multi-beam laser facilities, partially addressing some of the issues cited above (high repetition rate, targetry, etc.). This cannot be considered as a substitute of an Academic laser facility (“Omega-like”) in Europe.
    - Marvel Fusion company, based in Germany, has no plans for facility construction, at present.
    - GenF company, based in France, considers building of an intermediate laser implosion facility to achieve ignition in the direct drive scheme and create an experimental platform for the fusion reactor design.
    - First Light Fusion, based in the UK, although not a laser scheme is based on inertial techniques.
- European access to USA laser facilities is now rather limited and difficult. Laser time through LaserNetUS could be an option, but a suitable Europe-USA agreement needs to be set.
- The path to a future IFE reactor is long and presents significant physical and technological challenges. The dramatic improvement of the NIF results in ICF experiments during last three years demonstrates that there is a high potential for success, but this cannot be achieved without dedicated laser facilities. These are lacking in Europe, which has indeed a significant scientific community and expertise. A key point for the worldwide progress of the IFE research is then to build a European laser facility dedicated to IFE studies.

Conclusions

The expert group in ICF/IFE made significant efforts to activate the ICF research in Europe and bring it to a level competitive with the scale of research conducted in the USA and needed for resolving scientific and technological bottlenecks and commercialisation of fusion energy. However, an engagement of key partners has not yet been achieved, which is an indispensable step for postulating the IFE project for the ESFRI roadmap. This has to be the main goal of the expert group for the next year.

Another important point is establishing collaboration between the expert group proposing an academic IFE project with industry and private companies. The development of a new generation of lasers compatible with the ICF requirements, the development of technology for mass fabrication of targets, design and engineering of reactor systems, materials and environment are outstanding problems that cannot be resolved within academic research institutions and require strong and long-term collaboration with industry. These issues have many common points with magnetic fusion and can be addressed by establishing a tighter collaboration within the Eurofusion consortium and Laserlab-Europe.

References

1. S. Atzeni, D. Batani, C. N. Danson, L. A. Gizzi, M. Perlado, M. Tatarakis, V. Tikhonchuk, L. Volpe, An evaluation of sustainability and societal impact of high-power laser and fusion technologies: a case for a new European research infrastructure, High Power Laser Sci. Eng. **9**, e52 (2021) doi: 10.1017/hpl.2021.41
2. S. Atzeni, D. Batani, C. N. Danson, L. A. Gizzi, S. Le Pape, J-L. Miquel, M. Perlado, R.H.H. Scott, M. Tatarakis, V. Tikhonchuk, L. Volpe, Breakthrough at the National Ignition Facility paves the way to inertial fusion energy, Europhys. News **53**, n°1, 18 (2022) doi: 10.1051/epn/2022106
3. MEMORANDUM Laser Inertial Fusion Energy (2023), https://www.bmbf.de/SharedDocs/Downloads/de/2023/230522-memorandum-laser-inertial-fusion-energy.html
4. D. Batani, A. Colaıtis, F. Consoli, C. N. Danson, L. A. Gizzi, J. J. Honrubia, T. Kuhl, S. Le Pape, J.-L. Miquel, J. M. Perlado, R. H. H. Scott, M. Tatarakis, V. Tikhonchuk and L. Volpe, Future for Inertial Fusion Energy in Europe: A roadmap, HPLSE doi:10.1017/hpl.2023.80
5. List of conferences and seminars where the HiPER+ roadmap was presented:
    - GSI scientific seminar (Darmstadt, April 2023)
    - EPCRD conference (Rethymno, April 2023)
    - Direct Drive and Fast Ignition workshop (Oxford, May 2023) – round table discussion
    - ELI ERIC: Laser-Induced Fusion steering committee (Prague, June 2023)
    - ICMRE conference (Zhuhai, June 2023)
    - SIOM scientific seminar (Shanghai, June 2023)
    - HPLSE conference (Suzhou, October 2023)
    - European Fusion Theory Conference (Padova, October 2023)
    - ELI Laser-Induced Fusion Kick-off Meeting (November 2023)

Work Package 2: Advanced Ignition schemes

Contributors: Robbie Scott (STFC, CLF, UK); Peter Norreys (University of Oxford, UK)

Indirect Drive Central Hotspot Ignition

The National Ignition Facility (NIF) uses a ‘hohlraum’ to convert laser light into soft x-rays; the ‘Indirect Drive’ (ID) approach to Laser Fusion. The x-rays then illuminate the implosion ‘capsule’ uniformly. The x-rays cause the capsule to ablate driving the implosion inwards. NIF ID uses the ‘central hotspot ignition’ ignition process whereby implosion kinetic energy is converted into internal energy as the implosion ‘stagnates’. As the implosion proceeds, the pressure within the implosion’s low density central void (hotspot) increases, principally due to the reduction in the hotspot volume. This pressure decelerates the shell extracting its kinetic energy and converting it into internal energy. This internal, or compressive, energy is typically equally partitioned between the hotspot and shell. Due to the near isobaric pressure profile across the hotspot and shell, it principally heats the low-density hotspot, while compressing the shell.

High implosion velocity is required to induce a sufficiently high hotspot central temperature for ignition. This high velocity can induce hydrodynamic instabilities which disrupt, or even destroy, the implosion. The most dangerous of these instabilities is the Rayleigh-Taylor instability.

Over its 12 years of experimental operation with DT cryogenic implosions NIF yields have increased by ~1000 times, achieving a fusion yield of 5.2MJ using an input energy of 2.2MJ in February 2024 [ref]. This corresponds to a fusion gain of 2.36, or a ‘capsule gain’ of 15.6, where capsule gain is defined as the neutron yield divided by the x-ray energy absorbed by the implosion. The disparity between these gains is primarily caused by losses caused by the hohlraum’s geometry. Due to this inefficiency, combined with the use of complex high atomic number targets (which will become radioactive), it is generally thought that Indirect Drive is not the optimal approach to Laser Fusion energy. It is thought that there is substantial potential to further increase NIF’s yield.

Direct Drive Central Hotspot Ignition

The Direct Drive approach to Laser Fusion uses the same central hotspot ignition process as Indirect Drive (ID), but instead of the laser energy being converted into x-rays, the lasers are directly incident on the implosion capsule. Thus, the Direct Drive approach is more energetically efficient than ID. However, small-spatial-scale non-uniformities in the laser beams’ intensity profiles create corresponding spatial variations in the local ablation pressure. This in-turn creates non-uniformities in the shape and/or density of the implosion capsule which act as ‘seeds’ from which the Rayleigh-Taylor instability grows. Due to the larger seed size, shorter ablation density scalelengths, lower mass-ablation rate, and thinner shells of DD in comparison to ID, DD has both worse Rayleigh-Taylor growth and higher susceptibility.

In comparison to ID, DD has the significant advantage for IFE that the targets are far simpler, have less mass, and have no high atomic number materials. To-date DD has obtained the highest performance on Omega, although this falls marginally short of that required to show ignition, when scaled to NIF's energy-scale. These implosions are thought to be principally limited by hydrodynamic stability; the highest performing implosions use high adiabat and high velocity, while according to simulation codes low adiabat, low velocity implosions are better for high gain.

Shock Ignition

Shock Ignition [Betti *et al.*, *Physical Review Letters,* 2008] is a variant of Direct Drive. Shock Ignition uses a reduced implosion velocity – too low to induce ignition on its own – instead Shock Ignition uses a spike in laser power to drive a strong shock into the fuel which heats the hotspot and compresses the cold fuel. The reduced velocity means that there is the potential for higher gain (due to the potential to increase fuel mass whilst still igniting) and reduced susceptibility to the Rayleigh-Taylor instability. However, Shock Ignition's increased laser intensity requirement (~1x10^{16} W/cm^2) increases susceptibility to laser-plasma interaction instabilities (LPI). LPI can both reduce laser energy-coupling to the implosion and accelerate electrons to high energy, creating 'hot-electrons'. These hot-electrons can pre-heat the cold fuel, thereby reducing its compressibility and hence fusion yield.

One DT cryogenic experimental shot-day has been performed on Omega in ~2008 [Theobald *et al., Physics of Plasmas,* 2008]. This showed encouraging results, with an increase in neutron yield of 3-4 times.

Shock-Augmented Ignition

Shock-Augmented Ignition [R.H.H. Scott et al. *Physical Review Letters,* 2022] is a recently invented variant of Shock Ignition in which a dip in the laser power is now added, preceding the power spike. The dip enables a strong shock to be launched more easily, meaning that the laser intensity requirement for the 'spike' is approximately 7 times lower than 'classical' Shock Ignition, at ~1.5x10^{15} W/cm^2. Shock-Augmented Ignition retains the advantages of 'classical' Shock Ignition, while the susceptibility to LPIs is predicted to be greatly reduced.

Shock-Augmented Ignition also has the advantage that due to the reduced power requirement; experiments can be performed on today's laser facilities at the energy-scale for which the system was designed. In contrast, if the intensity of 'classical' Shock Ignition is required, the capsule must be scaled down substantially, this in turn prevents the laser system's full energy from being used during the implosion's timescale.

Three Shock-Augmented Ignition experiments have been performed on the Omega laser facility at the Laboratory for Laser Energetics (LLE), University of Rochester. The first two Shock-Augmented Ignition experiments used Deuterium gas-filled implosion capsules. This tested the effect of varying the shock launching time by using a number of different laser 'pulse shapes' (laser power vs time). The pulse shapes varied the timing of the power dip and spike. The experiment was successful with results which closely matching the pre-shot radiation hydrodynamic simulations.

The third Shock-Augmented Ignition Omega experiment occurred in late November 2023 and used cryogenic DT ice layers. Again, this compared the simulated shock launching time against experiment and a close agreement was found. Using LLE's statistical implosion model a close agreement was found between the pre-shot predictions and the experimental results.

The initial results showed a close match between the simulated shock timing and experiment. These preliminary Shock-Augmented Ignition experimental results may be sufficiently promising to motivate more DT cryogenic experiments on Omega in the future.

Modelling suggests NIF's Indirect Drive approach is compatible with Shock-Augmented Ignition. Three Shock-Augmented Ignition experiments have been performed on the NIF laser facility over 2022-23. The first experiment used 1.1MJ of laser energy with Deuterium gas-filled implosion capsules. This tested both the ability to induce the variations in hohlraum radiation temperature as a function of time required for Shock-Augmented Ignition and the implosion sphericity. The radiation temperature vs time matched Hydra simulations within a few eV. The implosion was not spherical but instead prolate ('sausage' shaped). While spherical would have been better, the implosion shape is more easily corrected on NIF than the oblate shape.

The second NIF experiment was similar to the first but employed a different laser pulse in order to vary the 'contrast' of the dip in radiation temperature. Again, this closely matched simulations while the prolate shape remained.

The third experiment used 1.3MJ of laser energy with Deuterium-Tritium-Hydrogen cryogenic ice layer. The hydrogen was added to reduce the neutron yield to enable a 'clean' measurement of the implosion's fuel areal density. In igniting implosions, areal density is directly proportional to fusion yield and so should be maximised. Measuring areal density was the main goal of this experiment. In comparison to other comparable NIF implosions, the areal density of this Shock-Augmented Ignition implosion was 1.7 times higher.

Key Physics Issues for Direct Drive

The two main physics issues for all Direct Drive approaches to Laser Fusion are imprint and laser-plasma interactions. Based on our current understanding, both can be addressed by the adoption of broader bandwidth laser drivers; the broader bandwidth reduces coherence and hence the impact of LPIs. Furthermore, it increases the speed at which speckles move across the target surface, thereby reducing the time over which the lasers' irradiation non-uniformity is smoothed out.

There may also be the opportunity to address aspects of imprint and LPI via target design. For example, imprint may be reduced by employing foam buffer layer on the capsule outer surface and/or a high-Z coatings. High-Z dopants in the ablator have also been shown to be beneficial for the reduction of the Two Plasmon Decay laser-plasma instability. However, it isn't clear that the substantial (~40%) reduction in ablation pressure caused by Cross Beam Energy Transfer can be addressed by target-based solutions, therefore it is likely that some form of higher bandwidth laser driver, or 'zooming', will be required.

Strategic Direction

Currently the Direct Drive community isn't able to make a water-tight assertion that any of the Direct Drive approaches will definitely ignite at the 2MJ scale, although this is very close. In order to address this, two complementary paths forward are proposed:

1. Continued experiments on Omega, with the goal of improving performance, ideally by going to lower adiabat, slower, implosions due to their relevance to high-gain. This will inevitably be led by US colleagues. Where possible European colleagues should collaborate and get involved.
2. Developing the ability to simulate LPI and imprint in-line within radiation-hydrodynamics codes. These capabilities must then be verified against both dedicated experiments and current Omega implosion datasets. Subject to demonstrating their predictivity, these improved, benchmarked simulation capabilities can then be used to design lower adiabat, higher-gain implosions which utilise features available on future drivers, such as laser bandwidth. This is an area where Europe can lead.

Fast Ignition Methods

Fast ignition Laser Fusion methods typically rely on Direct Drive to compress the fuel. Instead of using an isobaric implosion, an isochoric (uniform density) implosion is employed. A beam of high-energy particles is then used to heat and ignite the fuel. The isochoric configuration has the potential to initiate ignition with less energy. Typically, the particle-beam is generated by the interaction of ultra-intense ($\sim 1\text{x}10^{20}$ Wcm^{-2}) lasers with the target. Lasers are likely necessary in order to get the required particle flux to ignite within the hydrodynamic timescale and with a total particle energy (integrated over the beam) within realistically achievable limits. It should be noted that the energy of such high-intensity lasers cannot be compared directly with those of ‘long-pulse’ (nano-second) lasers; due to the need to temporally compress high-intensity lasers using gratings, which have low damage thresholds and therefore require large-area gratings, the cost per Joule of high intensity laser energy is currently quite significantly more than the long-pulse equivalent.

Based on the amount of research performed to-date, the two main fast ignition methods are electron fast ignition [Tabak et al., *Physics of Plasmas*, 2004] and proton fast ignition [Roth et al. *Physical Review Letters*, 2001]. In both cases a dense metallic cone (see figure 1) is inserted into the fuel capsule to aid the transport of the particles into the compressed fuel. In the case of proton fast ignition, this cone also holds a thin membrane which acts as the proton source when illuminated on its rear surface by high-intensity lasers.

In order to heat the target using reasonable amounts of laser-energy, the particle beam must (a) have the correct energy spectrum in order that it deposits its kinetic energy at the correct depth within the target, and (b) have sufficient beam-density so that the beam’s energy is deposited in a small area. These parameters dictate the heated volume. This, combined with the local fuel density, dictate the total particle energy required to reach ignition temperatures. Increases in the heated volume causes the required ignition energy to rapidly increase. Consequently, much of the work on electron fast ignition has concentrated on the issue of electron divergence, due to its strong effect on the laser energy required for ignition. Numerous methods have been investigated; however, it isn’t clear that any have conclusively shown the divergence issue to be solved. Research on proton fast ignition has shown that protons can be focussed into the target. If the proton beam can be focussed sufficiently this property will reduce the high-intensity laser energy requirement.

In addition to the above issues regarding hotspot volume, the efficiency of laser to fast-particle coupling is inversely proportional the total energy required for the high-intensity laser, and hence its cost.

Electron and proton fast-ignition experiments to date have principally focussed on measuring and controlling the fast-particle beams, rather than integrated compression and heating experiments. The initial electron fast ignition experiments performed on Gekko looked very encouraging, however attempts to reproduce these using Omega EP coupled to Omega suggested the heating was primary shock-induced rather than via fast electrons. To our knowledge integrated proton fast ignition experiments have not been attempted.

‘Auxiliary Heating’ [ref] is a variant of electron fast ignition; instead of using an isochoric implosion, a sub-ignition central hotspot is proposed. This would then be heated via a beam of high-energy electrons which, according to the concept, will first pass through the dense shell, then deposit their energy preferentially within the hotspot due to a Landau damping-like instability. The idea was developed under our EUROFusion ToHGIFE (2014-2018) and RoHGIFE (2019-2021) consortium grants and has resulted in preliminary experimental tests on the equation-of-state of fusion relevant foam targets, using the Vulcan laser facility by the European consortium (R.W. Paddock et al. Phys Rev E 107(2), 25206 (2023)). The consortium has scheduled follow-on experiments on the GEKKO XII and the LULI2000 laser facilities later in 2024 and next year (2025). Understanding the microphysics of the scheme is the essential ingredient at this point in time.

The key physics issues for Fast Ignition are:

- fast-particle divergence,
- fast-particle energy spectrum,
- laser to fast-particle energy-coupling,
- demonstration of a high-performance implosion with embedded cone.

Ref: [https://lasers.llnl.gov/news/fusion-ignition-and-the-path-to-inertial-fusion-energy]

Work Package 3: Laser technologies for IFE platforms

Contributors: Prof. Constantin Haefner and Claudia Keibler-Willner (Fraunhofer ILT, Germany); Martin Divoký (HiLASE, Czech Republic); Leonida Gizzi (INO-CNR, Pisa, Italy)

Introduction

The number of facilities for laser fusion research with multi-kJ pulse energies is extremely limited. Currently there are 15 facilities in total. Only a few of them can provide a multi-beam configuration for implosion studies, including NIF in the US, LMJ in France, SG-II and SG-III in China, and ILE in Japan. Moreover, the OMEGA facility at LLE in Rochester, US and 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 the Phelix Laser at GSI Darmstadt [Bag2010] and the POLARIS Laser at the Helmholtz Center Jena [Hor2016] are used to perform key research and development supporting fusion science. Only NIF [Spa2016] is currently capable of ignition level studies. The design of these lasers dates to the 1990s and is based on flash-lamp pumping, a reliable and cost-effective technology that, however, sets severe constraints on energy efficiency, heat load and, ultimately, achievable average power. The NIF is the result of LLNL's half-century-long development of increasingly powerful Neodymium-doped glass (Nd:glass) laser systems. On the way to commissioning of the NIF several key components and technologies had to be specifically developed, like a large aperture (40×40 cm²) active laser cavity electrooptical switch (plasma electrode Pockels cell - PEPC), large aperture, high energy adaptive optics, high damage threshold lenses and optical coatings for UV light, a preamplifier module (PAM) amplifying the pulses by 10 orders of magnitude, a control system that automatically aligns and controls the performance of the laser, rapid growth of potassium dihydrogen phosphate (KDP), continuous melt production of high-quality Nd:glass (in collaboration with Schott and Hoya) 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]. There are further laser developments necessary for systems suitable as drivers for IFE.

Flashlamp systems have a low wall-plug efficiency, and the multi-kJ energy beams repetition rate is limited to every few minutes/hours. The NIF laser with 2 MJ output energy requires around 400 MJ of electrical energy for pumping, not including the cooling system and other utilities. In contrast, laser diode pumping with narrowband spectral emission has been established for applications requiring high average power. Laser diodes, featuring a wall-plug efficiency larger than 50%, deliver energy directly into the absorption band of the final laser material. This technology is regarded as the mandatory step towards an efficiency IFE driver, but no large-scale demonstration of laser diode pumping above the kJ level exists, mostly due to the high cost.

Challenges

Previous studies show that an IFE reactor must repeatedly achieve fusion of fuel pellets injected at a rate of 10 to 20 Hz for a 1 GW power plant, which corresponds to an average laser power of about 40 MW.

Diode-pumped solid-state lasers (DPSSLs) are the most promising approach for indirect drive, direct drive and fast ignition schemes. The fundamental physics and technology of DPSSLs for inertial confinement fusion (ICF) have already been developed for the National Ignition Facility [Bay2008] [Hae2017]. The energy in such a system is distributed across several hundred beamlines to ensure sufficiently symmetric illumination of the target. The optimum number of beamlines is given by a trade-off between the aperture sizes and cost per optic on the one hand and overall system complexity on the other hand.

The Diode Pumped Solid State Laser (DPSSL) systems offer high average power, high repetition rate (HRR) operation at high efficiency. Moreover, significant performance leaps are expected in the next decade concerning efficiency, output power and reliability as well, fabrication advancements and cost reduction.

Existing or planned laser architectures for high repetition rate (HRR)

While the above-mentioned facilities provide high pulse energies at low repetition rate and thus low average power (top left corner in Figure 1), the laser system for a fusion plant simultaneously requires both high pulse energy and high average power (top right corner in Figure 1). In the past decade several laser systems have been developed and commissioned that pave the way to higher efficiency as well as high pulse energy at high average power.

The High Repetition Rate Advanced Petawatt Laser System (HAPLS) [Hae2016], [Hae2017], is an aperture-downscaled fusion laser derived from LLNL's Laser inertial fusion energy study (LIFE) [Bay2011]. It uses a Helium-gas-cooled Nd:Glass amplifier to reach a pulse energy of 200 J at 1 µm and with a repetition rate of 10 Hz that is frequency doubled to pump an ultrashort pulse Ti:Sapphire amplifier. Compared to NIF, the architecture includes several modifications like pulsed power supplies and replacing flashlamps with laser diode arrays for pumping to reduce heat load and increase overall efficiency. Furthermore, optical components, especially laser gain media and frequency conversion crystals, are actively cooled. These modifications are critical contributions for an IFE driver laser and could be successfully tested within the HAPLS laser.

The DiPOLE laser (Diode Pumped Optical Laser for Experiments) is a rep-rated high-energy laser developed by the Central Laser Facility in the United Kingdom. It uses helium-gas-cryo-cooling (~150 K) for its Yb:YAG amplifier slabs to increase the material's low gain cross section (and therefore high saturation fluence) at room temperature , at the expense of a significantly reduced spectral band-width. DiPOLE100 laser systems with a pulse energy of 100 J at 10 Hz repetition rate have been built for HILASE in the Czech Republic [Pil2018] and the HIBEF end station on Germany's X-ray laser at DESY. The highest demonstrated pulse energy is 146 J at 10 Hz [Div2021]. The increase of the energy was achieved through development of novel optical coatings (e.g., all silica coatings using glazing angle deposition) with increased laser induced damage threshold (LIDT). To compensate for thermally induced birefringence, a polarimetric technique was developed to measure and optimize the polarization response of the HE-HAP DPSSL that allowed compensation of thermally induced birefringence losses by using just waveplates to less than 3.5 % for Bivoj/DiPOLE laser [Sle2022]. This uniformly polarized beam can be efficiently converted to second and third harmonic (for SHG over 75% at 95 J [Div2023], for THG over 50% at 50 J each for 10 Hz rep. rate). The Bivoj/DiPOLE system main power amplifier operates with 25% optical-to-optical efficiency. Pump diode efficiency reaches 50% (45% with power supply included). The overall efficiency of the power amplifier is above 10% without cooling. The biggest drawback of the Bivoj/DiPOLE system is liquid nitrogen cooling that is highly inefficient (20%) and drops down the efficiency of the whole laser system below 3%. With some modifications (e.g., direct Brayton cycle cooling), 10% efficiency threshold can be reached with current technology. The size of YAG crystals or ceramics is currently limited to values around 150 mm [Pre2018], but tests with bonding of 45 mm long pieces of Yb:YAG crystals were performed with excellent results [DeV2023] and pieces of Cr:YAG of up to 120 mm were bonded by Crytur for ELI Beamlines [Pre2018]. Extrapolating the energy upgrades, the current limit of output energy for this laser architecture lies around 600-800 J at repetition rate of 10 Hz.

In Japan, Hamamatsu and Osaka University demonstrated a laser-diode pumped, cryo-geni-cally cooled Yb:YAG ceramic amplifier stack with a pulse energy of 253 J at 0.2 Hz repetition rate [Sek2022]. Furthermore, a cryogenically cooled Yb:YAG ceramics thin-disk laser with 10 J at 100 Hz was developed by Osaka University [Ogi2022]. The HALNA (high-average-power laser for nuclear-fusion applications) design aims at 1 kJ at 10 Hz from a single aperture with a water-cooled Nd:Glass side-pumped zigzag slab. Currently, 21.3 J at 10 Hz are demonstrated [Yas2008].

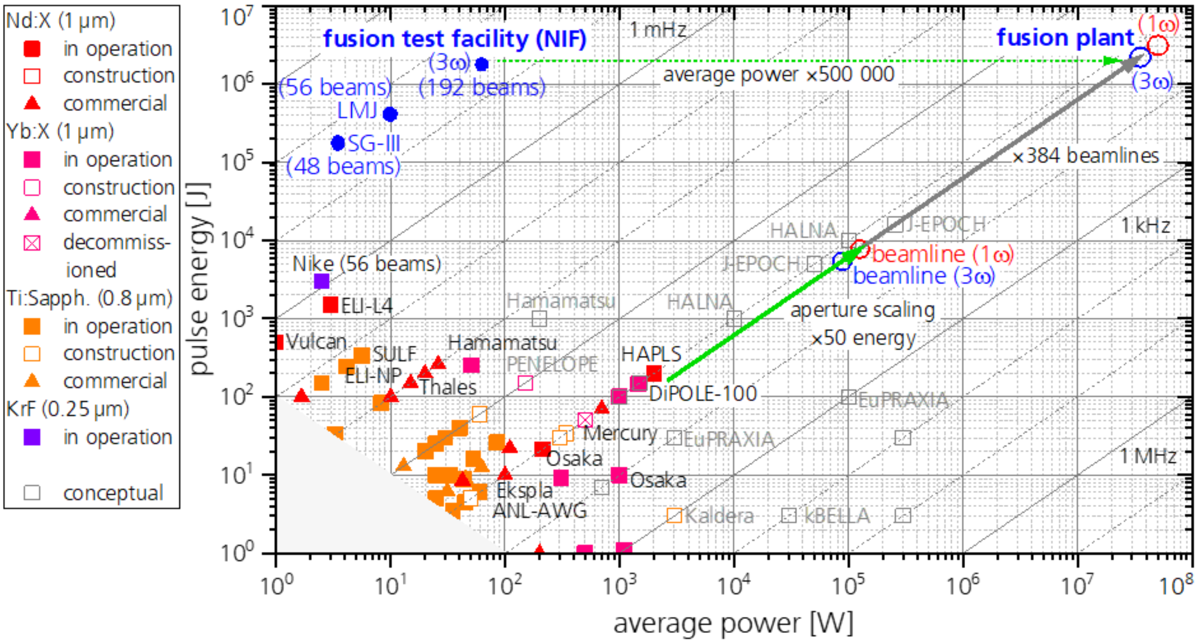


Figure 1: Overview of high-energy laser systems (ns, ps and fs pulses) and required scaling of pulse energy for an IFE laser driver (parameters of fusion plant according to the LIFE study, employing ns UV pulses for indirect-drive hot-spot ignition). Scaling from the frontiers of DPSSL technology approximately ×50 in performance improvement is needed, in addition to the necessary increase in wall-plug efficiency.

Scalability to IFE platforms

To fulfil the requirements for IFE (beamline with ~10 kJ pulse energy at 1ω, i.e. ~1 µm wavelength, 10 Hz repetition rate, 10 ns pulse duration, 10% wall-plug efficiency including THG), a transition with respect to pulse energy and average power from state-of-the-art lasers like HAPLS and DiPOLE to an IFE beamline and a full-scale IFE laser drive is required and shown in Figure 1 (arrow). To achieve this, several different technology gaps need to be surpassed.

- An integrated IFE beamline design must be developed, which includes the choice of the gain medium [Erl2011], amplifier configuration, aperture sizes as well as thermal management (active cooling, [Bay2011]). The design is needed to identify potential risks, opportunities, tech-nology gaps, supply chain issues, necessary developments, overall schedule and cost esti-mates for realizing a first-of-a-kind plant, and an estimate of the economy of scale.
- Closely connected to the beamline design is the availability of multiphysics simulation codes to better understand the physics of the design and optimize its parameters. An integrated control system for a single beamline using diagnostic data, the simulation code as well as AI based methods is required to tune the adaptive optics, the pump light distribution and other parameters for optimal performance of the laser system.
- The performance (power, reliability, emission spectrum) of high-power diode pump sources must be significantly increased, while at the same time production capacity must be increased significantly and the costs must be reduced by almost two orders of magnitude for an economically viable power plant [Hae2022].
- Technologies for economic and fast manufacturing of a huge number of large-aperture optical components with high precision need to be developed. These components require a high reliability at high-fluence laser operation and in the aggressive environment around the fusion target chamber (for the final optics). This includes passive optical elements for beam image relaying [Che2019], spatial filtering and focusing as well as nonlinear crystals that are used for frequency conversion (SHG, THG) [Bay2011, Hae2016], optical switches, optical isolators and laser materials, such as ceramics, crystal or ad-vanced glasses, with improved thermo-optical properties, longer storage time, or larger gain cross section. Furthermore, new passive and active components (adaptive optics) are required to compensate for large thermo-optical aberra-tions. Advanced surface finishes and dielectric coatings are needed to increase damage threshold and lifetime.

References

[Dan2004] C. N. Danson, P. A. Brummitt, R. J. Clarke, J. L. Collier, B. Fell, A. J. Frackiewicz, S. Hancock, S. Hawkes, C. Hernandez-Gomez, P. Holligan, M. H. R. Hutchinson, A. Kidd, W. J. Lester, I. O. Musgrave, D. Neely, D. R. Neville, P. A. Norreys, D. A. Pepler, C. J. Reason, W. Shaikh, T. B. Winstone, R. W. W. Wyatt, and B. E. Wyborn, IAEA J. Nucl. Fusion 44, S239 (2004)

[Hop2015] Hopps, N., et al., 2015. Comprehensive description of the Orion laser facility. Plasma Physics and Controlled Fusion 57 (6). https://doi.org/10.1088/0741-3335/57/6/064002.

[Zou2008] Zou, J.P., et al., 2008. Recent progress on LULI high power laser facilities. Journal of Physics Conference Series 112 (Part 3). https://doi.org/10.1088/1742-6596/112/3/032021.

[Obe2015] Obenschain, S., et al., 2015. High-energy krypton fluoride lasers for inertial fusion. Applied Optics 54 (31), F103. https://doi.org/10.1364/ao.54.00f103.

[Bag2010] V. Bagnoud, B. Aurand, A. Blazevic, S. Borneis, C. Bruske, B. Ecker, U. Eisenbarth, J. Fils, A. Frank, E. Gaul, S. Goette, C. Haefner, T. Hahn, K. Harres, H.-M. Heuck, D. Hochhaus, D. H. H. Hoffmann, D. Javorkov´a, H.-J. Kluge, T. Kuehl, S. Kunzer, M. Kreutz, T. Merz-Mantwill, P. Neumayer, E. Onkels, D. Reemts, O. Rosmej, M. Roth, T. Stoehlker, A. Tauschwitz, B. Zielbauer, D. Zimmer, and K. Witte, Appl. Phys. B 100, 137 (2010).

[Hor2016] M. Hornung, H. Liebetrau, S. Keppler, A. Kessler, M. Hellwing, F. Schorcht, G. A. Becker, M. Reuter, J. Polz, J. K¨orner, J. Hein, and M. C. Kaluza, Opt. Lett. 41, 22 (2016).

[Spa2016] M. L. Spaeth et al. “Description of the NIF laser,” Fusion Science and Technology 69, 25–145 (2016).

[Bar2004, Hae2009, DiN2015, Ale2020]

[Bay2008] A. Bayramian et al. "High-average-power femto-petawatt laser pumped by the Mercury laser facility," J. Opt. Soc. Am. B 25, B57-B61 (2008).

[Hae2017] C. L. Haefner, A. Bayramian, S. Betts, R. Bopp, S. Buck, J. Cupal, M. Drouin, A. Erlandson, J. Horacek, J. Horner, J. Jarboe, K. Kasl, D. Kim, E. Koh, L. Koubikova, W. Maranville, C. Marshall, D. Mason, J. Menapace, P. Miller, P. Mazurek, A. Naylon, J. Novak, D. Peceli, P. Rosso, K. Schaffers, E. Sistrunk, D. Smith, T. Spinka, J. Stanley, R. Steele, C. Stolz, T. Suratwala, S. Telford, J. Thoma, D. VanBlarcom, J. Weiss, P. Wegner, "High average power, diode pumped petawatt laser systems: a new generation of lasers enabling precision science and commercial applications", Proc. SPIE 10241, 1024102-1-5 (2017). https://doi.org/10.1117/12.2281050

[Hae2016] C. Haefner, "Application-enabling kiloWatt Average Power Petawatt Lasers," in Lasers Congress 2016 (ASSL, LSC, LAC), OSA Technical Digest (online) (Optica Publishing Group, 2016), paper JM2A.1.[Che2019] K. Chesnut, A. Bayramian, A. Erlandson, T. Galvin, E. Sistrunk, T. Spinka, and C. Haefner, "Entirely reflective slit spatial filter for high-energy laser systems," Opt. Express 27, 27017-27027 (2019).

[Bay2011] A. Bayramian et al. “Compact, Efficient Laser Systems Required for Laser Inertial Fusion Energy”, Fusion Science and Technology, vol. 60, 28-48 (2011).

[Sle2022] Slezák, O., Sawicka-Chyla, M., Divoký, M., Pilař, J., Smrž, M., and Mocek, T., Thermal-stress-induced birefringence management of complex laser systems by means of polarimetry, Scientific Reports, vol. 12, 2022, doi:10.1038/s41598-022-22698-9

[Pil2018] J. Pilar, M. De Vido, M. Divoky, P. Manson, M. Hanus, K. Erfel, P. Navratil, Th. Butcher, O. Slezak, S. Banerjee, J. Phillips, J. Smith, A. Lucianetti, C. Hernandez-Gomez, Ch. Edwards, J. Collier, T. Mocek, “Characterization of Bivoj/DiPOLE100: HiLSAE 100-J/10-Hz diode pumped solid state laser,” Proc. of SPIE 10511, Solid State Lasers XXVII: Technology and Devices, 105110X (2018).

[Div2021] M. Divoký, J. Pilař, M. Hanuš, P. Navrătil, O. Denk, P. Severová, P. Mason, T. Butcher, S. Banerjee, M. De Vido, C. Edwards, J. Collier, M. Smrž, and T. Mocek, “150 J DPSSL operating at 1.5 kW level,” Opt. Lett. 46(22), 5771–5773 (2021).

[Div2023] M. Divoky et al. "Kilowatt-class high-energy frequency conversion to 95 J at 10 Hz at 515 nm," High Power Laser Science and Engineering 11, e65 (2023), doi:10.1017/hpl.2023.60(2023).

[Pre2018] J. Preclíková, K. Bartoš, J. Kubát, M. Košelja, B. Rus, M. Divoký, T. Mocek, and J. Houžvička, "Large Scale Single Crystal Growth," in Laser Congress 2018 (ASSL), OSA Technical Digest (Optical Society of America, 2018), paper AM4A.1.

[DeV2023] Mariastefania De Vido, P. Jonathan Phillips, David Meissner, Stephanie Meissner, Gary Quinn, Saumyabrata Banerjee, Martin Divoky, and Paul D. Mason, "High energy, high pulse rate laser operation using crystalline adhesive-free bonded Yb:YAG slabs," Opt. Express 31, 28101-28111 (2023)

[Sek2022] Takashi Sekine, Takashi Kurita, Yuma Hatano, Yuki Muramatsu, Masateru Kurata, Takaaki Morita, Takeshi Watari, Takuto Iguchi, Ryo Yoshimura, Yoshinori Tamaoki, Yasuki Takeuchi, Kazuki Kawai, Yujin Zheng, Yoshinori Kato, Norio Kurita, Toshiyuki Kawashima, Shigeki Tokita, Junji Kawanaka, and Ryosuke Kodama, "253 J at 0.2 Hz, LD pumped cryogenic helium gas cooled Yb:YAG ceramics laser," Opt. Express 30, 44385-44394 (2022)

[Ogi2022] Jumpei Ogino, Shigeki Tokita, Shotaro Kitajima, Hidetsugu Yoshida, Zhaoyang Li, Shinji Motokoshi, Noboru Morio, Koji Tsubakimoto, Kana Fujioka, Ryosuke Kodama, and Junji Kawanaka, "10-J, 100-Hz conduction-cooled active-mirror laser," Opt. Continuum 1, 1270-1277 (2022)

[Yas2008] R. Yasuhara, T. Kawashima, T. Sekine, T. Kurita, T. Ikegawa, O. Matsumoto, M. Miyamoto, H. Kan, H. Yoshida, J. Kawanaka, M. Nakatsuka, N. Miyanaga, Y. Izawa, and T. Kanabe, “213 W average power of 2.4 GW pulsed thermally controlled Nd:glass zigzag slab laser with a stimulated Brillouin scattering mirror,” Opt. Lett. 33(15), 1711–1713 (2008)

[Erl2011] A. Erlandson et al., “Comparison of Nd:phosphate glass, Yb:YAG and Yb:S-FAP Laser Beamlines for Laser Inertial Fusion Energy (LIFE)”, Optical Material Express, vol. 1, 1341 (2011).

[Bay2011] “Compact, efficient laser systems required for laser inertial fusion energy,” Fusion Sci.Tech., 60 28 –48 (2011)

[Hae2022] Häfner C., Holly C., Hoffmann H.-D., “Status and Perspectives of High-Power Pump Diodes for Inertial Fusion Energy Lasers“, IFE Science & Technology Community Strategic Planning Workshop 2022

[1] P. Mason et al., *High Power Laser Science and Engineering* 6 (2018): e65. https://doi.org/10.1017/hpl.2018.56.

Work Package 4: Related technology development (targets, diagnostics etc)

Contributors: Luca Volpe (UPM, CLPU, Spain); Mattia Cipriani (ENEA, Italy), Petra Koester (INO-CNR, Italy), Chris Spindloe (CLF, Uk)

Diagnostics

INTRO: Delivering a conceptual design of the diagnostic set up for the ignition infrastructure operating at high repetition rate and in a harsh environment requires the implementation of a series of diagnostic methods for monitoring all the important phases of the target positioning, implosion and ignition by using optical, X-ray, particle beams, and nuclear based diagnostics. The set of diagnostics fielded on NIF or the Omega Laser Facility[1] needs to be reviewed with particular focus on the technical progress achieved in the past decade, as well as the impact on the overall project. The diagnostics selection for the ignition facility must be primarily designed for the direct drive geometry but also allow testing other ignition schemes to serve a broad community of European scientists.

The operation of the ignition facility requires the use of an extensive set of optical, nuclear and X-ray diagnostics for the radiation emanating from the target, combined with a high energy/power laser pulse for the radiography of the imploding capsule with X-rays and charged particles. Although these diagnostics have been constantly evolving, most of them were designed about 20 years ago and need to be reviewed according to technical progress in the past decade and for their impact on the overall project. The HRR operation constitutes a significant paradigm shift, implying a technical evolution towards a new generation of diagnostics. The diagnostics selection for a future direct drive laser fusion facility also needs to factor in the specificity of this facility: (i) the choice of a direct drive geometry; (ii) the need to accommodate various alternative ignition schemes; and (iii) the need to serve a broad community of European scientists working on high-energy-density physics. Diagnostics for laser implosion are classified in three main categories: optical, X-ray and neutron. This set can fully monitor the self-emission from the imploding target, when also complemented by additional package dedicated to the laser energy balance, e.g. Full Aperture Backscatter Stations (FABS). Fast secondary sources (X-rays, ions and neutrons) for the radiographic imaging of the implosion phase are also necessary. They can be achieved with intense picosecond pulses and require specialized diagnostics. Therefore, picosecond beams and related diagnostics must be implemented along with the nanosecond laser beams in the future facility, to support the research on alternative ignition schemes.

Diagnostics for ignition and high-gain facilities suitable for energy production must be as well developed. The first step will be to conduct a review about the existing diagnostics for fusion and high-energy-density experiments, classifying them according to their technological maturity and potential implementation for high rep-rate operation. Such diagnostics must be optimized and updated to the new scenario of direct drive experiments. Particular care must be devoted to solve issues related to the intense ionizing and non-ionizing radiations associated with the laser-plasma interaction under the HRR operation, identifying the appropriate technology creating diagnostics which can withstand high radiation fluxes. The short pulse radiation sources used for implosion imaging will be improved to achieve a high brightness, specific energy distribution and beam quality. The upcoming target technologies supporting high repetition rate operation must be also considered, including the water leaf, cryogenic hydrogen, thin liquid crystal films and dense gases. The high rep-rate operation implies the necessity to treat a large quantity of information with dedicated protocols. This could be addressed by studying new analysis techniques based on machine learning[2].

Targetry

INTRO: Coherent research on target development for ICF must integrate and assess the infrastructure required to build the targets whilst ensuring compatibility and coherence of target, diagnostics and facility-related critical function design aspects, including radiation and electromagnetic interference. The infrastructure to deliver targets within Europe is not as developed or coordinated as in the US, there is significant capability in France, but this is within CEA and access to the technology for non-defence use may be limited. In addition, a set of requirements for the equipment engineering design and positioning to allow a safe ignition facility operation must be defined followed by a conceptual design requirement for all major engineering parts of the fusion reactor. Indication of techniques to reduce by 90% the EMP effects on the critical equipment.

Target fabrication and management – The complexity of targets for ignition currently is prohibitive for a mass-produced capability, however moving to simpler direct drive type targets will enable the higher repetition rates technologies to be investigated with more confidence. It is clear though that the requested target features are still demanding with some but not all of these being: (i) cost being a small fraction of the energy value per target of the order of centimes of the euro; (ii) extremely large number of targets of the order of one million per day; and (iii) target surface roughness needs to be in the range of 10–100 nm with a precision of 10 µm. There has been a large amount of effort in the US and France to meet these demands but yield (targets that are acceptable) for these is still low. These objectives can also be achieved with low-density micro-structured materials or foams, which have gained interest recently thanks to advanced additive manufacturing, with high potential of cheap mass production and high precision being investigated but not at a production stage yet. The non-trivial internal structure of foams poses severe challenges for numerical simulations. It cannot be modelled as a homogeneous media and reduced models for the high-power laser interaction with foams must be implemented in hydro-codes. Foams can also be considered as secondary targets to be irradiated by high-power picosecond lasers for implosion diagnostics or for experiments on fast ignition. The high interest on these advanced materials by the international scientific community has led to the creation of the Laserlab-Europe AISBL Expert Group on Micro- and nano-structured materials for experiments with high-power lasers.

Target quality, cost and materials - The target quality, cost and materials must be assessed for the future implosion facility with a prospective view of a reactor. Important contributions to the target design can come from target laboratories and industry providers in the United States (General Atomics, LLE, LLNL), Japan (Institute Laser Engineering, Osaka), Europe (Scitech, UK) and China with specifications that must account for the feasibility of target mass-production technology and quality. The development of IFE targets comes as a result of different requirements: i) physics for a high fusion gain; ii) ease in injection, positioning, metrology and debris emission in a high-repetition-rate regime; iii) material technology maturity and potential. Experiments with state-of-the-art materials and structures will be performed to evaluate their performances under laser irradiation at IFE regimes in relation to the technologies of their production. This includes chemically produced foams and additive manufacturing. Laser facilities such as ENEA-ABC and PALS must be used, with laser time provided by the collaboration. The requirements i)-iii) must be combined with the experimental data to provide recommendations on the type of advanced targets for the future implosion facility. They will provide a basis for future experiments after the end of the project. Possible connections with the Laserlab-Europe group on structured materials, which has a recognized expertise in the field.

References

[1] https://www.lle.rochester.edu/omega-laser-facility-2/

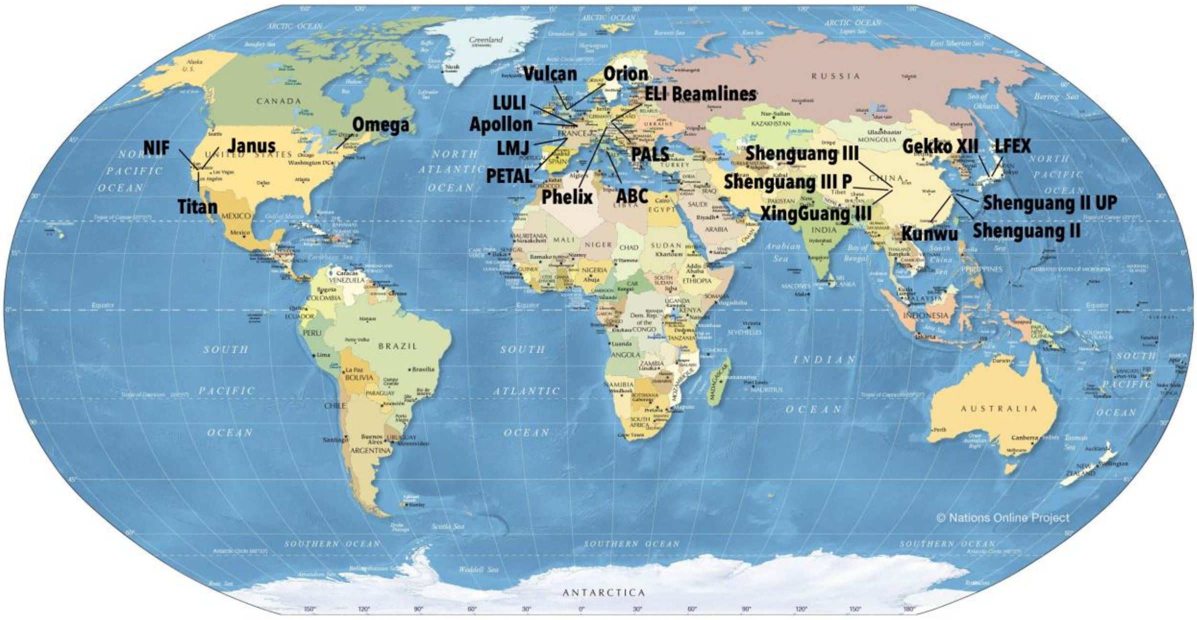
[2] V. Gopalaswamy, *et al.* Tripled yield in direct-drive laser fusion through statistical modelling, Nature 565, 581 (2019)

Work Package 5: Experiments on existing platforms

Coordinators: Fabrizio Consoli (ENEA, Italy), Gabriele Cristoforetti (INO-CNR, Italy) and Dimitri Batani (CELIA, University of Bordeaux, France) to this WP and with input to WP1.

We describe here the current situation on existing laser facilities for ICF/IFE studies, the outline of the critical points and potential ways forward to deal with them.

Brief summary of the situation about the main laser facilities of potential use for IFE studies



Europe:

- **LMJ, France**: the construction will be finished in 2025: 13 bundles (8 beams each) are already constructed and laser operates at energy of 300 kJ. The remaining 9 bundles will be installed in 3 years. Full operation with 176 beams and energy up to 1.4 MJ is planned for 2027. Academic access is already provided, although with a very limited number of shots. It is time to negotiate dedicated access for IFE research, in particular for target implosion studies. This requires a “programmatic” approach, which cannot be guaranteed by the current procedure for Academic experiments based on “best science” selection. Polar direct drive is a possible option.

- **Orion, UK**: has a long and short pulse capability (10 LP beams of ns duration 500J/beam, 351nm; 2 SP petawatt beamlines, 500J / 500fs, one operating in the green for ultra-high contrast). Typically, it fields one academic experiment per year, which must be led by a UK-based academic. In order to maintain Orion's international competitiveness, planned upgrades regard the enhancement of both the long pulse and the short pulse capabilities. The bandwidth option is still not planned.
- **Vulcan 20-20, UK**: Vulcan 20-20 will be operational after 2029/30. The reconstructed facility will house two experimental areas and a capability to field TIM based diagnostics. The facility will aid research towards new frontiers for clean energy, i.e., laser fusion, replicate and enable the study of high-energy-density astrophysical phenomena, and enable physics experiments with the potential to explore beyond the present Standard Model. Characteristics of the planned beams:
    - 20 PW, 400 J, 20 fs – 1 shot every 5 minutes
    - 100 TW, 100 J, 1 ps / 200 J, 10 ps, 1053 nm
    - VOPPEL (1 PW, 30 J, 30 fs)- 1 shot every 5 minutes, 880 nm
    - 10 kJ long pulse: delivered in six 20 cm beams in pulse lengths of 1-5 ns (possibility of extending to 15 ns) with temporal shaping capabilities, converted to the second harmonic (526 nm), with ~0.5% bandwidth, and with a repetition rate of 30 min. With the option in the second phase of the project to increase the overall energy up to 20 kJ by redirecting pump beams from the short pulse beams
- **ELI Beamlines, Czech Republic**: operates two high-energy, high-repetition-rate laser systems: L3 HAPLS (13J/27fs/3.3Hz) and L4n (1kJ/1-3ns/1shot per min). ELI BL is part of the ELI ERIC European infrastructure since Jan 2023. The P3 interaction chamber is one of the unique experimental platforms available for users at ELI BL. The L4n-P3 infrastructure provides kilo-Joule class, nanosecond, repetition-rate laser pulses with pulse-shaping capabilities at 2ω for high-energy-density physics starting from 2024. At the present, a variety of diagnostic systems allows dedicated science studies in laser-plasma interaction in the context of direct-drive inertial confinement fusion (FABS station for LPI experiments) as well as shock-based physics for the study of equation-of-state (SOP and VISAR station). The repetition rate allows for highly improved statistics of the experimental data.
- Several European institutions – LULI and IOGS: France; GSI and HZDR: Germany, ELI-Beamlines: Czech Republic - are partners in the INFRA-TECH project **THRILL**, awarded by EU in 2022 for the development of kJ/ns high repetition rate laser technology.
- The first stage of FAIR (Germany), includes two high repetition rate laser beams PW/ps/kJ, is planned for 2027.
- **PALS** (Czech Republic), **LULI** (France), **Phelix** (Germany) provide access to their facilities through Laserlab-Europe so far, but the situation may be different in the near future. So it becomes urgent to guarantee access for the European scientific community through other channels, that can provide financial support for the laser time and related expenses (travel & accommodation, targets, diagnostics, …)

- The new EU "**Laser4EU**" project was accepted for funding. It includes the new feature of funding projects more complex than just one campaign on one facility, including, for example, multiple campaigns not related to a single facility.

USA:

There is potential access to some facilities by participation in open calls and LaserNetUS:

- NIF (open calls through their Discovery Science access)
- OMEGA
- Titan
- Janus

Japan:

Access is possible at:

- Gekko XII
- LFEX

China:

Access is possible at:

- Shengguang II UP
- Shenguang III
- XingGuang III

Actual situation for ICF/IFE studies

The following physics issues can be investigated on existent laser facilities: fast electron generation and transport, impact of fast electrons on target hydrodynamics, study of nonlinear LPI effects: CBET, collective multi-beam interactions (SRS, TPD), advanced targetry (foam, ablator effects,…), technological issues related to high rep rates, chamber and interaction issues (activation, EMPs,…).

To be undertaken, some specific studies require the development of laser technology on future facilities. For example, experiments with large bandwidths can be performed on some existing facilities, by using chirped and non-recompressed beams, as for example in Vulcan, ELI-BL L4n, and probably at GSI (in a near future also at Omega). However, the available bandwidth is still too small with respect to what is needed for LPI mitigation. Furthermore, the bandwidth is chirped, which adds an additional difficulty in the understanding of the experimental results.

The current situation is clear: Inertial Fusion studies - with the potential to produce remarkable results - cannot be actually performed in Europe, with a few exceptions, with the laser access rules operating today. In all the existing facilities, proposals are selected by a committee, with no guarantee on the time schedule, required number of weeks, and opportunity to continue the same experiment over some years. A programmatic access is necessary. For instance, CEA is far from programmatic access to LMJ, and there is very limited actual time for academic access by European researchers. The Nouvelle Aquitaine region, with the contribution of the European Union, has funded the development of PETAL, the high-energy PW companion of LMJ, specifically for using it as an instrument for academic civilian research, and has encouraged academic access on LMJ-PETAL initiated by CEA. However, this resulted in a very limited number of shots, so far, because the facility is still under construction.

There is now in USA a strong interest in IFE, and this may be useful for pushing IFE in Europe, too. Modification of actual access rules is one of the issues to be promoted.

In Europe, there is no laser facility mainly dedicated to IFE studies. The only two high-energy multi-beam facilities (LMJ and Orion) are not designed for Direct Drive. The **HiPER+** project (under discussion) could be the key to deal with this issue of primary importance. But strong lobbying actions are essential to ask for the construction of a European facility dedicated to IFE studies (i.e in Brussels and in the main European Research Agencies).

In the future, it would be important to have a facility dedicated to IFE for Direct Drive studies at energy levels at least comparable to Omega with, in addition, the capability to address important technological issues such as repetition rate, advanced targetry, diode-pumped lasers, broadband lasers, chamber issues, etc.

The path to a future IFE reactor is long and presents significant physical and technological challenges. The dramatic improvement of the NIF results in ICF experiments during last three years demonstrates that there is a high potential for success, but this cannot be achieved without dedicated laser facilities. These are lacking in Europe, which has indeed a significant scientific community and expertise. A key point for the worldwide progress of the IFE research is then to build a European laser facility dedicated to IFE studies.

References

[1] S. Atzeni and, J. Meyer-Ter-Vehn, “The Physics of Inertial Fusion (Beam Plasma Interaction, Hydrodynamics, Hot Dense Matter)”, Oxford University Press, 2009

Work Package 6: IFE reactor issues (overlap with Tokamak technologies)

Coordinators: J. Manuel Perlado (IFN-GV, Universidad Politecnica de Madrid, Spain), Brian D. Appelbe (Imperial College London, UK)

Brief summary of the research in IFE technologies

In recent years there were no specific designs of IFE reactors and no dedicated research in some of the technological areas inside IFE reactors. However, research in advanced materials for IFE first wall and specific coating against corrosion and permeation has continued, and some new proposals based on modifications of previous designs has taken place as part of the pre-conceptual work in private companies. These are some new developments:

First Wall Materials:

a) **Fabrication and testing new advanced materials with enhanced properties to withstand the harsh conditions (combined effects of thermal loads and atomistic damage) taking place in IFE reactors.**

Using computational simulations at various scales (molecular dynamics and Monte Carlo) the behaviour of hollow W spheres under various irradiation scenarios expected in both inertial and magnetic fusion reactors has been studied.

3D nanostructures of W (isolated nanocolumns) have been fabricated. The influence of sputtering parameters (plasma power and deposition angle) on their morphology and microstructure has been studied. The sputtering yield of these nanocolumns under Ar and D irradiation has been studied experimentally and by computational simulations (molecular dynamics and Monte Carlo) in static and dynamic configuration. It has been observed that the geometry of the nanocolumns significantly decreases the sputtering yield and significantly influences its angular dependence. Computational studies have been carried out using Monte Carlo of the properties of the nanocolumns (length/diameter ratio) that they would lead to a maximum decrease in the sputtering yield.

To study the role of free surfaces in radiation-induced damage and in the behaviour of light species (H and He), isolated W nanocolumns, with different geometries, have been sequentially implanted with C+He+H in the Helmholtz-Zentrum Dresden-Rossendorf (HZDR). For comparison, commercial coarse-grained W samples have also been implanted under the same conditions. The characterization of the light species has been carried out using ion beam analysis techniques at the Centre for Materials Microanalysis (CMAM). The results are currently being analysed.

A review about the limitations for tungsten as plasma facing material in the diverse scenarios of the European ICF facility HiPER and on the use of alternative materials to massive W such as PFMs has been published [1].

New lines of collaboration have been opened among European magnetic and inertial groups (IFN-GV/UPM, CIEMAT, Dresden) for the characterization of isolated W nanocolumns under various irradiation conditions.

b) Extend, improve and validate computational models presently used for studies of radiation-induced damage in diverse materials.

Experimentally and by means of computational simulations (DFT and Monte Carlo) the permeation of H has been characterized as a function of temperature in nanostructured W coatings. Using DFT, the synergistic behaviour (energy, structure, charge and mobility) of various defects coexisting in W grain boundaries and in massive W has been studied.

c) Fabricate advanced materials to work as permeation and corrosion barriers.

SiC coatings have been deposited on EUROFER by sputtering in a planar configuration on semi-industrial setup. The influence of sputtering parameters (plasma power, Ar pressure and temperature) on the morphology and microstructure of the coatings has been studied. The influence of the deposition of an interlayer (bonding layer) on adhesion to the steel substrate has been characterised. The resistance of the coatings to corrosion when being in contact with solid pebbles and its behaviour as H permeation barrier have been studied under diverse temperature and radiation conditions. Also, the behaviour of D in implanted samples has been studied.

The corrosion behaviour, immersion in PbLi, of Al2O3 coatings, currently proposed for ITER, manufactured by ENEA using pulsed laser, has been characterized by using ion beam techniques (IBA). It has been observed that although immersion in PbLi does not produce a significant morphological modification in the coating, but the Li diffuses throughout the entire coating. The possible drawbacks that this could have under neutron irradiation, normal working conditions in a fusion reactor, have been discussed in terms of swelling and possible delamination of the substrate coating.

d) Contribute to identify and use experimental facilities which allows mimicking, as much as possible, radiation environments in inertial nuclear fusion reactors.

A table with the requirements necessary for a round robin experiment in the Plasma focus devices of the diverse laboratories participating in an IAEA Coordinated Research Project (CRP) of the radiation-induced damage in W samples has been produced for new experiments.

e) **IFE reactor technologies by proposing engineering solution to improve reactor operation and safety**.

The conceptual design of a ceramic breeding blanket with tritium breeding ratio tuning capabilities has been completed. In collaboration with CIEMAT, the behaviour of numerous materials has been studied for this concept; the best one is based on lithium titanate as breeder material (thickness ~50 cm), metallic beryllium as neutron multiplier (thickness 2 cm), zircaloy as structural material and heavy water in surrounding tank as neutron reflector (thickness 2 m). By varying the filling level of the tank, it is possible to modify the TBR between 1.0 and 1.1, which is a spectacular advance for fusion plants. A paper, related to this topic, has been published [2].

The interaction of high energy and high power lasers with targets produces large amounts of transient electromagnetic pulses (EMPs) having frequency content up to radiofrequencies-microwaves and intensities overcoming the MV/m. They can be serious threats for electronic equipment and personnel, especially in IFE experiments related to advanced schemes of Direct Drive, such as Shock Ignition and Fast Ignition [3]. The international scientific community is very active on dealing with this issue, for EMP field mitigation for safety, on one side, and for the exploitation of such intense fields and related currents for several promising applications. The Laserlab-Europe AISBL Expert Group on Laser-Generated Electromagnetic Pulses has been set on this purpose.

References

[1] R. Gonzalez-Arrabal, A. Rivera, J.M. Perlado, Limitations for tungsten as plasma facing material in the diverse scenarios of the European inertial confinement fusion facility HiPER: Current status and new approaches, Matter and Radiation at Extremes. 5 (2020) 055201. https://doi.org/10.1063/5.0010954.

[2] A. Fierro, F. Sordo, I.A. Carbajal-Ramos, J.M. Perlado, A. Rivera, Conceptual design of a ceramic breeding blanket for laser fusion power plants with online tunable tritium breeding ratio based on a variable neutron reflector: Remarkable no need of isotopic enrichment, Fusion Engineering and Design. 155 (2020) 111648. https://doi.org/10.1016/j.fusengdes.2020.111648.

[3] F. Consoli, V. T. Tikhonchuk, M. Bardon, P. Bradford, D. C. Carroll, J. Cikhardt, M. Cipriani, R. J. Clarke, T. Cowan, C. N. Danson, R. De Angelis, M. De Marco, J.-L. Dubois, B. Etchessahar, A. Laso Garcia, D. I. Hillier, A. Honsa, W. Jiang, V. Kmetik, J. Krása, Y. Li, F. Lubrano, P. McKenna, J. Metzkes-Ng, A. Poyé, I. Prencipe, P. Raczka, R. A. Smith, R. Vrana, N. C. Woolsey, E. Zemaityte, Y. Zhang, Z. Zhang, B. Zielbauer, D. Neely, Laser produced electromagnetic pulses: generation, detection and mitigation, High Power Laser Science and Engineering, 8, e22 (2020).

f) IFE Reactor Designs

The development of conceptual IFE reactors have a long history from HYLIFE-I/II, HIBALL I/II, KOYO, SOMBRERO, OSIRIS, and in the last decade LIFE (USA), KOYO-F and LIFT (JAPAN) and HiPER in Europe. A large Group of European groups & scientists is renewing HiPER+ based on previous reactor with dry wall and nanostructures as first wall, private XCIMER is basing the development in a new adaptation of HYLIFE-II (now named HYLIFE-III) based in thick jets of liquid metal and first wall of steel as first option, Longview Fusion Energy is renewing LIFE, and Focused Energy and First Light Fusion are also getting new research on IFE reactor design. No special public programs for IFE reactor, materials technologies exist in the world at the moment, only the proposals and ideas of those private companies.

Significant reports have appeared that, despite whether their conclusions are fully correct or not, start renewing the interest in the integral elements to define IFE reactors:

- US DOE Report of the 2022, Fusion Energy Science, “Basic Research Needs”, Tammy Ma & Ricardo Betti (coordinators) delivered in 2023;

- Positionspapier Fusionsforschung, Auf dem Weg zur Energieversorgung von morgen of the German Goverment in 2023,
- ‘Towards Fusion Energy 2023; the next stage of the UK’s fusion Energy Strategy’ published by UK government; and
- ‘Future for Inertial Fusion Energy in Europe: A roadmap’ D. Batani et al., High Power Laser Science and Engineering 2023.

In all of them an explicit mention to the technologies which are economically viable are mentioned.

Role of Europe and Facilities

It is true that a large portion of basic research for materials and systems associated with inertial and magnetic fusion reactors is valid for both options, but with some unique challenges, such as the need for laser optics on the chamber for inertial fusion reactors. Europe has certainly a tremendous capability for using teams in MCF to influence the design of Inertial Fusion systems.

Other potential first wall materials will have different irradiation conditions by neutrons + charged particles + radiation depending on the IFE options and need to be specifically studied, similarly to the structural materials and neutrons irradiation. In irradiation conditions nobody has yet studied the consequence of a pulsed regime versus a continuous regime.

Tritium breeding, handling and recovering, even with similar chemistry, significantly change in the inventory and then the design of system to be adequate to the correct licensing rules.

There are still many questions in the final design that need facilities to pursue the research. Concerning the key aspect for reactors of material damage, Europe will have in some years IFMIF-DONES in Spain that will provide the neutron source in the appropriate spectrum and fluxes to qualify materials under lifetime irradiation. However, such facility, prepared for magnetic option, is not useful to conclude the pulsed effects already unknown for large fluence. An ignition-preparatory facility in laser fusion having enough neutron generation in pulsed irradiation will be of great importance.

Work Package 7: Recruitment, training, diversity & inclusivity

Coordinators: Kate Lancaster & Nigel Woolsey (YPI, University of York, UK), Marta Fajardo (IST, Portugal), Michael Tatarakis (IPPL, Hellenic Mediterranean University, Greece)

Brief summary of current landscape

The biggest threat (and therefore potential opportunity) for fusion globally is growing the community sufficiently to support the development and delivery of fusion reactors in the later part of this century, this requires paying close attention to diversifying our community to make sure we train and recruit the best and brightest regardless of who they are. In the UK an evaluation done by Frazer-Nash reveals that our community must grow by an additional 2500-3000 new workers to support fusion within five years (an approximate doubling). For Europe then, the figures would be much higher in aggregate.

Equality, Diversity and Inclusion

The European inertial fusion community at the highest levels lacks visible diversity, particularly in relation to gender balance. This is in contrast to the situation in the US, particularly at LLNL, which has more visible high-profile women leading ICF programmes. At more junior levels, it’s better, but still not balanced. Some specific issues:

- EU led ICF conferences lack diversity on programme committees and on the resulting conference programmes;
- Lack of diverse range of individuals putting themselves forward for oral contributed talks at EU conferences;
- Poor knowledge of the makeup of our community means we are unable to understand issues and how to address them.

Training

- There has been some dedicated physics training in the area through the ERASMUS IPs, COST actions, and ERASMUS+;
- There are a limited number of general fusion training programmes across Europe;
- Some national labs provide training for students and new users (usually ~two week blocks);
- There are various workshops and summer schools for laser plasma / plasma / HEDS across Europe;
- FuseNET does work in this space but there is limited funding/activity in and around ICF related work.

Consequences of the current landscape in the Europe

- Lack of diversity in the workforce is detrimental to productivity. A more diverse workforce is more productive and more innovative;
- It is detrimental to funding – many funders require applicants to be committed to diversifying the workforce and if not, they will not be able to access funding;
- In terms of the wider fusion field – a lack of diversity is detrimental to energy justice. Who has access to fusion? Who is being exploited for raw materials and how do we protect the environment? How do we ensure past mistakes are not repeated? A diverse workforce ensures a diverse range of voices are heard in the design and delivery phases of new energy sources;
- In terms of training, if we do not grow our community sufficiently we will not be able to capitalise on current results and support the development and delivery of fusion reactors. A more diverse workforce also enables more people to enter the space.

How can the European community make a difference?

Action 1: Gain a better understanding of our community, the issues in our working environments that lead to lack of diversity and establish best practice moving forward.

Action 2: Identify training needs and ways of growing our community to satisfy the growing demand for personnel in the fusion space, and to ensure the workforce is diverse.

Specific actions within the context of Laserlab-Europe:

- Commit to a baseline level of activity to ensure a diverse community. The UK fusion consortium for example require people to sign up to the following:

> *‘The UK Inertial Fusion Consortium is an inclusive network of people. We value multiple points of view and recognise that diversity drives innovation. We aim to foster collaborations and research programmes to solve questions in inertial fusion in a way that is mindful of participants’ need to develop and manage their careers. We will adopt both top-down and grassroots approaches to supporting Consortium initiatives and setting objectives.’*
>
> *The UK Inertial Fusion Consortium encourages all members to:*
>
> - *Consider equality, diversity and inclusivity (EDI) in all activities*
> - *Respond constructively to EDI discussions at meeting*
> - *Foster awareness of equality in decision making*
> - *Be familiar with relevant policies and legislation through participation in EDI training within their home organisations*
> - *Bring information on equality initiatives to the attention of the Consortium*
> - *Celebrate EDI successes and developments*

To broaden the inertial fusion community, the UK Inertial Fusion Consortium will:

- *Include EDI as a standing item in all meetings*
- *Work to influence organisational and cultural change across high energy density physics*
- *Take forward suggestions to enhance equality, diversity and inclusion*
- *Promote a welcoming and supportive working and research culture*
- *Establish ad-hoc sub-groups in relation to specific areas of EDI, as appropriate*
- *Encourage schemes that support disadvantaged groups by any protected characteristic*
- *The Inertial Fusion Consortium will review, annually, EDI activities associated with its initiatives and activities.*

- Survey our community across various topics including awareness and training in EDI, culture of institutions and employers. Use this to identify areas of improvement and development.
- Establish a set of key performance indicators for our community to hold ourselves accountable. Make sure that activity is actually carried out.

In the context of the work across the work packages we must:

- Ensure balance at decision making levels
- Make sure ECR voices are heard in this context
- Decision making performed through the lens of EDI

In terms of supporting and helping our community:

- Establish ways for sharing best practice in EDI space, across recruitment and working environment;
- For European ICF conferences we must ensure balance on the programme committees and programmes. Develop and make sure people sign up to a code of conduct;
- For community experiments associated with this work – make sure all voices are heard on the experiment and make sure teams are as diverse as is possible;
- Develop and make sure people sign up to a code of conduct;
- Develop a shared EDI resource pool.

In terms of training:

- Review provision at a national and international level and identify and potential gaps;
- Explore training potential options at an international level to see if there is value added training at this level (as opposed to nationally);
- Provide ways of sharing this information across the participants.