Future for Inertial Fusion Energy in Europe: A roadmap

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Abstract

The recent achievements at the National Ignition Facility (NIF) in the USA consisting in reaching ignition of fusion reactions with laser-driven technologies set a historic milestone in fusion energy research by demonstrating inertial fusion using lasers as a viable approach for future energy production. Europe has a unique opportunity to empower research in this field at the international level, and the scientific community is eager to engage in this journey. We propose establishing a program on Inertial Fusion Energy (IFE) in Europe, with the missions to demonstrate ignition of fusion reactions with a laser and to develop pathway technologies to the commercial fusion reactor. This document proposes a roadmap for this program comprised of four complementary axes: i) the physics of laser plasma interaction and burning plasmas, ii) the high energy high repetition rate laser technology, iii) the fusion reactor technology and materials and iv) the reinforcement of the laser-fusion community by international education, training programs, and collaboration with research centers, industry and private companies, the establishment of joined activities with the private sector involved in laser-fusion. Along with high level of societal importance this project aims to stimulate a broad range of high profile industrial developments in laser and plasma technologies.

CONTENTS

I. EXECUTIVE SUMMARY

This document presents the result of discussions conducted by the initiative group listed above with the goal to propose a realistic but ambitious coordinated approach to the electric power plant based on the concept of inertial confinement fusion driven by high power lasers. Commercialization of fusion energy is beyond of the scope is this project. It will require involvement of major industries at the European level with a strong governmental support concerning the licensing, fuel supplying and social acceptance. This project aims on the creation of a scientific and technical basis that will enable future commercialization. The goal is to demonstrate the proof of principle of direct drive ignition of fusion reactions with lasers, followed by a sustainable high repetition rate high gain fusion by using the best possible laser technology and materials. This goal will be achieved on a time scale of 20 years and consists in the creation of a European Laser Fusion Research Centre – a joint venture of several major stakeholders – including research laboratories, universities and private companies. In parallel with resolving scientific and technological challenges, this Centre will enable development of innovative laser technologies, high resistance materials and high performance computing of a general societal interest thus demonstrating viability of inertial fusion energy, attracting private investments and providing education of qualified personnel.

The concept of inertial confinement fusion consists in a compression of a "target" made of a millimeter-size spherical capsule, filled with a mixture of deuterium and tritium (the "DT fuel"), more than thousand times and heating the compressed DT fuel to temperatures of tens of million degrees on a time scale of a few nanoseconds (billionth of a second). At such extreme conditions corresponding to pressures of hundreds of billions of atmospheres, the nuclei of deuterium and tritium fuse and release energy that can be transformed into heat and electricity. Till now, we did not know how much laser energy one needs to produce a surplus of nuclear energy. The experiment on the National Ignition Facility (NIF) the USA provides for the first time a quantitative response on this crucial question: what are the conditions needed for producing a large amount of fusion energy with lasers? It is demonstrated in December 2022 that with 2.1 MJ laser energy it is possible to achieve ignition, that is, to burn the DT fuel with 1.5 times more nuclear energy released than the laser energy needed to induce this process. This achievement opens the way for the next stage of research and development: a robust control of ignition; the design of targets able to produce approximately one hundred times more fusion energy than the laser energy input; to develop the supporting infrastructure, technology and materials for an IFE reactor that is expected to routinely produce about ten micro-explosions per second. According to existing projects, IFE power plants can be built on separable, modular technology; they are safe, offer a large flexibility in the energy production, and can be commercially viable.

There are two ways to compress the DT fuel: by the mean of a direct illumination of the target by laser light, this is the direct drive approach, or by the mean of X-rays produced by heating a gold cylinder, surrounding the target, with the laser beams, which generate the X-rays that implode the capsule, this is the indirect-drive approach. The indirect-drive ignition scheme explored at the NIF is necessary for defence applications, but the laser energy is used inefficiently. Contrary, the direct drive approach promises a $4-5$ times more efficient use of the laser energy. Thus, a lower energy is needed for ignition and a higher fusion energy yield can be achieved. Yet, there is no laser facility where the direct drive ignition can be demonstrated.

European scientists have made ground-breaking contributions to inertial fusion in theory, numerical developments and experiments. They performed pioneering works in the high energy density physics by studying laser-plasma interactions, including parametric instabilities and hot electron production and transport. European scientists are also taking the lead in the high field physics with short-pulse high-intensity lasers. These important contributions to the high-energy, high-density and high-field physics have led to two large-scale laser projects included in the roadmap of the European Strategic Forum for Research Infrastructures (ESFRI): High Power Energy Research (HiPER) dedicated to the inertial fusion energy and Extreme Laser Infrastructure (ELI) dedicated to fundamental studies of electromagnetic processes at extreme laser intensities. Unfortunately, due to the delay in achieving ignition at NIF, HiPER was stopped in 2013, while ELI is progressing successfully at three sites in Czech Republic, Hungary and Romania.

The recent achievement at the NIF calls for the resumption of the quest for inertial-fusion energy-based on the heritage and legacy of the HiPER project but at a new level of knowledge and technology developed over the last 10 years. Different from the national inertial fusion projects in the USA, Japan, Russia and China, European scientists propose a veritable international project HiPER+ dedicated to the civil fusion energy production and development of high-level spin-off technologies.

The European IFE project is built on the shock ignition scheme developed by the European academic community in a close collaboration with American scientists of the Laboratory for Laser Energetics at the University of Rochester. This scheme considers direct illumination of a spherical capsule with a specific laser pulse shape. According to preliminary experiments and numerical simulations, this scheme is promising ignition with the laser energy of about $0.4-0.5$ MJ and a higher energy gain with a 1 MJ laser. This scheme has already confirmed its advantages in the dedicated sub-scale experiments at the multi-beam, multi-kJ laser facility Omega in the USA. However, shock ignition faces scientific challenges, which require further investigations. This concerns the efficiency of laser-target coupling, the generation of a sufficiently strong shock to produce a robust, repetitive ignition, the development of lasers operating at high repetition rates and technologies for the target fabrication and energy recovery.

The project HiPER+ aims at the stage beyond the single shot ignition demonstration, on research and development related to the construction of a high-performance laser facility with a high repetition rate, the demonstration of a robust and repetitive fusion energy production, and then the design of a commercial inertial fusion power plant. It will be conducted at the European Laser Fusion Research Centre in close collaboration with national laboratories, universities, private companies and industry. The Centre will be able to conduct research and development activities at the best possible level, to test innovative target designs, advanced diagnostics, mass target fabrication, laser and fusion technologies and to provide an internationally competitive theoretical, computational and logistics support. The project HiPER has been a turning point that demonstrated the possibility to bring together the European community beyond the national limits, within one common research and development project directed to the inertial fusion energy production. The new project HiPER+ takes off from the heritage of HiPER with the lessons learnt from the NIF experiments and with the major advances in the laser technology – smart flash lamps and diode laser pumping – enabled by the ELI project.

A multi-beam laser facility operating at a few hundred kilojoule level and with a repetition rate of one laser shot per minute is the major milestone of this project. This will be a test-bed for researches on: physics of IFE targets; laser-target interactions; development of new laser and target technologies; design and testing of new materials resisting to extreme conditions of radiation, temperature and mechanical stress. This will be the first-in-the-world laser facility dedicated to research on inertial fusion energy and other applications in the high energy-density physics. It will unlock the major scientific and technological issues related to the ignition scale experiments and will address problems as: reproducibility of the capsule implosion, control and mitigation of different kinds of instabilities, optimization of target implosion and ignition schemes, injection and alignment of targets. Such laser facility will address also the technical aspects or primary importance: effects of target debris and vapours in the chamber, damage to optics and the chamber walls, activation of materials, protection from electromagnetic pulses and development of novel types of diagnostics.

The progress made by the laser technology in the last decade and the maturity of optics and laser industry make possible the building of such a facility at an industrial level as a modular structure, by replicating elementary blocks with an average power of a few hundred watts and laser pulse energy of a few kJ. The design and construction of such laser facility will also benefit the European industry since the elementary laser modules will find many other industrial applications: compact sources of protons and neutrons for material analysis and medicine, new generation of thrusters for space propulsion, material modifications with lasers, space debris removal, mass fabrication of high precision objects and many others. It will build also stronger connections with the magnetic-confinement-fusion research and development activities, which shares many common objectives in the design of the fusion power plant.

The creation of a European Laser Fusion Research Centre will be beneficial for both Science and Industry, by consolidating the research groups spread over the different countries, providing them a common, modern high performance research tool and prompting the development of innovative laser, material and optics technologies that are the key elements for the sustainable progress in the 21th century. This is the time to organize a new European IFE project that will make a breakthrough jump over ignition and prepare the technological bases with the future clear, sustainable, flexible and safe energy production.

II. BACKGROUND

The concept of laser-driven Inertial Confinement thermonuclear Fusion (ICF) was proposed in 1972 in seminal papers by American and Russian scientists [1, 2], which initiated a worldwide effort to demonstrate inertial fusion in the laboratory. After five decades of continuous progress toward ignition, scientists at the NIF at the Lawrence Livermore National Laboratory, USA, announced major advances: In the experiment on August 2021, about 70% of the input laser energy was converted into products of the deuterium-tritium (DT) fusion reactions [3–5]. In the experiment on December 2022, the released fusion energy surpassed by 50% the 2.1 MJ input laser energy [6]. These groundbreaking results provide an unambiguous demonstration of the validity and the feasibility of the concept of inertial fusion energy (IFE) with lasers. It is very likely that much larger energy gains will be demonstrated by the US scientists shortly.

The approach pursued by the Livermore scientists is based on the indirect drive scheme where the incoming laser radiation is first converted in soft X-rays in a gold cylinder cavity (hohlraum). Then, these X-rays symmetrically irradiate a spherical capsule filled with DT fuel positioned in the center of the cylindrical cavity. The radiation ablates the outer layers of the capsule, compressing the fuel inside more than a thousand times and heating it to a temperature of hundred millions degrees. These are conditions where the fusion reactions take place and release a surplus of energy in a form of energetic neutron and radiation. Since this is a national, defence-motivated program, the NIF laser was not built for conversion of the fusion energy in electricity, and the beam arrangement is not optimized for IFE. The facility time is shared between the stockpile-stewardship program, basic science experiments and ICF. As such, it is not well suited for open IFE research, both from a technical standpoint and a program standpoint. Similar national, defence-oriented programs are pursued in France, UK, China and Russia.

The indirect drive scheme can be considered for the energy production. A project LIFE has been developed by the Livermore scientists [7] based on a solid state laser technology, and a new startup company XCIMER has been organized recently aiming on the fusion energy production by using an excimer lasers [8]. However, this scheme suffers from very inefficient laser energy coupling to the target and a large mass of hohlraum that increases the amount of radioactive waste.

The direct drive approach consists in the direct laser irradiation of a capsule with a DT fuel thus bypassing the step of conversion in X-rays in the hollow gold cylinder. It is more efficient and better suited for energy production, but implosion is less stable and needs a better control. This is a promising approach for construction of a fusion power plant: an abundant, clean, sustainable and on-demand energy source for mankind. Research on the direct drive ICF are concentrated in the USA, UK and EU. The direct drive project HiPER (High Power Laser Energy Research facility) was included in the roadmap of the European Strategic Forum for Research Infrastructures (ESFRI) and conducted for 7 years from 2006 to 2013 [9].

HiPER was a unique European initiative with international participation on Inertial Fusion for Energy (IFE) aimed at exploring the science and technology of laser direct-drive fusion schemes, which are suitable for commercial energy production from laser-driven DT fusion reactions. In the second phase, HiPER project was focused on the shock ignition scheme, which promises ignition at a lower laser energy level and higher fusion energy gains compared to the conventional direct-drive scheme. It is based on existing robust laser technologies and many key elements can be tested at full scale on the existing laser facilities including NIF in the USA and LMJ in France. HiPER also had a key role in developing designs of Reactor technologies that allow us to define the research to be done and the risks associated to the different reactor systems. Another equally important objective of HiPER project was to build a sustainable, long-term, basic science program, strengthen the international collaboration and stimulate high level technological and industrial developments in the high power laser technology, high resistant materials and optics. HiPER has made however several strategic mistakes by promising to provide an electrical power plant in an unreasonable short time scale and by changing the strategy and goals in the course of project.

Unfortunately, HiPER was ahead of its time. Due to the delay in achieving ignition at NIF, HiPER finished its preparatory phase in 2013 [9, 10], and the direct involvement of Europe in ICF research has slowed down in the last 8 years because of a very low level of funding and a severely limited access to experimental facilities. Nevertheless, the funding coming mainly from the EUROfusion Enabling Research (ENR) action and some national projects has allowed to keep the community in Europe active and productive. The latest ENR action ”Advancing shock ignition for direct-drive inertial fusion” for the period 2021-2024 is the continuation of two previous ENR projects, aiming at realizing a European research program on Shock Ignition scheme (SI) and its implantation in a reactor, a promising approach to ICF developed in collaboration with US scientists [11, 12]. In addition, the funding from Erasmus+ program contributed to the training of young scientists in the fusion sciences [13]. Yet, the most important output of the HiPER project is its impact on the laser-fusion community, which has experienced an impressive growth in Europe, mainly directed towards the exploitation of a new generation of high-power, high repetition rate laser facilities [14].

The energy gain of 1.5 achieved on the NIF confirms that the physics of laser-driven ICF works as anticipated; thus enhancing the confidence that it could provide a viable solution for fusion energy. An inertial fusion reactor has advantages of a modular technology, flexible configuration, a low tritium inventory, and a relaxed constraint on first-wall damage. Moreover, ICF shares with magnetic confinement fusion common points such as energy recovery, structural materials, remote robotics in a harsh environment and tritium breeding and handling. Development of both approaches in Europe will certainly benefit each other and will enhance the probability of success in establishing a commercial fusion power plant. With a strong background in the plasma physics, material and laser technology accumulated over 50 years of intense research, European scientists are capable of taking a leading role in IFE research and development at an international level [15, 16].

The quest for clean and sustainable energy sources has attracted recently a growing interest from the private sector [17]. Investments into fusion startups have accelerated in the last years. In particular, in 2021 various fusion approaches, including laser fusion, attracted more than €2.3 B of venture capital funding, mainly for US companies. In Europe, industries join the nuclear fusion race with growing interest. For instance, industrial companies SIEMENS ENERGY, THALES and TRUMPF develop laser technology jointly with the German startup MARVEL FUSION, which raised €35 M in a funding round led by venture capital investor EARLYBIRD [18]. Another German-US startup company FOCUSED ENERGY [19] is building an IFE laser research facility in a public-private partnership with the US Department of Energy. There is an evident need for much better coordination of IFE research through the establishment of a new ambitious program in Europe. The HiPER+ initiative will pursue the original HiPER objectives at a new level of knowledge, technology and organization [16] .

III. ICF RESEARCH IN EUROPE

A. Physics of inertial confinement fusion

Inertial confinement fusion entails a large variety of interesting physical phenomena such as nonlinear laser-plasma interactions, target hydrodynamics and implosion symmetry, energy transport in the plasma by thermal and non-thermal particles and X-ray radiation, atomic physics, equation-of-state of matter at high energy densities, ionization processes and transition from solid state to plasma, fusion burn physics, generation of strong magnetic and electric fields and energy recovery. Correctly modeling target implosion under laser irradiation and fusion energy release, requires accounting for all these processes simultaneously, which needs of a significant amount of theoretical, numerical and experimental work supported by the development of innovative technologies and materials. In the last 20 years, the ICF community in Europe has made critical contribution in all those fields as summarized in the several key references: [20–30]. This work in turn feeds through to the development of state-of-the-art simulation codes [31–33], validated by experiments and used to explore implosion physics, target designs and implosion schemes.

The original ICF design is based on the central hot-spot ignition scheme, where a spherical shell target is symmetrically compressed at high velocity by a direct irradiation of lasers until it reaches a sufficient convergence ratio (also called ”fuel assembly” phase). The kinetic energy of the imploding shell is used for compression and heating of the fuel in the centre of the target to the level needed to ignite fusion reactions. The burn wave then propagates into the cold dense surrounding fuel material. This *Direct Drive scheme* has been extensively studied using experiments on the Omega laser by scientists from both US and Europe. The challenges of this scheme are also shared with the shock ignition approach. Several critical issues of both schemes have already been identified and addressed. However, the Omega experiments are limited by the laser energy of $20 - 25$ kJ, which is $20 - 50$ times below the ignition threshold. Demonstration of energy gain and of reliable energy production poses new challenges. One needs new laser reliable system able to perform many shots per day at MJ-level, a design of simple and robust targets capable to withstand typical laser system errors [34], suited for mass-manufacturing and cost effective. One of the possible solutions is the dynamic shell concept [35] using a foam as structural element.

An integrated approach must be developed that combines the physics requirements with material constraints, high performance diagnostics and technology availability. The reactor chamber design has to have an optimized laser port layout for both symmetry and robustness, compatible with the systems of target injection and energy recovery [36]. The materials that will be used for construction of the reactor chamber, target injection system, energy recovery and tritium production have to be resistant to harsh radiation environment, thermal loads and mechanical stresses so the reactor life time to be compatible with the commercial energy production. Addressing these formidable challenges is possible at the existent level of science and technology but it requires joint efforts of specialists from different domains of science and technology with a common project.

B. Shock ignition scheme

A large part of the ICF research in Europe has been focused on the shock ignition concept proposed and developed in collaboration with US scientists [11, 12]. In this scheme, the fuel assembly phase is separated from the ignition phase. The target is first compressed by a lower intensity laser radiation at lower implosion velocities and then ignited by a strong laser-driven spherical shock. The separation of these two phases is the major advantage of this scheme. It provides a more stable and energy efficient capsule implosion and a larger amount of compressed fuel for the same laser energy. The implosion is achieved with a relatively low intensity laser pulse of less than 10^{15} W/cm^2, which compresses the fuel at a low entropy to higher densities. The ignition of fusion reactions in the centre of the capsule is achieved with an additional short and intense laser pulse at the end of the fuel assembly pulse, which generates a strong converging shock of a pressure of $200 - 400$ Mbar propagating into the capsule. The timing of this spike pulse is optimized such that the strong shock arrives to the centre at the moment when the fuel compression is maximal. Once ignition conditions are reached in the central hot spot, a burn wave propagates through the high-areal-density fuel assembly, leading to high fusion gain. The typical laser power and timing window for the launching of the strong shock to achieve ignition are several hundred terawatts and several hundred picoseconds, conditions that are compatible with the characteristics of the existing laser facilities NIF and LMJ.

Preliminary, shock ignition experiments at the OMEGA laser facility in the USA at energy level of 25 kJ have demonstrated the advantages of the shock ignition scheme compared to the conventional direct drive scheme: the creation of a strong laser driven shock resulted in increased number of fusion reactions manifested in the number of detected neutrons [37] and a shock pressure exceeding 200 Mbar has been reported [38]. Other variants of the shock ignition scheme, potentially more efficient, have been proposed: the ignition shock driven by the laser radiation and hot electrons [39] and the shock augmented ignition by using a dip in the laser power before launching the shock

[40]. These schemes are under evaluation experimentally on high energy laser facilities.

C. Challenges in ICF

While the results of radiation hydrodynamic simulations and experiments are optimistic for the prospect of high gain with the direct drive scheme and shock ignition in particular, these schemes have scientific and technical challenges, which are yet to be addressed. The studies on IFE require sustained and coordinated efforts of the scientific community, close relations with the private sector and strong governmental support. One major physics question is that of laser–plasma interactions (LPI), particularly during the high-intensity laser spike pulse, which may reduce the amount of laser energy absorbed in target [41], reduce amplitude of the shock wave [34] and prematurely heat fuel by hot electrons [42]. Low-entropy implosions of standard direct-drive capsules have shown a high risk of failure, indicating new sufficiently resistant and robust target designs are needed. Furthermore, modulations of the ablator's surface and density inhomogeneities resulting from target fabrication and from sub-wavelength scale perturbations imprinted on the ablator by the laser irradiation can grow, reducing the igniting-shock launching window [43, 44]. Strategies for mitigation of laser imprint on the ablator have to be developed. The use of foam materials can be promising [45, 46]. Studies of the ignition physics must be coordinated with the development of a new generation of high energy, high repetition rate lasers, design of high performance plasma diagnostics and target mass fabrication technology.

Studies of the baseline HiPER target design [12] suggest that hot electrons, depending on their energy, could either improve the target performance or worsen it. Hot electrons with energies less than 50 keV do not produce deleterious effects, but amplify the shock strength and improve the target performance [47]. By contrast, more energetic electrons generated during the spike may ablate the DT ice inner interface and increase significantly radiation losses, preventing ignition [42]. These results highlight the necessity of designing more robust targets, taking into account the detailed characterization of nonlinear LPI effects, hot electron generation and transport.

LPI mitigation strategies allowing to reduce laser energy losses and to diminish or tune hot electron generation need to be investigated [48]. The manipulation of laser coherence time and the development of broadband lasers appear particularly promising for the suppression of LPI [49]. Increasing laser bandwidth between a few tenths of a percent to a several percent can inhibit laser filamentation and LPI. Laser zooming [50] for the spike pulse has been proposed to improve laser–shock coupling and to significantly reduce cross-beam energy losses. Improved control of LPI will also allow the testing of ignition schemes using second harmonic of Nd laser, instead of the third harmonic, which opens the way to a more efficient use of laser energy [23] and are better suited for operation at high repetition rates.

D. Lessons from the NIF ignition campaign and OMEGA laser facility

The European IFE project profits from the knowledge and experience acquired during the 12 years of experiments carried out on the NIF and from several thousands of direct-drive implosion experiments conducted at lower energy on OMEGA [51]. The failure of the National Ignition Campaign staring 2013 was due many issues that were not well controlled and understood at that time. They include insufficient symmetry of laser irradiation, laser plasma instabilities and defects in the target fabrication, which lead to premature development of hydrodynamic instabilities and shell break. Also insufficient precision of the radiation-hydrodynamic codes and a limited number of diagnostics available in the experiments did not provide the degree of accuracy needed to design a target that ignites in an experiment with a limited energy budget. The diagnostics were not capable to provide a detailed information about the processes going on in the capsule inside a closed hohlraum. The lasers were not capable of delivering precision pulses with sufficient repeatability, power stability and pointing accuracy.

Since that time, a large amount of work addressing these issues has been conducted. The issues related to the quality of implosion have been identified and resolves one after another. The physics included in the codes was greatly improved and provides now a better agreement with experiments and more stringent limitations on the parameter space where ignition and gain can be achieved. More than 60 high fidelity diagnostics have been developed on the NIF, all providing valuable insights into the physics processes in the imploding target. The laser performance is continuously improving as the operators have better control of the the beams quality qnd focusing, and better understanding the physics issues at play. More than a thousand implosion experiments performed on the NIF since 2009 and a large amount of numerical simulations have provided a large database, which is used for a fine tuning of hydro-codes, designing empirical scaling and improving it with machine learning techniques. Along with a significant improvement of the laser performance and target fabrication technology, the progress in theory, simulations and diagnostics is the main reason for the recent successes on the NIF. Similar progress in terms of diagnostics, codes and laser beam control was achieved in the last 10 years on the OMEGA facility. While the laser energy is limited to 30 kJ, it is configured in direct-drive and provides an invaluable test-bed for direct-drive physics.

The lessons from the NIF and Omega campaigns provide an important input for the European IFE project that will reduce the risks and accelerate the progress:

- The control of the shell symmetry during implosion has proven to be a key issue in the quest for ignition. It implies an advanced target design, high precision of laser beam focusing and a high quality of target fabrication: reduction of the surface roughness, suppression of asymmetry and control of homogeneity of the fuel layer by using a high performance metrology.
- The quality of laser irradiation on the capsule is crucial to achieve ignition. Deformations in the capsule resulting from a non-uniform irradiation must be reduced by improving the quality of laser beams and pointing precision.
- Hydrodynamic instabilities have to be better predicted and controlled. They were the main reason of the failure of the National Ignition Campaign in 2013, and their mitigation has led to the success of the most recent experiments.
- The control of laser plasma interaction is mandatory for efficient laser energy coupling to the target, energy transport and reduced fuel preheat. Direct drive experiments have shown the importance of controlling Cross Beam Energy Transfer (CBET) and its impact on the laser energy absorption and implosion symmetry.
- Recent successful Omega and NIF experiments strongly benefited from a large database that provided step-by-step improvements in the target performance based on machine-learning techniques [52, 53].

These conclusions are considered as important information in the development of the European IFE roadmap.

E. Laser technology developments

ICF research has provided a strong boost for the development of new laser technologies and dramatic growth of laser industry. In parallel, the advent of Chirped Pulse Amplification has led to the construction of ultrashort pulse, ultra-high intensity and high repetition rate laser facilities worldwide. Europe-based leading laser manufacturing companies Thales, Amplitude and Trumpf are capable of delivering turnkey high power, high repetition rate laser facilities and provide technical support for their operation. The European ESFRI projects, Extreme Light Infrastructure (ELI) [14] and European Plasma Research Accelerator with eXellence in Applications (EuPRAXIA) [54], stimulate rapid scientific and technological developments on a very short time scale aimed at high field science, particle acceleration and secondary radiation sources. Many of these developments have generated industrial products that are also impacting on other commercial areas including the medical and manufacturing industries.

The scientific communities in high energy density physics, plasma physics and high power laser technology are working closely with each other with large European research institutes having active research programs in all of these areas, which share common background knowledge. The laser-plasma community is a large and expanding community partially merging with the synchrotron and X-ray Free Electron Laser communities sharing a common interest in investigating extreme states of matter with ultrashort and high brightness X-ray pulses. These communities also share particle and radiation diagnostics and high power laser technologies, which has significantly advanced in the last 10 years.

The third and fourth generation Light Sources – synchrotrons and free electron lasers – on the one side, and high power, high intensity laser sources on the other, are at the core of many of the latest technological and industrial developments. However, access to these large facilities is strongly limited due to their high cost, low repetition rate and large size. A further revolution is needed to reduce their size and cost and to improve their reliability. Solid state lasers' average power and repetition rate are limited by the use of the flash lamp pumping. New approaches based on high efficiency diode pumping are paving the way to high average power, high efficiency and high repetition rate lasers. This transition is a necessary step for the IFE program and it will make lasers and laser-based light sources available to a broader community, empowering small and medium high tech enterprises, making them capable of industrial research currently only accessible at large installations.

The transition of high energy, single pulse lasers to high average power and high repetition rate is a key milestone for IFE research. Assuming an improvement of efficiency by a factor larger than 10, as anticipated by theoretical studies and demonstrated on sub-scale prototypes such as DiPOLE, the total energy needed per ignition cycle will still be above 100 kJ, which corresponds to an average laser output power of 100 kW at 1 Hz operation rate. In addition to this outstanding challenge, special requirements on the temporal and spatial laser pulse-shape are to be fulfilled. The architecture of the lasers has to allow also for a small installation size and a maintenance scheme for 24/7 operation.

The transition from a proof of principle demonstration of ignition of fusion reactions on the NIF to the repetitive operation required in a future reactor is at the core of this IFE project. Technical specifications for IFE lasers are extremely challenging, but these technological developments are largely overlapping with other needs for industrial applications. There are no doubts that innovative and ground-breaking solutions in laser technology will emerge soon. European laser industry is sufficiently mature today to take on the construction of such a modern multi-beam, high energy and high repetition rate laser facility. An ambitious IFE program will play a driving role by setting the laser specifications of interest for other high tech applications.

F. Reactor technology developments

The history of development of reactor designs in Europe comes from the 1980s [55, 56]. A significant European contribution, HIBALL and HIBALL-II, was developed for heavy ions driven IFE facility contemporary to several similar projects in USA. Some of the proposed solutions, such as INPORT concept of using porous, flexible tubes of woven C or SiC fibers to contain liquid metals inside the vacuum chamber of an ICF system [57], are of interest not only in inertial fusion but considered as a solution for magnetic divertor. IFE reactor designs have been significantly extended in the USA since the 1970s in collaboration with European groups on specific research subjects. From those computationally developed ideas a key IFE concept emerged that enabled first wall protection in IFE: thick liquid jets [58, 59], thin liquid [55, 60–62] and gas protections [7, 63] have been studied and in some cases also experimentally proved. The assessment of neutronic conditions for blanket structural materials has been extensively studied with numerical computations [64]. The conditions of activation and safety can be concluded from them. However, the conclusions concerning the neutron irradiated materials are waiting for experimental proof. These studies need coordination with similar research in magnetic confinement fusion, and also further studies for the specific IFE conditions of pulsed irradiation.

HiPER has marked a significant European step toward the design of a power plant prototype with a direct drive laser irradiation. The project has finished with a realistic computational design of the reactor systems including the chamber dimensional layout, the first wall and blanket design with cooling systems and the neutron management, damage and activation assessment and safety considerations [65–67]. Significant progress in the multidisciplinary science of materials at extreme conditions driven by the HiPER project [9, 10] has enabled improvements in the laser optics and structural materials, which are the key parts of the IFE chamber. This includes a better understanding of optical materials under extreme irradiation conditions [68, 69], tritium retention assessment, control of irradiation conditions of the first wall [70], resistance of the first wall materials to charged particles and X-rays [71, 72], and thermo-fluid dynamics for the cooling and energy recovering systems. Beyond the ignition demonstration, three operation modes for the IFE facility were considered in HiPER: (i) a burst mode demonstrating some key elements of the future power plant such as repetitive laser shots, target injection and debris mitigation and management, (ii) a prototype of the fusion reactor with a blanket and heat exchanger for the energy recovery and tritium breeding studies, and (iii) a demo power plant with the fuel breeding and electricity generation for the optimization and commercialization of the IFE technology. This strategy can be reduced to two steps (i) and (iii), thus reducing the overall time of the HiPER+ project. A chamber for goal (i) is the first affordable need to build a repetitive experimental facility, together with advances in power plant research (iii).

Improving the damage resistance and development of refurbishing optics technologies are indispensable parts of the IFE technical background, which are also needed for promoting the insertion of lasers in industry. Development of radiation and neutron resistant materials is the subject of common interest for all fusion energy projects. It could act as an incubator of innovative solutions indispensable for a future power plant and driving industrial development in other areas.

G. Targetry

The development of target mass fabrication, improvement of the target quality and metrology, and target injection technologies are of high importance. They will be in the scope in the IFE project and will also benefit other industrial applications. The target fabrication is under permanent development because of new challenges in the experiments not only linked to ICF/IFE but also to other science experiments on high energy density physics on x-ray radiation facilities such as ELI, XFEL, ESRF. The international situation is favorable for IFE with laboratories in USA (General Atomics, LLE, LLNL) in Japan (Institute Laser Engineering, Osaka) and in China.

Europe in particular made a great development in this area and, along HiPER project, IFE goal was very much upgraded and cooperative among the European groups. In the last years such cooperation was maintained (8th Target Fabrication Workshop, Oxford, UK, September 2022), and added through Laserlab Europe, that is working as good coordinator and launcher. The requirements on the target quality, the cost and materials are compatible with the technologies already developed in the industry. It is clear that their cost need to be a small fraction of the energy value per target, which has to be within 10's cents Euro, the repetition will be in the range $5-10$ Hz, the target surface quality in the range of $10-100$ nm and precision of 10 micron. Mass-produced cost-effective target configurations have to be pursued, a purpose that can be obtained potentially also thanks to low-density structured materials [35]. In particular, the recent achievements in the micro lithography and mass productions of micro chips share many technological requirements with IFE and will provide a solid reference point for future IFE technologies.

H. Safety

Safety and security are indispensable parts of the IFE project. They include reliable and sustainable operation of the laser, diagnostic, control and target injection systems, in particular, in the high repetition rate regime and harsh electromagnetic and ionizing-radiation environment.

The development of tailored strategies of mitigation for laser-generated electromagnetic pulses (EMPs) is of primary importance for the operation of any electronics, including experiment diagnostics, in the reactor. Nevertheless, their effects have to be reduced, because they represent a source of high risk, even in current high energy and intensity ICF experiments [73, 74]. It is well known that these fields scale with laser energy and intensity, and for direct drive irradiation schemes (Shock-Ignition and Fast-Ignition) we can expect these fields to be up to the MV/m level within the experimental chamber. On the other hand, the research activity related to EMP sources has a high potential for applications related to the generation of tailored magnetic [27] or electric [75] fields of high intensity, or traveling electromagnetic waves [76], that can be applied to advanced ICF configurations and also to a wide multidisciplinary set of different fields, capable to attract the interest of private companies.

I. ICF community and its competences

The academic community is working in inertial fusion in Europe in a tight collaboration with the national organizations such as CEA in France, AWE and UKRI in the UK, ENEA and CNR in Italy and CIEMAT in Spain and with the international partners in the USA, Japan and China. European scientists have made groundbreaking contributions to the ICF in the theory, numerical developments and experiments, and materials and reactor developments. They made important, and often pioneering, contributions in the study of laser-plasma interactions, including parametric instabilities and hot electron production and transport. European scientists are taking the lead in the high field physics with short pulse high-intensity lasers. They developed advanced plasma diagnostics based on laser-driven radiation and particle sources and use them for studying new extreme states of matter. European scientists contribute with new ideas and development to the specific IFE challenges appearing when studying the advance materials (nanomaterials) for first wall and coatings against corrosion, the neutronic transport, materials activation and damage modeling and proposing integral layout for IFE reactors. A large collaboration is followed in this area with programs on IFE in USA [77] and High Average Power Lasers Program (HAPL), and Japan and with magnetic European fusion in those common areas such as structural materials, cooling and tritium breeding.

Several laser facilities at the kJ energy level operate in France (LULI2000), Germany (PHELIX), Czech Republic (PALS, L4n) and UK (Vulcan). With three ELI pillars in the Czech Republic, Hungary and Romania joining an European institution ELI ERIC [14], Europe is the worldwide leader in high power laser facilities. However, there are only two multi-beam multi-kJ laser facilities in Europe: Orion in UK, operated by AWE, and LMJ-PETAL, operated by CEA, with a limited academic access. The lack of a research multi-beam, multi-kJ laser facility (like OMEGA in the USA or GEKKO in Japan) has limited the competence of European scientists in key subjects such as implosion of spherical targets and hydrodynamic instabilities. The contribution of the European scientific community to ICF for the last 10 years has been mainly related to the basic physics aspects leaving the integrated approach aside.

With the exception of the period of 2006-2013 of the HIPER project, there were no pan-European coordinated IFE programmes. Projects related to IFE are supported by short-term competitive low-level national funding, which is not compatible with a long-term coordinated collaborative project. Moreover, restrictions connected to the defense commitments in UK and France, complicate the exchange between the academic and government laboratories and private sector, which is needed for the development of high performance numerical tools, which are indispensable for high quality research. In contrast, magnetic confinement fusion research and technology development benefits from the coordination and financial support by the EUROfusion consortium at the international level with a long term focused program.

The project HIPER was a turning point that demonstrated the possibility to bring together the European community beyond the national limits within one common research and development project directed to ICF for energy production. Now is the time to restart an IFE project in Europe aiming at the construction of a joint, fully civilian, laser fusion research center at a new level of confidence, with improved laser technologies, high performance computing and with a motivated, high quality scientific team. A coordinated research program will be supported by a dedicated educational program on the master and doctoral level and an exchange program on the postdoctoral level. Such a program has been developed within Erasmus+ program and tested on a collaboration basis between several European universities [13].

The continuous achievements in IFE science, laser and material technologies and readiness of the laser fusion community provide a strong and valid background for a new European project, demonstrating the feasibility of the commercialization of laser fusion for energy production and paving a way for development of integrated technologies needed for a demo power plant. It will be conducted in close cooperation with European universities and research laboratories with industry and recently created private companies [78].

IV. EUROPEAN ROADMAP FOR THE INERTIAL FUSION ENERGY

The European IFE project is under re-construction with the in-kind contributions from the partner laboratories. Since the number of partners will increase with time, and the commitments and collaborations will evolve with increasing support at the national level, the project will gain details, milestones and will set the timeline. Here, in the first version of the IFE roadmap, we put together the main objectives on the long and short time scale, the scientific and technical components that are needed for the overall coherence of the project and achieving the ultimate goal of construction of the demonstrator of an ICF power plant ready for commercialization. This document serves as a guide for the partners to define and detail the points where they can make the key contributions and where they can offer their help to other partners.

The overall time scope of the project is estimated to 30 years, which are divided into three major periods of 10 years each with progressive shift of activities from research and development to engineering and technology:

1. Research and development in the IFE, addressing unresolved physics issues, improving numerical models and performing experiments on existent facilities. A medium scale multi-beam laser facility will be constructed during this period and the robust ignition will be demonstrated in single-shot experiments. At this stage the target design will be defined and reactor technology will be advanced. Development of laser technology will be focused on the diode pumping and increasing the laser bandwidth. Educational program in the inertial will be established.
2. To the end of second period a pilot IFE reactor will be constructed and high gain operation will be demonstrated in the burst mode. Readiness of the key IFE technologies will be demonstrated. This includes: development and testing of materials with the realistic radiation, thermal and mechanical loads, development of the target mass production technology, target injection and guiding.
3. Construction of the DEMO-IFE reactor, addressing the issues related to energy recovery, fuel conditioning, security and safety of operation. Addressing the issues related with a long term reactor operation: replacement of structural materials, refurbishing of optic elements, fuel supply. At this stage the solid state diode pumping laser technology DPSSL will be compared with other IFE drivers and the industrial production laser modules will be organized.

This project will be organized by setting up a Collaboration Agreement (Appendix **??**) between the European research laboratories and Universities, organizing joint experiments on high energy laser facilities, joint training of master and doctoral students and preparing a draft for inserting the European IFE project HiPER+ in the ESFRI roadmap in 2024-2025 based on support at national levels. The contributions of partners are presented in Appendix **??**.

The general roadmap is presented in the table. The subjects are grouped in four main research and development areas aiming to investigate the physics and technology issues, develop the community and, finally, to propose and test a power plant ready for commercialization. These areas are detailed in the following sections.

General roadmap of IFE project				
		Years 1-10	Years 11-20	Years 21-30
		R&D IFE	Pilot IFE reactor	DEMO-IFE reactor
A	Physics and technology of IFE	Achievement of robust ignition and burn. Addressing unresolved physics issues, choosing the reactor target design	Optimization of the target performance. Demonstration of reactor operation in the burst mode.	Development of IFE operation: improving efficiency, robustness and safety.
B	Development of IFE laser technology. Construction of IFE laser systems.	Development of a broadband DPSSL HRR laser technology. Design and construction is the prototype of the laser module. Construction of a multi-beam sub-ignition laser facility.	Construction of the ignition laser facility operating in a burst mode. Resolving issues related to long term laser operation.	Optimization of the IFE laser technology. Organization of the industrial production laser modules for the power plant and the supply chain, Construction of a DEMO-IFE facility.
C	Material science and reactor technology	Development of resistant optical materials. Identification of adequate materials for chamber construction and protection. Design of target insertion and tracking system.	Development of a laser-based neutron source. Testing of materials in pulsed regime. Mass-production target technology. Resolving security and safety issues. Development of remote handling techniques	Design of tritium breeding and handling system, cooling system and the energy recovery system. Design of the system of material control, replacement and refurbishing.
D	IFE community building, project management and development	Development of joint numerical tools, coordination of experimental activities. Personnel training. Collaboration with industry and private companies	Establishing of the public-private partnership. Design of a commercial fusion reactor. Establishing an educational and training system for the power plant exploitation	Integrated approach to the IFE power plant operation. Conception of the full life time power plant, operation regimes, construction and demolishing. Licensing and regulations

A. Physics and technology of IFE

1. Study of unresolved physics issues related to the laser plasma interaction.
2. Study of unresolved physics issues related to hydrodynamic instabilities and mix.
3. Study of unresolved physics issues related to advanced target design: foams and wetted foams
4. Study of unresolved physics issues related high gain physics

5. Development and testing of a reliable suite of numerical tools for the target design and interpretation of experiments.
6. Design, development and testing of advanced diagnostics for the laser-matter interaction, the emitted radiation and yield.
7. Integrated experiments on existing facilities.
8. Design of the IFE DEMO facility based on direct drive scheme and DT fuel.
9. Design of robust, technologically acceptable and cost effective high-gain targets.
10. Demonstration of a repetitive fusion ignition performance with a power plant relevant energy gain.
11. Considering other fusion fuels performance and alternative drivers.

B. Development of the IFE laser technology and construction of ICF laser systems

1. Development of a broadband kJ/ns high repetition rate laser module.
2. Development of adaptive spatial and temporal pulse shaping
3. Development of DPSSL technology.
4. Design and construction of high repetition rate laser module at 10 kJ and 10 kW.
5. Development of high repetition rate laser module for the neutron source for material testing.
6. Construction of the IFE-TEST facility using staged modular approach.
7. Upgrade and exploitation of IFE-TEST Facility (sub-Hz rep rate).
8. Construction of full-scale IFE-DEMO facility.

C. Material science and reactor technology

1. Assessment of challenges and solutions in the IFE reactor technology.
2. Chamber design for the burst mode operation.
3. Adequacy of chamber protection to the ignition scheme, and research on the first wall materials.
4. Design of blanket layout and connection with first wall and shielding.
5. Design of optical transport and final optics system.
6. Design and implementation of the technique of early detection of optical damages.
7. Development of IFE structural materials in collaboration with magnetic confinement.
8. Feasibility of a pulsing neutron source and assessment of materials in these conditions.
9. Blanket cooling design and power extraction system.

10. Electromagnetic safety. Development of EMP mitigation strategies.
11. Targets mass manufacturing for ignition scheme and development of injection and tracking systems.
12. Tritium handling systems
13. Protection and safety licensing procedures.

D. IFE community building, project management and development

1. Coordination of the research between the participating laboratories: planning of joint experiments, diagnostics and access to numerical tools.
2. Development of joint communication tools and outreach activities: seminars and workshops, task groups and cross-topic coordination.
3. Training the personnel in close cooperation with research laboratories and universities.
4. Development of public-private partnership. Collaboration on the development of laser fusion-related technologies and on the technology transfer also to other areas.
5. HiPER+ ESFRI proposal preparation.

V. DETAILED DESCRIPTION OF THE ROADMAP

In this section each roadmap entry is described in more details with tentative time scale and partners.

A. Physics and technology of IFE

1. *Study of unresolved physics issues related to the laser plasma interaction.*

   Studies of laser energy deposition, hot electron generation and transport will be developed. Reaching a detailed understanding of LPIs is crucial. Suppression of laser energy losses due to SBS, CBET and SRS is the key issue for the laser energy requirements and reactor design. Hot electrons generated by SRS and TPD have to be mitigated and the shock propagation needs to be optimized. Single beam interaction studies have to be complemented with multi-beam numerical simulations and experiments. Comparison studies at the third and second harmonic, mitigation of LPI with laser beam smoothing techniques and laser bandwidth control are necessary.

   This study includes theoretical developments and dedicated experiments for the first 10 years of the project. The participating laboratories are: IPPL/HMU (LPI mitigation), CNR-INO (LPI mitigation, HRR operation), CELIA (LPI theory and experiments, code development), ELI-BL (HRR experiments, LPI mitigation).

2. *Study of unresolved physics issues related to hydrodynamic instabilities and mix*

   Controlling the hydrodynamic instabilities of the imploding shell and fuel mix between the hot spot and cold shell near the stagnation times are of prime importance for achieving a robust ignition with a limited energy budget. This will be achieved by developing a better models of nonlinear evolution of Rayleigh-Taylor (RT) instability and by performing fully 3D numerical simulations of the target implosion. The improved models will include such effects as self-generated magnetic fields, shell preheat by hot electrons and density stratification.

   Studies will include the early-time symmetry tuning of the ablator and of the quality of laser irradiation. Modulations of the ablator surface resulting from the target fabrication as well as from nanoscale perturbations imprinted on the ablator by nonuniform laser irradiation will be quantified and included in the target design. The methods of mitigation of the symmetry nonuniformities and the fill tube at the implosion phase will be developed.

   According to the NIF and LLE experience, this study is of high importance and will be conducted throughout the project time. The first decade will be dedicated to the target design, which is resistant to asymmetry of target irradiation and defects of target surface. Furthermore, mitigation of hydrodynamic instabilities at the acceleration and deceleration phases will be achieved by reducing the laser imprint and optimizing the laser pulse temporal profile. At the second stage, after achieving ignition, other target designs will be investigated adopting them to the technology of mass production, cost efficiency and robustness. The participating laboratories in this study are: IPPL/HMU, ENEA, CNR-INO, CELIA, LULI.

3. *Study of unresolved physics issues related to advanced target design: foams and wetted foams*

   Low-density structured materials present one of promising possibilities to control and mitigate hydrodynamic instabilities by smoothing the density gradients, suppressing or reducing the growth rate of unstable models. To this purpose the foam material properties will be described with better equations of state validated in laser experiments. Kinetic modeling using the PIC codes will be used for characterization of the process of foam homogenization and energy transport. A particularly promising material for target fabrication are additively manufactured foams that combine a low density with a high mechanical stiffness.

4. *Study of unresolved physics issues related high gain physics*

   The key questions beyond ignition are related to the efficiency of burning the cold fuel in the shell and achieving the highest possible burn fraction. In this context the unresolved issues are related to the effect of the shell density on the stopping power of alpha particles and on the cross sections of nuclear reactions, possible separation of deuterium and tritium in the shell and non-equilibrium ion distributions. An accurate modeling of the neutron and X-ray transport in the burning plasma will be also addressed.

   Studies of fuel ignition will be focused on the shock ignition scheme and its variations. The choice of this scheme has been made by the European fusion community during the HiPER project, and the research conducted last ten years are in agreement with this decision.

   The alternative ignition schemes, such as the standard direct drive scheme and fast ion ignition, will be considered at a “keep in touch” basis in order to acquire knowledge and information on advanced target design and physics issues. It will be used for the reactor target design, which will be made in the second decade of the project after the demonstration of ignition. All participants will contribute to this study.

5. *Development and testing of a reliable suite of numerical tools for the target design and interpretation of experiments.*

   Advanced 3D computational modelling using the best physics models at adequate resolution is also required. The key element is the high performance 3D radiation hydrodynamic ALE code available to all partners of the project on the common and protected platform. The code must be complemented with the adequate libraries of equation of state and opacities, the models describing nonlinear LPI effects, electron energy transport, fusion reactions, neutron and alpha-particles transport and energy deposition. This code should be validated by the comparison with the existing hydro-rad codes and experiments. Validation of such code requires a revision of legislation with respect to nuclear non-proliferation.

The hydro-rad code should be completed with kinetic PIC and VFP codes describing the microscopic physics of laser-plasma interaction, ignition of fusion reactions and nuclear burn. In particular, ion kinetic studies of burning plasma are indispensable for optimization the energy release. It is also important to develop inline and post-processing diagnostics for comparison with experiments. In addition, it is necessary to develop codes for modeling the interaction of lasers with low-density structured materials. This suite of numerical tools will be developed in the first ten years of the project. The participating laboratories are: University di Roma, CELIA, UPM (ETSIA, IFN-GV), ENEA.

6. *Development of high performance diagnostics for the laser-matter interaction.*

It is of primary importance to develop high performance diagnostics for the laser-matter interaction, the target evolution and the particle and electromagnetic radiation produced by them, to be operated at high-repetition rates. This includes design, development, testing and validation in large-scale experiments of high-performance, high-repetition rates diagnostics for the laser-matter interaction, the high spatial and temporal resolution radiography measuring the perturbations growth, generation of energetic particles and electromagnetic radiation. The diagnostic design needs to take into account the harsh environment where it will operate, undergoing large fluxes of ionizing and EMP radiation. The optical and X-ray diagnostics commonly used in the laser plasma interaction experiments have to be complemented with a large spectrum of nuclear and gamma-ray diagnostics including secondary and tertiary reactions detailed studies of ignition and burning phases. In addition real-time diagnostics, an advanced nanometer-scale target metrology will be developed for the pre-shot characterization of the ablator surface and quality of target layering. These diagnostics will be developed during the first decade of the project. The participating laboratories are: IPPL/HMU, ENEA, CNR-INO, CELIA, LULI, ELI-BL, CLPU. During the second decade, high-performance target metrology, quality of the laser amplification chain and the quality of each shot will be developed for the real time performance assessment of the fusion reactor.

7. *Development of AI guided technology for the data analysis and target design optimization.*

An efficient management of the project, interaction between different work packages, optimization of target designs, record and analysis of the shot performance will be achieved by developing a common structured database. Construction of the database will require participation of the specialists in the informatics and development of AI tools, which are not yet in the project. AI tools will be used optimization of the target irradiation by laser beams, target design, mitigation of hydrodynamic and parametric instabilities etc. This development will be based on the ongoing studies in CELIA and RAL.

8. *Integrated experiments on existing facilities.*

   Ignition schemes will be studied on available non ignition facilities. Access to European facilities for LPI and HED physics studies will be coordinated by Laserlab-Europe, including Phelix (GSI), LULI2000 and Vulcan. ELI Beamlines will provide access to the L4n beamline. LMJ/PETAL academic access will be used for LPI and implosion studies. A collaboration with NIF and LLE is of strategic importance with this respect for testing the key elements of ignitions schemes at MJ energies. Integrated experiments on LMJ-PETAL, will be designed aiming at demonstrating the key physics elements and incorporating full diagnostics systems. All participants will contribute to this study.

9. *Achievement of high gain ignition. Down selection of the reactor target design.*

   This is supposed to be accomplished in the end of of the first decade or at the beginning of the second decade. It requires access to a multi-beam direct drive laser facility with energy of a few hundred kJ or MJ. This could be a single shot facility constructed outside this project or a HRR facility constructed within this project. This will be a major milestone of the project demonstrating our capacity to achieve a robust, repetitive ignition in the direct drive shock ignition scheme. It will demonstrate the technology readiness in terms of the laser performance and target manufacturing.

   This achievement will provide the basis for defining the way to access the second major step: reactor operation in the burst model: the target design capable to produce gains ~ 100, technologically suitable for mass production and cost efficient, the laser parameters needed for energy production, the reactor design and the main elements for the power plant design. At that stage other options will be analyzed in terms of their competitiveness with the shock ignition, laser performance and advantages for commercialization. This step may include the use of the second harmonic of Nd laser, or short wavelength gas lasers Kr or Ar, warm targets etc.

10. *Design of the IFE DEMO facility.*

Such a design should include high level engineering based on the research conducted at previous steps of the project. It includes: laser driver design, fusion chamber design, physics modelling, target design, target injection and tracking systems, accuracy control systems, machinery and other supporting plants, laser and chamber construction, construction of supporting plants and workshops, safety and security systems and licensing. This step will start at the end of the second phase with the goal to have an operational facility in the mid of the third phase.

11. *Design of robust, technologically acceptable and cost effective high-gain targets.*

    This step corresponds to the third phase of the project: optimization of the DEMO power plant performance and meeting the competitiveness criteria for commercialization. It may include testing other ignition schemes of different nuclear fuels, designing schemes of direct transformation of products of nuclear fusion into electricity, design specialized fusion power plants for other applications such a hydrogen fabrication, production of radioisotopes, space propulsion and fundamental research. Some of these applications need not high fusion gains and can be developed at the second stage of project as spin-offs providing early valorisation of investments and enhancing the general credibility of IFE.

12. *Demonstration of a repetitive fusion ignition performance with a power plant relevant energy gain.*

    This is the last step of the project aiming at assessing the quality of DEMO design, performance of each of modules, quality of integration, efficiency of supplying systems (optics and first wall damage detection and reparation) and environmental effects. The network of personnel training and power plant licensing will be also developed. Experience from DEMO exploitation with provide input for further developments of fusion power.

B. Development of the IFE laser technology and construction of ICF laser systems

1. *Development of a broadband kJ/ns high repetition rate laser module.*

    Development of a scalable module capable of kJ/ns operation at high repetition rate at the Hz level is currently a challenging task, requiring a step-change in laser pumping technology that is now rapidly emerging (see next item). The first step required here is already at a level sufficient to enable unprecedented developments in laser-plasma science and technologies. Assuming broadband operation, such modular beamline will also be capable, after compression, of short pulse, > 10 PW operation for ultra-relativistic interactions and fundamental physics studies. High repetition rates here may open to the feasibility of low cross-section measurements.

2. *Development of adaptive spatial and temporal pulse shaping.*

   For the most efficient coupling of the laser energy to target an adaptive reduction of the focus size and a free choice of large energy steps within the driving pulse are highly desirable. These options may improve the shell compression, the ignition shock drive efficiency and energy gain. These features are beyond the capability of to date laser systems, but that is a technically feasible possibility. The technique can be developed and tested at existing high energy facilities (Phelix (GSI), LULI2000, Vulcan, ELI Beamlines).

3. *Development of DPSSL technology.*

   Transition from flashlamp pumped lasers to diode pumped systems can enable a two orders of magnitude gain in wall plug efficiency. Just as an example, the NIF laser uses 300 MJ of electricity to generate 2.1 MJ of third harmonic light, corresponding to 0.7% wall plug efficiency. This poor efficiency is due to the flashlamp pumping. Moreover, the 298 MJ of energy losses are converted into heat that must be removed from the system, requiring the long time (hours) needed to recover shot conditions. Diode pumping is selective (pumping wavelength is tuned to the absorption wavelength of the gain medium) and extremely efficient (diodes have an efficiency up to 50%), leading to an overall wpe of up to 20%, more that 30 time more efficient that flashlamp pumping. The reduced heat load enables high repetition rate, high average power operation. DPSSL technology is advancing fast, with fully diode-pumped joule-scale lasers now emerging commercially. Scalability to kJ-scale systems is mainly limited by cost of diode modules that, however, is continuing to decrease at a fast rate, now around a few €/W and expected to reach a few €/kW once mass production will be established.

4. *Design and construction of high repetition rate laser module at 10 kJ and 10 kW.*

   This is an intermediate step based on the successful operation of the kJ/ns and DPSSL operation outlined above. Scaling to the 10kJ/10kW level will require significant funding, but with reduced risk for the required, proven technology.

5. *Development of high repetition rate laser module for the neutron source for material testing.*

   Neutron production by laser-plasma acceleration has reached a full laboratory demonstration for base-level values of the number of neutrons per laser pulse energy. Projection to high neutron fluxes needed for fusion and other nuclear tests will require further development for increased wall-plug efficiency and repetition rate. Quantitative analysis of both experimental results and theoretical simulations shows that the rate of neutrons required for material testing is well within the limits of current laser-driven neutron generation, either by proton beam or electron beam as demonstrated by the results of pioneering experiments, at many laser installations already moving in this direction, motivated by emerging nuclear applications.

6. *Construction of the ICF-TEST facility using staged modular approach.*

   Construction of a multi-beam laser ICF-test facility with a repetition rate of a few minutes and 100 kJ energy level for the ignition studies and technology development. A minimum number of 10 kJ beamlines will be required to establish an IFE-Test facility capable of scaled implosion studies, similar to the existing OMEGA facility in the US, but with high repetition rate operation.

7. *Upgrade and exploitation of ICF-TEST Facility (sub-Hz rep rate).*

   This is the intermediate step towards the full IFE-TEST, for establishing the direct-drive implosion studies for ignition, needed diagnostics and target operations.

8. *Construction of full-scale IFE-DEMO facility.*

   This is the ignition scale facility, similar to NIF, but capable of significantly higher repetition rate and aimed at demonstrating exploitable Inertial Fusion Energy for future reactors. (in progress). Construction of a European Laser Fusion Facility based on a modular laser technology, multiple laser beams and MJ-scale energy level.

C. Material science and reactor technology

1. *Assessment of challenges and solutions in the IFE reactor technology.*

   The roadmap in this area will start with a first step providing an assessment of the challenges that will identify the priorities in the IFE experimental reactor technology research and those complementary with magnetic fusion.

2. *Chamber design for the burst mode operation.*

   Related to the first proposed facility of repetition-low gain, the conditions of the chamber without blanket (no energy extraction and breeding) will be assessed to have no insurmountable problems, and the computational response will demonstrate that present knowledge allows us to build it. In addition, the particles and radiation transport will give the appropriate response related to activation, safety and protection.

3. *Adequacy of chamber protection to the ignition scheme, and research on the first wall materials.*

It has been mentioned the availabilty in IFE of chamber protection. The definition of such a protection is very much dependent on the type of ignition scheme, that conditions the vacuum of the chamber the penetration on it and other factors. Then a first study and decision according with laser and target technologies is the choice and design of the protection; or get a dry wall chamber in which the selection and development of adequate materials will be critical. With that in mind the adequate materials of the First Wall could be very different and with different challenges from the damage and lifetime.

4. *Design of Blanket layout and connection with first wall and shielding.*

   The development of chamber (first wall and blanket) is very much different between the first step (ICF-TEST) of roadmap designing the burst chamber than that of DEMO (IFE-TEST). The request of materials and systems will be of very different challenges. In any case a first development needed is that of Multiscale Modelling for covering both facilities. 3D computational capability for transport has been very much improved in the last years to cover the full description of very complex systems with a very large detail; neutrons, charged particles and radiation transport in very detailed CAD/CAM 3D geometries give key answers such as activation, damage, heating and breeding. A definition of potential irradiation and gains from target will allow to fix those magnitudes.

5. *Design of optical transport and final optics system.*

   Optical transport and final optics system in reactor experience a large radiation and thermal load. The chamber design must minimize impact of charged particles, radiation and neutron damage. This is linked to the development of dielectric materials or grazing-incident metallic mirrors resistant to such damage both to thermal loads and irradiation. Experiments are still needed in this area and experimental campaigns need to be done in state-of-art neutron and charged particles facilities.

6. *Design and implementation of the technique of early detection of optical damages.*

   Development of the optics refurbishing technology for high energy HRR laser systems. Development of innovative highly resistant optical materials for high repetition rate, high power laser systems, defining the system for efficient long lifetime final optics. Concerning those materials, experiments on the neutron damage in optics need to be developed in existing facilities.

7. *Development of IFE structural materials in collaboration with magnetic confinement.*

   The development of first wall materials is a key issue in IFE chamber still under full design. The main irradiation comes from charged particles and radiation with a double effect: very high thermal loads and atomistic defects. The effect is dependent of the potential protection available. The proposal of W has been demonstrated not to be acceptable for a dry wall; advance materials, such as nanomaterials, are being proposed. In addition to the Multiscale Modeling analysis of such effects, an experimental campaign is proposed using present charged particles facilities (H, He) in Europe such as FZK Dresden in Germany, JANNUS in Saclay France and CID in CIEMAT Spain, and others which are double and triple beams of charged particles systems with surface and deep irradiation that could also mimic primary damage of neutrons. Facilities from magnetic fusion such as the Italian Divertor Tokamak Test (DTT) facility in ENEA-Frascati, with availability to study very high thermal loads, can be incorporated to our strategy.

8. *Feasibility of a pulsing neutron source and assessment of materials in these conditions.*

   The neutron damage of structural materials in the blanket of the reactor is a key challenge. The neutron doses can be computed with great detail in the 3D geometry of the reactor. The present knowledge of the accumulated neutron doses and neutron fluxes indicate that new materials, some already proposed, need to be fully experimentally proved. The very advance multiscale of materials from DFT-quantum level to macroscopic modeling through well developed molecular dynamics, kinetic Monte Carlo and dislocation dynamics, are not enough to get final conclusions. It is then absolutely needed the construction of neutron source facilities for the material tests. We consider here two regimes: i) that of continuous irradiation to get the accumulated dose of neutrons for what we will have the definitive Neutron Source from Magnetic European Project IFMIf-DONES and other ions equivalent facilities, ii) that of pulsed IFE regime for what no facility to reach similar conditions to those in a reactor is existing or proposing yet. It is here proposed the development of research in the neutron sources based in lasers in which some laboratories in Europe (RAL-CLF, Queens University, Belfast, TU Darmstadt) have been working and also potential cooperation with ILE Osaka in its laser-driven neutron source. Collaboration with very specific experimental facility, White Sand Reactor (USA), for extremely high neutron intensity similar to that achievable from one shot at ICF will be explored.

9. *Blanket cooling design, and power extraction system.*

   Design of the reactor blanket drives among other goals to the definition of the coolant circuit. Assuming that the design will be based on liquid metals coolant (FLiBe, FLiNaBe) which are some of the first options in IFE, a full computational study will give the magnitudes for heat extraction, tritium breeding and potential permeation through coolant system. The use of appropriate physico-chemical properties of these materials including the phase transition under blanket operation is critical to adequately get the goal. For such task we envision the collaboration with KAIROS project in USA which produces a high-purity coolant for reactors based on its fluoride salt-cooled. Because PbLi is also a good coolant option similar studies will be developed. Different loops of LiPb are in Europe under magnetic program that will be also of reference in that case. The previous definition of the (i) coolant and (ii) breeder performance in the blanket is linked to the (i) power extraction system, and (ii) the tritium handling includes the recovery-treatment and refueling system. In spite of the specific characteristic of the blanket, the research and design of this system is very much related to that considered in magnetic fusion, except the consideration of the tritium inventory and storage characteristics. A strong link must be implanted between target, fuel cycle and blanket teams.

10. *Electromagnetic safety. Development of EMP mitigation strategies.*

    The high levels of radiofrequency-microwave fields expected especially in advanced direct-drive schemes (SI/FI) set the problem of their minimization for saving electronics and diagnostics as one of the issues of primary importance, even for experiments performed much before than the reactor time. Although primary sources of these fields have been identified [79], there are others with significant potential of developing high fields [80], and these have to be fully understood in order to mitigate/suppress them. Dealing with EMPs requires both development of tailored diagnostics systems, and multi-scale extensive modeling taking account the time-varying electromagnetic environment within the experimental chamber during and just after the interaction. Investigations on these topics require extensive dedicated experimental campaigns with multi-diagnostic setups in large scale facilities. And then the following step is the design, development and test of suitable mitigation strategies that can take into account the multi-source nature of these fields. This implies on one side reduction/inhibition of each/most of the source mechanisms, and on the other side the development of Electromagnetic Compatibility (EMC) methodologies for robust electronics and diagnostics to be used in the reactor, with involvement of private companies active in the EMC area.

11. *Targets mass manufacturing for ignition scheme, and development of injection and tracking systems.*

    Mass manufacturing, design systems for target launch, tracking and guiding. Design of laser-target synchronization systems.

12. *Tritium handling systems*

    The existence of tritium all over the circuit of the reactor, and the well known activation of materials by neutron irradiation, drives to the existence of radionuclides of low and medium lifetimes in the reactor. That imposes to the IFE technology a mandatory well defined determination of the radiation doses in the full geometry of the reactor. This task is well covered in Europe through very detailed codes computing the fluxes and dose, such as those in Spain actually being reference in the 3D ITER study. More in advance the tritium must be extracted from the cooling circuit and pass to a process of cleaning and epuration to constitute part of the fuel involved in the capsules. That process, although already started to be studied in programs such as HAPL in USA and certainly getting benefit of the many research doing in magnetic will be studied from a second and third phase of this roadmap.

13. *Protection and safety licensing procedures*

    The interior of the reactor chamber and the materials in it will not allow the handling management of the systems in its interior. Moreover, the radiation still leaking from blanket must be stopped and do not be any danger for workers and public in general.Then a very robust and dedicated technology for remote handling under irradiation need to be developed. Europe has in this area, through magnetic fusion and other very large radiation facilities, and other areas a profitable and large knowledge-base to benefit from. The radiological protection will be studied from the detailed calculations of radiation flux escaping from the blanket; those careful calculations will condition the design of the building of the protection. A very important aspect is the Nuclear Safety Regulatory Bodies involving in the task of defining the licensing conditions of facilities such as those proposed both DEMO and more in the future a commercial plant.

D. IFE community building, project management and development

1. *Coordination of the research between the participating laboratories: planning of joint experiments, diagnostics and access to numerical tools.*

   The primary aim of this action is to establish an effective coordination scheme for the HiPER+ project for the promotion of the necessary research i.e., experiments and simulations. In particular, the action aims at implementing best practices to ensure efficient as well as controlled operations of the partners and support access to laser facilities and simulation hubs. The approach to reach this aim is twofold. On the one hand, universities and research organizations as well as the private start-up companies in IFE will devote strong efforts to enforce together common studies to improve the understanding of IFE related physics and technology. On the other hand, the exchange between academic and industrial partners will strengthen the optimization of methods, tools and diagnostics development. This interaction will lead to the identification of integrated knowledge for the more efficient implementation of knowledge devoted to an efficient planning of experiments and simulations. Laserlab Europe which unites the European landscape in laser-based interdisciplinary research can play an important role in promoting the necessary access to its laser facilities.

2. *Development of joint communication tools and outreach activities: seminars and workshops, task groups and cross-topic coordination.*

   The primary aim of this action is the development of joint actions towards an integrated communication platform. Such joint communication strengthens the ability of HiPER+ partners for efficient development of the IFE scientific and technological landscape. The development of communications tools is based on three pillars namely networking, coordination, collaboration, outreach activities. The basic networking tool has been developed on the face of the "collaboration agreement" which defines the basic rules. Task-Performing Groups (TPG) coordinated by the Coordinating Committee (CC) has been chosen as the most effective method to facilitate the planning and coordination of actions. With the contribution of Laserlab Europe the following TPGs have been established [81]:

   - European IFE roadmap,
   - Advanced Direct Drive schemes,
   - Laser technologies for IFE platforms,
   - Related technology development (targets, diagnostics etc.),
   - Experiments on existing platforms,
   - IFE reactor issues (overlap with Magnetic Fusion technologies).

   Under the platforms and tools mentioned above common HiPER+ activities related to seminars, workshops, conferences, lobbying on the national and European levels, dissemination and training are effectively promoted.

3. *Training the personnel in close cooperation with research laboratories and universities.*

   Development of a common educational program on the master and doctoral levels. Exchange programs between laboratories. Building the necessary knowledge and human capital in IFE in Europe requires building expert capacities, providing training, enabling access and mobility opportunities of experts related to IFE science and laser technologies within Europe and wider. To reach the goal various actions and tools will be used.

- Erasmus+ mobility tools and actions. Key Action 2 (KA2) “Cooperation among Organisations and Institutions” in particular, which also involves cooperation with the private sector (e.g. start-ups), is advantageous for the nature of HiPER+ activities.
- Erasmus+ “Partnerships for Innovation” supports projects (such as HiPER+) with the ambition at achieving systemic impact at European level developing the capacity to deploy the project outcomes on a European scale. The tool focus on thematic areas with strategic importance for Europe’s growth, competitiveness and social cohesion which ideally fits to the scope of HiPER+. The following sub-actions are comprised under this type of partnerships a) Alliances for innovation and b) Forward Looking Projects.
- Training at MSc level. Running English spoken MSc courses earlier developed by HiPER+ partners using the Erasmus Curriculum development programme can be adopted to the strategy.
- Development of a Doctoral School between HiPER+ partners on High Energy Density Physics studies. This action will enable training at the Doctoral level and reinforce enlargement of the European Community in IFE related physics and technology. This action can partially be supported by Erasmus+ tool.

4. *Development of public-private partnership. Collaboration on the development of laser fusion related technologies and on the technology transfer also to other areas.*

   Embracing the concept of public-private partnerships (PPPs) with in IFE platform can prepare the conditions for essential capital when conditions are mature. Furthermore, PPP’s is a tool to enhance the scopes of HiPER+ since collaboration with the private sector and the continuously growing landscape of fusion oriented start-ups enhances the scientific and technological ability allowing for a better risk management. PPPs can be implemented in various ways such as:

   - Conclusion of a cooperation agreements,
   - Collaboration studies in common IFE areas of interest,
   - Laser technologies for IFE platforms,
   - Technology development actions such as in targetry, diagnostics, large scale simulations, materials, reactor etc.
   - Exchange of knowledge where commonly decided,
   - Participation in HiPER+’s training activities,
   - Mutual support in lobbying strategies and dissemination activities.

5. HiPER+ *ESFRI proposal preparation.*

   Entering the HiPER+ in the ESFRI roadmap is the first indispensable step in the project development. It will provide the international visibility, national recognition and possibility for accessing a dedicated financial support. The timeline of proposal preparation and guidelines are described in the next section.

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