Inertial Fusion Energy Drive Technology

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Primary Author:
Constantin Haefner
Fraunhofer Institute for Laser Technology,
LLT RWTH Aachen University, Aachen
Email: constantin.haefner@ilt.fraunhofer.de
Phone: +49 241 8906-500

Co-Authors:
Laboratory for Laser Energetics, Rochester
Jonathan Zuegel, Michael E. Campbell

Lawrence Berkeley National Laboratory, Berkeley
Peter A. Seidl, Roger O. Bangerter, Andris Faltens, Thomas Schenkel

Lawrence Livermore National Laboratory, Livermore
John Barnard, Alvin Erlandson, Alex Friedman, Thomas Spinka, Vincent Tang,
Mark Herrmann, Harry McLean

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The U.S. has seen a steady growth in energy consumption across all major end-use sectors, with electricity and natural gas growing fastest. World electricity demand increased by 3.1 % in 2017[1] with China and India accounting for 70%S of this growth. In the United States, electricity generation increased 13 fold since 1950, with a record upturn by 4% in 2018[2]. Despite the impact of the Covid-pandemic resulting in a reduced demand for energy (~6% drop from 2019 to 2020), the need for decarbonization of the energy sector and bringing sovereign and weather-independent energy sources online have never been greater. Inertial Fusion Energy (IFE) offers the prospect of a carbon-free energy source with a virtually unlimited supply of fuel. Unlike nuclear fission, fusion power plants would not produce large amounts of highly radioactive nuclear waste that require long-term disposal. The recent breakthrough at the National Ignition Facility (NIF) at Lawrence Livermore National Lab achieved 1.35 MJ of fusion yield, more than 70% of the gain needed for ignition demonstrating a robust plasma burn. It moved ICF and the DT-physics platform to the threshold of Fusion Ignition.

Three principal research efforts in the United States are aligned along the three major energy sources for driving implosions and achieving the needed high energy density plasma conditions:

- solid-state lasers, including NIF at LLNL and OMEGA at the University of Rochester Laboratory for Laser Energetics (LLE);
- pulsed power systems, that drive high currents to achieve high magnetic fields or intense x-rays, the largest of which in the US is represented by the Z Machine at Sandia National Laboratories (SNL), and
- particle beams as heavy ion fusion drivers and for fast igintition are being explored by a series of groups, including at Lawrence Berkeley National Laboratory (LBNL).

Adapting these technologies for IFE i.e. electrical power plants based on inertial confinement fusion (ICF) physics and technology, will require target physics designs, driver and energy conversion systems that can operate at repetition rates of 0.1 to 20 Hz; whereas the repetition rate is mainly determined by the net electric power of the plant (typically ~1000 MWe); the fusion target yield, thermal power (i.e. MWt), conversion efficiency and capacity factor, and the amount of recirculating power. Each of these driver technologies – lasers, particle beams, and pulsed power – represent different opportunities and risks, but all require major advances. This white paper covers systems driven by lasers and ion-beams.

Laser technologies supporting IFE and HED experiments

The U.S. inertial confinement fusion (ICF) program developed many technologies that naturally extend to IFE and future HEDP programs, where energy scalability, repetition rate, and precision are required, including: multi-channel, high-bandwidth/high-contrast pulse shaping; programmable laser beam shaping; high-performance large optical elements and optical coatings; diode pumping; and thermal management. Many of these advances leveraged commercially available technology and many were transferred from laboratory development to industry. Technical research and development (R&D) is required to develop fourth-generation laser sources suitable for IFE.

Without claiming to be exhaustive, new schemes to effectively produce and deliver laser energy to IFE targets have been proposed and research and development is ongoing. These could provide sufficient bandwidth to suppress laser-plasma instabilities (LPI) and irradiation uniformity to further

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[1] https://www.iea.org/geco/electricity/

[2] U.S. EIA, "Electric Power Monthly Report", https://www.eia.gov/electricity/monthly/current_month/epm.pdf

reduce seeding hydrodynamic instabilities: see "Laser-Plasma Interactions Enabled by Emerging Technologies"[3], and "Science and Technologies that Would Advance High-Performance Direct-Drive Laser Fusion"[4]. One proposed IFE laser driver concept[5], StarDriver™, uses a multi-beam laser architecture to provide large system frequency bandwidth with many beamlets per unit solid angle. The beamlets can be relatively narrowband or broadband, but the ensemble spans a wide spectral and angular frequency range to maximize fusion performance. A highly modular, diode-pumped, solid-state laser (DPSSL) architecture based on suitable laser gain materials would enable an attractive development pathway with spin-off opportunities for other industrial and scientific applications. Another laser driver concept based on optical parametric amplification shows promise for delivering the required bandwidth in every beamline. Preliminary research is underway at LLE to scale this approach to existing facilities, like OMEGA and the National Ignition Facility (NIF), as a potential option for Fourth-generation Laser for Ultra-broadband eXperiments (FLUX) technology.

Laser-Driven Intertial Fusion Energy

LLNL developed a pre-conceptual design and plan for delivering an operational fusion power plant based on laser-driven ICF "Laser Inertial Fusion Energy – LIFE."[6] Critical subsystem technologies, such as DPSSL lasers, were developed further leading to novel designs that leveraged the vast expertise in laser physics and architectures previously developed for ICF. A diode-pumped, gas-cooled Nd:glass laser concept was conceived capable of producing 8-kJ/5-ns/15-Hz pulses with wall plug efficiency of about 15%. To speed up laser development and to reduce risks, the design uses components and materials that could be produced at the scale, quality and quantity required for a power plant.

From 2013-2016, the Advanced Photon Technology (APT) Program of the NIF and Photon Science Directorate at LLNL built and delivered a sub-scale version of this IFE laser concept. It serves as a frequency-doubled 200-J laser for pumping a titanium-doped sapphire amplifier capable of producing 30-J/30-fs/ 10-Hz pulses – the world's first 10-Hz PW laser system – named the High-Repetition Rate Advanced Petawatt Laser System[7] (HAPLS). The HAPLS has been in operation[8] since its delivery and supports HED and discovery science experiments at the ELI-Beamlines Facility in the Czech Republic, including the generation of secondary sources such as X-rays, electrons, protons and neutrons, as well as commercial applications. Although the HAPLS pump laser was constructed for other purposes, its creation and testing have validated design choices, retired important development risks and pointed toward potential improvements of the proposed IFE laser design. It also enabled cooperative research agreements with US companies that have resulted in innovations and new, competitive products. This investment ($53M) by the European Union in laser technology developed in the US illustrates how investments in ICF and IFE laser technology enabled advances in other areas

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[3] "Laser-Plasma Interactions Enabled by Emerging Technologies", whitepaper submitted by Dr. John Palastro to 2020 National Academy of Sciences "Bringing Fusion to the Grid"

[4] Science and Technologies that Would Advance High-Performance Direct-Drive Laser Fusion" submitted by Dr. Stephen Obenschain to 2020 National Academy of Sciences "Bringing Fusion to the Grid"

[5] Eimerl, *et al.*, StarDriver: "A Flexible Laser Driver for Inertial Confinement Fusion and High Energy Density Physics," J Fusion Energ. (2014) 33:476–488.

[6] A. Bayramian, S. Aceves, T. Anklam, K. Baker, E. Bliss, C. Boley, A. Bullington, J. Caird, D. Chen, R. Deri, M. Dunne, A. Erlandson, D. Flowers, M. Henesian, J. Latkowski, K. Manes, W. Molander, E. Moses, T. Piggott, S. Powers, S. Rana, S. Rodriguez, R. Sawicki, K. Schaffers, L. Seppala, M. Spaeth, S. Sutton & S. Telford (2011) Compact, Efficient Laser Systems Required for Laser Inertial Fusion Energy, Fusion Science and Technology, 60:1, 28-48, DOI: 10.13182/FST10-313

[7] C. L. Haefner *et al.*, "High average power, diode pumped petawatt laser systems: a new generation of lasers enabling precision science and commercial applications ", Proc. SPIE 10241, Research Using Extreme Light: Entering new Frontiers with Petawatt-Class Lasers III, 1024102, 2017; https://doi:10.1117/12.2281050.

[8] Facility commissioning performance 0.5PW@3.3Hz

that in turn propelled technology for ICF and IFE. This was very beneficial to build and retain expertise in our nation's specialized workforce, innovate technology, and allowed to practice key aspects of IFE laser technology.

ICF and IFE continue to generate spinoffs with potential for advancing US standing in scientific and medical technology as well as national security. These rep-rated laser systems emerging from IFE laser technology development represent a watershed moment for plasma science and research. Unlike previous systems that were flashlamp pumped and operated single shot, repetition-rated laser systems operate quasi-CW: the systems operate in steady state making them more robust, reliable and most importantly repeatable. This performance enables a new approach to quantitative plasma and material sciences. Repetition rates determine the number of experiments that can be conducted, ultimately the rate of advancing knowledge, exploiting modern data and analysis tools, target design innovation and developing applications in scientific research, medical technology, and national security. With many aging facilities, the US must provide its next generation appropriate training grounds and facilities that open up access to new and exciting discoveries.

Proposed technical R&D

Additional priority and funding support is required for developing next-generation laser technologies that will expand the capabilities of HEDP and fundamental plasma physics research, and position the U.S. for future IFE exploration and implementation.

- D*iode-pumped, solid-state laser materials*
    - Broadband materials that allow normalized laser frequency detuning of up to ten percent ($\Delta\omega/\omega_0 \sim 10\%$) would support the StarDriver™ concept at around 1053nm. One promising approach incorporates non-optically active buffer ions in Nd:CaF_2 crystals. Furthermore, the high thermal conductivity of these crystals may lead to new efficient and thermally robust gain materials for inertial fusion lasers[9].
    - Laser materials with low quantum defects to reduce heat loading must be tested and developed, such as Tm:YLF, for MegaWatt-class-average-power, mid-infrared, short-pulse lasers. Laser materials research and development has waned in the U.S. with most active research now occurring in Asia, particularly China. Renewed stewardship of this field is needed to maintain critical expertise.
- *Improved thermal management methods* – Gas-cooling enabled high-average-power lasers, such as HAPLS and DiPOLE[10]. Extending this technology to higher extraction rates and new gain materials for IFE laser drivers as well as developing new and even more efficient conductive schemes. First concepts with liquids have been prototyped in industry.
- *Optical parametric amplifiers (OPA) for broadband, incoherent drivers* – OPAs are used extensively for ultrafast lasers where coherent radiation with large bandwidths is required to support short, bandwidth-limited pulse widths. Incoherent radiation is desirable for ICF drivers but OPAs operating in this mode are practically unexplored. Theoretical and experimental studies are warranted to identify potential modes of operating OPAs to realize a solid-state version of echelon-free induced spatial incoherence (ISI)[11] or other advanced laser formats.[12]

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[9] R. Soulard *et al.*, "Co-doping Nd :CaF2 with buffer ions for inertial fusion application," paper ATu2A.18, OSA Laser Congress 2018, Boston, MA.

[10] J. P. Phillips *et al.*, "High energy, high repetition rate, second harmonic generation in large aperture DKDP, YCOB, and LBO crystals," Opt. Express 24, 19682-19694 (2016). https://doi.org/10.1364/OE.24.019682

[11] R. Lehmberg & J. Goldhar, "Use of Incoherence to Produce Smooth and Controllable Irradiation Profiles with KrF Fusion Lasers, Fusion Technology, 11:3, 532-541, (1987). DOI: 10.13182/FST87-A25033

[12] B. Afeyan & Stefan Hüller, "Optimal Control of Laser-Plasma Instabilities Using Spike Trains of Uneven Duration and Delay: STUD Pulses," arXiv:1304.3960v1 [physics.plasm-ph]

- *StarDriver™ system optimization* – StarDriver™ systems deploying many (10^4 to 10^5) beamlets offer an excellent opportunity for optimizing inertial confinement fusion laser driver configurations that would enable almost arbitrary control of wavelength, spatio-temporal properties, polarization, and focusing. Detailed system studies are required to maximize laser performance, while observing important practical considerations like wall-plug efficiency, beam delivery, controls architecture, and total cost of construction and operation.
- *Advanced optical materials* – The development of various optical materials and technologies such as nonlinear gain switches and optical isolators consistent with high average power and IFE-pulse energies, optics and coatings that can handle high fluences with many GigaShots of high-peak-power pulses, high-efficiency, broadband diffractive gratings, etc. are required for the next generation, high average power, IFE drive laser technology.
- *Semiconductor diode technology* – For a fusion power plant uising Nd:Glass, pulsed diode arrays with power density ~20 kW/cm², wavelength 890nm, MTTF of 14-20 GShots and repetition rate 10-50Hz at a price target of ~0.007 $/W for packaged devices are required, accounting for approximately one third of the total drive laser costs. While power and brightness performance can be met today, significant R&D and new innovations are required to reduce diode system cost by ~100x and extending lifetime ~7-10x.

Progress developing laser-driven inertial fusion energy as a viable option for the future depends on a commitment to both basic research of scientific challenges, and applied research and development of laser driver technologies to make it a reality. The former has been supported for decades by NNSA, but the latter requires a home that can help bridge the gap between the laboratory and practical implementation.

Heavy Ion Driven IFE (Heavy Ion Fusion)

Charged particle accelerators are a promising driver of inertial fusion energy (IFE), offering opportunities and challenges that are complementary to laser and pulsed energy drivers. Energetic ions deliver energy to a fusion target through collisions with electrons and nuclei of the target. There is no critical density in this process. Particle accelerators have high wall-plug efficiencies (>20%), operate at high repetition rates, long MTBRs and have high availability. Challenges and opportunities for heavy ion fusion and IFE were summarized in the 2013 National Research Council report "An Assessment of the Prospects for Inertial Fusion Energy"[13][14]. To this day, some ten years later, the beam requirements for heavy ion fusion drivers with ion currents of ~1 MA during a few ns at ~5 GeV to deliver ~5 MJ are still daunting[15], as are the requirements for ion-driven fast ignitions (e.g., 10 kJ in 20 ps)[16].

We propose the following technical R&D elements to establish new learning curves that will result in a new blueprint for an economical fusion power plant with heavy ion drivers and supporting hybrid IFE approaches.

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[13] National Research Council. An Assessment of the Prospects for Inertial Fusion Energy. Washington, DC: The National Academies Press, (2013). http://www.nap.edu/catalog.php?record_id=18289

[14] R. W. Moir, et al., "Hylife-ii: A molten-salt inertial fusion energy power plant design", Fusion Tech. 25, 25 (1994)

[15] R. O. Bangerter, A. Faltens and P. A. Seidl, "Accelerators for Inertial Fusion Energy Production", Rev. Accel. Science and Tech. 6, 85, (2013), DOI: 10.1142/S1793626813300053].

[16] J.C. Fernández, et al.,"Fast ignition with laser-driven proton and ion beams", Nucl. Fusion 54, 054006 (2014)]

Proposed Technical R&D

- Target experiments with heavy ion pulses up to 50 kJ in 100 ns will be available at FAIR[17], Germany, starting in 2025. This will allow a new class of experiments where targets can be heated to temperatures of up to ~50 eV. These experiments will provide data to benchmark driver parameters, fusion target and reactor chamber designs[14]. We propose that the US IFE community engage with FAIR to participate in selected experiments on ions for IFE.
- Our ability to model and simulate particle accelerators has improved remarkably in recent years due to advances in physical understanding, the development of more efficient codes, and increases in computing power[18]. We propose a modeling and simulation program on final focusing and beam propagation in IFE reactor chambers to identify show stoppers, retire risks and inform new, economical designs for driver beams, targets and reactor integration.
- We propose to assess recent accelerator science and technology developments, including laser-plasma, pulsed power and multi-beam ion accelerators (recently demonstrated with over 100 beams) that can drastically change the economics equation for ion beam drivers and fast ignition approaches for IFE. Lower cost, higher performance pulsed power switches based in SiC have enabled a new high power induction linac design at lower cost[16]. RF linac components were recently made using additive manufacturing techniques[19]. Optimized laser-ion acceleration promises efficient acceleration of intense pules of high energy ions and protons[18]. While these technologies are still at the proof-of-concept stage compared to driver (or fast ignition pulse) requirements, they are examples of new directions in accelerator research and development that can now be used to develop low-cost fusion drivers. One technological example with overlapping synergies for multiple driver approaches is high-power switches (lower cost, long lifetime, faster, e.g., 200 kV in 10 ns). For ion drivers, these could reduce inductor cell costs and enable shorter pulses in a more efficient driver (efficiencies of up to 50% seem possible for wall plugs, versus ~30% today). We propose to invest in these promising development paths and scale the demonstration components to high beam power at orders of magnitude lower cost compared to currently deployed technologies. If successful, the result will be a new class of high-power ion accelerators for economic fusion energy.

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[17] K. Schoenberg, et al., "High-energy-density-science capabilities at the Facility for Antiproton and Ion Research", Phys. Plasmas 27, 043103 (2020); https://doi.org/10.1063/1.5134846

[18] J.-L. Vay, et al., "Warp-X - A new exascale computing platform for beam–plasma simulations", Nucl. Instr. Meth. A 909, 476 (2018)

[19] Q. Ji, et al., "Beam power scale-up in microelectromechanical systems based multi-beam ion accelerators", Rev. Sci. Instr. 92, 103301 (2021)