LD-FIRST (Laser Driven Fusion Integration Research and Science Test Facility)

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Abstract

An integration and test facility that serves as a full-scale community testbed for foundational technologies needed for fusion concepts spanning IFE to MFE will need a modular design and flexible capability. We propose to build on the singular achievement of fusion ignition and scientific breakeven at the National Ignition Facility (NIF) [1] and leverage decades of Inertial Fusion Energy (IFE) science and technology research, including the LLNL Laser Inertial Fusion Energy (LIFE) effort [2], for such a facility, called LD-FIRST. Operating with deuterium-tritium fuel, LD-FIRST is envisioned to produce reactor level 14.1 MeV neutron output to enable full scale materials and performance testing of fusion blankets and fuel cycle systems, while accelerating foundational component and system technologies for the community. Leveraging the point source nature of Inertial Confinement Fusion (ICF) and the modularity possible with IFE, LD-FIRST could serve as an accelerated testbed for multiple blanket module concepts relevant to IFE and MFE, with tailorable irradiation rates dependent on distance to the center of the target chamber. Yearly displacements-per-atom (DPA) of 10 or higher could be achieved for meter-scale objects even at just ~10 MJ yields per shot (a NIF goal in 2024, with 3.88 MJ as the highest yield in 2023) if IFE scale rep-rates of ~10 Hz can be achieved. LD-FIRST would offer key risk-mitigation for fusion power development, diversifying research pathways synergistically with other complementary integrated demonstration facilities such as ITER. LD-FIRST is currently at the ideation stage but can heavily leverage the significant LIFE study (which built on a substantial body of prior IFE system design efforts [2a]) to accelerate the design and delivery. It will be essential to have this project be driven by substantive partnerships with the IFE, MFE, ICF, and public and private sectors and their associated supply chain vendors, building on many ongoing discussions to define the detailed requirements and pathways to LD-FIRST.

The development and deployment of LD-FIRST on a relevant timescale would capitalize on the US's historic lead in fusion science and accelerate US leadership in fusion energy to meet the US Department of Energy (DOE)'s bold decadal vision for fusion commercialization.

Research for world-leading science and technology gaps for a fusion pilot plant

The achievement of scientific breakeven and controlled fusion plasmas robustly in the alpha dominated ignited regime retires one of the biggest risks facing fusion and is 'one of the most impressive scientific feats of the 21st century' [3]. LD-FIRST will build on world-leading ICF physics and plasma science being conducted on the NIF at LLNL with its ICF partners at US national laboratories, universities, and private industry. Laser-based inertial fusion presents an attractive, near-term approach for an integrated fusion testbed because: 1) requisite driver scale and resulting gain have been demonstrated through proven and repeated ignition on the NIF – a capability that is uniquely held world-wide and only by the US Department of Energy; and 2) technology development and demonstration can occur in parallel due to the decoupling of driver and structural components, with transparent risk assessment and management.

The LD-FIRST facility will address the following research objectives and science and technology gaps for the community:

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- Demonstrate integrated operation of fusion, thermal, electrical, and closed fuel cycle systems;
- Provide a fusion environment for full-scale testing of advanced materials and components, quantifying materials degradation due to bombardment by energetic Deuterium-Tritium (DT) fusion neutrons;
- Test the nuclear performance of candidate fusion blankets and ancillary systems operating at-scale with complex structures and coolants under prototypic conditions;
- Test all aspects of the fuel cycle, including separating hydrogen isotopes from impurities that will come from the plasma exhaust and blanket, and isotopically separating the hydrogen;
- Establish the basis for a robust concept of operations for a fusion power plant;
- Quantify the Reliability, Availability, Maintainability, Inspectability (RAMI) characteristics of the new and coupled technologies;
- Provide information on failure modes and recovery methods from the component level through sub-systems and whole-plant operations – including data on the optimization of cold/warm start-up, maintenance cycles, and system responsiveness for future load-following on the grid;
- Collect data for qualification and certification for licensing a commercial fusion plant; and
- Drive vendor readiness and supply chains for fusion rollout via early facilitization.

A phased, milestone-based approach would be taken to achieve LD-FIRST, with each step demonstrating foundational IFE science and technology that many IFE concepts can leverage and build further on as LD-FIRST is developed and constructed. Fundamentally, nearly all IFE concepts rely on a similar combination of driver, high yield target, target fabrication and injection, target chamber, blanket, and fuel processing sub-systems coupled with the balance of plant to produce power. LD-FIRST is envisioned to demonstrate these technologies at scale. It would benefit from, but does not need to have plant gain greater than 1 to achieve its mission as a full-scale fusion materials and system testbed.

While it remains to be seen whether a laser driven approach can scale to economic power delivery, there is a much lower threshold for a near-term fusion testbed. The community would benefit from the following characteristics of the LD-FIRST facility:

- The inherently high burn efficiency from IFE (10-30% fuel burnup) supports a wide phase-space for testing blanket technologies and for closing the fuel cycle.
- The complete decoupling of fusion performance from the choice of first wall material, paired with the simplicity of varying the heat loading (via r^2 distance scaling from the point source), allows the testing of a full range of candidate MFE and IFE first wall materials and blanket assemblies.
- IFE's compatibility with pure lithium blankets allows for a very high Tritium Breeding Ratio (TBR), providing a potential source of excess tritium to feed into other fusion plants / testbeds.

The development and delivery of an LD-FIRST facility can take advantage of the following:

- For this facility to be energy efficient (e.g., no net power from the grid), there is a need to couple reasonable extensions of the fusion gain demonstrated on the NIF to the use of high efficiency semiconductor laser diode lasers. The desired diode performance is nearly available on the market today – with the primary obstacle being the need to scale the production volume. Investments in this area are consistent with the goals of the CHiPS Act and would have many spin-off benefits to other industrial applications.
- The integrated pre-conceptual design for a similar-scale facility from the substantial Laser LIFE design and development effort led by LLNL with team members consisting of multiple DOE Laboratories, industry partners, and several electrical utilities.

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Impact to the FES mission and beyond

LD-FIRST would have impact far beyond the FES program, with the maturation of spin-out technologies for industry's use of high-power lasers; scaling of the semiconductor industry's production of diodes for multiple market applications; and provision of tritium and ^{3}He for national and industrial purposes. Opportunities for partnerships with DOE National Nuclear Security Administration (NNSA) could also provide strong science and technology spin-ins to, and spin-outs from, NNSA's Stockpile Stewardship mission.

Facility description

The conceptual design for the LD-FIRST facility could build from the extensive work performed in the LIFE effort during 2008-2014 [2], updated according to lessons learned from the construction of high energy, 10 Hz diode-pumped solid state lasers [4-6], recent advances by the semiconductor diode industry [7], and latest concepts from the emerging IFE private sector. It would be a highly instrumented and flexible test facility to inform the design choices for a wide range of IFE and MFE power plant concepts.

The LD-FIRST facility could consist of a NIF-like laser configuration from the perspective of the fuel and target (to ensure robust benchmarking of gain performance), as shown in Figure 1. Diode-pumped solid-state lasers (DPSSLs) are deployed in line-replaceable units (LRUs) using a sufficiently high diode pump power to achieve a wall-plug efficiency of 10-15% at 10-20 Hz pulse repetition rate [8, 2]. The fuel targets are injected into the center of a quasi-spherical blanket system and tracked/engaged using telecoms-technology for self-aligning laser schemes, avoiding the need for absolute positioning and/or movement of large optics [8].

A conservative and cost-saving approach to facility design relative to the LIFE effort could be adopted since LD-FIRST is a community test facility for technology maturation and not a commercial reactor. One example of this is the need for only moderate gain, with candidate options in the Target Gain= $G_T = Q_{sci} = 12$ to 18 range, dependent on overall facility optimization. G_T is defined as fusion energy produced divided by laser energy, E_{laser}, delivered to the target. At the higher range of this gain enough electricity can be generated to power the facility making it self-sufficient, assuming laser efficiencies in the ~15% range. NIF achieved a G_T=1.9 from E_{laser}=2.05 MJ in 2023 and NNSA is exploring paths to Gain 10 and above on NIF now that the fundamental physics of fusion burn and ignition have been demonstrated. The results from this research will provide a sound basis to set requirements for LD-FIRST. As an intermediate step in the development path of the facility, it could be operated at lower gain, but at the cost of needing an auxiliary 100MWe plus source to power the facility. Such a step, with e.g. G_T~5, could still achieve ~10 DPA per year for meter-scale re-entrant test assemblies.

Leveraging LIFE designs, the blanket itself could be a modular system that would be inserted/extracted on a periodic basis to facilitate the testing of multiple design options (see Figure 2) that would provide a Tritium Breeding Ratio (TBR) >1. It would be constructed from a conventional ferritic-martensitic steel, with attention paid to impurity content to deliver a waste disposal rating (WDR) < 0.1 after a service life of 3-4 years. Exchange on this timeframe avoids excessive embrittlement, keeping the materials damage within a few DPA. This modular replacement approach is facilitated by the fact that the first wall / blanket system does not need to be a hermetically sealed chamber for an IFE facility; it is contained in an outer vacuum vessel that is at sufficient radius to survive for the lifetime of the facility [9, 2]. The primary coolant flow and

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processing rates would be designed to maintain tritium levels below ~60g in the coolant and ~100g in the structural materials, underpinning a robust safety basis [11-12].

Importantly, this approach also enables the inclusion of large re-entrant panels that sit closer to the fusion point source, enabling accelerated lifetime tests of new candidate materials and assemblies. Figure 3 shows annual DPA rates as a function of the distance from the target to the test sample for various operating scenarios. For comparison, the International Materials Irradiation Facility (IFMIF) has been projected to produce peak DPA rates in small samples of structural metals of ~20 DPA per year [10]. Sample survivability versus stand-off distance in such a facility remains a subject of investigation.

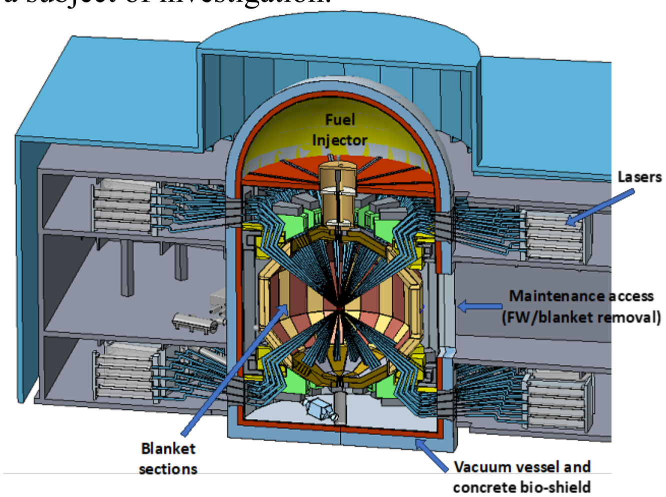
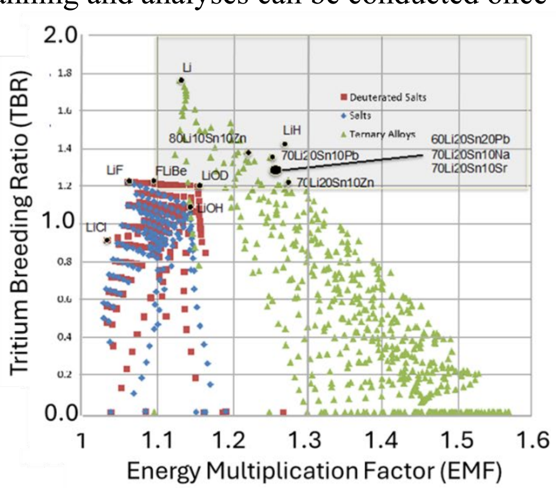
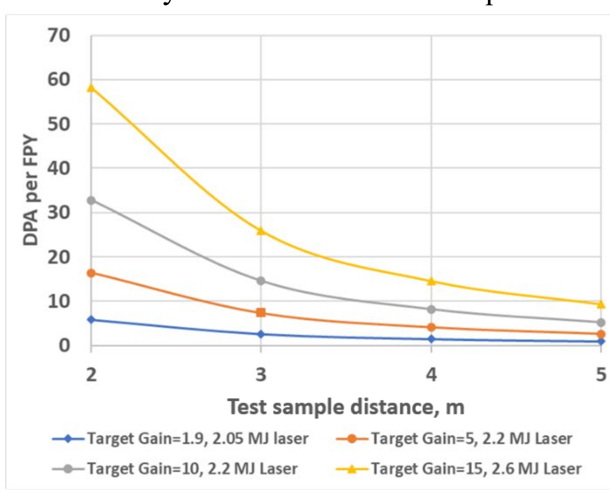


Figure 1. *Nominal cross-section of the LD-FIRST facility, leveraging LIFE designs. An annular array of laser beamline boxes [8] occupies the upper and lower levels, suppling beams to the center of a ~12m diameter chamber that supports the thermal/breeding blanket systems. The blanket assembly is modular (shown in brown/gold sections), allowing periodic exchange for evaluation / maintenance / replacement. This chamber is contained in an outer vacuum vessel and concrete shield wall. Thermal cycling and fuel cycling equipment is not shown. The balance of plant is housed in an adjacent building.*

Given a modular architecture, LD-FIRST could potentially be deployed in a sequential manner allowing for initial tests within the decadal timescale, dependent on funding availability and informed by continued progress on NIF. For example, the facility could start with a base number of beamlines which could be increased later for higher facility performance. Cost and schedule planning and analyses can be conducted once the community has established base requirements.





(Left) Figure 2. *The high burn fraction from IFE (10-30%) and the decoupling of plasma performance from first wall configuration provide for a wide phase-space of candidate breeding materials that can be tested. This plot shows simplified 1D analysis results for TBR vs EMF for a range of Li alloys and salts.*
(Right) Figure 3. *Predicted Displacements Per Atom (DPA) per Full Power Year (FPY) for various nominal LD-FIRST 10 Hz operating points and test sample distance to target chamber center.*

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Facility context with respect to: 1) research gaps, needs, and opportunities 2) activities in the international research programs, and 3) private industry or public private partnerships

LD-FIRST has the potential to close many major technology gaps as an at-scale integrated test facility and would reduce the need for multiple independent testing facilities. LD-FIRST addresses the most important research needs and gaps in the DOE 2022 IFE Basic Research Needs (BRN) [2d] report for a laser driven IFE, including much S&T common to both MFE and IFE. LD-FIRST would also directly address core research needs outlined in the FESAC Long-Range Plan, the Bold Decadal Vision, and the NASEM Bringing Fusion to the US Grid report.

Leveraging the approach taken by the IFE STAR hubs, the design and delivery approach would be configured to maximize the opportunities for participation by historically underrepresented groups and communities, with engagements already underway with Texas A&M University, UC San Diego, UC Berkeley (all three are minority serving institutes), the University of Oklahoma, UCLA, University of Rochester, and MIT to drive a vibrant education and workforce development enterprise.

Currently, no fusion integrated power-plant test facility exists in the world. This would be new and unique. LD-FIRST could incorporate strong partnerships with other countries with fusion roadmaps including Germany (industry and government), the United Kingdom, Japan, France, and laser infrastructure in Europe (ELI).

This proposal will incorporate a broad partnership across academia, national laboratories, and a wide array of industrial partners. There are multiple IFE companies that will benefit from the laser-specific elements of LD-FIRST's ability to test performance and operations characteristics of a laser fusion power plant – whether in advance of the construction of a Fusion Pilot Plant (FPP) or alongside this to aid ongoing optimization. Initial discussions on LD-FIRST with potential industry partners such as General Atomics and Longview Fusion Energy Systems have been positive. Moving forward, the IFE STAR Hubs and Milestone program which contains a range of public-private partnerships would be leveraged and built on for an LD-FIRST facility that best serves community needs.

Facility concept readiness

Significant prior work (e.g. LIFE effort) and current community efforts can be leveraged to provide the basis for the preconceptual design for this proposal. Once the mission need is granted, this would allow rapid progress to be made to CD-1 and subsequent baselining, taking advantage of the extensive set of academic, national lab, and industrial partnerships that have already been established through the IFE STAR hubs and the IFE Collaboratory. Some examples of the details of a design can be found below, as a subset of the publicly available materials on LIFE [2]:

- Integrated plant design [2b, 12, 13]
- High repetition-rate laser technology design [8] and reduction to practice [4]
- Modular, replaceable first wall / blanket and accelerated materials test platform [9,12-13]
- Fuel target manufacturing [14], injection/engagement [15], and survival [16] studies
- Options for closing the DT fuel cycle [17]

Within the context of the FIRST facility description and what has already been laid out for the mission for such an integrated test facility, LD-FIRST would be in category 2(b) in regard to "readiness for construction".

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