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Lasers for Inertial Fusion Energy

C. P. J. Barty

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C. P. J. Barty 1)

1) Lawrence Livermore National Laboratory (LLNL), Livermore, California USA

E-mail contact of main author: barty1@llnl.gov

Abstract. The achievement of controlled fusion burn and gain with mega-joule-class laser facilities such as the National Ignition Facility (NIF) at Lawrence Livermore National Laboratory, lays the foundation for future energy systems based on inertial confinement fusion. The technical challenges for laser inertial fusion energy systems are numerous and include the generation and operation of cost-effective, robust, mega-joule lasers that can operate at repetition rates of 10-20 Hz and are capable of accurately hitting fusion pellets on the fly injected into a target chamber.

1. Introduction

Laser Inertial Fusion Energy (LIFE) may provide a transformational solution to the growing global demand for energy that is scalable, proliferation-resistant, and that generates negligible nuclear waste [1, 2]. To produce energy competitive with alternative power plants, the LIFE laser driver must operate at a high repetition rate ($\geq$10 Hz) with high efficiency (>10%), while maintaining the beam quality required for focusing to a small spot suitable for compressing the fusion target. Scaling from the 192 National Ignition Facility (NIF) laser to a laser for LIFE requires increases of ~10^5 in rep rate and ~20X in efficiency, adding significant challenges to the laser design. To achieve this, a change in technology is required. Increased repetition rates generate more waste heat that can cause beam quality degradation due to phenomena such as thermally-induced stress-birefringence. In addition, reductions in the laser size and cost are important to make LIFE plants easy to site and cost-competitive with alternative power sources. The technical and financial constraints point to the adoption of diode pumped solid state lasers, building from existing markets in the low power diode industry (e.g. for televisions) and high power applications (e.g. cutting and welding). Size constraints complicate thermal management, and cost constraints could potentially limit the use of the diode laser pumps needed to achieve efficient, reliable operation at high repetition rates.

2. Laser Issues and Design Considerations

To first order, the laser system requirements for LIFE have been well understood for more than two decades (*see Figure 1*). The laser must have energy on par with present fusion demonstration systems, i.e. of order a few mega-joules, needs to operate at a repetition rate of approximately 10 Hz and must be efficient enough (>10%) as to not consume an appreciable amount of the generated fusion power in its operation. In addition it must have high availability and be composed of optical components that are capable of operation continuously for extended periods of time (up to years) without damage.

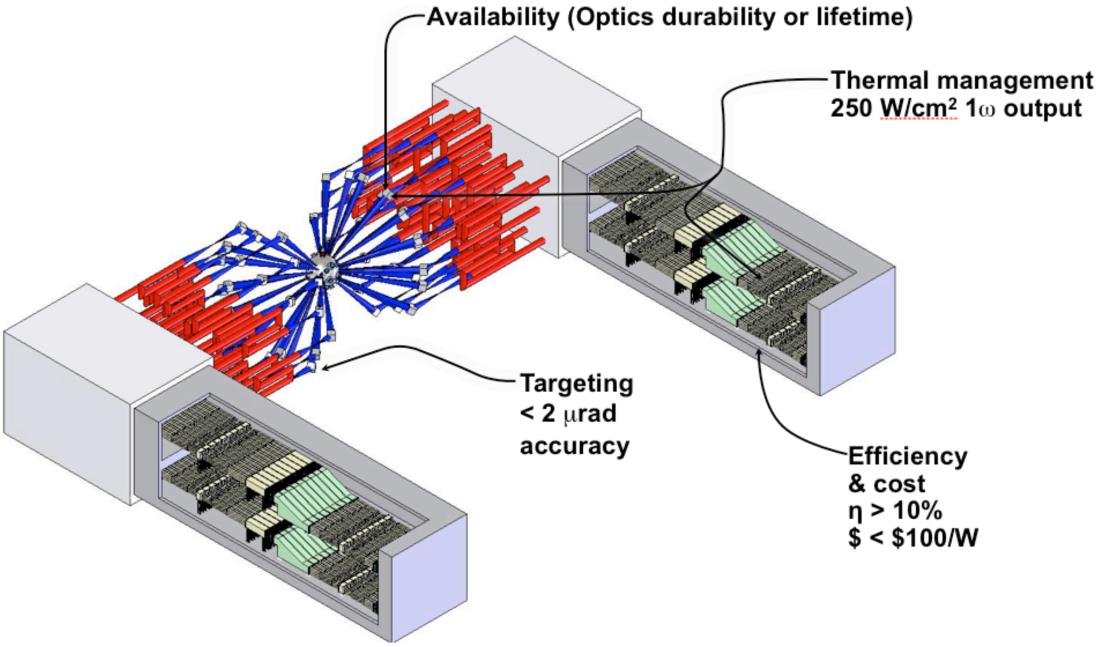

Figure 1. General layout of an IFE power plant, listing the primary laser and optical challenges for laser-based inertial fusion energy.

The laser architecture of existing inertial confinement fusion demonstration facilities worldwide is based upon solid-state, glass laser technology. In these systems, large slabs (40cm x 80cm) of Nd-doped glass are excited by the discharge-generated radiation from Xe-filled flashlamps. This approach is both relatively economical and scalable to the MJ-class energies required for fusion burn and gain. The overall wall plug efficiency, i.e. laser energy/electrical energy required to excite the laser is however, low and does not meet the efficiency requirements for a fusion power system. In addition, a significant amount of the Xe discharge radiation is absorbed in the laser glass and does not contribute to laser amplification. This excess absorbed energy heats the glass and induces distortions on the laser beam. If this excess heat is not removed it may lead to fracture and destruction of the laser glass. Because of the relatively poor conductivity of laser glass, the repetition rate at which high quality laser pulses can be produced to drive a fusion target is limited to minutes if not hours, i.e. 4 to 6 orders of magnitude below the requirements for fusion energy. A different approach is needed for a fusion energy drive laser.

Several new laser technologies have emerged over the past decade and now form the basis for energetic laser systems that can both operate at the high repetition rates and the high overall electrical to optical efficiencies required for fusion energy power generation. One key technology is high power diode laser arrays. Diode lasers efficiently convert electricity into light that in turn can be used in place of flashlamps to excite a solid state laser. Moreover because diode laser array emission can be matched specifically to the absorption bands of a laser material, significantly less residual heat is deposited into the laser medium and as result it is possible to operate diode-pumped lasers at high repetition rates. While diode lasers are now common in DVD and CD players, the development of high power arrays of diodes lasers is still relatively new and an active topic of research and development. Diode cost dominates the economics of fusion energy laser systems. Development of new, transparent ceramic laser materials that are more effectively matched to diode laser excitation can reduce the overall diode laser requirements and system cost and is now an active area of research. The combination of diode laser excitation and new materials in turn enables development of new compact laser architectures that are both cost effective and compatible with rapid, modular installation and robust plant operation.

In previous work we have studied approaches that relied heavily on NIF technology as a starting point for future LIFE laser designs. That effort yielded a relatively low risk, but high cost NIF-like design at current diode prices [2]. The advent of advanced gain media, including new crystalline and ceramic laser materials, development of deterministic magneto-rheological finishing (MRF) of optics, high spatial resolution adaptive optics, near-field spatial filters, and higher damage threshold optics and optical coatings are examples of advanced laser technology that the LIFE laser system could use to dramatically reduce the LIFE laser size and cost.

In our NIF-like design, laser-diode pumping replaces flash-lamp pumping. Nd:glass amplifier slabs are sliced into a number of thinner "slablets" allowing heat removal by flowing helium gas between them, as successfully demonstrated in our 10 Hz, 600 Watt, Mercury Laser [3]. The Nd^{3+} ion energy storage lifetime in NIF laser glass is ~ 350 μs, placing a high demand on peak pump-diode output irradiance (> ~ 5 kW/cm^2). Changes in the laser architecture allow the laser design to become substantially more compact and lower cost. These changes include use of gain media with longer energy storage time (lowering diode cost), other new laser materials, devices, and architectures. Design of laser systems using new features incurs risk because some of the required design parameters are unknown or lack sufficient accuracy to guide optimization. These include the fracture toughness, spectroscopic & optical properties, damage threshold or long-term optical durability, and practical fabrication size limits of the new materials and/or devices.

The cost of a LIFE power plant today would be dominated by the cost of the laser diode pumps. These components are now commercially available as 1 cm-long, edge-emitting bars with typical power levels of 150~200W/bar and volume pricing $2~10/Watt for the current market demand. Discussions with several suppliers indicate that 65~80% of the cost is due to assembly and packaging, and is highly dependent on the scale of manufacture. Costs are limited by an interlocking set of requirements that include precision bar mounting, strain- and solder-driven reliability constraints, and microlensing for fast-axis divergence control [4]. While unpackaged semiconductor die can likely be cost reduced into the 1¢/Watt range or less, scaling of the packaging and assembly costs remains a challenge. LLNL's "Vbasis" technology platform [5] made a significant contribution in this area by using batch microlens alignment and micromachining-enabled precision bar placement to simplify package assembly for 100W bars. Vbasis provides a guiding set of principles for enhancing diode cost/performance, but will not support large bar power increases due to reliability issues such as solder electromigration [6]. The application of engineered materials and mesostructures to a Vbasis-style design enables higher power diode operation and improved cost/performance for these key components.

The combination of compact multipass laser architectures pumped by efficient, low cost diode arrays enables the construction of laser drive systems for inertial fusion energy that are both reliable and cost effective for production of electrical power from fusion.

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Appendix 1: References

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Appendix 2: Keyword Index

direct drive

drivers

economic aspects

fusion power

indirect drive

inertial confinement

laser fusion power plant

laser systems