Development of Laser Fusion Energy

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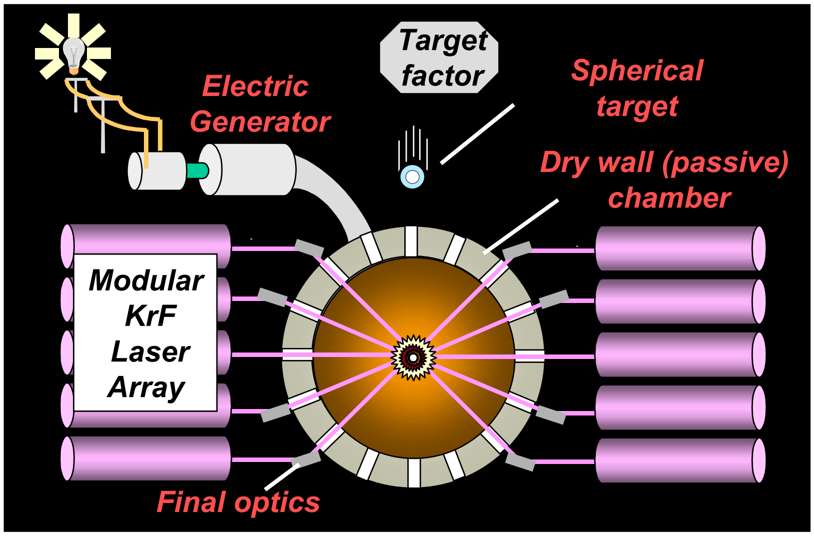
Introduction:

We are carrying out an R & D program to develop fusion energy with laser drivers and direct drive targets.[1] This is an integrated research program that develops the main components simultaneously. This ensures that the key interface issues are properly addressed.

In this approach, an array of high-energy laser beams symmetrically and directly illuminates a cryogenic target that has been injected into a chamber. The deuterium-tritium fuel in the target undergoes thermonuclear burn and the energy is used to generate electricity. A conceptual drawing is shown below:



The attractiveness of this concept lies in its inherent simplicity, its separable architecture, and the modular nature of the laser driver. The targets are spherical shells, which in principal can be fabricated in a single droplet generator. Thus, they naturally lend themselves to automated, low cost production. Moreover, none of the target components need to be recycled. The first wall is a passive structure that does not have to hold vacuum. Not having to worry about vacuum integrity allows more choices for the first wall material, such as advanced composites or two-component structures. It also allows the wall to be made in individual sectors that can be replaced during the plant lifetime. The separable nature of the power plant allows the principal components to be developed separately before being integrated into the system. Just as importantly, it allows economical upgrades as new technologies are developed. The laser is modular, and would consist of a number (about 60) of identical beam lines. Hence it is only necessary to develop one of these lines to develop the entire system. All of these factors significantly reduce the development costs for this approach.

This program leverages off the target design, laser development, and high energy density physics research carried out in DOE/NNSA Defense Programs, as well as the materials and component research carried out in the DOE/Office of Science fusion program. Thus it capitalizes on two main research thrusts in DOE to provide a solution to our nation's long-term energy needs.

Progress:

While there are still science challenges that must be met to realize this concept, there have also been sufficient advances in target design, target experiments, lasers, and associated technologies to make this a front runner for fusion energy. For example:

1. We have developed target designs, based on codes that are being benchmarked with experiments, that show gains of 120-180. This is sufficient for a fusion power plant. These are 1-D calculations. Integrated 2-D designs are under development and look promising. The ablator of current high-performance targets is a layer of low density foam with DT wicked into it. The foam can significantly increase the laser absorption. These designs also make use of the experimental observation that a thin high Z coating outside the target significantly reduces the laser imprint, and hence mitigates the growth of hydrodynamic instabilities.

2. Two types of lasers are being developed: Krypton Fluoride (KrF) gas lasers at NRL, and Diode Pumped Solid State Lasers (DPPSL) at LLNL. Both have the potential to meet the fusion energy requirements for rep-rate, efficiency, durability and cost. Both lasers expect to have "first light" during CY 02. The Electra KrF laser (photo below) uses double sided electron beam pumping of the laser gas. We have commissioned a "first generation" pulsed power facility that is being used to develop the laser components. This facility produces two 500 kV, 100 kA, 100 nsec electron beams. The pulsed power system can run continuously at 5 Hz for five hours. This is unprecedented for a system this size. We have used our experimentally validated beam propagation/deposition codes to build a hibachi concept that can meet the durability and efficiency requirements. We have developed an advanced KrF kinetics model that predicts the results of existing experiments and is now being used to design future systems. We also demonstrated an advanced laser triggered solid state switch that will be the basis for a durable, efficient pulsed power system.

The Electra KrF Laser Facility

3. The "Mercury" laser system (photo below) employs three technological advances: efficient and reliable diodes, Yb-doped crystals, and active cooling with near-sonic helium gas flow for rep-rated operation. The dual-ended, longitudinal pumping design allows for more uniform pumping and thermal loading on the crystals than traditional side pumping schemes. The power amplifiers are four-passed to extract the stored energy into the laser beam. The first laser head assembly has been fabricated and installed. This includes four 80 kW diode arrays, relay telescopes, low distortion gas cooling of the amplifier head, and the reverser hardware which allows the beam to be re-injected for multi-pass operation. The program has also developed high quality laser crystals in the large sizes needed for this system.

The Mercury DPSSL Facility

4. In target fabrication, we have investigated the properties of several high-Z coatings. Measurements show an Au-Pd alloy meets the requirements for DT permeation times, and has high IR reflectivity to help the target survive as it traverses the hot chamber. We have developed an advanced divinyl-benzene foam that can meet the requirements for low oxygen content and straightforward over coating. We have already made shells from this material. Our economic analysis shows the targets can be made for less than \$0.15 each, which is below the economic requirement from power plant studies.

5. For target injection, we are performing experiments to determine the thermal response and mechanical properties of solid DT. We have demonstrated the concept of a separable sabot to protect the target during acceleration, and have started construction of a system to study injection and tracking. This injector is designed to accelerate any IFE target (both indirect and direct drive) and thus is important for the entire inertial fusion program.

6. In final optics, we have established that, at least in small laser spot sizes, a grazing incidence aluminum mirror is both highly reflective (>98%) and can significantly exceed the required laser damage threshold (> 50 J/cm^2 vs. the required 5-8 J/cm^2).

7. In reactor chamber designs, we are developing models for how the chamber conditions evolve between shots. We have established an operating window for target yield, chamber radius, and chamber gas pressure that will avoid first wall vaporization, allow target injection without compromising the frozen DT fuel, and operate at a reasonable efficiency. Long term material behavior under alpha bombardment is an open issue. Consequently we have started experiments to exposed candidate first wall materials to ions and x-rays at fusion relevant fluences, spectra, and temperature. In the past we used the Z (x-rays) and RHEPP (ions) facilities at Sandia. We will augment these with a new repetitive x-ray source at LLNL, as well as the triple ion beam facility at ORNL.

8. Power plant studies have shown that this approach can be economically attractive.

Program principles:

The Laser IFE Program follows three key overarching principles:

1. It is a coordinated, integrated effort. All the components of Laser IFE are developed in concert with one another.

2. The program addresses issues that are unique to Laser IFE, and leaves generic issues (e.g. blankets, some materials, breeders, safety, etc.) to the much larger fusion program and to future research.

3. The program stresses experimental validation and predictive capability.

Program Plan:

We have formulated a three-phase program to develop laser-fusion energy. (This structure has been agreed upon by the fusion community.) Specific milestones must be met to go to the next phase:

Phase I *(1999 to about 2005):* The present "Proof of Principle" program.

Lasers: Develop technologies that can meet fusion energy requirements for efficiency (> 6%), repetition rate (5-10 Hz) and durability (> 100,000,000 shots continuous). The lasers will demonstrate the illumination uniformity and pulse shaping needed for fusion. The laser technologies employed must scale to reactor size laser modules and have attractive costs for commercial fusion energy.

Final Optics: Achieve laser induced damage threshold (LIDT) requirements of more than 5 Joules/cm^2. Develop a credible final optics design resistant to degradation from neutrons, x-rays, gamma rays, and energetic ions.

Reactor Chambers: Develop a viable first wall concept that is economically feasible for a fusion power plant.

Target Fabrication: Develop methods to fabricate cryogenic DT targets that meet the requirements from the Target Design codes. Combine these methods with established mass production costing models to show targets cost will be less than $0.25.

Target Injection/Tracking: Build an injector that accelerates targets the equivalent distance of the chamber (6.5 m) in less than 60 milliseconds. Demonstrate target tracking with sufficient accuracy for a power plant (+/- 20 microns).

Target Design: Develop credible target designs using multi-dimensional codes that have sufficient gain (> 100) and stability for fusion energy. Benchmark the underlying codes with experiments.

Phase II (*approx 2006-2012*): The Integrated Research Experiments (IRE)^2. These bring together the key components.

Lasers: Build a full-scale laser beam line for a reactor using the best laser choice to emerge from Phase I. The beam line will demonstrate all the fusion energy requirements, including efficiency, rep-rate, and durability.

Final optics/target injection: Demonstrate the full scale beam line can be steered to hit a target injected into a chamber, with the required precision.

Target fabrication/injection: Demonstrate mass production of fusion class targets. Demonstrate injection into a fusion chamber environment.

Power Plant Design: Produce a credible design for a laser fusion power plant that meets the technical and economic requirements for commercial power.

Chamber/Final Optics: Evaluate candidate materials/structures in a non-fusion environment.

Target Physics: Validate design codes with target physics experiments at fusion scale laser energies on the NIF.

Phase III *(2012 to about 2025)*: The Engineering Test Facility (ETF). This full-scale laser facility (1.5-2.5 MJ) would demonstrate repetitive high fusion yield. The ETF would also evaluate components and demonstrate fusion power.

1. Major Participants are:
Government Labs: Naval Research Laboratory, Lawrence Livermore National Laboratory, Los Alamos National Laboratory, Oak Ridge National Laboratory,
Sandia National Laboratory, Princeton Plasma Physics Laboratory.
Industry: General Atomics, Titan-Pulse Sciences Division, Schafer Corp, Science Applications International Corp, Northrop-Grumman Corp, Coherent, Inc, Commonwealth Technology, Inc.
University: UC San Diego, Univ of Wisconsin, UCLA, and Univ of Rochester Laboratory for Laser Energetics, Georgia Institute of Technology.

2. Phase II would include two major facilities:
   a) Laser IRE (Integrated Research Experiment) includes: Full energy laser beam line, target chamber, optics, target injector
   b) Target IRE includes: Mass production cryo target plant, cryo target injector, surrogate IFE chamber