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Grand Challenges of Inertial Fusion Energy

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Abstract

As soon as practical, Earth's low-cost, abundant, environmentally attractive fusion energy resources should be applied to the urgent global challenges of climate change, energy supply, economic growth, and the developing world. A National Ignition Campaign is under way at the recently completed National Ignition Facility (NIF) at Lawrence Livermore National Laboratory (LLNL) to ignite high-gain inertial fusion targets in the 2010–2012 time frame. Achieving ignition on NIF could be the catalyst for national and global leaders to support the development of inertial fusion energy (IFE) to meet the future's worldwide electric power demand. With sustained, high-priority funding could practical IFE be possible by the 2020 timeframe? The answer lies in how well can the community address and solve technical challenges in four key areas: achieving ignition, producing advanced targets and drivers, creating a practical fusion engine, and developing economical fusion power plants.

1. Introduction

At the National Ignition Facility[1], an extraordinary three-year inertial fusion ignition campaign is under way[2,3]. Ignition, advanced drivers and targets, fusion engines, and inertial fusion power plants are four grand challenges that may define a path to accelerated development of inertial fusion energy (IFE). The ultimate goal is to develop economically attractive IFE power plants that will attract large-scale commercial funding to enable global deployment.

Ignition – Ignition is a grand challenge[4]. Laser heated hohlraums energize tiny super-implosions designed to ignite propagating thermonuclear burn[5,6]. Record high velocities, densities, symmetry, and temperatures must be achieved before excessive growth of plasma and hydrodynamic instabilities occur and impede the process.

Advanced Targets and Drivers—NIF will enable the testing and development of advanced targets. High-gain spark-ignited targets can be initiated with several megajoules of 2ω laser light. Very high-gain fast-ignitor targets[7,8,9,10] can be imploded with hundreds of kilojoules of 2ω laser light or ignited with an estimated hundred-kilojoule petawatt pulse of laser light[11,12]. A small mass of high-density, fast-ignited DT may be used to ignite a 10-times larger mass of DT with density less than 10 g/cm^3. Alternatively, low-density DT may be imploded, in principle, more efficiently with a small mass of driver-ignited chemical propellant than with a 10% efficient laser, energized by a 40% power plant. Fusion yields as high as 1000 MJ may eventually be achieved.

Similarly, high repetition rate/efficient/high-average-power drivers[13,14] are being developed that can energize efficient implosions, including 2ω diode-pumped ceramic lasers capable of 10 shots per second. In addition, advanced petawatt fast ignition lasers are being developed that could reduce the cost of implosion laser systems.

Thermonuclear Engine—A burst mode, heat capacity, thermonuclear engine with fusion performance comparable to the International Thermonuclear Experimental Reactor (ITER)[15] may be feasible. Time and cost would be reduced by the use of highly modular drivers and target factories, as well as by implementing advanced lasers and targets. The repetition rate would gradually be increased to create a powerful 14-MeV neutron source. Radiation-hardened materials[16] for IFE and magnetic fusion energy (MFE) fusion reactors and Laser Inertial Fusion Energy (LIFE) fission hybrids could be developed[17]. Development of LIFE pure fusion reactors could be accelerated by using high-temperature fusion chambers with protected first walls to avoid the long-duration qualification of new 14-MeV neutron radiation-hardened materials and to achieve high thermal-electric efficiencies.

IFE Power Plants—Reduced driver and target costs will enable accelerated development of economically attractive IFE power plants. Successive generations of IFE power plants with economic advantages enabled by continuing advances in drivers and targets could well succeed at meeting the exacting criteria of future global energy requirements.

Detailed plans should be developed to assess the feasibility and estimated costs of accelerated IFE development.

2. Ignition

Ignition is the pivotal grand challenge. The National Ignition Campaign (NIC) at LLNL includes hardware and infrastructure needed to execute the initial ignition experiments and to continue research on ignition in subsequent years. Key elements of the campaign include target design code validation and equipment, such as diagnostics and the cryogenic target system.

During the ignition process, laser-heated hohlraums energize tiny super-implosions designed to ignite propagating thermonuclear burn. High velocities, densities, symmetry, and temperatures must be achieved before excessive growth of plasma and hydrodynamic instabilities occur.

In the NIC, hundreds of highly diagnosed experiments will be conducted to improve the physics approximations used in the target design codes. Unknowns will be bounded, and the target design will be optimized. "Black swan" failures modes, including phenomena that do not follow Gaussian statistics are judged to be unlikely, but cannot be precluded.

Consequently, alternative targets are being developed and may be utilized, including polar direct-drive shock-ignited targets[18,19], two-shell targets, and fast ignition targets.

Fast-ignited isochoric targets may be one of the most promising advances to the point design spark-ignited isobaric targets currently being used in the ignition campaign. In the fast ignition approach, in which compression is separated from the ignition phase, implosion velocity and density are less than those in spark ignition, so in principle, fast ignition will allow some relaxation of the requirement for maintaining precise, spherical symmetry in the implosion. The improved energy gain is estimated to be as much as a factor of 10 over the spark-ignited approach. For these reasons, enhanced performance fast-ignited targets may be a leading candidate for use in fusion engines and economically attractive power plants.

3. Advanced Targets and Drivers

After ICF target designs achieve ignition, performance may be improved in post-ignition NIF experiments, beginning with the point design indirectly driven target used in current NIF ignition experiments. Although indirectly driven target schemes were proposed for inertial confinement fusion 50 years ago, and extraordinary improvements have been made, I believe there is still high potential for performance improvement after ignition is demonstrated.

A major goal for IFE is to significantly reduce target[20] and driver costs, which would reduce costs of fusion engines and future power plants. As a first step, it has been estimated that the driver capital cost can be reduced to less than $400 M, which corresponds to 800 kJ at $500/joule, based on current driver development trends. An annual target cost of $30 M, corresponds to a 1,000-MJ-target yield with a 3-Hz repetition rate, assuming a 30¢ cost per target. Maximum target improvements may reduce these costs another factor of two (to about 5% of the capital cost and gross income of a 1-GWe power plant).

Directly driven fast ignition targets are estimated to yield ~250 MJ when imploded with an 800-kJ laser. To increase the fusion yield several fold, the isochoric imploded density distribution may be modified to create a steep density gradient (or density step). The ignition laser energy is reduced by the use of high DT densities, and the implosion laser energy is reduced (or the DT mass and yield increased) by the use of lower DT densities. With density-radius products greater than ~1 g/cm^2, thermonuclear burn may be propagated from a small mass of high-density fast-ignited DT to ignite a 10-times larger mass of low-density DT.

George Zimmerman of Lawrence Livermore National Laboratory has run a 2D LASNEX explosion calculation of a density step approximation to a density gradient. The initial configuration for the calculation is shown in Fig. 1 The calculation of a fast-ignited hemispherical DT mass, density 300 g/cm^3, $\rho R \sim 3$ g/cm^2, exploding into a 10 times larger hemispherical DT mass, density 30g/cm^3, $\rho R \sim 1.4$ g/ cm^2 is shown in Fig. 2. In the calculation, the fast-ignited mass explodes and ignites the 10-times larger mass, 10-times lower density hemisphere, and the total yield increases ~ 10 fold.

If the compression energy invested in the lower-density hemisphere is used to add high-density mass to the 300 g/cm^3 hemisphere, the explosion yield increases by about four fold. Consequently, the gain is increased ~2.5 fold by use of the density step. With 800 kJ of laser energy, a density gradient may be used in a directly driven fast ignited target to increase the yield from 250 MJ to ~600 MJ. If the implosion efficiency can be increased as the density and implosion velocity are reduced, even higher yields may be achieved.

If DT densities as low as a few g/cm^3 are ignited, dense pusher-tampers and efficient cannon-like implosion systems may be utilized (instead of ablative implosions). Inertial tampers may also increase the DT burn efficiency and fusion yield.

In another option, very small driver energies may be used to initiate ~100 grams of chemical propellant (costing ~10¢) to energize cannon-like implosions to a few g/cm^3. Use of magnetic fields should also be explored. Fusion yields of 1,000 MJ may be achieved with enhanced performance fast-ignited targets.

In light of these various alternatives, instead of developing more complex target designs to increase the target yield, it may be possible to develop simple lower-cost targets. Greatly increased efforts should be devoted to the development of advanced targets given the importance of this factor on the future of IFE.

4. The Fusion Engine

Assuming advanced target factory modules are developed in parallel with high-performance targets and high-performance driver modules, these advances would significantly reduce the cost of a fusion engine and fusion power plants and could serve as a catalyst to initiate accelerated fusion engine and IFE development programs.

The physical separation of the driver, target factory, and fusion explosion chamber in the fusion engine (and power reactor) minimizes radiation damage. This separation, the high modularity of the driver and target factory, and the small size and high improvement potential of the driver and targets may enable rapid evolution of the fusion engine.

Fusion chambers must be constructed to operate at a high temperature, more than 500 degrees Celsius, to enable high thermal-electric efficiencies for the power conversion system. The fusion explosion chamber first wall radiation damage and cyclic fatigue may be greatly reduced by using a protective shield to mitigate exposure to intense heat and radiation from the target's X rays, ions and neutrons.

An fusion engine could be constructed to operate initially as a surged heat capacity system, e.g., a shot every 100 seconds for 1,000 seconds. Performance would then evolve by increasing the repetition rate and operating time, e.g., to a greater than one-Hz, 100-MW fusion power system operating 80% of full time.

Applications of a fusion engine 100-MW, 14-MeV neutron source might include exploration of fission waste burn-up, breeding enough tritium to enable startup of many full-scale fusion reactors, development and testing of advanced radiation-hardened materials, and development of nonproliferation safeguards for fusion power plants. Demonstration of the technological feasibility of economically attractive inertial fusion power plants would be accomplished as rapidly as possible.

5. IFE Power Plants

With strong sustained government funding of an IFE power plant development program, less than 30 years (possibly 10 to 15) may be required to develop the first economically attractive IFE power plant, i.e., a power plant that would be replicated, rapidly improved, and deployed in large numbers, using large-scale commercial funding (or large-scale government funding in China and other controlled economies)

Several years would be subtracted from IFE development time by a near-term surge in funding to accelerate achievement of ignition and development of advanced targets, modules of advanced drivers and target factories, and a prototype high-temperature fusion explosion chamber.

With accelerated development, in the 2020s fusion energy may begin to contribute to solving 21st Century problems – including climate change, energy supply, economic growth, and the rise of the developing world.

IFE power plants will have powerful genetic advantages that may enable rapid improvement. With cheap, clean inexhaustible fusion fuel available to all nations, IFE may excel in a long-range competition of future energy sources.

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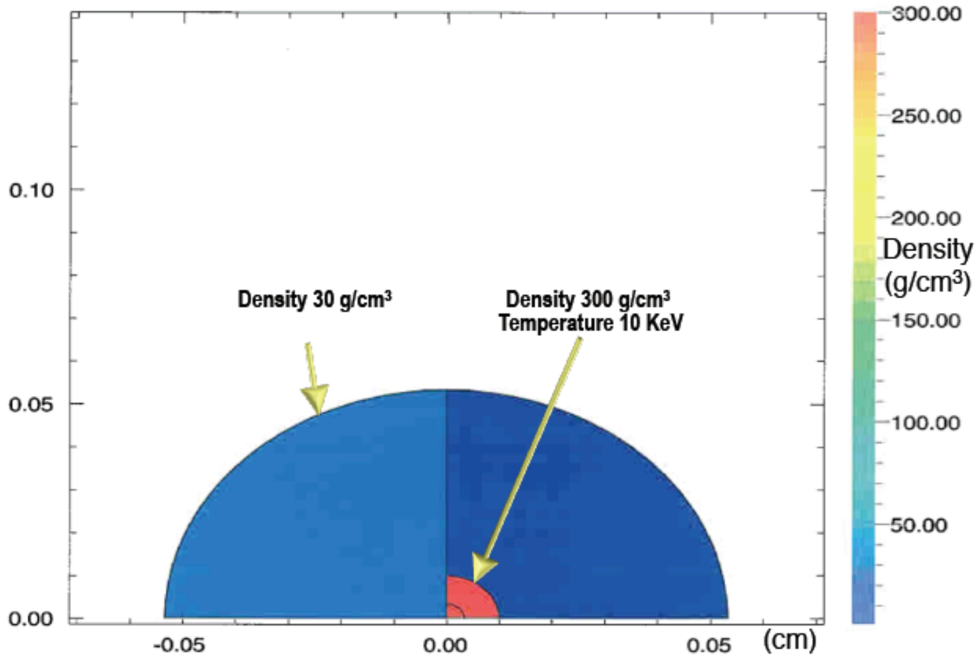

Fig. 1 Initial configuration for calculations of ignition across a 10X density step

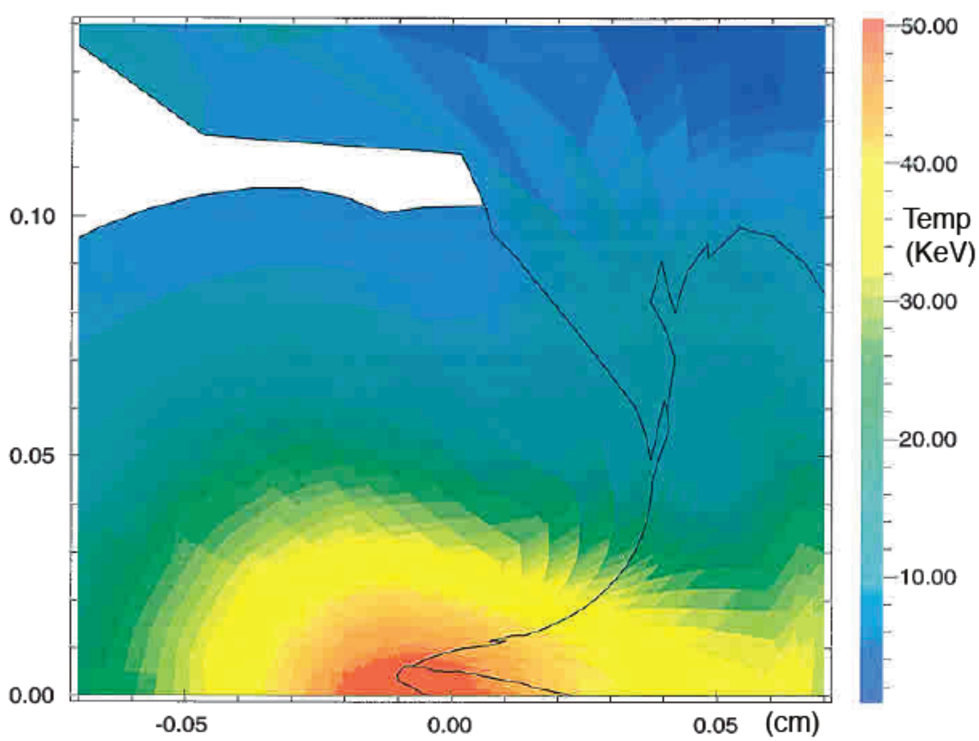

Fig. 2 Fusion driven explosion of the high-density fuel ignites the 10X lower density fuel (George Zimmerman - private communication)

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