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Inertial Fusion Science and Technology for the Next Century

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Inertial Fusion Science and Technology For the Next Century

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Abstract

This paper reviews the leading edge of the basic and applied science and technology that use high-intensity facilities and looks at what opportunities lie ahead. The more than 15,000 experiments on the Nova laser since 1985 and many thousands more on other laser, particle beam, and pulsed power facilities around the world have established the new laboratory field of high-energy-density plasma physics and have furthered development of inertial fusion. New capabilities such as those provided by high-brightness femtosecond lasers have enabled the study of matter in conditions previously unachievable on earth. These experiments, along with advanced calculations now practical because of the progress in computing capability, have established the specifications for the National Ignition Facility and Laser MegaJoule and have enhanced new scientific fields such as laboratory astrophysics. Science and technology developed in inertial fusion have found near-term commercial use, have enabled steady progress toward the goal of fusion ignition and gain in the laboratory, and have opened up new fields of study for the 21st century.

1. Introduction

Over the past 25 years there has been steady progress in understanding the conditions under which ignition of inertial fusion targets might be achieved at the smallest possible drive energy. This progress has accelerated in the last 14 years with extraordinarily rapid developments in instrumentation, theory, computational simulations, and with the larger laser, particle beam, and pulsed power facilities that became available in the mid-1980s. The laser and pulsed power facilities developed for inertial fusion have also proven to be outstanding research tools for the fundamental study of high-temperature and density plasmas (sometimes called high-energy-density science). The field of inertial fusion sciences and applications (IFSA) can provide an exciting and sound basis for new capabilities for the next century.

Lasers, ion beams, and pulsed power facilities reproducibly concentrate energy in space and time and thus can create diagnosable plasmas that exist for picoseconds to tens of microseconds at extremely high-energy density. Such experiments can reach plasma electron and ion temperatures $>10^8$ K, pressures $>10^{11}$ atmospheres, and radiation temperatures $>3.5 \times 10^6$ K. For example, radiation temperatures of 94 eV, 151 eV, and 288 eV have been produced in cylindrical gold hohlraums with diameters of 4.8, 1.6, and 1 mm respectively.[1] Resulting radiation fluxes $>10^5$ GW/sr/cm^2 can be used for fusion capsule compression or for a variety of measurements of basic material properties and/or physical processes. Large laser facilities doing such experiments include Nova (recently shut down), Omega, and Nike in the United States, Gekko XII in Japan, Phebus in France, Helen and Vulcan in the United Kingdom, and Iskra in Russia.

Chirped pulse amplification techniques have been applied to many small lasers in the United States, France, Japan, and elsewhere to achieve extraordinarily high-power intensities ($>10^{20}$ W/cm^2) and make possible the study of relativistic plasmas.[2] That the extremely high fields ($\sim10^{14}$V/m), energy densities ($\sim3 \times 10^{10}$ J/cm^3), and pressures (~300 Gbar) produced are being used to do very interesting science is attested to by the more than 60 papers on the subject presented at IFSA'99.

Pulsed power progress with Z pinches has resulted in record x-ray power output from fine wire arrays. Experiments at the Z machine at Sandia National Laboratories have produced 280 TW of x-ray power output with high efficiency. Joint experiments with Lawrence Livermore National Laboratory (LLNL) and Los Alamos National Laboratory are under way to use this new capability for high-energy-density plasma physics experiments. Two sessions of IFSA'99 are devoted to progress in Z-pinch experiments.

Gesellschaft für Schwerionenforschung is steadily increasing its heavy ion, high-energy (MeV-GeV/nucleon) beam intensity (×1000 upgrade nearing completion) and is planning to add a kJ/petawatt laser to complement its particle beam capabilities. The laser will help diagnose high-energy-density plasmas created by the ion beams and can also create hot, dense plasma in which to study ion stopping.

The progress in fundamental science has significantly furthered development of inertial fusion energy (IFE). The more than 15,000 experiments on Nova and the many thousands more in other facilities around the world have provided the basis for construction of facilities intended to ignite targets for the first time.

In this paper the authors will review (by showing representative examples, principally from laser experiments) the exciting progress that is being made in basic high-energy-density sciences. We will also discuss new strategies being developed by the community for fusion energy development. *Figure 1* shows construction activities on the National Ignition Facility (NIF) at LLNL. Recently revised calculations indicate that NIF target performance may even exceed that forecast for the baseline targets. We are currently reassessing how to bring the NIF on line; there will be some delay and increased costs, but there is strong will to complete the NIF Project.

Figure 1. Aerial view of NIF (left photo) taken April 23, 1999, showing the nearly complete Optics Assembly Building (upper right), the complete shells of the laser bays, and the half-complete concrete structure of the target area building (lower left). The 10-m-diameter Al target chamber (right photo) was set into place in the target area building after a dedication ceremony June 11, 1999, featuring Secretary of Energy W. Richardson.

2. High-Energy-Density Science

For convenience, we will consider high-energy-density science in three categories: use of the ultrahigh powers of femtosecond lasers, laboratory astrophysics, and studies of material properties at high-energy densities.

2.1 Femtosecond Laser Science and Developments

The development of chirped pulse amplification has made possible extremely high-power ($>10^{15}$ W), short-pulse ($<10^{-12}$ s), high-brightness lasers that can irradiate targets at intensities approaching 10^{21} W/cm^2.[3] Such lasers are being used to study the feasibility of the fast igniter concept for high-gain IFE targets (see the many papers at this conference) and also for research in relativistic plasma physics. Experiments have shown that a significant fraction of high-intensity light is converted into relativistic electrons [4,5] with energies up to 100 MeV.[5,6] Intense gamma rays created in electron collisions have led to the production of positrons.[6] As shown in *figure 2*, these gamma rays induce (γ,n) and (γ,p) nuclear reactions, photo-dissociation of nuclei, and activated radionuclides in a wide range of materials.[6,7] High-energy proton beams are generated and, in turn, induce strong (p,n) nuclear reactions. These data suggest that high-intensity lasers may provide new sources of ions, nuclear particles, and radionuclides, which may have significant future scientific and technical applications.

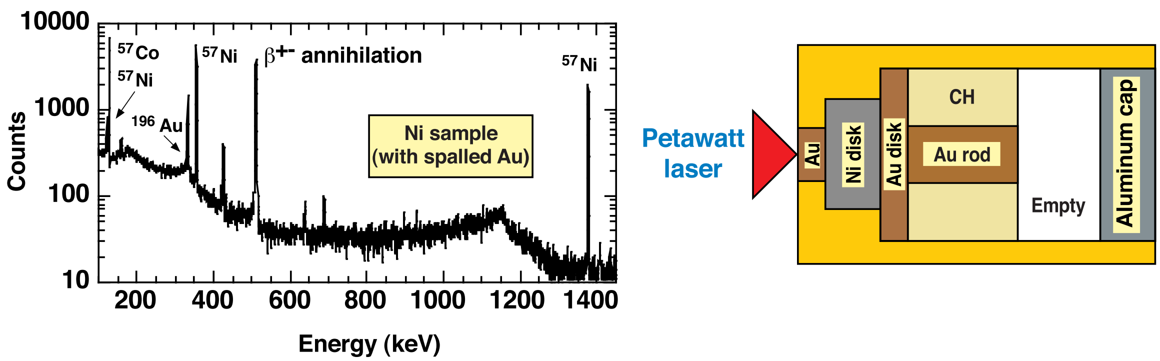

Figure 2. The Petawatt laser at LLNL has produced strong nuclear (γ,xn) activation.

The Petawatt laser has also been focused upon deuterium clusters created in a gas jet, and 2.45-MeV neutrons have been observed from the resulting fusion reactions.[8] *Figure 3* shows the experimental arrangement. A gas jet produced a deuterium cluster density of 10^{18} to 10^{19} cm^{-3}. The graph in the figure shows the dramatic increase in neutron yield per shot as the peak laser intensity is increased. This experiment produced interesting science, and the technology should be studied as a possible neutron source for fusion materials testing.

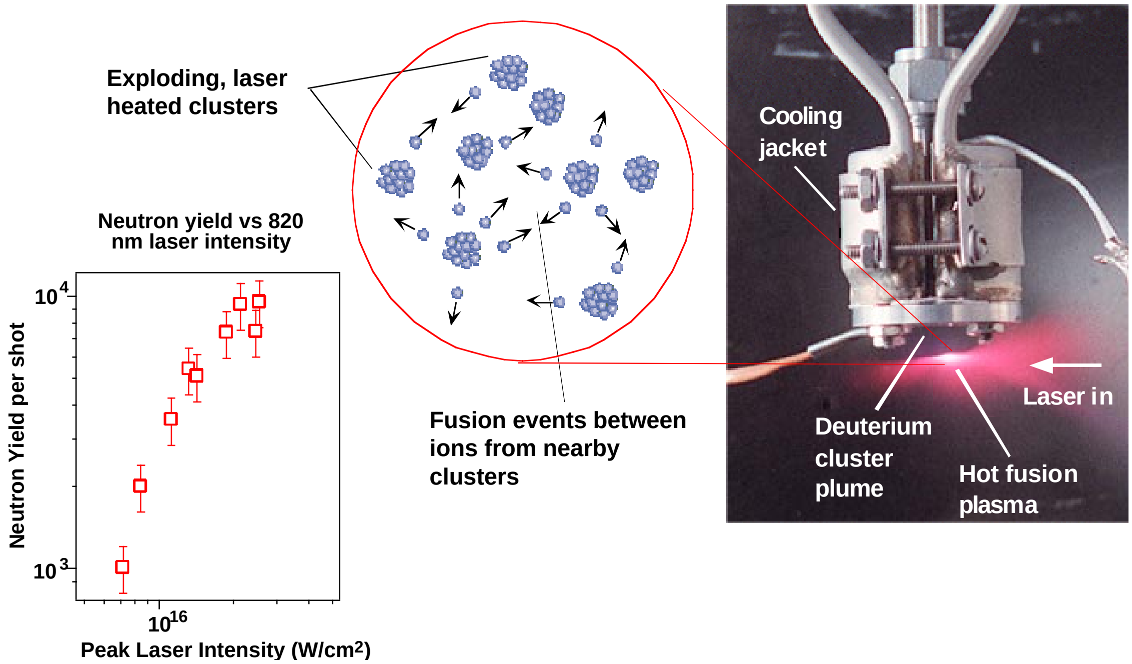

Figure 3. D-D fusion reactions have been induced by focusing an ultrashort laser pulse onto a jet of deuterium clusters (Nature 398, 489 [1999]).

The femtosecond pulse laser technology is also finding near-term applications in materials manufacturing processes. Drilling and cutting can be done with the short-pulse laser more precisely and with little or no heat-damaged zone created. The physical processes involved in the interaction of such short (<1 ps) high-power laser pulses and matter are very different from those involved with long (>10 ps) pulses. Experiments have been done with metals, ceramics, and biological materials with no collateral damage and with micron-scale precision. This feature has already been found useful in specialized cutting applications.

2.2 Laboratory Astrophysics

Two workshops on laboratory astrophysics and many laboratory experiments over the last few years have contributed greatly to the understanding of what is required to exploit laboratory-scale experiments to better understand astrophysical phenomena. Experimental programs are ongoing in the following topics:

- Explosion hydrodynamics—supernovae.
- Radiative jets—Herbig-Haro objects.
- Solid-state flow—earth interior.
- Ablation fronts—Eagle nebula ("pillars of creation").

Papers at this conference in the Laboratory Astrophysics sessions and a third workshop scheduled for March 2000 at Rice University illustrate progress in this developing field.

Striking similarities were observed between simulations of hydrodynamic instability growth in inertial fusion capsule implosions and core-collapse supernova explosions, in spite of the huge scale difference.[9,10] It has been shown that the physics is invariant in Euler's equation by making suitable scale transformations.[11] *Figure 4* (also from Ref. 11) shows that, by proper design of a laboratory experiment, the calculated velocity, density, and pressure profiles of a supernova explosion can also be reproduced. *Figure 5* shows the experimental arrangement, x-ray radiograph, and model/data comparisons of Richtmyer–Meshkov and Rayleigh–Taylor instability growth at the Cu-CH interface of an accelerated target employed in the laboratory experiments.[12,13] Excellent agreement is observed. Recent striking experiments display the explosive phase of an x-ray-heated cylinder, which qualitatively compares quite well with the calculated supernova explosion.[14,15]

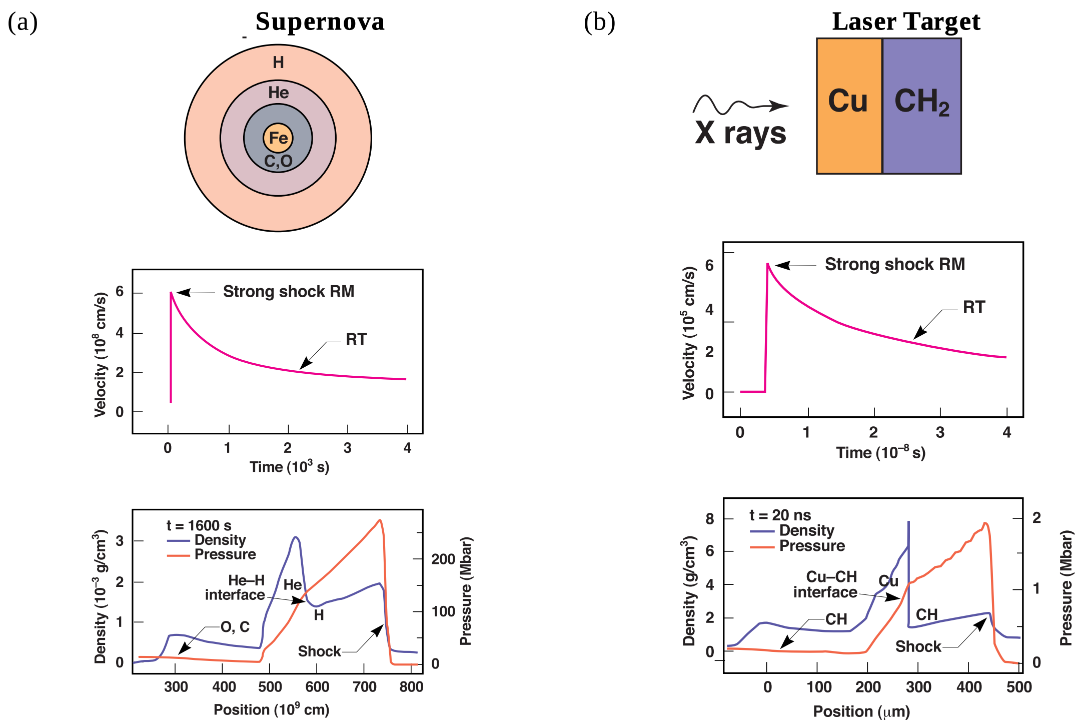

Figure 4. Velocity, density, and pressure profiles for a supernova (a) that are reproduced in a laboratory experiment driven by laser-generated x rays (b).

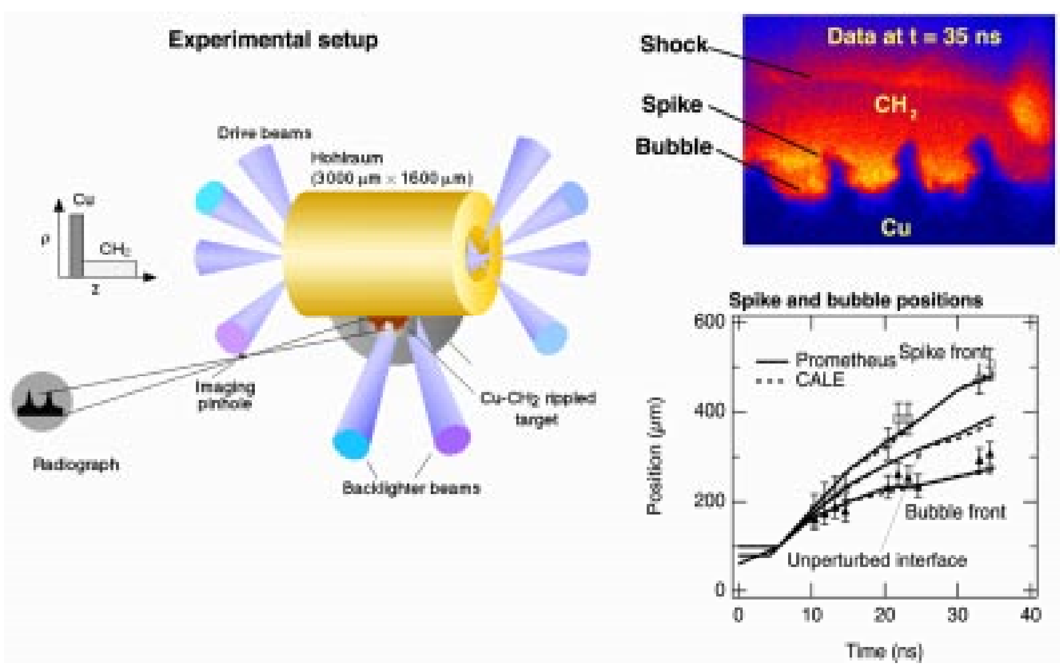

Figure 5. Scaled core-collapse supernova experiments on the Nova laser mimic the hydrodynamics at the helium-hydrogen interface with surrogate materials.

Astrophysics is currently witnessing a spectacular extra-galactic colliding plasma experiment in the ejecta-ring collision of SN1987a. The question has been posed: can laboratory experiments help us understand what is going to happen during this collision? *Figure 6* shows some observations of the SN1987a remnant, an experiment designed to study certain aspects of the collision [16] and earlier simulations relevant to the event.[17] Three papers at IFSA'99 will explore this use of laboratory experiments further.[18,19,20]

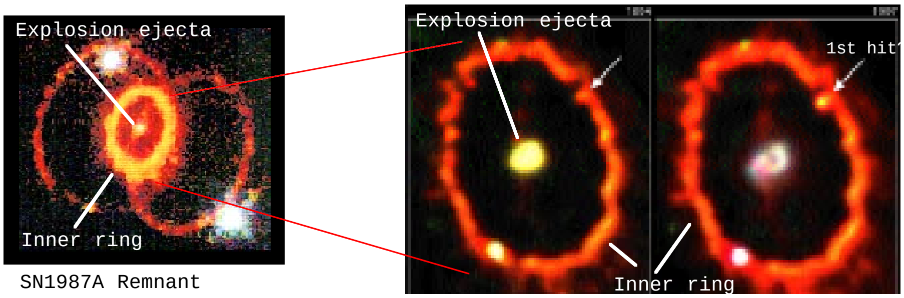

Figure 6. Laboratory experiments are being done to help understand what will happen during the collision of explosion ejecta with the preexisting ring of debris in SN1987a.

2.3 Material Properties at High-Energy Densities

An understanding of the equation of state (EOS) of hydrogen at pressures exceeding 1 Mbar is important for planetary science, brown dwarfs, and IFE. Study of the EOS along a principal Hugoniot for numerous materials up to tens of megabars has been made possible by high-energy-density facilities. For example, a study of the compressibility of liquid deuterium at pressures from 0.2 Mbar to 3.4 Mbar using Nova has revealed high compressibility.[21] This is understood as linked to pressure-induced molecular dissociation corresponding to the transition to metallic hydrogen. The results, shown in *figure 7*, were obtained with numerous diagnostics. Similar insulator-to-metal transitions have also been seen for LiF at ~6 Mbar and carbon (diamond) at ~10 Mbar.

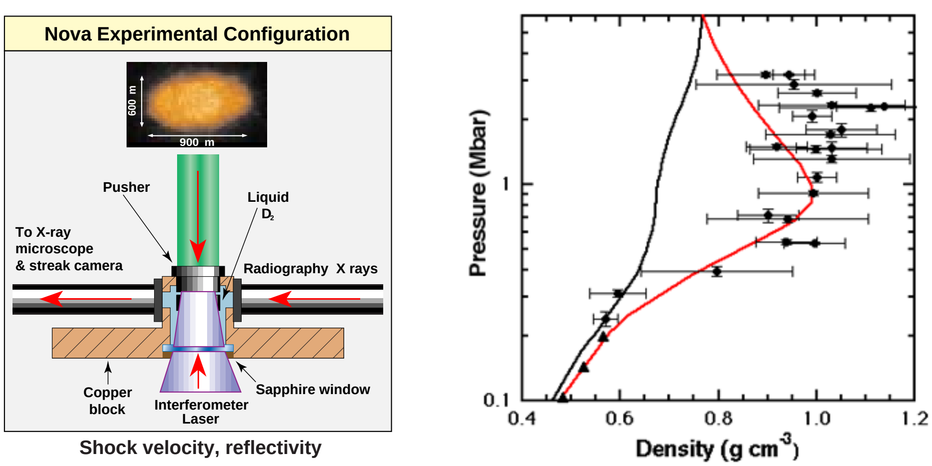

Figure 7. Laboratory experiments used Nova laser energy to produce a shock that allowed measurement of the EOS of hydrogen at megabar pressures.

3. Inertial Fusion Energy Development

To build and sustain support for the development of fusion energy, the community must show that a fusion power plant will be competitive with other forms of energy. It must be competitive from all viewpoints, e.g., economics, safety, environmental impact, reliability, maintainability, political issues such as nonproliferation, licensing issues, waste disposal, spin-off applications, and affordability of development. IFE is a potentially attractive approach to fusion energy on all counts. The basics of why this is so and how an attractive power plant can be developed have been described in a number of places.[22,23] In particular, IFE has an affordable development path resulting from:

- The separability and modularity of components and systems.
- The breadth of possible attractive options in targets, drivers, and chambers.
- The leverage from other applications of ICF technology such as those in national security, high-energy physics, and industry.
- The fact that engineering development of power plant chambers can be done in scaled, lower-cost reaction chambers.[24,25]

Progress in target physics has been steady, supported in the United States by the Department of Energy (DOE) for national security purposes. Accelerator technology is furthered by the high-energy physics community, and lasers are being developed by industry for other purposes.

The goal of the NIF is to achieve ignition and significant energy gain in the laboratory for the first time. Given the progress in the field and the attractive features of IFE, a development plan has been formulated by the community that, if funded and successful, would lay the technical foundation for beginning construction of an engineering test facility (ETF) in the second decade of the next century. The goal of this facility would be to produce average fusion power (in the range of 100 to 400 MW) and to demonstrate the operability, environmental and safety features, and the economics of IFE for a project cost in the range of $2B to $3B.

The proposed development program has been formulated with the entire U.S. fusion community on a common basis. The IFE "road map" that has resulted from this effort is shown in *figure 8*. This figure shows the different stages of development and demonstration—concept exploration, proof of principle, performance extension, and fusion energy development (the ETF) leading to a demonstration plant. To progress to higher, more costly stages, specific scientific and technical objectives must be met. The existing ICF program engages the road map at the first three levels, with significant ongoing investment by DOE's national security program (illustrated by the shaded region in the performance extension stage). Examples of activities in the first level include exploring ways of extending the successful Z-pinch efforts into an IFE concept (repetition-rate, stand-off, waste stream), examining the high-gain ($G > 200$) "fast igniter" concept in which isochorically compressed fuel is ignited by a separate high-intensity driver, and exploring high-gain ($G > 100$) indirect-drive target concepts with lasers. Examples of the second stage include the development of high rep-rate (>5 Hz) 100-J class KrF (the Electra project at the Naval Research Laboratory) and diode-pumped solid-state lasers (Mercury project at LLNL). Overview papers on the status of each driver are included in IFSA'99.

The third stage includes the demonstration of ignition and gain on the NIF and Laser MegaJoule (LMJ) and the construction of high rep-rate, multikilojoule (~15 kJ to 300 kJ) drivers that also address key chamber issues (driver/chamber interface, beam propagation in the chamber, etc.). Because of these system objectives, these facilities have been named integrated research experiments (IREs).

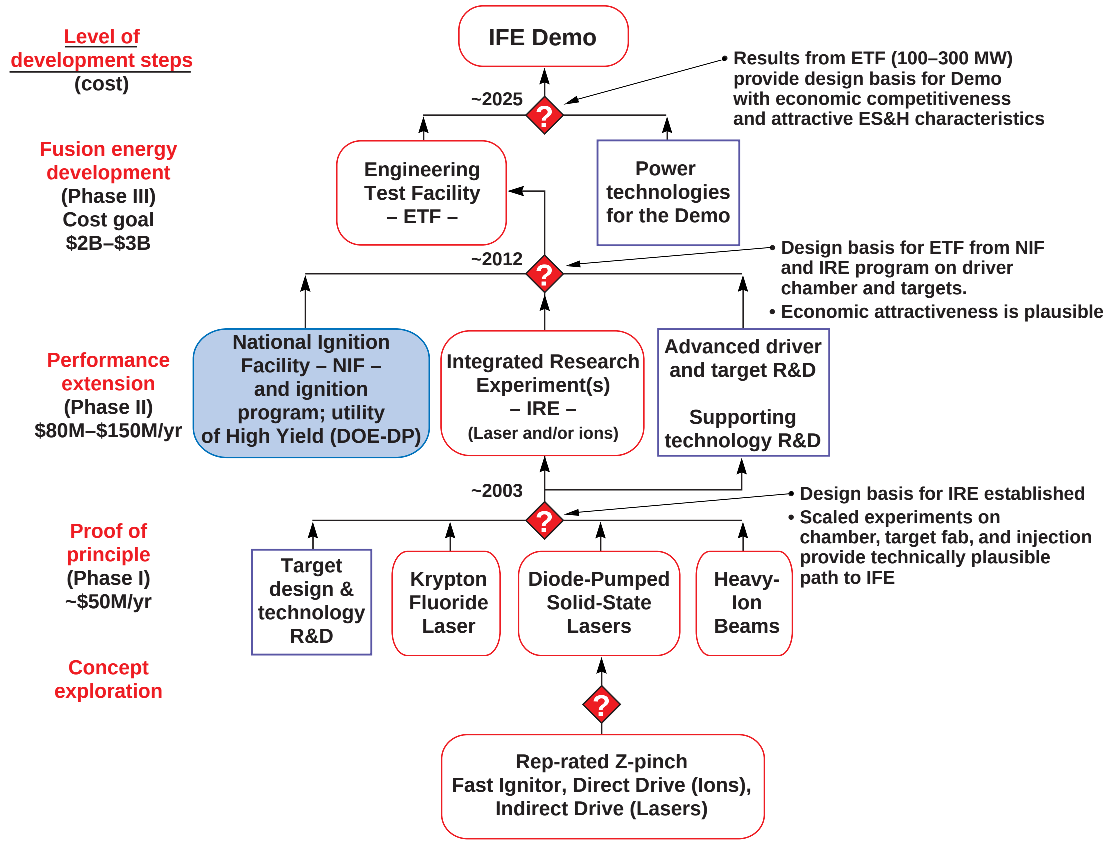

Figure 8. An affordable IFE development plan is illustrated in the IFE "road map."

The results of the IREs and the target physics from the NIF, described in the next section, would form the basis of proceeding with an ETF. In the ETF, a power-plant-scale, high-pulse-rate driver would drive reaction chambers to demonstrate the ability of the various chamber concepts to operate at 5–10 Hz. In an IFE power plant, the combination of rep-rate and capsule yield determine fusion power. These variables are independent for IFE. Therefore, reaction chambers scaled down to the size necessary for lower-yield targets could test the ability to achieve the necessary rep-rate.[24] These low-power chambers would be less expensive. Separately, experiments in a single-pulse chamber could demonstrate the high yield necessary to obtain a driver efficiency/target gain product greater than about ten, a necessary condition for IFE power plant economics.[22] Significantly, the low yield necessary to do the high-rep-rate demonstration will have already been demonstrated on the NIF.

Finally, if the ETF is successful, an IFE demo could be built. Depending upon the outcome of the ETF experiments, it may only be necessary to add a high-power reaction chamber to the driver and target factory built for the ETF, to close the fuel and target materials cycles, and to add electricity-producing systems. This development path would be more affordable than one that requires completely separate facilities at each stage.

4. The National Ignition Facility

Demonstration of the critical features of ICF and IFE targets, that is, ignition and propagating thermonuclear burn, is a principal goal of the NIF, now under construction at LLNL (see *figure 1*). The NIF is intended to be an extremely flexible facility. It will have the ability to irradiate both indirect- and direct-drive targets with a variety of pulse formats, including the complicated pulses required for high-gain IFE targets. The NIF should be able to do experiments relevant to all target types and most drivers. *Figure 9* shows current projections for gain expected from a variety of target types, including fast ignition targets. The fast ignition curves, of course, are based on models that have not yet been validated by experiments. However, the figure shows why we are so interested in this high-risk but high-payoff approach. The NIF will truly be able to explore all options. A number of papers on the baseline targets and on the fast ignition approach are presented at IFSA'99.

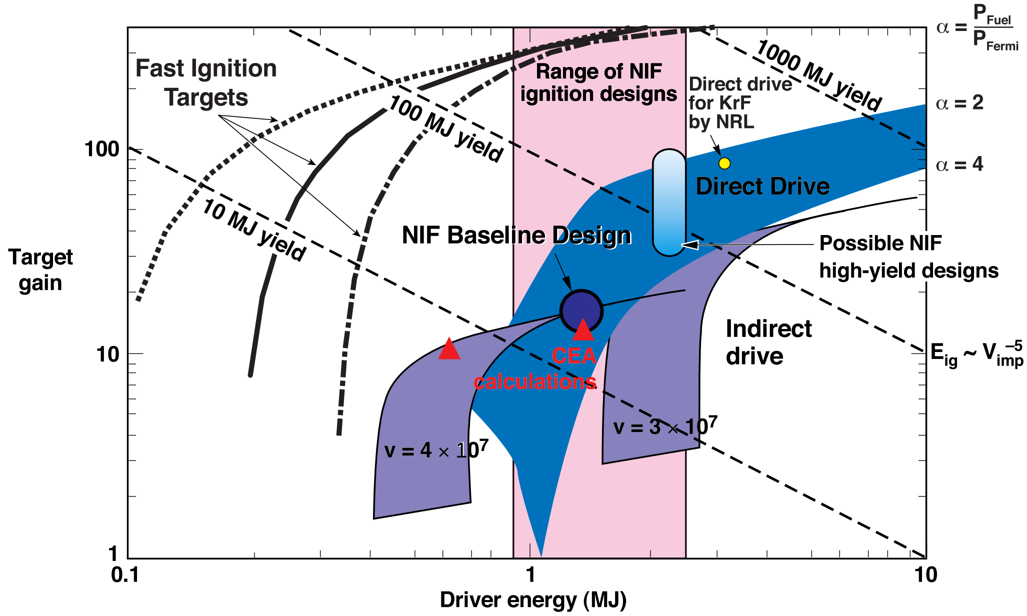

Figure 9. The NIF will map out ignition and gain curves for many target concepts.

More recently, work exploring higher gain with indirect-drive targets has shown promise. In *figure 10*, the energy-power parameter space available on the NIF is shown along with the location of the nominal, gain 10 design and one with gain 30. As shown in the figure, by optimizing the hohlraum and laser, it may be possible to produce indirect-drive targets in which the capsule absorbs >600 kJ of x rays (the baseline NIF capsule absorbs 150 kJ of x rays). Such targets may produce gains greater than 30 with yields of 70 to 100 MJ.[26]

- **Lower power, longer pulse shapes can give more energy from NIF (260 eV vs 300 eV)**
- **Material mixtures ("cocktails") reduce hohlraum wall losses**
- **Slightly larger capsule/hohlraum size increases coupling efficiency to capsule**
- **Longer pulses increase the radiation fraction absorbed by a capsule**
- **Slight LEH closure reduces hole losses**

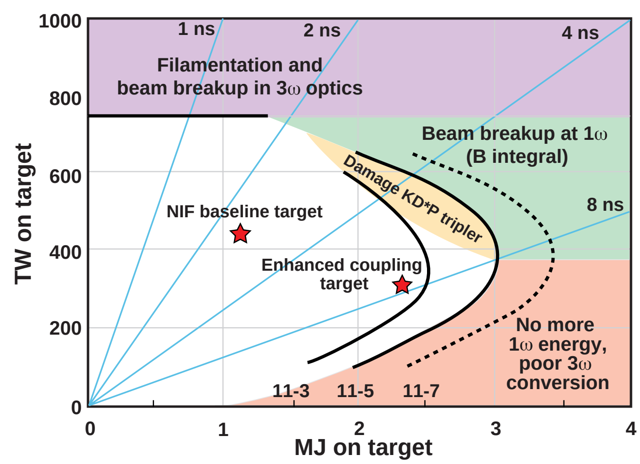

Figure 10. Recent calculations are exploring ways to increase the capsule energy on the NIF for indirect-drive targets.

The NIF also promises to extend the work done in basic high-energy-density plasma physics, laboratory astrophysics, and all the fundamental fields discussed above. The experiments that have been done to date on all the high-energy-density facilities have established the fundamental feasibility to obtain useful data to further a wide variety of fields. Experiments are being designed now for the NIF and LMJ that will utilize their fullest capabilities.

Inertial fusion has value for analyzing nuclear weapon performance. Consequently, there is concern about proliferation of weapon-relevant information through inertial fusion work. Progress in IFSA and the ability to share future results will depend on the Comprehensive Test Ban Treaty and on reducing global nuclear danger. The next century has the potential to be very exciting for all inertial fusion sciences and applications.

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