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The US ICF ignition program and the Inertial Fusion Energy Program

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ABSTRACT: There has been rapid progress in inertial fusion in the past few years. This progress spans the construction of ignition facilities, a wide range of target concepts, and the pursuit of integrated programs to develop fusion energy using lasers, ion beams and z-pinches.

Two ignition facilities are under construction (NIF in the U.S. and LMJ in France) and both projects are progressing toward an initial experimental capability. The LIL prototype beamline for LMJ and the first 4 beams of NIF will be available for experiments in 2003. The full 192 beam capability of NIF will be available in 2009 and ignition experiments are expected to begin shortly after that time.

There is steady progress in the target science and target fabrication in preparation for indirect drive ignition experiments on NIF. Advanced target designs may lead to 5-10 times more yield than initial target designs. There has also been excellent progress on the science of ion beam and z-pinch driven indirect drive targets.

Excellent progress on direct-drive targets has been obtained on the Omega laser at the University of Rochester. This includes improved performance of targets with a pulse shape predicted to result in reduced hydrodynamic instability. Rochester has also obtained encouraging results from initial cryogenic implosions[1].

There is widespread interest in the science of fast ignition because of its potential for achieving higher target gain with lower driver energy and relaxed target fabrication requirements. Researchers from Osaka have achieved outstanding implosion and heating results from the Gekko XII Petawatt facility and implosions suitable for fast ignition have been tested on the Omega laser[2].

A broad based program to develop lasers and ions beams for IFE is under way with excellent progress in drivers, chambers, target fabrication and target injection. KrF and Diode Pumped Solid-State lasers (DPSSL) are being developed in conjunction with dry-wall chambers and direct drive targets. Induction accelerators for heavy ions are being developed in conjunction with thick-liquid protected wall chambers and indirect-drive targets.

PAPER: In the past couple of years, there has been exceptional progress in inertial fusion across a wide range of inertial fusion target concepts as well as in ion beam, laser, and z-pinch approaches to Inertial Fusion Energy (IFE).

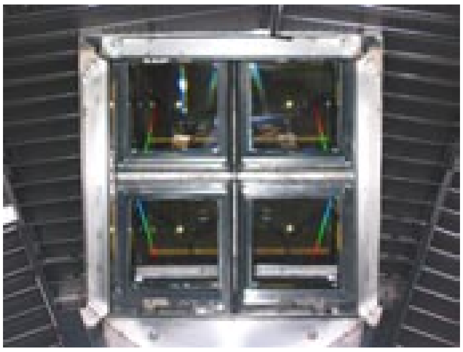
The NIF Conventional Facilities are Complete

The beampath infrastructure for all 192 beams is complete and the first four beams have been activated for experiments

Figure 1. The National Ignition Facility.

There has been rapid progress on construction of the National Ignition Facility (NIF) in beamline infrastructure for all 192 beams has been installed. The first 4 beams (1 Quad) have been installed on the target chamber as shown in Fig. 2. On a single beams basis, the NIF has achieved all of its performance objectives as indicated in Table 1. Initial diagnostics are being activated for the first experiments planned to begin in the summer of 2003. As more beams are added, a wide range of increasingly complex experiments will be possible. Completion of the full laser system is expected in 2008 and the first ignition campaign can begin following the completion of the cryogenic system, expected a year later.

Quad 31b beamtubes and optics are installed and operational



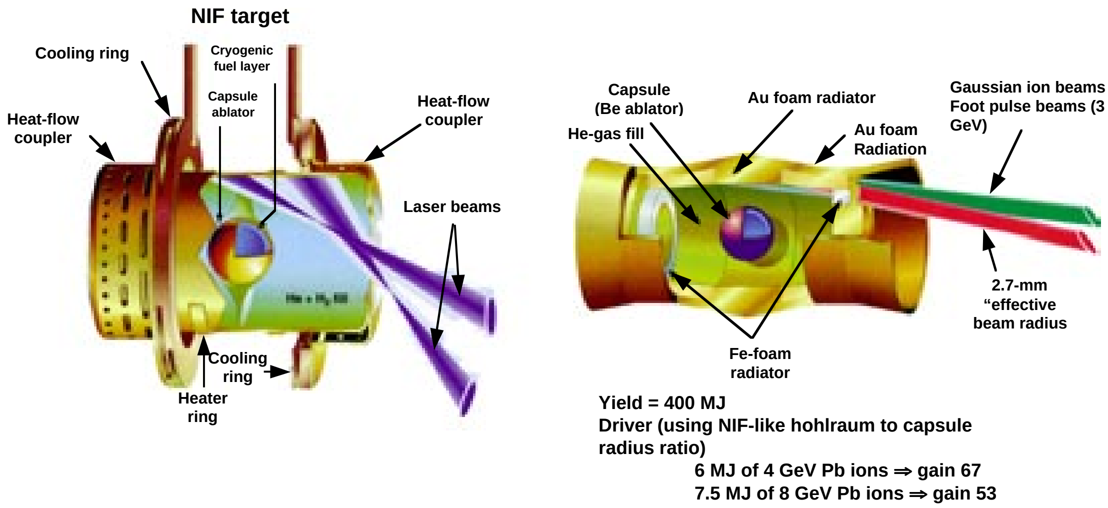
View from inside the target chamber

Figure 2. First four NIF beams installed on the target

- The NIF Early Light (NEL) commissioning of four laser beams has demonstrated all of NIF's primary performance criteria on a per beam basis
  - 21 kJ of 1ω light (Full NIF Equivalent = 4.0 MJoule)
  - 11 kJ of 2ω light (Full NIF Equivalent = 2.2 MJoule)
  - 10.4 kJ of 3ω light (Full NIF Equivalent = 2.0 MJoule)
  - 25 ns shaped pulse
  - < 5 hour shot cycle (UK funded)
  - Better than 6% beam contrast
  - Better than 2% beam energy balance
  - Beam relative timing to 6 ps
- Static x-ray imager and streaked x-ray detector operational and acquiring data at the target chamber

Table 1. NIF has begun to commission its experimental systems and will begin 4 beam (1 quad) experiments this summer.

There are wide ranges of target types being pursued in inertial fusion. Both direct drive and indirect drive with lasers will be tested on NIF. As shown in Fig. 3, much of the information about laser-driven indirect drive targets is applicable to indirect-drive targets imploded with other drivers. This is the basis for confidence in indirect-drive targets being designed for use with ion-beam drivers being developed for IFE as discussed below. The ability to apply information on laser-driven indirect-drive targets to indirect-drive with other drivers has been demonstrated in the past couple of years for z-pinch driven targets. In the past year, as indicated in Fig. 4, there has been substantial progress in the use of z-pinch driven x-ray sources in a double-ended hohlraum design with many similarities to the type of hohlraum being examined for ion-beam targets. This progress now makes it plausible that z-pinch drivers could eventually be successfully developed for high-gain inertial fusion applications including IFE. Any of these targets can be ignited using central hot spot compression during the implosion process or by “fast ignition” with a short pulse laser following compression as discussed below.



- **Capsule physics (hydrodynamics, ignition, and burn propagation)**
- **Symmetry control**
- **Hohlraum energetics**

Figure 3. The physics issues for ion beam target design for IFE and NIF targets have much in common

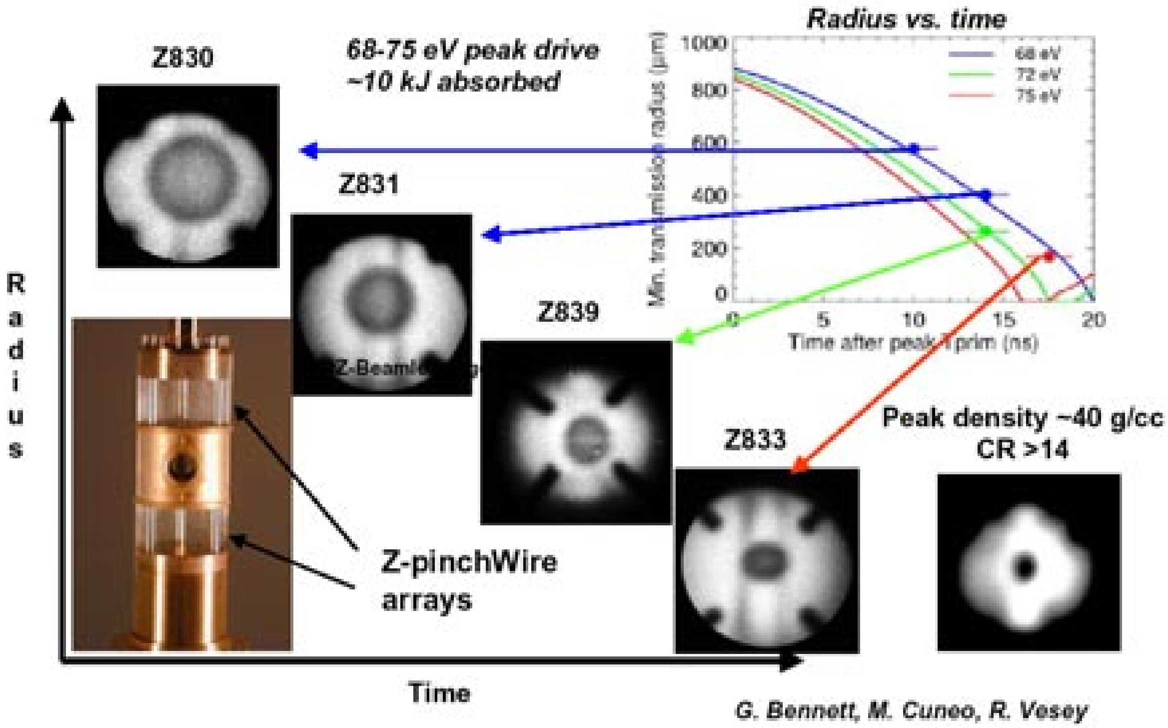


Figure 4. Substantial progress has been made on the symmetry of double z-pinch driven indirect drive targets

The Omega facility at the University of Rochester is being utilized for a wide range of experiments in both direct drive and indirect drive. Although originally designed with 60 uniformly arranged beams for uniform illumination for direct drive, it is possible to use up to 40 beams in a geometry, which is very effective for indirect drive. Figure 5 shows the level of quantitative understanding of indirect drive that has been achieved on Omega. Because the beams on Omega can be arranged in a geometry with much of the flexibility of NIF, it has been possible to get excellent performance from indirect drive targets with convergence greater than 20, as indicated in Fig. 5.

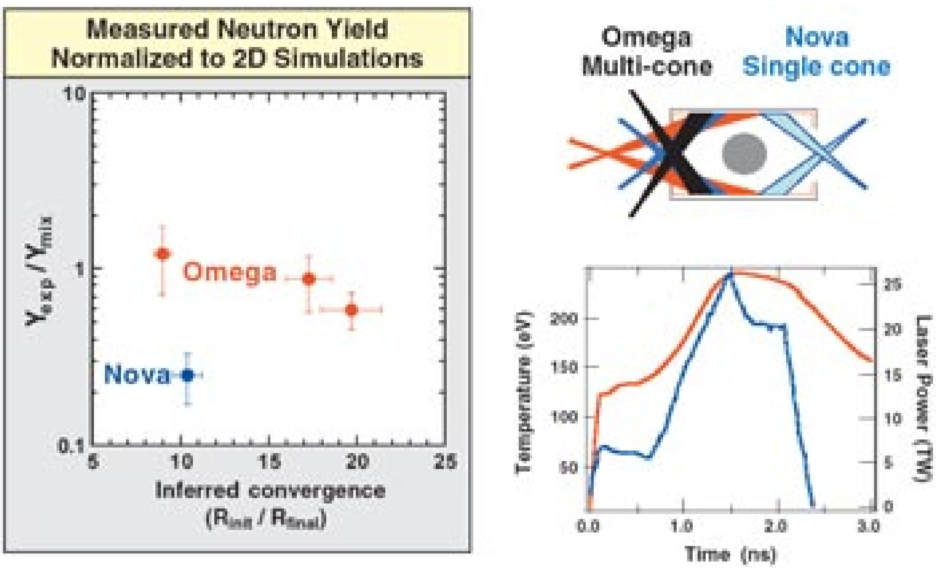


Figure 5. Using NIF-like illumination geometry, recent 3w implosion experiments show excellent agreement with simulations.

The choice of laser wavelength is central to the ICF indirect drive program. As indicated in Fig. 6, laser-plasma interaction (LPI) impacts a wide range of physics issues essential for ignition. Hohlraum energetics, implosion symmetry and pulse shaping in a variety of ways. The NIF specifications were chosen to achieve ignition using indirect drive with 0.35 μm laser light. The laser wavelength was chosen to minimize adverse laser-plasma interaction (LPI) effects. Experiments during the 1970's with 1 μm and longer wavelength lasers demonstrated the importance of shifting to shorter wavelength. Both the Nova laser and the Omega laser have utilized 0.35 μm very effectively. A large data base on hohlraum energetics, implosion symmetry, hydrodynamic instability and pulse shaping, and implosions was developed for setting the specification for NIF[3]. However, a predictive capability for LPI remains elusive, and optimization of beam conditioning and hohlraum design will be among the early experiments on NIF. Although 0.35 μm remains the baseline laser wavelength for ignition on NIF, there is the intriguing possibility that coupling at 0.53 μm could turn out to be acceptable. The Gekko XII laser at Osaka uses 0.53 μm light for direct drive. LLNL explored the use of 0.53 μm light for indirect drive on the Novette facility and some LPI coupling experiments were carried out on Nova. Although a systematic examination of 0.53 μm light for indirect drive has not been carried out, the expectation is that the achievable hohlraum temperatures will be lower than at 0.35 μm. Based on the experience at 1μm and 0.35 μm, ignition hohlraums are limited by LPI effects[3] to a density in the beam propagation path of 0.1-0.2 of the critical density where $n_c = 10^{21}/\lambda^2(\mu m)$. The dominant source of plasma in a hohlraum for ignition type pulses is radiation driven blowoff from the hohlraum wall. This blowoff increases as the hohlraum temperature increases. Since the critical density scales as $1/\lambda^2$, the achievable temperature is lower for longer laser wavelengths as indicated in Fig. 7. The operating window for ICF ignition is constrained by the LPI, which sets a maximum temperature and by capsule hydrodynamic instabilities, which set a minimum temperature. The minimum temperature set by hydrodynamic instabilities is indicated in Fig. 7 for a capsule surface roughness of 200 Å. Between the maximum temperature set by LPI and the minimum temperature required by hydrodynamic instability, there is the ICF "bird's beak" ignition region. The higher hohlraum temperature allowed by 0.35 μm light permits higher implosion velocities and higher compressed fuel density and a lower energy ignition threshold. However, NIF operating at 0.53 μm may be able to deliver 2.5 MJ or more, enough energy to get into the ignition window at about 250 eV indicated in Fig. 7. Lasnex ignition calculations with green light, shown in Fig. 8, indicate that at 250 eV, symmetry can be controlled in the usual way by appropriate choice of beam pointing and pulse shape. The input energy for this calculation was 3.3 MJ and the calculated yield was 50 MJ. There is significant uncertainty about the temperature achievable with green light. To begin further exploration of LPI effects, one beam on Omega has been modified to operate at 0.53 μm. Initial experiments, as shown in Fig. 9, indicate that for the intensity and hohlraum density appropriate for 250 eV hohlraums, the scattering levels were less than 10-15%. However, critical issues for indirect drive include precise location of the beam deposition within the hohlraum in a configuration designed for implosions. It will probably not be possible to test some of these more subtle effects until NIF has activated at least 48 beams. There are a wide variety of uses of NIF, which may benefit from the use of green light so the Livermore Lab Director is providing Laboratory Directed Research and Development Funds (LDRD) to implement one quad of green beams on NIF. This quad will be available in FY05. The first quad of NIF, which is coming up in the blue, will be converted to the green at the time that the second quad becomes operational. If the results of the initial experiments are sufficiently promising, more green beams could be added in a phased program.

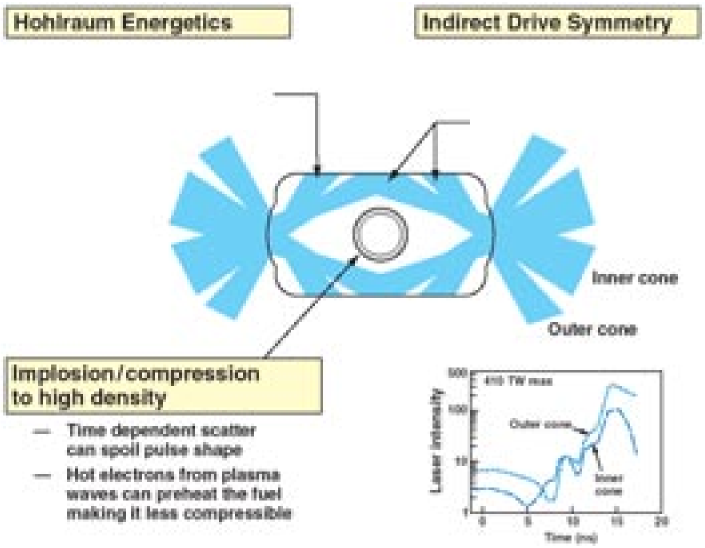
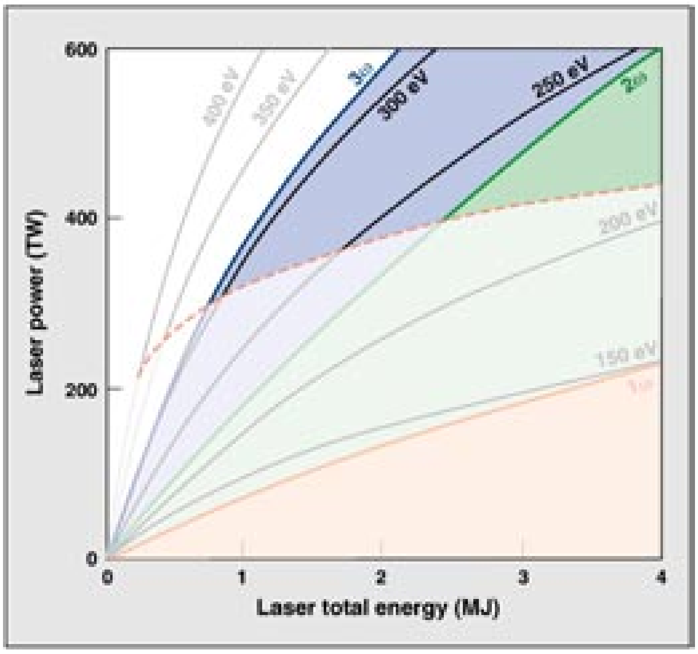


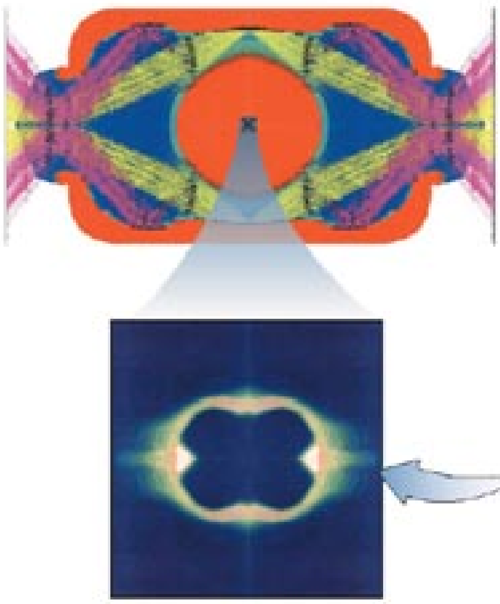
Figure 6. The choice of laser wavelength is central to the ICF Indirect Drive Ignition Program



- **LPI experience indicates plasma densities must be limited to $n/n_{crit} \approx 0.1$ to 0.2. Because n_{crit} is proportional to $1/l^2$, achievable hohlraum temperatures are lower for longer wavelengths since radiation ablation is the main source of plasma**

- **There is a minimum T_R that is dictated by keeping hydrodynamic instabilities under control. The red dashed line corresponds to those temperatures needed for a surface roughness of ~200Å**

Figure 7. The ICF “bird’s beak” ignition region in power and energy is based on constraints for LPI and hydrodynamic instabilities



- Laser energy into hohlraum: 3.3 MJ
- Capsule absorbed energy: 400 kJ
- Calculated yield: 50 MJ

Fuel Density Profile at ignition

Figure 8. Symmetry can be controlled in the usual way by repointing beams and/or adjusting relative beam powers

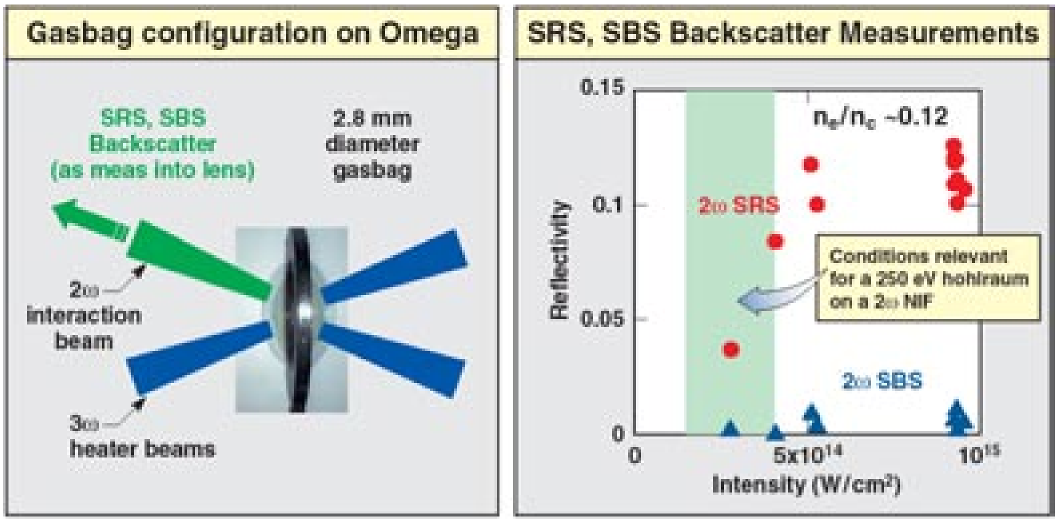


Figure 9. LPI studies on Omega indicate acceptable levels of backscatter at 2w for these conditions. Upcoming experiments will check for backscattered light outside the lens.

The baseline ignition program will use NIF's 0.35 μm light capability. The indirect drive ignition plan, shown in Fig. 10, makes use of existing facilities, and early NIF to optimize the ignition design. As more beams are added, a wide range of increasingly complex experiments will be possible. Completion of the full laser system is expected in 2008 and the first ignition campaign can begin following the completion of the cryogenic system, expected a year later.

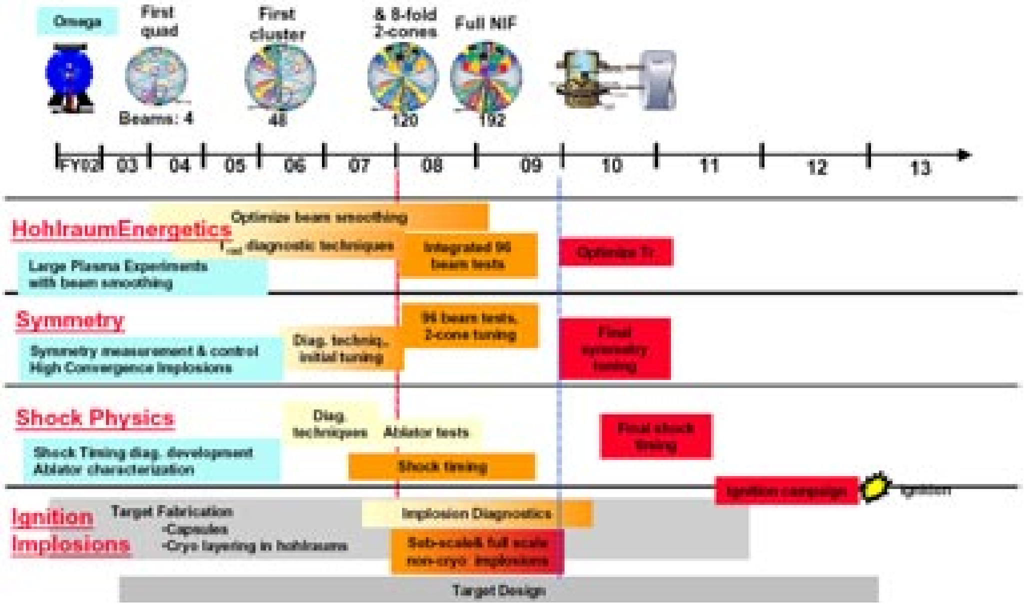


Figure 10. The indirect drive Ignition Plan makes use of existing facilities, and early NIF, to optimize the final ignition design.

Control of hydrodynamic instabilities is a key to the successful development of direct drive targets for IFE. Increasing the adiabat of direct drive targets is one way of reducing the level of hydrodynamic instability growth. A target with a higher adiabat is thicker during the implosion process and has higher ablation rates. However, such a target also reaches lower density and has lower gain. It is possible to develop targets that have a higher adiabat on the outside of the target, which is ablated off during the implosion, while maintaining a lower adiabat in the fuel. One approach to doing this is the use of a “picket” pulse at the beginning of the implosion as indicated in Fig. 11. This initial picket produces a decaying shock, which generates more entropy in the outside of the ablator. By the time the shock from this picket reaches the fuel layer, the shock strength has decayed sufficiently that the fuel remains on a lower adiabat. Picket fence experiments carried out on the Omega laser had both higher absolute yields and higher yields relative to predicted 1D yields compared to implosions without a picket as shown in Fig. 11. Current 2D calculations indicate that it may be possible to achieve gains greater than 50 on NIF using targets with picket fence pulses.

Cryogenic fuel layers are required for almost all ignition and high gain inertial fusion targets. A multiyear science and engineering effort has been required to develop a reliable and precise cryogenic system on the Omega laser. This system, shown in Fig. 12 has many of the features that will be required of the cryogenic system on NIF or LMJ. Initial experiments with this system are quite encouraging. Although current cryogenic layers produced using this system have several microns of long wavelength variation in the layer thickness, experiments are achieving results close to those predicted in 2D calculations. High adiabat targets (square pulse targets with α~25 where α is the ratio of the pressure at a given density relative to the Fermi pressure) are achieving yields close to those calculated in 1D. Targets with α~4, near the adiabat required for direct drive ignition targets on NIF have achieved a yield of about 10% of the 1D yield, in agreement with 2D calculations which include the long-wavelength ice layer roughness as shown in Fig. 13.

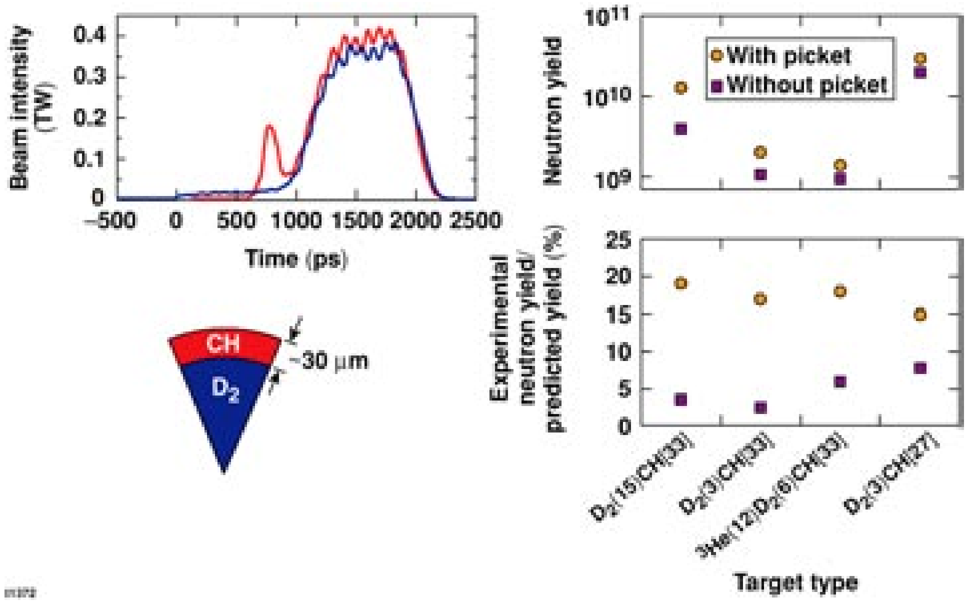


Figure 11. Initial adiabat shaping experiments with CH shells show a dramatic improvement in target performance.

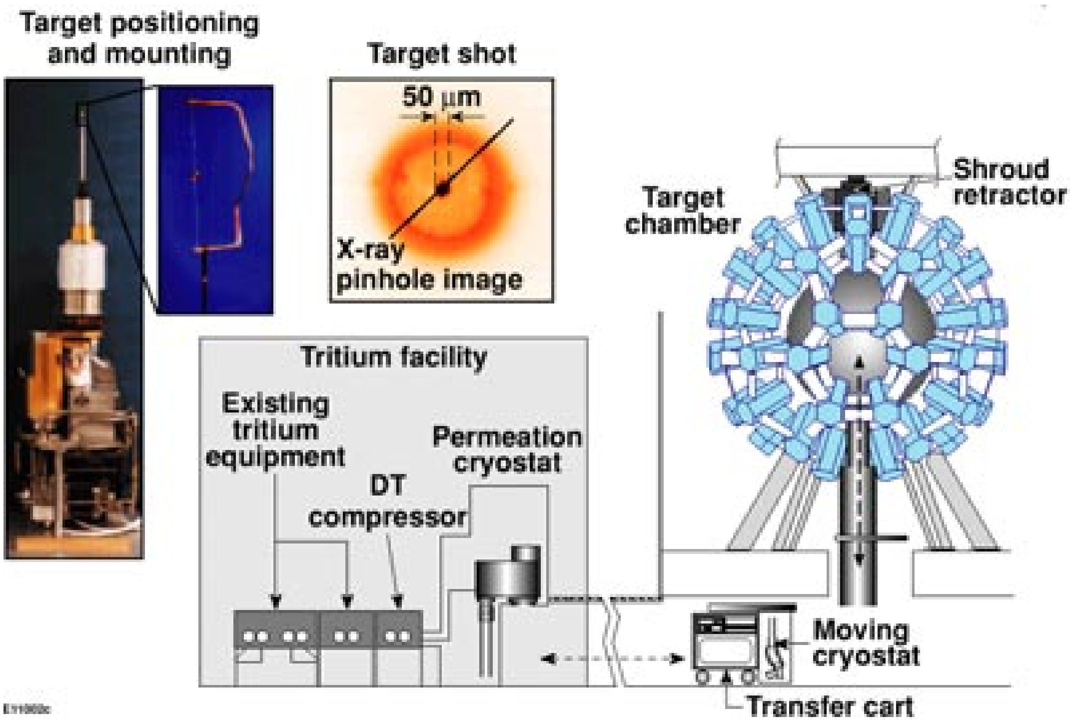
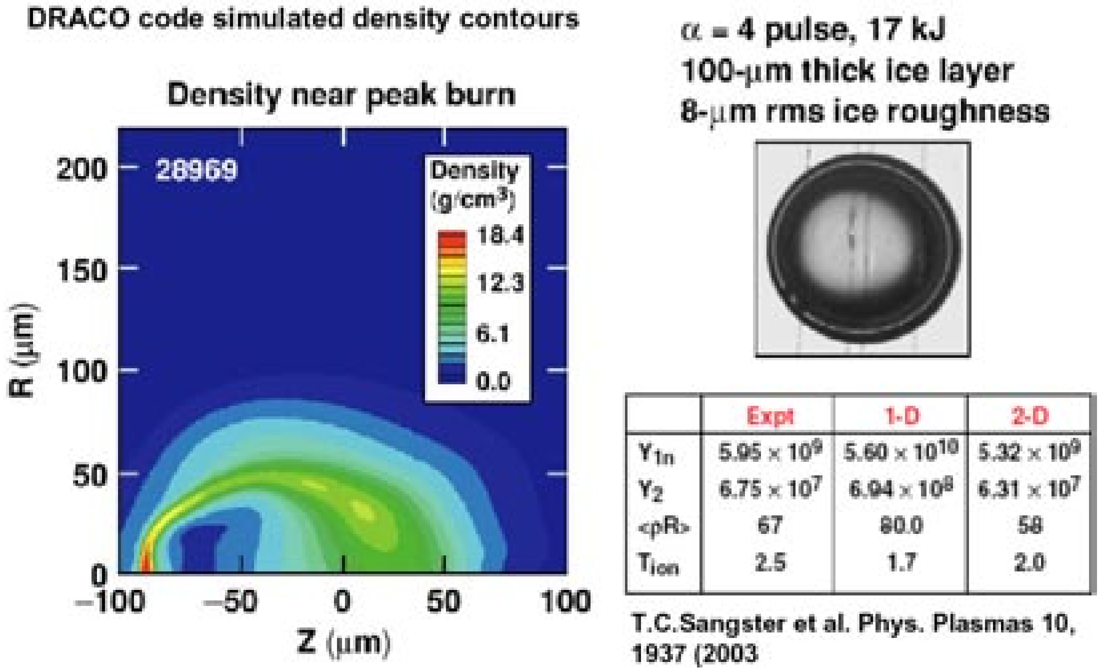


Figure 12. Multi-year science and engineering effort (with GA) was required to produce a reliable and precise cryogenic target experimental capability.



	Expt	1-D	2-D
Y_{1n}	5.95×10^9	5.60×10^{10}	5.32×10^9
Y_2	6.75×10^7	6.94×10^8	6.31×10^7
$\langle \rho R \rangle$	67	80.0	58
T_{ion}	2.5	1.7	2.0

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Figure 13. Initial 2D hydrodynamic simulations show good agreement with experimental α=4 cryogenic target results

Fig. 14 shows the projected gain curves for various target types. Fast ignition offers the possibility of higher gain at lower driver energy as well as relaxed target fabrication tolerances. In conventional ICF, the outer part of the fuel is compressed to high density while at the same time, appropriate pulse shaping and target design is employed to achieve a central hotspot, which initiates the burn. In fast ignition the initial implosion is designed to achieve high density with a central hot spot. The hot spot is created by a separate driver with an intensity of about 10^{20} W/cm^2, which last for a few picoseconds. This high intensity laser produces MeV electrons that can generate the needed hot spot. Although the physics of hot electron production and transport in the high intensity ignitor beam is poorly understood, recent experiments on the Gekko XII laser have been very successful in demonstrating the key elements of the concepts in scaled experiments[2]. In these experiments, a gold cone was inserted into a CD plastic shell, which was then imploded around the gold cone. The dense core of the plastic ends up near the tip of the cone, which makes it possible for the short pulse "ignitor" beam to generate high energy electrons close to the compressed material, thus minimizing the difficulty of energy transport into the compressed shell. The Gekko experiments had nearly a factor of 1000 increase in neutron yield when 350 joules of short pulse energy was added to the 2.4 KJ of compression energy. The dependence of this yield on the timing of the short pulse, and the ion temperature inferred from the spread of the neutrons is consistent with calculations. There are plans for facility upgrades in both the US and Japan to further explore the physics of fast ignition. In the US, there are proposals to add short pulse capabilities to Omega and the Z-machine as well as to NIF as shown in Fig. 15. If these experiments are successful, it would be possible to add a short pulse capability on up to 20 of NIF's 192 beams in order to demonstrate ignition and high yield. In Japan, an upgrade to Gekko, called FIREX is proposed.

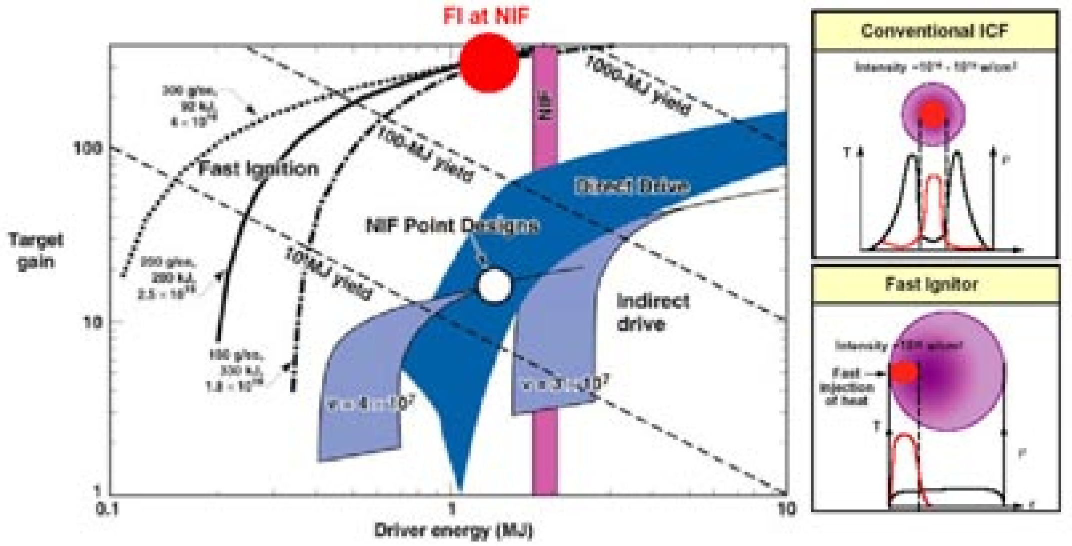


Figure 14. There is worldwide interest in fast ignition which potentially gives more gain and lower threshold energy than indirect or direct drive.

SNL Z Beamlet / Z

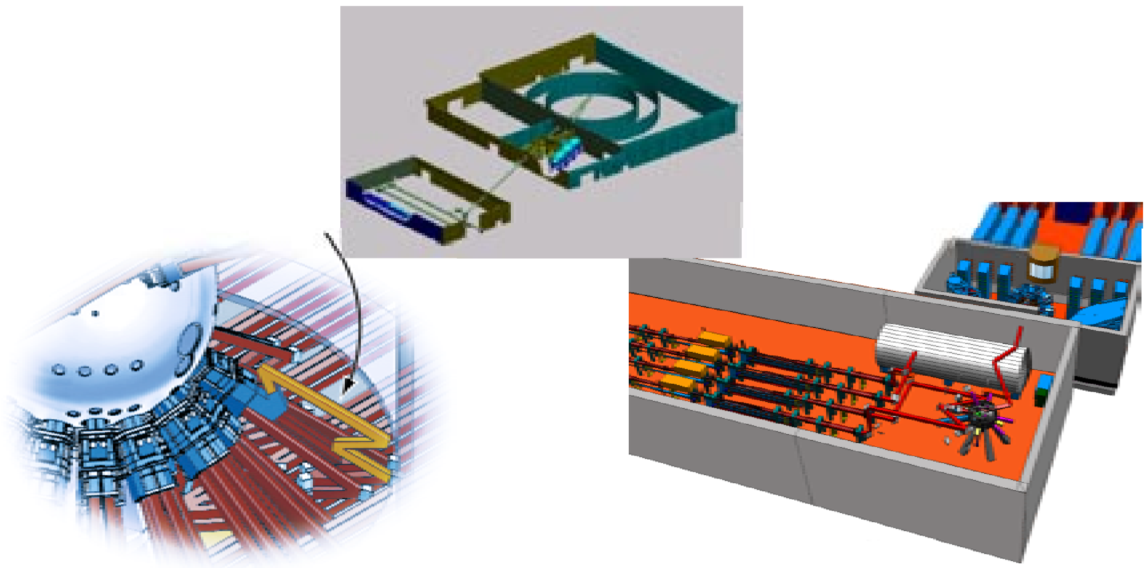


Figure 15. New U.S. facilities proposed for FY06/07 would support a ‘proof of principle’ study of fast ignition

In the US, the inertial fusion community envisions a development plan that proceeds in three phases to an engineering test facility (ETF) as indicated in Fig.16. Three types of drivers including ion beams, lasers and z-pinches are being considered. Phase I programs to develop ion-beam inductions accelerators as well as KrF and Diode-pumped solid-state lasers (DPSSL’s) are under way.

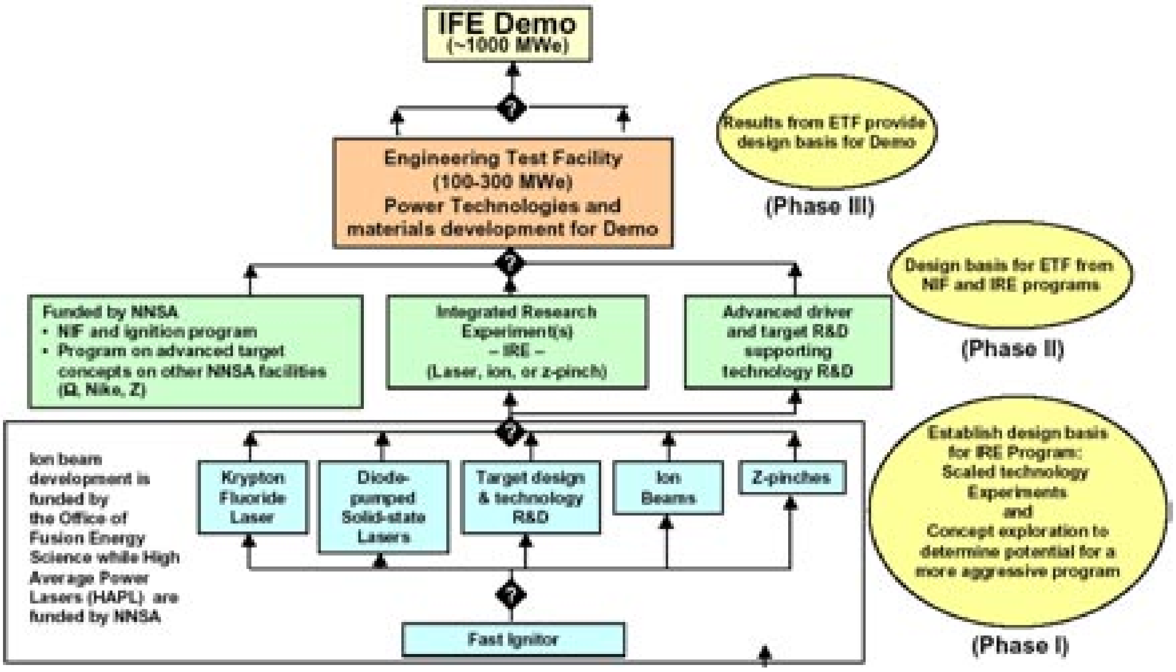
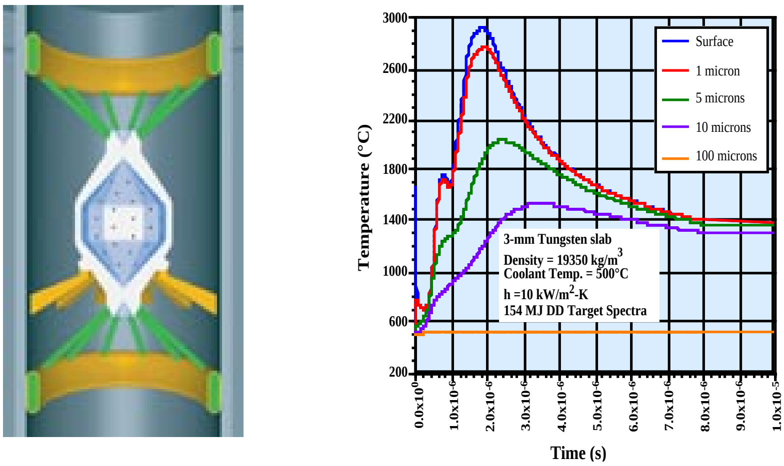


Figure 16. The US IFE Community Development plan proceeds in three phases to an Engineering Test Facility (ETF).

The program to develop lasers currently envisions dry wall chambers with direct drive targets as the optimal combination, while the ion beam program is concentrating on thick liquid protected chambers and indirect-drive targets. The work on dry-wall chambers is concentrating on first-wall response to target emissions as shown in Fig. 17 for the Sombrero chamber. The Z-machine and RHEPP-1 facility at Sandia National Lab can produce near relevant threats as indicated in Fig. 18. The program in thick liquid walls is concentrating on producing the type of liquid jets required by the HYLIFE II chamber shown schematically in Fig. 19. As indicated in Fig. 20, using water jets with the required Reynolds number and Weber number, these experiments have been very successful in demonstrating all the types of jets required.

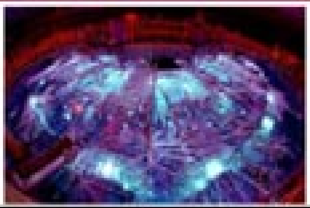


The dry-wall Sombrero chamber uses low pressure gas and/or armor coating to protect the first wall from x-rays, ions and debris.

Temperature response of tungsten armored first wall indicates melting point will not be exceeded.

Figure 17. The U.S. Program in Laser IFE on Dry-wall chambers work is focused on first wall response to target emissions

X-rays-
Z –machine
(Sandia)



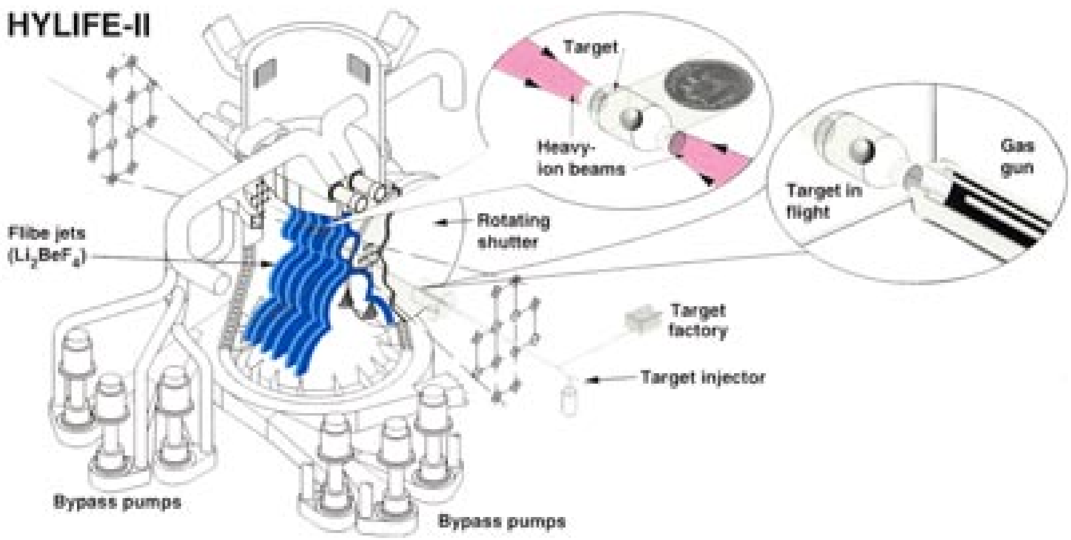
Ions-
RHEPP-1
(Sandia)

	Material	Predicted Ablation Threshold	Measured Ablation Threshold	Measured Roughening Threshold	Predicted Threat to wall 154 MJ target	Predicted Threat to wall 400 MJ target
X-rays (10 nsec exposure)	Pyrolitic Graphite	4.0 J/cm^2	3.5 - 4 J/cm^2	2.5 J/cm^2	0.40 J/cm^2	1.20 J/cm^2
	Tungsten	not done yet	2 J/cm^2	1.3 J/cm^2		
IONS (60 nsec exposure)	Pyrolitic Graphite	4.5 J/cm^2	3.5 - 4 J/cm^2	2.5 J/cm^2	8.5 J/cm^2 (1.41 J/cm^2)	21.1 J/cm^2 (3.52 J/cm^2)
	Tungsten (pure)	4.75 J/cm^2	5 J/cm^2	1.25 J/cm^2		
	Tungsten + 25% Re	Not yet modeled	5 J/cm^2	3.5 J/cm^2		

* Wall at 6.5 m, parenthesis are adjusted threat for time, $t^{1/2}$ scaling

SNL (Experiments)
Wisconsin (modeling)

Figure 18. Materials evaluation: Both the Z-machine and RHEPP produce near relevant threat and measured ablations thresholds are close to code predictions.



If successful, this approach to chambers can drammatically reduce the materials developments needs for fusion

Figure 19. The U.S. heavy ion fusion program is concentrating on liquid wall chambers and indirect drive targets. If successful, this approach to chambers can dramatically reduce the materials developments needs for fusion.

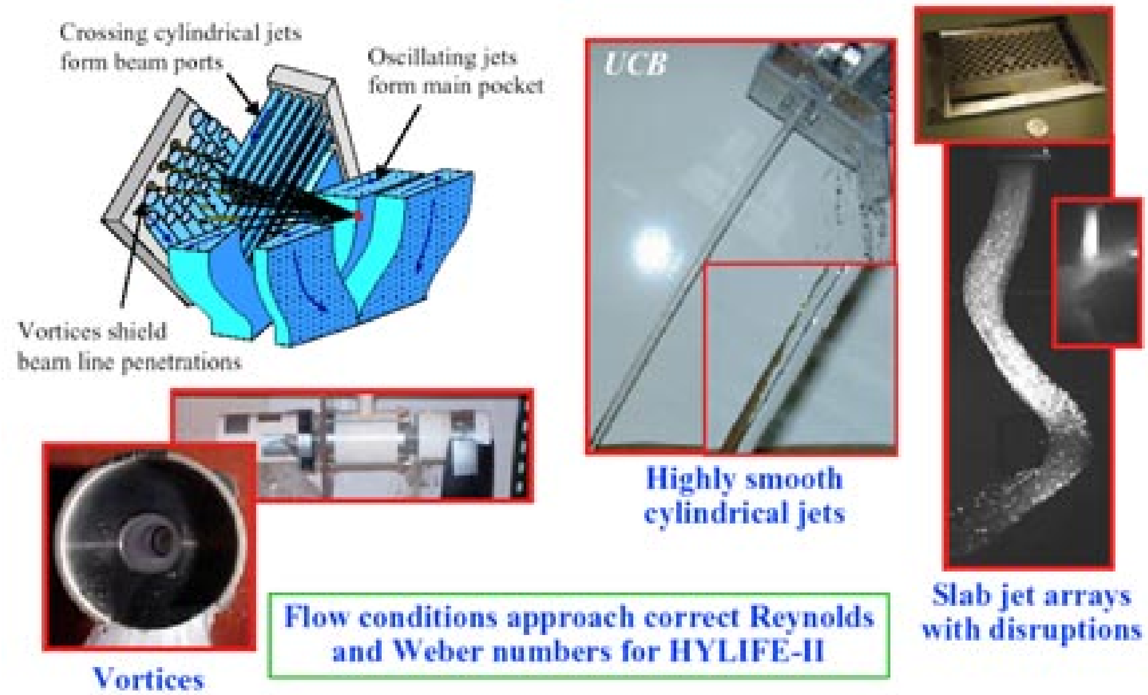
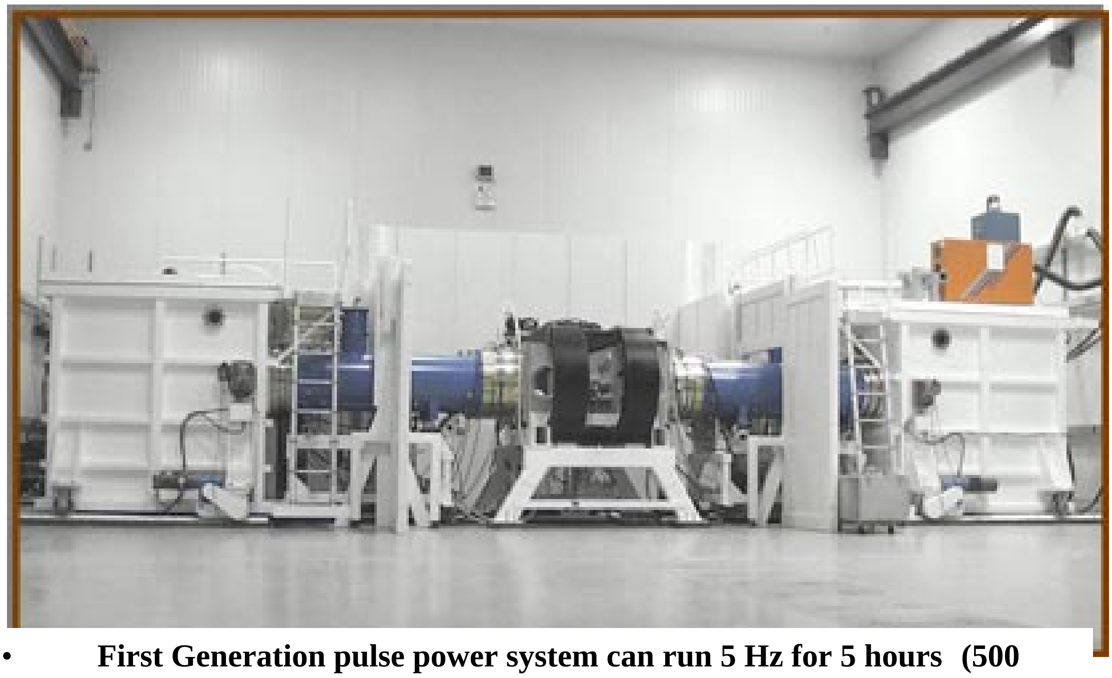


Figure 20. Scaled experiments have created the major classes of flows needed for thick-liquid-wall chambers being evaluated for Heavy Ion Beam driven fusion.

The goal of the Phase I driver experiments is to develop the database for the Phase II Integrated Research Experiment (IRE) Program. The Electra facility at NRL, shown in Fig. 21, is the major US facility for developing KrF lasers. Early results from Electra are shown in Fig. 22. The Mercury facility at LLNL, shown in Fig. 23 is the major facility for developing DPSSL's. It is now operating with the first of two amplifier heads as indicated in Fig. 24. Both facilities are scheduled for completion in FY05. The ion beam program, currently includes separate experiments on source development, high current transport, and neutralized focusing. The source development facility shown in Fig. 25 is being used to develop a compact multi-beamlet injector concept, important for achieving a low cost accelerator. The High Current Experiment (HCX) shown in Fig. 26 is exploring high fill factor and electron cloud effects in space charge dominated beams. The Neutralized Transport Experiment (NTX), shown in Fig. 27, is exploring the effects of plasma neutralization on the focusing of space charge dominated beams. Initial experiments are quite encouraging. These experiments would be followed by an integrated beam experiment (IBX), combining all of these steps, prior to an IRE facility.



- **First Generation pulse power system can run 5 Hz for 5 hours (500 keV, 100 kA, 100 nsec @ 5 Hz (25 kW))**

- **Excellent test bed for developing laser components**

Figure 21. The major U.S. facility for KrF laser development for IFE is the Electra laser at NRL, scheduled for completion in CY2005

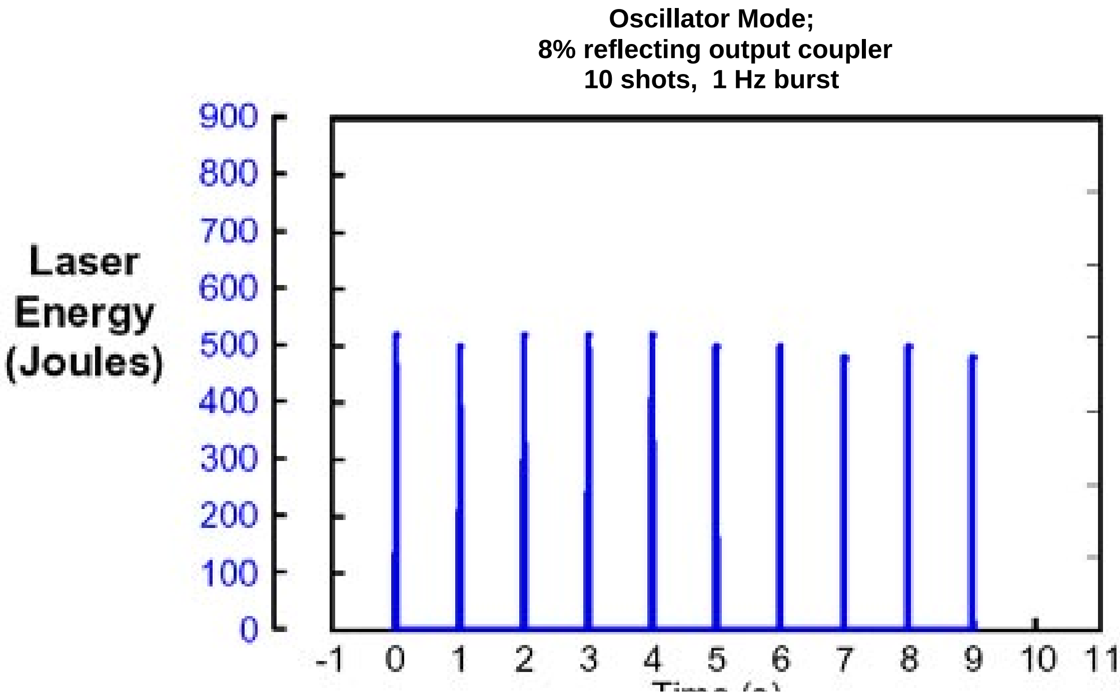


Figure 22. Achieved 500 J at 1 Hz bursts in oscillator configuration for 10 shots

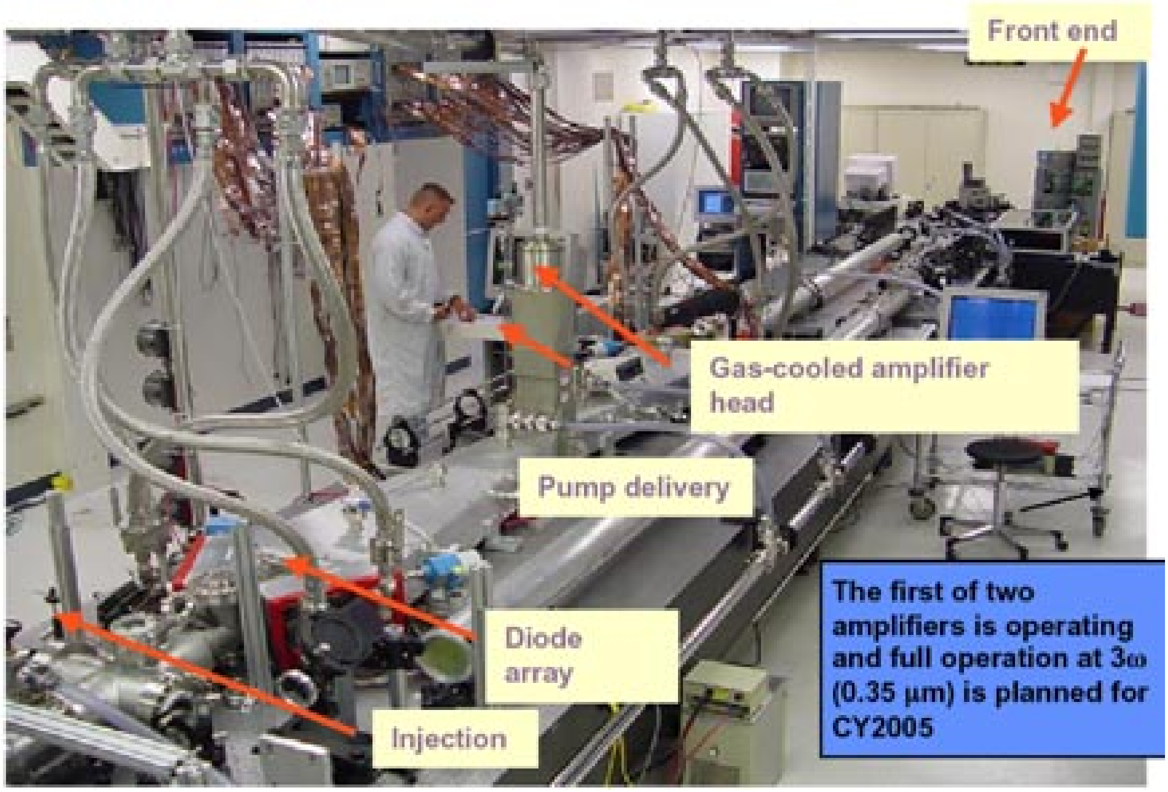


Figure 23. The Mercury laser at LLNL is designed to be a 100J, 10Hz, 10ns DPSSL laser at 1/10th scale of a kJ-class beam line for Inertial Fusion Energy

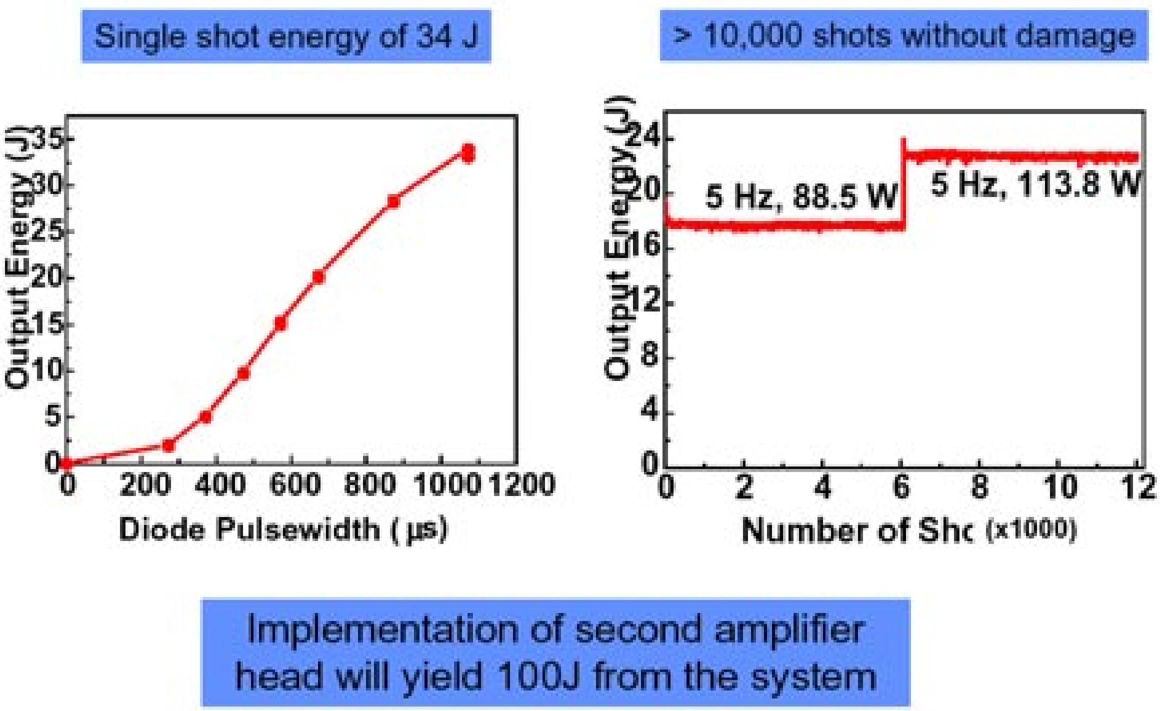


Figure 24. The Mercury Laser is operating reliably with the expected performance

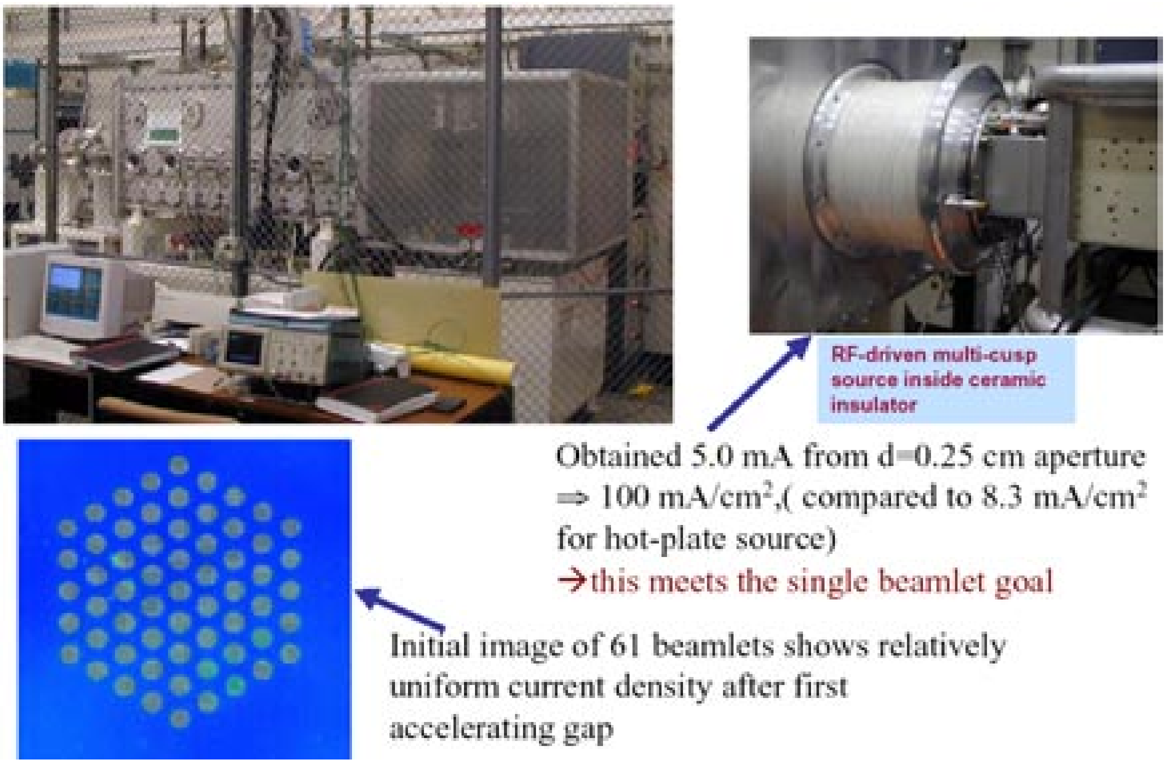


Figure 25. STS is being used to characterize Argon plasma source for a multi-beamlet injector concept.

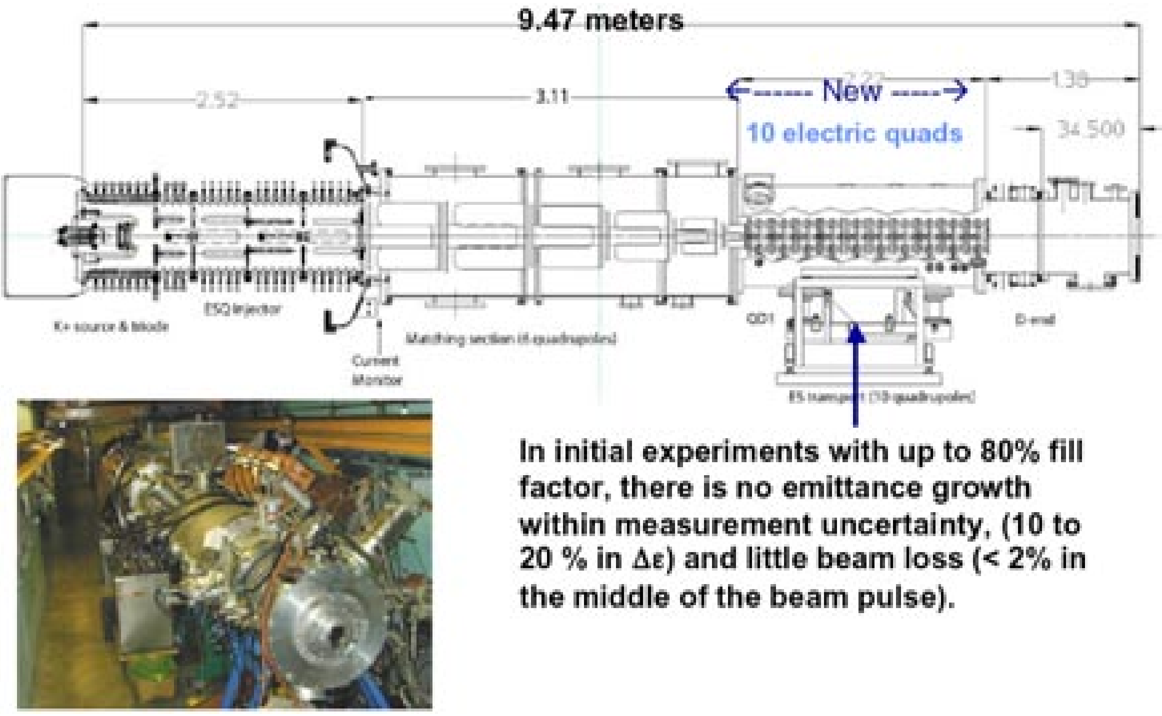
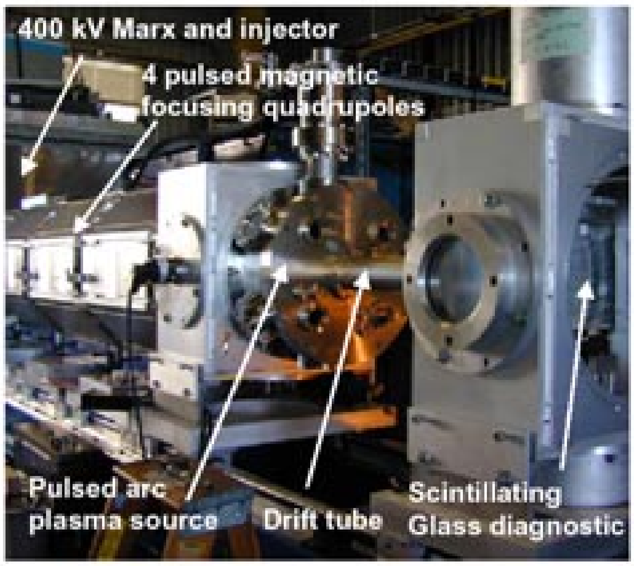


Figure 26. The High Current Experiments (HCX) is exploring high fill factor and electron cloud effects in space charge dominated beams



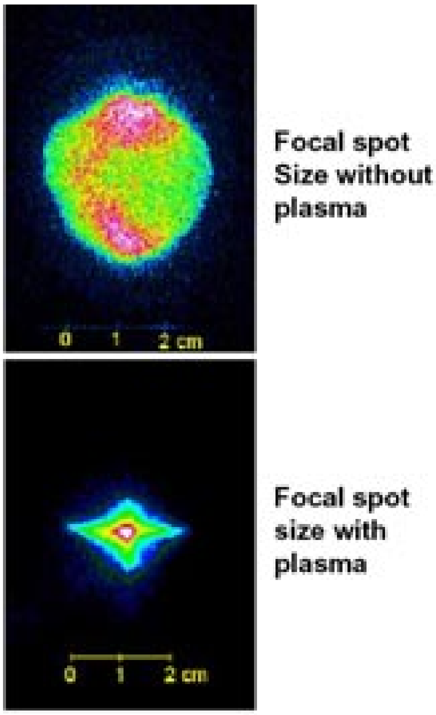


Figure 27. The Neutralized Transport Experiment (NTX) is exploring the effects of plasma neutralization on the focusing of space charge dominated beams.

In conclusion, there has been rapid progress in inertial fusion in the past couple of years:

- The conventional facilities and the beamline infrastructure for all 192 beams of NIF are complete. The four beams of NIF (1 quad) have been activated and are delivering energy to the target chamber in preparation for experiments in the summer of 2003. NIF is on track for completion in 2008 with ignition experiments to begin following completion of the cryogenic target system about 1 year later.
- There is steady progress in the target science and target fabrication in preparation for indirect drive ignition experiments on NIF. Advanced target designs, including those that may be able to utilize NIF’s green light capability, may lead to 5-10 times more yield than initial target designs
- There has been excellent progress on the science of ion beam and z-pinch driven indirect drive targets
- There has been excellent progress on direct-drive targets at the University of Rochester including very encouraging cryogenic implosions
- There is worldwide interest in the science of fast ignition and outstanding results from the Gekko XII Petawatt facility on heating and compression. Facility upgrades to further explore the physics of fast ignition are planned in the US and Japan.
- A broad based program to develop laser and ions beams for IFE is under way with excellent progress in drivers, chambers, target fabrication and target injection

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[1] T.C. Sangster et al., Phys. Plasmas 10, 1937 (2003)
[2] R. Kodama et al., Nature 418, 933 (Aug 2002)
[3] J.D. Lindl, Phys. Plasmas 2 (11), 3933 (1995)