Summary of Inertial Fusion

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Abstract. There has been rapid progress in inertial fusion since the last IAEA meeting. 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 and ion beams.

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 about 1 year. Ignition experiments are expected to begin in 7-9 years at both facilities.

There is steady progress in the target science and target fabrication in preparation for indirect drive ignition experiments on NIF and LMJ. Advanced target designs 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.

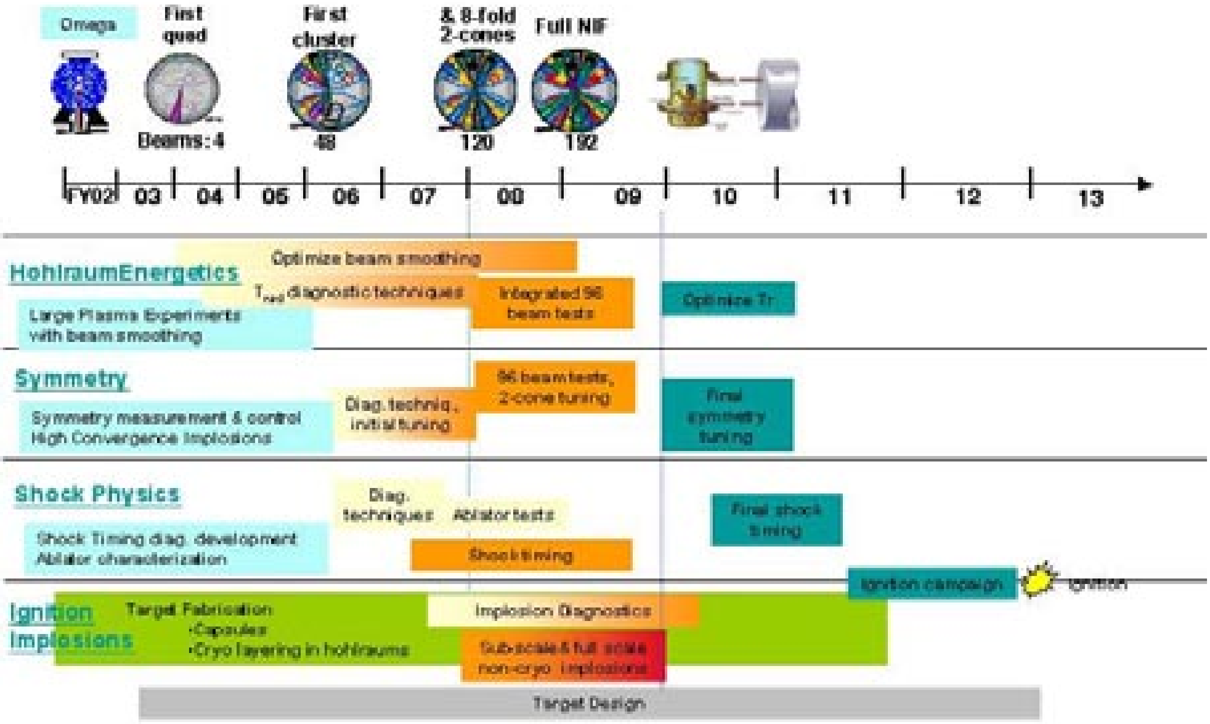
Excellent progress on direct-drive targets have been obtained at the University of Rochester. This includes improved performance of targets with a pulse shape predicted to result in reduced hydrodynamic instability. Rochester has also obtained encouraging results from initial cryogenic implosions.

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 Petawatt facility.

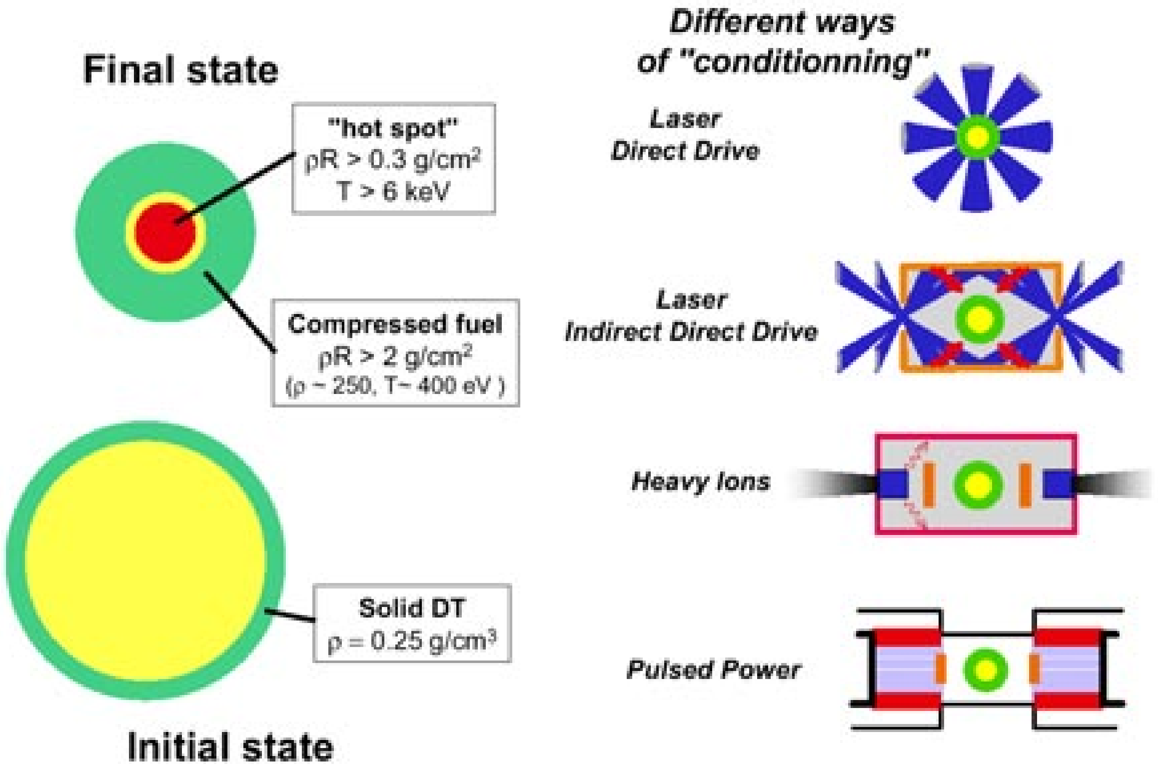
A broad based program to develop lasers and ions beams for IFE is under way with excellent progress in drivers, chambers, target fabrication and target injection. KrF and Diode Pumped Solid-State lasers (DPSSL) are being developed in conjunction with dry-wall chambers and direct drive targets. Induction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

There has been exceptional progress since the last IAEA meeting 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).

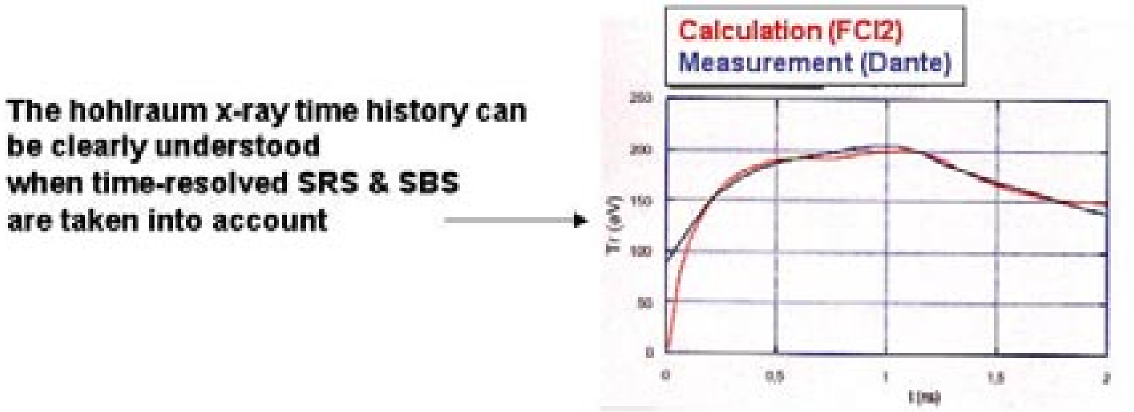
There has been rapid progress on construction of the NIF ignition facility in the United States. First light to target chamber center of the first four beams (a single Quad) of the 192 beam NIF is expected by April 203 and first experiments are being planned for late summer of 2003. As more beams are added, a wide range of increasingly complex experiments will be possible as indicated in Figure 1. Completion of the full laser system is expected in 2008 and the first ignition campaign can begin following the completion of the cryogenic, expected a year later. The Laser Integration Line (LIL), the engineering prototype for the LMJ ignition facility in France is nearing completion. Groundbreaking for the LMJ is expected in 2003.



There are a wide range of target types being pursued in inertial fusion, as shown in Figure 2. Both direct drive and indirect drive with lasers will be tested on NIF and LMJ. Indirect drive targets driven with a laser also provide much of the physics needed to have confidence in indirect drive targets imploded using ion beams or z-pinch pulsed power drivers. 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.

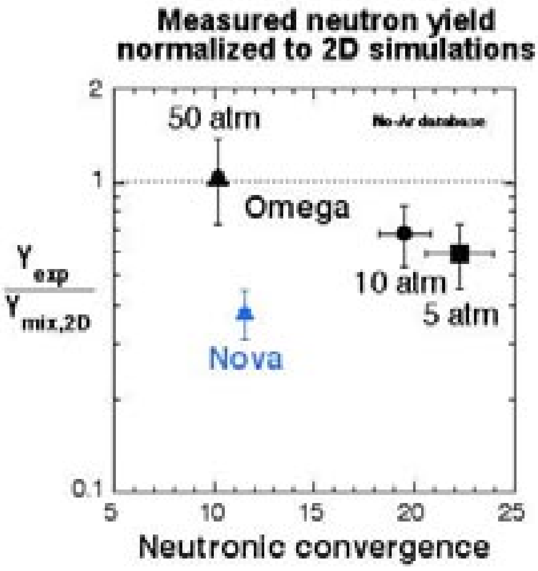


The Omega facility at the University of Rochester is being utilized for a wide range of experiments in both direct drive and indirect drive. Although originally designed with 60 uniformly arranged beams for uniform illumination for direct drive, it is possible to use up to 40 beams in a geometry, which is very effective for indirect drive. Figure 3 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, as indicated in Fig. 4, it has been possible to get excellent performance from indirect drive targets with convergence greater than 20.

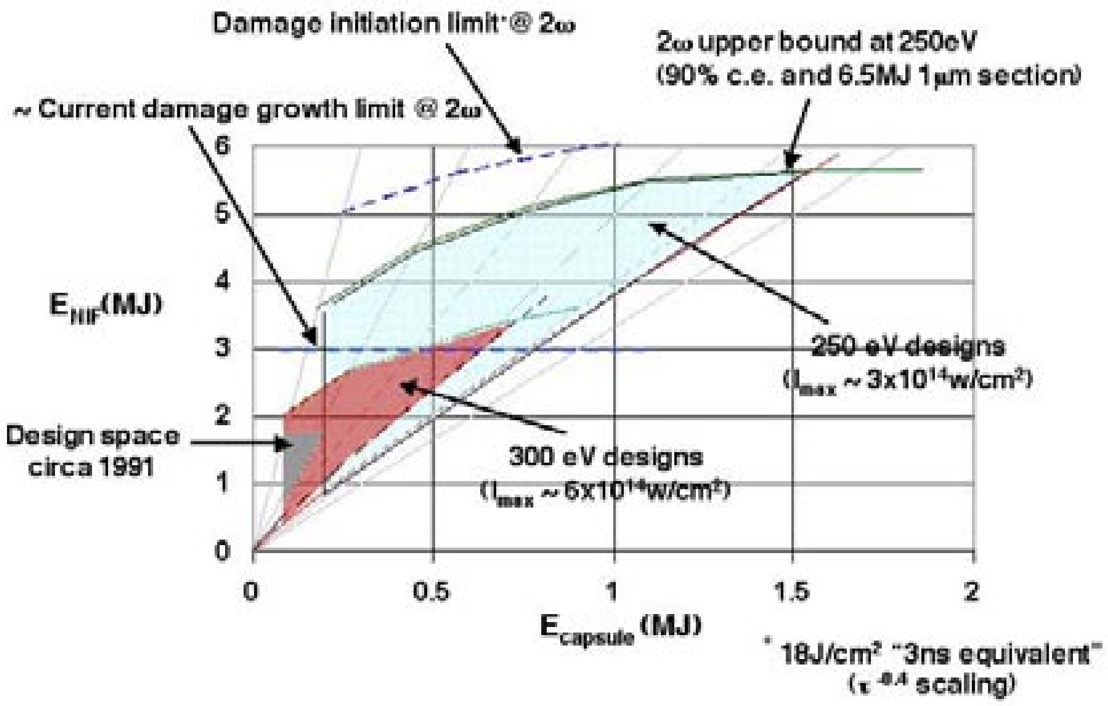

The hohlraum x-ray time history can be clearly understood when time-resolved SRS & SBS are taken into account


CEA has a long history of work on this topic :

- Octal (Limeil - 1982 ...)
- Phebus (Limeil - 1986 ...)
- Nova (Livermore - 1995 ...)
- **Omega (Rochester - 1999 ...)**

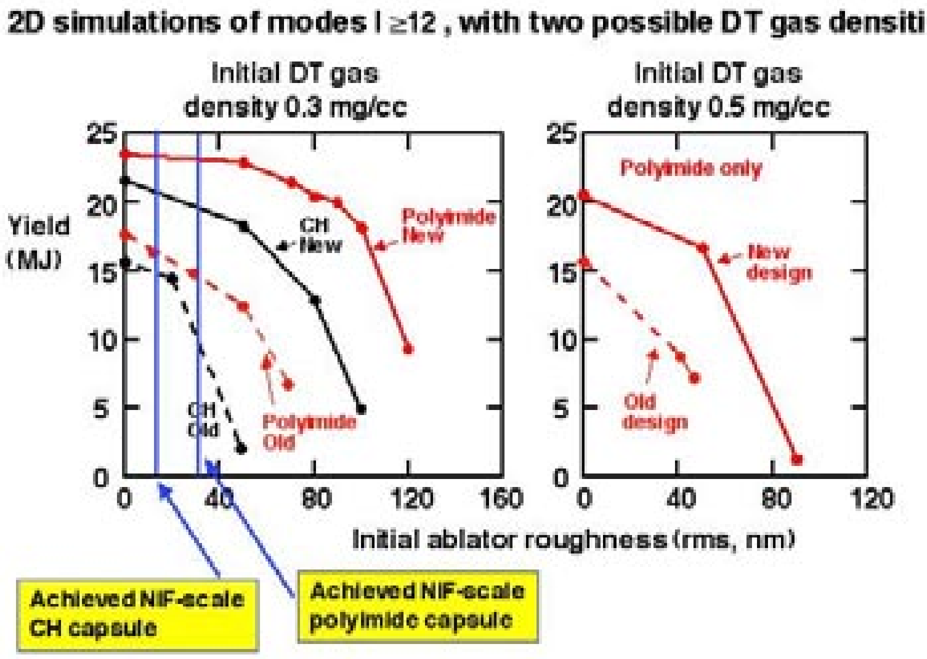


The NIF specifications were chosen to achieve ignition using indirect drive with 0.35 μm laser light. The laser wavelength was chosen to minimize adverse laser-plasma interaction (LPI) effects. Experiments during the 1970's with 1 mm and longer wavelength lasers demonstrated the importance of shifting to shorter wavelength. Both the Nova laser and the Omega laser have utilized 0.35 μm very effectively and a large database was developed for setting the specification for NIF. 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 for ignition on NIF, there is the intriguing possibility that coupling at 0.53 micron could turn out to be acceptable. Gekko XII at Osaka uses 0.53 mm light for direct drive. LLNL explored the use of 0.53 mm light for indirect drive on the Novette facility and some LPI coupling experiments were carried out on Nova. However, a systematic examination of 0.53 μm light for indirect drive has not been carried out. If the LPI coupling is acceptable, there is a substantial upside potential on NIF as indicated in Figure 5. NIF performance is largely determined by optical damage in the final output optics. Two damage thresholds are important, the initial damage threshold, and the

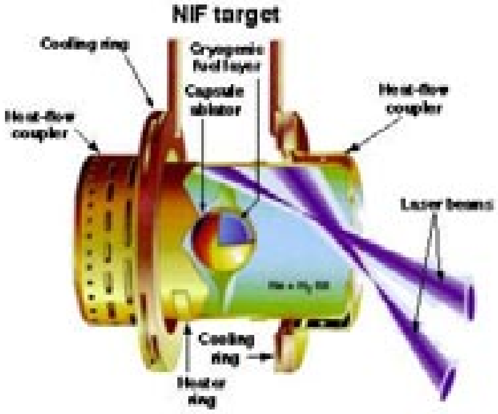


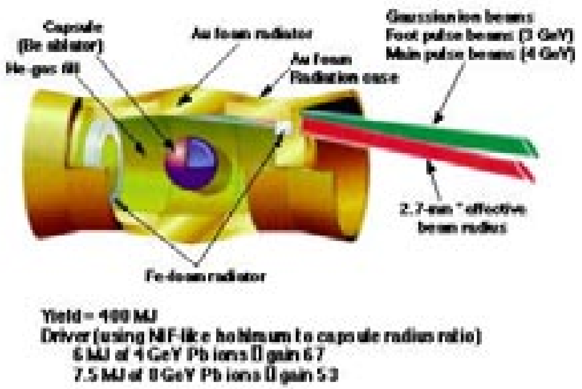
threshold for further growth after initial damage. The threshold for damage growth is about a factor of two lower than the threshold for initial damage for both 0.53 and 0.35 μm light. However, both limits are about a factor 2.5 higher for 0.53 μm light. The additional energy would open up a much larger target design space. Target yields could substantially exceed 100 MJ, which would far exceed the initial design goal of targets with yields of 10-15 MJ. To begin further exploration of LPI effects, one beam on Omega has been modified to operate at 0.53 μm. Although much more work is required, initial experiments; indicate that the scattering fraction, although somewhat higher than for 0.35 mm, would be acceptable. 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.

In addition to the possibility of being able to implode larger higher yield targets on NIF than originally envisioned, there has been substantial optimization of the baseline target designs for NIF. As originally indicated for Be ablator targets (REF Wilson), CH and Polyimide (PI) ablator targets optimize with thicker ablator and/or thicker fuel layers than the original baseline designs. These more optimal targets designs are more robust to both fuel layer and ablator roughness as indicated in Figure 6. Two-dimensional hydrodynamic instability calculations (for modes greater than l=6) indicate that targets can now be fabricated which meet the requirements with a substantial margin.

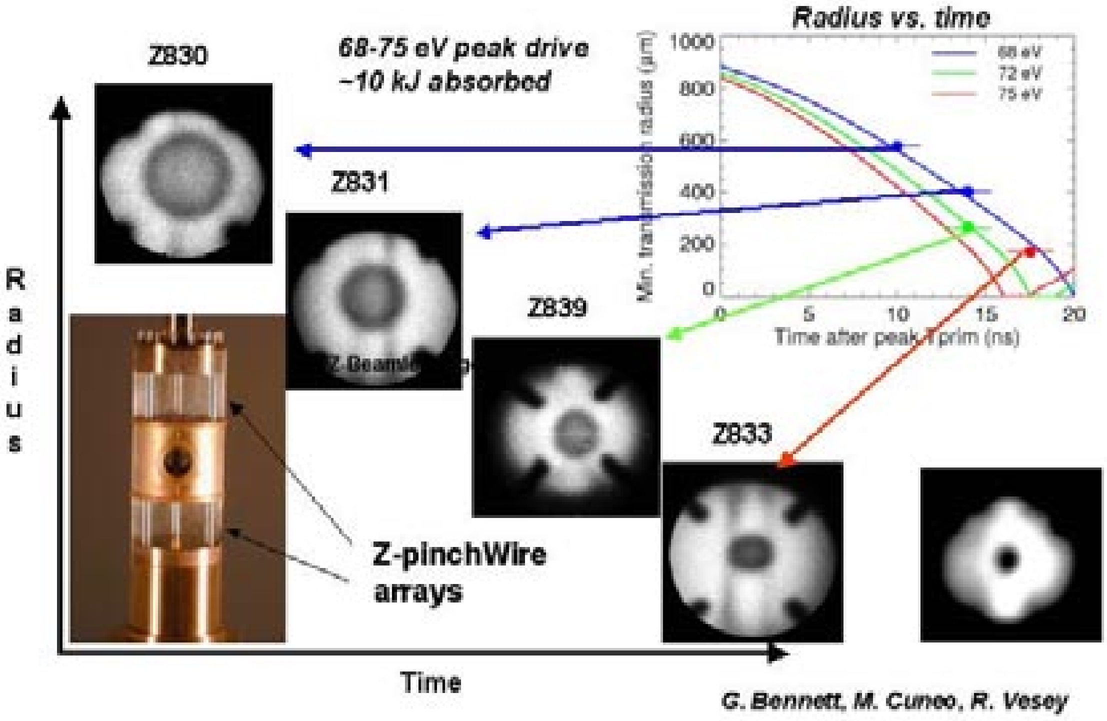

2D simulations of modes l ≥12 , with two possible DT gas densities

Much of the information about laser-driven indirect drive targets is applicable to 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 shown in Fig. 7. The ability to apply information on laser-driven indirect-drive targets to indirect-drive with other drivers has been demonstrated in the pas couple of years for z-pinch driven targets. In the past year, as indicated in Fig. 8, 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.



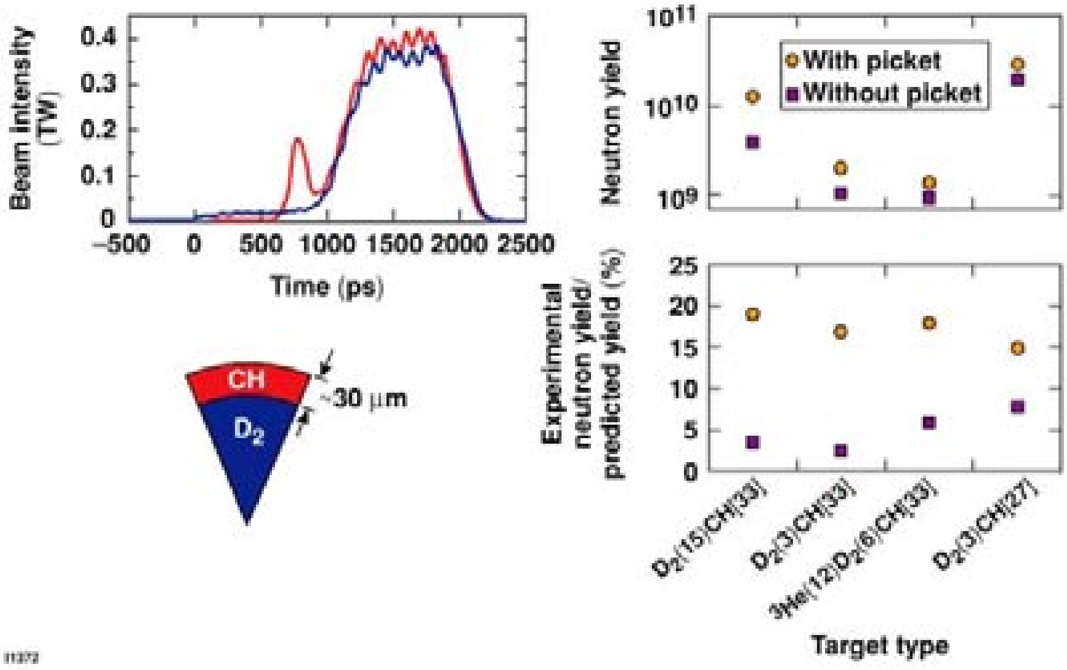


- Capsule physics (hydrodynamics, ignition, and burn propagation)
- Symmetry control
- Hohlraum energetics

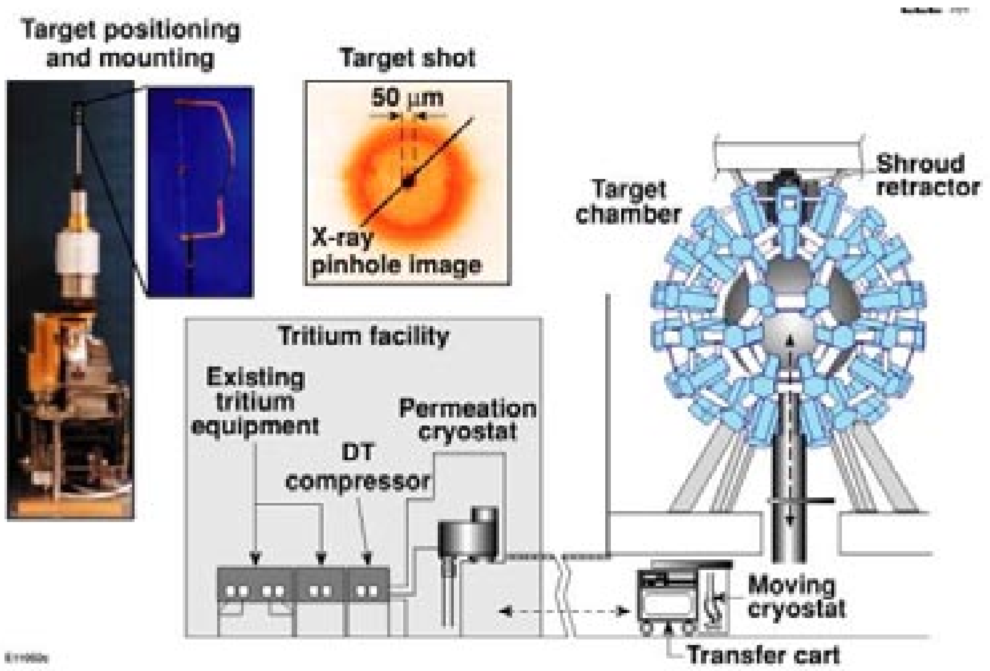


G. Bennett, M. Cuneo, R. Vesey

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, which 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. 9. This initial picket produces a decaying shock, which generates more entropy in the outside of the ablator. 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. Current 2D calculations indicate that it may be possible to achieve gains greater than 50 on NIF using targets with picket fence pulses.

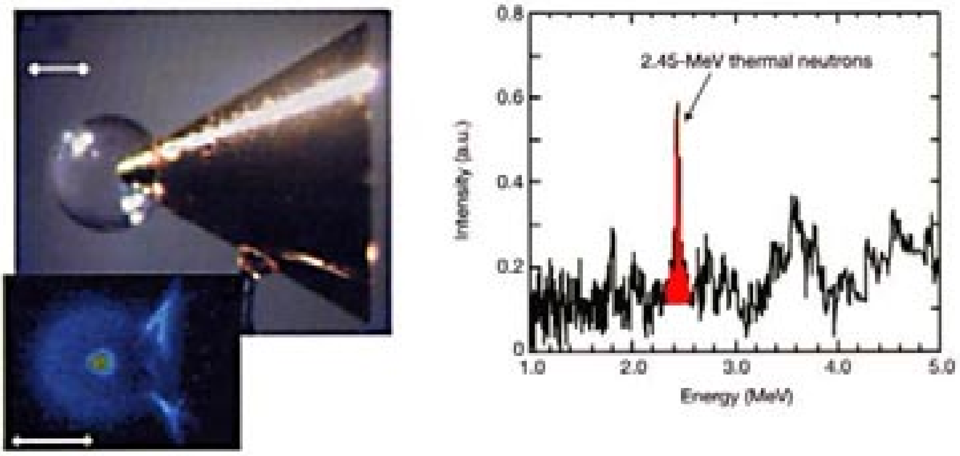


Cryogenic fuel layers are required for almost all ignition and high gain inertial targets. A multiyear science and engineering effort has been required to develop a reliable and precise cryogenic system on the Omega laser. This system, shown in Fig. 10 has many of the features that will be required of 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. 11.



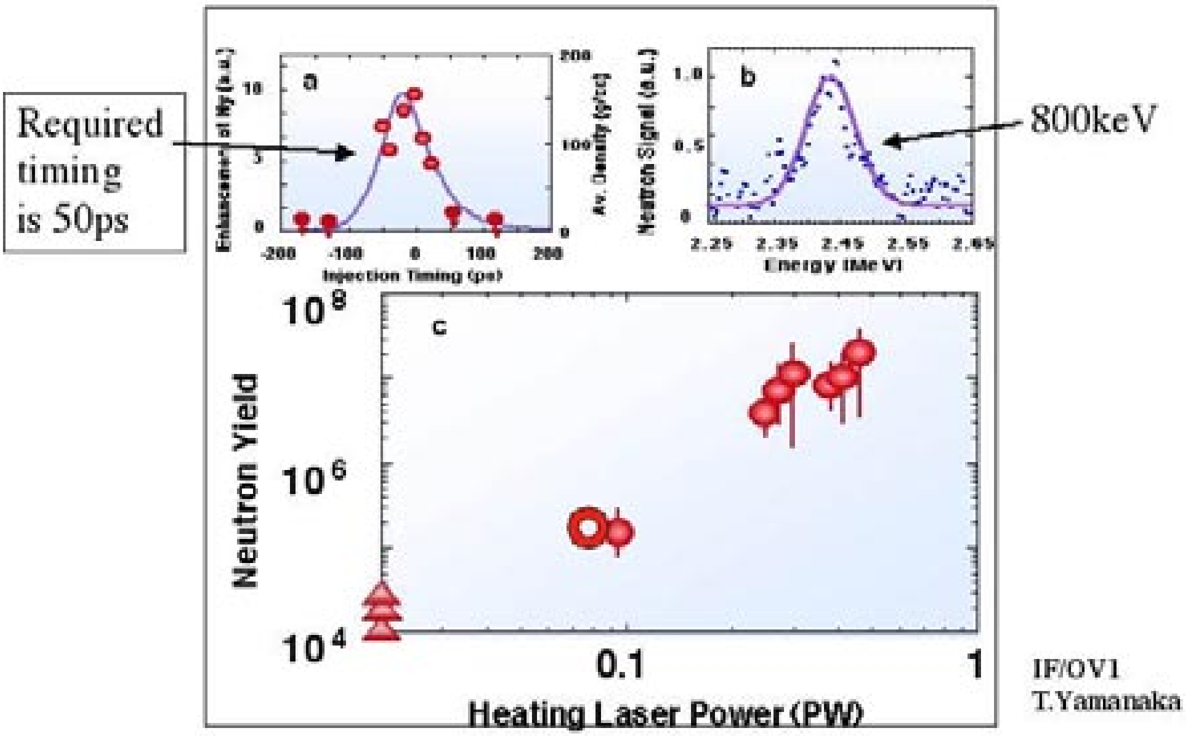
Fast ignition offers the possibility of higher gain at lower driver energy as well as relaxed target fabrication tolerances. Although the physics of hot electron production and transport in the high intensity ignitor beam is poorly understood, recent experiments on the Gekko XII laser have been very successful in demonstrating the key elements of the concepts in scaled experiments. 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 as indicated in Fig. 12. The cone 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. Figure 13 shows the neutron yield from the shell as a function of the energy in the short pulse beams. There is nearly a factor of 1000 increase in neutron yield when 350 joules of short pulse energy is 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. 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. In the first phase of this upgrade, a 10 KJ short pulse capability would be added to Gekko. In the second phase, a 60 KJ upgrade to Gekko would we added.

Enhanced neutron output from fast heating of deuterated direct drive shell implosion on Gekko XIII laser (Japan,UK) R. Kodama, et al., Nature 412, 798 (2001)



1.2 KJ compression pulse + 60 J, 100 tw fast heating pulse

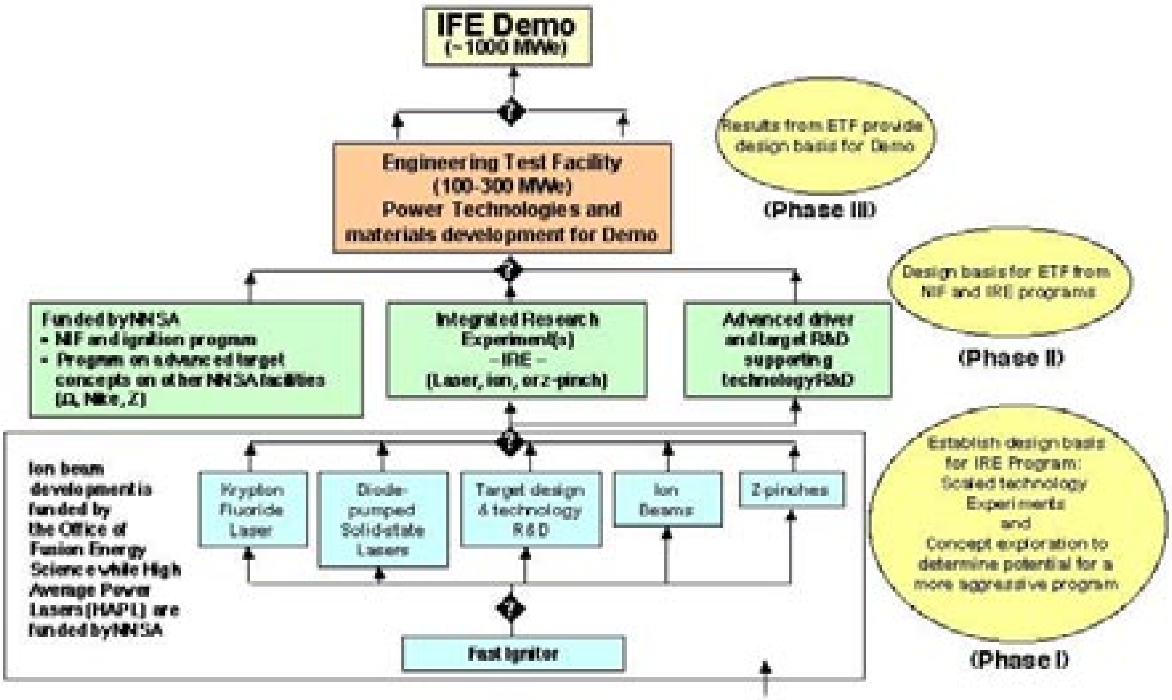
In the US, the inertial fusion community envisions a development plan, which proceeds in three phases to an engineering test facility (ETF) as indicated in Fig.14. Three types of drivers including ion beams, lasers and z-pinches are being considered. Phase I programs to develop ion-beams inductions accelerators as well as KrF and Diode-pumped solid-state lasers (DPSSL's) are under way.



Required timing is 50ps

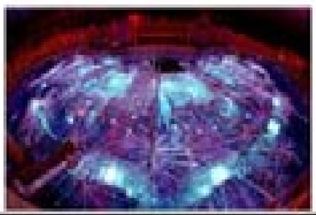
800keV

IF/OV1
T.Yamanaka

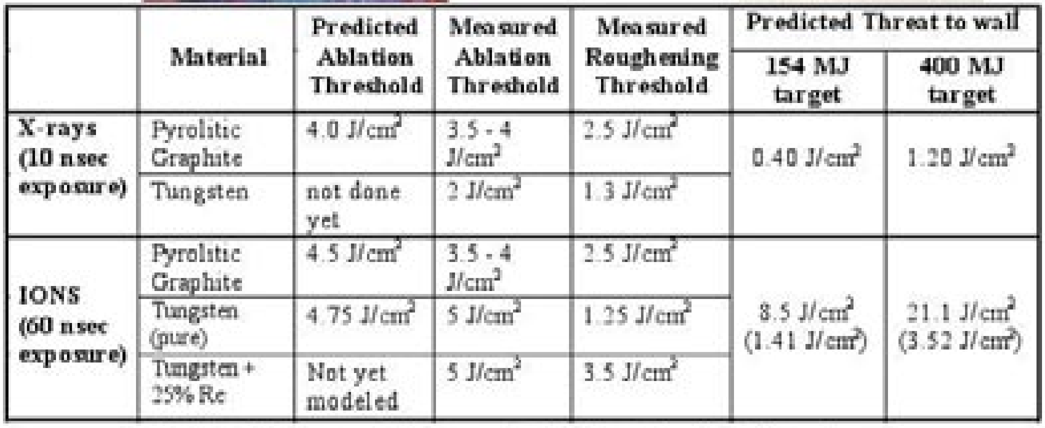


The program to develop lasers currently envisions dry wall chambers with direct drive targets as the optimal combination, while the ion beam program is concentrating on thick liquid protected chambers and indirect-drive targets. The work on dry-wall chambers is concentrating on first-wall response to target emissions. The Z-machine and RHEPP-1 facility at Sandia National Lab can produce near relevant threats as indicated in Fig. 15. The program in thick liquid walls is concentrating on producing the type of liquid jets required by the HYLIFE II chamber. As indicated in Fig. 16, 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.

X-rays-
Z –machine
(Sandia)



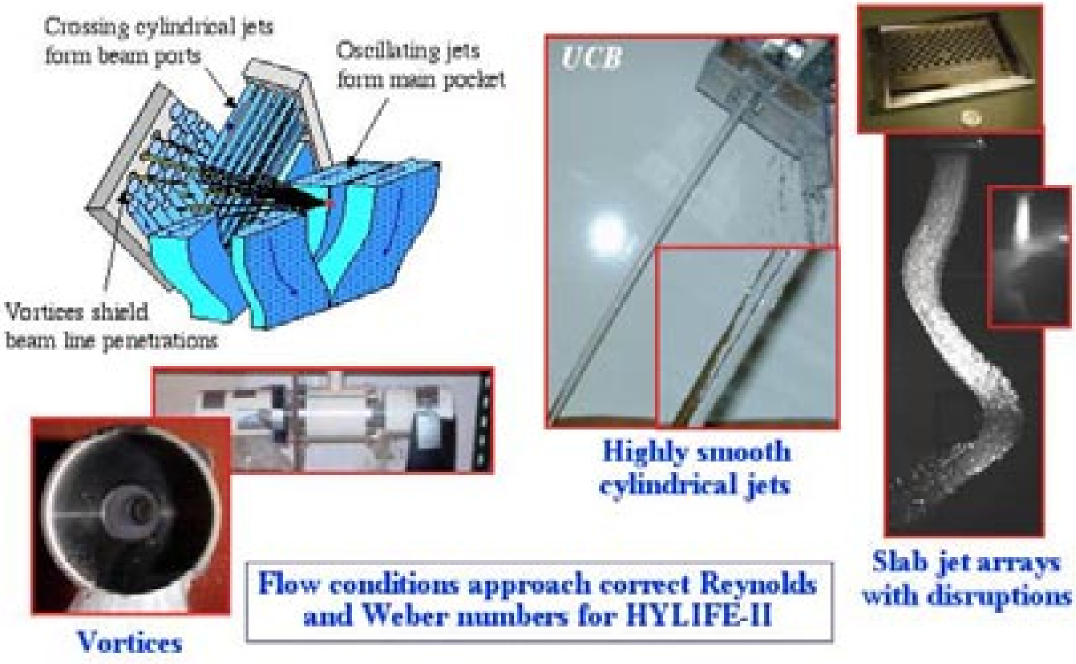
Ions-
RHEPP-1
(Sandia)



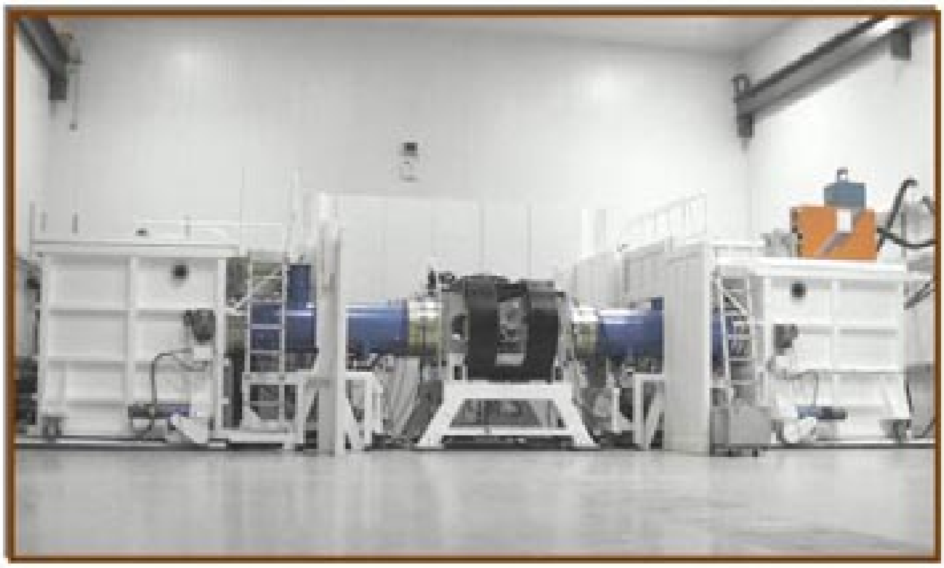
	Material	Predicted Ablation Threshold	Measured Ablation Threshold	Measured Roughening Threshold	Predicted Threat to wall	
					154 MJ target	400 MJ target
X-rays (10 nsec exposure)	Pyrolitic Graphite	4.0 J/cm^2	3.5 - 4 J/cm^2	2.5 J/cm^2	0.40 J/cm^2	1.20 J/cm^2
	Tungsten	not done yet	2 J/cm^2	1.3 J/cm^2		
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

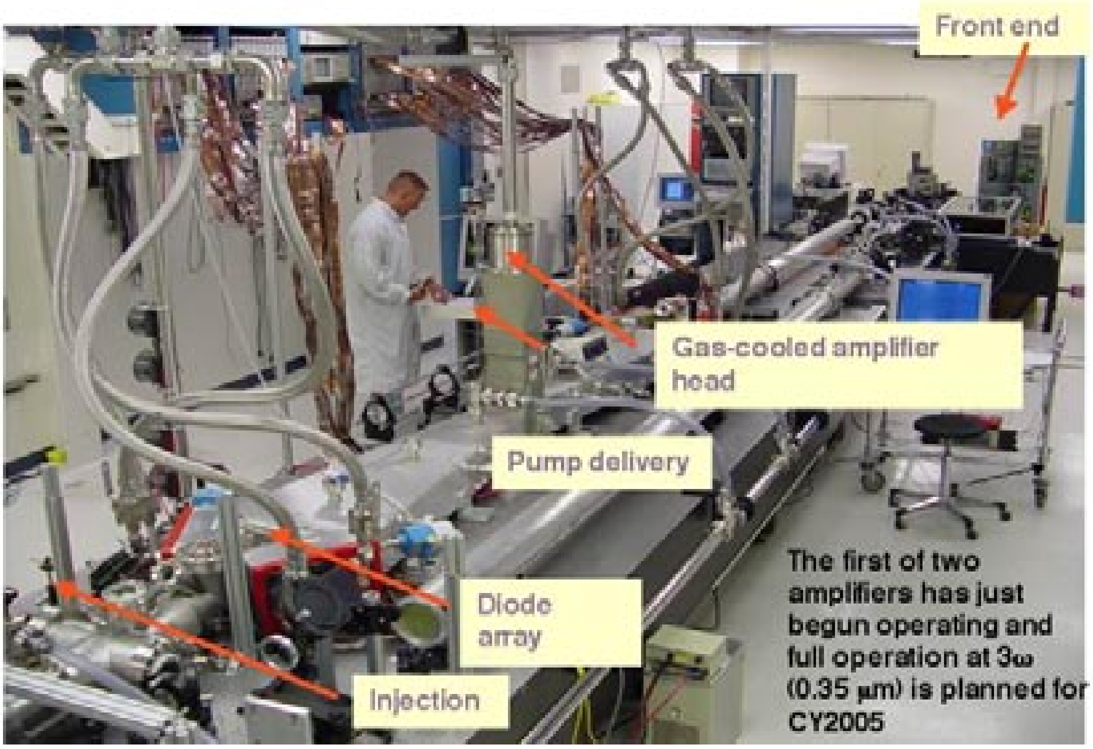
SNL (Experiments)
Wisconsin (modeling)



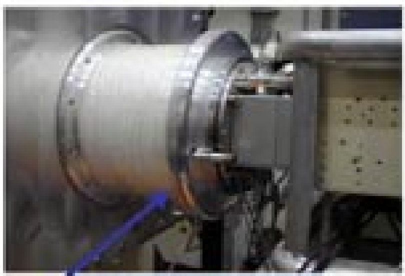
The goal of the Phase I driver experiments is to develop the database for the Phase II Integrated Research Experiment (IRE) Program. The Electra facility at NRL, shown in Fig. 17, is the major US facility for developing KrF lasers while the Mercury facility at LLNL, shown in Fig. 18 is the major facility for developing DPSSL's. Both facilities, which have just begun early operations, are scheduled for completion in FY05. The ion beam program currently includes separate experiments on source development (Fig. 19), high current transport (Fig. 20), and neutralized focusing (Fig 21). 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.



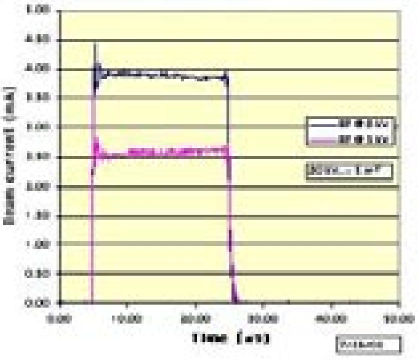
- First Generation pulse power system can run 5 Hz for 5 hours (500 keV, 100 kA, 100 nsec @ 5 Hz (25 kW))
- Excellent test bed for developing laser components



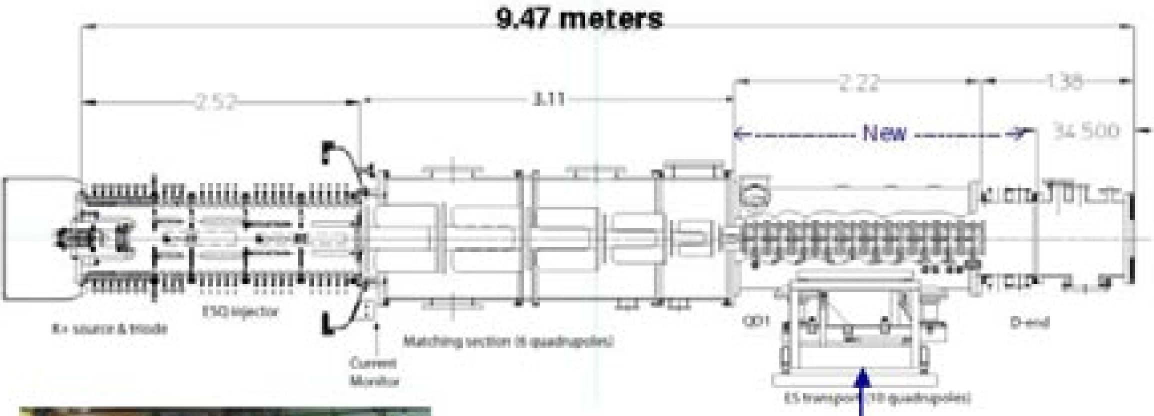
The first of two amplifiers has just begun operating and full operation at 3ω (0.35 μm) is planned for CY2005



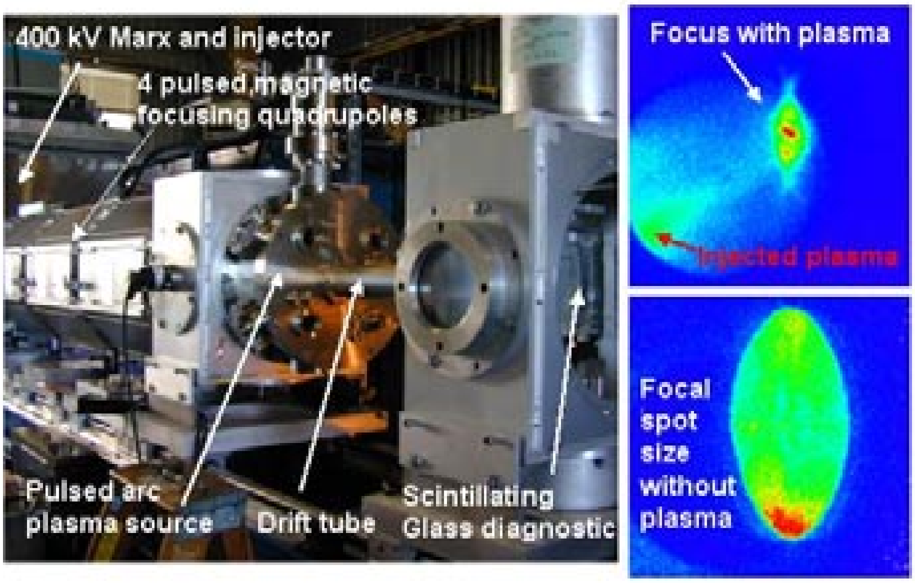
RF-driven multi-cusp source inside ceramic insulator



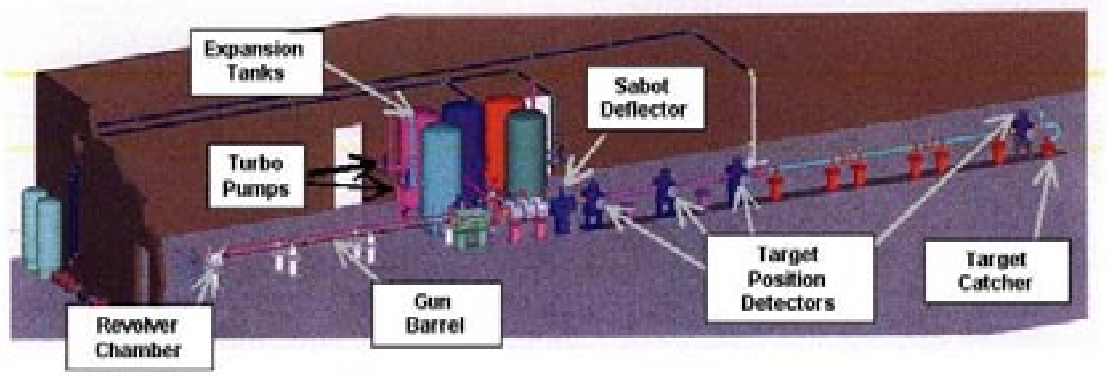
Obtained 3.9 mA from d=0.25 cm aperture => 80 mA/cm².
(compare to 8.3 mA/cm² for hot-plate source)
→A slight improvement in RF power or source plasma confinement should produce the desired J > 100 mA/cm²



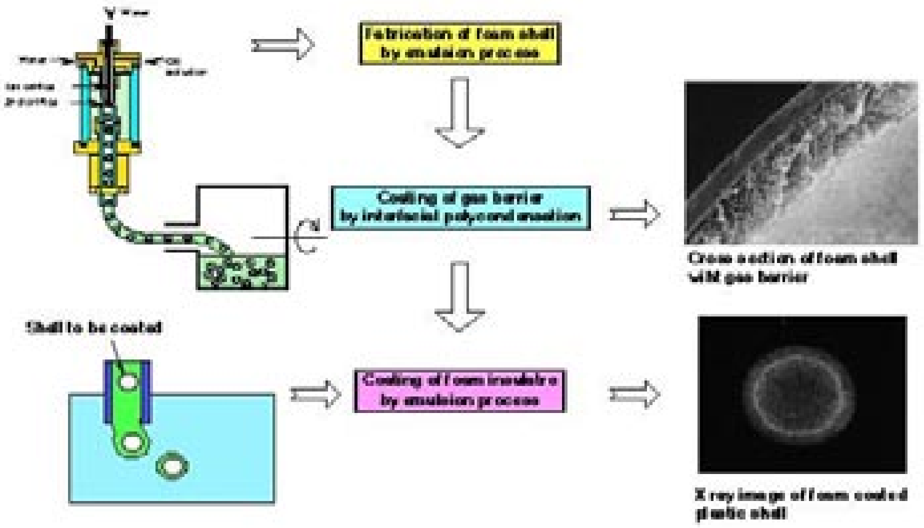
In initial experiments with 60% fill factor, there is no emittance growth within measurement uncertainty, (10 to 20 % in $\Delta\varepsilon$) and little beam loss (< 2% in the middle of the beam pulse).



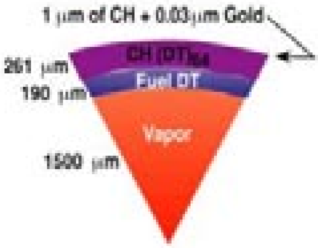
In conjunction with the experiments on drivers and chambers are experiments on target injection and fabrication. A facility to test the injection of both direct drive and indirect drive targets, shown in Fig. 22, is being constructed at General Atomics. Because the hohlraum provides a large thermal shield, it is expected that it will be straight-forward to inject indirect drive targets. Limiting the temperature rise of the fuel layer in direct drive targets to ~0.5 K is calculated to impose a major constraint on the operating conditions for dry wall chambers. Cost Developing fabrication processes that will allow fabrication of inertial fusion targets for ~$0.05/100 MJ of yield is a major challenge for inertial fusion. There has been substantial progress in developing approaches to mass production of the foam shell targets envisioned for direct drive as indicated in Fig. 23 and Fig. 24. Encouraging cost estimates have been developed for a factory to produce shells based on the processes shown in Fig 24.

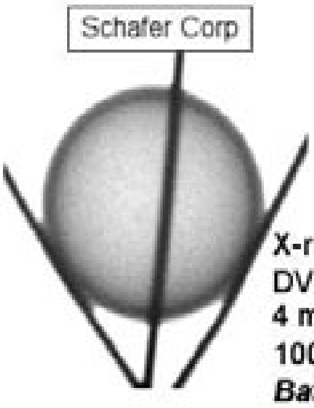


- Uses gas gun technology
- Will test target injection and tracking at 6 Hz
- Will test both direct and indirect drive targets



NRL radiation preheat target

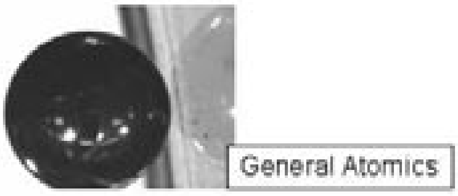




Established chemistry for foam shells

X-ray radiograph of DVB foam shell
4 mm dia, 400 μwall,
100 mg/cc
Batch of 300

Developed thin Au/Pd coatings with high DT permeability and IR reflectivity



In conclusion, there has been rapid progress in inertial fusion since the last IAEA meeting:

- Two ignition facilities are under construction (NIF and LMJ). The LIL prototype beamlines for LMJ and the first 4 beams of NIF will be available for experiments in about 1 year. Ignition experiments are expected to begin in 7-9 years at both facilities
- There is steady progress in the target science and target fabrication in preparation for indirect drive ignition experiments on NIF and LMJ. Advanced target designs 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
- Excellent progress on direct-drive targets at the University of Rochester including very encouraging cryogenic implosions

- There is world wide interest in the science of fast ignition and outstanding results from the Gekko Petawatt facility on heating and compression

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