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A TURNING POINT IN THE U. S. INERTIAL CONFINEMENT FUSION PROGRAM*

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1. Introduction

The goal of the U.S. ICF Program is to obtain a high-yield (100 to 1000 MJ) and high-gain (about 100) thermonuclear fusion capability in the laboratory. It has long been recognized that before such a laboratory facility is constructed, it must be demonstrated that laboratory conditions can be created that will, with high probability, lead to high gain if a driver of sufficient energy is built and that such a facility can be built at reasonable cost. Thus, the two major aspects of the U.S. program address target physics and driver development. Four main driver candidates are actively being pursued: 1) solid state lasers (principally Nd:glass), 2) KrF gas lasers, 3) light ion beams (Li ions accelerated by ion diodes), and 4) heavy ion beams (A ~200, accelerated by linear induction accelerator). The target physics aspect of the program is further divided into indirect and direct drive targets. In indirect drive targets the driver beams are aimed at a material near the capsule to generate x-rays, which then are absorbed in the fusion capsule ablator to produce the implosion. In direct-drive targets, the driver beams are aimed at the surface of the capsule. However, even in this case it should be recognized that the beam energy is deposited in the plasma surrounding the capsule, then transported to the ablation surface by electrons. The seven principal participants in the U.S. program are Lawrence Livermore National Laboratory, Los Alamos National Laboratory, Sandia National Laboratories, KMS Fusion, University of Rochester, Naval Research Laboratory, and Lawrence Berkeley National Laboratory. All of these participants have programs ranging in size from about $3M per year to $66M per year that address one or more of the target physics or driver development aspects of the National Program. Experimental target physics results recently obtained, principally for indirect-drive targets, have led to high confidence that a suitably-shaped 10 MJ pulse is sufficient to achieve high-gain and yields of 100 to 1000 MJ will result.

2. Conditions needed for high gain

As is well known, the efficiency with which any plasma will burn depends on the plasma density, confinement time and thermonuclear reaction cross section. For ICF, the fuel density-radius (ρr) product corresponds to the $n\tau$ used as a figure of merit in magnetic fusion. *In our targets, the burn fraction Ø is just:*

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$$\varnothing = \frac{\rho r}{\rho r + 6} \qquad 1)$$

for DT fuel, where ρr is expressed in g/cm^2. Thus, for a ρr of 3 g/cm^2 a burn fraction of about 30% results.

Compressing the target allows us to obtain reasonable burn fractions at a much smaller DT mass. The fuel mass in a capsule is:

$$M = \frac{4}{3}\pi \rho R^3 = \frac{4}{3}\pi \frac{(\rho r)^3}{\rho^2} \qquad 2)$$

At the liquid DT density, 2.5 kg of fuel is needed to obtain a ρr of 3 g/cm^2. This would produce a very large yield! However, if we can compress the fuel to a density of ~200 g/cc, then only a few milligrams of fuel are needed to obtain the same ρr. The fuel is compressed by doing PdV work on it. Less work is required if we start at a large density so cryogenic fuel is desirable. The pressure is generated by applying a high power intensity to the ablator. In both direct and indirect drive targets the achievable power intensifies and thus the pressures (P) are limited.

Now,

$$\int P dV = \varepsilon M = \varepsilon \rho 4 \pi R^2 \Delta R$$

$$\text{for 1000 fold compressions } dV = \frac{4}{3}\pi R^3, \qquad 3)$$

where R is the initial fuel radius. Therefore, the specific energy obtainable to ignite the fuel is,

$$\varepsilon = \frac{P}{3\rho \frac{\Delta R}{R}}$$

Equation 3 tells us that for any given density and obtainable pressure, we would like to have as low an initial $\Delta R/R$ as possible to provide the most energy to ignite the target. Thus, levitated spherical shells are an advantage. There is a limit however. The larger the aspect ratio, $(\Delta R/R)^{-1}$,the more likely that nonuniformities in the shell or in the drive pressure will cause breakup before the desired ten fold decrease in radius of the main fuel is achieved. Compressing the fuel is energetically very cheap. It takes only about 10^7 J/g to compress liquid DT to 200 g/cc, while it takes about 10^9 J/g to heat it to 10 keV. Since only ten or fifteen percent hydrodynamic efficiencies are anticipated (ratio of energy in compressed core to energy in ablator) it would require a very large driver to heat the entire mass of fuel. The answer is to ignite a small percentage of the fuel, a hot spark plug, and allow the thermonuclear burn front to propagate into and ignite the cold fuel outside. To do this successfully, the spark plug must be very symmetrically compressed and end up with a ρR greater than about 0.3 g/cm^2 —the alpha particle deposition range in hot DT. This requires an overall convergence to the final spark plug radius of about 40. Figure 1 shows before and after drawings of the capsule geometry. To accomplish these conditions successfully for reasonable capsule aspect ratios requires pressure uniformity of 1–2% on the outside surface. To be as energy efficient as possible requires efficient transfer of drive energy to the ablator, little preheating of the fuel from external sources like hot electrons or energetic ions, and minimization of shocks in the fuel to keep it on a low adiabat. This last requirement suggest gradual acceleration by a shaped power pulse with 10:1 to 100:1 ratio of peak to lowest intensity.

3. Recent results

3.1 Target fabrication

One of the difficulties that ICF has had meeting the requirements described above is that we didn't know how to build targets with the levitated spherical shells of DT fuel described in Fig. 1. There have been a couple of developments that indicate it is possible to build such targets. First it was suggested by KMS Fusion and confirmed experimentally by LANL, that if the proper mass of DT were frozen inside a capsule, heating caused by the beta decay of the tritium would cause sublimation from the thicker to the thinner parts of the shell and eventually the shell would symmetrize itself. There is some experimental evidence that this process will lead to a sufficiently uniform shell within a few hours which would certainly make it of interest to ICF. The only potential difficulty with the process is the fact that at the temperature of solid DT it is not clear whether there can be enough gas in the interior of the shell to make a good spark plug. Schemes are being sought to address this issue.

A second method of manufacturing a free standing thick liquid DT layer has also been found. We at LLNL originated the concept of wicking up liquid DT into a machined low density foam shell. We found Aerogel, a SiO_2 foam that has been manufactured for years for particle detector in high energy physics, had many properties of density, cell size and uniformity that we desired as a matrix for liquid DT. The average atomic number of SiO_2 is higher than we would wish for our purposes and so we embarked on a development program that resulted in materials like that shown in Fig. 2. This is a CH foam with a density of about 50 mg/cm^3 and a surface finish of less than 1 μm. We have demonstrated that it can be manufactured and that it will support a freestanding layer of liquid DT. Furthermore the vapor pressure from liquid DT near its triple point produces just about the right gas density desired to make a good spark plug.

3.2 Direct drive targets

Much work on direct drive targets has been devoted to improving the uniformity of illumination of the surface. NRL has been developing induced spatial incoherence (ISI) and the University of Rochester has installed random phase plates on the OMEGA laser. Both techniques have shown dramatic improvements in the uniformity of the beams on target. However, significant additional progress is needed as demonstrated in Fig. 2. Plotted is the ratio of experimental to calculated one dimensional yield as a function of target convergence ratio. Shown are the envelops for many experiments done on the Omega and Gekko lasers. The most likely interpretation of the fall off in the ability to predict the yield as the convergence ratio increases is that the symmetry and/or hydro stability needs to be improved.

There has been much publicity about achieving record neutron yields that requires a comment. The record neutron yields have been achieved using large-radius, thin-shelled, glass balloons. The laser causes the thin shell to explode rather than ablating from the outside. This drives a strong shock into the gas. When this shock rebounds from the center, large temperatures result, which, in turn, cause large neutron yields, even though the fuel is at relatively low density. These high neutron production results are valuable for diagnostic development but they have little relevance for obtaining high gain. Figure 3 shows the expected yield of this target type as a function of drive energy. As can be seen, the expected yield will not exceed breakeven even at drive energies of 10 MJ.

3.3 Indirect drive targets

Progress in the indirect drive target physics program has been better. Just about every one of the criteria needed to produce high gain in the laboratory as specified by the 1986 NAS study, have been met or exceeded and more importantly, the results of the experiments can now be predicted a priori with great confidence.

Figure 5 shows the most recent data from LLNL and from University of Rochester on efficiency of conversion of absorbed laser light into x-rays. This data shows that for intensities below a few times 10^{14} W/cm^2 conversion efficiencies above 70% can be obtained. The difference between the data obtained from Omega and that from Nova suggests that the greater beam uniformity of Omega may be leading to an improvement in conversion efficiency. Joint NRL/LLNL experiments suggest that ISI smoothed beams also give higher x-ray conversion efficiency than non-smoothed beams by as much as 30%. These results indicate that smoothed beams may be of value in indirect drive targets as well as for direct drive ones.

Another positive result is that externally caused preheat has ceased to be a problem for indirect-drive targets driven by lasers. The hot electron production that was characteristic of 1 μm light has virtually disappeared for wavelength of 0.5 μm or shorter. Experiments have yet to be done with ion drivers to measure the severity of the preheat problem caused by energetic ions of too long a range (e.g., protons mixed in with Li ions).

A great deal of the recent effort in indirect-drive targets has been to measure and demonstrate control of the factors that affect symmetry. Sophisticated diagnostics have been developed to graphically show where the energy is being absorbed as a function of time, the hohlraum spectrum and the uniformity of the energy transfer to the ablator. Due to classification restrictions, this data cannot be disclosed. However, the final proof of the uniformity obtained comes from the resulting uniformity of the implosions and the convergence ratios obtained that are close to one dimensional predictions. Figure 6 shows two images of compressed indirect drive targets. Figure 6a shows a pancaked core that resulted from a deliberately asymmetric drive profile that had higher intensity at the poles. Figure 6b shows the symmetric implosion that resulted when the pole high drive was "corrected". Of great importance is the fact that the shapes in both cases matched pre-experiment LASNEX calculations and are repeatable.

Figure 7 shows the ratio of experimental yield to 1-D LASNEX calculated yield for these experiments as a function of overall convergence ratio (ratio of initial ablator radius to final spark plug radius). These data were taken from ablatively-driven capsules. The neutron yield of the gas is calculated with a one dimensional code, assuming no mix of the ablator into the DT gas. If, due to asymmetries, the shell were to break up or there were significant mix of shell material into the gas, we would expect the measured yield to be orders of magnitude less than the calculated yield. Indeed, before the recent work on symmetry this was the case. Figure 7 shows, however, that the experimental yield is near the clean, 1-D yield up to convergences of about 35. It also shows that if the symmetry is degraded either spacially or temporally, the measured yield is more than an order of magnitude less than the calculated yield. To obtain the results shown for the convergence 35 capsules implies that we did achieve the necessary 1–2% drive uniformity. In these experiments more was measured than neutron yield. In each case we measure hohlraum temperature, temperature gradients, fuel temperature, burn time, fuel ρR, and pusher ρR in addition to yield and we take x-ray and neutron pinhole images of the imploding fuel at various times to observe the symmetry and resulting convergence ratio directly. For the symmetric high convergence targets all these measurements are now consistent with each other and with pre-experiment calculations.

4. The next steps

As is well known, in the U.S. there are classified aspects of the ICF program that cannot be discussed here in detail. Suffice to say, the experimental results from these have been equally positive. Considering both the classified and unclassified target physics results we can now say that high target gain is feasible and our best estimate at the present time is that it will require a drive energy of 5–10 MJ of 0.35 μm light, properly pulse shaped. For a square or gaussian shaped pulses about a factor of ten more energy would be required. All the above results have been obtained with unshaped pulses. Properly shaped pulses should give better results. The major target physics activity at Nova over the next two years will be to do the pulse shaped experiments.

Driver development programs have been carried out at LLNL (solid state lasers), LANL (KrF lasers), SNL (light ion beams), and LBNL (heavy ion beams) in parallel with the target physics programs described above. Important progress has also been made in all of these programs but emphasis has been on the target physics. With the recent positive results, however, there will now be a shift in emphasis toward driver development for a high gain facility. Design and construction of such a Laboratory Microfusion Facility (LMF) is becoming a major goal of U.S. programs even while continuing to collect target physics data using the present facilities. The DOE has asked the major ICF participants to propose ways to obtain such a capability as early as 1997. It is establishing scientific panels to review the status and prospects of each of the driver candidates so that it can select a facility design by the FY 91 time frame. Since early last year a DOE chaired committee comprised of all ICF laboratories has been working out a set of requirements for the LMF. The goal would be a facility in which experiments with yields of 100 to 1000 MJ could be done about once a week, with 300–500 experiments per year being done at lower energies. Such a facility would be oriented toward establishing the feasibility of using high gain ICF as an electric power source, doing basic physics experiments on matter at high energies and densities, using the large energy fluxes for experiments, collecting data necessary to design an ICF engineering test reactor, and doing experiments to establish the feasibility of using ICF for other applications such as space vehicle propulsion. It would become a truly unique and versatile facility.

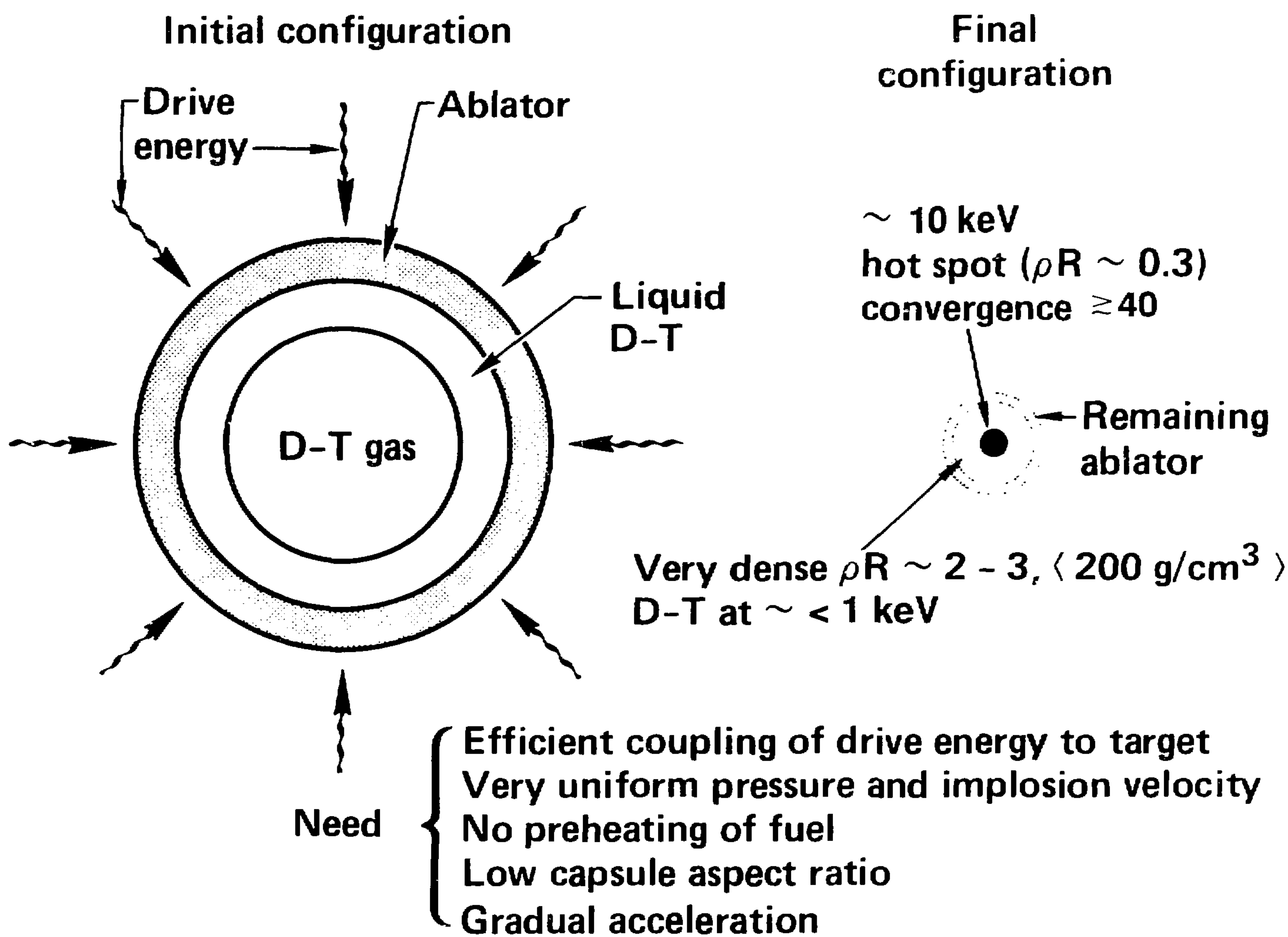
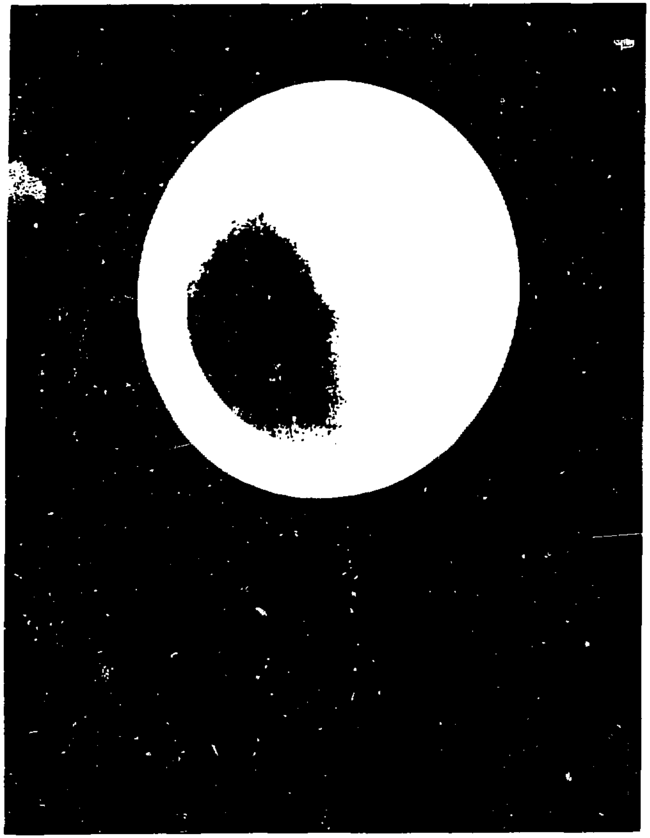


Fig. 1 High gain conditions are difficult to achieve.

W. J. Hogar
Fig. 1



Several candidate CH foams With ~ 50mg/cm^3 identified

Surface finishes $\lesssim 1\ \mu m$

Wicks up liquid DT to provide a thick, free-standing fuel layer

Fig. 2 Low density, low Z porous foams are a nearly ideal material for high gain ICF targets.

W. J.
Fig. ?

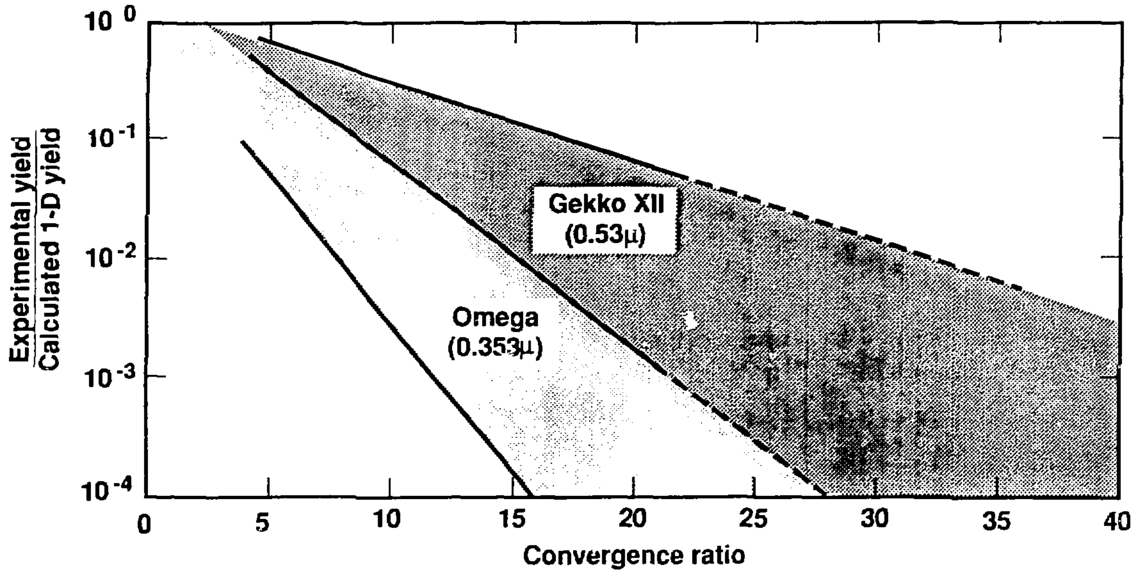


Fig. 3 Significant progress has been made in addressing critical implosion issues for direct drive but much improved symmetry (and/or hydro stability) must still be achieved.

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Fig. 3

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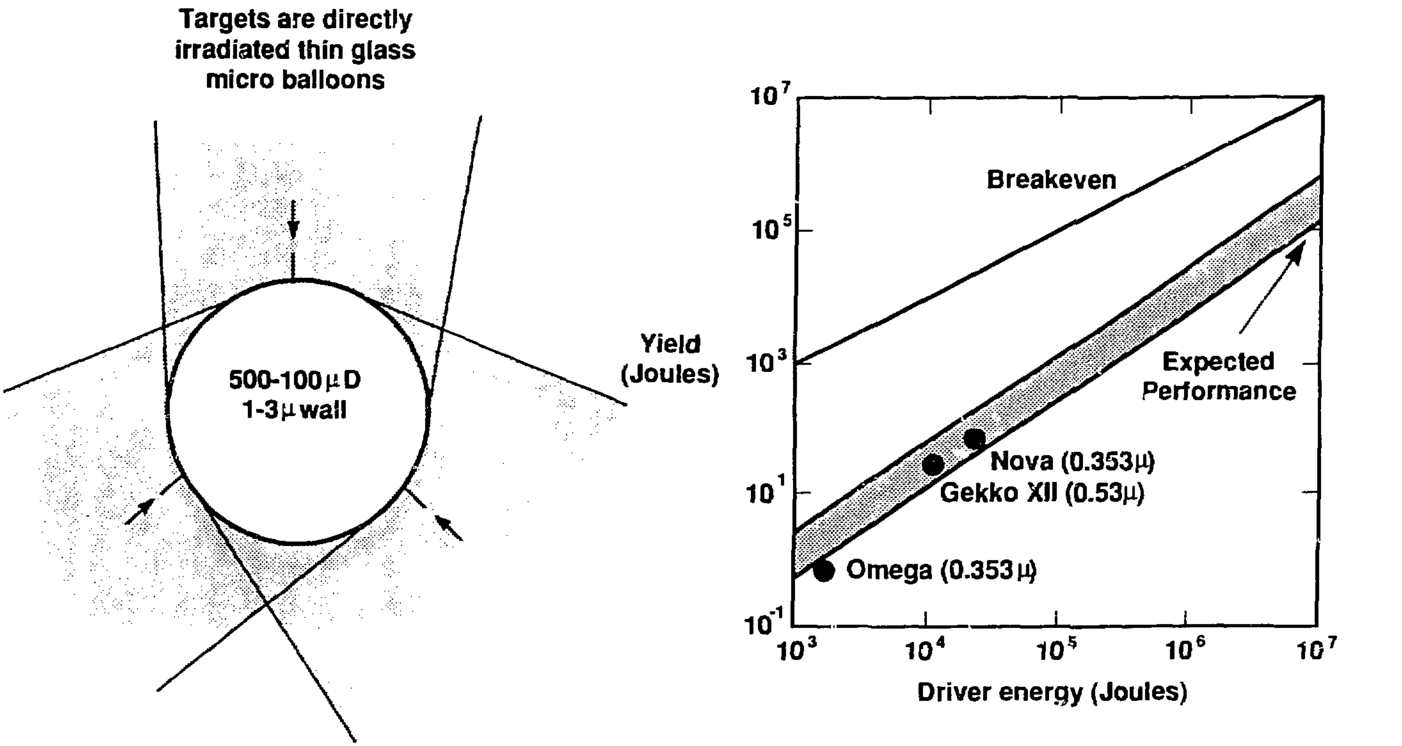

Fig. 4 Current high temperature laser driven implosions are low convergence, low density implosions which do not scale to high gain.

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Fig. 4

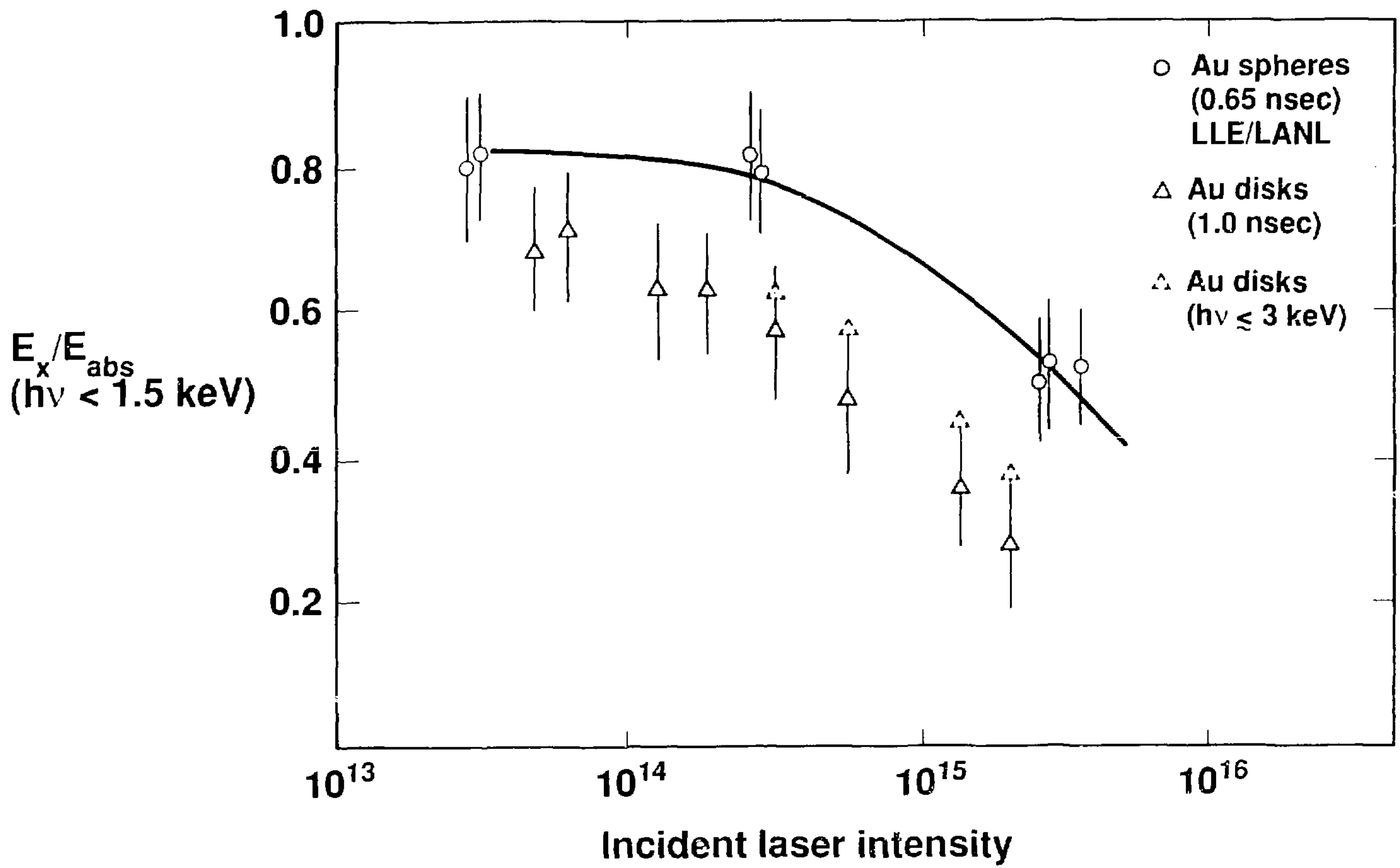
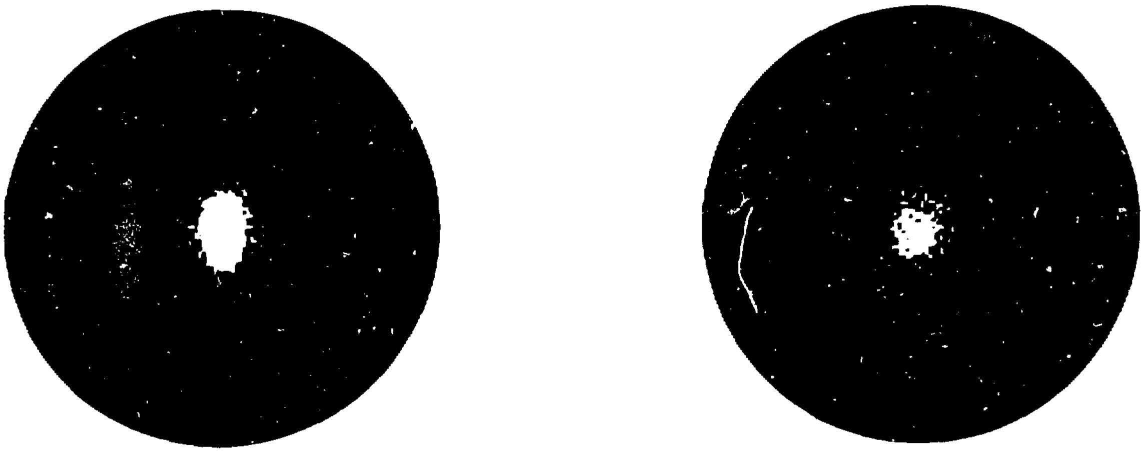


Fig. 5 X-ray conversion exceeds 70% for $I \sim 10^{14}$ W/cm^2.

W. J. Hoga-
Fig. 5

Shape of the emission region is matched by LASNEX calculations and can be experimentally optimized



Pole high drive

Symmetric implosion within resolution of experiment

Fig. 6 An x-ray framing camera is used to measure symmetry of self-emission from imploded capsules.

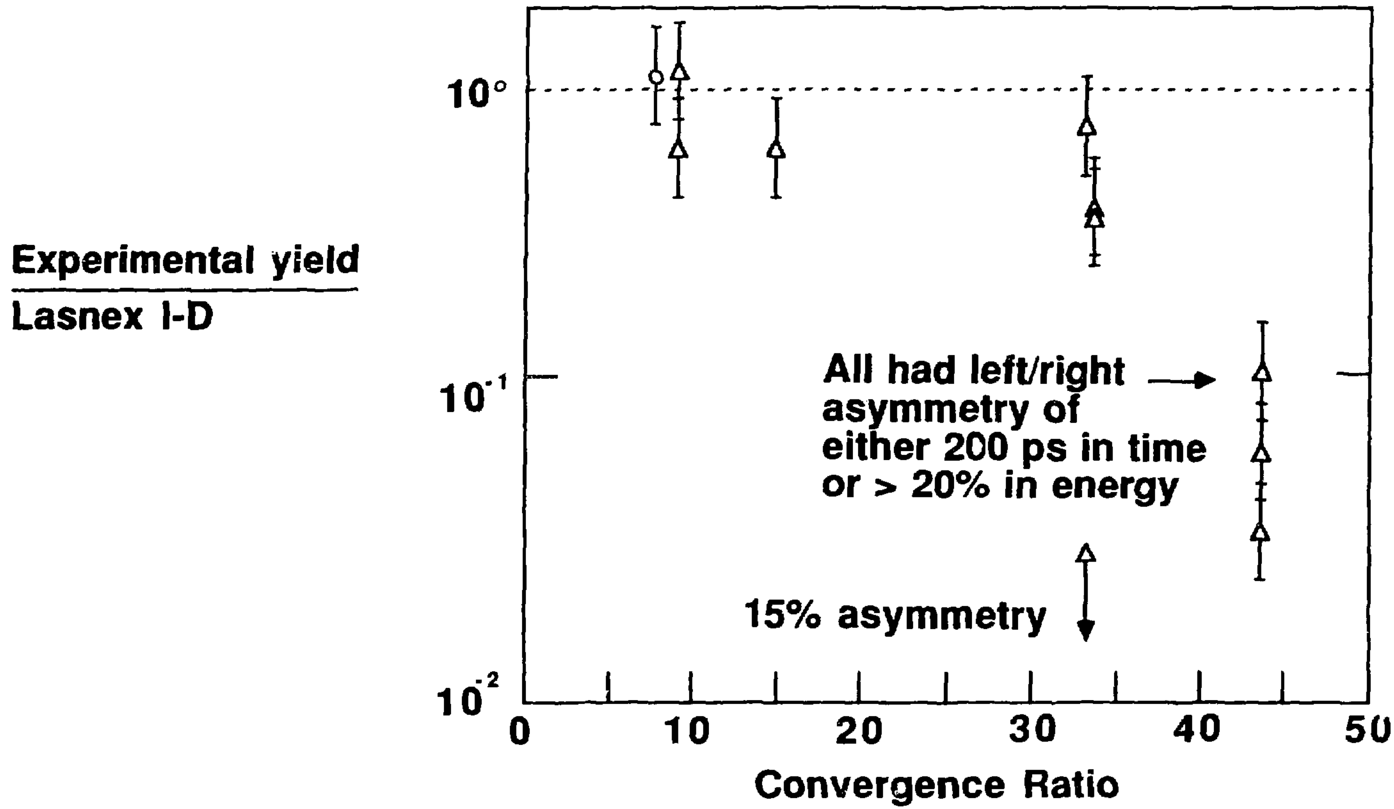


Fig. 7 In optimized hohlraums, we have achieved near 1-D yield with Convergence ratio in excess of 30.

W. J. Hogan
Fig. 7