Inertial Fusion Target Development*

K.R. Schultz
General Atomics
P.O. Box 85608, San Diego, California 92186-9784

ABSTRACT

The next series of inertial fusion experiments will approach and then achieve the conditions for ignition. These planned experiments include those at the OMEGA Upgrade laser at the University of Rochester, and at the National Ignition Facility proposed to be built at Lawrence Livermore National Laboratory. To achieve sufficient density to approach ignition conditions with reasonable laser power, these experiments call for cryogenic targets.

In this paper, we review the specifications for these ignition targets, describe the coordinated R&D program of the ICF Labs (Lawrence Livermore, Los Alamos and University of Rochester) and General Atomics to develop this technology, and describe the next steps in target technology from ignition to fusion energy application, and

INTRODUCTION

Research on inertial fusion has made steady progress in recent years [1–3], and the world's fusion community is ready for the next series of inertial fusion experiments, which will approach and achieve ignition. These next experiments include the OMEGA Upgrade laser recently completed at the University of Rochester Laboratory for Laser Energetics [4], the GEKKO XII Upgrade experiment being planned at the Osaka University Institute of Laser Engineering [5], the National Ignition Facility being designed in the USA [6], and the Megajoule laser being planned in France [7]. Key parameters for these facilities are summarized on Table I.

1) *OMEGA Upgrade*: OMEGA Upgrade has 60 Nd:glass laser beams frequency-tripled to 351 nm and has demonstrated focusing more than 30 kJ on target. The goal of this facility is to validate high-performance directly-driven fusion capsules as a part of the USA's national strategy toward demonstrating ignition and modest gain in the laboratory. It is designed to implode targets to convergence ratios greater than 20, achieve Raleigh-Taylor growth factors in excess of 500, and reach ion temperatures of 2–3 keV and area densities of 0.2 g/cm^2. Cryogenic direct drive capsules will be used, and with realistic multi-dimensional analysis, gains of less than one are predicted.

2) *GEKKO XII Upgrade*: Extensive technical research and development for the next laser system GEKKO XII Upgrade has been carried out at ILE Osaka University with collaborations throughout Japan. The output power of the system is designed to be 300 kJ of blue light (third harmonics) in a 3 ns main pulse. The system will be assembled in the present GEKKO XII building. This upgrade is being proposed for operation around 2000. Both direct and indirect drive targets will be considered.

3) *National Ignition Facility (NIF):* The National Ignition Facility (NIF) is the planned next facility in the US ICF program. A conceptual design has been completed by a multi-Lab team and accepted by the US Department of Energy. If construction is approved as hoped, the NIF will be operational in 2002. The NIF design features 192 laser beams from multi-pass Nd:glass lasers and will deliver 1.8 MJ of 351 nm light at 500 TW power to target. This should provide a safety margin of about two to achieve ignition. Indirect drive targets with cryogenic capsules will be used to achieve ignition and gain of up to 25. Direct drive experiments are also planned.

Table I
Machine Parameters and Experiment Schedule for OMEGA Upgrade, GEKKO XII Upgrade, NIF and Megajoule

Facility	Laser	No. Beams	Uniformity	Operation	Status
OMEGA Upgrade	Nd:glass 30 kJ, 40 TW at 351 nm	60	<2% rms	April 1995 Cryo: 10/98	Built
GEKKO XII Upgrade	Nd:glass 300 kJ, 250 TW at 351 nm	96	0.5%	Around 2000	Proposed
NIF	Nd:glass 1.8 MJ, 500 TW at 351 nm	192	≤2% rms	Fall 2002	Proposed
Megajoule	Nd:glass ~2 MJ, 500 TW at 351 nm	288		2002	Proposed

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4) *Laser Megajoule (LMJ):* Megajoule is the laser being designed by the French Centre d'Etudes de Limeil-Valenton to obtain ignition and burn. The planned facility will employ 288 Nd:glass laser beams using a four-pass architecture similar to that of the NIF, and being developed in cooperation with Lawrence Livermore National Laboratory. About 2 MJ at 351 nm will be required. Indirect drive targets with cryogenic capsules are planned, with experiments to begin in 2002 if funding is approved.

II. TARGET REQUIREMENTS

The ICF facilities described above will need high quality, cryogenic targets. In order to stop alpha particles and achieve ignition, the central "hot spot" of a compressed capsule must have a temperature of 5 keV and a density-radius product (ρr) of 0.3 g/cm^2. To achieve this with minimum driver energy and with minimum compression to limit growth of instabilities requires very uniform capsules and starting at as high a density as possible. This means using a cryogenic target. To provide a central hot spot to achieve ignition requires a central gas volume for heating by adiabatic compression. Thus a high quality spherical cryogenic shell of solid or liquid DT is needed, surrounding a gas core in equilibrium with the shell.

A. *Direct Drive Targets*

Direct drive requires very uniform illumination beams because there is no smoothing effect of a hohlraum. Experiments on the NIKE KrF laser show excellent beam uniformity is possible, better than 1.5% rms for a single beam, extrapolating to <0.45% for the 44 beam system [8], which bodes well for direct drive with multiple beams. OMEGA Upgrade has 60 beams for good uniformity, and should achieve better than 2% rms. Since the experiments planned will try to verify analysis of capsule compression with this high quality illumination, it is important that the targets be of still higher quality. A typical direct drive target is shown in Fig. 1.

1) *OMEGA Upgrade:* The OMEGA Upgrade Program Plan [9] maps out an extensive series of experiments, beginning in April 1995 and culminating with hydrodynamic-equivalent implosion experiments with cryogenic targets in late 1999. The cryogenic target experiments represent the ultimate goal of the UR/LLE program; i.e. to study the physics associated with the hot spot and main fuel layer in a capsule whose performance is similar to that of NIF direct-drive capsule designs. The predicted performance parameters of this experiment are a hot-spot convergence ratio of 20, a fuel ion temperature of 2–3 keV and an areal density >0.2 g/cm^2. This series of experiments will require a series of targets with increasingly more stringent specifications. These specifications ultimately call for polymer shells 710–990 ±0.5 μm inside diameter with a 5 μm wall and a 100 μm solid or liquid DT layer with total thickness uncertainty of ±0.25 μm. The non-concentricity of the capsule must be less than 0.5 μm and the surface finish must be better than 200 Å outside and 1000 Å inside. The requirements for surface finish are actually more stringent than for the NIF because of the smaller target size.

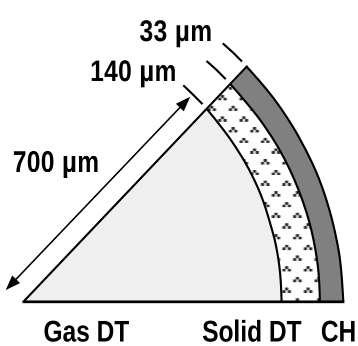

Fig. 1. Direct drive target for GEKKO XII Upgrade

2) *GEKKO Upgrade:* Osaka University has proposed to investigate fuel ignition with a 300 kJ, blue laser system "KONGHO" by achieving laser non-uniformity σ–rms less than 0.5%. A target design for ignition demonstration with the GEKKO XII upgrade laser system has a 1D pellet gain for 300 kJ input of about 2. The target consists of a DT gas core of 1400 μm diameter, a DT solid layer of 140 μm, and a CH ablator layer of 33 μm. The gas density in the void is 0.2 mg/cm^3, corresponding to a temperature of about 17 K.

B. *Indirect Drive Targets*

Indirect drive involves directing the laser beams into a metal container called a hohlraum where the light is converted to x-rays which fill the hohlraum. This conversion reduces drive non-uniformities and creates wavelengths that are more effectively absorbed in the capsule placed inside the hohlraum. This relaxes some of the constraints on beam uniformity from those of direct drive, but may not relax the constraints on target quality. Indirect drive has been the major focus of the ICF program and the NOVA experiments at LLNL [10], and will be the primary focus of the NIF experimental program. Indirect drive targets may also be used in the OMEGA Upgrade and GEKKO Upgrade experiments.

1) *NIF Targets:* A typical NIF target is shown on Fig. 2. It consists of a 2 mm diameter doped polymer shell 160 μm thick, surrounding an 80 μm thick layer of frozen solid DT, in the center of a cylindrical gold hohlraum, 0.9 cm long by 0.55 cm in diameter. The hohlraum walls are actively cooled with cold high pressure helium gas. The accuracy specifications for these targets are similar to those currently used for NOVA, but the larger size of the NIF targets makes these specifications effectively more stringent, as shown on Table II. Another NIF target design incorporates a beryllium capsule, which promises increased ignition margin.

III. TARGET DEVELOPMENT NEEDS AND STATUS

While high quality targets are now being produced for NOVA, GEKKO XII, and other experiments, the next seriesof ICF experiments will require further improvements in size and quality. The step to cryogenic targets is especially challenging.

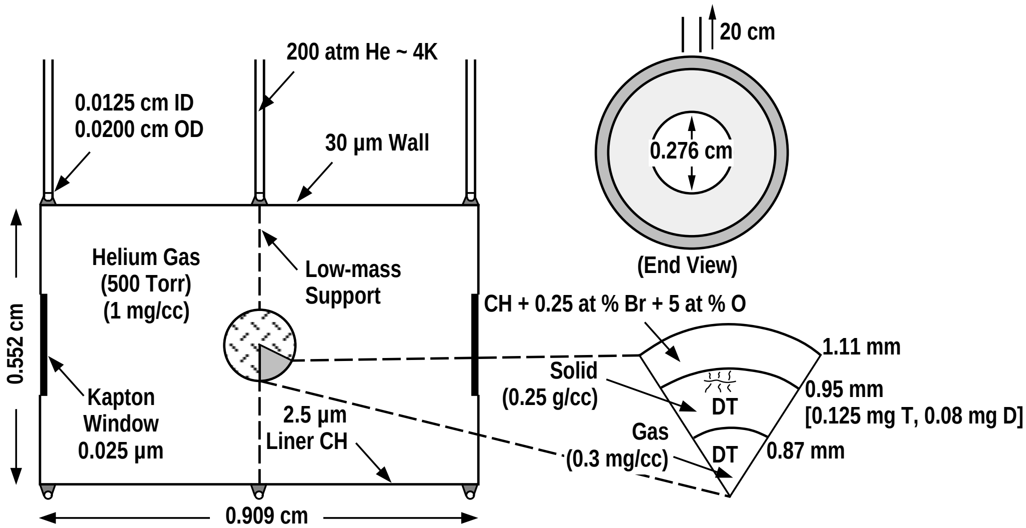

Fig. 2 . An indirect drive target for NIF

Table II
Typical Target Capsule Specifications

Characteristic	NOVA	OMEGA Upgrade	GEKKO XII Upgrade	NIF
Shell Diameter	200–600 µm	700–1400 µm	1000–2000 µm	1000–3000 µm
– Required accuracy	<1%	<0.05%		<0.5%
Shell Thickness	3-5 µm	5-25 µm	20-40 µm	5-25 µm
– Required accuracy	1 µm	0.25 µm		1 µm
Fuel Layer Thickness	–	50–100 µm	100–150 µm	50–100µm
– Required accuracy	–	1 µm		1 µm
– Required non-concentricity	–	<0.5 µm		<1 µm
Capsule Accuracy: External				
– Non-sphericity				
– Surface finish	<1%	<1%	<0.5%	<1%
Internal	<1000Å	<200Å	<200Å	<1500Å
– Non-sphericity				
– Surface finish	–	<1%	<0.5%	<1%
	–	<1000Å		<5000Å

A. *Capsules*

The spherical shells or "capsules" that hold the DT fuel in current experiments such as NOVA at LLNL are about 0.5 mm in diameter, or smaller, with specifications as shown on Table II. Future experiments will need shells from 1 to 3 mm in diameter with similarly strict specifications.

1) *Polymer shells:* Fabrication of uniformly thick fuel capsules with high sphericity and fine surface finish is essential for inertial fusion experiments. Current techniques utilize thermodynamic properties of the material such as surface tension to make the spherical shape. Mainly two techniques are used to make polymer shells for current laser systems whose output power ranges from 10 to 40 kJ. One is to use a droplet generator on a drying column and the other is to use an emulsion suspended in water.

In the droplet method, polystyrene dissolved in a volatile solvent is injected into a heated column as a series of droplets. As the droplets fall, the solvent evaporates and a skin forms on the surface. Further evaporation of the solvent leads to blowing of the droplets into shells with a wall thickness of a few microns [11,12]. Polystyrene is quite permeable to hydrogen, so these shells are used as a mandrel and a few-µm-thick polyvinyl alcohol layer is added on the surface to keep the fuel inside. An ablation layer of polymer produced by a glow discharge polymerization process is coated on the outside to control the implosion mode.

In the density-matched emulstion method [13], a dual or triple nozzle-in-orifice droplet generator [14] is used to produce shells with diameter and wall thickness controlled in a narrow range. The inner water phase (W_1) is a solution of a surfactant whose total density is 1.05 g/cm^3. Polystyrene is dissolved in a mixture of di-n-butyl phthalate and diethyl phthalate with the mixing rate adjusted so that the total density of the "oil" phase is 1.07 g/cm^3. A cylindrical-hollow oil-column injected from the nozzle is broken into W_1/O droplets that are sent to a drying bath. The W_1/O/W_2 emulsion in the bath is stirred and heated to 70°C to evaporate the solvent. After drying is completed, the shells are dried in air to remove water in the void.

Using this technique, 400 to 2300 μm diameter polystyrene shells with 5 to 20 μm walls have been fabricated at Osaka University. Figure 3 shows a micrograph of a 2.25 mm diameter polystyrene shell with a 15.7 μm wall. The uniformities of wall thickness were >99.5% for <1 mm diameter shells and >98% for 2 mm diameter shells, respectively. The surface finish was <10 nm. Further technological innovations will be necessary to apply this technique to make future power plant class targets (5 mm to 1 cm diam.) because the hydrodynamic forces on the material are much larger than the thermodynamic forces in this large diameter range.

B. *Cryogenic Layers*

All of the future ICF experiments, and all designs for inertial fusion power plants call for cryogenic targets. Creating a cryogenic target that meets the exacting specifications required is a significant challenge. Cryogenic targets need uniform fuel layer thickness and density, and a smooth inner surface finish. Experiments will need both solid and liquid targets (15 to 22 K) to cover the central gas density range of interest, shown in Fig. 4. For solid layers, the primary issue

Fig. 3. Micrograph of a 2.25 mm polymer shell made by Osaka University.

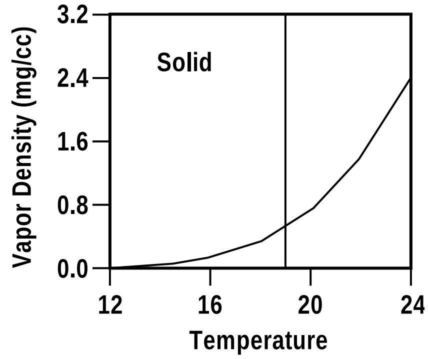

Fig. 4. Temperature/density diagram for cryogenic targets.

is achieving a uniform thickness and smooth surface. For liquid layers, the challenge is supporting a uniform layer against gravity.

1) *Solid Layering*: Uniform thin solid layers (~few microns) have been successfully created by simply rapidly cooling the gas-filled capsule and freezing the fuel onto the inner surface [15]. For thick layers, gravity causes a thicker layer at the bottom than the top. If the outside of the capsule is held at a uniform temperature and a heat source is created inside, fuel will migrate from the thicker (hotter) zones to the thinner (cooler) zones, eventually giving a uniform layer.

Beta Layering. For DT fuel the beta decay of the tritium can provide the heat necessary to achieve a uniform layer. This technique is called "beta layering." Since decay heat is a volumetric phenomenon, a thick layer of DT will produce more heat than a thin layer. If the outside of the shell is maintained at constant temperature, thick zones will be hotter than cold, and fuel will migrate by sublimation and condensation from the thick areas to the thin, eventually yielding a uniform layer. Experiments at Los Alamos have successfully shown that thick (~100 μm) layers of DT can achieve a high degree of uniformity [16] as shown in Fig. 5. The surface finish of these solid surfaces appears to be somewhat rougher than desired for NIF or OMEGA Upgrade. To get below about a 2 μm rms finish may require more heat flux through the layer than beta decay can provide [17] as shown in Fig. 6. Additional heat flux might be provided by microwave heating.

Microwave Heating. In the plasma layering technique, a glow discharge in the capsule void is initiated by an external rf field to symmetrize the non-uniform solid layer [18]. Plasma layering may smooth the inner surface more effectively than does β layering alone. The plasma layering technique has a heat source in the void of the shell and a temperature gradient exists at the surface even after the solid layer is symmetrized. Further, a higher heat flux can be obtained than is possible with tritium decay heating alone. Surface smoothing by microwave and infrared heating is being pursued at Osaka University and LLNL.

2) *Liquid Layering*: Liquid is naturally smooth, but achieving adequate uniformity is the challenge for liquid

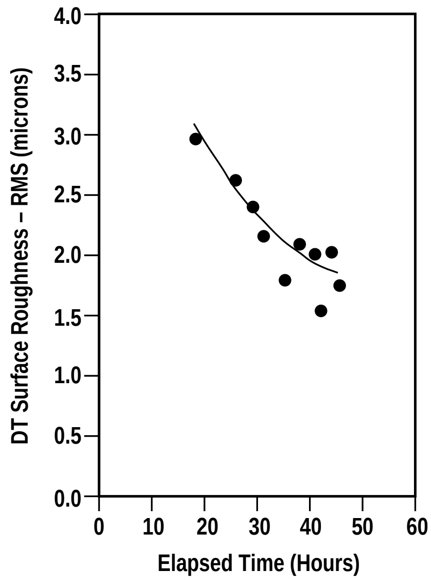

Fig. 5. Beta layering uniformity vs. time.

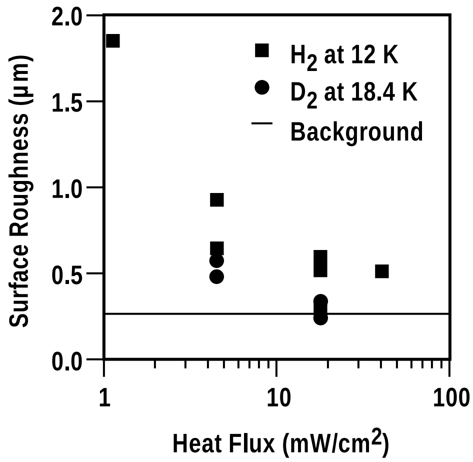

Fig. 6. Surface roughness vs. heat flux. Beta heating in 100 µm DT is ~0.5 mW/cm^2

cryogenic targets. Some mechanism must be provided to support the liquid against gravity.

Thermal Gradient Techniques. By establishing a thermal gradient from bottom to top across a shell filled by a single species (H_2, D_2 or T_2), a uniform layer can, in principle, be established as fluid evaporates at the bottom, condenses at the top, and flows back down the sides. This has been done for thin layers (~10 µm) in small shells (200–600 µm) [19]. For thick layers, however, the thermal gradient that would be required is so large that it is impractical [20]. For mixtures such as DT, the surface tension differences created by the partial segregation of D and T that occurs when the lower boiling point D_2 evaporates first, can drive a flow of fluid within the liquid layer. A small temperature gradient from top to bottom of a DT- or HD-filled capsule can transport liquid up the sides of the capsule. Experiments are now underway at LLNL to determine if this technique can be adequately controlled to create a stable, uniform layer. To date, the researchers have shown that layers as thick as 75 µm in a 2 mm shell can be supported by temperature differences of a few K, however uniform, stable layers have yet to be achieved. These thermal gradient techniques are shown in Fig. 7.

Wetted Foam Shells. Surface tension can also be used to support liquid fuel in a low density foam. Spherical shells of polymer foam have been used by Osaka University to make cryogenic liquid targets for GEKKO XII laser experiments [21]. The fabrication of low-density foam shells with high sphericity and uniformity occupies an important role in the wetted foam shell technique. The foam layer must be covered by an appropriate normal density plastic layer to prevent the fuel boiling off. The fuel is loaded so that the foam layer is slightly overfilled with liquid fuel to obtain a smooth inner surface. When the excess fuel is less than a couple of micrometers in thickness, the influence of sagging of the excess fuel should be acceptable since the majority of the fuel is supported by the foam layer. Achieving ignition, however, may require a free liquid layer 10 or more microns thick. This would have to be supported by some technique

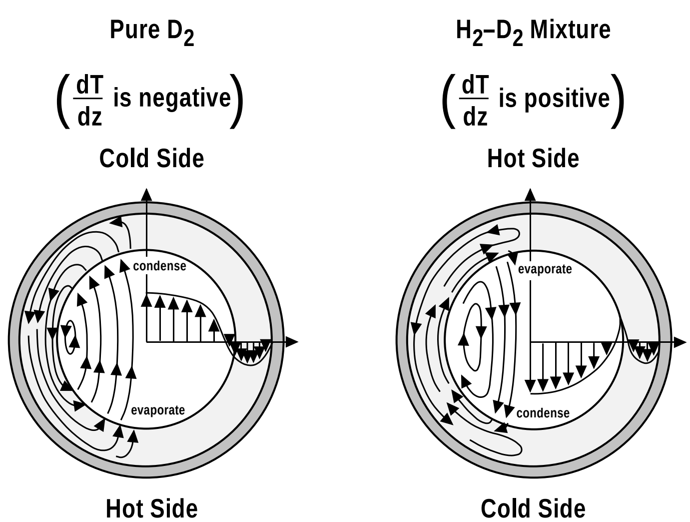

Fig. 7. Thermal gradient layering diagrams

such as thermal gradients. The foam layer must be transparent to allow optical characterization of the fuel layer when it is saturated with liquid fuel.

Bare polymer foam shells have been developed using phase separation of a polymer solution [22], and by gelation of trimethylolpropane trimethacrylate (TMPT) W/O/W emulsion [23]. The overcoating of the foam shell was carried out using an interfacial polycondensation technique [24]. Production of improved foams using ethylene glycol dimethacrylate (EGDM) is also being purused [25]. Work is now under way at Lawrence Livermore National Laboratory to develop an overcoated foam shell based on resorcinol-formaldehyde foams. These promise smaller foam cell size and better optical transmission for characterization.

Foam shells having <50 mg/cm^3 density, diameters of 600 to 1550 µm and wall thickness of 10 to 50 µm were coated with a normal density plastic layer having thickness of 4 to 10 µm. An example is shown in Fig. 8. The foam shells presently appear to have cell size of about 1 µm, which results in light scattering, reducing clarity of observation of the interior liquid. Finer foams are being pursued at Osaka and LLNL.

Zero Gravity/Free Fall. Surface tension will smooth out the shape of a bubble in zero gravity, leaving a perfect sphere. To center the bubble inside a liquid filled capsule requires an additional force. The very weak London-van der Waals force can provide this for thin layers. Analysis shows that a thin layer will symmetrize quickly in the low gravity environment (~10^{-3} G) of free fall [26]. To avoid deceleration by air drag in the imperfect vacuum of an ICF target chamber requires that the low density of the target be augmented by mounting it to a high density object. Thus a potentially promising technique may be augmented-mass free fall of an overfilled foam shell. Free fall targets also lead in the direction needed for inertial fusion power plants.

Fig. 8. Micrograph of overcoated foam shell.

C. *Cryogenic Characterization*

ICF target capsules are currently very carefully characterized by optical interferometry and x-ray techniques to determine diameter, wall thickness, concentricity and sphericity, all measured in multiple views to get effective three dimensional characterization. The outside surface can be measured with an atomic force microscope while the capsule is on a rotator to characterize the surface modes. For cryogenic capsules, in addition the inner fuel layer thickness, uniformity and surface finish must be measured. Present experiments use optical shadowgraphy. Future plans call for multi-axis interferometry. Techniques to measure the inner surface finish by use of an optical sphere mapper are being pursued, but are presently unproven. Opaque shells are a particular concern for characterization. Direct drive targets may need a UV barrier on the surface of the shell to prevent the laser beam from pre-heating the cryogenic fuel. UV barriers that are transparent in the visible region appear possible, but require development. As mentioned above, current foam shells have large enough cell size to interfere with characterization and transparent foams with smaller cell size are being developed. Ultrasound and NMR characterization techniques are also being pursued.

D. *Cryogenic Target Handling*

In addition to being carefully fabricated, carefully filled and layered, and carefully characterized, cryogenic targets must be carefully handled. Elaborate cryogenic systems will be needed to fill, layer, and characterize targets, and then insert and align them in the target chamber [27,28]. Cryogenic fuel layers are very sensitive to temperature, and require good thermal control after the target has been layered. It is estimated that a temperature changeof more than 0.2 K will affect the quality of the target. Bare targets can only survive ~20–100 ms in a room temperature target chamber before this limit is reached, requiring the use of thermal shrouds that can be quickly withdrawn just prior to shot time. Hohlraums significantly aid thermal control. A cryogenically cooled hohlraum will thermally protect a capsule, allowing use of simple slow-acting shutters over the laser entrance holes, rather than fast-acting shrouds.

E. *National Cryogenic Target Program*

In the USA, the challenges of developing cryogenic targets for the next series of ICF experiments are being pursued in a coordinated effort known as the National Cryogenic Target Program. The efforts of LLNL, LANL, UR/LLE and General Atomics are being coordinated to develop the cryogenic targets and target handling systems that will be needed for OMEGA Upgrade, NIF and beyond.

IV. EXTRAPOLATION TO INERTIAL FUSION POWER PLANTS

Recent inertial fusion design studies show that both KrF direct drive and heavy ion beam (HIB) indirect drive designs have the potential to be attractive, economic power plants [29]. It is possible that indirect drive with a light ion beam (LIB) driver using extraction diodes also can lead to an attractive power plant [30].

A. *Targets*

The targets for inertial fusion power plants will be very similar to ignition targets, just perhaps a bit larger. Cryogenic capsules with a solid or liquid DT layer inside a polymer shell will be needed. The hohlraums for HIB or LIB drivers are different from those of indirect drive laser targets. HIB drivers will need a high-Z radiation converter material to absorb the ion beam and produce the x-rays needed to compress the capsule [31] as shown in Fig. 9. One-sided illumination may be possible. LIB targets will consist of a spherical, foam-filled hohlraum with the cryogenic capsule in the center. This will require uniform irradiation by multiple light ion beams, and appears well-suited to the geometry of the extraction diodes being developed [32].

B. *Fabrication Requirements*

ICF targets currently are hand-crafted, very carefully and thoroughly characterized, and must include many different designs and variations to satisfy the needs of the experimentalists. The cost associated with the production of these targets is high; they cost several thousand dollars each. An inertial fusion power plant will consume from 1 to 10 targets per second, 24 hours a day. For inertial fusion to be economically competitive as a commercial energy source requires that the targets will have to cost no more than about 30¢ each [33]. Power plants, however, will require only a limited number of target designs, and they will need characterization only as a part of the production quality control process. While development is needed of target designs and fabrication techniques that are well-suited to efficient, economical mass production techniques, design studies done to date [34], show promising ideas, and we expect that this development will be successful.

C. *Target Injection Concepts*

Targets for current inertial fusion experiments are individually mounted on stalks, fibers or plastic "tents" that hold the targets firmly in place as they are carefully aligned before the shot. Cryogenic targets are carefully protected by shrouds that keep thermal radiation from the room temperature target chamber from overheating the fragile target and then are pulled rapidly out of the way just prior to the shot, as described above. Power plants will need thermally protected rapid insertion mechanisms that maintain strict temperature control of the targets as they are injected to precisely the right location at the driver focus in the center of the high temperature reaction chamber at the rate of several per second. The engineering challenge is formidable. Little development has been done on this vital aspect of inertial fusion energy, but design studies [35] do indicate promising directions.

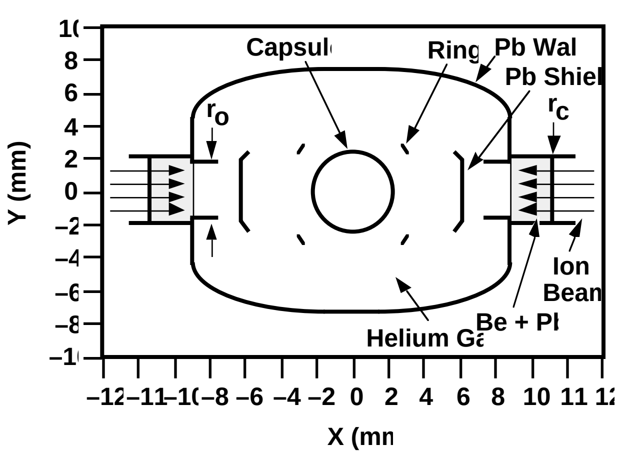

Fig. 9. HIB target for inertial fusion energy application

V. SUMMARY

The target needs of the next ICF experiments that will lead toward ignition and energy are different from those of today's experiments. The future experiments on OMEGA Upgrade, GEKKO XII Upgrade, the National Ignition Facility and Megajoule will need large, precise, cryogenic targets. Development is needed on a number of aspects of these targets, including shell fabrication, characterization, cryogenic layering and target handling. However, coordinated R&D programs are in place and work is in process to carry out the needed development. It is vital to the success of inertial fusion that this work be sustained. Coordinated effort, like the National Cryogenic Target Program in the USA, will help make the development activities as efficient and effective as possible, and should be encouraged.

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