

A credible pathway for heavy ion driven target fabrication and injection

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Abstract

The Target Fabrication Facility (TFF) of an inertial fusion energy (IFE) power plant must supply about 500,000 targets per day. The target is injected into the target chamber at a rate of 5–10 Hz and tracked precisely so the heavy ion driver beams can be directed to the target. The feasibility of developing successful fabrication and injection methodologies at the low cost required for energy production (about \$0.25/target, approximately 10^4 times less than current costs) is a critical issue for inertial fusion energy. A significant program is underway to develop the high-volume methods to supply economical IFE targets. This article reviews the requirements for heavy ion driven IFE target fabrication and injection, and presents the current status of and results from the development program. For the first time, an entire pathway from beginning to end is outlined for fabrication of a high-gain, distributed radiator target. A significant development and scale-up program will be necessary to implement this pathway for mass production of IFE targets.

Keywords: Fabrication; Fusion; Heavy ions; Inertial; Targets

1. INTRODUCTION

Inertial fusion energy (IFE) power plant conceptual designs have been published over the past several decades (Meier, 1994; Moir *et al.*, 1994). A variety of target designs have been analyzed for heavy ion fusion (HIF), including the promising “distributed radiator” design illustrated in Figure 1 (Tabak *et al.*, 1998). This target requires illumination by a number of beams from two sides, focused in an annular ring on the ends of the target. The ion beams deposit their energy all along the nearly cylindrical hohlraum materials, thus the term *distributed radiator*. The distribution of radiation is accomplished by tailoring the density of radiator materials in the target, which means that fabrication of a number of special high-Z doped CH foams and high-Z (metal) foams are required. These hohlraum materials are the subject of development tasks unique to the HIF target. Other manufacturing aspects of the HIF target are similar to laser-driven direct-drive IFE targets and to current experimental

inertial confinement fusion targets (e.g., spherical shells, permeation filling). Possible material substitutions to the original target design (for manufacturing and cost reasons) are also indicated in Figure 1 (D. Callahan-Miller, pers. comm.).

General Atomics (GA) and Los Alamos National Laboratory (LANL) are carrying out the development work associated with the IFE target supply as a joint effort. The near-term programmatic goal for the development work is definition of a “credible pathway” for supplying targets in the quantities needed and at acceptable costs. Details, including equipment sizing and process times for some of the processes, are starting to take shape. Spherical capsules can be formed by direct microencapsulation of polystyrene. Capsules can be filled by permeating deuterium–tritium (DT) through the walls, and then cooled to ~ 20 K to reduce the capsule internal pressure and to allow removal of excess DT. Layering of the DT can be accomplished by placing the filled cryogenic capsule into a highly uniform temperature environment, either in a cryogenic fluidized bed (bare capsules) or in a cryogenic layering tube (within a hohlraum). Production of the hohlraum and its internal components can be accomplished by processes such as casting, injection molding, doping of CH foams, and laser-assisted chemical vapor deposition. Injection of the target into the chamber

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Part	Material	Density (g/cc)
A	AuGd ⁴ (high-Z only)	0.1
B	AuGd (high-Z only)	13.5
C	Fe (Au-doped CH foam)	0.016
D	(CH) _{0.97} AuM _{0.03}	0.011
E	AuGd (high-Z only)	0.11
F	Al (silica aerogel)	0.07
G	AuGd (high-Z only)	0.26
H	CD ₂ (He gas)	0.001
I	Al (CH or doped CH)	0.055
J	AuGd sandwich (high-Z only)	0.1/1.0/0.5
K	DT	0.003
L	DT	0.025
M	Be _{0.995} Br _{0.005} (or CH)	1.845
N	(CD ₂) _{0.97} Au _{0.03}	0.032

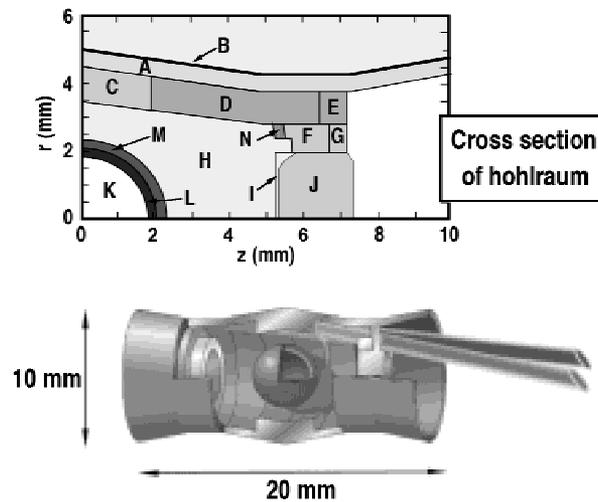


Fig. 1. Distributed radiator target design for heavy ion fusion (possible material substitutions are shown in parentheses; Callahan-Miller & Tabak, 2002).

can be done with a gas gun or an electromagnetic-based accelerator.

While the process details for the fabrication steps are not yet known (and a significant development program is still required), we can now outline the entire pathway from initial manufacture of materials to filling, layering, and injection of a high-gain target suitable for energy production from heavy ion driven inertial fusion. This outline of the process steps for HIF target supply is presented below.

2. TARGET PRODUCTION PROCESS STEPS

2.1. Target supply requirements and issues

The basic requirement for the TFF of an IFE power plant is to provide about 500,000 targets per day (at ~ 6 Hz) with precision geometry, and with precision cryogenic layered DT fuel. Target fabrication for inertial fusion is being investigated by a number of institutions throughout the world, including Russia (Koresheva *et al.*, 2001), Japan (Norimatsu *et al.*, 1999), China (Lin *et al.*, 2001), France, and the United States (Goodin *et al.*, 2001a). The feasibility of developing successful fabrication methodologies that can supply targets at the low cost required for economical energy production (about \$0.25/target, approximately 10^4 times less than estimated current costs) is an important issue for heavy ion driven inertial fusion.

2.2. Fabrication of spherical capsules

Targets for HIF include a CH polymer spherical shell (capsule) to contain the DT fusion fuel and to fix the fuel geometry. Density matched microencapsulation has been used in the laboratory to produce similar capsules from polystyrene (Norimatsu *et al.*, 1994). This fabrication step is relatively

well understood and demonstrated, although work remains to scale the process to larger batches and to increase product yields for IFE. An analysis and preliminary layout of a mass-production facility to produce polystyrene capsules has been carried out (Fig. 2). Initial estimates of the production cost for an “*n*th-of-a-kind” plant results in values of about 11 cents per capsule,^a leaving significant value in the total cost goal to manufacture and assemble the remaining target components (i.e., the hohlraum and its distributed radiators).

2.3. Permeation filling with DT fusion fuel

Filling of polymer capsules with hydrogen isotopes by permeation through the wall, removal of the excess DT after cooling to cryogenic temperatures (to reduce the capsule internal pressure and prevent rupture), and transport under cryogenic conditions has been demonstrated in the laboratory (Meyerhofer & McCrory, 2001; Goodin *et al.*, 1996). Estimates of the DT filling (and layering) time and models to predict its effect on tritium inventory in the TFF have been prepared (Schwendt *et al.*, 2003). A critical parameter affecting tritium inventory is the choice whether to fill the capsule prior to assembly into the hohlraum or to fill the capsule within the hohlraum. The void space within the hohlraum can result in up to $30\times$ more tritium inventory required during the pressurization step; this factor essentially requires filling prior to hohlraum assembly which, in turn, means that a cryogenic assembly step for the hohlraum is required. Using cryogenic assembly, the inventory models indicate that operating with less than ~ 1 kg tritium in the TFF may be feasible (Fig. 3).

^aIncludes estimates of the cost to fill the capsule with DT and to layer the DT (but does not include hohlraum and assembly costs).

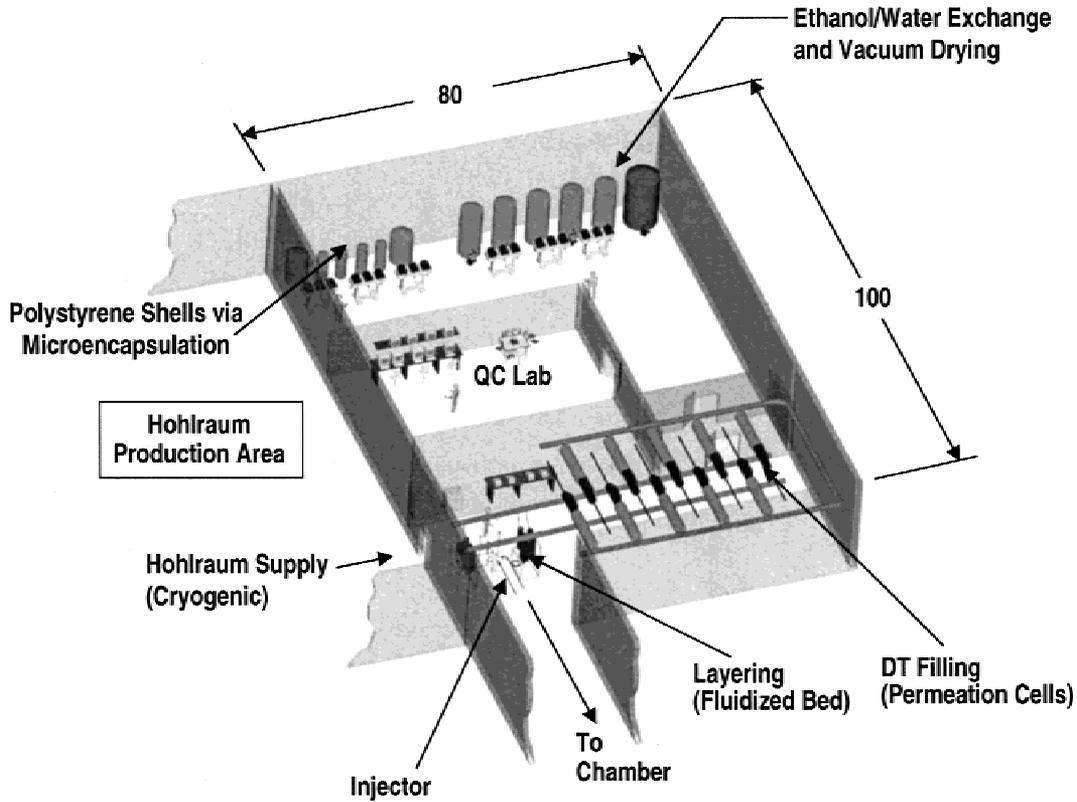


Fig. 2. Initial layout of a mass-production facility to produce 500,000 capsules per day (one component of the HIF distributed radiator target).

2.4. Layering of the DT fusion fuel

Layering (Hoffer & Foreman, 1988; Martin *et al.*, 1988), the process of redistributing the cryogenic DT fuel into a smooth uniform layer inside the ablator, has a critical effect on the performance (gain) of the target. Layering requires establishing an extremely precise ($\sim 250 \mu\text{K}$), uniformly spherical temperature distribution at the surface of the capsule. A cryogenic fluidized bed is being evaluated experimentally for the capability to provide this temperature environment. The basic concept is for the fluidized bed to rapidly randomize the targets yielding a very uniform time-averaged sur-

face temperature. Room temperature surrogates in place of hydrogen were used to provide a proof-of-principle demonstration of fluidized bed layering, and to gather initial operational data. Figure 4a shows surrogate (neo-pentyl alcohol) samples that were layered in a fluidized bed with injection of IR energy. Figure 4b shows an alternate concept of layering with the capsule assembled within the hohlraum. Thermal analyses have shown that in-hohlraum layering is possible. However, it will require careful control of hohlraum dimensions, alignments, and material properties to remain within the $250 \mu\text{K}$ temperature uniformity at the capsule surface. Layering in a fluidized bed would require very rapid (a few seconds or less) removal of the layered capsule from the bed, assembly into the hohlraum, and injection. In-hohlraum layering has the distinct advantage of allowing slower cryogenic assembly (i.e., prior to layering).

	HIF Target
Buckle Pressure	449 atm
Fill Time	2.8 hr
Tritium Inventory with beta-layering	0.57 kg
Tritium Inventory with beta-layering + IR	0.27 kg

- 6 shots per second*
- Void fraction – 5%
- Fill Temp – 27°C
- Cool time – 1/2 hr
- Evac time – 1 hr
- β layer time – 8 hr
- IR layer time – 2 hr
- Fill overpressures are 75% of buckle pressure

Fig. 3. Estimates of theoretical minimum tritium inventories for filling and layering of HIF targets indicate that very low tritium inventories can be obtained.

2.5. Fabrication of the hohlraum components and final assembly

The challenge of the HIF target that is unique for fabrication is its distributed radiators. Several of the low-density high-Z materials specified can be provided by metal doping of CH-based foams. Figure 5a shows electron micrographs of doped foams, confirming survival of the basic foam structure through the doping process.

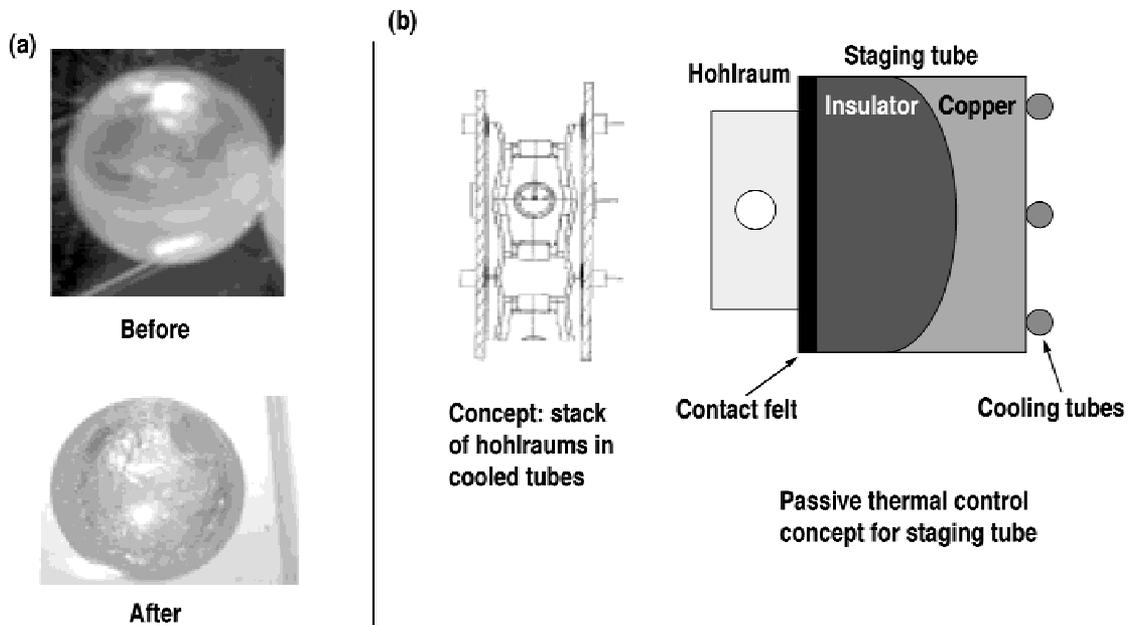


Fig. 4. Two layering methods for HIF targets appear to be feasible: (a) a cryogenic fluidized bed (a proof-of-principle experiment has been accomplished using a surrogate for hydrogen) and (b) in-hohlraum layering (thermal analyses indicate temperature control is feasible).

Several of the radiator components must be high-Z material only (no low Z). To fabricate these materials, a new process, high-pressure laser chemical vapor deposition (HP-LCVD), is being developed. This is a process that is rapid and thus amenable to production scale-up. Experiments will develop methods for depositing pure high-Z, low-density

materials. As illustrated in Figure 5b, a precursor molecule containing the high-Z element of interest is laser-decomposed to form lattices of high-Z, low-density material. Diffractive optics are used to generate an array of hot foci on an initial substrate, and the fibers are grown normal to the substrate by thermal decomposition of the precursor mixture. As the

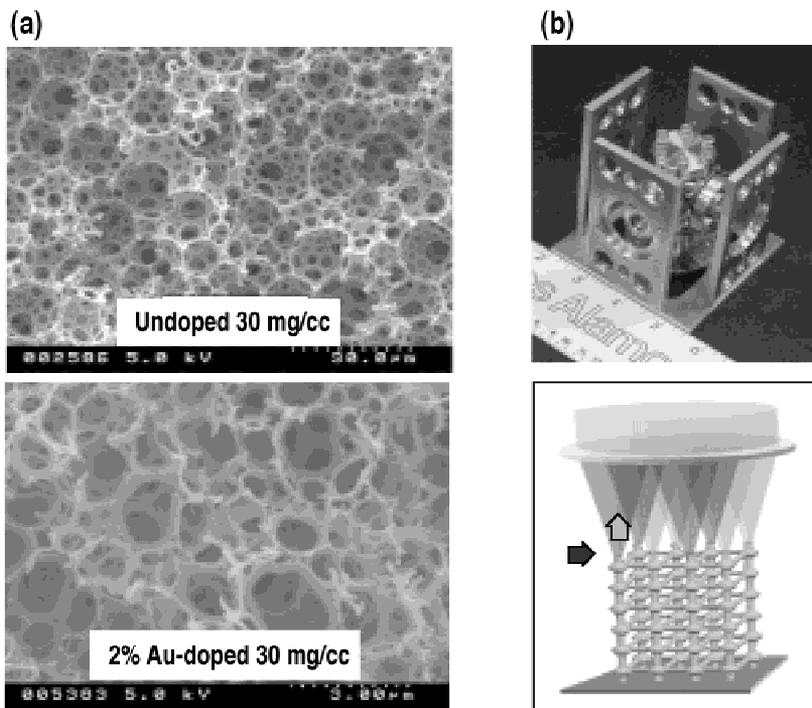


Fig. 5. Metallic foams for the components of the HIF hohlraum can be formed by (a) high-Z doping of low-density CH foams or (b) HP-LCVD (allows *in situ* deposition of low density high-Z materials).

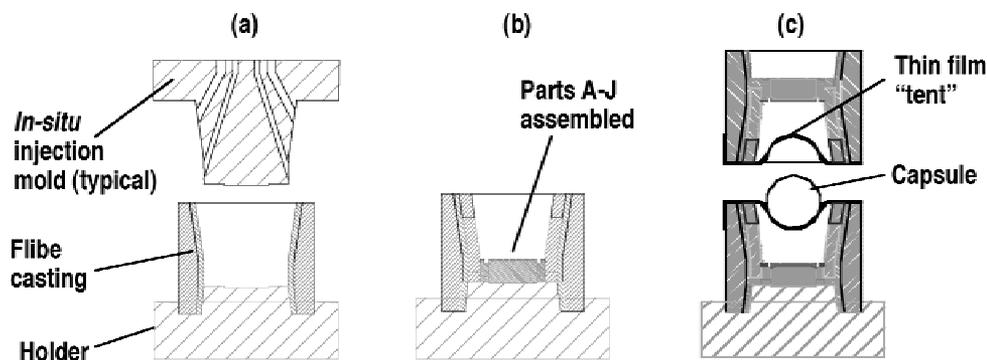


Fig. 6. Selected steps in the assembly process envisioned for the HIF distributed radiator target: (a) use of *in-situ* injection molding to form radiators, (b) completed half of hohlraum with Parts A through J in place, (c) final assembly with layered cryogenic capsule supported by thin films.

entire array is grown under computer control, the overall shape of the material can be varied at will, and (axial and radial) material gradients can be built into the lattice—simplifying the design and assembly of target hohlraums.

Assembly of the hohlraum is envisioned as follows:

1. A casting of Flibe^b (in two halves) is done to provide mechanical support for the target during handling and injection.
2. Sputter coating or “exploding wire” techniques are used to coat the inside of the Flibe casting with the high-density Au/Gd mixture (Part B in Fig. 1).
3. LCVD is used to produce the low-density metal foam (Part A) *in situ* in the hohlraum halves (this part requires high-Z material only).
4. The casting is placed into a holder for further processing (Fig. 6a).
5. The remaining components requiring high-Z only (Parts E, G, and J) are produced by *in situ* LCVD in the holder.
6. Remaining radiator components (Parts C, D, F, I, and N) are assembled in place after separate fabrication (or possibly injection molded *in situ* depending on material strength and ability to isolate components and prevent diffusion during molding) as illustrated in Figure 6a, b.
7. Thin films (e.g., Kapton) are placed over the two hohlraum halves to hold the cryogenic capsule in place (note that all steps through this point can be at room temperature where conventional adhesives can be utilized).
8. The capsule (Part M) is filled at room temperature in a high pressure cell via permeation of DT (Parts K and L) through the polymer wall, then cooled to cryogenic temperatures (to reduce the DT vapor pressure so excess external DT can be pumped away without bursting the capsule).

^b Flibe is a mixture of LiF and BeF₂ that is the coolant in the chamber, thus the choice for structural material.

9. The capsule is placed in a cryogenic fluidized bed to provide the uniform temperature environment required for layering (IR or microwave energy may be injected into the bed to speed the layering process and improve the ice surface finish).
10. The assembled hohlraum halves are cooled to cryogenic temperatures to receive the filled, layered capsule.
11. The final assembly of the hohlraum halves with the capsule take place, trapping the capsule in precise position between the thin films.
12. A thin film is placed over each end of the assembled hohlraum, trapping the He gas (Part H).

3. TARGET INJECTION

GA has designed and is currently assembling a 6-Hz experimental target injector that can accelerate and track either direct-drive targets or HIF indirect-drive targets (Fig. 7). The Flibe casting noted above provides structural integrity during injection (polymer inserts or rings may be used to reduce barrel wear due to contact with the Flibe). The thin film which was placed over the upstream end of the target hohlraum provides a surface for the propellant gas to apply force. Tracking system requirements for HIF are to inject targets at high velocity (≤ 170 m/s), with a positional repeatability of less than ± 5 mm,^c and track the targets to allow alignment of the driver beams with the target to less than about ± 200 μ m. A gas gun provides the target acceleration. The propellant gas removal system removes most of the propellant gas to minimize the effect of the remaining gas on the heating and trajectory of the targets. Target position detectors will optically sense the target’s location as it passes. This target position data will then be used to predict the time and place that the targets will reach the chamber center. In addition to design of this experimental system,

^c Desired positional values may be less than ± 5 mm to minimize the size of Flibe channels for beam steering, thus reducing the shielding needed outside the chamber.

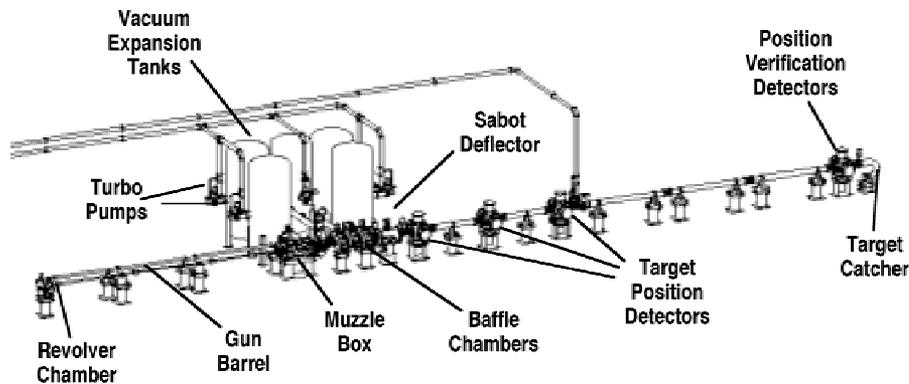


Fig. 7. Schematic layout of experimental target injection and tracking system designed to show accuracy of placement and position prediction for both direct drive and HIF targets.

modeling of the target injection process has been conducted to show survival of the cryogenic DT during injection (Goodin *et al.*, 2001b). A backup system based on an electromagnetic acceleration method is also being evaluated.

4. SUMMARY AND CONCLUSIONS

Supplying $\sim 500,000$ targets per day at a cost that allows economical energy production is a key issue for inertial fusion. Targets designs for heavy ion driven inertial fusion with suitable gain for energy production have been proposed, reviewed, and published. Research programs for fabrication and mass production of these targets are underway. An evaluation of the current status of these research programs has resulted in an outline of potential processes for manufacture of the components, filling with DT fuel, cryogenic layering, assembly, and injection of these targets. While a significant development program is still needed to bring these targets to reality, this article outlines, for the first time, an entire set of potential manufacturing processes for a HIF target supply.

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