Design and Fabrication of Foam-insulated Cryogenic Target for Wet-wall Laser Fusion Reactor

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Abstract. A foam insulated cryogenic target was proposed for use in a future laser fusion reactor with a wet wall. This scheme can protect the solid DT layer from melting due to surface heating by adsorption of metal vapor without significant reduction in the target gain. Design spaces for the injection velocity and the acceptable vapor pressure in the reactor are discussed. Basic technology to fabricate such structure was demonstrated by emulsion process. Concept of a cryogenic fast-ignition target with a gold guiding cone was proposed together with direct injection filling of liquid DT.

1. Introduction

In a future laser fusion reactor, fuel pellets are injected into the firing position at a repetition rate of a few Hz. Wet wall scheme of the reactor chamber is one of the attractive one to protect the first wall from ablation due to the energetic ions from the burning plasma. [1] After laser irradiation, the vapor pressure in the reactor camber rapidly rises to several hundred Torr and then decreases toward the initial value according to cool down of the inner surface of the first wall. The vapor pressure and the temperature at the injection of the target are estimated to be 0.05 Torr, 650 ^{o}C in the conceptual design reactor KOYO. [2] The target for conventional central ignition mode is usually a cryogenic target with 4-mm-diameter, 300-μm-thick, spherical hollow solid DT inside a thin gas barrier. [3] Such cryogenic target with thin ablator would be hard to survive due to strong surface heating caused by adsorption of metal vapor in the reactor. [4] Because of the large latent heat of condensation of metal vapor, almost all molecules colliding with the cold target surface condense on the surface. As the results, the cryogenic layer begins to melt before it reaches the firing position and the melted portion degrades the spherical symmetry of the pellet because of its change in the volume.

To prevent the melting, we propose a foam-insulated target that has a middle density (0.05 to 0.25 g/cc) foam layer. Use of a low-density foam layer to mitigate the Rayleigh-Taylor instabilities is reported elsewhere. [5] Requirements for the foam layer are a) appropriate thermal insulation, b) minimum influence on the gain, c) sufficient mechanical strength for the acceleration, and d) capability of mass production.

2. Central Ignition Target

2.1 Influence on Gain

Influence of the foam layer on the gain was numerically simulated with ILESTA_1D[6]. Figure 1 (a) is a standard cryogenic target for ignition experiment and Fig. 1 (b) is a foam

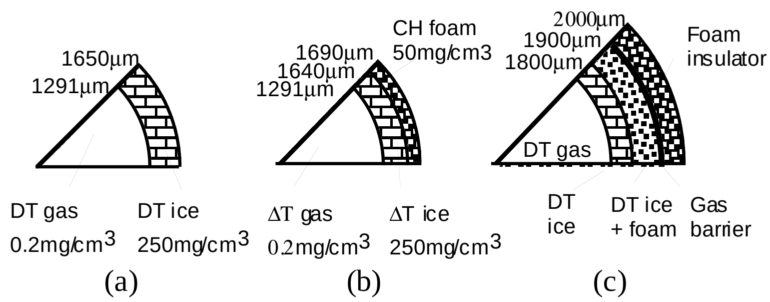


FIG. 1 Model cryogenic target (a), foam insulated target with the same mass (b) and reactor class target (c).

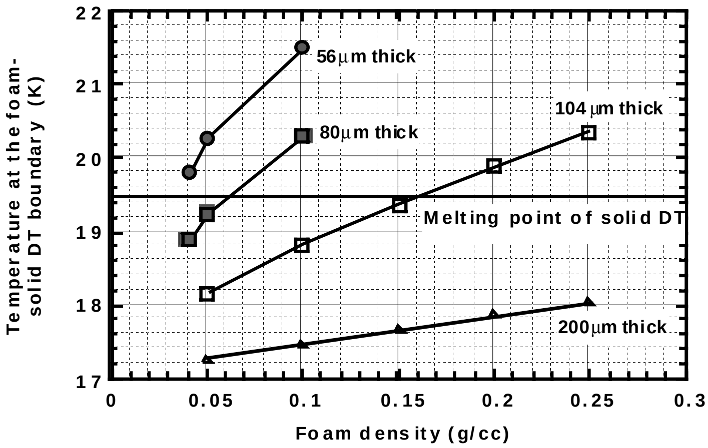


FIG. 2 Temperature at the foam- solid-DT boundary. The vapor pressure, the radius of chamber, and the injection speed are 0.05 Torr, 5 m and 300 m/s, respectively.

insulated cryogenic target. The total masses of each target are the same. These targets are irradiated by 1.2 MJ, 3ω laser. The pulse length was 12 ns. The temporal intensity is adjusted to get the maximum yield. Obtained gains are 35 for (a) and 40 for (b), respectively. These results indicated that coating of foam layer seems possible without significant reduction in the gain.

2.2 Insulation Effect

To evaluate the insulation effect, we estimated thermal load on the injected pellet by assuming 100% adsorption of impinging metal vapor (Pb instead of $Li_{17}Pb_{83}$ for simplification). When the vapor pressure of metal in the chamber is 650 ^{o}C, 0.05 Torr, the average thermal load on a pellet injected into the chamber at a speed of 300 m/s is 8 W/cm^2 that is larger than that of blackbody radiation from the chamber wall.

To know the lifetime of a cryogenic target shown in Fig.1(c), temporal change of the temperature at the boundary of the solid DT layer and the foam insulation layer was calculated. Since the gas barrier is usually less than several microns, the influence of the gas barrier was ignored for simplification. The calculation includes spectral transmittance of the deposited lead layer, the spectral transmittance and the absorption of polystyrene foam layer and the spectral emissivity of the deposited lead layer. In this calculation, reported thermal conductivity for a bubble type foam structure was used. [7] Since we have no data on the heat conductivity and the specific heat of solid DT, we used those of solid deuterium instead.

Calculated temperatures at the boundary of the polystyrene foam and the solid DT layer are shown in Fig. 2 when the pellet arrived at the center of 5 m diameter chamber. In this calculation, the initial temperature of solid DT layer is assumed to be 17K. This result indicates that a 80-µm-thick, 50 mg/cc foam layer can protect the solid DT layer form melting.

2.3 Design Space

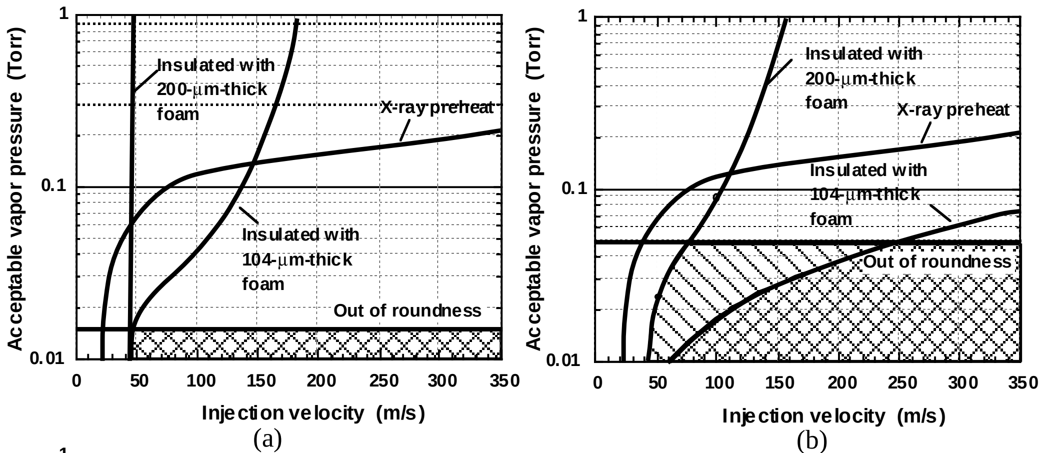
Design spaces of the injection velocity and the vapor pressure in the wet walled reactor were calculated including the gain reduction due to preheat of the fuel by x-rays from the deposited lead layer, the out-of-roundness degradation due to nonuniform deposition of the lead and the melting of the cryogenic layer. The results are summarized in Fig. 3 where design spaces for 4-mm-diameter, targets with a 50 mg/cc (a), 150 mg/cc (b) and 250 mg/cc (c) foam insulation layer are shown, respectively. The targets with lower density foam are intended to reduce the RT instabilities and the target with the 250 mg/cc (density of solid DT) foam layer is expected to have no RT instabilities at the solid DT / foam boundary.

Our numerical simulation indicated that the average thickness of lead layer deposited on the surface during the flight to the firing position must be less than 0.1 μm to keep the target gain>100. This result is indicated by a curve named x-ray preheat in the figures. After the target is injected into the reactor, the vapor primary deposits on the leading side of the target. Even if the target is sufficiently spun around an axis perpendicular to the flight direction, the thickness of the deposited layer takes its maximum value at the equator. As the result, the out-of-roundness increases with the deposition of lead. Nonuniform deposition of heavy lead on the right foam layer would be new seeds for RT instabilities. For simplification, we converted the thickness of the lead layer to the thickness of the foam using $\delta r_{foam} = \rho_{lead}\ \delta r_{lead} / \rho_{foam}$. The result is compared with the extrapolated NIF goal assuming linear growth of RT instabilities. Since the out-of-roundness is determined only by the lead in a column along the flight path to the center of reactor, it is independent on the injection velocity and given by horizontal lines in the figures. A design space for a 104-μm-thick foam target is indicated by cross hatch and an additional area for 200-μm-thick foam target is shown by oblique hatch.

When the density of the foam is 50 mg/cc, insulation performance is sufficient to prevent the solid DT layer from melting and the out-of-roundness is the most critical issue because of the large density difference between the foam and lead. The lower limit for the injection velocity is given by the melting of the cryogenic layer due to the thermal radiation. So the dependence on the foam thickness and the density is small. When the thickness of the foam is 200 μm, it provides wide design space for the vapor pressure.

3. Fast Ignition Target

Detailed designs of the fast ignition target for break-even experiments and the reactor are now in progress. Figure 5 (a) is the current idea for a target for ignition and burn experiment called the FIREX project. We are going to use foam method to make a uniform solid fuel layer. This target consists of a low-density foam shell coated with a gas barrier and a cone to allow direct heating of the compressed core by the PW laser. This cone prevents refraction of the PW laser by expanding low-density plasma. We are going to use foam technique because required cooling uniformity is not so important as that for beta layering and IR heating. The fuel is loaded into the void through a gas feeder pipe at a cryogenic temperature although



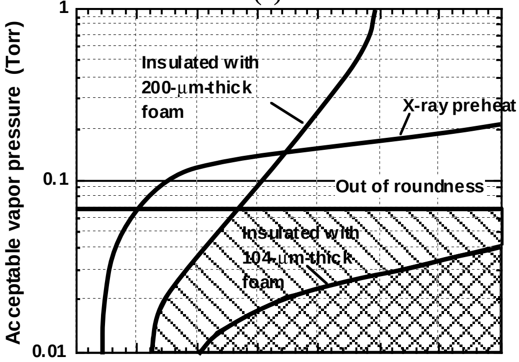
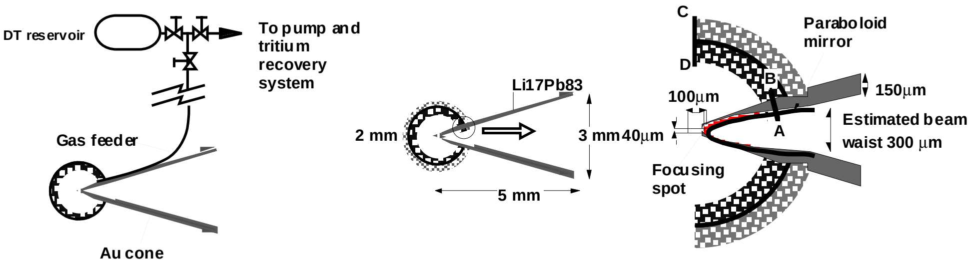
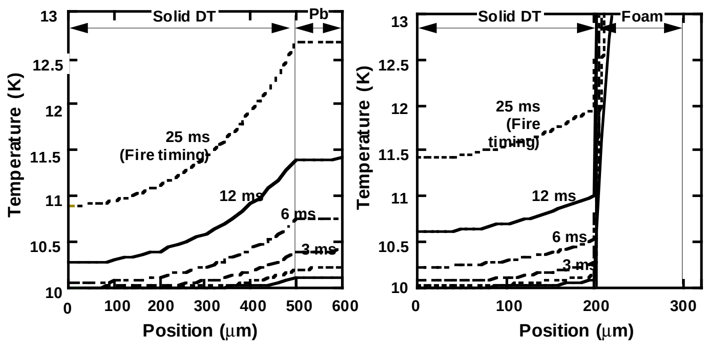


FIG. 3 Design spaces for 4-mm-diameter, targets with a 50 mg/cc (a), 150 mg/cc (b) and 250 mg/cc (c) foam insulation layer. The cross hatched area is the design space for a target with 104 μm thick foam layer and the oblique hatched area is an additional one for 200-μm-thick foam.



(a) (b)

FIG. 4 Fast ignition target for FIREX experiment (a) and for reactor (b).



(a) (b)

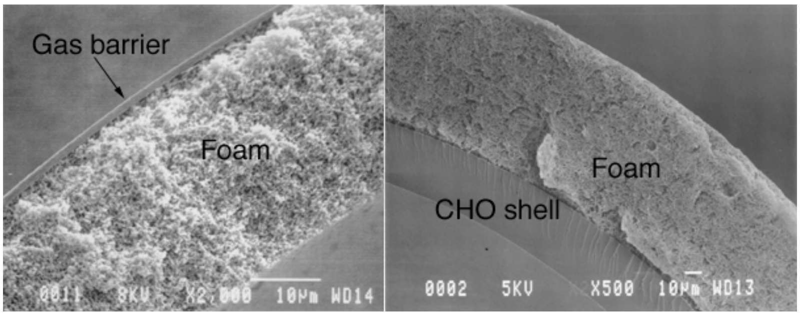
FIG. 5 Temperature profile along the lines A-B and C-Din Fig. 4 (b)

normal targets are loaded by diffusion across the barrier at room temperature. The liquefied fuel penetrates into the foam leaving a void inside. The initial temperature is 10 K to reduce the density in the void. Higher vapor density in the void reduces the density of compressed core. The diameter of the capsule ranges in 500 μm to 2 mm, depending on the laser energy for compression.

Figure 4 (b) is a cross section of the fast ignition target for reactor use. Basic structure is the same as that for FIREX but the capsule is coated with a foam insulation layer. Typical diameter of the capsule is 2mm. The dimension of the cone is 3-mm-diameter, 5-mm-long and the thickness of the wall at the top is 10 μm. The material is the same of that for the first wall of the reactor. We are considering two types of the cone, both aiming to use the cone as a focusing device. One is a conventional straight cone and the other has a paraboloid mirror inside. Because of the refraction limit of the PW laser, estimated focusing spot of the beam at the reactor center is 300 μm. We had to focus the beam to the 50-μm-diameter compressed core.

The critical issue of this target is melting of solid DT at the cone. In the first ignition target, the thermal load is concentrated on the cone while the central ignition target is dispersed on the whole surface due to spin. We calculated the temporal temperature profile along the line A-B in Fig. 4(b). The resultant temperature profile at the cone/solid DT is shown in Fig. 5(a). The initial temperature, the injection velocity, the radius of chamber, the vapor pressure and the vapor temperature are 10K, 200 m/s, 5m, 0.05 Torr, and 650 ^{o}C, respectively. Because of large thermal conductivity, the cone provides no insulation effect but the temperature at the boundary of solid DT and lead cone is 12.2K, far below the melting point of solid DT. This is due to the large heat capacity of the cone. Since there is no gas barrier on the inner surface of solid DT, sublimation of solid DT contacting with the cone would be new issue.

The temporal temperature profile along the line C-D in Fig. 4(b) is shown in Fig. 5(b). The



(a) (b)

FIG. 6 Foam shell with gas barrier (a) and CHO shell coated with foam layer (b)

initial conditions are the same as before but the foam density and the thickness are 250 mg/cc and 96 μm, respectively. Since the cone works as a wake shield, the heat load at the side depends on the static component only that is much less than that on the leading side (i.e. cone). The temperature increase during the flight to the center is only 0.7 K.

4. Status of fabrication

A modern high gain target design needs 4-mm-diameter, 300-μm-thick foam shells coated with gas barrier and insulation layer (see Fig. 1(c)). We experimentally demonstrated coating of a gas barrier on foam shells (Fig. 6 (a)) using emulsion process followed by interfacial polycondensation technique and coating of a foam-insulation-layer on shells (Fig.6 (b)) by emulsion process. The detailed technique of the gas barrier coating is written elsewhere.[8]

Coating of foam insulation layer on a plastic shell was carried out as follows. After plastic shells filled with water are completed, they are immersed in a new oil solution containing monomers (Trimethylolpropan trimethacrylate, TMPT) to synthesis the foam layer. The solution with capsules is poured into a stirred bath filled with a 5% poly(vinyl alcohol) (PVA) solution to coat the capsules with the oil solution. By polymerizing the monomers in the oil phase, three dimensional networks of polymers are formed. Then, shells are dried in supper critical drying method using liquid carbon dioxide.

Although the diameters were less than 1 mm, basic technologies for mass production are demonstrated. We recently extended these technologies to fabricate reactor-class shells whose diameters range in 3-5 mm. Result of the first trial was promising.

5. Summary

A foam insulated cryogenic target is proposed for use in a future laser fusion reactor with a wet wall. Our simulation results indicate that foam-insulated cryogenic targets for both central ignition and fast ignition can be delivered to the firing position without melting. Sublimation of solid DT contacting with the cone would be the next issue. Emulsion process seems to be a powerful candidate for mass production of such target.

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