Study on possible fuel layering sequence for FIREX target

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Abstract. A new procedure of fuel layering for the Fast Ignition Realization Experiment (FIREX) target is proposed. A conical laser guide heating technique was experimentally demonstrated in principle as the followings. It employed the target consisting of a polystyrene (PS) shell, a fill tube and a conical laser guide. At first, liquid fuel was fed into the shell and existed around the conical laser guide because the surface tension of the fuel must cause it. Then, it was solidified. The laser light provided a heat source to the conical laser guide so that the solid fuel was moved to the other interior of the shell. This process resulted in missing solid fuel around the conical laser guide. To fill the vacant space, liquid fuel was added as temperature was raised to the melting point. After the liquid fuel addition, temperature was lowered to the solidification point again. During this process, most of the solid fuel could survive.

1. Introduction
Development of a cryogenic target is one of the important issues for the FIREX project. A foam shell method [1] is a possibility. Its layering process must be modified to the FIREX target based on its configuration. Collaboration research by the Institute of Laser Engineering (ILE), Osaka University and the National Institute for Fusion Science (NIFS) has been conducted to develop it. However, some issues: a foam shell fabrication, residual voids in a foam-solid fuel layer, characterization of the layer and so on are still remaining. The foam shell with a 500 µm diameter has been developed at ILE [2]. However, more several years should be required to complete it. The characterization has also been studied using a dummy foam target [3]. We preliminary demonstrated the system to characterize the layer of solid fuel soaking the foam material. Thus, the development of the foam shell method strongly depends on the foam shell fabrication. To ensure supplying solid deuterium (D₂) fuel targets within several years, alternative methods should be considered.

To date, applying volumetric heating method has been studied for the FIREX target [4]. Assuming a D₂ and normal hydrogen (n-H₂) mixture fuel, the ortho-para conversion of n-H₂ was considered as the heat source. Its heating effect was tested using n-H₂ only. Solid H₂ could be moved from the warmer to the cooler part in a shell. The ortho-para conversion, however, can generate much lower heat power than other heat sources such as the beta-layering for a DT fuel [5] and the infrared heating for a D₂ fuel [6]. Therefore, longer duration is required to complete fuel layering, which might be impracticable. Furthermore, according to calculations, the target temperature profile was not spherical..
isotherms because the conical laser guide played a role of a heat exchanger. Target temperature control is essential. On the other hand, the infrared heating has been studied for the OMEGA target [7]. Forming D₂ fuel targets for central ignition was demonstrated. This technique is specialized to the target with spherical symmetry. Thus applying the volumetric heating process to the FIREX target is worth considering, whereas it must be more complicated than that to the OMEGA target.

Conical laser guide heating is proposed as a new heat source. This external heat source has a possibility to supply sufficient energy for fuel redistribution and should provide a simpler layering procedure than the conventional heat sources. The new idea is experimentally demonstrated in principle using a dummy target.

2. Proposed layering procedure by conical laser guide heating technique

We propose the new layering procedure applying the conical laser guide heating technique. Figure 1 shows the schematic of the sequence. (Step 1) Liquid fuel is filled around the conical laser guide owing to its surface tension and then solidified. (Step 2) Solid fuel moving requires temperature gradient in the shell. We employed the laser heating technique as an external heat source. The conical laser guide is irradiated with laser light to provide a heat source. The solid fuel would sublime around the conical laser guide and condense somewhere. In natural convection cooling, the shell surface has uniform heat transfer. Therefore, the solid fuel could uniformly redistribute to the other interior of the shell. This process results in missing a solid fuel around the conical laser guide. (Step 3) After the redistribution, as temperature increases to the melting point, additional liquid fuel is supplied to the vacant space. This process time is as short as possible so that most of the solid fuel can survive. The Steps 2 and 3 are repeated until the completion of fuel layering.

![Figure 1. Proposed layering sequence applying the conical laser guide heating technique. During the sequence, the target is cooled by gaseous helium with suitable temperature for each step.](image)

3. Demonstration of the new technique

3.1. Experimental details

Figure 2 shows the photograph of the dummy target consisting of a PS shell, a gold conical laser guide and a glass fill tube. A 2 mm diameter shell was employed for easy observation of the layering processes. The conical laser guide was attached vertically to the shell. The target was put in the dedicated apparatus [8] and cooled by ambient gaseous helium (GHe) in a target chamber with viewing windows. A temperature controllable thermal shield was equipped in it. To heat the conical laser guide through a view window, a 5 mW He-Ne laser was applied. The laser light had too much energy to transmit moderate heating power on the conical laser guide. Therefore, it passed through two
neutral density filters of ND20 and ND30 in series to reduce its energy. A shutter was utilized to intermittently irradiate with the laser light. Open and close time were 7 and 5 sec, respectively. As a surrogate fuel, n-H\textsubscript{2} was used. Its ortho-para conversion might become a volumetric heat source. It was experimentally confirmed that the effect was negligible small.

![Figure 2. Dummy target with PS shell.](image)

3.2. Layering demonstration
The new technique was experimentally demonstrated in principle. Figures 3 show photographs on each step in the sequence corresponding to that in Figure 1. To supply liquid H\textsubscript{2} (LH\textsubscript{2}), the shield temperature was controlled at 13.40 K, which was not equal to the GHe and target temperatures. Gaseous H\textsubscript{2} (GH\textsubscript{2}) pressure was increased across the saturated vapour pressure and LH\textsubscript{2} started to appear around the conical laser guide. Its supply was stopped just before the meniscus was inverted by gravity. The LH\textsubscript{2} layer should be contiguous around the shell. Then, the temperature was lowered to 13.20 K; the transition to a solid state was occurred. After the solidification, crystalline solid H\textsubscript{2} was observed as shown in figure 3(a). To ensure the solid state during the laser heating process, the temperature was set at 13.10 K. Then the conical laser guide was being heated. The photograph of the first Step 2 was missed; therefore, figure 3(b) represents the second laser heating process after the first fuel addition. Solid H\textsubscript{2} was forming a uniform layer except for around the conical laser guide in figure 3(c). To add LH\textsubscript{2} to the vacant space, the temperature was raised to the melting temperature of 13.40 K; after LH\textsubscript{2} addition, lowered to 13.20 K for solidification. During this process, most of the solid H\textsubscript{2} could survive. Figure 3(d) shows successful LH\textsubscript{2} addition. This process has another function that the solid surface is made smooth. The solid layer in figure 3(d) has a smoother surface than that in figure 3(c). If the fuel quantity does not meet the specification for a laser experiment, the sequence of Steps 2 and 3 is repeated. Eventually, a thick layer was formed as shown in figure 3(e). In this case, LH\textsubscript{2} was added four times and the whole process required within 8 hours. Thickness of the solid layer is 132–223 \textmu m. Conspicuous variation is beside the conical laser guide, which might be caused by the surface energy difference in LH\textsubscript{2} addition. The inserted fill tube and applied glue must make the surface energy non-uniform. If the thinnest and thickest thicknesses, both locating around the conical laser guide, are ignored, the variation is reduced to 155–192 \textmu m. Defects on the interior surface are also estimated at the maximum of ~30 \textmu m. This demonstration does not satisfy the required specification on the FIREX target at all. However, the conical laser guide heating technique has the possibility to realize a uniformly thick layer for a non-spherical symmetric target.

![Figures 3. Photographs on each step corresponding to that in figure 1.](image)

4. Calculation
The temperature distribution during the laser heating process (Step 2) is roughly evaluated using the ANSYS code. Steady state condition is considered to simulate maximum temperature raise. The 2D axisymmetric model is shown in figure 4. Ambient GHe temperature is assumed at 13.10 K where comes from the experiment. Uniform surface heat transfers of 23.6x10^{-6} W/mm²K for the shell and 0.44x10^{-6} W/mm²K for the laser guide are applied. Radiation from room temperature and the latent heat of sublimation are not considered. The conical laser guide is irradiated by the laser light with the heat flux of 31.7x10^{-9} W/mm², which is evaluated according to the laser energy and its frequency, the irradiating area and the absorption coefficient of gold.

Figure 5 shows the calculated temperature profile. The temperature gradually decreases from the conical laser guide to the shell bottom. The difference of ~0.7 mK is created in the solid layer. It must be enough for the solid fuel to move from the warmer to the cooler part. Compared to the melting temperature of 13.20 K from the experiment, the calculated maximum temperature of 13.102 K is much lower. The sublimation-condensation process was obviously below the melting temperature.

Figure 4. 2D axisymmetric model of target. Figure 5. Temperature profile in laser heating

5. Summary
The new technique of the conical laser guide heating was proposed, which employs no volumetric heat source such as the IR heating. Fuel layering was experimentally demonstrated in principle. It has the possibility to realize a uniformly thick layer with a D₂ fuel for the FIREX target.

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