21st IAEA Fusion Energy Conference
Chengdu, China, 16 - 21 October, 2006

IAEA-CN-149/ IF/P5-1

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NIFS-863 Oct. 2006

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**Abstract** The Fast Ignition Realization EXperiment (FIREX) project was launched at the Institute of Laser Engineering (ILE), Osaka University. Key technologies are developments of high-energy lasers and solid fuel targets, also called a cryogenic target. ILE and the National Institute for Fusion Science (NIFS) started a cooperative study on the target in 2003. It has a unique appearance designed for the project. To realize its specification, a foam shell method is applied as a fuel layering technique. Subjects of the target development are fabrication of a foam shell, assembling the foam shell and other parts to form the target, and fuel layering. In this paper, accomplishments and some remaining issues of the target development are described.

## 1. Introduction

The program of the FIREX project is underway at ILE, which comprises two phases: FIREX-I and FIREX-II. There are two key technologies to execute the project: developments of high-power lasers and a cryogenic target. For FIREX-I, the GEKKO XII of a compression laser with 10 kJ/2 ns is going to be applied; and the Laser for Fusion EXperiment (LFEX) of a heating laser with 10 kJ/10 ps is under construction. To achieve ignition and burning in FIREX-II, both lasers will be upgraded. The target of the FIREX project has a new and unique design which have been proposed by ILE. Target specification will be modified in proportion as laser power for each phase. This paper focused on the target development for FIREX-I.

So far, some methods as fuel layering technique: beta-layering [1,2], plasma heating [3] and so on, have been established for a cryogenic target for the central ignition experiment. Their methods are based on redistribution of solid fuel after feeding to the shell and, therefore, can be utilized basically for the spherical target. A non-spherical symmetric target is going to be applied for FIREX and an applicable layering method should be studied. In the case of a foam shell method, fuel layering is controlled by capillarity of liquid fuel in a foam shell as a fuel supporting material. Therefore, the final fuel layer formation depends on the quality control of foam shell fabrication. This method can be only possibility of fuel layering technique for the FIREX project.

Subjects of the target development are fabrication of the foam shell, assembling the foam shell and other parts to form the target, and the fuel layering technique. Difficulty of the foam shell fabrication comes from its small size of 500 µm in diameter. The shell must have a thin foam layer with a high uniformity and a low density. Furthermore, the technology to drill a hole for a conical laser guide and a fuel feeder in the shell has to be established. Fuel layering in a non-spherical symmetric target such as the foam shell target for FIREX has not been studied yet, and uniform fuel layer formation and fine fuel-quantity control are expected to be challenging.

Collaboration to develop the target between ILE and NIFS began in 2003. ILE, responsible for the foam shell target fabrication, has developed a foam material, and the foam shell target is being fabricated. At NIFS, the apparatus for the off-site demonstration of the fuel layering process has been developed; and the foam shell method as a fuel layering technique is being tested. In this paper, accomplishments and some remaining issues of the target development are described.

## 2. Foam shell method for fuel layering

The target, called the foam target, has a unique appearance (see FIG.1.). It consists of three parts: a foam shell, a conical laser guide, and a gas or liquid feeder. The foam is low-density porous plastic, which covers inner surface of the shell as a supporting material of the fuel. To prevent gas leak, a plastic gas barrier parylene coats the shell. The conical laser guide for guiding the heating laser to the core plasma, which is made of gold, is partially inserted into the shell. To directly supply the fuel, the gas or liquid feeder made of glass with 30/10 μm outer/inner tip diameters is connected to the shell.

The foam shell method is the only candidate of fuel layering technique. The fuel layering procedure is expected to be easier than that of the others because of no redistribution process. The target is cooled down close to the triple point of the fuel. The liquefied fuel is fed into the shell though the feeder and is soaked up by the foam in terms of capillarity. After regulation of the liquid fuel quantity, the temperature is controlled at less than the triple point and the fuel is solidified. Then, the characterization of the solid fuel layer follows. Finally, an ideal cryogenic target would be formed.

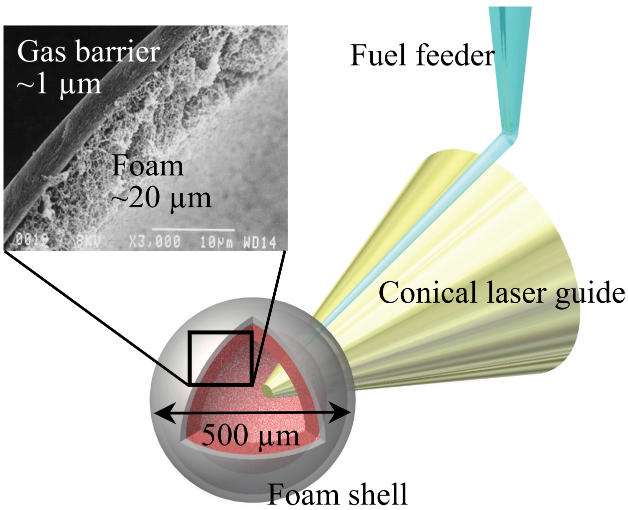
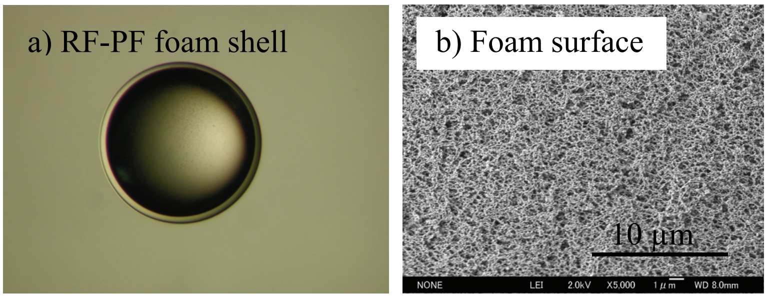



*FIG. 1. Foam target for FIREX-I.*

## 3. Fabrication of the foam shell target

The foam shell fabrication is one of most important issues in FIREX. The foam material must be an ultra low density (~10 mg/cm$^3$) with high uniformity for ideal implosion. Furthermore, the characterization of the fuel layering by optical instruments requires transparency in the visible




*FIGs. 2. RF-PF foam shell.*

region. A resorcinol /formalin - phloroglucinolcarboxylic acid /formaldehyde (RF-PF) shell has been successfully developed (see FIGs. 2.). Details of the foam shell fabrication method were reported in reference [4, 5]. It has a radius of 252±0.3 μm with a thin foam layer of 19.3±1.3 μm. However, the density of the foam layer was ~100 mg/cm$^3$, which is still higher than the required density. The foam shell fabrication method is going to be modified to realize the specification of FIREX.

The target assembling technique has been developed. To attach the conical laser guide and the gas feeder, the shell was drilled by laser beam machining. FIG. 3. shows the shell surface after the machining. The hole with required accuracy could be opened without damage on the shell by precise laser power control and repetitious laser irradiation. FIG. 4. shows the assembled foam target. The conical laser guide and the feeder were inserted into the hole, and the gap was sealed with epoxy resin. After that, the shell surface was coated with the parylene membrane. The minimum glue fillet should be filled on the shell, and the work depends on the skill of a technician at present. The shell is not enough transparent for visual observation of the fuel layering. Its low transparency might be caused by the coating process of the parylene.

The differences of thermal contraction among the materials are related to thermal stress and would damage the target. Therefore, the validity of the target was confirmed at cryogenic environment; the epoxy resin was useful as the adhesive to assemble the target. The detail of the validity check on target assembling was reported in reference [6].

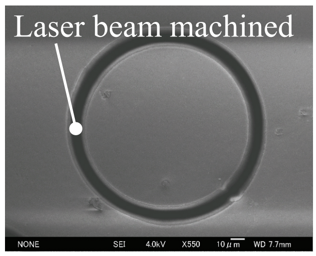



*FIG. 3. Foam shell with a hole.*

## 4. Apparatus for the demonstration of the foam cryogenic target

The apparatus for the off-site demonstration of the fuel layering process is composed by the cryogenic and the optical systems as shown in FIG. 5. The minimum requirements of the apparatus are that controllable temperature at the target can is less than the triple point of $H_2$ and the vibration on the systems is attenuated as small as possible for the target inspection.

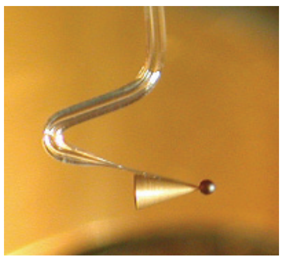


*FIG. 4. Assembled RF-PF foam shell target.*

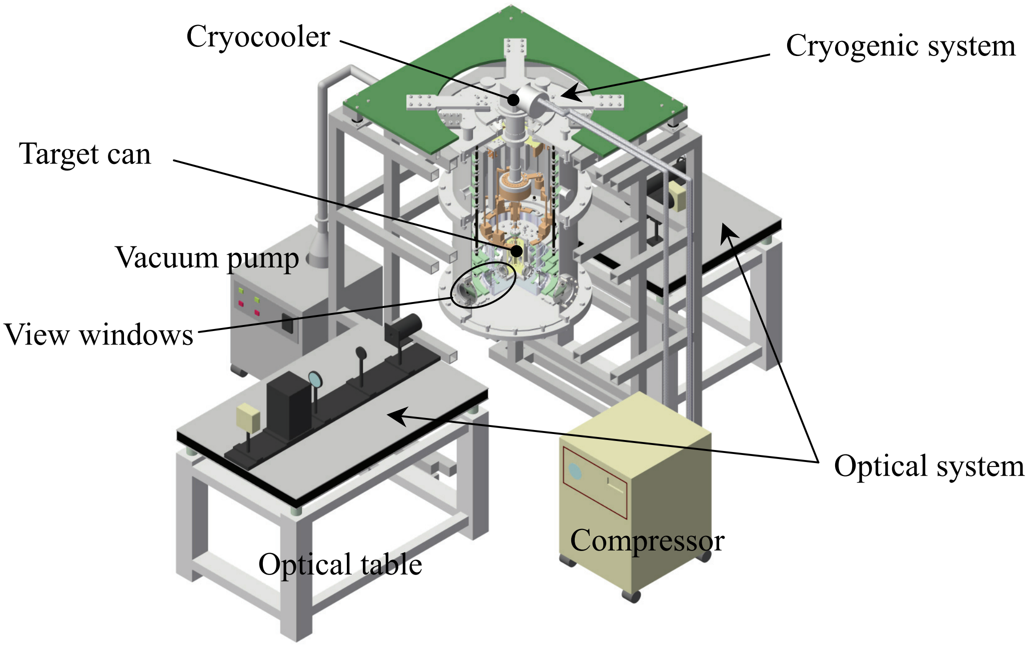



*FIG. 5. Apparatus for the off-site demonstration of the fuel layering.*

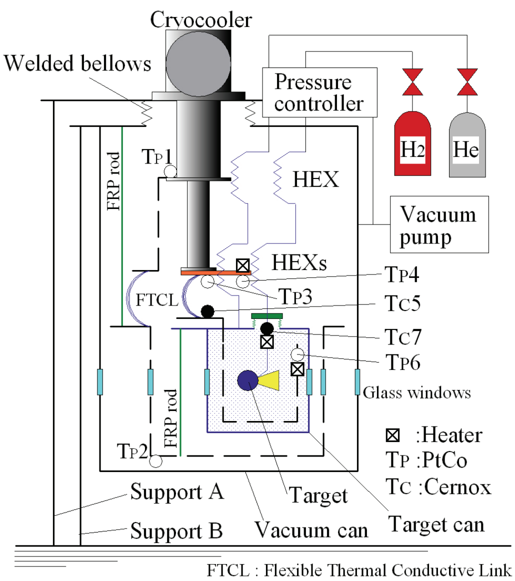



*FIG. 6. Flow diagram.*

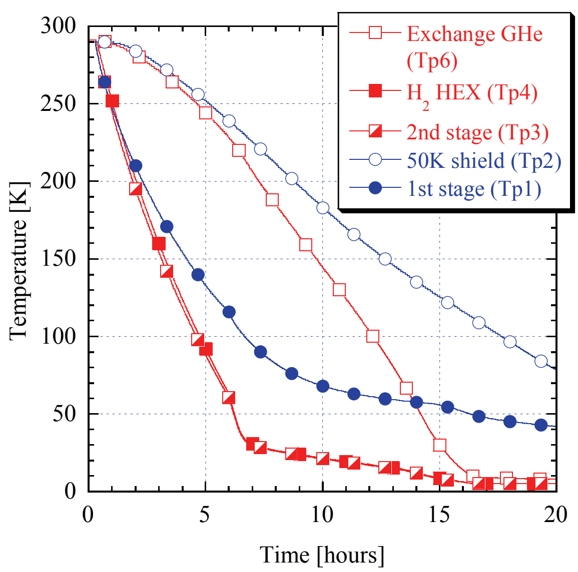



*FIG. 7. Cool-down curve.*

To observe the fuel layering process, two kinds of instruments: the Mach-Zehnder interferometer with a light sauce of a He-Ne laser and a CCD camera with the 200 mm Micro-Nikkor (Nikon) lens were arranged. A shearing interferogram can be observed using the interferometer. They were installed on optical tables with vibration isolators. Both pictures of a real image and an interference pattern can be taken at the same time.

The cryogenic system was designed and fabricated for the off-site fuel layering test. Its details were already reported in reference [7]. At that point, the achieved temperature of the system was 10.9 K because of the heat leak through viewing windows at 50 K shield without an infrared cut filter. Furthermore, the temperature distribution along the gas flow was not suitable for the fuel layering test. To improve the cool-down performance, the cryogenic system was modified as shown in FIG. 6.: an independent heat exchanger for fuel cooling with fine temperature control was added at $2^{nd}$ stage of the cryocooler, and glass view windows coated with an infrared cut filter were installed at the 50 K shield. The cool-down curve after the modifications is shown in FIG. 7. The lowest temperature was improved from 10.9 K to 7.0 K. Vibration control is also the important factor of the apparatus. The laser displacement sensor with 0.5 µm accuracy, LK-G155 by Keyence Corporation, was used to measure the relative throb of the target itself and the interferometer. It was confirmed that the relative throb was attenuated below 4~5 µm.

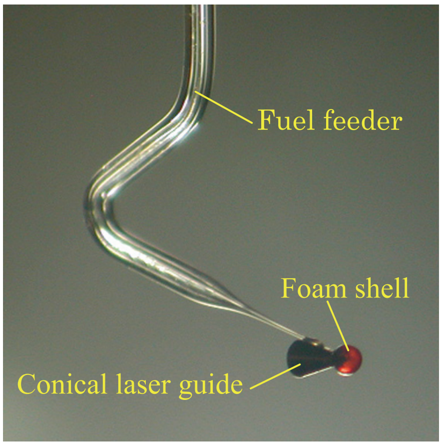



*FIG. 8. A dummy foam target.*

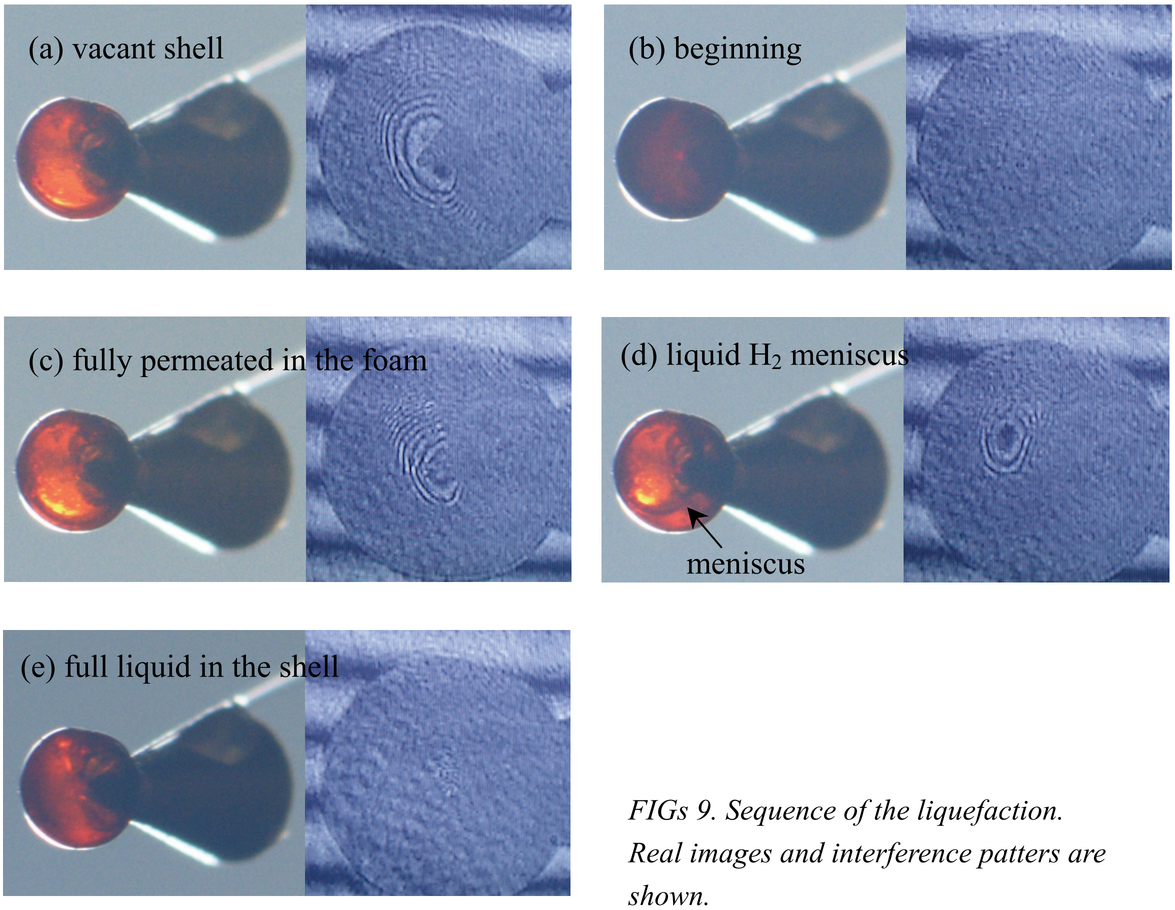
### 5. Fuel layering of a dummy foam shell target

### 5.1. Dummy foam target

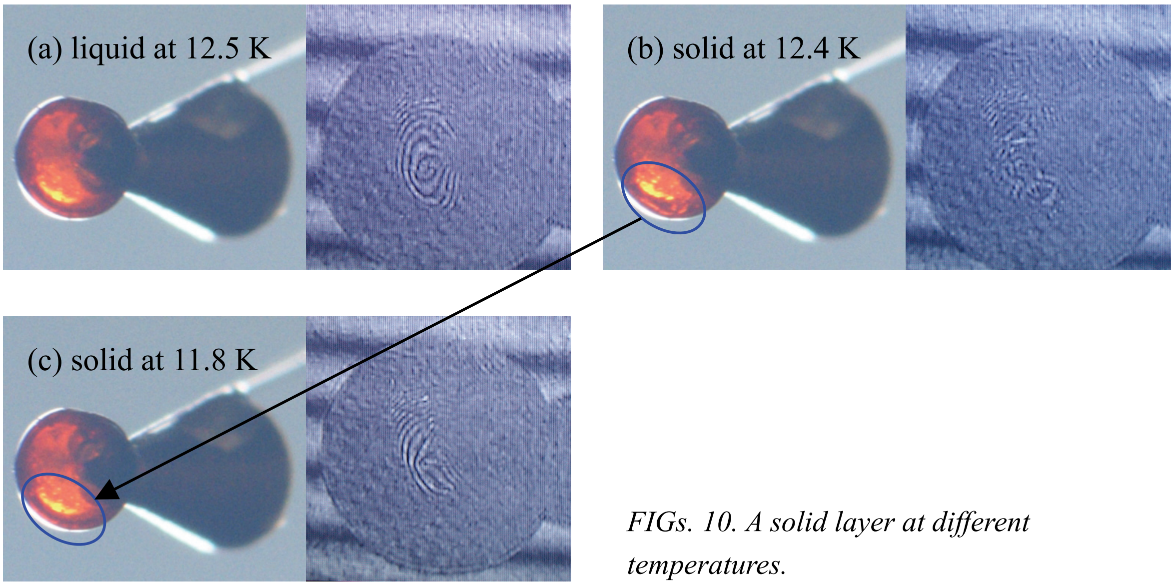
For the preliminary fuel layering test, a dummy foam target was fabricated as shown in FIG. 8. The foam shell is ~800 µm in diameter with a foam thin layer of ~60 µm, which was supplied from General Atomics (GA). The shell size is larger than that for FIREX-I, however, the property of the foam shell as a supporting material of the fuel can be examined. The inner tip diameter of the glass feeder is ~20 µm. The assembling method is the same way as that for the practical foam target. In the case of this target, the glue for sealing was remained on improper places on the shell. For the practical target, the optimum glue fillet has to be formed.

### 5.2. Demonstration of fuel layering

Solidification and liquefaction of $H_2$ were demonstrated using the dummy target. Normal-$H_2$ was substituted for the fuel of $D_2$ or DT, due to self-imposed controls of NIFS. The target was cooled by exchange gaseous He (GHe) of 20 Pa, and its temperature was controlled between 13.0 K and 11.0 K with a resolution of 100 mK. For liquefaction, the GHe temperature was kept at 12.5 K. Gaseous $H_2$ ($GH_2$) was filled in the shell and liquefaction was occurred at 7.3 kPa. According to the saturated vapour pressure of $H_2$, the temperature for the liquefaction must be ~14 K. The temperature difference between the exchange GHe and the inside of the shell results in ~1.5 K. Judging from the simple estimation [6], it is due to thermal resistances at the shell surface and in the shell itself. FIGs. 9 (a)-(e). show the progress of the liquefaction in the shell. The liquid $H_2$ ($LH_2$) seems to be uniformly filled in the foam material in terms of capillarity until the meniscus appears on the inner surface of the foam shell. The liquid quantity was adjustable. As the liquid quantity that $LH_2$ fully permeates the foam material was

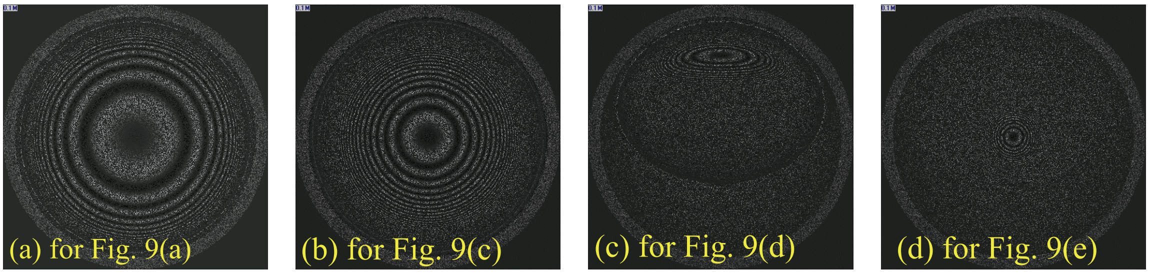



*FIGs 9. Sequence of the liquefaction. Real images and interference patters are shown.*




*FIGs. 10. A solid layer at different temperatures.*

kept constant, solidification was conducted. Adequate solid $H_2$ ($SH_2$) quantity could be remained in the shell by regulating both $H_2$ pressure and the target temperature during the solidification process. FIGs. 10(a)-(c). represent a solid layer at different temperatures. When the GHe temperature was 12.4 K, the phase transition to solid was occurred. In the case of the




*FIGs. 11. Calculated interference patterns.*

foam shell method, the phase transition did not make the fuel layer opaque. At this point, the crystallization of the $SH_2$ seems not to be uniform (see FIG. 10(b).). Then, the temperature was decreased, and the solid layer might become better condition at 11.8K (see FIG. 10(c).).

### 5.3. Interference patterns on the fuel layering

The interference patterns during the layering process were compared with the calculation by the code developed by Koresheva et al. [8]. For the calculation, the refractive indexes: 1.14 for the liquid fuel and 1.4 for the foam material were assumed. FIGs. 11(a)-(d). show the calculated patterns corresponding to the layering stages of FIGs. 9(a), (c), (d) and (e), respectively. The sequence of the experimental interference pattern is similar to that of the calculation. The resolution of the experimental results is quite low compared to that of the calculation. Its improvement must be considered from both aspects of the optical system and the vibration control remaining at the target.

## 6. Summary

The foam cryogenic target for FIREX-I has been developed by the collaboration between ILE and NIFS, and the research is now in progress. The accomplishments and the remaining issues are the followings:

1) The RF-PF foam shell has been developed, and the required specification for FIREX-I was almost achieved except for the density of the foam material. The foam shell fabrication method is going to be modified to realize the ultra low density of ~10 $mg/cm^3$.
2) The target assembling technique could be established and is available for the practical foam cryogenic target. The minimum glue fillet for sealing should be carefully filled on the target.
3) The apparatus for the off-site demonstration of the fuel layering has been developed. The cryogenic system has enough performance to test the fuel layering. The improvement of the resolution on the optical observation must be considered from both aspects of the optical system and the vibration control remaining at the target.
4) The fuel layering was tested using the dummy foam shell target. The $LH_2$ seems to be uniformly filled in the foam material in terms of capillarity until the meniscus appears on the inner surface of the foam shell. Adequate $SH_2$ quantity could be remained in the shell by regulating both the $H_2$ pressure and the target temperature during solidification process.

The crystallization of the $SH_2$ seems to depend on the exchange GHe temperature, and the optimum condition is expected to realize the ideal fuel layering.

**Acknowledgement**

The authors would like to thank Dr. Abbas Nikroo and Dr. Dan Goodin from GA for supplying the foam shell. Thanks are due to Mr. K. Okada for his contribution in fabricating the apparatus.

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