Developments of characterization of the foam shell target for Fast Ignition Realization Experiment-I (FIREX-I)

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Abstract. Equipments and techniques have been developed for characterization of the foam shell target for the FIREX-I. An interference measurement technique is planned to use to measure the quantity of fuel in a foam shell. A preliminary experiment of the interference measurement technique was carried out. Experimental results indicate the refractive index of RF foam is near 1.08 and that of vacant RF foam containing liquid H₂ is near 1.22. Calculations indicate the refractive index of vacant RF foam is 1.07 and that of RF foam containing H₂ is 1.19. Some causes of these differences were discussed.

1. Introduction
The fast ignition concept is attractive because a high gain would be achieved by smaller laser energy than the central ignition [1, 2]. The FIREX-I is underway at ILE to realize fast ignition [3]. The foam shell method is proposed as a fuel layering technique to realize its target design [4]. To develop a uniform and non-spherical fuel layer, foam is used to support the fuel. To measure the quantity of the fuel in the foam shell is especially important for deciding the timing of irradiation of the additional laser. In the foam methods, the foam layer is uniformly filled with the fuel by capillary attraction. Therefore it is impossible to judge the fuel is full or not by measuring the edge of the surface of the fuel. It is necessary for the FIREX-I to develop a measurement technique originally. As the foam is filled with the fuel, the reflective index of the foam layer increased. The change has an influence on the optical path length through the foam shell. The interference measurement technique can measure the optical path length. The interference measurement technique is considered as a candidate to examine the quantity of the fuel. A preliminary experiment using a dummy target and a dummy fuel was carried out to confirm that the interference measurement technique has possibilities to examine the quantity of the fuel.

2. Experimental setup
The experimental set-up is shown in figure 1. The interferometer was similar to the Mach - Zehnder interferometer. The laser beam was separated into two optical paths upside and downside behind the target. The diameter of the laser beams are about 20mm. There are two parts in the one optical path, passing through the target and not passing through the target. The upside beam was shifted during combination. The upside optical path through the target interferes with the downside optical path not passing through the target. To prevent heating up the foam shell, the intensity of the laser was
decreased by a Neutral Density (ND) filter. Vacuum cans have six windows. Visible rays (wavelength: 400nm-700nm) can pass through these windows. There was an interference filter (VPF-25C-10-50, sigma-koki) in front of the CCD (DS-Fi1-L2, Nikon). Light the wavelength is only nearby 632.8nm can pass through the interference filter. The interference images were forwarded to the CCD camera by the imaging lens system. The system scaled these images down 0.8 times. The relay lens is placed near the window. The objective lens is adjusted to be the shell’s edge in focus.

The target consists of three parts: a foam shell, a guide cone made of gold and a fuel feeder made of glass. The foam shell is made of resorcinol-formalin. The cell size of the RF foam is about 200nm. The diameter of the foam shell is larger and the thickness of it is thicker than the foam shell needed for FIREX-I project [4]. The gas barrier made of poly-pala-xylylene coated the foam shell by chemical vapour deposition. The thickness of the gas barrier is 5.3 μm.

The cryogenic system was designed and fabricated for the off-site fuel layering test. Its details were already reported in reference [5]. The target temperature was controlled by the heat exchange gas-He filled in the vacuum can. During the demonstration, the temperature of the gas-He was controlled at 12.5K. Gaseous H₂ was used as the substitute for D₂ or DT fuel. Gaseous H₂ filled in the shell and liquefaction occurred at 8.5 kPa. The pressure of H₂ was controlled to stop liquefaction when liquid H₂ would be fully filled in the RF foam layer. If the shell was overfilled, meniscus was happen near the cone. When meniscus was the smallest (it was judged by visual inspection), the shell was considered to be fully filled.

3. Calculations
Refractive indexes $n$ are calculated by using Lorentz-Lorenz function

$$\frac{M (n^2 - 1)}{\rho (n^2 + 2)} = \left(\frac{4\pi N_A}{3}\right) \alpha = R_0$$  \hspace{1cm} (1)

where $M$ is molecular weight, $\rho$ is density, $N_A$ is Avogadro’s constant, $\alpha$ polarizability and $R_0$ is the molar refraction. The molar refraction is peculiar to the substance. The relevant refractive indexes calculated by using equation (1) are shown in table 1. The trace of the ray passing through double layer shell is shown in figure 2. Here, $n_0$, $n_1$, $n_2$, and $n_3$ are the refractive indexes of relevant media. A
is the coordinate of the input ray, and I is that of the output ray in the observation plane. The input ray is parallel to the horizontal axis. Angle $\alpha$ is given by

$$\alpha = \arcsin \left( \frac{y_b}{R} \right).$$  \hspace{1cm} (2)

The relation between angles $\alpha$ and $\beta$ is given by using Snell’s law

$$n_0 \sin \alpha = n_1 \sin \beta.$$  \hspace{1cm} (3)

The coordinate of the point of C is calculated by using the following equation

$$\left[ (-\tan(\alpha - \beta)(x_c - x_b) + y_b)^2 + x_c^2 = (R - b)^2 \right].$$  \hspace{1cm} (4)

Repeating like these calculations equation (2)-(5), it is easy to get the coordinates of D, E, F, G and H. The coordinate of the observation plane I is calculated by using

$$y_i = \frac{x_h y_g - x_g y_h}{x_h - x_g}.$$  \hspace{1cm} (5)

After all coordinates are calculated, the length of the optical path is calculated by using

$$L = n_0 AB + n_1 (BC + FG) + n_2 (CD + EF) + n_3 DE - n_o GI.$$  \hspace{1cm} (6)

### Table 1. Refractive indexes.

| Material                      | Refractive index |
|-------------------------------|------------------|
| Gas-He                        | 1.00             |
| Gas-H$_2$                     | 1.00             |
| Poly-pala-xyylene             | 1.66             |
| RF-foam                      | 1.07             |
| RF-foam containing liquid H$_2$ | 1.19             |

### Figure 2. Schematic view of the ray tracing.

**4. Results and discussions**

The experimental results were shown in figures 3 and 4. It was measured where the dark-line spectrums are. The optical path length against output ray coordinates in observation plane was calculated by using equations (2)-(6) and the values of table 1. Experimental results and calculation results were shown in figures 5 (a) and (b). They indicate the refractive index of RF foam is neighbouring 1.08 and that of RF foam containing liquid H$_2$ is neighbouring 1.22. The experimental results differ from the calculation results shown in table 1.

There might be some causes of the differences. The first is the thickness of the foam might not be 60$\mu$m. Because of our procedural error, the target was assembled before the thickness was measured. It is difficult to measure the thickness correctly after assembling. The second is the shell shrunk. To investigate how they affect, optical path lengths of each case are calculated. Figure 5 (c) expresses the results in dimensionless units (i.e. radius = 1). The thickness effect can largely account for the observed difference in refractive index. The thicker the thickness is, the larger the refractive index is in appearance. In the case of the vacant shell, the same phenomena happen. On the other hand, the shrinkages have the opposite influence. When the shell shrunk, the refractive index is small in appearance. If the overfilling with H$_2$ happens, interference fringes must warp by the influence of gravity. It is found the overfilling could not happen, because the fringes of the figure 4 don’t warp.
The conditions of calculation for table 1 differ from that of cryogenic temperature. It is

**Figure 3.** The interference image of the vacant target.

**Figure 4.** The interference image of the target containing liquid H₂.

**Figure 5.** Graphs of the different refractive index of foam layer at vacant shell (a) and the filled shell (b). Graph of the different condition at the index n=1.19 (c). They show the differences of the length from the first dark-line spectrums.

uncertain how it has the influence on the calculation results of the refractive indexes.

For future works, the total system has to be improved. The thickness must be measured precisely beforehand. In addition, it is necessary to investigate how the shell shrinks. The refractive index of RF foam at 12.5K has to be examined. Improvement of imaging lens system to get high resolution images and using the high quality shell are planned.

5. Summary
The primitive experiment of interference measurement technique carried out. Because of our procedural error, many problems remain. After solving these problems, the interference measurement technique may be candidate of the characterization method for FIREX-I.

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References
[1] Yamanaka T 1983 Institute of Laser Engineering Internal Report Osaka University 5–6
[2] Tabak M, Hammer J, Glinsky E M, Krue L W, Wilks C S, Woodworth J, Campbell E M, Perry D M and Mason R J 1994 Phys. Plasmas 1 1626-34
[3] Azechi H and the FIREX project 2006 PlasmaPhys. Control. Fusion 48 B267-75
[4] Nagai K et al. 2005 Nucl.Fusion 45 1277-83
[5] Iwamoto A et al. 2006 Fusion Engineering and Design 81 1647-52