

Ion Generation Using Frozen Xenon Target for Laser Ion Source^{*}

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A frozen laser target that is in the gaseous phase at room temperature is advantageous for a laser ion source because it can avoid the accumulation of damage from laser irradiation by regeneration of the target surface by additional gas freezing. In this study, the possibility of forming a xenon ion beam with a current sufficient for heavy-ion inertial fusion (HIF) was investigated. The relationship between the frozen target growth and resulting ion current was analyzed to determine the optimal condition of laser irradiation that ensures stable supply of ion beams for a long time. A frozen target of xenon was formed on a mount cooled to 20 K using a Gifford McMahon cryocooler, and plasma was generated using a Nd:YAG laser. The results showed that it is possible to supply a sufficient ion current for application of singly charged ions as a driver for HIF. Additionally, it was indicated that the xenon responsible for forming the plasma existed only at a certain depth from the target surface. The results imply that it is possible to obtain a stable ion supply for a long time by irradiating the target with a laser after the frozen xenon grows to a sufficient thickness.

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1. Introduction

Heavy-ion inertial fusion (HIF) is a method for energy generation via nuclear fusion. HIF requires heavy ion beams with a large current and a low charge state. Various acceleration methods have been suggested thus far [1–4], and ion beams with ion mass numbers of 84 to 238 amu are reported in many cases [5] because ions with larger masses can be focused on a small fusion target more easily than lighter ions. Laser ion sources, which can generate a large current ion beam with various ion species using solid targets [6–9], have been studied for HIF applications. The capability of applying a laser ion source to HIF has been investigated in terms of the ion beam current, pulse duration, and emittance [10–12].

However, damage to a solid target by laser irradiation accumulates during the ion beam supply which limits the lifetime of the laser target. To develop a target for laser ion sources with longer lifetime, a laser target with a frozen substance made of gaseous species at room temperature has been explored because it can avoid accumulating damage from laser irradiation by the continuous regeneration of the target surface by gas freezing [13].

However, it is unclear whether a high ion current, similar to conventional solid targets, can be obtained from a laser ion source using such a frozen target. In addition, one of the related issues with the laser ion source using a frozen target is the unstable repeated supply of ions. In this

study, the possibility of forming a singly charged ion beam with a current sufficient for HIF was investigated. The relationship between the frozen target growth and resulting ion current has been analyzed to determine the optimal condition of laser irradiation, such as the frequency for a stable supply of ion beams. Krypton, xenon, and radon can be candidate ion species for the frozen target because their mass numbers are in the range of the HIF driver requirement. However, non-radioactive heavier ions are more appropriate from the viewpoint of usability and ion beam focusing ability. Therefore, in the present work, frozen target using xenon has been investigated as a candidate driver beam for HIF [14].

2. Experimental Setup

Figure 1 shows a schematic of the experimental setup. A Gifford McMahon cryocooler unit SRDK (cold head RDK-408D2 and compressor CSW-71C, Sumitomo Heavy

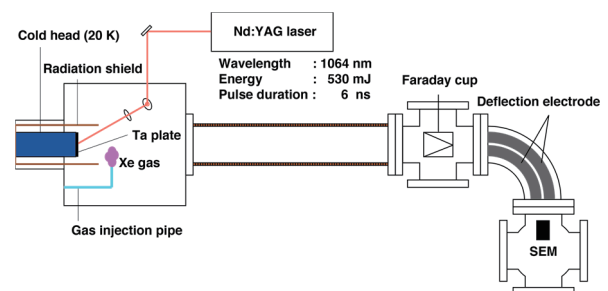


Fig. 1 Schematic of experimental setup.

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Industries) was used to cool xenon gas. By attaching a radiation shield in contact with the 1st stage (43 K) of the cryocooler, the radiation heat was partly prevented from reaching the cold head of the 2nd stage (4.2 K). The cold head temperature during the experiment was 20 K, which resulted from the balance between the cooling by the cryocooler and the radiation heating from the environment. A tantalum plate, which is relatively resistant to laser ablation [15], was used as the substrate to grow the xenon target.

To investigate the relationship between the growth speed of the frozen xenon target and the background pressure, the pressure in the vacuum chamber was controlled by changing the flow rate of the xenon gas injection after evacuation at approximately 10^{-4} Pa. The flow rate of xenon gas was controlled using a mass flow controller SEC-7320 M (HORIBA STEC). It should be noted that a maximum xenon pressure of 8×10^{-4} Pa was realized with a maximum flow rate of 1 sccm in the controllable range, and the pressure could not be increased further because the cold head worked as a cryopump.

A Nd:YAG laser with a wavelength of 1064 nm, pulse width of 6 ns, and energy of 530 mJ was used to generate plasma. After the plasma passed through the 1.5 m transport tube, the ion current waveform was measured using a Faraday cup (FC). To extract ions from the plasma, a voltage of -5 kV was applied to the suppressor electrode to prevent secondary electron scattering. The ions reached the cup after passing through an aperture with a diameter of 10 mm and a suppressor electrode mesh with a transmission of 85%.

The ion charge state distribution was analyzed using an electrostatic ion analyzer. The analyzer provided a spectrum of ions for every laser shot by detecting ions with a specific charge state and kinetic energy that could pass between the deflection electrodes. The ion species and charge state distribution could be determined from the change in the spectrum obtained by scanning the voltage applied to the ion deflection electrodes. The ions passing between the deflection electrodes were detected using a secondary electron multiplier (SEM) (Hamamatsu Photonics, R2362).

In HIF, low charge-state ions are required as the driver beam, as mentioned in the introduction. Therefore, it is necessary to keep the power density of the laser low to generate plasma in which singly charged ions are dominant. However, the reproducibility of plasma generation could be poor when the laser power density is close to the threshold for plasma generation. To balance these factors, the laser was focused on a 0.33 cm^2 area on the target with a lens and the laser power density was set to $3 \times 10^8 \text{ W/cm}^2$.

3. Result and Discussion

Figure 2(a) shows the ion current waveform obtained with the FC when the xenon pressure in the chamber was adjusted to 8×10^{-4} Pa and the laser was irradiated on the

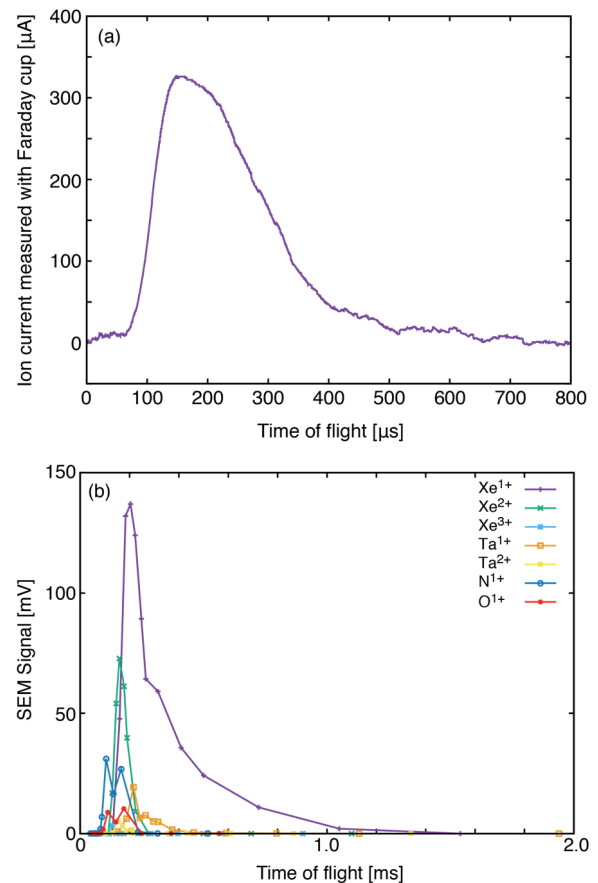


Fig. 2 (a) Ion current waveform measured with the FC and (b) ion species and charge state distribution obtained with the electrostatic ion analyzer by laser irradiation with 60 s intervals.

frozen xenon target at time intervals of 60 s. The current is approximately $300 \mu\text{A}$ at the peak and the pulse duration of the full width at half maximum is approximately $200 \mu\text{s}$. Because the ion current of the laser ion source decreases inversely to the 3rd power of the plasma transport distance [16], a beam current of 300 mA could be obtained by extracting the beam at a position 150 mm from the target, which is one-tenth of the transport distance in this experiment. The ion current was similar to that obtained using conventional solid targets [12], and satisfied the requirement for the HIF driver.

Moreover, the ion charge state distribution measured by the electrostatic ion analyzer under the same conditions shows that plasma with Xe¹⁺ ion dominance could be generated, as shown in Fig. 2(b). However, the observed ions included a small amount of tantalum ions, arising from the Ta substrate used for freezing xenon. In addition, oxygen and nitrogen ions derived from the frozen residual air molecules were detected.

Next, the change in the amount of Xe¹⁺ and Ta¹⁺ ions produced as a function of the laser irradiation time interval was investigated under the same experimental conditions. Figure 3 shows the amount of Xe¹⁺ and Ta¹⁺ ions

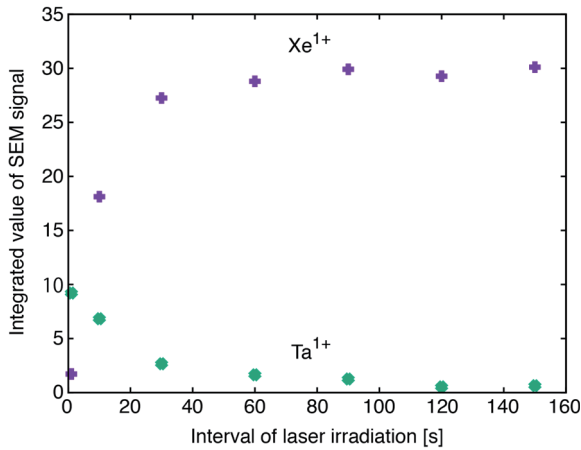


Fig. 3 Variation in amount of Xe¹⁺ and Ta¹⁺ ions generated as a function of the interval of laser irradiation.

obtained by integrating the time-of-flight signals (as shown in Fig. 2 (b)) over time for each ion. The amount of Xe¹⁺ ions increases as the laser irradiation interval increases and saturates at approximately 60 s. This implies that only a thin xenon layer within a certain depth from the surface in the frozen target is ablated by laser irradiation when the thickness of the xenon target is sufficient for a laser irradiation interval longer than 60 s.

In contrast, the concentration of tantalum ions decreases with increasing laser irradiation interval. This indicates that when the growth of the xenon target is insufficient, the tantalum substrate can be ablated with the xenon target. In addition, the Ta¹⁺ signal does not disappear completely after the xenon ion signal is saturated. This may be because the laser transmits through the xenon target and generates ablation plasma on the tantalum, or alternatively, the tantalum plasma is generated secondarily by contact with the generated xenon plasma. In any case, the generation of tantalum plasma can be prevented by increasing the thickness of the xenon target.

Figure 4 shows the changes in the ion current peaks as a function of the laser irradiation time intervals obtained for three xenon pressures of 2×10^{-4} , 4×10^{-4} , and 8×10^{-4} Pa. At any pressure, the ion current increases as the time interval increases and tends to be constant after exceeding a certain time interval. The ion current becomes constant at an irradiation interval of approximately 60 s under a xenon pressure of 8×10^{-4} Pa. This result is in agreement with the tendency of the amount of Xe¹⁺ produced, as shown in Fig. 3; therefore, the change in the peak of the ion current corresponds to the amount of xenon ions generated. In addition, it can be observed that the laser irradiation interval times, at which the ion current saturates, decreases as the xenon pressure increases. This indicates that the frozen xenon target grows faster as the pressure increases.

To predict the thickness of the frozen xenon target to supply xenon ions with a saturated current, the target

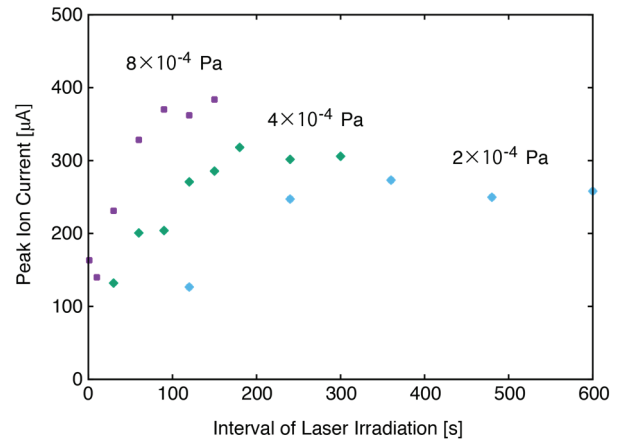


Fig. 4 Variation in peak ion current measured with the FC as a function of the interval of laser irradiation under the pressures of 2×10^{-4} , 4×10^{-4} , and 8×10^{-4} Pa.

growth rate was estimated. The flux F [$\text{m}^{-2}\text{s}^{-1}$] of the xenon atom that collides with the substrate can be obtained using the following equation:

$$F = \frac{P}{\sqrt{2\pi m k_B T}}, \quad (1)$$

where p is the pressure of the xenon gas, m is the xenon atomic mass, k_B is Boltzmann constant, and T is the temperature of the xenon gas. Based on the flux, the growth rate of the xenon target expressed by the increase in the thickness g [m/s] was calculated as follows:

$$g = \frac{FA}{1000\rho N_A}, \quad (2)$$

where A is the atomic weight of xenon, N_A is Avogadro constant, and ρ is the xenon ice density [17]. Assuming the time interval of laser irradiation where the current peak is 90% of the constant value shown in Fig. 4, was used as the threshold for obtaining saturated current. These time intervals were 234, 151, and 72 s under pressures of 2×10^{-4} , 4×10^{-4} , and 8×10^{-4} Pa, respectively. The thickness of the xenon target at these times could be obtained by multiplying Eq. (2) by the growth time, and were estimated to be 37, 48, and 46 nm, respectively. These estimations indicate that laser irradiation with a power density of 3×10^8 W/cm² causes ablation of a target thickness of approximately 50 nm. This means that if the target is thicker than 50 nm, the damage to the substrate can be suppressed, and a laser target with a long lifetime can be realized. Although a higher laser energy density is required to increase the ion current, it has been previously demonstrated that a target with a thickness of the order of 100 nm is useful to avoid the ablation of the substrate for a laser power density of 10^9 W/cm² or more through an experiment using the target of Al coated by thin Au [18].

The above results show that the Xe¹⁺ ion beam current required for HIF can be obtained by irradiating the laser with a power density of 3×10^8 W/cm² every 72 s,

which corresponds to a frequency of 0.014 Hz when the xenon pressure is maintained at 8×10^{-4} Pa. It is necessary to supply ions at a repetition of approximately 1 - 10 Hz for the HIF driver, which means that the target growth rate has to be increased by approximately 100 times than that obtained in this experiment. Because the growth rate of the target is proportional to the pressure, the pressure of xenon should be increased 100 times to obtain a 100 times larger growth rate. However, the mean free path of the ions at a pressure of 8×10^{-2} Pa is too short to transport the ion beam. Therefore, it is necessary to perform differential pumping to increase the gas supply while maintaining low pressure in the chamber, or some techniques such as gradually changing the laser irradiation position need to be considered to reduce the frequency of laser irradiation at the same position.

4. Conclusion

The possibility of forming a xenon ion beam with sufficient current to satisfy the requirement for an HIF was investigated. The relationship between the growth of the frozen xenon target and resulting ion current was analyzed to determine the optimal conditions for laser irradiation to supply ion beams stably for a long time. The results imply that the generation of plasmas containing the Xe^{1+} ion is dominant using a frozen xenon target on a tantalum substrate cooled to 20 K, and it can supply a sufficient ion current of singly charged ions to drive the HIF. In addition, it was demonstrated that the amount of xenon ions increased as the time interval of laser irradiation increased and saturated after a certain period of target growth. This indicates that xenon plasma formation occurs only at a certain depth from the surface. This result implies that a stable ion sup-

ply to avoid the accumulation of damage to the target is achievable by irradiating a laser after frozen xenon grows to a sufficient thickness.

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