USE OF SOLIDIFIED GAS TARGET TO LASER ION SOURCE

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Abstract

We generated laser produced hydrogen plasmas as part of a future laser ion source. Hydrogen, which is in gas state at room temperature, needs to be cooled to solid target for laser irradiation. We generated solid hydrogen targets in our laser ion source chamber with a cryogenic cooler. By irradiating the solid hydrogen with a Nd:YAG laser (532nm half-wavelength), we generated hydrogen ion.

INTRODUCTION

Laser ion source is capable of generating highly ionized particles and high intensity beams by irradiating a solid target with a pulsed laser. Features of various heavy ion generations using a pulsed laser have been investigated [1] [2]. However hydrogen which is in gas state at room temperature has not been able to be used as a laser ion source target because the target of a laser must be solid. Therefore to apply hydrogen to a laser ion source target, we have investigated how to convert hydrogen gas to solid with a Gifford McMahon cryocooler (Sumitomo RDK-408D2) and observed hydrogen ice [3]. To verify whether this method can be available for laser ion source, we irradiated the ice with a Q-switched Nd:YAG laser (532nm half-wavelength, THALES SAGA230/10) and examined a Laser Produced Plasma (LPP).

MATERIALS AND METHODS

We placed the cryocooler cold head inside of the target chamber. The cryocooler can cool down to 43 K at the first stage with a cooling capacity of 50 W and to 4.2 K at the second stage with the capacity of 1 W. The structure of the fabricated equipment to generate the solidified hydrogen target is shown in Fig. 1. Hydrogen gas is solidified by being sprayed into bottom of a hole machined at cooled copper volume attached to the second stage. And the solid hydrogen is irradiated with the Nd:YAG laser with a pulse energy of 750 mJ and pulse length of FWHM 5.5 ns. A sensor was installed to measure the temperature of the copper volume. Heat conduction through the temperature sensor lead can be estimated at 0.005 W which can be neglected. A copper plate surrounding the second stage to shield against direct radiant heat was attached to the first stage. This shield has a hole with a diameter of about 20 mm for the passage of the laser beam and the ablated plasma. We wrapped a plastic tube which guides hydrogen gas from the outside of the vacuum chamber around the shield for the pre cooling of the gas.

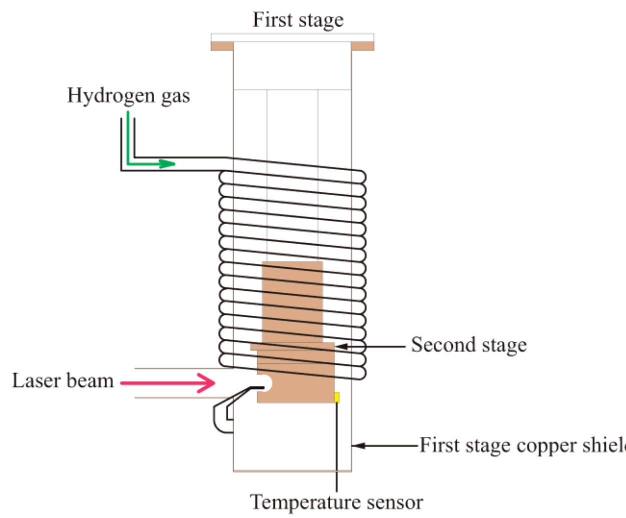

Figure 1: Solid hydrogen production equipment.

The experimental setup for measurement of the LPP is shown in Fig. 2. The instrument consists of an optical system about the laser beam, the cryotarget described above, a Faraday Cup (FC) to measure the ion current of the LPP, an Electrostatic Ion Analyser (EIA) to verify the existence of hydrogen ion included in the LPP and a Secondary Electron Multiplier (SEM, Hamamatsu R2362) to convert small ion currents after EIA to measurable signal. After reflection by three dielectric mirrors, the laser beam is focused by a plano convex lens with focal length of 800 mm and it goes into the vacuum chamber passing through a BK7 window. Then the laser beam is reflected by another dielectric mirror, and the solid hydrogen target described above is irradiated with the laser beam. The irradiation angle is 6 degrees with respect to the normal to the surface.

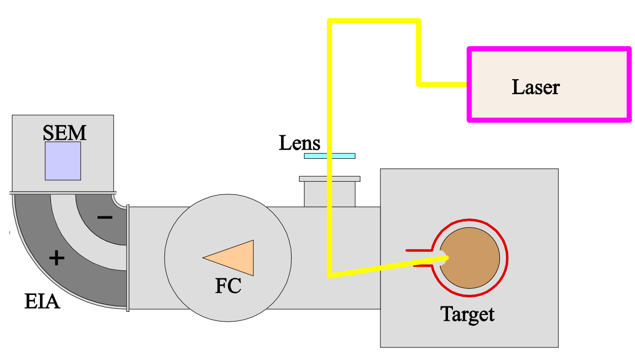

Figure 2: Overall view of the experimental setup.

The FC is located 2.3 m from the target. To separate the ions from the electrons, a suppressor mesh in front of the FC was biased to –2.5 kV. This mesh has 85 % of transparency. To collimate the beam going into the FC, a grounded aluminum plate with a hole of 10 mm diameter was placed before the suppressor mesh.

The SEM following the EIA is located 3.7 m from the target. The EIA consists of a pair of cylindrical electrodes which have a deflecting angle of 90 degrees with a gap length of 5 mm. The bending radius is 100 mm. If the both electrode are energized to –V [V] and +V [V] respectively, the condition that an ion can pass through the EIA is

$$V = \left(\frac{r_b}{r_a}\right)\frac{T}{z} = \left(\frac{102.5}{97.5}\right)\frac{T}{z} \cong 0.05\frac{T}{z}$$

where r_a [mm], r_b [mm], T [eV], z are the inside radius of the electrodes gap, the outside radius, a kinetic energy of the ion and the charge state of the ion respectively. Then the Time Of Flight (TOF) [s] is obtained by

$$t = \frac{L}{v} = L\sqrt{\frac{m}{2eT}} \cong L\sqrt{\frac{m}{40Vze}}$$

where L [m], v [m/s], m [kg], e [C] are the flight distance of the ion, velocity of the ion, mass of the ion and elementary electric charge, respectively.

RESULTS

The temperature of the cold volume was monitored as 3.5 K. Then hydrogen gas was sprayed into the target area. The flow rate of the hydrogen was restricted not to pressurize the target chamber exceeding 10^{-4} Pa. There was no temperature increase observed. When we fed the hydrogen, the vacuum started to oscillate. This oscillation synchronized to the compression cycle of the cooler. The vacuum oscillation is also observed in an experiment using Ne gas we tried before. This is considered that the outermost hydrogen molecules are repeating evaporation and solidification synchronizing to the temperature oscillation. By increasing the temperature of the second stage from about 4 K to about 10 K, we observed a tremendous increase of the vacuum pressure. The pressure rapidly exceeded 1 Pa which was the measurable limit of our vacuum instrumentation. One can say that large amount of hydrogen has been solidified on the cold surface.

When we irradiated the cryotarget with the Nd:YAG laser (half-wavelength), a red colored light was emitted, while the red light could not be observed without laser safety glasses due to the strong green light emission of 532nm laser beam (see Fig. 3). The strength of the red light emission depended on the laser shot intervals. The longer interval of laser shots led to the stronger light emission. Therefore we could consider the red light emission was caused by excitations of the hydrogen plasma. At the same time, the pressure of the target chamber increased rapidly from 10^{-4} Pa to 10^{-1} Pa. The pressure returned to the original state of 10^{-4} Pa without delay. However, a few second after the laser irradiation, the pressures of the target chamber, the FC chamber and the SEM chamber increased abruptly and simultaneously. This sudden pressure change continued intermittently for more than an hour with decreasing the amplitude of the pressure change bit by bit.

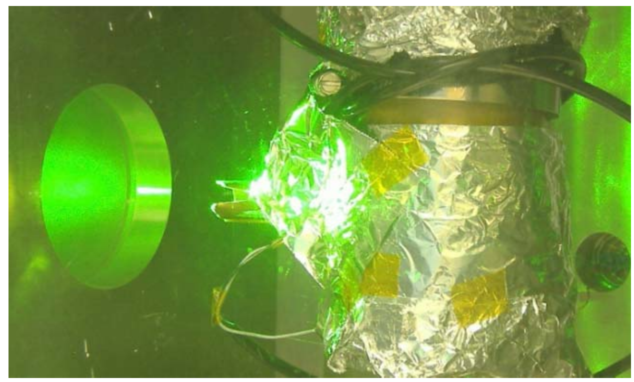

Figure 3: Half-wavelength Nd:YAG laser focused the solidified hydrogen target.

There is a valve which was installed between the target chamber and the FC chamber and the plasma passage could be separated. When we closed the valve, the following three patterns of phenomena were observed. (a) the pressure oscillations remained in both of the target chamber and the plasma transfer line. (b) remained only in the target chamber. (c) remained only in the plasma transfer line. At the moment, the reason of the pressure oscillation is not clear and the further investigation is required.

To verify the generation of H^+ ions, we analysed the LPP using the EIA. The waveform measured by the SEM when the deflector electrodes of the EIA are energized to 0.5 V, is shown in Fig. 4.

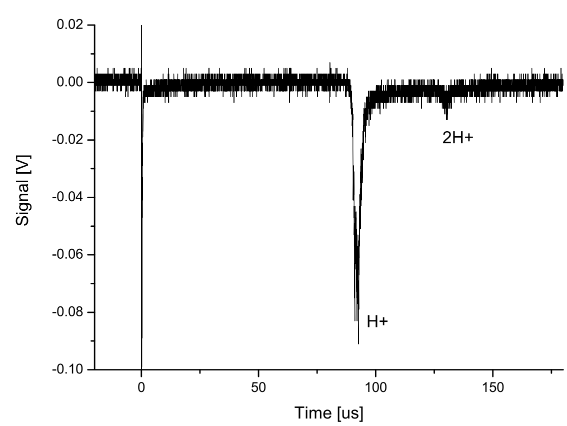

Figure 4: Peaks of H^+ ions and H_2^+ ions with the EIA voltage of 5 V.

The peak which arrived in 90 s represents ion currents of H^+ and the peak which arrived in 130 s represents that of H_2^+.

Fig. 5 (Upper) shows the total ion current of the LPP measured by the FC. By changing applied voltage to the EIA, the H^+ signal obtained from the SEM can be converted to Fig. 5 (Lower), where the time scale is transformed to the FC position. From the signals of the SEM, we found that the LPP was composed of H^+, H_2^+, C^+, C^{2+}, O^+, Cu^+ and Cu^{2+} ions. The obtained raw date from the SEM showed that H^+ ion current was dominant. However it is difficult to compare the currents of various species from the SEM, since multiplication factors of the SEM may depend on the mass of ion species and incident velocities. In the experiment the first electrode of the SEM was energized to -3.5 kV. Also, the peak position in time scale of the FC signal did not coincide to that of the H^+ ions measured by the SEM (see Fig. 5). We cannot clearly say that the total current is mostly composed of H^+ ions.

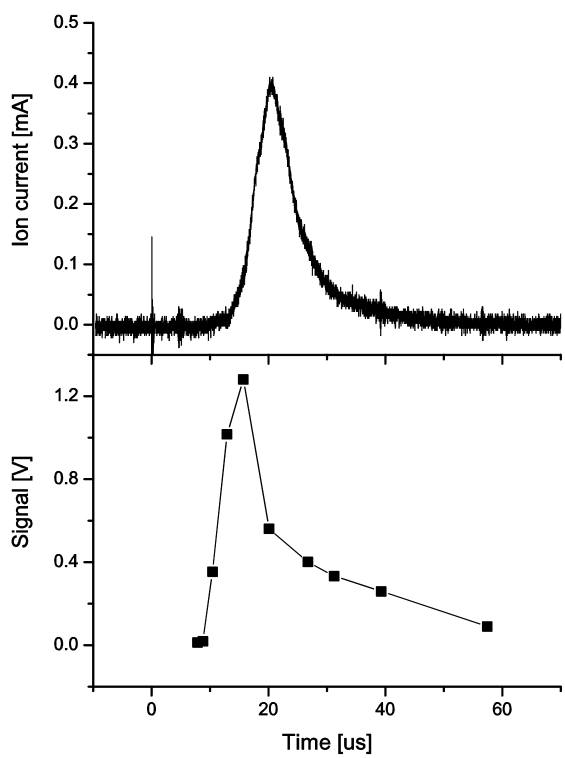

Figure 5: (Upper) Total ion current measured by the FC. (Lower) H^+ ions measured by the SEM.

The total current obtained by the FC depends on the laser shots intervals like as the strength of the red light emission did. The longer interval of laser shots corresponded to the lower total ion current. On the other hand, the total ion current could be increased by the more laser power output, or by decreasing the spot size. From these observations, we speculate that the Cu ions may occupy the large portion of the total ion current measured by the FC.

The laser spot size was estimated about 2 mm of diameter from the size of the foot print of the laser irradiation to the cooled copper surface. The laser power density and the energy density of this experiment were estimated at about 2 GW/cm^2 and 10 J/cm^2 respectively.

CONCLUSION

We generated the hydrogen ice with a 4 K cryocooler for a future laser ion source target. By irradiating it with a half-wavelength Nd:YAG laser, we produced a plasma with red light emission. The total ion current measured by the FC was smaller than we expected at first. Furthermore, the ratio of H^+ ions included in the plasma may occupy small fraction. It might be a good solution for pure hydrogen plasma generation to install a robust substance which can endure against the laser exposure. To utilize the hydrogen gas based laser ion source, we will continue further study.

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