DESIGN STUDY OF HIGH REPETITION RATE LASER ION SOURCE FOR HIGH POWER BEAM PRODUCTION

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Abstract

We are studying a laser ion source (LIS) for a high average beam power heavy ion beam production. A LIS is the most intense source of pulsed highly-charged ions using a laser ablation scheme. By increasing the repetition rate, a LIS based heavy ion beam would approach the average beam power based on a low beam current and continuous beam regime. In addition, a high-repetition-rate LIS can be used as a heavy ion source for a medical accelerator with spot scanning technique. This paper will describe the requirements to realize the high repetition rate operation.

INTRODUCTION

A laser ablation ion source (LIS) is well-known as a pulsed ultra-intense source of highly-charged heavy ions of more than hundreds mA of beam current. This ion source usually produces highly-charged heavy ions from a solid bulk material irradiated by a pulsed high power laser, and operates at less than 1 Hz in general. However, there are increasing demands of high power beam for example for accelerator driven systems and neutron production, and demands of high-repetition operation for a spot scanning for medical accelerator for cancer treatments. To meet these demands with heavy ion beams, we have been studying a high-repetition-rate LIS. A very high beam current operating at high-repetition-rate could approach average beam power of a continuous machine of a low current beam. Rapid improvements of lasers and accelerator technologies such as a Fixed Field Alternating Gradient accelerator (FFAG) make this scheme more feasible up to 1 kHz. A FFAG for proton acceleration already demonstrated 100 Hz operation [1]. By decreasing beam current, a LIS also can be used as a heavy ion source for a medical accelerator using a rapid cycle synchrotron [2].

LASER POWER

In this study, a laser which has a nano-second pulse width is considered. This is a kind of laser we have used for our research. Shorter laser pulse width of may benefit to increase a laser power density to increase charge states and to decrease damages on a target. But there may be not

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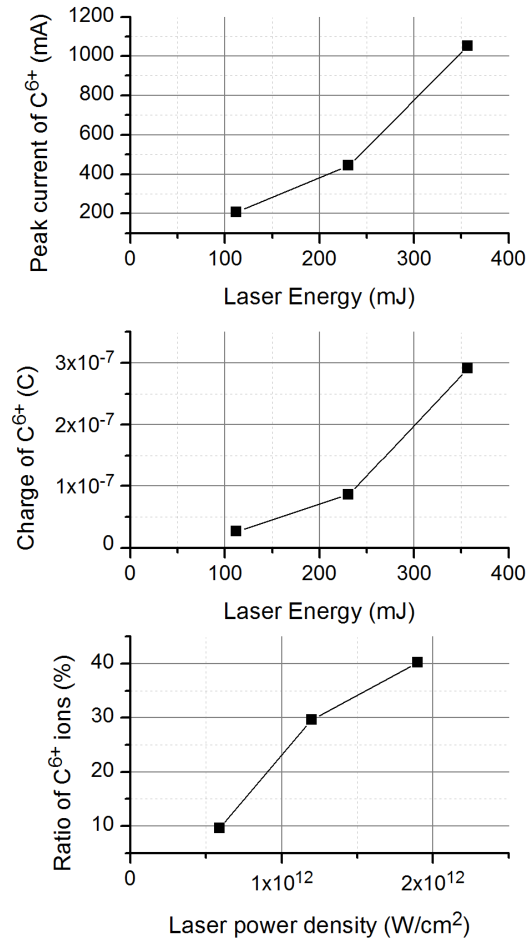

Figure 1: Properties of C^{6+} ions scaled to 0.2 m from target and aperture of 10 mm in diameter. Laser energy of 110, 230, and 360 mJ corresponds to laser power density of 5.9E11, 1.2E12, and 1.9E12 W/cm^2, respectively.

enough time to develop ionization if the laser pulse width is too shot. For long term stable operation, the laser power density should be minimized as keeping enough number of ions of interest to minimize damages on a target and unwanted debris. We experimentally investigated the relationship between the laser power density and C^{6+} generation. A 3-mm-thick graphite target was used as a target. The charge state distribution of carbon plasma was analysed as same method as shown in [3].

We used a Quantel laser Brilliant B (λ = 1064 nm, max. 850 mJ, 6ns) for this experiment. Figure 1 shows the peak current, charge per pulse, and percentage of C^{6+} ions scaled at 0.2 m from a target and 10 mm aperture in diameter based on the result of the experiment. This could be the condition for ion extraction. We used three different laser energy of 110, 230, and 360 mJ on a target. The corresponding laser power density on a target was 5.9E11, 1.2E12, and 1.9E12 W/cm^2, respectively. As increasing the laser power density, the ratio of C^{6+} ions was increased. Based on the result, we selected to use 230 mJ for this design study because of the reasonable amount of C^{6+}.was generated.

STABILITY OF LONGITUDINAL TARGET POSITION

The stability of an ion source is crucial for reliable operation of particle accelerators. For a LIS, it is essential to keep the laser power density on a target stable. This means the distance between a focusing lens and a laser irradiation target should be kept constant. Figure 2 shows the relationship between lens position along a laser path and time of flight of ion signal in laser produced plasma measured by a FC. Time structure of plasma was different when a lens position is changed by 0.25 mm, which indicates that the plasma temperature and charge state distribution is different. The focal length should be kept as small as possible, at least less than 0.2 mm.

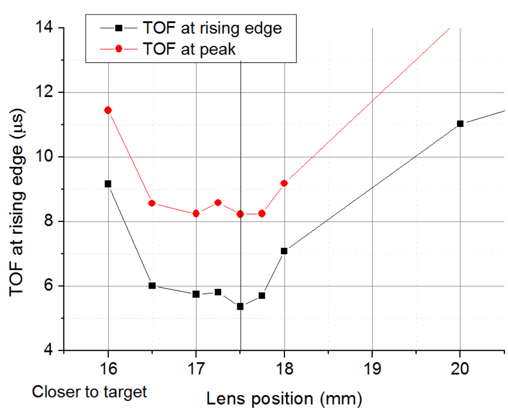

Figure 2: Difference of time of flight of carbon signal detected by a FC as a function of a focusing lens position along a laser path.

TARGET SHAPE

To better manage the target longitudinal position, the use of a planar solid bulk target such as more than several mm of thickness has been our choice. However, the disadvantage of a bulk target is that the life time is limited by surface area and the size of a vacuum chamber becomes large to increase the target size to increase life time, though low-repetition-rate operation is possible with the bulk target. Recently we tested a use of a thin sheet of a graphite as shown in [3]. The result showed that there are only small differences of highly-charged ion production for the target thickness at least more than 25 µm. Thinner target than 25 µm was not tested. We propose to use a roll of a graphite sheet as a laser irradiation target. The life time problem of a target will be solved with the use of a rolled target.

VACUUM

Pumping of a target chamber is one concern for the high-repetition-rate operation because neutral atoms are emitted in addition to plasma in the process of laser ablation. We estimated the amount of carbon atoms emitted by a laser irradiation of 230 mJ on a 25-µm-thick graphite target. The target was fully penetrated after a laser shot. Based on the material removed from the target (1.8 mm in diameter, 25 µm of thickness, 1.9 g/cm^3 of density), the estimated number of emitted atoms per shot was 6E18. We also tested the pressure increase in a vacuum chamber (0.062 m^3) caused by laser ablation. Figure 3 shows the pressure increase in an isolated chamber after a gate valve to a turbo pump was closed at t = 0. The pressure was increased by 1.5E-3 Pa after single laser shot. This corresponds to 2E16 atoms per pulse. The difference of the number of atoms could be absorbed on the chamber surface or escaped from the chamber. Pumping system of the high-repetition-rate LIS needs to evacuate at most this number of atoms at plasma generation area. Further investigation and testing is required to estimate the required pumping system more precisely because some material is emitted as solid debris.

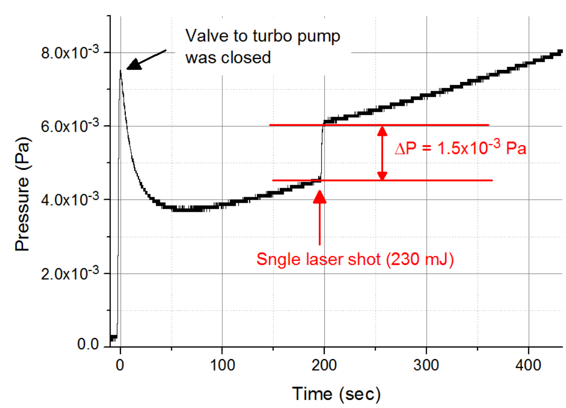

Figure 3: Pressure increase in an isolated chamber after a gate valve to a turbo pump was closed at t=0.

EXTRACTION AND ACCELERATION

Direct Plasma Injection Scheme (DPIS) is an established scheme for high current highly-charged heavy ion production and acceleration. In this scheme, high density laser ablation plasma, which has initial expansion velocity toward the normal direction to a target surface, moves as plasma to Radio Frequency Quadrupole linear accelerator (RFQ). Ions are extracted inside of a RFQ and immediately captured in strong rf field to minimize the space charge problem in a low energy beam transport section. A solenoid magnetic field is often applied in a

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Table 1: Estimation of Average Beam Power

Rep. rate (Hz)	Beam current (mA)	Pulse width (μs)	Charge (nC/pulse)	Energy (MeV/u)	Average current (μA)	Average power (kW)
100	50	2	100	400	10	48
100	100	2	200	1000	20	240
500	100	2	200	1000	100	1200
1000	100	5	500	1000	500	6000

plasma drift region to transversely confine the laser produced plasma. Acceleration of more than tens of mA of C^{6+} beam after a RFQ was already achieved with DPIS [4, 5].

ACHIEVABLE BEAM POWER

We estimated the possible average beam power using a high-repletion-rate LIS. We used the experimentally achieved charge state distribution of carbon ions from a 25-μm-thick target irradiated by 230 mJ of laser energy (power density = 1.2E12 W/cm^2). Figure 4 shows the charge state distribution scaled at 0.2 m from a target and 10 mm aperture in diameter. The ratio of C^{6+} ions was 46% and the total charge of C^{6+} is estimated as 125 nC per pulse. Assuming a solenoid field can fully confine the plasma expansion in transverse direction, the peak current will be inversely proportional to the distance from a target, and the beam pulse width will be proportional to the distance from target, respectively, as keeping the charge per pulse. Table 1 shows the example of the possible average beam power. The feasibility of these scenarios mainly depend on the development of lasers and high energy accelerators such as FFAG, but LIS is capable of delivering fully stripped C^{6+} with hundreds mA of beam current and more than 100 nC per pulse as described before. Our study shows that it is possible to deliver mega-watt of average beam power of heavy ion beam using a LIS.

CONCLUSION

We investigated the design of a high-repetition-rate LIS for fully stripped C^{6+} ion beam. A LIS using a Nd:YAG laser (230 mJ / 6 ns, laser power density on a target 1.2E12 W/cm^2) can provide hundreds mA and 125 nC of C^{6+} beam per pulse. The ratio of C^{6+} ion is 46% in this case. A target system to mount and move a target should be designed to keep the distance between a focusing lens and a target surface less than 0.2 mm. A roll of thin graphite target which has a thickness of at least more than 25 μm (less thickness was not tested) is a preferable choice to overcome the life time concern. Our study shows that it is possible to deliver mega-watt of average beam power of heavy ion beam using a LIS.

ACKNOWLEDGMENT

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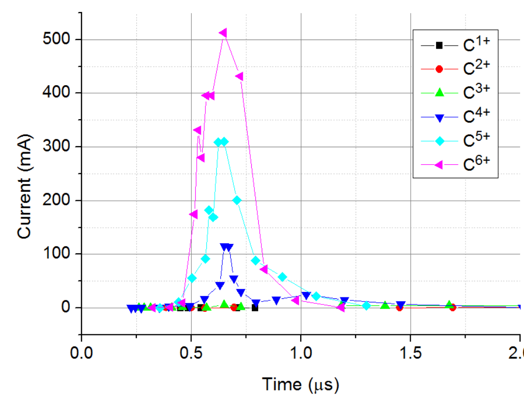

Figure 4: Charge state distribution of carbon ions scaled to 0.2 m from target within ϕ 10 mm aperture generated by a 230mJ/6ns laser shot.

REFERENCES

[1] Y. Yonemura et al., Nucl. Instr. and Meth. A576, 2007, pp.294–300.

[2] D. Trbojevic et al., "Lattice Design of a Rapid Cycling Medical Synchrotron for Carbon/Proton Therapy", IPAC11, San Sebastián, Spain, September 2011, p. 2541, 2011.

[3] T. Kanesue et al.,"Generation of highly-charged carbon ions from thin foil target", presented at IPAC'17, Copenhagen, Denmark, May 2017, paper MOPIK052, this conference.

[4] T. Kanesue et al., Rev. Sci. Instrum. 81, 02B723, 2010.

[5] T. Kanesue et al., Appl. Phys. Lett. 105, 193506, 2014.