LASER ABLATION ION SOURCE FOR HIGHLY CHARGE-STATE ION BEAMS*

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Abstract

The KEK Laser ablation ion source (KEK-LAIS) is under development in order to generate highly ionized metal and fully ionized carbon for future applications. Laser ablation experiments have been carried out by using Nd-YAG laser (0.75 J/pulse, 20 ns) at the KEK test bench. Basic parameters such as a charge-state spectrum and momentum spectrum of the plasma and extracted ion beam current have been obtained. Extraction of C ions from the LAIS is described.

INTRODUCTION

The KEK Digital Accelerator (KEK-DA) is a 10 Hz fast-cycling induction synchrotron without a large-scale injector [1]. The KEK-DA is capable of accelerating any species of ion, regardless of its possible charge state. At this moment, low-charge-state gaseous ions are provided from the X-band ECRIS [2], which is installed in the high-voltage platform. Induction synchrotron was proposed as an alternative to a RF synchrotron. Recently an ideal induction synchrotron has been designed as a hadron driver for cancer therapies [3]. It does not use a conventional injector system consisting of RFQ, DTL, and carbon stripper foil. It is indispensable to produce full-stripped carbon ions in the ion source. This compact hadron driver demands carbon ions of over10^8 per pulse in pulse width of a few µs. Now acceleration of carbon ions delivered from the KEK-LAIS in the KEK-DA is planned, where the beam emittance of around 50 mm mrad is expected just after the post acceleration of 200 kV.

The LAIS has been developed at KEK since 2012, as a method to easily produce highly charged ions at low cost [4]. Plasma in the LAIS is produced as a result of interaction between the laser and a target substance, and drifts downstream to the extraction region, where an ion beam is extracted from the plasma by applying high voltage of a few tens kV across the acceleration gap.

At KEK LAIS test bench the laser systems of Spectron SL800 (wavelength; 1064 nm, pulse width; 20 ns, energy; 750 mJ) is used as a driving laser. After some brief explanation of the experimental set-up, the results of observation of the Carbon charge state spectrum are described at first. Next the dependence of extracted ion beam current on the guiding magnetic flux density and the extracted voltage are shown and a preliminary consideration on these results is given.

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EXPERIMENTAL SET UP

Layout of the KEK-LAIS Chamber is depicted in Fig. 1. The detailed KEK-LAIS is described in Ref. 4.Used target is Graphite (IG-110), which has the density of 1.77 g/cm^3 , the homogeneous fine grain structure, and 5 mm in thickness. The LAIS chamber is evacuated by a turbo molecular pump that maintains chamber pressure on the order of 3×10^{-4} Pa.

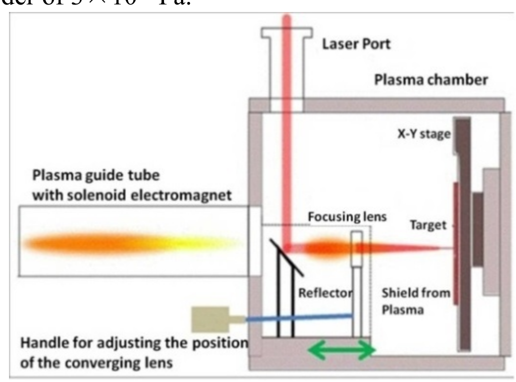

Figure1: Layout of LAIS Chamber.

Measurement of Carbon Plasma Charge State Spectrum

Schematic of the KEK-LAIS test bench, which was used to obtained the plasma current and the charge state spectrum, is depicted in Fig. 2, where the LAIS chamber, 1.5 m-long solenoid, Faraday cup (FC), and electrostatic ion analyser (EIA) are shown. A total ion beam current was observed with the FC with the aperture of 1cm in diameter located 2.6 m downstream from the carbon target. The suppressor voltage of the FC was set −2.5 kV to separate ions from plasma electrons and induced secondary electrons. The FC chamber is evacuated by a turbo molecular pump that maintains the chamber pressure at around 1×10^{-5} Pa.

The energy and charge state distribution of ions were measured by using an EIA. After 4.1 m long free expansion from the target, the ablation plasma reaches the slit located just before the bending section of the EIA; the collimated plasma enters into the bending section through the slit of less than 0.1 mm wide. Ions with a selected velocity width passes through the narrow channel, which is formed by two 90◦ bending electrodes. These electrodes radius are 15.3 and 15.8 cm, respectively. Two bending electrodes are applied the voltage V_0 of the same amplitude but opposite polarity. The selected ions then pass through the other slit and are detected by the micro channel plate (MCP, HAMAMATSU F4655-14), applied a biased voltage of -2.0 kV. The EIA chamber is evacuated by a turbo molecular pump that maintains the chamber pressure at around 4×10^{-6} Pa.

The detailed analysis procedure that has been well established is described in Ref. 5. In the data analysis, we have normalized beam current and TOF signals by assuming an observation point 1 m downstream from the target. To do this, we used the following scaling relations: T (time of flight) ~ L, I (ion current) $=1/L^3$, where L is the distance from the target.

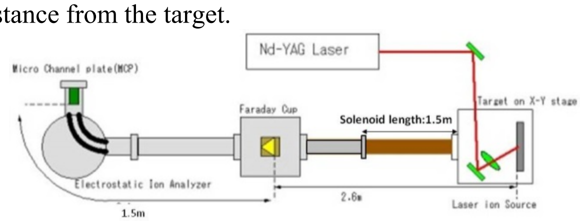

Figure 2: Charge Stage Spectrum Measurement Set-up.

Ion Beam Extraction

The test stand for the carbon ion beam extraction is depicted in Fig. 3. The distance from the target to the extraction gap is 1.3 m, where the 1m-long solenoid magnet is placed, and the distance from the extraction gap to the FC is 0.8 m. The extraction electrodes consist of the orifice with an aperture of 2.8-4mm in diameter and parallel plate type electrode of ground potential. The gap of electrodes that are installed just after the solenoid magnet is 1.8 cm. The extraction voltage of 5~30 kV is applied across the extraction gap. The FC with an aperture of 2 cm in a diameter is used with a bias voltage of -500V.

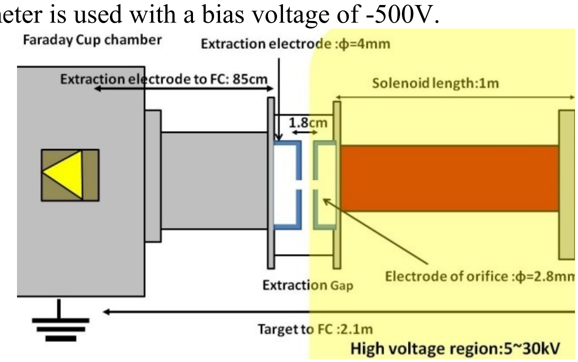

Figure 3: Extracted Ion Current Mesurement Set-up.

EXPERIMENTAL RESULTS AND DISCUSSION

Carbon Plasma Charge State Spectrum

Figure 4 shows the carbon charge state spectrum for Z=1, 2, 3, 4, 5, 6 and H^+. This results have been obtained without the guiding magnetic fields. The FC and MCP signals are averaged over 10 shots data. These results indicate that C^{4+}, C^{5+} and C^{6+} are dominant in the ablation plasma. Table1 summarizes basic parameters for C^{6+}, C^{5+} and C^{4+}. The C^{6+}, C^{5+} and C^{4+}'s pulse width (half width) are1.94, 0.98, 1.49 µs and the number of particle, which is extracted at the distance of 1.3 m from the target through the orifice, is estimated to be 5.61, 3.68, and 5.5×10^8 particles, respectively. These parameters meet the request from the KEK-DA.

Figure 5 shows the guiding field dependence of the carbon plasma current density. This result is given with averaged values and deviations as a result of averaging over 20 shots data. The current density has peak at 50 Gauss applied to the plasma, and starts to decrease after 50 Gauss.

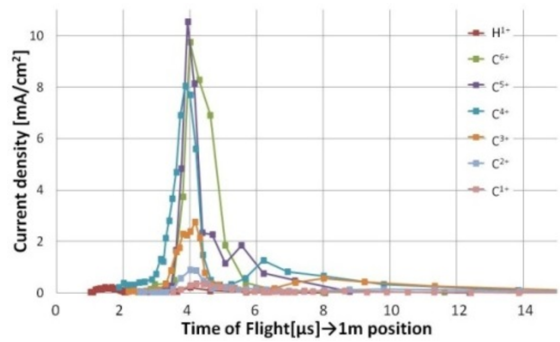

Figure 4: Carbon Charge State Spectrum at the 1 m normalized position.

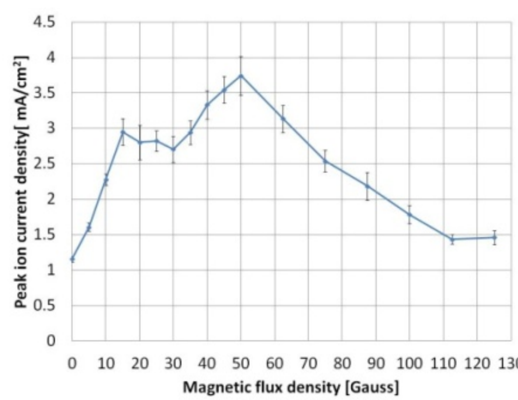

Figure 5: Magnetic Flux Density Dependence of Carbon Plasma Current Density.

Table 1: Carbon Ion Parameters

	C^{6+}	C^5	C^{4+}
Half width [µs]	1.94	0.98	1.49
Peak pulse positon [µs]	4	3.9	3.9
Peak current density [mA/cm^2]	9.7	11	8
Density (Half width) $\times10^{10}$ [particle/cm^2]	1.54	1.01	1.51
Density (Full width) $\times10^{10}$ [particle/cm^2]	2.2	2.31	3.52

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Measurement of Carbon Ion Extraction

Figure 6 shows the extraction voltage dependence of extracted carbon beam. The ablation plasma is known to be generated with about 10 to 15 degree divergence angle in a localized area of 200μm in diameter at first [4, 6]. In a case of natural drift or expanding without any guiding, the maximum divergence angle with which a fraction of ions can passes through the extraction orifice is estimated to be less than 1.1×10^{-3} rad (see Fig.7). This suggests that a whole beam passing through the orifice can arrive the FC with the inner radius of 1 cm unless there is an acceleration voltage across the extraction gap.

Meanwhile, IGUN simulations tell us that the radial electric fields give an outer edge particle a divergence angle of 2.3×10^{-2} rad at the extraction voltage of 20 kV; the extracted beam radius at the FC is estimated to be around 2.1cm. Since the divergence angle is proportional to the extraction voltage, we have to consider this divergence when the ion beam current observed by the FC with the finite aperture size of 2 cm is assessed. However, we will ignore this divergence in the following discussion for the simplicity. The largest impact of acceleration on beam propagation is the reduction in divergence, $x'=dx/ds=(dx/dt)/(ds/dt)$. The denominator in the definition almost instantaneously changes associated with acceleration in the narrow gap.

In cases with the guiding magnetic field of more than 25 Gauss, there are three notable properties for the observed beam current: (1) the observed beam current at a low extraction voltage (< 5 kV) is lower than that in the case of no-guiding, although the guided total current density is larger (see Fig. 6), (2) the observed beam current increases linearly with the extraction voltage until 25 kV, and (3) beyond 25 kV it varies depending on the guiding flux density. Though we have no experimental or numerical justification at this moment, the property (1) may be explained by the following speculation. A large fraction of the ion beam with a larger divergence angle is guided by the solenoid magnetic fields and the larger divergence prevents a whole beam from entering into the FC aperture. The property (2) may result from a substantial reduction of the divergence due to acceleration. Beyond the acceleration voltage of 25 kV, we find unexplained results. These facts are left unsolved. Direct beam profile measurement will be required along the beam pass from just after the extraction gap.

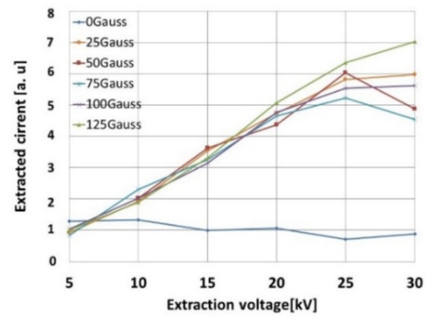

Figure 6: The extracted carbon ion vs. the extraction voltage for different guiding fields.

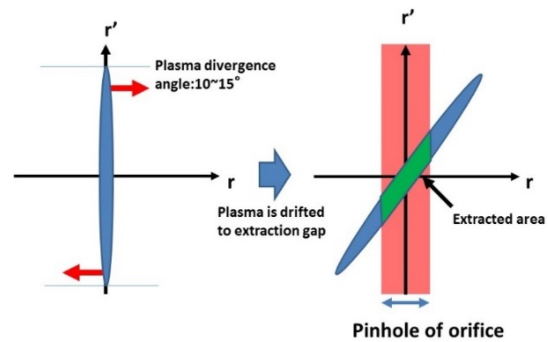

Figure 7: The estimated phase space of plasma, when immediately after generation plasma and immediately before extracted.

FUTURE PLAN

The LAIS set-up will be mounted in the high voltage platform of the KEK-DA soon. Selected C^{6+} ions are planned to be post accelerated with an additional 200 kV and introduced into the LEBT of the KEK-DA. Then, essential beam parameters such as the emittance will be measured before the coming summer.

SUMMARY

The Laser ablation experiment using the laser SL-800 has been carried out and the basic parameters of carbon ion beam have been obtained. These results indicate that C^{4+}, C^{5+}, and C^{6+} are dominant and their intensities fulfil the demands from the KEKDA.

ACKNOWLEDGEMENT

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REFERENCES

[1] K.Takayama *et al*., Phys. Rev. ST-AB 17, 010101 (2014).
[2] Leo Kwee Wah *et al*., in *Proc. ECRIS'10*, August 23-26, 2010 Grenoble, France, paper TUPOT15.
[3] Leo Kwee Wah *et al*., Phys. Rev. ST-AB 19, 042802 (2016).
[4] N.Munemoto *et al*., Rev. Sci. Inst. 85, 02B922 (2014).
[5] S. Kondrashev *et al*, .Appl. Phys. Lett. 100, 103301 (2006).
[6] K.Kondo *et al*., in *Proc. IPAC'10*, May 23-28, 2010 Kyoto, Japan, paper THPEC054.