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LASER ABLATION ION SOURCE FOR THE KEK DIGITAL ACCELERATOR

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Abstract

A laser ablation ion source (LAIS) that provides a fully ionized carbon ion beam is under development in a collaboration between KEK and BNL. It turned out that the laser pulse width dependence of C^{6+} current and energy is very large. Modified Langmuir-Child law formula was evaluated to examine C^{6+} ion beams delivered from LAIS with a large initial velocity. It is compared with IGUN simulations. A example of extraction region design is given with beam properties such as beam emittance.

INTRODUCTION

The KEK digital accelerator (KEK-DA) is a 10 Hz fast cycling induction synchrotron (IS) [1]. The KEK-DA is capable of accelerating arbitrary ions from ultra low energy of a few tens of keV to high energy of hundreds of MeV [2][3]. So far the x-band permanent magnet ECRIS [4] has been employed as an ion source. It can provide gaseous ions but not metal ions. Meanwhile, a digital accelerator has attracted a large attention in various societies for a wide variety of applications. Its application as a cancer therapy driver is among them, where fully stripped carbon ions are required. C^{6+} ions delivered from an ion source will be immediately accelerated in the digital accelerator. From these reasons, R&D works on a laser ablation ion source (LAIS) as a possible candidate of ion source, which can provide necessary high charge-state metal ions and fully stripped carbon ions started in 2012.

Main features of the LAIS recently developed in a collaboration between KEK and BNL are summarized below [5].

1) A small electric power is sufficiently enough.
2) Its system is simple. (vacuum chamber implemented with the target stage, optical equipments, laser)
3) Low cost (using laser is commercially available.)

Recent experimental results on carbon targets are reported here. It turned out that the generated ion current and charge spectrum are strongly dependent of the laser pulse width. In addition, it is noted that a drift energy of carbon ions is order of 10 keV. This fact affects on designing of the extraction region downstream from the LAIS. In order to refine the design of the extraction region including the orifice, which divides the plasma region and extraction region, and the extraction electrode, a space-charge limited current (SPLC) in a case with an initial velocity has been reconsidered. The analytic result in an idealized planar diode is compared with IGUN code simulations. A large difference in the SPLC density in magnitude between them has been found, although the extraction voltage dependence or initial energy dependence can be in agreement with each other. It is not concluded whether or not this difference can be attributed to the geometrical difference between an infinite parallel plate model and realistic 3D model. Assumed the initial beam energy and current density, the extraction region has been designed, resorting to the IGUN code.

LASER PULSE WIDTH DEPENDENCES OF C^{6+} CURRENT AND ENERGY

The characteristic of laser pulse-width dependence of the laser ablation plasma has been studied by using two Nd-YAG lasers (Laser A; λ=1064 nm, EL=750 mJ, τ=6 ns, Laser B; λ=1064 nm, EL=750mJ, τ=150~500 ps). Details of the experimental arrangement are given in Ref. 5. The laser pulse width dependence of the C^{6+} peak current density at the observation point 1m downstream from the target is shown in Fig.1. It turned out that C^{6+} peak current density strongly depends on the laser pulse width. Laser A can generate an about 30 times high current C^{6+} ion beam, compared with that of Laser B. Drift energy of each charge state ion, which is evaluated from TOF measurements, is shown in Fig.2. The drift energy and its spread in the case of Laser A is 8.1 keV and ±2.3 keV, respectively. This result suggests that the momentum spread, Δp/p, just after post acceleration of 200 kV is 5.6×10^{-3}. The momentum spread accepted by the KEK-DA is 10^{-2}. Consequently, Laser A has been decided to be employed for the KEK-LAIS.

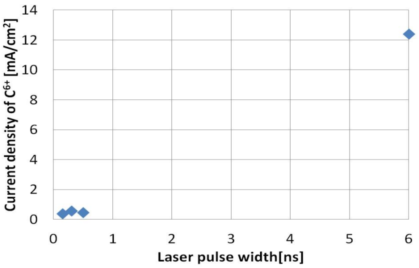

Figure 1: The C^{6+} peak current density vs. laser pulse-width.

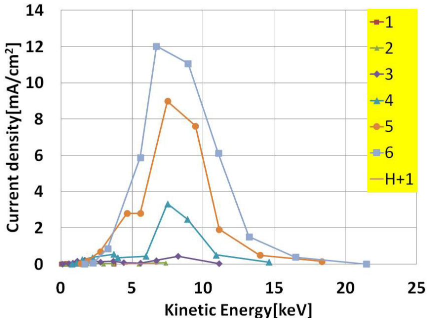

Figure 2: Current density spectrum for each charge state.

MODIFIED LANGMUIR-CHILD LAW

The plasma, which is generated in the LAIS employing Laser A, arrives at the extraction region with kinetic energy up to 20keV. Namely, the extracted ions rush headlong into the extraction region with an initial velocity. Formula of the Langmuir-Child law for a SCLC density [6] had been derived assuming that an initial velocity of charged particles of concern is zero. Since it is straightforward to extend the concept of space-charge limitation to the present case, we try this below. Assuming an infinite flat plate model of cathode and anode, in which the voltage distribution should become as shown in Fig.3, let evaluate the SPLC density in the case with an initial velocity. A fraction of ions with the initial velocity of v_0 enters into the region, resulting in modification of the potential $\phi(s)$, which satisfies the Poisson equation,

$$\frac{d^2\phi(\mathrm{s})}{ds^2} = -\frac{K}{\left[V-\phi(s)\right]^{1/2}} \tag{1}$$

where $K = \frac{i}{\varepsilon_0}.\sqrt{\frac{Am}{2Ze}}$ and $V = V_0 + \phi_0$ $\left(\phi_0 \equiv \frac{Am}{2Ze}v_0^2\right)$.

A and Z are mass number and charge-state of ions, i is the current density, and V_0 is the extraction voltage. Space charge forces, which are generated by early arriving ions, act on incoming ions so as to push back them up stream. However, incoming ions never stop in the region, because they have an initial velocity. When a number of incident particles are increased, what happens? At some number of particles, a velocity of ions becomes zero at some position, $s=p$, on the orbit coordinate between the Cathode-Anode due to strong space-charge forces. If the electric field simultaneously becomes to be zero at this position, the ion stream will stop. This is a kind of singular point. Just before this ion intensity, we can expect a steady-state flow of ion beam. This is a space-charge limited ion flow. A current density at this state is called the SPLC density. The Space-charge limit condition is characterized by $v(p)=0$ and $d\phi(p)/ds=0$. Under this condition, the space-charge limited current density is obtained in this formula.

$$i(V_0) = \frac{4\varepsilon_0}{9d^2}\sqrt{\frac{2Ze}{Am}}\cdot\left[\phi_0^{3/4} + \left(V_0+\phi_0\right)^{3/4}\right]^2 \tag{2}$$

In the limit of $\phi_0=0$, Eq. (2) is in agreement with the well-known Langmuir-Child law. As expected, it is apparent from Eq. (2) that the initial energy leads to a larger SPLC. Eq. (2) is represented by the solid lines of Fig.5. This result indicates that the extracted current density increases significantly and the required extraction voltage can be set to be small, avoiding undesired discharge.

In order to qualitatively justify above views and quantitatively obtain an expected SPLC density for an actual 3D configuration of the extraction region, IGUN simulation has been carried out. Fig.4 shows the SPLC density for different drift energies as a function of V_0. It is notable that the SPLC density curve decreases beyond some extraction voltage for a lower initial energy. Relatively strong transverse electric fields dependent of the orifice geometry gives focusing effects on a beam, resulting in a localized large charge density in the extraction gap. Consequently the space-charge limited current is reduced. In addition, there are substantial differences in magnitude between the theoretical prediction from Eq. (2) and IGUN simulation results even for cases with a higher initial voltage. This difference may be attributed to geometrical factors such as an effective gap length, although we have no enough confirmation at this moment.

Introducing a correction factor, let compare the dependence of the SPLC density on V_0 and drift energy. The effective gap length may be defined in the form of $d_{eff}=Cd$. It is noted that C should depend on V_0. However, C is set to be 5.8 here. The SPLC density $i_{IGUN}(V_0)$ obtained by the IGUN code simulation is reconstructed with a help of this correction term as follows,

$i^*(V_0) = f\left(C\right)\cdot i^*_{IGUN}(V_0) + i(V_0=0)$ where

$i^*_{IGUN}(V_0) = i_{IGUN}(V_0) - i_{IGUN}(V_0=0)$

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$i^*(V_0)$ is plotted on Fig. 5. We can seen that phenomenologically, there seems to be no big difference between both.

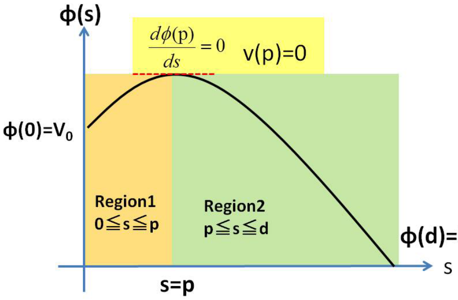

Figure3: The potential distribution in a planar diode

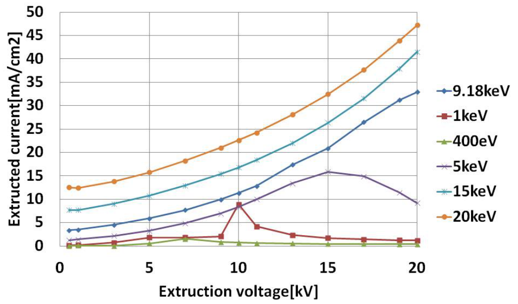

Figure4: Space charge limited current density of simulated by IGUN code.

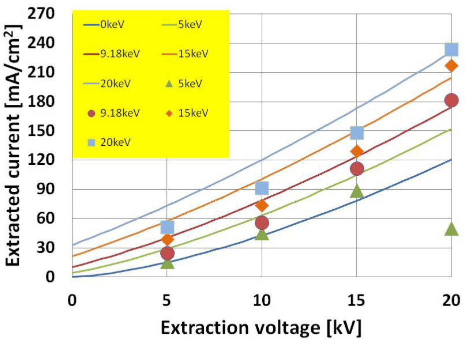

Figure 5: Modified Langmuir-Child law (solid line) and IGUN simulation with correction (colour dot).

A TYPICAL EXMAPLE OF THE EXTRACTED BEAM

The extraction region is designed, using the IGUN code. Its typical example is given in Figs.6 and7, in which the orifice with an aperture radius of 1.6 mm and extraction electrode of 4mm radius with length of 12.5 cm are shown together with beam trajectories. The acceleration gap is 6 mm. Following plasma parameters: T_e=400 eV, T_i=2 keV, and UI=8 ± 2 keV are assumed. The space-charge limited current density is 0.024 A/cm^2. The obtained normalized emittance of beam at the end of extraction electrode is 0.01~0.03 mm mrad, which is sufficiently smaller than the acceptable normalized emittance of the KEK-DA of 1.45mm mrad, although large emiitance increasing through the Einzel lens, post acceleration region, and low energy transport line must be supposed. Combination of nonlinear space-charge forces, the radial electric field components in the electrostatic devices, and fringing fields in the guiding magnets along the LEBT is known to become the sources of emittance growth.

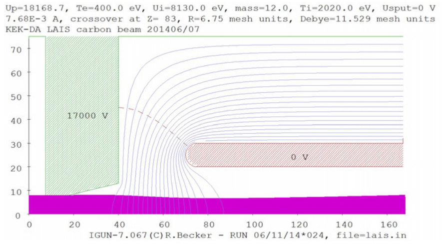

Figure 6: IGUN simulation in the extraction region.

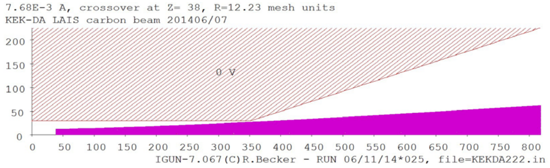

Figure7: IGUN simulation in the rear part.

CONCLUSION

1) C^{6+} current from the LAIS strongly depends on the laser pulse width.
2) C^{6+} ion beams have the initial drift energy of 8 eV.
3) The modified Langmuir-Child raw qualitatively gives the dependence of the space-charge limited current density on initial velocity and extraction voltage. Its absolute value should be obtained by a simulation code such as IGUN.

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