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INFLUENCE OF GRID CONTROL ON BEAM QUALITY IN LASER ION SOURCE GENERATING HIGH-CURRENT LOW-CHARGED COPPER IONS

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Abstract- *We examined grid-controlled extraction for a laser ion source using a KrF laser. By using grid-controlled extraction in the over-dense regime, we found that the ion beam current waveforms were stabilized more significantly as the grid bias raised from –90 V to –280 V. The normalized emittance of 0.08 πmm-mrad measured without the grid control was improved to 0.06 πmm-mrad with the grid control. In contrast to this observation, the grid bias disturbed the pattern of the beam extracted in the source-limited regime. Fast extraction was carried out using a high-voltage pulse with a rise time of ~ 100 ns. The grid control suppressed successfully the beam pedestal originating from the plasma pre-filled in the extraction gap.*

I. INTRODUCTION

Heavy ion fusion (HIF) driver accelerators are supposed to supply the heavy-ion beam pulses of several MJ with an ion energy of 3 to 10 GeV (15 to 50 MeV/u) to the reactor chambers. Then the number of ions per pulse ranges 3 to 10 $\times 10^{15}$. The space-charge effect plays an important role for such dense ion beam in particular at the low-velocity section. The HIF driver is designed to share the beam with several tens of high-current injectors for avoiding the beam divergence due to the space-charge force.[1] Even in such a HIF driver scenario, each ion source must generate heavy ions of ~ 10^{14} per pulse. Low-charged ions of 1+ to 3+ are desirable from the view-point of beam transport in the accelerators and cost-effective analyses on the total system.[2] Moreover the beam brightness is essential because the ion beams must be delivered for several kilometers and be focused to a spot of a few millimeters on a fuel target placed in the reactor chamber. This high-brightness condition requires the ion source to supply ion beams with a normalized emittance of lower than 1 πmm-mrad.[3] In the driver accelerators, the beams are compressed from ~ 10 μs finally to 10 ns as the ion energy increases.[1] So the ion source is required to generate ~ 10^{14} low-charged heavy-ions over ~ 10 μs.

Compared to other conventional plasma sources, the laser-produced plasma has several advantages such as a wide range of ion species, large ion flux, high drift velocity, high reproducibility and so on. So far the laser ion sources have been developed to generate highly charged heavy ions from a hot plasma having a temperature above 100 eV. [4] To examine the applicability of laser ion sources for HIF injectors, we intended to produce low-temperature source plasmas (<10eV) that contain primarily low-charged ions. The inverse bremsstrahlung process forms ablation plasmas with plasma temperature of T_e given by the following equation; $T_e \propto (I\lambda^2)^{2/3}$ where I is laser intensity and λ wavelength of laser light.[5,6] This equation suggests us to use a laser of short wavelength and low intensity. We have so far studied the basic properties of the source plasmas produced by a Nd:YAG laser or a KrF excimer laser at intensities of 10^8-10^9 W/cm^2. Low-charged copper ions were extracted at a current density of the order of tens of milliamperes.[7-9] The dominant charge states were 2+ and 1+ at 15 μs after the ion extraction and the mean ion charge was 1.5 to 1.3 between 15 and 60 μs. However the extracted beam current showed strong modulation in time.

In laser ion sources ion flux of the source plasma varies largely with time. The flux variation makes the ion emission surface unstable, which leads to strong modulation of the extracted beam current. We adopted the grid-controlled extractor to our laser ion source to control the emission surface.[10,11] However, the transverse electric field formed around the grid may cause an increase in transverse momentum of the ions. In addition, the virtual anode degrades the directivity of the ions. In this work we examine the influence of the grid control on the ion-beam optics.

To test the ion acceleration using the induction modules, it is desired to supply the ions with a pulse of a fast rise time synchronizing with the induction voltage. However, when the beam is extracted from the laser ion source with a fast-rise pulse voltage, the extracted beam waveform has a pedestal due to the plasma pre-filled in the extraction gap. We examine the grid control to remove the pedestal from the waveform of the fast extraction.

II EXPERIMENT

A KrF excimer laser (λ=248 nm) irradiated a copper disc placed at the end of a 50-cm-long drift chamber to produce the cold source plasma as shown in Fig.1. The laser pulse had an energy of 350 mJ and a duration of 30 ns. The typical laser intensity on the target surface was 4×10^8 W/cm^2. After the source plasma expanded in the drift chamber, the ions were extracted from the plasma with a DC voltage of up to 25 kV. The extraction gap consisted of two planer electrodes having apertures of 10 mm in diameter. The gap spacing was 18 mm.

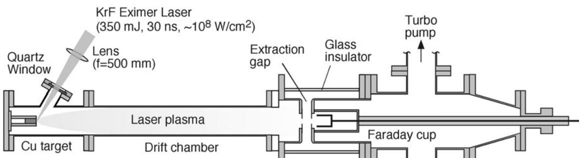

Fig.1 Layout of laser ion source

For grid-controlled extraction, a fine stainless-steel mesh (250 mesh/inch, ϕ35 μm) was attached to the anode aperture as depicted in Fig.2. The grid bias voltage was applied to the anode mesh to prevent plasma electrons from penetrating in to the gap. The minimum grid bias voltage $|V_g|$>41 V was obtained from the condition that the ion sheath thickness is larger than half of the grid spacing of 67 μm.[11] So we applied a bias voltage of –90 V to –280 V to the grid by using batteries.

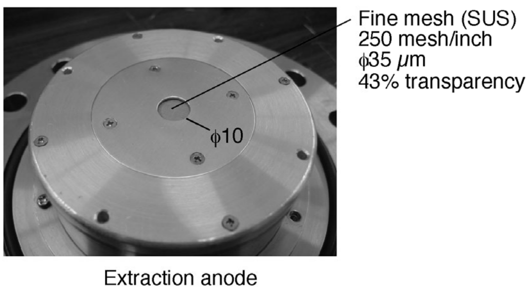

Fig.2 Picture of anode with mesh

Beam emittance was measured with pepper-pot method. A pepper-pot plate having 20 ×20 holes of ~90 μm in diameter with a spacing of 1 mm was placed at 20 mm downstream from the cathode. A micro-channel plate (MCP) assembly backed with a phosphor screen detected beam images at 22 mm downstream from the pepper-pot plate. The MCP was operated with a high-voltage gate pulse of 100 ns duration. The sensitive area of the MCP was 24 mm in diameter.

In order to examine the grid-controlled extraction on the beam emittance more precisely, we modified the extraction electrodes as following. The aperture of the anode was made smaller to 5 mm in diameter to define the beam boundary more clearly. The cathode plate was replaced with a stainless-steel mesh sheet to transmit even the periphery of the diverted beam to the MCP. The transmission of the mesh cathode was 81 %. The mesh cathode was expected to define the geometrical distribution of the extraction potential better than the cathode plate with an aperture.

A fast extraction of the beam was carried out applying a high-voltage pulse of up to 20 kV to the cathode where both anode and cathode had apertures of 10 mm in diameter. The extraction pulse had a rise time of 60 ns and a decay time of 20 ms. Fig.3 shows a high-voltage network and a pulse shape of the high-voltage. We used a spark gap as a switching device.

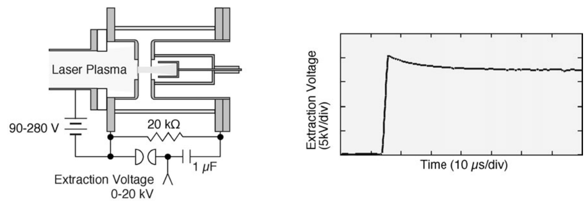

Fig.3 A schematic of fast extraction and a pulse shape of extraction voltage

III RESULTS

The ion flux supply from the source plasma is enough for the beam extraction when the extraction voltage V_E is low. We define this regime as over-dense mode. With the grid control at the grid bias of –90 V, the current density of the extracted beam increased in proportion to $V_E^{3/2}$ between V_E= 5 kV and V_E=9 kV (over-dense regime) and then revealed saturation. At V_E>10 kV, the source plasma could not supply enough ions corresponding to the current density defined by the extraction voltage (source-limited regime).[11] We measured the dependence of the ion beam waveforms on the grid bias in the over-dense regime at V_E=5 kV. The grid bias was scanned from –90 to –280 V. The current density was ~ 3 mA/cm^2 over 20 μs. The waveform contained 3×10^{11} and 7×10^{11} ions at V_E=5 kV and 9 kV, respectively. Fig.4a indicates that the waveforms became more stabilized with increasing bias voltage. This fluctuation of waveforms could result from the time dependence of the ion charge states; the charge states of 1+ and 2+ became dominant at time later than 20 μs after the laser irradiation. For the comparison Fig4b shows the beam profile observed without the grid control. In this case the beam fluctuation is more remarkable. It is clear that the grid-controlled extraction suppress the strong fluctuation of the ion beam waveforms.

Fig.5 shows the normalized emittance of the extracted copper beams measured as a function of grid bias for the over-dense regime at V_E=6.0 kV. The data point obtained without the grid control is also depicted for comparison. At first it should be noted that the emittance was lower than 0.1 πmm-mrad irrespective of the grid control. The grid control improved slightly the emittance. This observation was not in accord with the simple expectation that the transverse electric force of the grid deteriorate the emittance. The emittance observed with the grid-controlled extraction was independent of the grid bias. The grid bias of –90 V was enough to control the beam extraction. The present observation suggests that the virtual anode formed between the anode and the cathode filtered the ions, which had large transverse momentum.

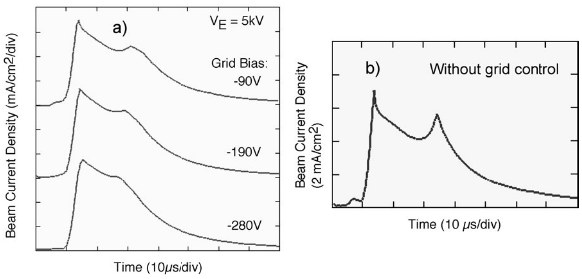

Fig.4 Dependence of ion beam waveforms on grid bias voltage. Extraction voltage is 5 kV. a) with grid control at bias voltages of at –90, -190 and –280 V, b) without grid control.

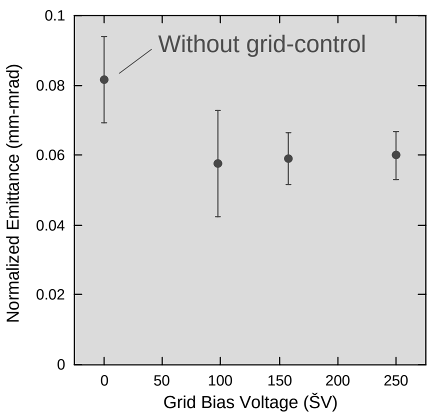

Fig.5 Normalized emittance measured as a function of grid bias

In contrast to the over-dense mode, the beam extraction was influenced by the grid bias. Fig.6 shows the pepper-pot images observed for the source-limited regime where the extraction voltage was 15.3 kV. The images were recorded after 20 µs from laser irradiation with an exposure time of 100 ns. As the grid bias increased, the disorder of the beam pattern became more remarkable. This observation indicates that the grid potential deflected the ions significantly and disturbed the emittance.

However in the above measurement we used the anode electrode with an aperture of 10 mm in diameter. This aperture size was rather large compared to the sensitive area of the MCP because the extracted beam was diverging. This geometrical condition interfered the transmission of the ions. So we measured the pepper-pot images using the anode with an aperture grid of 5 mm in diameter and the mesh cathode. Fig.7 shows the pepper-pot images taken in the over-dense regime at the extraction voltage of 6 kV. In this case we observed no disturbance of the beam pattern. In the over-dense regime where the beam extraction was governed by the space-charge limited current, the grid bias did not influence the beam pattern.

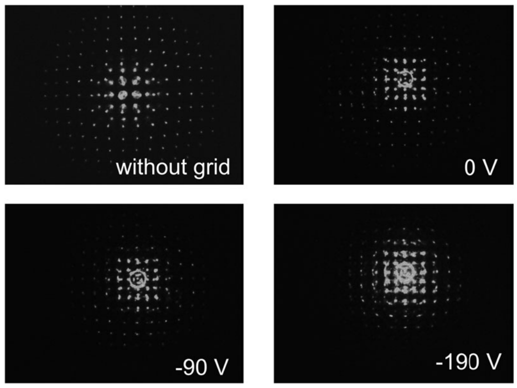

Fig.6 Pepper-pot images taken in a source-limited regime.

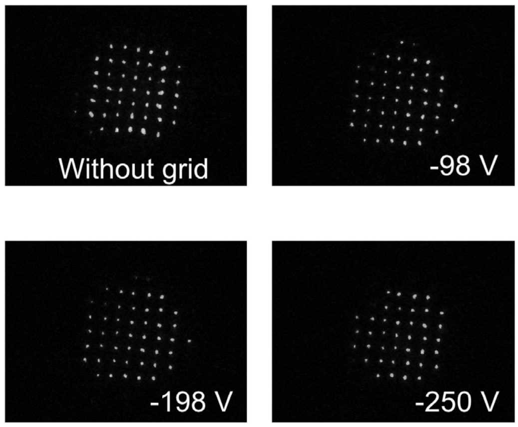

Fig.7 Pepper-pot images taken in an over-dense regime

Fast extraction of the beam was demonstrated using the grid control. Fig.8 compares the current density profiles measured for three cases. When the grid control was not active corresponding to a) and b), the beam pedestal was obvious. Once the grid was biased at –90 V, the beam pedestal disappeared. The grid control suppressed the beam leakage due to the plasma pre-fill. The rise time of the beam current was 60 ns.

IV SUMMARY

We developed a grid-controlled laser ion source using a KrF excimer laser for production of source plasma of copper. The waveforms of the ion beam were stabilized applying the grid-controlled extraction in an over-dense regime. As the grid bias

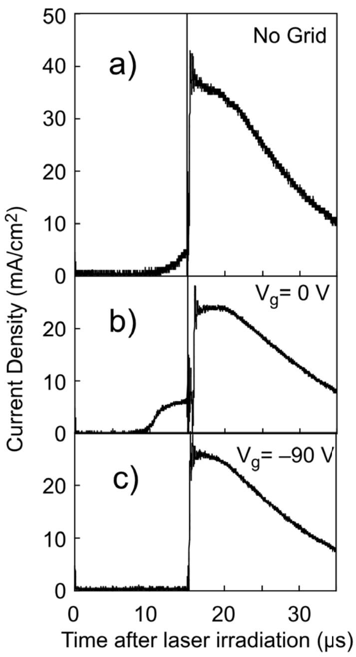

Fig.8 Profiles of beams extracted with a fast high-voltage pulse. a) an anode had no grid, b) an anode with grid was used but bias was not applied to grid, c) grid-controlled extraction at bias of –90 V.

increased from –90 V to –280 V, the ion beam waveform was stabilized more. The normalized emittance measured in the over-dense regime was improved from 0.08 πmm-mrad to 0.06 πmm-mrad with the grid control. The emittance was independent of the grid bias. This observation suggests that the virtual anode between the anode and the cathode filtered the ions with large transverse momentum. The transverse electric force formed around the grid did not interfere the emittance in the over-dense regime. We demonstrated that the grid control was also useful for the fast extraction. The ion-beam waveform was free from the pedestal and had a rise time of 60 ns.

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