BNL-112226-2016-CP

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Presented at the 16th International Conference on Ion Sources
New York Marriott Marquis Hotel, New York, NY
August 23 – 28, 2015

May 2016

Collider-Accelerator Department

Brookhaven National Laboratory

U.S. Department of Energy
Office of Science, Office of Nuclear Physics

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Effect of solenoid in various conditions of laser ion source at Brookhaven National Laboratory[a)]

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(Presented XXXXX; received XXXXX; accepted XXXXX; published online XXXXX)
(Dates appearing here are provided by the Editorial Office)

In the laser ion source (LIS) at the Brookhaven National Laboratory (BNL), a solenoid is used to guide the laser ablation plasma and modulate the extracted beam current. Many types of ion species are guided. In some cases, the plasma plume is injected into the solenoid away from the solenoidal axis. To investigate the effects of the solenoid on the beam extracted from the plasma that has the different properties, the beam current was measured in the setup of the LIS at the BNL. The beam current of Li, Al, Si, Fe, and Au increased when the magnetic field was applied. For most of the species the peak current and the total charge within a single beam pulse increased around 10 times with a magnetic field less than 100 G. In addition, for some species the rate of increase of the peak currents became smaller when the magnetic flux densities were larger than certain values depending on the species. In this case, the current waveforms were distorted. At the same magnetic field value, the field was more effective on lighter species than heavier ones. When plasma was injected offset from the axis of the solenoid, peak current and total charge became half those without offset. The experimental data are useful for the operation of the LIS at the BNL.

I. Introduction

With a laser one can produce many types of heavy ions from solids, and the development of lasers has improved the reproducibility of the ion production. A laser ion source (LIS) is operated to produce singly charged heavy ion beams for injection into an EBIS for the Relativistic Heavy Ion Collider and the NASA Space Radiation Laboratory at the Brookhaven National Laboratory (BNL)[1]. In the LIS, the plasma plume produced from a solid target drifts normal to the target and is injected into an extraction electrode placed at a distance of 3 m. A solenoidal coil is wound on the vacuum pipe between the target and the electrode, set to adjust the input of the plasma into the electrode and the current of the extracted ion beam.

Previous research reported the enhancement of the beam current by applying a solenoidal magnetic field on carbon and copper plasma. In the research, the center of the plasma plume was on the solenoidal axis[2,3]. However, in the LIS system at the BNL, the plasma is produced with many types of species, and the center of the plasma plume is off the solenoidal axis in some cases. To produce the required beam with the LIS, one needs to get a better understanding of the effect of the magnetic flied on plasmas with different properties. Therefore, to investigate the effects of the solenidal field on the beam extracted from many types of plasma, we measured the extracted beam current using a solenoid in the setup of the LIS at the BNL.

II. Experimental Setup

Figure 1 is a schematic of experimental setup. Linearly moving targets called XY targets for on-axis plasma production and rotating targets for off-axis production were used. The target chamber was evacuated to the range of 1.2×10^{-8} Torr.

In the XY target system, plates of several types of species (Li, Al, Si, Fe, Au) were placed on a linear stage. The linear stage was moved slowly during laser pulsing to avoid seriously damaging the target surface, as well as moved to switch the target species. Quantel Brilliant B TWINS (wave length is 1064 nm, pulse width is 6 ns, spot size was 0.31 cm^2) was used for the XY target. The laser spot on the target surface was on the axis of the solenoid. In the rotating target system, Al and Au ring targets were placed on a disk. The laser spots on Al and Au rings were at distances of 46 and 56 mm from the axis of the solenoid, respectively. The disk was rotated to avoid seriously damaging the target surface. A Quantel Brilliant B (wave length is 1064 nm, pulse width is 6 ns, spot size was 0.92 cm^2) was used with the rotating targets. The target species

[a)]Contributed paper published as part of the Proceedings of the 16th International Conference on Ion Source, New York, USA, August, 2015.
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was selected by changing laser path with a wedged window.

Figure 2 shows current waveforms of Fe beam measured by the CT as a function of time after the laser shot. Each curve is average of 8 pulses. The laser spot was on the solenoidal axis. The red curve is the current without magnetic field and the others are with magnetic fields. The current waveform increased as magnetic field increased from 0 to 17 G, and the peak current was about 10 times as much as without magnetic field. After that, the rate of increase of the peak current became smaller. On the other hand, when the field was larger than 17 G, the pulse width and the total charge in a single beam pulse still increased.

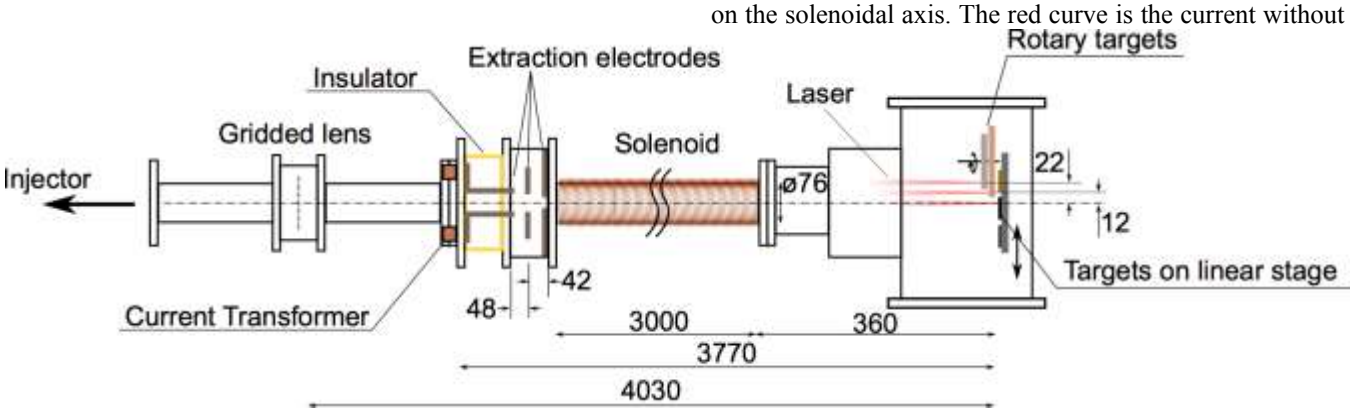

Figure 1 Experimental setup

The length and the inner diameter of the solenoid were 3000 mm and 76 mm, respectively. A copper wire with 2.1 mm diameter was wound 1430 turns per 1 layer and the solenoid had 2 layers. A current of 1A in the solenoid generated 11.6 G at center. The coil was energized with a DC power supply.

The vacuum chamber and the solenoid were biased up to around 20 kV and the ion beam was extracted using a 3 electrode extraction system. The first electrode was at the vacuum chamber potential. The potential of the intermediate electrode was adjusted for each ion species to extract a parallel beam. The electrode at the downstream side was grounded. The beam current was measured with a current transformer ACCT-S-082[4] (CT) and also on a metal mesh added to a gridded lens. It was confirmed that the extracted beam was approximately parallel by observing that the current waveform measured with the CT was similar to that on the mesh.

III. Results and discussions

A. Difference of magnetic effect among species

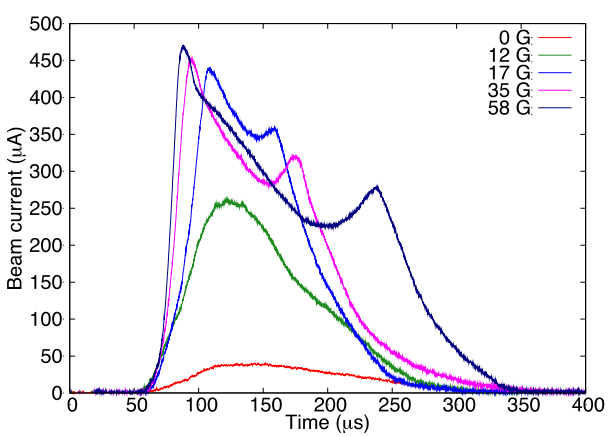

Figure 2. Fe current measured with a current transformer in the presence of magnetic field

The peak current and the total charge for each species were measured with changing magnetic field. The same laser energy (420 mJ) and the power density were used for all species. Furthermore, the laser spot was on the axis of

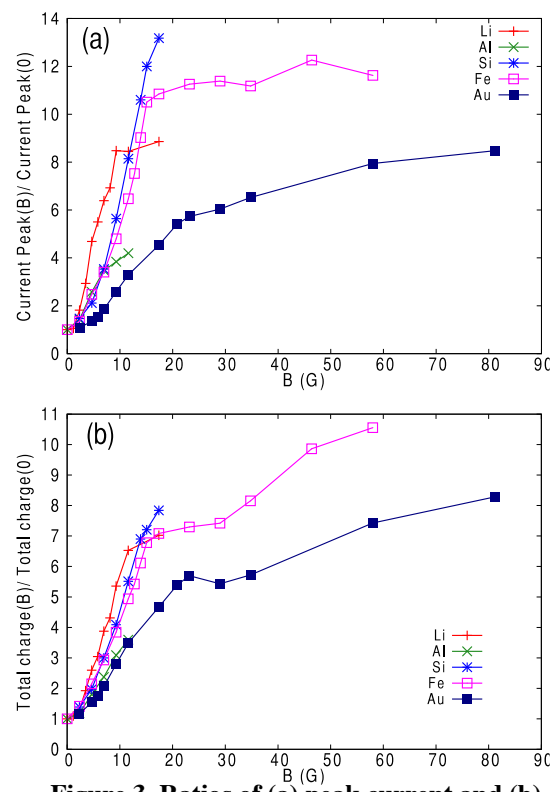

Figure 3. Ratios of (a) peak current and (b) total charge within a single beam pulse of each species with/without magnetic field, respectively

the solenoid. Figures 3(a) and 3(b) show the results. The vertical axes of Figs.3(a) and 3(b) are the ratios of the current peak and the total charge with/without the field, respectively. As shown in Fig.3(a), the ratios of the peak currents of any species increased with increasing magnetic field. This ratio, for species other than Al, became around 10. The plots of Li, Fe, and Au had the points where the rate of increase of the ratios became smaller. For instance, the ratio of Fe increased more gradually when the magnetic field was larger than 17 G. As for Al and Si, this tendency was not observed in our experimental condition. Larger magnetic field could not be used because the plasma ion current became too high to be extracted parallel. Figure 3(b) shows that the total charge of any species increased as the magnetic field increased. The ratios for the species other than Al reached around 10 with magnetic field less than 100 G. Similar to the peak current, the rate of increase of the charges of Li, Fe, and Au became smaller after certain magnetic flux densities. In addition, the shape of the current waveform became distorted as shown in Fig.2.

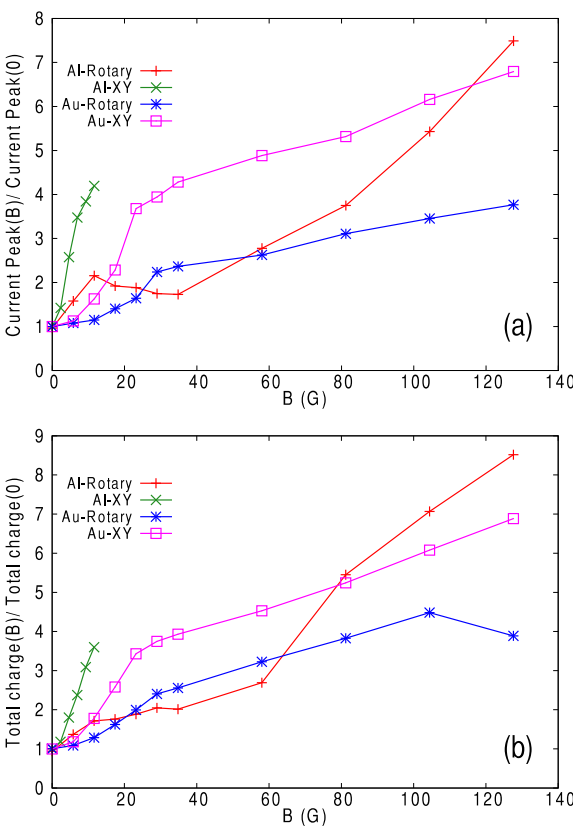

Figure 4. Ratios of (a) peak current and (b) total charge with/without magnetic field of Al and Au on rotary or XY targets as functions of magnetic flux density

It was found that the increase of the current and the total charge of the lighter species were larger than that of the heavier species when a certain magnetic flux density was applied. This means that greater magnetic field is needed for heavier species in operation.

Figure 3 can be used to determine the magnetic flux density required to produce a desired beam current and total charge. In addition, it can be determined whether a magnetic flux density will cause the distortion of the current waveform for Li, Fe, and Au.

B. Influence of off-axis plasma production

The current and the total charge were measured when the laser spot was away from the axis, and compared this with the on-axis results. The laser energy was adjusted so that the currents of on-axis and off-axis were same. The laser energies were 420 mJ for the on-axis Al target, 851 mJ for the off-axis Al target, 550 mJ for the on-axis Au target, and 851 mJ for the off-axis Au target. Figures 4(a) and 4(b) show the results. The red and green plots are the results for Al of off-axis and on-axis, respectively. The blue and purple plots are the results for Au of off-axis and on-axis, respectively. It was found that both the current and the total charge of Al and Au produced off-axis were half those of on-axis. Fig. 4 is useful to determine the value of the magnetic flux density for the operation of the LIS.

IV. Conclusion

Effects of a solenoidal magnetic field on beam current extracted for several species (Li, Al, Si, Fe, and Au) and for off-axis vs. on-axis production were investigated in the setup of the LIS at the BNL. For all species, the peak current and the total charge within a single beam pulse increased with the solenoid. Species other than Al increased around 10 times with a magnetic field less than 100 G. The rate of the increase as a function of B of the peak current of Li, Fe, and Au became smaller when the magnetic flux densities were larger than certain values depending on the species. On the other hand, the peak current and total charge of lighter species were larger than those of the heavier ones when the magnetic flux density was same. When plasma was produced off the solenoidal axis, both the peak current and total charge became half. The experimental data are useful for the operation of the LIS.

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