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Plasma shape control by pulsed solenoid on laser ion source

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ABSTRACT

A Laser ion source (LIS) provides high current heavy ion beams with a very simple mechanical structure. Plasma is produced by a pulsed laser ablation of a solid state target and ions are extracted by an electric field. However, it was difficult to manipulate the beam parameters of a LIS, since the plasma condition could only be adjusted by the laser irradiation condition. To enhance flexibility of LIS operation, we employed a pulsed solenoid in the plasma drift section and investigated the effect of the solenoid field on singly charged iron beams. The experimentally obtained current profile was satisfactorily controlled by the pulsed magnetic field. This approach may also be useful to reduce beam emittance of a LIS.

1. Introduction

Various types of ion sources are being used to provide heavy ion beams to accelerators in the world. Most of the leading heavy ion facilities employ electron beam ion source (EBIS) [1,2] or electron cyclotron resonance ion source (ECRIS) [3–5]. In spite of this world trend, we have focused on studying the laser ion source (LIS) [6]. The LIS is recognized as a high intensity heavy ion source in the field [7], which can induce higher current beams with the simpler structure than other types of ion sources. In a LIS, plasma is produced by ablation of a solid state target and expands into vacuum. The plasma generation and ionization is driven only by a laser shot without any external electromagnetic confinement forces. Instantaneous laser energy deposition on a dense solid material can ionize considerable amount of atoms, not like other ion sources which use gases or vapors as source materials.

On the other hand, it was quite difficult to manipulate the beam parameters of a typical LIS, since the initial formation of plasma is determined only by the condition of the laser irradiation. Within the range of laser power density from 10^8 to 10^{13} W/cm^2 on the target, which is our region of interest, the laser energy is absorbed mainly by inverse-bremsstrahlung process and the plasma temperature is increased. The charge state of ions is developed and reaches equilibrium due to the high collision rate. The charge state distribution is frozen after the collision rate is decreased as plasma expands. The velocity spread shows a shifted Maxwell–Boltzmann distribution at the beam extraction point [8]. This typical beam profile of the LIS may cause a problem. For an accelerator application, the design of accelerators after an ion source must carefully consider the highest beam current. The accelerators need to accommodate the peak value of the current distribution. For example, the maximum beam current from the injector at beam injection of a synchrotron is typically determined by a constant value called space charge limit. To maximize the total yield of accelerated ions and injection efficiency, a LIS is required to provide ion beam pulse with constant beam current.

In addition, modification of a temporal current waveform affects ion beam emittance. A typical LIS consists of a laser, a solid target, plasma drift section, where the induced plasma expands, and ion extraction electrodes. After ionization process at the target surface, plasma adiabatically expands in the drift section while moving towards the extraction point. Generally initial beam emittance of an ion source is related to an ion temperature in the plasma since the transverse motions of the ions are given by the thermal distribution. Because a LIS typically has a long drift section (a few tens of centimeters to several meters), only a very small fraction of the plasma, which is collimated within the solid angle between a focused laser spot on the target and the extraction aperture, is extracted as an

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ion beam. The extracted beam should have very small transverse energy distribution, or emittance, due to the thermal effect in the plasma creation.

However, an ion beam from a LIS normally has small but certain amount of beam emittance. In our measurement, typical ion beam emittance measured by a pepper pot emittance monitor was about 0.038π mm mrad (normalized, root mean square). This emittance is mainly caused by temporal variation of plasma density at the ion beam extraction point. The boundary shape between plasma and an ion beam is determined by a relationship of plasma density and the space charge limit current density described as Child–Langmuir equation. The equation is described as [9]

$$j_i = \frac{4\varepsilon_0}{9}\sqrt{\frac{2eZ}{m_i}\frac{1}{d^2}}\left(\sqrt{U_0}+\sqrt{U_0+U_{ac}}\right)^3 \qquad (1)$$

where $j_i, \varepsilon_0, e, Z, m_i$ and d are current density, dielectric constant, elementary charge, charge number, mass of the ion and gap width between plasma boundary and cathode, respectively. Kinetic energy of ion, which represents flowing plasma, is given as U_0. U_{ac} is the extraction potential in the gap. This equation indicates that the boundary shape changes as kinetic energy of ion and plasma density changes. Therefore the divergence of extracting beam is changing within a single ion beam pulse. By controlling the temporal current density precisely, the beam emittance from a LIS could be minimized. This scheme potentially has a significant impact on future high current accelerator projects.

However we could not have an efficient knob to control the beam current profile in a conventional LIS configuration. To overcome this issue, we propose to use a rapidly changing solenoid magnetic field at the plasma drift section to obtain desired temporal current profile. Our recent studies showed that a static solenoid field enhances the ion beam current dramatically (factor of several tens by one to two hundred Gauss of the solenoid field) [10–13]. Also relatively short solenoids have been examined by other group [14,15]. In our studies, static solenoid fields ranging from a few Gauss up to about 500 Gauss with various solenoid lengths up to 3.0 m were tested. We confirmed that a longitudinal magnetic field guides low and high charge states ions and reduce the diverging angle of the expanding plasma. As a result, the temporal current profile was enhanced. For instance, when we apply 4.2 Gauss on the solenoid, we gain about 30 % increase on singly charged Cu ion beam current. A new LIS equipped with a 3.0 m solenoid was installed to provide primary ion beam for the Relativistic Heavy Ion Collider–Electron Beam Ion Source (RHIC–EBIS) used for RHIC and NASA Space Radiation Laboratory at Brookhaven National Laboratory (BNL) [16,17]. The solenoid was used to adjust ion beam current.

2. Introduction of pulsed solenoid

A static magnetic field is very useful to adjust the entire current profile. However, temporal structure of the ion beam cannot be controlled. When the rising and falling time of a pulsed solenoid field is shorter than the ion current profile, the temporal structure can be controlled to be close to a flat-top beam shape. To verify the idea, we fabricated a short solenoid with a simple pulsed power supply and investigated the effect of the pulsed magnetic field on laser produced plasma experimentally.

For the test, a new solenoid was built. This has 50 turns of 2.0 mm copper wire wound around a glass tube (96 mm in outer diameter, 110 mm long). Due to the fast ramp rate, an instantaneous high voltage, typically a few kV, was needed to pulse the coil. The coil was driven by a pulsed power supply consisted of a 0.63 μF capacitor, a 3 kV HV power supply, and a Behlke fast switch (HTS 61-40). The achieved ramp rate was about 10 μs for the rising waveform. To eliminate the influence of the high voltage potential on the expanding plasma, the entire coil was surrounded by a grounded aluminum foil which has a narrow slit to prevent the azimuthal flow of the eddy current. Fig. 1 shows a photo of the pulsed solenoid.

3. Experimental layout

The influence of the pulsed solenoid field on iron plasma produced by a Nd:YAG laser was measured. The pulse coil shown in the previous section was inserted in the existing LIS test bench. Fig. 2 shows a setup used for the experiment. The pulsed coil was positioned in vacuum at 200 mm downstream of a 1-mm-thick iron target. We used the iron target since it has a medium range mass and is robust against laser exposure. A 3-m-long solenoid was followed to provide a static magnetic field of 4.2 Gauss. A Faraday Cup (FC) is placed at the exit of the long solenoid at 3300 mm away from the target to measure ion beam flux in laser produced plasma. A mesh in front of the FC was biased by -3.5 kV to extract ions from plasma. A grounded 10 mm diameter aperture was placed before the mesh to collimate plasma. The setup was kept in vacuum at the pressure about 6×10^{-4} Pa.

To simplify the experiment, we used the plasma dominantly containing singly charged ions, which has slower expansion velocity than that of plasma with highly charged ions, so that the ramp rate

Fig. 1. Photograph of the pulsed solenoid.

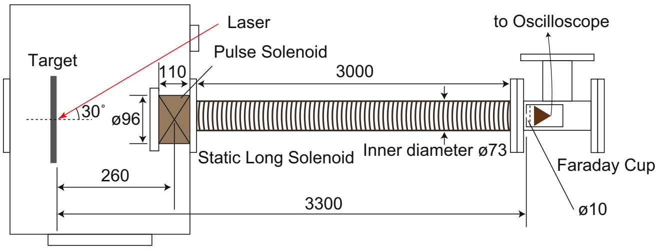

Fig. 2. Experimental layout. Dimensions are in millimeters.