CONTROL OF LASER ABLATION PLASMA BY PULSED MAGNETIC FIELD FOR HEAVY ION BEAM PRODUCTION*

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Abstract

To improve the total charge and quality of a beam pulse from the laser ion source (LIS) operated at Brookhaven National Laboratory (BNL), we attempt to modify the beam current profile to be flatter by applying a pulsed magnetic field to the plasma. For this purpose, we investigated the suitable magnetic field experimentally with a quasi-steady field. We found that a magnetic field decreasing from 90 G to 60 G within 10 μs is expected to create a flat current profile. To drive such a current, we designed a coil and a modified LC discharge circuit. The coil will be installed into LIS at BNL and the effect will be tested.

INTRODUCTION

In the laser ion source (LIS), a pulsed ion beam is extracted from plasma generated by laser irradiation on a solid. The source provides many ion species such as Li, C, Al, Si, Fe, and Au ions to the Relativistic Heavy Ion Collider and the NASA Space Radiation Laboratory (NSRL) at Brookhaven National Laboratory (BNL) [1]. Typically, the plasma drifts and spreads three-dimensionally with a constant velocity distribution in the absence of an external force [2]. The current of the ion beam extracted from the freely spreading plasma varies drastically in time within a single beam pulse. The shape of the current waveform is determined by the velocity distribution and cannot be controlled without applying an external force. In this case, the total charge in a pulse is maximized when the peak current is equal to the space charge limit current while current in most part of beam pulse is less than the limit current by several tens of percent. This means that we can increase the total charge if we can control the current waveform. In addition, the extraction from the varying plasma flux causes larger emittance than estimated by the thermal energy spread. Therefore, as an upgrade of LIS for NSRL operation, we attempt to generate a flat-topped, long beam pulse by controlling the plasma plume with a pulsed magnetic field. A magnetic field can modify the plasma shape. Therefore, we expect to generate a flat-topped beam current by changing the magnetic field in accordance with the plasma density distribution.

To predict a suitable pulsed magnetic field, we investigated the dependence of the plasma flux waveform on the strength of a quasi-steady magnetic field. We designed a coil and a pulse circuit for Fe plasma on the basis of the experimental results.

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EXPERIMENTAL SETUP

The experimental setup is shown in Fig. 1. The laser target was a Fe plate. Laser energy, spot size, and power density on the target were 380 mJ, 0.1 cm^2, and 6x10^8 W/cm^2, respectively. The power density was almost the same as that of LIS at BNL and mainly produces singly charged ions. A six-turn coil with a 50 mm diameter and 5 mm length was placed at a distance of 260 mm from the target. The distance was determined with the configuration of the present LIS at BNL. The coil current was generated by a pulse circuit composed of 50 μF storage capacitor. The time scale of the current change was much larger than the duration of plasma passing through the coil. The decrease in magnetic field during the plasma traversal was 10%, small enough to consider the field generated by the coil as steady. A negatively biased ion probe with a 2 mm diameter aperture was used to measure the plasma flux as an ion-saturated current density. The bias voltage was -180 V. The probe was placed at a distance of 690 mm from the target.

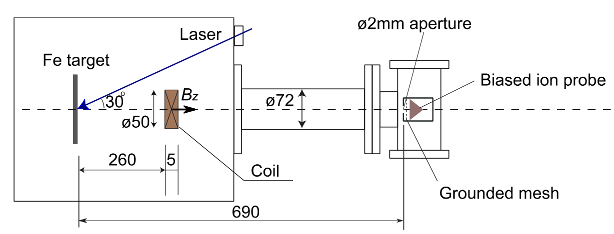

Figure 1: Experimental setup.

RESULTS AND DISCUSSIONS

Figure 2 is the graph of the measured plasma flux. The horizontal axis is time from laser shot. The red curve is the flux without the magnetic field and the other curves are with the field. As shown in the figure, the fast and slow parts of the plasma were enhanced by several tens of gauss magnetic field. In addition, as the field increased, the peaks of both parts increased more while the peak times of the fast part were almost constant and those of the slow part shifted forward.

Based on these results, we can design a suitable pulsed magnetic field. Because the two parts of the plasma were

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affected, the time profile of magnetic field would be complicated if we control both parts. Therefore, to avoid this complication, we do not control the fast part and do not apply the magnetic field to it. This can be achieved by raising the field rapidly after the fast part of plasma passes through the coil. After that, we control the slow part to increase the plasma flux to make the magnitude equal the original peak around 20 μs. As experimental results showed, the peak of slow part was slower as the magnetic field was weaker. Therefore, if we apply 90 G on the region of the plasma around 25 μs, 70 G on the region around 40 μs, and 60 G on the region around 60 μs, the plasma flux of each region is expected to be almost matched to that of the original peak. To apply each magnetic field strength on each region of the plasma, we need to generate the appropriate magnetic field at the time when each region arrives at the coil. The arrival time at the coil for each region can be calculated from the arrival time at the ion probe. Because each region moves with constant velocity, each arrival time is proportional to the flight distance. So, if we fix the position of the coil, the arrival times are determined and then, the fall time of the magnetic field is determined accordingly.

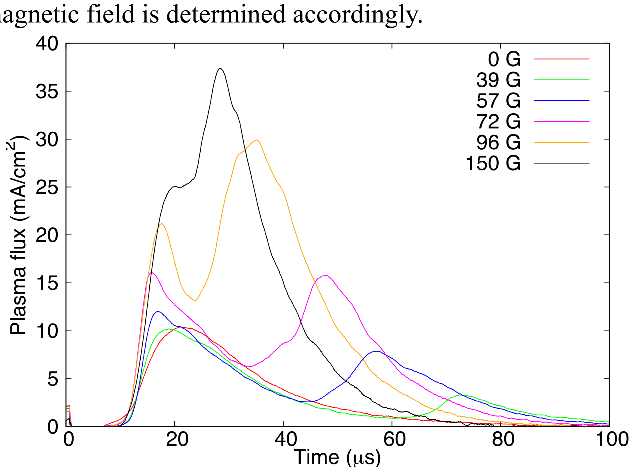

Figure 2: Plasma flux measured at a distance of 690 mm from the laser target with and without magnetic field.

DESIGN OF COIL AND PULSED CIRCUIT

Mechanical Design

To avoid obstructing the plasma, the diameter of coil is 75 mm, matching the vacuum pipe in the LIS at BNL. The length of the coil is 75 mm; that is larger than what is used in the present experiment to decrease the current in the coil and obtain a more uniform magnetic field profile. The coil center is at a distance of 220 mm from the target, this is determined by the configuration of the present LIS. A wire is wound 100 times and there are two layers of coil. The winding number determines the inductance of the coil and the field strength generated by a given current. Therefore, the number was determined by the design of the pulsed circuit driving the coil. When the coil current rises rapidly, the coil is charged up and the electric field can affect the plasma if it is not shielded. To shield the coil, we insert a thin aluminium tube into the coil. The tube has a longitudinal slit to prevent the rising magnetic field from inducing an azimuthal eddy current.

Design of Pulsed Circuit

Because the velocity distribution was constant [2], plasma flux waveform at a distance from the target is similar. Namely, if the normalized waveform at a distance z from the target is described as $i(t)/i_{peak}(z)$, the normalized waveform at the other distance z' is described as $i(tz/z')/i_{peak}(z')$. Therefore, we can calculate the plasma flux waveform at the coil center at a distance of 220 mm from the taret with the waveform at 690 mm. The red curve in Fig. 3 is the calculated waveform without a magnetic field. We can find that the arrival time of original peak at the coil center is around 8 μs and the time of the part reaching the ion probe at 60 μs is around 19 μs. Therefore, the required time profile for the magnetic field rapidly rises to 90 G around 8 μs and then decreases to 60 G around 19 μs.

To drive such a current, we designed an LC circuit modified to set rise and fall time independently as shown in Fig.4. Capacitor C1 is a discharge capacitor that determines the rise time. The discharge starts when switch S1 is turned on. Capacitors C3 and C4 determine the fall time. If switch S2 is on, C4 is connected to C3 in parallel and the fall time becomes longer. After the plasma passes through the coil, S1 is turned off and the circuit begins recovering. During recovery, C1 is recharged by V1 through R1 and C3 and C4 are discharged through resistors R3 and R4. Because the LIS at BNL produces beam to NSRL around once per four seconds, R1, R3, and R4 are determined to complete recovery within four seconds. The calculated coil current is shown by the green curve in Fig.3. The peak current can be adjusted by varying the charging voltage. The pulsed coil will be installed into the present LIS and the performance will be tested.

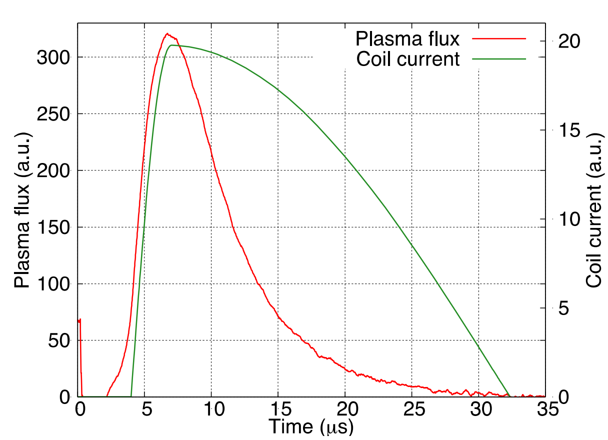

Figure 3: Plasma flux at center of coil and coil current.

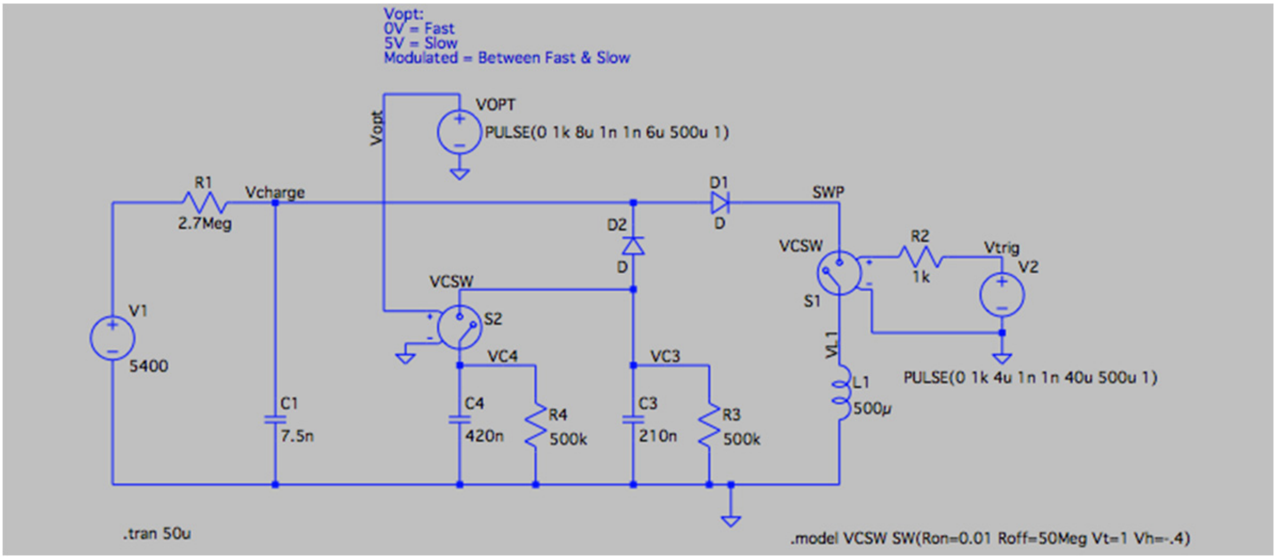

Figure 4: Pulse circuit diagram.

SUMMARY

We are studying the effect of a pulsed solenoid field on laser ablation plasma to improve quality and total charge within a signle pulse of an ion beam. We collected the basic data on a test bench and then found that the magnetic field decreasing from 90 G to 60 G within 10 µs is expected to produce a flat current profile. To prove the advantage of the pulsed solenoid, we will install a specially designed pulsed solenoid in the Laser Ion Source for the RHIC-EBIS (LION) at BNL. The electrical and mechanical design was finished and we started fabrication.

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