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CONTROL OF PLASMA FLUX WITH PULSED SOLENOID FOR LASER ION SOURCE

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Abstract

In a typical configuration of a laser ion source, the plasma flux into an extraction electrode changes transiently. We try to make the constant plasma flux within a pulse with use of a pulsed magnetic field. Here to estimate the optimal magnetic field, we investigated the effect of the steady magnetic field generated by a coil on the plasma experimentally. We observed the plasma flux enhancement and the dependency of the enhancement on the longitudinal velocity of the ions and the magnetic flux density. The dependency indicates the magnetic field acts like a solenoid lens. We may predict the plasma flux enhancement by calculation of the orbit of a virtual charged particle whose mass is between those of the ion and electron.

INTRODUCTION

Laser ion source is expected to produce high current pulsed beam of many type of heavy ions. The ion source has been studied as highly charged ion source [1,2] and high flux ion source [3]. These days it began to produce the some type of heavy ions to the accelerator at Brookhaven National Laboratory. The ion source can produce several μA current and 100 μs pulse width.

In typical laser ion source, the plasma is produced on the target surface, drifts for some distances, and is injected to an extraction electrode. The plasma flux at the electrode is not constant within a pulse because of the dispersion in drifting due to the broad and non-uniform ion velocity distribution. The distribution is described by shifted-Maxwell distribution [4]. The change of the plasma flux level leads a transiently changing shape of the sheath boundary [5]. Thereby, the integrated emittance is larger than the stroboscopic emittance at a certain time slice. In addition, the beam current extracted from the plasma is not constant within a pulse.

To prevent the transient effect, we try to control the plasma flux density at the extraction electrode with use of a pulsed magnetic field generated by a coil. The radial Lorentz force is expected to not only change the divergence of the drifting plasma but enhance the flux density at the extractor also. So, if we apply the pulsed magnetic flux density according to the transient flux level of ablation plasma, we can expect to make the flux level flat.

The interaction of a drifting plasma and a magnetic field varies according to the physical quantity of the plasma and the magnetic field. Typically, the plasma is taken as conductive fluid in a large time and space scale, while taken as the particles in a small scale. In the present paper, to estimate the optimal pulsed magnetic field, we investigated the effect of the steady magnetic field on the plasma experimentally. We scanned a plasma flux detector that is an ion probe along the beam axis and change the magnetic flux density.

EXPERIMENTAL SETUP

Figure 1 is a brief schematic of the experimental set up. A Nd:YAG laser (THALES SAGA 230) irradiated a Fe target with pulse width of 6 ns. The laser energy was 500 mJ. The pressure in the chamber was 7×10^{-5} Pa.

A 6-turn coil with 50 mm in diameter and 5mm in width generated the pulsed magnetic field. The coil was covered with an aluminum sheet for electrically shielding. The current in the coil was produced from a capacitor. Because the decay time was much longer than the duration of the plasma passing throw the coil, the magnetic flux density decreased less than 10 %. We took the magnetic field as constant.

A biased ion probe was used to measure the plasma ion current. The bias voltage was 200 V that was determined experimentally to get the saturated ion current. The ion probe could scan from 500 to 1200 mm from the target surface. A 2-mm-diameter aperture and a metal mesh whose transparency was 90.3 % was grounded and placed in front of the probe.

RESULT AND DISCUSSION

We measured the plasma flux as a function of the magnetic flux density at $L = 690$ mm distance from the target. Figure 2 is the result. The horizontal axis is the time from the laser irradiation. The vertical axis is the plasma ion current. We show the magnetic flux density B_c at the centre of the coil in the upper right of the figure. The figure shows that the two peaks at the front and rear appeared in the presence of the magnetic field. The height of the two peaks and the time of the rear peak depended on the magnetic flux

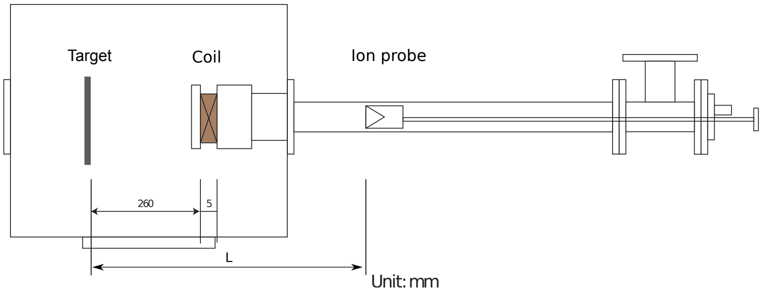

Figure 1: Schematic of experimental setup

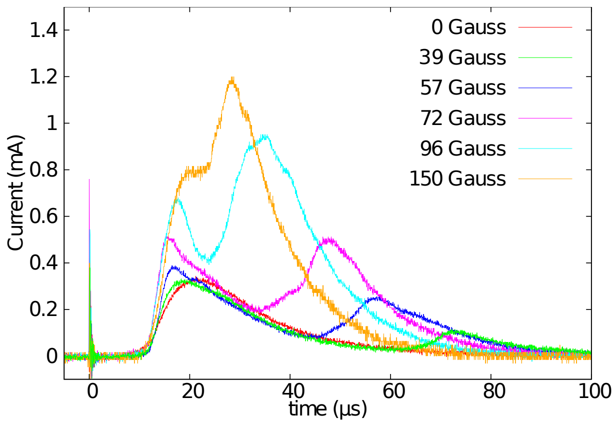

Figure 2: Flux at L = 690 mm

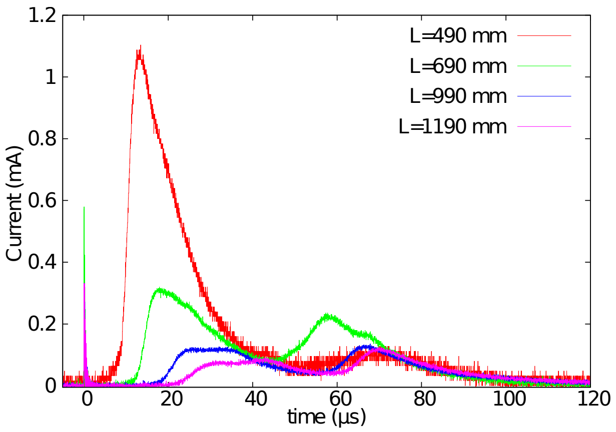

Figure 3: Flux at B_z = 57 Gauss

density. We may control the plasma flux by changing the magnetic flux density transiently according to the dependency.

The rear peak shifted frontward as B_c increased. The appearance of the peak and the shift indicate that the peak resulted from the lens effect of the coil magnetic field. A focal length of a solenoid lens depends on the longitudinal velocity v_z of a charged particle. If the coil magnetic field acts like solenoid lens, the dependency on v_z makes a flux peak at the ion probe because v_z of the ions in the plasma are distributed. In addition, as the magnetic flux density is larger, the faster ions would focus at the ion probe. The dependency of the time of the rear peak on B_c means that of v_z of the ions on B_c.

The front peak did not shift so much. It indicates that the mechanism of the flux enhancement would differ from that of the rear peak. The front one may result from the transient distortion of the magnetic field caused by the eddy current in the plasma.

We fixed B_c = 57 Gauss and measured the plasma flux at L = 490, 690, 990, and 1190 mm. As shown in fig.3, the front peak shifted rearward and the height decreased as L became larger. The shift means that the time of flight of the ions increased with increasing L and the decrease resulted from the three dimensional spread of the plasma [4]. In this case, the front peak at each L was composed of the same ions that have a velocity v_z. On the other hand, the rear peak did not shift and the height did not decrease so regularly. These means that the peak was not composed of the same ions and the the plasma did not spread three dimensionally. The difference of the front and rear peaks also indicates that the plasma focused by the coil magnetic field and the velocity of the ions composing of the rear peak depended on the B_c and L.

To investigate the relation between B_c and v_z of the ions that compose of the rear peak, we measured the flux with changing B_c and L. The v_z of the ions can be estimated by the division of the probe position L by the time of the rear peak. Figure 4 shows the plot of the relation of B_c and v_z at each L. The horizontal axis is B_c and the vertical axis is the v_z. The distance L are shown in the upper right of the figure. We took and plot 5 data under the same condition, that is, same B_c and L. At any distance, v_z seems to be proportional to B_c when B_c is less than 100 Gauss. The tendency also indicates the lens effect of the coil magnetic field on the plasma. If the paraxial ray, thin lens, and non relativistic approximation are assumed, the relation among v_z, B_c, and the focal length f of a solenoidal lens is described as

$$\frac{1}{f} = \left(\frac{B_c}{v_z}\right)^2 \left(\frac{q}{2m}\right)^2 \int_{z_1}^{z_2} (B_z/B_c)^2 dz \qquad (1)$$

where m is the ion mass, q is the ion charge, B_z is the longitudinal magnetic flux density on the axis, and the solenoidal magnetic field is assumed to be present from z_1 to z_2. So, it follows that v_z is proportional to B_c when f is fixed. Figure 4 also shows the increase of v_z with increasing L when B_c is

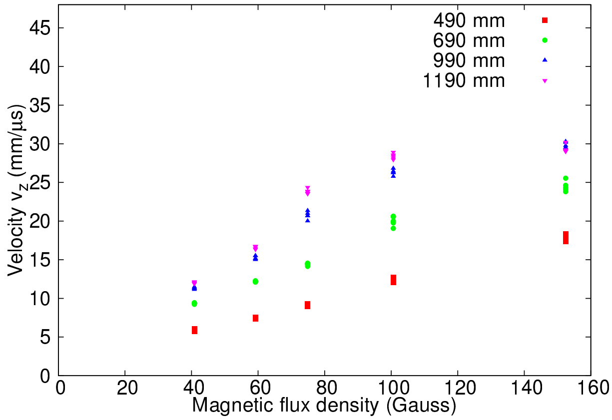

Figure 4: B vs V_z

constant. The tendency corresponds to the relation among v_z and f of a solenoid lens.

The relation among v_z, B_c, and L obtained by the experiments, when B_c was less than 100 Gauss, indicates that we can treat the effect of the coil magnetic field on the plasma as a solenoid lens. So, we may be able to explain the relation by the orbit of a virtual charged particle whose mass is between those of the Fe ion and electron. Some researchers claimed that the focal length of an ion beam neutralised by co-moving electrons corresponds to that of the charged particle whose mass is $\sqrt{m_i m_e}$, where m_i is the mass of the ion and m_e is that of the electron [6–8]. They derived the mass from the assumption that the angular momentum of the electron is conserved and the radial force on the electron equillibrate. We can get the dependency of $(v_z/B_c)^2$ on $f = L - 260$ mm from the experimental data. Then, we can estimate the mass of the virtual particle comparing the obtained dependency with the equation (1).

Figure 5 shows the dependency of $(v_z/B_c)^2$ on f obtained from the experimental results and a fitting line. The equation of the line was set up from the equation (1) and the fitting parameter was the mass m. The integration of $(B_z/B_c)^2$ was calculated numerically from -140 to 660 mm. We assumed a singly charged ion. The obtained m was $2.8 \times m_p$, where m_p is the mass of proton. The result shows that we can explain the dependency of $(v_z/B_c)^2$ on f roughly with use of a virtual ion whose mass number is 2.8. We can predict the relation among v_z, B_c, and L and the optimal magnetic field to control the plasma flux into an extraction electrode.

The mass of the virtual particle is about 16 times larger than the geometric mean of those although the mass is between those of the Fe ion and the electron. The variance may be caused by the eddy current in the plasma or the collision of the electrons or the electron and ion. Some researchers [7, 8] pointed out that the focusing force in a solenoid would be decreased by the electron pressure or the eddy current. In addition, the ion-electron collision breaks the conservation of the angular momentum.

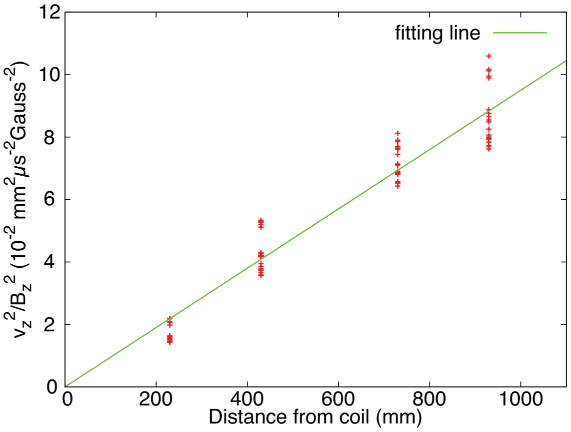

Figure 5: f vs $(V_z/B_c)^2$

SUMMARY

To predict the optimal pulsed magnetic field to make the constant plasma flux within a pulse, we investigated the effect of a constant coil magnetic field on a laser ablation plasma. The magnetic field increased a part of the plasma flux that formed a peak. The part changed as functions of the magnetic flux density B_c and the distance L from the target and the ion probe. The change means the velocity of the ions that composed of the peak depended on B_c and L. We considered the dependency caused by the lens effect of the coil magnetic field on the ions in the plasma. Then, we estimated the mass of a virtual charged particle that can be used to predict the dependency roughly. The virtual particle can be used to predict the optimal pulsed magnetic field.

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