Plasma Transport in Periodic Magnetic Field by Permanent Ring Magnets

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(Received 27 November 2012 / Accepted 7 December 2012)

The feasibility of plasma transport in periodic magnetic fields was studied for the pulse length control and modulation of laser ablation ion sources. The field was created by permanent magnet rings and the plasma ion flux was investigated as a function of the field profile and the transport distance. The results showed that the field is effective for the plasma guiding and the transport efficiency depends on the field profiles. The results also indicated that collective effects play an important role in the plasma guiding.

Keywords: laser ablation plasma, laser ion source, magnetic confinement, magnet, plasma guiding

DOI: 10.1585/pfr.8.1206005

Laser ion sources are expected to be used for applications requiring high flux and highly charged ions. Because the source plasma is produced by a short-pulse (~10 ns) laser, the beam pulse length is controlled by changing the plasma drift distance L between the laser target surface and the ion extraction electrodes [1]. However, the extracted beam current decreases significantly with L ($\sim L^{-3}$) because of free expansion of the laser ablation plasma. The effects of a solenoidal magnetic field on the laser ablation plasma have been investigated to transversely confine the plasma and gain a higher ion flux [2–5]. In this paper, we propose a plasma guiding method using permanent magnet rings instead of solenoids. Permanent magnets neither generate heat load nor require electric power. Thus, a plasma guiding system using permanent magnets is expected to be more compatible with a beam injector.

Magnetic field profiles with permanent magnet rings inevitably have cusp-like fields at the entrance and the exit of the magnet array. Charged particles cannot pass through the field without restraint because they tend to move along magnetic field lines. On the other hand, the collective effects of plasma [6] may assist the plasma transport. The field profiles in the array of permanent magnet rings also depends also on the interval of each magnet. Although the peak field strength can be enhanced by increasing the intervals between the magnets, the field fluctuation becomes more apparent, which might be harmful for the drifting plasma. Thus, we investigated how the laser ablation plasma is transported through the periodic magnetic fields.

A schematic of the experimental arrangement is shown in Fig. 1. A KrF excimer laser (248 nm, 20 ns) was focused on a copper target by a lens with a focal length of 300 mm. The laser pulse energy was $\sim 1.2 \times 10^2$ mJ, and the laser spot area was ~0.8 mm^2 on the target. The power density was estimated to be 8×10^8 W/cm^2. A Faraday cup with a 6 mmϕ aperture was placed on the center axis of the drift tube to measure the plasma ion current. Voltages of −300 V and −400 V were supplied to the Faraday cup and secondary electron suppressor, respectively. The chamber pressure was of the order of 10^{-4} Pa. The distance between the target and the front edge of the first magnet was 350 mm, and the inner diameter of the drift tube was 47 mm.

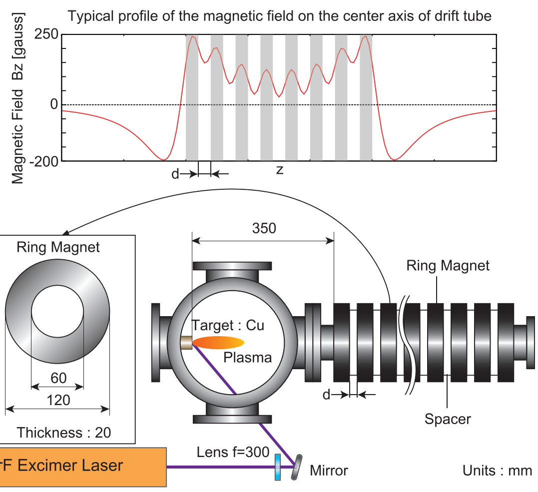

Fig. 1 Schematic of experimental arrangement and typical magnetic field profile.

Ferrite magnet rings of $\sim 4 \times 10^2$ G at the center of the ring were used. The outer and inner diameters were

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120 mm and 60 mm, respectively, and the thickness of the ring was 20 mm. The graph in Fig. 1 shows an example (d = 20 mm) of the longitudinal magnetic field B_z induced by eight magnet rings. The shaded regions show the locations of the magnets; the magnetic field has small peaks at the center of each magnet. As the interval between each pair of magnets d increases, the amplitude of the magnetic field becomes large. Various magnetic field configurations were tested with intervals of 0, 10, 20, and 40 mm. The total length of the magnet array was ~300 mm for all configurations. The polar directions of the magnets were always the same.

We measured the plasma ion currents without magnets and with four different magnetic profiles and compared them to find the condition in which the plasma can be efficiently transported. The measurement was repeated three times at each Faraday cup position. All currents had a Maxwell-Boltzmann-like waveform with a most probable velocity of 2×10^6 cm/s. Figure 2 shows the variations in the peak current density as a function of the plasma drift distance from the target. We can see that the plasma flux was proportional to L^{-3} without magnets and it was clearly enhanced by the magnetic field. Surprisingly, the current densities were already enhanced before entering the first magnet (L ~ 300 mm), which indicates that the plasma was collected by the converging magnetic field in front of the magnet array. Although the current densities decreased at 350 mm due to the cusp-like field, they were enhanced again at the entrance of the first magnet (L ~ 400 mm). Owing to these enhancements by the magnetic field, the ion flux could increase by almost an order of magnitude throughout the transport region compared with that of the freely expanded plasma. The result also showed that the decay rate of the current density depended slightly on the field configuration. The decay rates with magnets of 10 mm and 20 mm intervals were obviously smaller than those with the other configurations.

Figure 3 shows the peak current densities of the plasma flux measured by a multi-aperture (ϕ = 2 mm) Faraday cup. The radial positions of the apertures were 0, 7, and 14 mm from the center axis of the drift tube. As shown in Fig. 3, the distribution of the current density was homogeneous without the magnetic field. In contrast, when the magnetic field was applied, the current at the center of the drift tube was enhanced compared with those at the other two positions.

If we assume that the plasma temperature is ~1 eV, the magnetic Reynolds number R_m was estimated to be ~1. This means that the plasma electrons were almost fully magnetized because the magnetic field can diffuse into the ablation plasma rapidly (~0.01 µs) during plasma expansion (~10 µs). On the other hand, the ion Larmor radius was estimated to be not less than ~20 mm under a maximum magnetic field of 500 G at r = 0 and the radial velocity derived from the maximum divergence angle of the ions entering the drift tube. This indicates that the diameter of

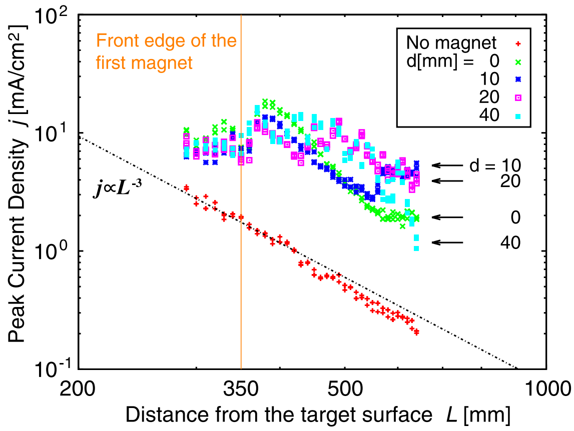

Fig. 2 Peak plasma flux as a function of transport distance with four types of magnetic profiles and without magnetic field.

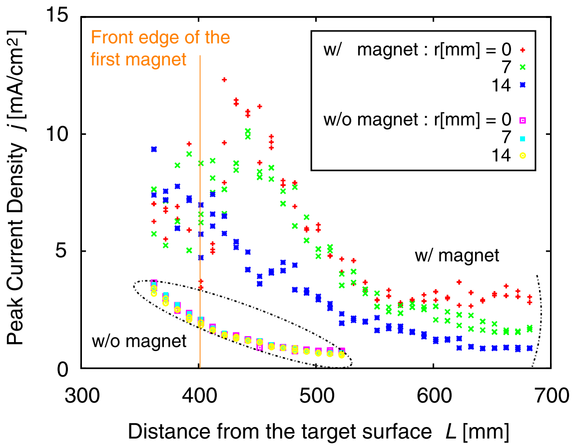

Fig. 3 Plasma flux at r = 0, 7, and 14 mm with (d = 0) and without magnetic field.

the gyration is comparable to or larger than that of the drift tube. Obviously, a single-particle model cannot describe the experimental results, which implies that the collective effects of plasma contribute to the guiding mechanism of the ablation plasma [6].

We investigated the effect of the periodic magnetic field formed by permanent magnet rings on the transport of laser ablation plasma. The results showed that the plasma ion flux increases significantly with the magnetic field, in particular at the entrance of the first magnet. The results also indicate that the guiding effect can be optimized by considering the collective effects of the plasma.

We thank Prof. T. Kikuchi for his encouraging advice. This work was partially supported by Grant-In-Aid for Scientific Research (A) (KAKENHI No. 23240082).

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