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Formation of dense, electromagnetically accelerated plasma for laboratory astrophysics

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Abstract. We proposed tapered pinch discharge as a measure to conduct laboratory astrophysics experiments. Basic behaviors of the plasma have been characterized using a prototype device. Results show that the plasma flux and velocity depend on initial gas density, discharge current and taper geometry. Those behaviors can be illustrated with a simple model considering the pinching dynamics of the current sheet based on a 1 dimensional (1-D) equation of motion. Achievable value of the tapered pinch plasma is estimated and compared with required plasma parameters based on scaling parameters for laboratory astrophysics.

1. INTRODUCTION

Formation of collisionless plasma shock wave and acceleration of charged particles are considered to be related to the interaction between a high-speed plasma flow and a magnetic field in space. As an approach to study unclear mechanisms of the phenomena, not only observation using satellites and numerical simulation, but also laboratory astrophysics has attracted great attention [1]. The phenomena are expected to be well reproduced in laboratory, if parameters relevant to the astrophysical phenomena satisfy a scaling condition.

There are important scaling parameters to reproduce the astrophysical phenomena in laboratory. For the formation of collisionless shock, Alfvén Mach number M_A, plasma beta β and inertial length over plasma size are thought to be important scaling parameters. Table 1 shows a comparison between average value of solar wind plasma and laboratory plasma based on the dimensionless parameters. According to Table 1, a dense, high-speed plasma flow is required for conducting the interaction experiment. Plasma parameters such as plasma velocity U, ion density n_i, ion temperature T_i and plasma size must be separately controlled for parametric study of the laboratory astrophysics.

2. TAPERED PINCH DISCHARGE

2.1 Concept and advantages

Lasers [2], z-pinch discharges [3] and arc channels [4] have been conventionally used to drive the high-speed flow. However, in case of hydro-dynamical acceleration, heating up and expansion processes are inevitable for making the flow, in which the density and the flow speed are gas-dynamically correlated. On the other hand, in case of electro-magnetic acceleration, such a correlation is expected to be weak.

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Table 1. Important scaling parameters for interaction experiments between plasma and magnetic field in the solar system.

Parameter	Solar wind	Laboratory
Density n (cm^{-3})	7	$\sim 10^{15}$
Fluid velocity (km/s)	450	$\sim$100
Ion tamperature (K)	1.2×10^5	$\sim 10^5$
Magnetic field |B| (T)	7×10^{-9}	$\sim$0.1
Plasma size L (m)	$\sim 10^7$	$\sim$0.1
MA	7	7
β	0.6	0.6
$(c/\omega_{pi})/L$	$\sim$0.01	$\sim$0.01

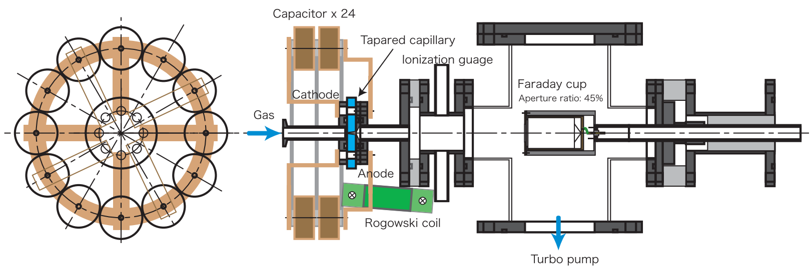

Figure 1. Schematic diagram of discharge chamber.

We proposed a new type of plasma source using a z-pinch discharge with a tapered capillary [5]. In this scheme, the current sheet in the tapered capillary not only radially compresses but also axially accelerates the plasma. The electromagnetic energy is converted to the thermal energy and the kinetic energy in radial and axial directions of the moving plasma. In previus study [6], an argon plasma was accelerated to 700 km/s by a tapered pinch discharge with a fast pulse power generator, which drove a load current of 80 kA with a pulse width of 70 ns. In this device, the geometry of tapered capillary is expected to play an important role in distributing the energy.

This scheme is expected to be suitable for a parametric study of the laboratory astrophysics because of the weak correlation between the plasma parameters. However, behaviors of tapered pinch plasma in the capillary and out of the capillary are not clear. We intend to clarify the behavior of tapered pinch plasma by checking the relationships between the experimental conditions (i.e., initial gas density in the capillary, discharge current wave-form, and capillary geometry) and the plasma parameters (i.e., axial velocity, flux, and temperature) in a prototype capillary device.

2.2 Experimental apparatus

The tapered capillary was filled quasi-statically with a well-defined density of argon gas by differential pumping and pre-ionized by an RC ($\sim$400 μs) discharge of 15 A for moderating the nonuniformity of the discharge. An LC-inversion-type pulse generator with a capacitance of 12 nF was installed for driving the main discharge circuit, as shown in Fig. 1. The length and inlet radius of the tapered capillary were 10 mm and 0.5 mm, respectively. The moving plasma flux was measured as a function of the gas density, the peak discharge current and the taper angle by a Faraday cup. The velocity is estimated by time of flight (TOF) method. The main discharge current was measured by a Rogowski coil.

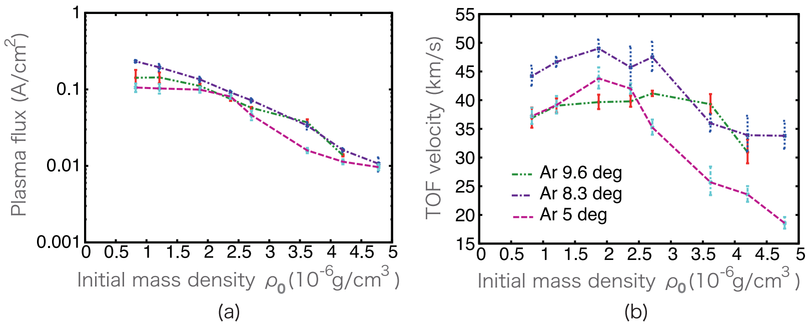

Figure 2. Dependence of plasma flux and velocity on initial mass density. (a)(b) Peak discharge current is 6 kA. Taper angle θ is 8.3 deg. Faraday cup is located at 20 cm from end of the capillary.

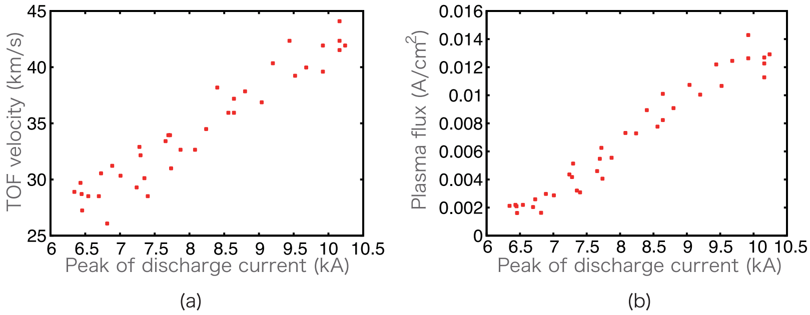

Figure 3. Plasma parameter scaling for discharge current. (a)(b) Points in the figure show experimental results. Taper angle θ is 8.3 deg. Argon gas is filled in the capillary, where initial mass density $\rho_0 = 2.4 \times 10^{-6}$ g/cm^3. The Faraday cup is located at 40 cm from end of the capillary.

2.3 Important parameters of electromagnetically driven plasma

In the tapered capillary, the current sheet is sequentially pinched along the z axis. Radial motion of the current sheet is described by 1-D equation of motion with slow-plow model as shown by Eq. (1),

$$\frac{d}{dt}\left[\rho_0 \pi (r_o^2 - r^2)\frac{dr}{dt}\right] = -\frac{\mu_0 I^2(t)}{4\pi r} + 2\pi r P_0 \left(\frac{r_0}{r}\right)^{2\gamma}, \tag{1}$$

where, ρ_0, P_0 and r_0 are initial mass density, initial pressure and initial radius. Equation (1) indicates that the current sheet is basically controlled by initial mass density ρ_0, discharge current wave form $I(t)$ and initial radius r_0. In case of 2 dimensional motion, the taper angle θ is important parameter instead of the initial radius r_0. Above parameters are expected to affect the motion of plasma.

3. EXPERIMENTAL RESULTS AND DISCUSSIONS

The plasma velocity and the flux are shown as a function of the initial mass density in Fig. 2(a) and (b). Figure 2(a) shows that the plasma flux is inversely proportional to ρ_0 and almost independent of the taper angle θ. On the other hand, the plasma velocity depended on the taper angle as shown in Fig. 2(b). This means the taper angle affects mainly plasma velocity, in this operating condition.

Figure 3(a) and (b) show the relationship between those parameters and the peak discharge current. The plasma flux and velocity increased with the range of peak discharge current. If the plasma flux and velocity increase linearly with peak discharge current, the plasma flux and the velocity can reach

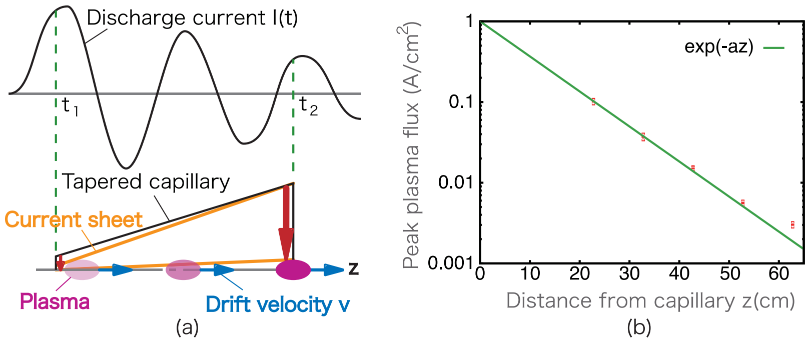

Figure 4. Behavior of the plasma in the capillary and drift region. (a) Synchronization between current sheet and moving plasma. (b) Decay rate of plasma flux, where points show measured peak plasma flux and the solid line is a fitting by exponential decay with (a = 10).

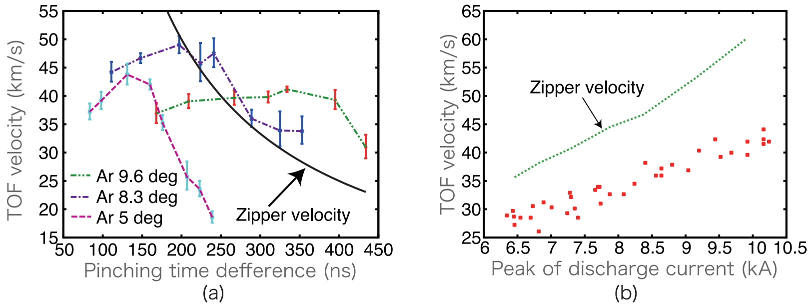

Figure 5. Correlation of plasma velocity with zipper velocity.

40 A/cm^2 and 500 km/s respectively at the discharge current of 100 kA. However, this is not assured extrapolation because higher discharge current tends to induce plasma instability strongly.

For formation of dense, high speed flow, the critical factor is synchronization between the radial pinching of current sheet and the axial movement of plasma. Then the plasma parameters must be correlated with pinching times at inlet and outlet of the capillary. Figure 4(a) shows an illustration of the pinching process, where t_1 and t_2 mean time that radius of current sheet reaches to 50 μm at inlet and outlet of the capillary. Those are calculated with Eq. (1) and measured dischage current. Plasma velocity can be estimated by zipper velocity $l/(t_2 - t_1)$, here l is the length of capillary, under the assumption that plasma moves at constant velocity from inlet to outlet of tapered capillary during pinching time difference. Figure 5 shows the comparison between the plasma velocity and the zipper velocity. We expected that the plasma flux and velocity maximize when the pinching time difference is close to the zipper velocity. As shown in Fig. 5(a), the plasma velocity can be related to the zipper velocity at $\theta = 8.3$ deg. This result means if experimental condition is optimized, plasma velocity can be related to the zipper velocity. The plasma velocity versus the discharge current is shown in Fig. 5(b) together with the zipper velocity. In Fig. 5(b), it is thought that the motion of plasma does not synchronize with the radial motion of current sheet. It is important to make clear how the plasma flux depends on the peak discharge current and the taper angle θ. Although the experimental results do not agree entirely with theoretical estimation without plasma accumulation in the tapered capillary, the results indicate the dependence of the plasma velocity on the zipper velocity.

4. SUMMARY

Plasmas produced by a taper pinch discharge were characterized. Results show dependences of plasma flux and velocity on the initial gas density, the discharge current and the taper geometry. Results also indicate a correlation of the plasma velocity with zipper velocity. This means if the axial motion of the plasma can be synchronized with the pinching process in the taper capillary, we can obtain a denser, higher-speed and controllable plasma for laboratory astrophysics.

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