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Characteristics of Dense, High-speed Plasma with Tapered Pinch Discharge
テーパピンチ放電を利用した高密度・高速プラズマの特性

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We proposed tapered pinch discharge as a measure to produce dense high-speed plasma flow. Basic behaviors of the plasma have been characterized using a prototype device. Results showed that the plasma flux and the velocity depend on initial gas density, discharge current and the 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.

1. Introduction

A dense, high-speed plasma flow has attracted much interest in semi-conductor industry, as an energy driver for inertial confinement fusion and as a tool for laboratory astrophysics [1]. Laser [2], z-pinch discharge [3] and arc channel [4] has been conventionally used to drive the high-speed plasma. 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 weak.

We proposed a new type of plasma device with tapered pinch discharge for the formation of dense high-speed plasma flow [5]. The current sheet in a tapered capillary radially compresses and axially accelerates the plasma. Using this scheme, an argon plasma was accelerated to 700 km/s by the tapered pinch discharge driven by a fast pulse power generator, which drove a load current of 80 kA with a pulse width of 70 ns [6]. The electromagnetic energy is converted to the thermal energy and the kinetic energy in radial and axial directions of the moving plasma. In this device, the geometry of tapered capillary is expected to play an important role in distributing of the energy.

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. 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 (~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, peak discharge current and 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.

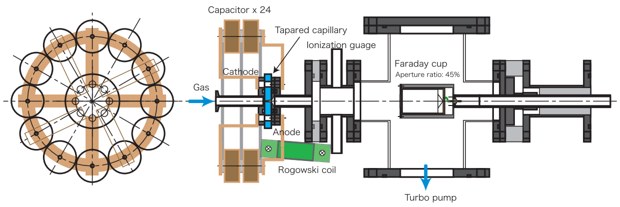

Fig.1. Schematic diagram of discharge chamber

3. Important parameters on electromagnetically driven plasma

Radial motion of the current sheet is described by 1-D equation of motion with slow-plow model, as shown by Eq. (1),

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

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 the tapered capillary, the current sheet is expected to be sequentially pinched along the z axis.

Then, the taper angle θ is important parameter instead of the plasma radius.

4. 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. As expected by Eq. (1), the flux and velocity increased with discharge current.

For formation of dense, high-speed flow, the critical factor is synchronization between the radial pinching of current sheet and z direction movement of plasma. Then the plasma parameters must be correlated with pinching times at inlet and outlet of the capillary. Figure 4 shows an illustration of the pinching process, where t_1 and t_2 mean the times that radius of current sheet reaches to 50 μm at inlet and outlet of the capillary. The time is calculated with Eq. (1). If plasma moves during $(t_2 - t_1)$, plasma velocity should be correlated with zipper velocity $l/(t_2 - t_1)$, here l is the length of capillary.

Figure 5 shows the results. As shown in Fig. 5(a), the plasma velocity can be related to the zipper velocity at θ = 8.3 deg. This result means if

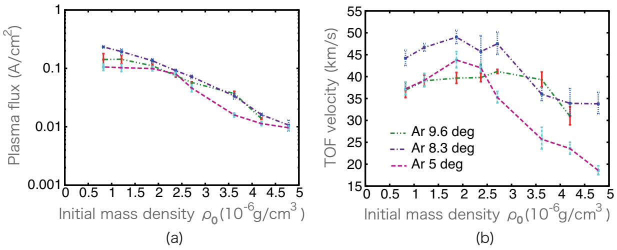

Fig.2. Dependence of plasma flux and velocity on initial mass density in the capillary

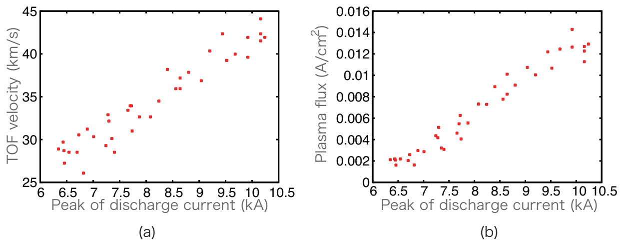

Fig.3. Dependence of plasma flux (b) and velocity (a) on peak discharge current at taper angle θ: 8.3 deg. and $\rho_0 = 2.4 \times 10^{-6}$ g/cm^3 (Ar). Faraday cup is located at 40 cm from the end of the capillary.

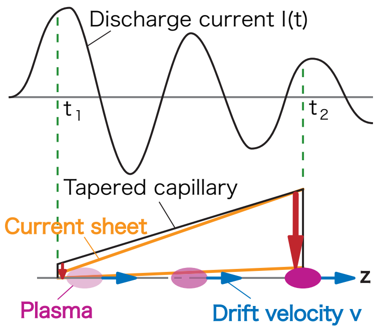

Fig.4. Pinching dynamics in the tapered capillary

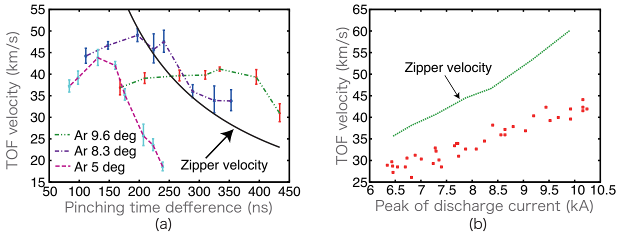

Fig.5. Prediction of plasma velocity with zipper velocity

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. Although the experimental results do not agree entirely, the results indicate the dependence on the zipper velocity.

5. Summary

Plasmas produced by a taper pinch discharge were characterized. Results showed dependence 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 axial motion of the plasma can be synchronized with the pinching process in the taper capillary, we can obtain dense, high-speed and controllable plasma.

References

[1] S.V.Lebedev et al.: Mon. Not. R. Astron. Soc. **361** (2005) 97.

[2] A. R. Bell, P. Choi, A. E. Dangor, O. Willi, D. A. Bassett and C. J. Hooker: Phys. Rev. A, **38** (1988) 1363.

[3] J. W. M. Paul, L. S. Holmes, M. J. Parkinson and J. Sheffield: Nature **208** (1965) 133.

[4] M. Inutake, A. Ando, K. Hattori, H. Tobari and T. Yagai: J. Plasma Fusion Res. **78** (2002) 1352.

[5] K. Adachi, M. Nakajima, T. Kawamura, K. Horioka: Plasma and Fusion Research, **6** (2011) 1201019.

[6] K. Horioka, M. Nakajima, T. Aizawa and M. Tsuchida: AIP Proc. Dense Z-Pinches **CP409** (1997) 311