Formation Mechanism of Dense High-Speed Plasma Flow in Tapered Capillary Discharge

Koichiro ADACHI, Mitsuo NAKAJIMA, Tohru KAWAMURA and Kazuhiko HORIOKA

Department of Energy Sciences, Interdisciplinary Graduate School of Science and Engineering,
Tokyo Institute of Technology, 4259 Nagatsuta-cho, Midori-ku, Yokohama 226-8502, Japan

(Received 1 March 2011 / Accepted 30 March 2011)

We propose a new type of plasma source using a pinch discharge in a tapered capillary, which generates a dense moving plasma by electromagnetic compression and acceleration. The axial velocity and flux of the moving plasma are controllable and can be maximized by adjusting the taper angle. The behavior can be illustrated with a simple model considering the pinching dynamics of the current sheet.

Keywords: moving plasma, pulse power device, z-pinch, laboratory astrophysics

DOI: 10.1585/pfr.6.1201019

High-speed plasma flows have attracted much interest for conducting laboratory astrophysics experiments [1]. The formation of dense, high-speed plasma is essential for those applications and the investigation of related plasma phenomena. Devices such as a laser [2], z-pinch [3], or arc channel [4] are conventionally used to drive the high-speed flow. However, dense, high-speed flow is difficult to form by hydrodynamic acceleration because of rarefaction waves accompanying the acceleration process. Also, a strong correlation among velocity, temperature, and density in hydrodynamically accelerated plasma is undesirable for almost all applications, especially parametric studies in astrophysics. Pinching plasmas in a plasma focus system can form high-energy density, high-speed plasmas [1, 5]. Electromagnetic acceleration can avoid the need to heat the plasma in order to increase the axial velocity. Therefore, a dense plasma can be formed by a compression process in a z-pinch system. However, the plasma parameters are difficult to control owing to nonuniform gas discharge.

We propose a new type of plasma device for the formation of dense high-speed plasma flow, in which the plasma parameters can be controlled by manipulating the operating conditions. Figure 1 shows a schematic diagram of the proposed scheme. 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 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 [6]. The electromagnetic energy is converted to the thermal energy and axial kinetic energy of the moving plasma. In this device, the geometry of the tapered capillary is expected to play an important role in distributing of the energy. We intend to clarify the relationships between the experimental conditions (i.e., initial gas density in the capillary, discharge current waveform, and capillary geometry) and the plasma parameters (i.e., axial velocity, flux, and temperature) of the taper-pinched plasma.

A 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. 2. 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 and taper angle by a Faraday cup (FC) located 22 cm from the capillary's aperture. The main discharge current and voltage were measured by a Rogowski coil and a high-voltage probe at the end of capillary, respectively.

Figure 3 shows typical waveforms of the discharge current, voltage, and plasma flux. The FC signals for three successive shots are overlaid. The signals photo-induced at the metal surface of the FC were also detected during pinch discharge. As shown, the reproducibility of the plasma for-

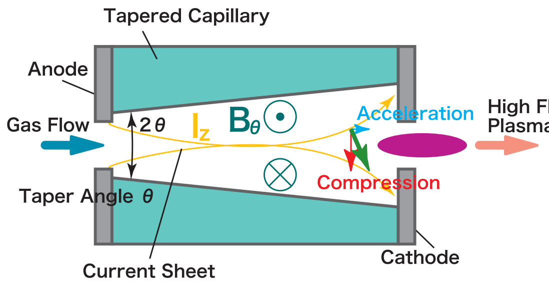

Fig. 1 Schematic of the plasma acceleration process in tapered capillary discharge.

---

author's e-mail: adachi.k.ad@m.titech.ac.jp

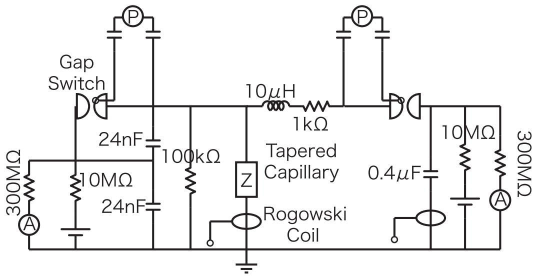

Fig. 2 Circuit diagram of a pulse power device.

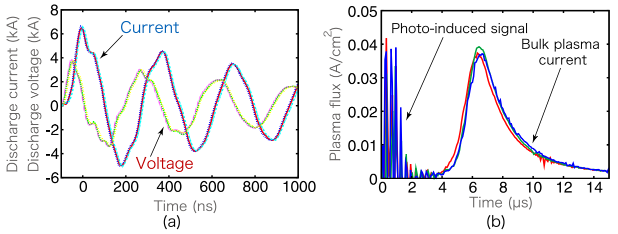

Fig. 3 Typical waveforms of (a) discharge current, and voltage and (b) plasma flux formed by capillary discharge with initial gas density; $n_0 = 7 \times 10^{16}\,\mathrm{cm}^{-3}$, taper angle of $\theta = 11$ deg, and length = 10 mm.

mation was sufficient for a parametric study of the taper-pinched plasma. When the gas density was $\sim 7\times10^{16}\,\mathrm{cm}^{-3}$, the plasma's axial velocity was estimated to be ~30 km/s using the time of flight of the flux signal.

Next, we examine the acceleration mechanism in the taper-pinched plasma. The basic behavior of the current sheet is expected to be described by the equation of motion using a snowplow model, as shown in Eq. (1),

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

where P_0, ρ_0, r_0, and γ are the initial gas pressure, initial mass density, initial radius, and specific heat ratio. We assumed $\gamma = 5/3$ for simplicity. This equation shows that the dynamics of the current sheet are determined by the initial gas density, initial radius, and discharge current waveforms. The pinching time of the current sheet can be estimated using Eq. (1). Here the pinching time was defined as the time during which the plasma's radius shrinks to one-tenth of the initial radius r_0. Figure 4 shows a schematic diagram of the relationship between the behavior of the moving plasma in the tapered capillary and the discharge current. A plasmoid moving axially at velocity v_0 is expected to form at time t_1 when the plasma is pinched at the capillary inlet. The current sheet accelerates the plasmoid and recompresses the pinching plasma at time t_2 at the outlet. A dense, high-speed plasma can be expected to be formed by matching the axial motion of the plasma and the radial motion of the current sheet.

We measured the plasma flux signals over a wide range of gas densities and taper angles. Figure 5 shows the dependence of the axial velocity and plasma flux on the difference in the pinching times at the inlet and outlet of the tapered capillary ($t_2 - t_1$). As Eq. (1) indicates, the difference in the pinching time is a function of the gas density and taper angle. As shown, the flux and speed of the plasma depend strongly on the pinching time and taper angle. In this condition, at a taper angle of 8.3 deg, we think the plasmoid was accelerated by matching the axial and radial motions and the plasma flux increased. Because the axial velocity is not proportional to the plasma flux, these parameters can be controlled separately.

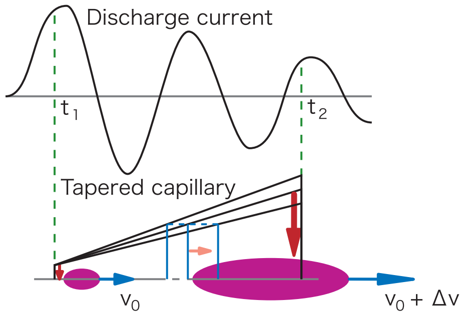

Fig. 4 Schematic illustration of acceleration mechanism in taper-pinched plasma.

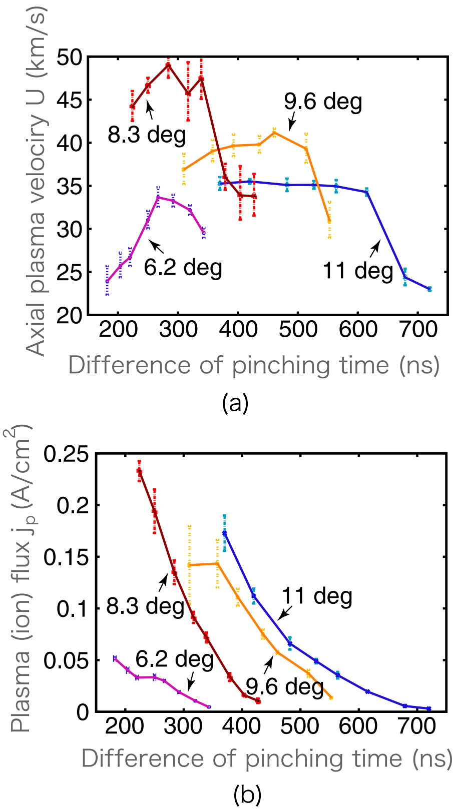

Fig. 5 Dependence of plasma speed and flux on the difference in pinching time.

In conclusion, a new type of acceleration method for dense plasma using a tapered capillary pinch was demonstrated. The result shows that, by adjusting the taper angle, we can create argon plasma flows with an axial velocity of $\sim$50 km/s, a flux j_p of $\sim$0.25 A/cm^2, and an ion density of $\sim 10^{11}$ cm^{-3}. The result also indicates that the speed and flux of the plasma can be scaled up by further adjustment of the operating conditions.

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

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

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

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

[5] V.V. Aleksandrov, E.V. Grabovski, G.G. Zukakishvili, K.N. Mitrofanov, S.F. Medovshchikov and I.N. Frolov, Plasma Physics Reports **34**, 830 (2008).

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