Experimental and numerical studies on plasma behavior flowing across perpendicular magnetic field

T Takezaki, K Takahashi, T Sasaki, T Kikuchi, and N Harada
Nagaoka University of Technology, Nagaoka, Niigata, Japan
E-mail: ttakezaki@stn.nagaokaut.ac.jp

Abstract. To understand particle acceleration mechanisms in a collisionless shock, we have investigated the behaviors of a one-dimensional fast plasma flow in a perpendicular magnetic field by experimental and numerical simulations in a laboratory scale experiment. The velocity of the plasma flow generated by a taper-cone-shaped plasma focus device has varied by the gradient of the perpendicular magnetic field. The plasma flow has accelerated by applying the magnetic field with the negative gradient. To clarify the behavior of the plasma flow in the perpendicular magnetic field, numerical simulations based on an electromagnetic hybrid particle-in-cell (PIC) method have been carried out. These results indicate that the magnetic field gradient affects the plasma flow velocity.

1. Introduction
To understand astrophysical phenomena, laboratory scale experiments with well-defined behavior are required for an experimental evaluation of several numerical model studies [1–8]. A collisionless shock plays a key role in generation of high-energy particles in outer space. The particle acceleration mechanisms in the collisionless shock have been considered the Fermi acceleration, which works diffusive shock acceleration due to electromagnetic turbulence, and the shock drift or surfing accelerations obtained by the upstream magnetic field in a magnetized shock [9–13]. For the experimental evaluation of these acceleration mechanisms, Drake [3] has estimated the required conditions, which depend on the hypersonic plasma flow and the magnetic field, to generate the collisionless shock in laboratory scale experiments.

In order to generate the hypersonic plasma flow in laboratory scale experiments, a method by using laser ablations or pulsed-power discharges has been demonstrated [14–19]. To simplify the plasma behavior and the distribution of applied magnetic field, we have developed a taper-cone-shaped plasma focus device by using the pulsed-power discharge [20]. The device has generated a one-dimensional fast plasma flow with well-defined behavior for understanding astrophysical phenomena.

In this study, to understand the particle acceleration mechanisms in the collisionless shock, the experimental and the numerical simulations in the laboratory scale experiment have been demonstrated. To evaluate the plasma flow as a function of magnetic field distributions, we have investigated behaviors of the plasma flow generated by the taper-cone-shaped plasma focus device in two types of perpendicular magnetic field distributions. The numerical simulations based on an electromagnetic hybrid particle-in-cell (PIC) method have been carried out for understanding the effect of the magnetic field gradient on the plasma flow.
2. Behaviors of plasma flow generated by taper-cone-shaped plasma focus device in perpendicular magnetic field

The taper-cone-shaped plasma focus device with an acrylic tube produces the quasi-one-dimensional hypersonic plasma flow [20]. The length of the acrylic tube is \( L = 20 \) mm. The velocity of the plasma flow using helium gas discharge is about 10 km/s which the Mach number corresponds to \( M_a \sim 10 \). To investigate the behavior of the plasma flow in perpendicular magnetic field, permanent magnets (\( \phi = 5 \) mm and \( h = 5 \) mm) were set on the acrylic tube, as shown in Fig. 1. The direction of the applied magnetic field is \( z \) perpendicular to the propagation direction \( x \) of the plasma flow. To evaluate the plasma flow as a function of magnetic field distributions, we have changed the position of the permanent magnets. The magnets were located at 10 mm from the end of the electrode called as \( B_{\text{cent}} \). On the other hand, the magnets were located at 0 mm called as \( B_{\text{st}} \). The difference of magnetic field gradients affects the propagation of the plasma flow.

Figure 2 shows streak images of the plasma flow in the acrylic tube with each magnetic field distribution. The initial gas pressure in the chamber is 2.0 Pa with \( B_{\text{cent}} \) shown in Fig. 2(a), and 0.5 Pa with \( B_{\text{st}} \) shown in Fig. 2(b). As shown in Fig. 2(a), the velocity of the plasma flow with \( B_{\text{cent}} \) decreased from 14 km/s to 10 km/s. By contrast, the velocity of the plasma flow with \( B_{\text{st}} \) increased from 12 km/s to 14 km/s shown in Fig. 2(b). These results indicate that the magnetic field gradient has affected the variation of the plasma flow velocity.

![Figure 1](image1.png)

**Figure 1.** Experimental setup and magnetic field distributions in the acrylic tube.

![Figure 2](image2.png)

**Figure 2.** Streak images of the plasma flow in the acrylic tube. (a) With the magnetic field distribution \( B_{\text{cent}} \) at 2.0 Pa, (b) with the magnetic field distribution \( B_{\text{st}} \) at 0.5 Pa.
3. Numerical simulations based on electromagnetic hybrid PIC

In order to understand the behavior of the fast plasma flow generated by the taper-cone-shaped plasma focus device in the perpendicular magnetic field, we have carried out four-dimensional space \((x, v_x, v_y, v_z)\) numerical simulations based on an electromagnetic hybrid PIC method [21, 22] with the simple modeling of the magnetic field gradient as shown in Fig. 3. In the initial condition of the numerical simulation, the thermodynamic equilibrium is assumed due to the plasma focus. The ions having the thermodynamic equilibrium, which the average velocity is 10 km/s, are set from -10 mm to 0 mm on the axis \(x\). These ions are assumed fully single ionized condition. The ion temperature \(T_i\) and the ion number density \(n_i\) are respectively estimated to be 9000 K and \(9.5 \times 10^{18} \text{ m}^{-3}\) by using Rankine-Hugoniot relation with strong shock condition for the initial gas pressure \(P_0 = 0.01 \text{ Pa}\), the room temperature \(T_0 = 300 \text{ K}\), and the Much number \(M_a = 10\). The region from 0 mm to 20 mm indicates the region of the acrylic tube. The initial shock front is set at \(x = 0 \text{ mm}\). The collision between the ions and the neutral particles forehand the shock front is neglected because of the Knudsen number \(K_n = \frac{L}{\lambda_{in}} > 1\), where \(\lambda_{in}\) is the mean free path between the ion-neutral collision, and \(L = 20 \text{ mm}\) is the system scale length. The mean free path \(\lambda_{in}\) is estimated as \(\lambda_{in} = \frac{1}{4\sigma_{He} n_0}\), where \(\sigma_{He} = 10^{-19} \text{ m}^2\) is the cross section of helium for electron [23], \(n_0\) is the number density of the neutral particles forehand the shock.

To simplify the model of the magnetic field gradient, we applied the positive gradient magnetic field called as \(B_{pos}\) and the negative gradient magnetic field called as \(B_{neg}\), as shown in Fig. 3.

Figure 4 shows the time evolution of the ion number density \(n_i\) (upper graph) and the time evolution of the shock front (lower graph). The time evolutions of the density differ depending on the magnetic field distributions. However, the discontinuous surface of the density has been formed in both magnetic field distributions because the magnetic pressure affects the plasma flow. To compare with the experimental results, we followed the discontinuous surface as the shock front of the plasma flow such as the streak images. The dotted lines, as shown in the lower graphs of Fig. 4, indicate the initial velocity of the plasma flow. The initial velocity of the plasma flow has been faster than the initial average velocity of the ions, because the faster ions in the initial Maxwell distribution propagate at first and form the discontinuous surface. The plasma flow with \(B_{pos}\) has decelerated. On the other hand, the plasma flow with \(B_{neg}\) has accelerated. These results indicate that the acceleration and deceleration of the plasma flow have varied by the direction of the magnetic field gradient.

4. Conclusion

To understand particle acceleration mechanisms in the collisionless shock, we have investigated the behavior of the plasma flow across the perpendicular magnetic field by the experimental and the numerical simulations in the laboratory scale experiment. The velocity of the plasma flow generated by the taper-cone-shaped plasma focus device has varied by the gradient of the perpendicular magnetic field. The plasma flow has accelerated by applying the magnetic field with the negative gradient. The numerical simulation results show that the acceleration (or
With positive gradient magnetic field $B_{\text{pos}}$, the dotted lines in the lower graphs indicate the initial velocity of the plasma flow. The plasma flow accelerates by the electric field induced by the grad-$B$ drift with the negative gradient.

To understand the fast plasma flow as a function of several magnetic field structures, we will experimentally evaluate the ion energy distribution function and its plasma parameters.

Acknowledgments
This work is partly supported by the NIFS Collaboration Research Program (NIFS14KLEH042).

References
[1] Leroy M et al. 1982 Journal of Geophysical Research: Space Physics 87 5081–5094
[2] Ryutov D et al. 1999 The Astrophysical Journal 518 821
[3] Drake R 2000 Physics of Plasmas 7 4690–4698
[4] Quest K B 1986 Journal of Geophysical Research: Space Physics 91 8805–8815
[5] Kato T N and Takebe H 2008 The Astrophysical Journal Letters 681 L93
[6] Gargaté L and Spitkovsky A 2012 The Astrophysical Journal 744 67
[7] Stockem A et al. 2014 Scientific Reports 4
[8] Bulanov S et al. 2015 Plasma Physics Reports 41 1–51
[9] Bell A 1978 Monthly Notices of the Royal Astronomical Society 182 147–156
[10] Blandford R D and Ostriker J P 1978 The Astrophysical Journal 221 L29–L32
[11] Decker R and Vlahos L 1985 Journal of Geophysical Research: Space Physics 90 47–56
[12] Begelman M C and Kirk J G 1990 The Astrophysical Journal 353 66–80
[13] Hoshino M and Shimada N 2002 The Astrophysical Journal 572 880
[14] Bell A et al. 1988 Physical Review A 38 1363
[15] Courtois C et al. 2004 Physics of Plasmas 11 3386–3393
[16] Kondo K et al. 2006 Review of Scientific Instruments 77 036104
[17] Morita T et al. 2010 Journal of Physics: Conference Series 244 042010
[18] Kuramitsu Y et al. 2011 Physical review letters 106 175002
[19] Adachi K et al. 2015 IEEE Trans. FM 135 366–372
[20] Sasaki T et al. 2014 J. Phys. Soc. Proc I 015096
[21] Winske D et al. 2003 Space Plasma Simulation (Springer) pp 136–165
[22] Tsuno S et al. 2014 IEEE Trans. Plasma Sci. 42 3732–3741
[23] Mitchner M and Kruger C H 1973 Partially ionized gases (Wiley New York)