Study on interaction of pulsed-power-driven plasma flow and perpendicular magnetic field

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ABSTRACT

To understand particle acceleration mechanisms in non-relativistic collisionless shocks, we have investigated an interaction between a pulsed-power-driven plasma flow and a perpendicular magnetic field. The ion current from the plasma flow in the perpendicular magnetic field was measured by an ion collector. The valuation of the ion current waveform without and with the perpendicular magnetic field was observed. With the magnetic field, the ion current preceding the main current was observed. Results of numerical simulation based on an electromagnetic hybrid particle-in-cell method qualitatively agreed with experimental results.

Keywords

Plasma focus, laboratory astrophysics, hybrid particle-in-cell

1. Introduction

Elucidation of generation process of cosmic rays is important issue in astrophysics and space physics. The characteristic of cosmic rays is non-thermal energy distribution with a power-law spectrum, and the highest energy of cosmic rays reaches to 10^{20} eV [1]. Collisionless shocks such as heliospheric shocks or supernova shocks have been discussed to play an energy source for generation of cosmic rays [2-4]. In the relativistic region, first-order Fermi acceleration, which is a theoretical model of particle acceleration in collisionless shocks, has been explained the power-law energy distribution of cosmic rays and the process how to gain the energy from electromagnetic fields [5-6]. However, to drive first-order Fermi acceleration, charged particles must be accelerated from the non-relativistic region to the relativistic region. The process for driving first-order Fermi acceleration have been not clarified because of the non-linear interaction of electromagnetic fields and the charged particles [7-8]. In order to clarify particle acceleration mechanisms in non-relativistic collisionless shocks, the understanding of behaviors and interactions of plasma flow and electromagnetic fields in non-relativistic region is required.

A plasma flow with a similarity for astrophysical phenomena in a laboratory scale experiment provides “in-situ” observation of the astrophysical phenomena [9-11]. The similarities of the laboratory scale experiment to the astrophysical phenomena, such as a mean free path of particles, the velocity of the plasma flow, or plasma beta are considered. To obtain a fast plasma flow in a laboratory, experiments using laser ablation or pulsed-power discharge has been carried out [12-18]. We have proposed a tapered cone plasma focus device to obtain a quasi-one-dimensional fast plasma flow for laboratory astrophysics [19-20].

In this study, to understand an interaction between fast plasma flow and perpendicular magnetic field, we have investigated behavior of a one-dimensional plasma flow generated by the tapered cone plasma focus device in a perpendicular *B*-field by measuring a plasma ion current. A numerical simulation based on an electromagnetic hybrid particle-in-cell method has been carried out for the comparison with the experimental results.

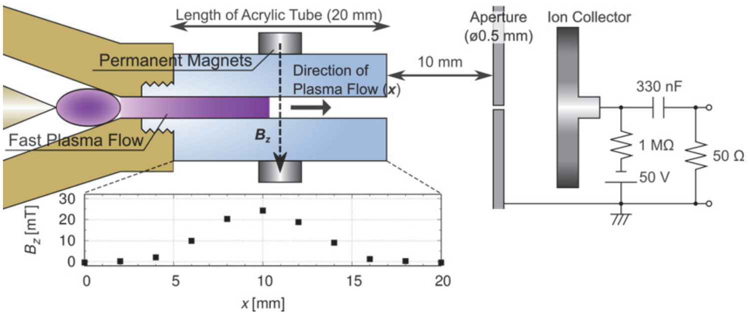


Fig. 1 Schematic image of the experimental setup to apply the perpendicular *B*-field using permanent magnets and to measure the plasma ion current using the ion collector (IC).

2. Experimental Setup

The tapered cone plasma focus device with a guiding acrylic tube (length of 20 mm) produces a quasi-one-dimensional fast plasma flow with the velocity of 30 km/s in a helium gas discharge at 0.3 Pa [20]. Figure 1 shows the experimental setup to apply an external perpendicular *B*-field, and to investigate ion behavior. In order to apply a magnetic field B_z perpendicular to the plasma flow direction x, permanent magnets were set on the acrylic tube. The peak of the *B*-field is 25 mT at the center of the acrylic tube. To measure a plasma ion current from the plasma flow, an ion collector (IC) biased at –50 V with an aperture of ø0.5 mm was set coaxially to the electrodes and the acrylic tube. The distance from the end of the acrylic tube to the aperture is 10 mm. The ion current was measured through a high-pass filter with the cutoff frequency of 10 kHz.

3. Results and Discussions

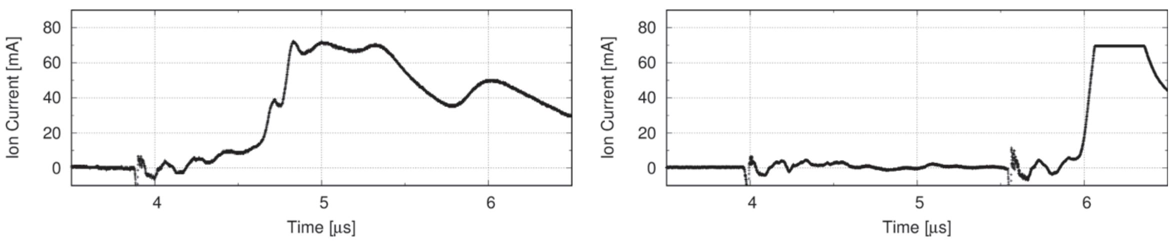
3.1 Measurement of the plasma ion current without and with the perpendicular magnetic field

Figure 2 shows the plasma ion current measured by the IC without and with the perpendicular *B*-field. Without the *B*-field, the initial distortion has been detected at 3.9 μs, and the current has reached to the peak of 70 mA at 4.8 μs. The time from the initial distortion to the peak is 0.9 μs. On the other hand, with the *B*-field, the main ion current has been delayed, and it has been detected at 5.6 μs. The ion current of a few mA preceding the main current was observed.

3.2 Numerical simulation for plasma flow

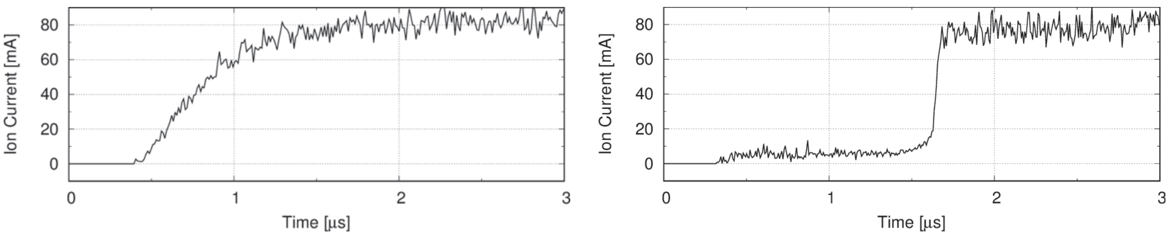
To simulate the plasma behavior generated by the tapered cone plasma focus device, a numerical simulation based on an electromagnetic hybrid particle-in-cell (PIC) method has been carried out [20]. The ion current at 30 mm is compared with the experimental results as shown in Fig. 2.

Initial conditions for the numerical simulation were decided by the comparison of experimental results. The average velocity of super particles is 30 km/s. We assumed singly ionized helium ions and thermodynamic equilibrium, and thus the electron temperature and electron number density becomes $T_e = T_i$ and $n_e = n_i$.



(a) w/o *B* (b) w/ *B*

Fig. 2 Ion current waveform measured by the IC. (a) without the *B*-field and (b) with the *B*-field. Without the *B*-field, the initial distortion was detected at 3.9 μs, and the current reached to the peak of 70 mA at 4.8 μs. The time from the initial distortion to the peak is 0.9 μs. With the *B*-field, the main ion current was delayed, and was detected at 5.6 μs. The ion current of a few mA preceding the main current was observed.



(a) w/o B (b) w/ B

Fig. 3 Ion current waveform at 30 mm numerically simulated by the electromagnetic hybrid PIC method. (a) without the B-field and (b) with the B-field. The peak of ion current both without and with the B-field were 80 mA. Without the B-field, the current was detected from 0.5 µs, and reached to the peak at 1.5 µs. The rising time of the current is 1 µs. With the B-field, the current was sharply increased at 1.5 µs, and the current with a few mA preceding the main current was confirmed.

The electron temperature of the plasma flow has been experimentally estimated to be $T_e \sim 2.6$ eV from the optical emission spectroscopy [20]. The ion number density is estimated to be $n_i \sim 10^{20}$ m^{-3} with assuming fully-ionized-plasma of the initial helium gas in the chamber as below; the initial number density of neutral helium in the chamber is calculated by using ideal gas law, $n_{\mathrm{He}} = P_0 / k_{\mathrm{B}}T_0$, where P_0 is the initial gas pressure in the chamber, k_{B} is the Boltzmann constant, and T_0 is the initial temperature. The initial number density of neutral helium is estimated to be $n_{\mathrm{He}} \sim 10^{20}$ m^{-3} with the initial pressure $P_0 = 0.3$ Pa, and the room temperature $T_0 = 300$ K.

Figure 3 shows the ion current waveform at 30 mm numerically simulated by the electromagnetic hybrid PIC method. The ion current I_i was calculated as below:

$$I_i = J_{ix}S_{\mathrm{ap}} \quad (1)$$

where J_{ix} is the ion current density on x direction at 30 mm represented by the super particles, S_{app} is the cross section of the aperture with the diameter of ø0.5 mm. The peaks of the ion current both without and with the perpendicular B-field are 80 mA. Without B-field, the current has been detected from 0.5 µs, and the peak current has been reached at 1.5 µs. The rising time of the current is about 1 µs. On the other hand, with B-field, the current has been sharply increased at 1.5 µs, and the current with a few mA preceding the main current has been confirmed. These results qualitatively agree with the experimental results shown in Fig. 2.

4. Conclusions

We have observed the plasma ion current from the plasma flow generated by the tapered cone plasma focus device both in without and in with the perpendicular B-field. Without B-field, the peak of the ion current was 70 mA, and the rising time of the current was 0.9 µs. On the other hand, with the B-field, the detected time of the main ion current was delayed, and the rising time was shorter than without the B-field. In addition, the current of a few mA preceding the main current was observed. The numerical results simulated by the electromagnetic hybrid particle-in-cell method qualitatively agreed with the experimental results.

To investigate the ion behavior in the perpendicular B-field, we will evaluate the dependence of the behavior of the ion current on the peak of the B-field, and the dependence of the detected time of the ion current on the distance to the detector.

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