Ion Acceleration Independent of the Electric Current Direction in Z-Pinch Plasma

Mineyuki NISHIO, Hiroshi SAKUMA and Keiichi TAKASUGI[1)]

Graduate School of Science and Technology, Nihon University, Tokyo 101-8308, Japan
[1)] *Institute of Quantum Science, Nihon University, Tokyo 101-8308, Japan*

(Received 8 October 2010 / Accepted 11 December 2010)

Ions accelerated in z-pinch experiments with either positive or negative discharge were measured by using a Thomson Parabola analyzer in order to understand the directional tendencies of the ion acceleration. Ions having energy on the order of MeV were observed in both positive and negative discharges. The velocity and energy of each ion species were measured to be considerably similar in magnitude, in spite of the difference in the polarity of the power supplies. The highest-velocity ions with different charges in each measurement lay on the constant velocity line. The model independent of the current direction should be considered as the main mechanism of ion acceleration in this study.

Keywords: z pinch, ion acceleration, Thomson Parabola analyzer, positive and negative power supplies

DOI: 10.1585/pfr.6.1201009

Accelerated ions having energy on the order of MeV have been observed in many studies of high current experiments, particularly in the plasma foci [1, 2] and z pinch systems [3, 4]. Charged voltages of the main power supplies of these systems are several tens of kV, thus the understanding of any acceleration mechanism is required. Some acceleration models are discussed as the potential mechanisms of the acceleration, such as an induced electromotive force caused by increase of inductance [5, 6] and/or resistivity [7, 8], the kinematic effect under the calculated electric fields [9, 10], and a displacement current caused by the blocking of the conduction [11]. In all the above theories, the direction of the accelerated ions are assumed to be the same as that of the electric currents. The models of these theories are collectively called the "current-directional electric field model" in this study. Although few experimental observation [3] have reported the reversed acceleration of ions, no comparative experiments have been carried out. Because it is difficult to measure the electric field in the fast and microscopic phenomena of pinch, the nature of the particle acceleration process by the electric field still remains undefined. Experimental observations using another approach are needed. Assuming that the above-mentioned current-directional electric field model is the main mechanism, the reversal of polarity of the power supply should reverse the acceleration direction of ions. Accordingly, either positive or negative power supplies were examined in the same gas-puff z-pinch experiment system in this study.

The SHOTGUN-III device at Nihon University was used for the gas-puff z-pinch discharge in this study. The charged voltage of the bank was ±20 kV. The initial discharge media was a puffed Ar gas (5 atm in plenum). Details of the experimental setup are discussed in the previous work [12]. According to authors, the acceleration phenomena become more predominant in the divergent gas-puff

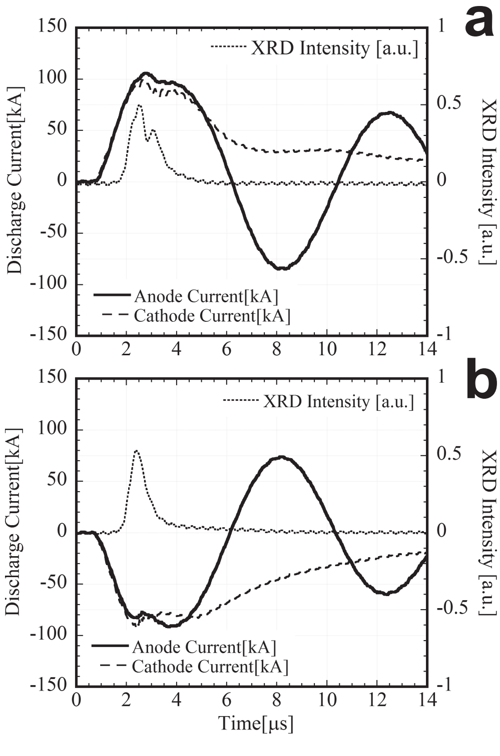

Fig. 1 Typical waveforms of discharge currents and XRD signal intensities with (a) positive and (b) negative discharges.

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author's e-mail: nishiomp@shotgun.phys.cst.nihon-u.ac.jp experiments than in the conventional straight gas-puff z-pinch experiments. In this study, a 30° divergent gas nozzle installed on the center conductor was used. Discharge currents were measured by two Rogowski coils (the anode and cathode Rogowski coils were located outside the vacuum chamber and between two electrodes, respectively). Soft x-ray intensity was detected by x-ray diodes (XRDs) with a Ni photocathode. A Thomson parabola analyzer [13] was used to measure the accelerated ions. The analyzer was located on the discharge axis, and it was able to detect only ions ejected toward the axial direction from the center conductor to the opposite electrode. In both the measurements with positive and negative discharges, the intensity of the applied static electric field and pulsed magnetic flux density for parabola analysis were 5 kV per 8 mm and 0.6 T, respectively. The ejected ions went through the two pinholes, and were recorded on the detector plate ("Baryotrak-P", Nagase-Landauer Co., Ltd.) after the deflection by the fields.

Figure 1 shows the typical waveforms of discharge currents and XRD signal intensities. Electric currents were reversed by the reversal of polarity of the power supply. In both discharges, the abrupt current decrement indicated the increment of the plasma impedance by the pinch. As shown in the cathode currents of Fig. 1, the current flowing through the pinch plasmas did not oscillate in any discharge in spite of the periodic waveforms measured by the anode Rogowski coil. This unidirectional current flow occurring in the gas-puff z-pinch implosion is called a "self-crowbar" current [14, 15]. The x-ray radiations associated with strong implosions were detected only at the first half period of the anode current waveforms. The strong implosions should have dominant influence on the particle acceleration in a pinch plasma, so it is indicated from the detection of x-ray radiations that the acceleration can occur only at the first half period of the anode current. Because the currents at the pinch timing of both the positive and negative discharges flow oppositely, as shown in the cathode current waveforms in Fig. 1, parabolas obtained in the two discharge conditions should reflect only the difference in the direction of the current flowing through the plasmas.

Figure 2 shows the resultant parabolas in the (a) positive and (b) negative discharges. The exposures of discharges for the parabola analysis were carried out over 40 shots in both measurements. The distributions obtained show three parabola curves in each figure. Judging from the comparative experiments, the difference in concentration levels (i.e., ion flux) of each parabola between positive and negative discharges is minimal. Ion species were determined to be Ar^+, Ar^{2+}, and Ar^{3+} beginning at the bottom in Fig. 2. Velocities and kinetic energies per charges of the parabolas in Fig. 2 are listed in Table 1.

Comparing experiments of positive and negative discharges, three results were obtained: (1) Ions having energy on the order of MeV were observed in measurements of both positive and negative discharges. (2) The velocity and energy of each ion species were measured to have similar magnitudes of accelerations both in the same and opposite direction of the electric currents, as shown in Table 1. (3) The highest velocity ions with different charges in each figure lay on the constant-velocity lines (Eq. 6 in Ref. [13]). These results show that the direction of the acceleration could not depend on the direction of currents. This contradicts the existing current-directional electric field model,

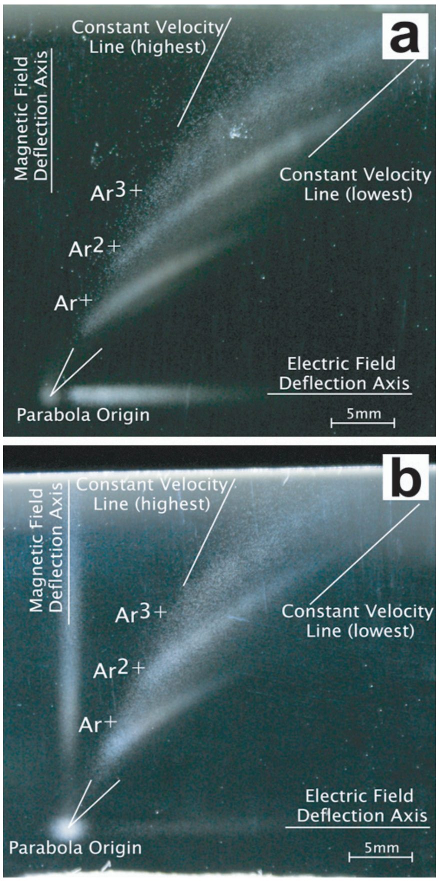

Fig. 2 Resultant parabola curves in measurements with (a) positive and (b) negative discharges.

Table 1 Highest and lowest velocities and kinetic energies per charges of parabolas in Fig. 2. Units of velocities v and energies per charges E/Z are "km/sec" and "MeV/Z", respectively.

	Positive		Negative	
	max v max E/Z	min v min E/Z	max v max E/Z	min v min E/Z
Ar^+	1.9×10^3 0.8	1.0×10^3 0.2	1.9×10^3 0.7	1.1×10^3 0.2
Ar^{2+}	2.0×10^3 0.4	1.0×10^3 0.1	2.0×10^3 0.4	1.1×10^3 0.1
Ar^{3+}	2.1×10^3 0.3		2.0×10^3 0.3	

because ions should not be accelerated toward the opposite direction to the supposed strong electric fields dependent on the current direction. A reasonable mechanism of particle acceleration in the z-pinch plasma of this study are concluded to be independent of the electric current direction. Pointed out as an example of the physical processes independent of the current direction, a mechanical reflection effect caused by the radially and axially moving cylindrical magnetic wall or a trapping effects caused by a potential trough propagating in symmetrical directions along the axis may have an important role in acceleration.

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