Characterization of High-Energy Ions in the Divergent Gas-Puff Z-Pinch

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ABSTRACT

Characterization of high energy ions was conducted to understand the acceleration mechanism of ions in the divergent gas-puff z-pinch. It was reconfirmed that there was also ion acceleration in the negative discharge. Comparison of ion acceleration in Ar and Kr discharges was carried out, and the maximum acceleration energy was almost the same.

Keywords

Divergent Gas-Puff Z-Pinch, High-Energy Ion, Ion Acceleration, Thomson Parabola Analyzer

1. Introduction

Divergent gas-puff z-pinch has been devised for the realization of efficient soft x-ray point source. In the divergent gas-puff z-pinch experiments, hard x-ray which has never been observed in the conventional gas-puff z-pinch was observed, and the generation of high-energy electrons was revealed [1]. In addition, the generation of high-energy ions was revealed from the ion measurement. By changing the direction of the discharge current, high-energy ions were observed as well. The presence of ion acceleration which does not depend on the direction of current was revealed [2].

Divergent gas-puff z-pinch is similar to the plasma focus in that it is non-uniform pinch in the axial direction. Generation of high-energy ions has also been observed in the plasma focus. The acceleration mechanism has been understood to be due to electromagnetic induction [3]. Ion acceleration which does not depend on the direction of the current could not be explained by electromagnetic induction, and the statistical acceleration model by the shrinking magnetic wall was proposed [4].

In order to investigate the origin of ion acceleration, the pinhole measurement of ions were made. Ion distribution in the double coaxial structure was observed, and the structure was found to be dependent on the direction of the current. In addition, it was also clear that the high-energy ions were generated from the spot-like ion source [5].

In this research the past measurements of high-energy ions was reexamined, and the dependences of discharge current and ion species on the ion acceleration were investigated.

2. Experimental Setup

Figure 1 shows a schematic diagram of the SHOTGUN III z-pinch device used in the experiment. The device consists of 12 μF capacitor bank. It uses a ±40 kV power supply, and it is possible to perform both positive and negative discharges. An annular divergent gas nozzle is mounted on the inner electrode. The ejection angle is 10 degrees outward. The diameter of the nozzle and the distance between the electrodes are both 30 mm. Ar or Kr gas is used in the experiment. The plenum pressure is set to 5 atm. The material of the inner electrode is stainless steel, and that of the outer electrode is aluminum.

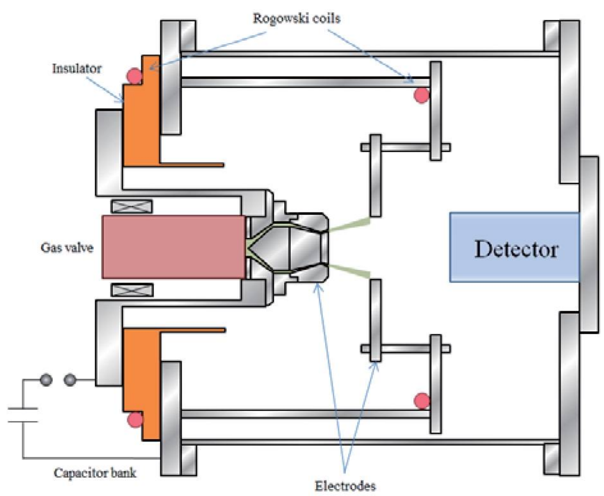


Fig. 1 Schematic diagram of the SHOTGUN III z-pinch device

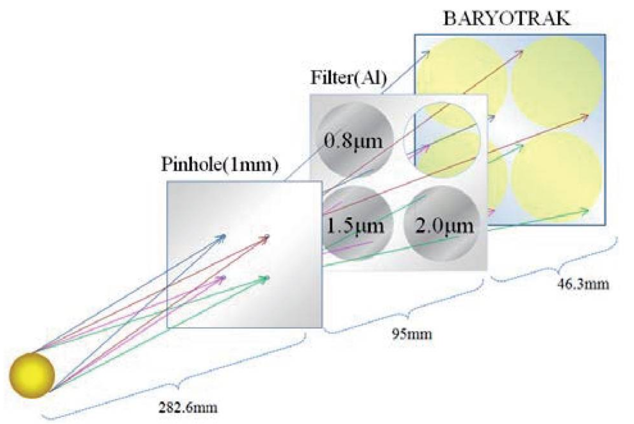


Fig. 2 Schematic drawing of the filtered 4-hole ion pinhole camera

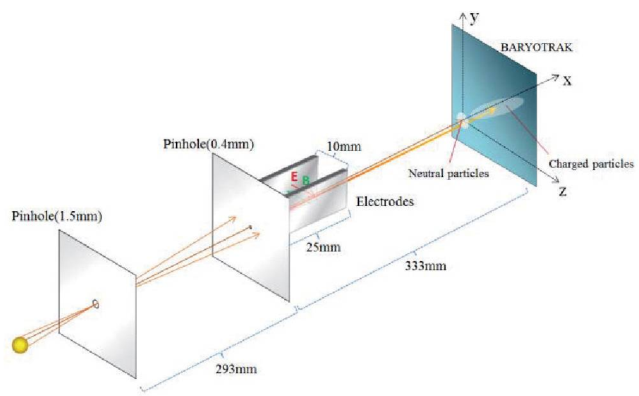


Fig. 3 Schematic drawing of the Thomson-parabola analyzer

Figure 2 shows the 4-hole ion pinhole camera with filters to evaluate approximate energy and the spatial distribution of the accelerated ions. The filters are made of Al, and the energy of the transmitted ions is calculated from maximum range of Ar ion in Al. Three kinds of Al filters (0.8 μm, 1.5 μm, and 2.0 μm) are used in the measurement. The corresponding energies are 0.7 MeV, 1.7 MeV and 2.5 MeV, respectively.

Figure 3 shows a schematic drawing of the Thomson parabola analyzer. Electrodes and the magnetic poles are arranged in parallel behind two pinholes. Each ion is changed in the direction perpendicular to each other by the electric and magnetic fields. By the magnitude of the deflection the energy and ion species can be measured precisely.

BARYOTRAK (67 x 67 x 0.9 mm) is used for the detection of accelerated ions. This is an improvement over the general ADC (allyl diglycol carbonate) plastic plate which is known as CR-39. It is a solid track detector used for detection and dosimetry of neutron, proton, alpha particle and cosmic rays, whose energy exceeding 100 keV.

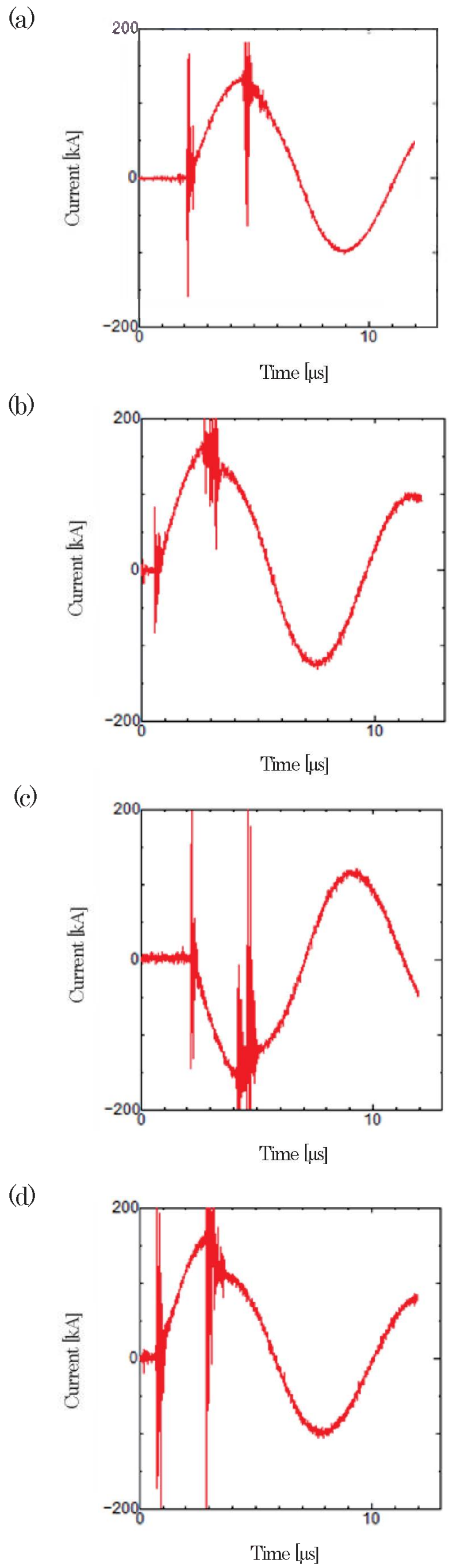


Fig. 4 Current waveforms of typical discharge in (a) Ar +20 kV, (b) Ar +25 kV, (c) Ar -25 kV and (d) Kr +25 kV.

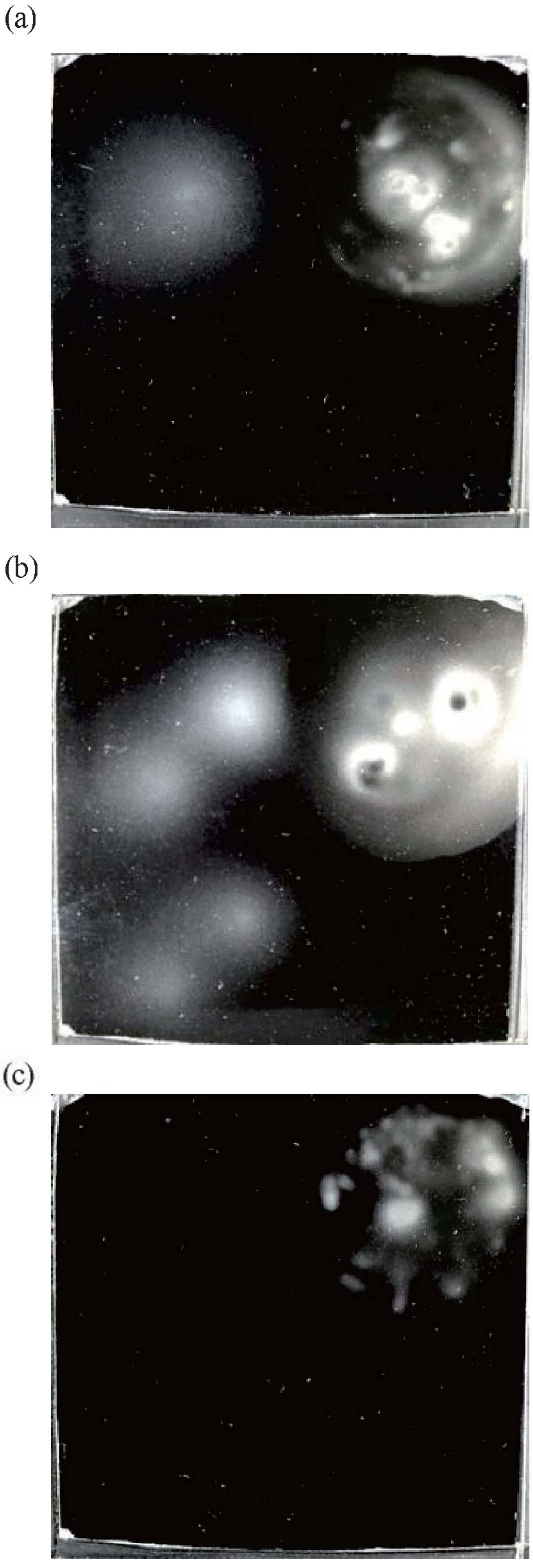


Fig. 5 4-hole ion pinhole measurements of Ar discharge at (a) +20 kV, (b) +25 kV and (c) -25 kV.

3. Discharge Characteristics

Figure 4 shows typical current waveforms of (a) +20 kV Ar discharge, (b) +25 kV Ar discharge, (c) -25 kV Ar discharge and (d) +25 kV Kr discharge. Pinch occurred near the peak of each sine wave. The current dropped rapidly at the pinch due to the increment of plasma inductance. The currents were (a) 131.5 kA, (b) 161.8 kA, (c) -159.9 kA and (d) 158.3 kA. By comparing (a) and (b), the current was roughly proportional to the charging voltage. The decrement of current at the pinch was also large at high charging voltage. By changing the discharge polarity no big difference was observed. By comparing Ar and Kr discharges the decrement at the pinch was large at Kr discharge. The reason is that the temperature of the plasma by the adiabatic compression in the course of the plasma contraction increases, the temperature rise is suppressed due to the large radiation loss in Kr compared to Ar, resulting in reaching a smaller radius. Therefore, the induced electromotive force due to radial contraction is considered to be large in Kr.

4. Ion Pinhole Measurements

Ar discharge was performed by changing the charging voltage, and ion pinhole measurements were made. Figure 5 shows the results of (a) +20 kV, (b) +25 kV and (c) -25-kV. Each data shows no filter (upper right), 0.8 μm Al (upper left)、1.5 μm Al (lower left) and 2.0 μm Al (lower right) filters as shown in Fig. 2.

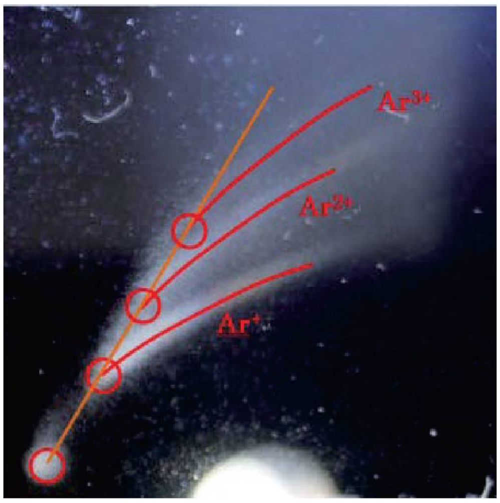
At +20 kV ion tracks were observed at no filter and 0.8 μm filter. At +25 kV ion source was separated in two parts. Ion tracks were observed at no filter, 0.8 μm and 1.5 μm filters. In the positive discharge, an increase in the energy of the ions was confirmed with increasing charge voltage. However, in the negative discharge at -25 kV ion tracks were observed only at no filter, and no ion passing through the filters was observed. Distribution of ion track appears to be spread throughout the field of view as well as the center.

4. Thomson Parabola Measurements

Measurements using the Thomson parabola analyzer were made by changing the discharge gas. The charging voltage was fixed to +25 kV. Figure 6 (a) shows the Thomson parabola measurement in Ar discharge. Horizontal and vertical axes represent deflections by electric and magnetic fields, respectively. Singly to triply ionized Ar ions were observed. The ions of maximum velocity are aligned in a straight line, which shows a constant velocity. Figure 6 (b) shows the Thomson parabola measurement in Kr discharge. Singly to triply ionized Kr ions were observed. The ions of maximum velocity are also aligned in a straight line, which shows a constant velocity.

The results of the analysis are summarized in Table 1. The results show that the maximum energy rather than the maximum velocity were equal in Ar and Kr discharges. From this result we cannot

(a)



(b)

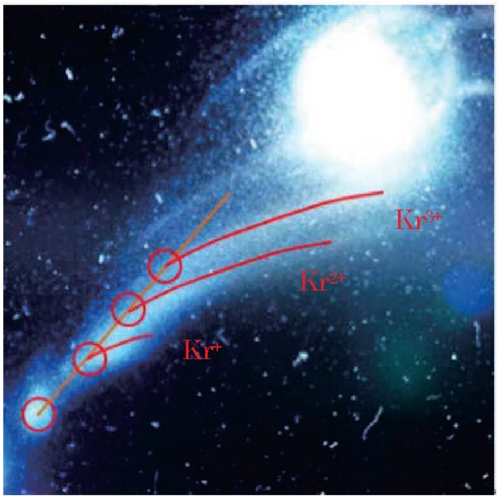


Fig. 6 Thomson parabola measurement of (a) Ar discharge and (b) Kr discharge.

Table 1 Summary of most accelerated ions in (a) Ar and (b) Kr discharges.

(a)

	Ar^{+}	Ar^{2+}	Ar^{3+}
v [m/s]	2.3	2.3	2.3
E [MeV]	1.1	1.1	1.1

(b)

	Kr^{+}	Kr^{2+}	Kr^{3+}
v [m/s]	1.6	1.6	1.6
E [MeV]	1.1	1.1	1.1

conclude anything simply for ion acceleration. Because it remains a possibility of difference such as in the current waveform or the shrinking velocity of the magnetic wall, although the experimental condition was fixed for two types of gas discharges. It is necessary to make experiment in the same discharge such as to do it with mixed gas.

5. Summary and Discussion

First it is with respect to the pinhole measurement with Al filter, the increase of acceleration energy was confirmed with increase of charging voltage, even accelerated ions in the negative discharge was confirmed. The presence of accelerated ions in the negative discharge means the presence of the acceleration mechanism that does not depend on the current direction. However, the acceleration energy in the negative discharge was smaller than the positive discharge, it is conceivable that the acceleration effect of the induced electromagnetic force was applied.

In the Thomson parabola measurement, constant velocity of ions in the different charged states were observed in the same experiment. This is a result that supports the statistical acceleration model due to the shrinking magnetic wall. In the comparison of Ar and Kr discharges, the resulting acceleration energy was almost the same, although the induction voltage estimated from the change in the current is larger in Kr discharge. It is necessary to confirm the reproducibility by fixing the experimental conditions. It is also important to do the experiment with a mixed gas.

Although it was not shown in the experimental results that the reproducibility of pinch was changed by changing the nozzle width of the gas puff. In other words, the shape of the gas is no longer sharp by expanding the nozzle width, the plasma becomes unstable, and the pinch often occurs off the axis. As a result, no significant change was observed in the energy of the ions, but significant errors can be caused in the Thomson parabola measurement. It is necessary to carry out the experiment to examine well for the nozzle width.

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