Emission of High-Energy Ions in the SHOTGUN III Divergent Gas-Puff Z-Pinch Experiment

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Abstract. Ion pinhole measurements of high-energy ions were conducted on the divergent gas-puff z-pinch plasma. Two types of ions, 1.7 – 2.5 MeV and 0.1 – 0.7 MeV, were observed. The former was observed only on the axis. The latter showed quite different characteristics between positive and negative discharges. These ions were considered to be accelerated by inductive electric field generated by the pinch.

1. Introduction
The gas-puff z pinch is a repetitive and efficient system for producing high energy-density plasma [1]. The plasma focus can repetitively converge the plasma to a small spot. The divergent gas-puff z pinch has been devised for the realization of efficient radiation source combining both advantages [2]. In the experiment of the divergent gas-puff z-pinch, hard x-ray of 150 – 200 keV, which has not been observed in the conventional gas-puff z pinch, was observed near the surface of anode. This is considered to be caused by electron beam that occurred by the pinch.

Owing to the existence of electron beam, the generation of ion beam has also been expected simultaneously. High energy ions have been observed in plasma focus, and the mechanism of the ion acceleration has been attributed to electromagnetic induction [3]. The ion measurement using a pinhole has been conducted in this system, and a coaxial structure of ion distribution has been observed [4]. The divergent gas-puff z pinch is similar to the plasma focus in that it is a nonuniform system in the axial direction.

Ion measurement using Thomson parabola energy analyzer has been conducted on the Ar divergent gas-puff z-pinch plasma [5]. The emissions of singly to triply ionized Ar ions with the energy of MeV-order have been identified in the axial direction. Experiment on the ion generation relating to the direction of discharge current has been conducted using the bipolar charging power supply. And the generation of these ions has been identified in the axial direction independent of the current direction [6].

In this research, the ion pinhole measurement was conducted to understand the mechanism of high-energy ion generation in the divergent gas-puff z-pinch discharge. And the energy-dependent spatial distribution of ions was measured using a filtered pinhole camera. The relation between the ion distribution and the direction of the current was investigated using the bipolar charging power supply.
2. Experimental setup

The experiment was carried out on the SHOTGUN-III device at Nihon University (Fig. 1). The energy storage section consists of 40 kV, 12 μF capacitor bank. The advantage of the device is that the bank can be charged to either positive or negative, so that the dependence of polarity of the current can be examined.

Gas-puff was performed by a high-speed gas valve and an annular divergent Laval nozzle mounted on the center conductor. The angle of divergence was 10 degrees. The nozzle diameter was 30 mm, and the inner diameter of opposing electrode was 60 mm. The distance between the electrodes was 30 mm. Ar was used as the operating gas, and the plenum pressure of the gas valve was 5 atm.

In order to investigate the spatial distribution of high-energy ions emitted from the pinch plasma, ion pinhole measurement was conducted. The ion pinhole cameras were placed both axially and radially, as shown in Fig. 2. The diameter of the pinhole was 1 mm. As the distance between the center of electrodes and the pinhole was nearly equal to that between the pinhole and the detector, almost equal size image should be obtained. Track detector Baryotrak-P (CR-39) was used for detecting ions. It is sensitive to ions above 100 keV, and electrons are not detectable [3]. In this experiment each detector was cut as 67 × 67 mm.

A high-speed camera with an image intensifier (Hamamatsu V3347U) was used for the observation of radial motion of the plasma.

3. Divergent gas-puff z-pinich discharge

In the typical operation of divergent gas-puff z pinch, peak discharge current appeared at about 2 μs after the start of discharge. The current was about 100 kA at the charging voltage of 20 kV. A current dip was observed just after this moment. This indicated the increase of circuit inductance due to the pinch, and the generation of soft x-ray was also observed.

Figure 3 shows visible framing photographs at the charging voltage of 20 kV. Each exposure time was 100 ns, and the photographs were taken at 1.3, 1.8, 2.0, 2.1 and 2.3 μs after the start of discharge, respectively. At 1.3 μs the shape of the plasma was similar to that of the initial gas, and the motion of the plasma was little. At 1.8 μs the plasma shrunk near the anode. The

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**Figure 1.** Schematic diagram of the SHOTGUN III divergent gas-puff z-pinich device.

**Figure 2.** Arrangement of the ion pinhole measurement system.
Rayleigh-Taylor instability developed over the plasma column. At 2.0 μs the plasma shrunk strongly just in front of the anode and collapsed on the axis. At 2.1 μs the shrink took place over the plasma column, and the plasma was expanding slightly. At 2.3 μs a helical MHD (kink) instability developed, and the plasma began to expand.

The peak current and the pinch time were quite similar at the charging voltage of -20 kV. These evidences indicate that there is no big difference between the positive and the negative discharges in the discharge path and the sequence of radial motion.

4. Ion pinhole measurement
At first, the experiment was carried out at the charging voltage of 20 kV. Figure 4 shows the ion tracks in the axial and radial directions. Double coaxial ion tracks were obtained by the axial detector. The diameter of the outer circle was about 40 mm, and the diameter of the center circle was about 16 mm. And the tracks extending to the right was observed in the radial detector.

Next, the experiment was carried out at -20 kV. Figure 5 shows the ion tracks to the axial and radial directions. A small spot of ion tracks was observed in the axial direction, which was quite different from positive discharge. And the tracks extending to the left was observed in the radial detector. Crucial difference appeared in the ion tracks by the difference of the polarity of
Then filtered measurement with 4-hole pinhole camera was conducted. The charging voltage was 20 kV. Figure 6 shows the ion tracks with 0.8, 1.5, 2.0 μm Al filters and without a filter. The tracks without a filter show coaxial structure. Spot images of ion track were observed with 0.8 μm and 1.5 μm filters. No ion tracks was observed with 2.0 μm filter. The size of the spot was about 2 mm, which was almost the same as that of discharge with negative power supply.

5. Summary and discussion

Ar ions which pass through 0.8 μm, 1.5 μm and 2.0 μm Al foils have the energy exceeding 0.7 MeV, 1.7 MeV and 2.5 MeV, respectively. There are two types of high energy ions. The first ions have tracks of coaxial structure, which cannot come over 0.8 μm filter. The energy of these ions is between 0.1 and 0.7 MeV.

The second ions have tracks of a spot on the axis, which can come over 1.5 μm filter. The energy of these ions is between 1.7 and 2.5 MeV. As the spread of ion tracks in a spot is small, the ions were thought to have come from the pinch plasma which was observed at 2.0 μs in Fig. 3. These ions were considered to be the same as the ions which were detected by Thomson parabola analyzer [6]. Although the filtered measurement was not made for the negative discharge, the high-energy component should have been included in the observed spot in Fig. 5 (a). Those high-energy ions were possibly generated by some acceleration mechanism independent of the current direction.

The ions which form the coaxial structure were observed only in the positive discharge. The diameter of the center circle was about 16 mm, and it is considerably larger than the pinch plasma. The ions near the anode surface were considered to be accelerated by inductive electric field which occurred at the moment of pinch. The diameter of the outer circle was about 40 mm, and it was beyond the plasma diameter. The ions in this part came through the outside of the plasma, and the orbits were bent by the magnetic field. The direction of Lorentz force acting on the ions was to converge them toward the cathode. The ion tracks observed in the radial detectors had similar tendency to them.

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