Deuterium ion beam formation in a vacuum arc discharge system with a deuterated cathode

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Abstract. The formation of deuterium ion beams in a vacuum arc with a deuterium-saturated zirconium cathode was studied using a MevvaV.Ru vacuum arc ion source. The multi-aperture ion-optical system of the source was replaced by a string ion-optical system to measure and compare the current–voltage characteristics and current density distributions over the beam cross-section obtained with the two systems. The study shows that the string system with a deuterated cathode provides a beam current 1.4–1.5 times higher than the multi-aperture system does, all other things being equal, and that the beam divergence with the string system is also higher. The total pulse current of deuterium ions in the beam ranges to about 1 A.

1. Introduction
Vacuum arc discharges with a deuterium-saturated (deuterated) zirconium cathode are used for producing pulsed neutron fluxes in vacuum neutron tubes \([1, 2]\), which are miniature sealed-off vacuum arc ion sources with a pulse duration of about 1 µs \([1]\). The efficiency of this type of device is determined by the neutron generation rate. One of the ways to increase the efficiency is to increase the fraction of deuterium ions in a deuterated-cathode vacuum arc plasma by increasing the total arc current. As has been shown \([3]\), the deuterium ion fraction attained in the plasma of a short kилоampere vacuum arc is 80%, being twice as large as the fraction of deuterium atoms in the cathode material.

In the study reported, the deuterium ion current extracted from a deuterated-cathode vacuum arc plasma was increased through optimizing the ion beam formation and acceleration system of a MevvaV.Ru vacuum arc ion source \([4]\) for which its multi-aperture ion-optical system, which was used in our previous experiments \([3, 5]\), was replaced by a string ion-optical system. Compared to the multi-aperture system, the string system provided a higher ion extraction efficiency from the discharge plasma, allowing us to increase the total current of multiply charged ions and hence the number of deuterium ions in the beam at the same discharge parameters. Another advantage was that the string system improved the pumping of the anode cavity of the source and decreased the content of residual impurity ions in the beam.
Below we present the results of our study, including measurements and comparison of the current–voltage characteristics, emission parameters, and radial ion current density distributions obtained with the string and multi-aperture ion-optical systems.

2. Experiment

Figure 1 shows a schematic of the Mevva-V.Ru vacuum arc ion source with a string ion-optical system. The vacuum arc cathode was made of zirconium saturated with deuterium to 40 at%, i.e., the cathode material contained 0.67 deuterium atoms per zirconium atom. It was shaped to a diameter of 6.4 mm and was placed in a ceramic tube with a wall thickness of 1 mm on which a ring trigger electrode was mounted. Upon applying a voltage pulse of 14 kV with a current of 40 A between the cathode and trigger electrode, a vacuum arc was initiated by a ceramic flashover and operated with a current of 100–300 A at a pulse duration of 250 µs between the cathode and anode. The anode volume was filled with cathode spot plasma, and then, ions were extracted from it through an emission grid of diameter 10 cm. The ion beam was formed as an accelerating voltage of 10–60 kV was applied between the emission grid and grounded acceleration grid. The electron flow produced in the region of ion beam transport was reflected by a deceleration grid to which –2 kV was applied.

The ion current was measured using a magnetically insulated Faraday cup with a hole area of 10 cm² located at 80 cm from the ion source. The Faraday cup could be moved along the beam radius with a step of 1 cm. For measuring the ion current density distribution over the beam cross-section, the hole diameter of the Faraday cup was decreased to 1 cm. The mass-charge state of the beam was analyzed using a time-of-flight mass spectrometer with a gate diameter of 22 cm and base length of 1 m [6] located at 1.4 m from the ion source. The experimental system was pumped by a cryogenic pump to a minimum pressure of 3×10⁻⁷ Torr.

The main design feature of the ion source shown in figure 1 is its string ion extraction system rather than the multi-aperture system used previously [4]. The multi-aperture system comprised three identical electrodes, each with a thickness of 4 mm, diameter of 199 coaxial holes of 3 mm, and geometric transparency of less than 50%. The string system also comprises three electrodes. Its emission electrode represents a grid with a wire diameter of 0.4 mm, mesh size of 3×3 mm, and geometric transparency of 75%, and its acceleration and deceleration electrodes represent a grid of
parallel strings of diameter 0.4 mm stretched with a step of 5 mm such that the geometric transparency of each electrode is 92%. The much higher geometric transparency of the string ion-optical system, compared to the multi-aperture one, should increase the ion current density, improve the pumping of the anode cavity of the source, and decrease the amount of impurities in ion beams, all other things being equal.

3. Experimental results and discussion

Figure 2 shows typical arc currents and ion beam currents measured by the Faraday cup on the beam axis for the multi-aperture and string ion-optical systems. It is seen that the ion beam current for the string system is 1.4–1.5 times higher than for the multi-aperture one, all other things being equal, and this is due to the higher geometric transparency of the string system.

**Figure 2.** Arc current and ion beam current for multi-aperture (a) and string ion-optical system (b). Arc current is 200 A, the accelerating voltage is 30 kV, cathode ZrD$_{0.67}$.

Figure 3 shows the current–voltage characteristics of the ion source for the multi-aperture and string extraction systems. It is seen that the ion current for the string system is higher and that the dependences for the two systems differ noticeably. This is because in any ion source with multi-aperture extraction [4, 7], varying the accelerating voltage or the arc current changes the plasma boundary position in the emission electrode holes such that the ion beam extracted through them becomes defocused, part of the ions goes to the surface of the acceleration electrode rather than to its coaxial holes, and the ion beam current to the collector decreases. Besides, the electrode surface

**Figure 3.** Ion beam current to Faraday cup vs extraction voltage for multi-aperture (1, 3) and string extraction system (2, 4). Arc current is 100 A (1, 2) and 200 A (3, 4).
bombarded by accelerated ions is sputtered, and the ion beam is thus contaminated. The string ion-optical system is free of these shortcomings, and its current–voltage characteristic either increases or shows saturation.

Figure 4 presents the radial ion current density distributions measured at 80 cm from the ion source. It is seen that the ion beam divergence for the string system, compared to the multi-aperture one, is higher. The ion beam diameter at which the ion current density measures 50% of its maximum is 13.3 cm for the string system and 11.2 cm for the multi-aperture one. As the accelerating voltage is increased, the beam divergence in both cases decreases slightly.

The radial ion current density distributions (figure 4) and on-axis ion current to the Faraday cup (figure 3) at the same distance from the ion source allow us to estimate the total pulse current of the ion beam. At an arc current of 200 A and accelerating voltage of 30 kV, it reaches 1.9 A for the multi-aperture system and 3 A for the string one. As the accelerating voltage is increased to 60 kV, the total current for the multi-aperture system decreases to 1.4 A whereas its value for the string system increases to 4 A. Our time-of-flight analysis of the ion beam mass-charge state shows that at the arc parameters used, the ratio of deuterium to zirconium in the beam is 40 at%, which coincides with its value in the cathode material. The mean charge state of zirconium ions in the beam is 2.2. As has been noted [5], such a mean is lower than the mean charge state of a beam with a pure zirconium cathode: 2.6 [8]. In view of the foregoing, we can estimate the total current of deuterium ions. For the string ion-optical system at an arc current of 200 A and accelerating voltage of 30 kV, the total current of deuterium ions is 0.7 A, and at 60 kV, it can reach 1 A.

4. Summary
The formation of deuterium ion beams in a vacuum arc discharge with a deuterated zirconium cathode was studied using a MevvaV.Ru vacuum arc ion source whose multi-aperture ion-optical system was replaced by a string ion-optical system. The study shows that the string system provides an ion beam current 1.4–1.5 times higher than the multi-aperture system does, all other things being equal, and that the beam divergence with the string system is also higher. The current–voltage characteristic with the string system is increasing, and the total pulse current of deuterium ions in the beam ranges to about 1 A.

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