Miniature high current metal ion source

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A small, simple ion source for the production of high brightness beams of metal ions is described. A metal vapor vacuum arc discharge is used to establish the high density plasma from which the ion beam is extracted. The source is finger sized, and can produce pulsed metal ion beams with current up to the 10-mA range.

A new kind of ion source has recently been described[1-4] with which high current beams of metal ions can be produced. This source makes use of a metal vapor vacuum arc (MEVVA) as the mechanism for creating the high density metal plasma from which the ion beam is extracted. Beams of a wide range of metal species have been produced, spanning the periodic table from lithium to uranium. Beam currents of over 1 A have been measured, with extraction voltage from 10 to 60 kV. The initial beam diameter is 2 cm and the normalized emittance is as low as 0.02π cm mrad.

We have developed a miniaturized embodiment of the MEVVA source which is only about 1.5 cm in diameter and 6 cm in length; we have called this the MicroMEVVA ion source. The MicroMEVVA beam is of current up to about 15 mA at an extraction voltage of 15 kV and the initial beam diameter is 1 mm. We describe here the source construction and the measurements we have made to date.

The source is simple in the extreme, being little more than an assemblage of metal and alumina tubes one within another. A photograph of the assembled MicroMEVVA is shown in Fig. 1(a), and of the disassembled components in Fig. 1(b). From right to left in Fig. 1(b) the components are central trigger electrode, trigger-cathode insulator, cathode, cathode-anode insulator, anode, anode-extractor insulator, and extractor. The outer surface of the anode cylinder was machined down to a slightly smaller diameter, over that half of its length close to the extractor, so as to increase the surface path length between anode and extractor; in this way the maximum extractor voltage that could be maintained without breakdown was increased to 15 kV. The dimensions of the metal and alumina tubes were determined primarily by what was readily available out of laboratory stock; certainly the source could be miniaturized yet further if need be. The axial spacings of the components seemed to be uncritical, and were approximately as follows: the trigger electrode tip was in the plane of the end of the cathode cylinder, which in turn was several millimeters withdrawn from the anode plane; the anode-extractor gap was about 0.75 mm. The diameters of the anode hole and the extractor hole were the same, 1 mm. We varied some of these dimensions and saw only small changes in the source performance. In the embodiment used here, all the metal pieces were stainless steel, excepting the cathode cylinder which was either stainless steel or titanium. The beam composition is determined by the cathode material, and to change the ion species the cathode cylinder, or at least its exposed tip, should be changed.

A schematic of the electrical circuit used to drive the source is shown in Fig. 2. Typically the trigger pulse is several kilovolts in amplitude and of duration a few microseconds. The arc supply was simply the *RC* discharge of a 12-μF capacitor through a 2.5-Ω resistor; the capacitor was charged to 100–200 V and the arc current was thus 50–100 A. A more controlled approach would be to use an *LC* pulse line for the arc current supply, as has been done for MicroMEVVA's big brother, the MEVVA. Nonetheless this simple supply is adequate.

For these tests the source was located within a large vacuum chamber at a base pressure in the mid 10^{-6} Torr range. Diagnostics included a magnetically suppressed Faraday cup to measure ion beam current and a time-of-flight diagnostic to measure the ion beam composition and charge state distribution (charge-to-mass ratio of the beam components). The diagnostics have been more fully described elsewhere.[3]

Figure 3 is an oscillogram showing the ion beam current and the arc current for a typical shot. The pulse length is approximately 50μs, and is determined by the time taken for the current to decay down to a value at which the arc extinguishes, about 10 A. The extraction voltage here was 15 kV,

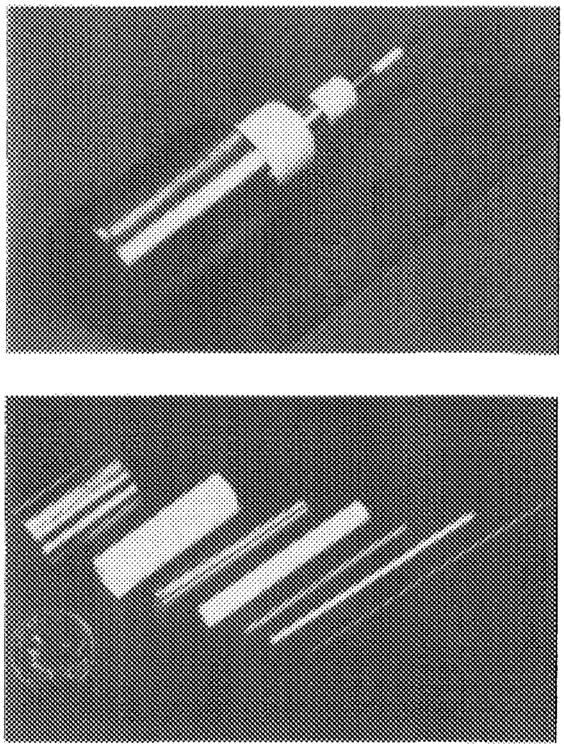

FIG. 1. Photograph of the MicroMEVVA ion source: (a) assembled; (b) disassembled.

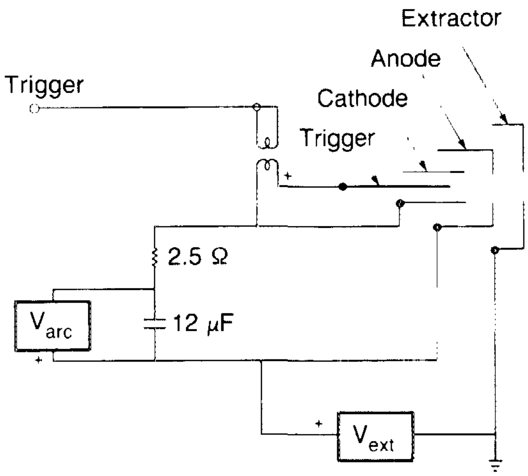

FIG. 2. Schematic of the electrical circuit used to drive the ion source.

and the beam current about 10 mA for an arc current of a few tens of amperes. It is interesting to note that the beam current pulse shape does not precisely follow the arc current; this is due to changes in the geometry of the plasma meniscus at the extractor as the plasma density varies.[5-7] The beam noise ($\delta i/i$) is about 10%, and shot-to-shot reproducibility is fair. The diameter of the Faraday cup was 5.0 cm, and the source was located about 15 cm distant from the cup; this implies that the beam current is contained within a half-angle divergence of 10°. Here the cathode material was stainless steel, and the dominant beam component was Fe^{2+}. The measured beam current is thus contained within an emittance of 0.01π cm mrad (normalized). This is a good emittance figure.

The electrode serving as trigger and the electrode serving as cathode may be interchanged with only slight effect on the beam output. The beam current is much the same in either case, but the current fluctuation level is somewhat greater with the center pin as cathode.

The beam current is plotted as a function of extractor voltage in Fig. 4, for the case of a stainless-steel cathode. The maximum current measured was 14 mA at 15 kV. Note that the scatter in the measured data points indicates the shot-to-shot variation in the extracted current. The solid curve is that calculated from the Child–Langmuir equation,[7-9]

$$j_i = 1.72 \left(\frac{Q}{A} \right)^{1/2} \frac{V^{3/2}}{d_{\mathrm{eff}}^2} \ \mathrm{mA/cm}^2, \qquad (1)$$

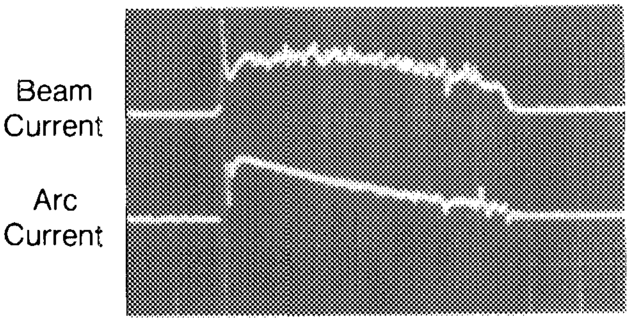

FIG. 3. Oscillogram showing the extracted ion beam current (upper trace; 10 mA/cm) and the arc current (lower trace; 50 A/cm). The extractor voltage was 15 kV. Sweep speed 10 μs/cm.

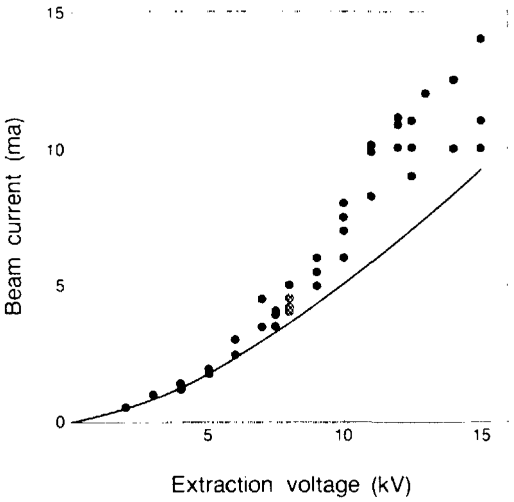

FIG. 4. Extracted ion beam current vs extractor voltage. The solid curve is that predicted by the Child–Langmuir theory [Eq. (1)] using the experimental values without any normalization.

where Q and A are the charge (electronic units) and mass (amu) of the ion species, V the extraction voltage in kV, and d_{eff} the effective extractor gap in cm. It is usual to take

$$d_{\mathrm{eff}} = d_{\mathrm{gap}} + r_{\mathrm{ext}} , \qquad (2)$$

where d_{gap} is the anode-extractor spacing and r_{ext} is the radius of the hole through which the ions are extracted from the plasma meniscus. The fit of the data to this prediction is excellent, and may be a consequence of the fact that as the arc current decays and so also the plasma density, the plasma parameters are well matched to the extraction optics at least somewhere in the decay—the extracted ion beam current maximizes at the optimum and this is the ion current that is measured.

The spectral composition of the beam was measured with a time-of-flight Q/A diagnostic, and typical data obtained from such a measurement are shown in Fig. 5 for the case of a titanium cathode. The dominant component is Ti^{2+}, with some Ti^{+} and Ti^{3+}; a small amount of H^{+} and

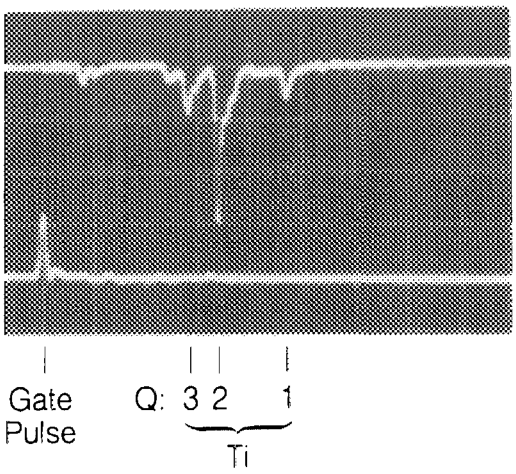

FIG. 5. Beam spectral analysis obtained with the time-of-flight diagnostic. Extraction voltage was 15 kV; titanium cathode; sweep speed 1 μs/cm.

C^+ (or, less likely, Ti^{4+}) contaminants can also be seen. This charge state distribution is quite similar to that produced by the MEVVA ion source at high arc current. The similarity can be taken as supporting evidence for the hypothesis that all the plasma physics, including the determination of the charge state distribution, takes place within the cathode spots.

In summary, the miniaturized embodiment of the MEVVA ion source that we have described here provides a means of producing beams of metal ions in the 10-mA range using a small and very simply constructed ion source.

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