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Mevva ion source operated in purely gaseous mode

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We have operated a vacuum arc ion source in such a way as to form beams of purely gaseous ions. The vacuum arc configuration that is conventionally used to produce intense beams of metal ions was altered so as to form gaseous ion beams, with only minimal changes to the external circuitry and no changes internally to the ion source. In our experiments we formed beams from oxygen (O^+ and O_2^+), nitrogen (N^+ and N_2^+), argon (Ar^+), and carbon dioxide (C^+, CO_2^+, O^+, and O_2^+) at extraction voltage of 2–50 kV. We used a pulsed mode of operation, with beam pulses ~50 ms long and repetition rate 10 pulses per second, for a duty cycle of about 50%. Downstream ion beam current as measured by a 5 cm diameter Faraday cup was typically 0.5 mA pulse or about 250 μA time averaged. This time averaged beam current is very similar to that obtained for metal ions when the source is operated in the usual vacuum arc mode. Here we describe the modifications made to the source and the results of our investigations.
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I. INTRODUCTION

Vacuum arc ion sources are an established and versatile tool for forming high current metal ion beams.[1–3] In the usual mode of operation of these sources the beam contains virtually all metal ions, with only minimal gaseous ion impurity content. It has been shown that gas can be deliberately introduced into the vacuum arc plasma discharge so as to form beams containing controllable mixtures of metal and gaseous ion species.[4,5] Hybrid metal-gaseous ion beams can be advantageous for some metallurgical ion implantation applications, for example for forming buried oxide layers.[5] Although the metal–gas ion ratio can be varied over a wide range by this method, it is not possible to reduce the metal ion content to less than several percent, and thus beams of purely gaseous ion species cannot be formed. It would be experimentally convenient if it were possible to use a vacuum arc ion source not only to form metal ion beams and mixed metal–gas ion beams, but also to form beams containing only gaseous ions. One would then have a single ion source for producing ions beams of virtually all of the metallic and gaseous elements of the Periodic Table. We have developed such a method. Requiring only minor reconfiguration of the external electrical system and no changes at all to the ion source hardware, the technique allows quick and simple changeover from metal ion or hybrid mode to purely gaseous-ion mode. Here we describe the ion source system setup that we have used and outline the results obtained that exemplify purely gaseous mode operation.

II. DESCRIPTION OF THE ION SOURCE AND EXPERIMENTAL SETUP

Our approach to forming purely gaseous ion beams was to replace the vacuum arc as plasma formation mechanism by a gaseous plasma which is a type of hollow cathode glow discharge, while still utilizing the same geometry and mechanical configuration as for the metal vapor arc. The work was carried out at the Lawrence Berkeley National Laboratory using the Mevva V ion source that has been fully described elsewhere.[1,6,7] A simplified schematic of the ion source is shown in Fig. 1. Only three small modifications were needed: (i) a gas inlet feed was utilized (this change had been made previously as part of earlier hybrid metal–gas ion beam work;[5] the optional gas inlet is a permanent part of the Mevva source); (ii) the polarity of the trigger pulse and of the arc power supply (the LC pulse forming line as used for the vacuum arc configuration) was reversed; this needed no more than switching around the leads; (iii) installation of a current-limiting high power resistor of 1–3 kΩ in the plasma discharge circuit.

The source was mounted to a vacuum chamber as used normally for Mevva-V ion source experimental work.[1,7] Base vacuum pressure was about 1×10^{-6} Torr, and operation gas was fed into the source such that the chamber pressure was about $1-2\times10^{-4}$ Torr. A magnetically suppressed Faraday cup with 5 cm diameter entrance aperture was located 65 cm downstream from the ion source extractor, and was used to monitor the ion beam current. The Faraday cup was radially movable and could be retracted completely from the ion beam path so as to allow operation of a time-of-flight (TOF) charge state analysis system[1,8,9] by means of which the ion beam charge-to-mass composition was measured.

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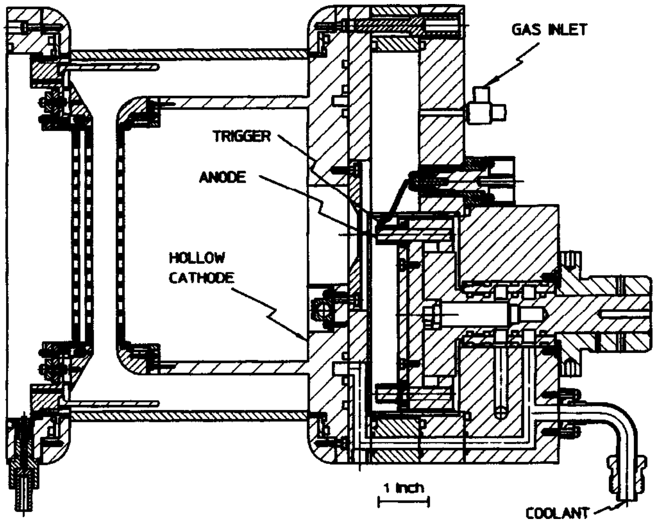

FIG. 1. Schematic of the Mevva ion source as configured to operate in gaseous mode.

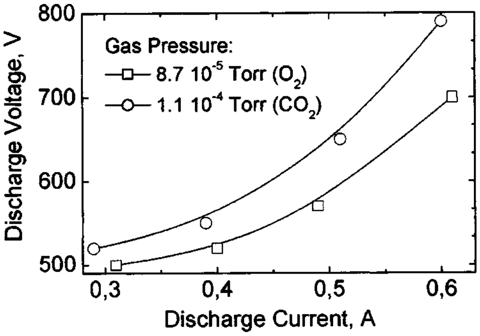

FIG. 2. Voltage–current characteristics of the glow discharge formed in the ion source plasma cavity for oxygen and carbon dioxide gases.

III. GASEOUS SOURCE AND BEAM CHARACTERISTICS

When the source is triggered by a high voltage (~3 kV), high current (~5 A), negative pulse applied between the trigger electrode and the anode (where presently the anode is what was previously the vacuum arc cathode), a hollow cathode glow discharge plasma[10–12] is formed in the cavity that now includes a hollow cathode and the extractor grid at cathode potential. As is usual for low pressure glow discharges with anode–cathode surface area ratio $\sim(m_e/M_i)^{1/2}$, most of the discharge voltage is located at the negative cathode drop. Plasma ions accelerated by this potential bombard the cathode surface and produce secondary electrons, which are then accelerated into the plasma volume by the cathode potential drop. The electrons oscillate within the hollow-cathode plasma configuration, establishing an efficient ionization mechanism in the gas. The thickness d_c of the cathode fall region may be estimated from the Child–Langmuir equation as

$$d_c = 2/3[\epsilon_0(2e/M_i)^{1/2}(\phi_c{}^{3/2}/I_d)S_c(1+\gamma)]^{1/2}, \tag{1}$$

where ϕ_c is the cathode potential drop, I_d is the discharge current, S_c is the hollow cathode surface area, and γ is the secondary electron emission coefficient. For typical discharge conditions as in the present work, ϕ_c is of order $\sim$500 V; also, here, $I_d \approx 0.5$ A, $S_c \approx 700\ \mathrm{cm}^2$, and $\gamma \approx 0.1$, and the thickness d_c of the cathode fall region determined from Eq. (1) is about 0.5 cm. On the other hand, the ionization mean-free-path for energetic electrons within the hollow cathode region is

$$\lambda = I/(3.3\times 10^{16} P\sigma_i), \tag{2}$$

where P is the gas pressure and σ_i is the cross section for electron impact ionization. For our experimental condition ($P \approx 2\times 10^{-4}$ Torr and $\sigma_i \approx 10^{-16}\ \mathrm{cm}^2$), λ is about 15 m. Since $\lambda \gg d_c$ (and also $\lambda \gg l_c$, where $l_c \approx 10$ cm is the characteristic length of the hollow-cathode cavity), the electrons execute many ($>10^2$) oscillations between ionizing collisions. Thus, finally, the probability of ionization is uniform throughout the volume, and a uniform density plasma of gaseous ions is formed by the reflexing electrons.

The series current-limiting resistor that was installed in the discharge power supply circuit determines the current and also extends the pulse length. In vacuum arc mode, when the arc impedance is very low (a few tens of mΩ), the discharge current is typically 100–300 A and the pulse length, determined by the LC pulse line, is usually 250 μs. In gaseous mode (hollow cathode glow mode) the discharge current is typically about 0.5 A and the pulse length, now determined by the glow discharge extinction, is about 50 ms. (We did not address the possibility of dc operation, clearly a very different power supply system would be required as well as enhanced source cooling.) Figure 2 shows the measured discharge voltage–current characteristics and Fig. 3 shows a typical oscillogram of the discharge and beam current time histories. We point out that the ion beam noise ($\delta I_{\mathrm{beam}}/I_{\mathrm{beam}}$) is quite low, of order 1% rms.

The beam current as measured by the downstream Faraday cup is shown in Fig. 4 as a function of ion source extractor voltage. This is the pulse current (beam current measured when the beam pulse is on); for the 50% duty cycle used in the present work, the time-averaged beam current is one half of this value. The Faraday cup, being downstream 65 cm and having a 5 cm diameter entrance aperture, collects a current (I_{FC}) that is a only a small fraction of the total ion beam current (I_{tot}) formed at the extractor, i.e., the beam is

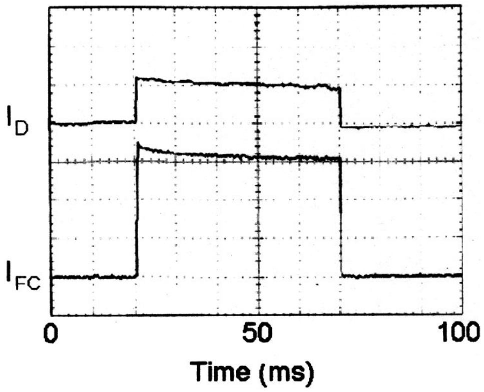

FIG. 3. Typical oscillogram showing: (upper trace) discharge current I_D supporting the plasma glow (0.2 A/cm); and (lower trace) ion beam current I_{FC} measured by downstream Faraday cup (200 μA/cm); sweep speed is 10 ms/cm.

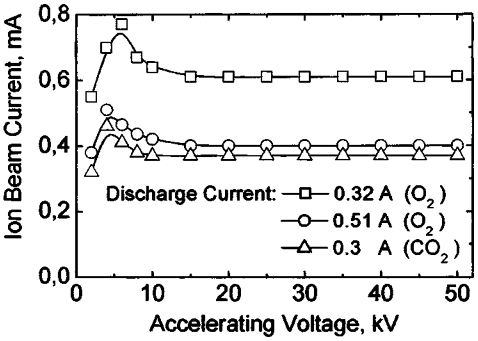

FIG. 4. Ion beam current measured by a 5-cm-diam Faraday cup located 65 cm downstream from the ion source, as a function of ion source extraction voltage.

not a particularly low divergence beam, and only a small fraction of the beam cross section is intercepted by the Faraday cup collector. We estimate $I_{FC}/I_{tot} \sim 0.01-0.1$. We can define $\alpha = I_{ion}/I_d$ as an efficiency parameter of the source, which here is equal to about $10^{-2}-10^{-3}$. This compares favorably with the ratio S_{emiss}/S_{tot}, where S_{emiss} is the area of the plasma within the ion source cavity that is presented to the extractor and S_{tot} is the total surface area of the plasma within the ion source cavity.

A time-of-flight charge state spectrum of the ion beam, for the case of oxygen gas feed, is shown in Fig. 5. The beam is composed of about one third singly ionized O^+ and two thirds singly ionized molecular O_2^+. In the work described here we did not attempt to maximize the atomic ion fraction. We also produced beams from nitrogen, argon, and carbon dioxide, with the same accelerating voltage and having approximately the same beam current. We could not detect the presence of any metal ions (for example, from the cathode, anode, or extractor grid materials) for this mode of operation, within the TOF instrumental resolution of ~1%.

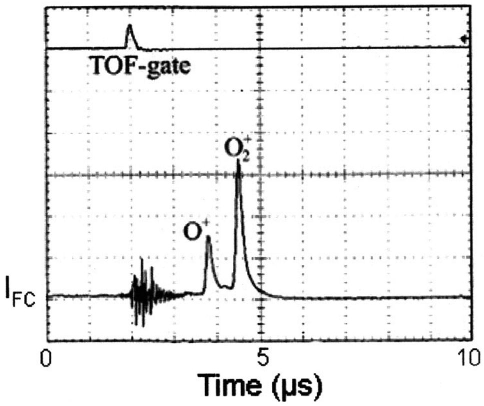

FIG. 5. Time-of-flight oscillogram showing the charge state distribution of an oxygen ion beam. Vertical axis is the ion current to a distant Faraday cup.

We have demonstrated the operation of a vacuum arc ion source in a purely gaseous ion beam mode. The changes to the vacuum arc ion source that are required to implement this mode of operation are quite simple and minimal, and the source can be changed in a matter of minutes from metal ion mode to gaseous ion mode without need for breaking vacuum. Beams of gaseous ions can be produced with pulsed current about 1 mA, pulse width of order 50 ms and duty cycle about 50%, corresponding to a time-averaged ion beam current of several hundred microamperes. This time-averaged ion current is essentially the same as that normally obtained when the source is used to form metal ion beams in vacuum arc mode. The beams are stable and reproducible. This development broadens the range of application of the vacuum arc ion source to include all of the elements of the Periodic Table, both gas and metal species.

ACKNOWLEDGMENTS

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[1] I. G. Brown, Rev. Sci. Instrum. **65**, 3061 (1994).
[2] S. P. Bugaev, A. G. Nikolaev, E. M. Oks, P. M. Schanin, and G. Yu. Yushkov, Rev. Sci. Instrum. **65**, 3119 (1994).
[3] I. G. Brown and E. M. Oks, IEEE Trans. Plasma Sci. **25**, 1222 (1997).
[4] A. N. Tyimentsev, Yu. P. Pinzhin, A. D. Korotaev, A. E. Behert, A. O. Savchenko, Yu. R. Kolobov, S. P. Bugaev, P. M. Schanin, and G. Yu. Yushkov, Nucl. Instrum. Methods Phys. Res. B **80/81**, 491 (1993).
[5] E. M. Oks, G. Yu. Yushkov, P. J. Evans, A. Oztarhan, I. G. Brown, M. R. Dickinson, F. Liu, R. A. MacGill, O. R. Monteiro, and Z. Wang, Nucl. Instrum. Methods Phys. Res. B **127/128**, 782 (1997).
[6] I. G. Brown, J. E. Galvin, R. A. MacGill, and F. J. Paoloni, Rev. Sci. Instrum. **61**, 577 (1990).
[7] I. G. Brown, M. R. Dickinson, J. E. Galvin, X. Godechot, and R. A. MacGill, Nucl. Instrum. Methods Phys. Res. B **55**, 506 (1991).
[8] I. G. Brown, J. E. Galvin, R. A. MacGill, and R. T. Wright, Rev. Sci. Instrum. **58**, 1589 (1987).
[9] I. G. Brown and X. Godechot, IEEE Trans. Plasma Sci. **19**, 713 (1991).
[10] E. M. Oks, A. V. Vizir, and G. Yu. Yushkov, Rev. Sci. Instrum. **69**, 853 (1998).
[11] A. V. Vizir, G. Yu. Yushkov, and E. M. Oks, Rev. Sci. Instrum. **71**, 728 (2000).
[12] N. V. Gavrilov, G. A. Mesyats, G. V. Radkovski, and V. V. Bersenev, Surf. Coat. Technol. **96**, 81 (1997).