Gas and Metal Ion Sources

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I Inroduction

The positive ion sources are now of interest owing to both their conventional use, e.g., as injectors in charged-particle accelerators and the promising capabilities of intense ion beams in the processes related to the action of ions on various solid surfaces[1]. For industrial use, the sources of intense ion beams and their power supplies should meet the specific requirements as follows: They should be simple, technologically effective, reliable, and relatively low-cost. Since the scanning of an intense ion beam is a complicated problem, broad ion beams hold the greatest promise. For the best use of such beams it is desirable that the ion current density be uniformly distributed over the beam cross section. The ion beam current density should be high enough for the treatment process be accomplished for an acceptable time. Thus, the ion sources used for high-current, high-dose metallurgical implantation should provide for gaining an exposure dose of $\sim 10^{17}$ cm^{-2} in some tens of minutes. So the average ion current density at the surface under treatment should be over 10^{-5} A/cm^2. The upper limit of the current density depends on the admissible heating of the surface under treatment. The accelerating voltage of an ion source is dictated by its specific use; it seems to lie in the range from ~ 1 kV (for the ion source used for surface sputtering) to ~ 100 kV and over (for the ion sources used for high-current, high-dose metallurgical implantation).

The above requirements are met by mevva-type metal-ion sources depending for their operation on a vacuum arc[2]. The successful development of this type of ion source is testified both by the growing number of research groups that develop and use such sources and by the buildup of relevant publications (see Ref. 2). Metal ion beams can be produced by a variety of methods[3,4], among which the concept harnessed in the mevva-type sources, the extraction of an ion beam from the plasma produced by the cathode spots of a vacuum arc, is distinguished by a number of fundamental advantages[4-6]. The cathode spots of a vacuum arc eject directed plasma jets consisting of the cathode material. Therefore it is possible to produce a plasma medium for the generation of a beam of ions of any conducting material, composite materials included. The ion current fraction in the plasma is rather high, 6–10% of the vacuum arc current. Despite the high temperature in cathode spots, they operate on the cathode surface being cool as a whole; so such a discharge system possesses all advantages of a cold emitter. A vacuum arc can operate at residual gas pressures as low as is wished and at any currents exceeding the threshold current for the existence of a cathode spot. With the fact that this method is simple to realize, the reasons for the intense development of this type of source are obvious.

Both metal and gas ion beams can be used for surface treatment, and it is not clear now which of these two types of ion beams will find preferred use.

A well-developed application of ion sources is the production of intense beams of positive gas ions. As a rule, for the generation of plasma a type of low-pressure discharge is used. The ion sources based on an arc discharges in a magnetic field[7], with their constructional features, show the highest energy efficiency and gas economy. The replacement of the hot emitter by the plasma of a vacuum arc will eliminate the energy consumption for heating and prevent the cathode from contamination and blowout at an abnormally increased pressure.

II A gas/metal ion source

(a) The principle of operation

We have developed a gas/metal ion source named TITAN[8,9] where a metal ion beam

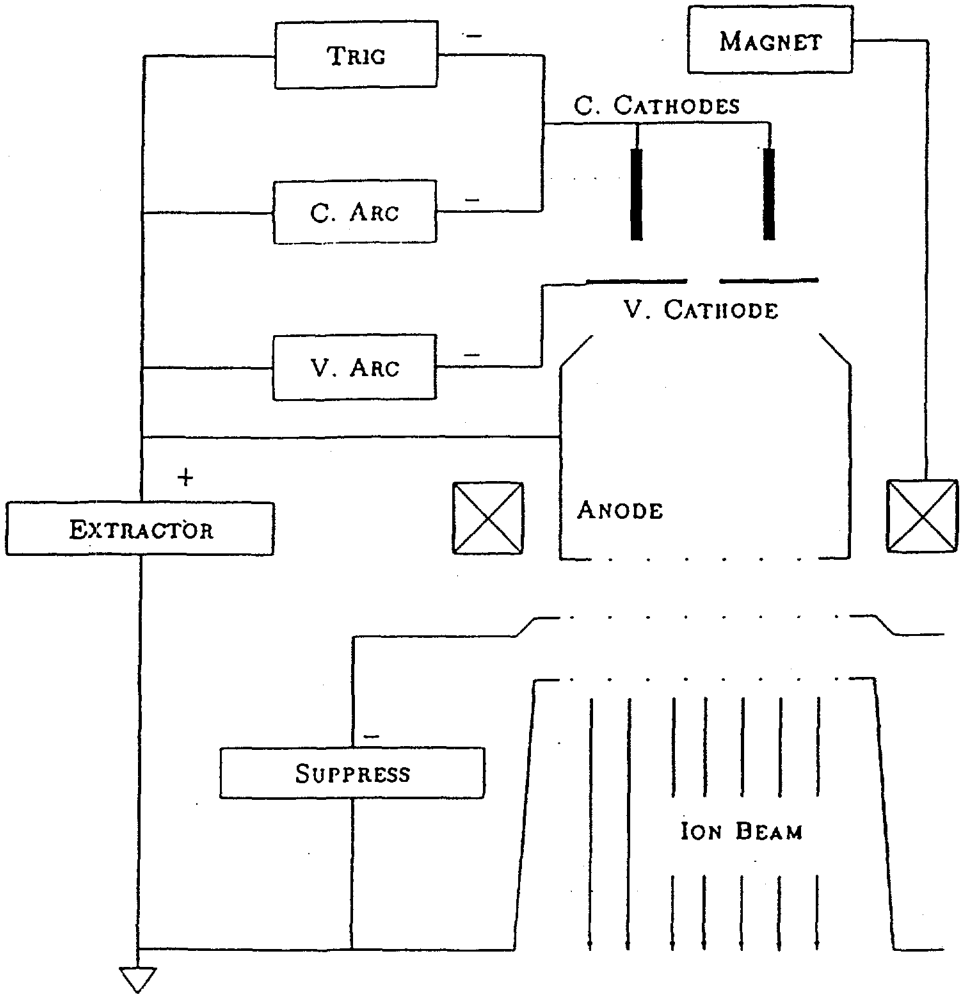

Fig. 1. The electrode system of the TITAN ion source.

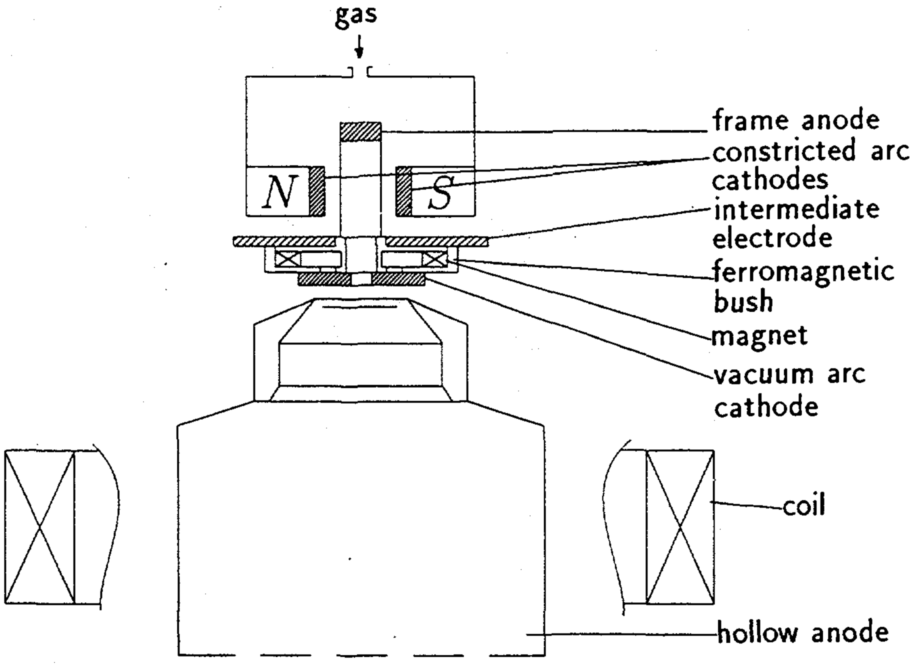

Fig. 2. The discharge chamber of the TITAN ion source.

is generated like in a mevva source and a gas ion beam like in a cold-cathode duoPIGatron with a common hollow cathode (Fig. 1). For the production of gas ions a constricted arc is ignited between the cold cathodes and the hollow anode; it is constricted by a hole in an intermediate electrode (Fig. 2). The constricted arc cathodes are placed in a Penning discharge chamber where plasma-forming gas is supplied. Making the working gas flowing and the discharge operating in one path through the constriction hole allows efficient ionization of the gas by the electrons having passed through the double layer to produce in the hollow anode a gas-discharge plasma necessary for the generation of an ion beam. The vacuum arc powered from an independent power supply is initiated between the vacuum arc cathode and the hollow anode. When the arc operates, the cathode material plasma fills the hollow anode producing the ion-beam-generating medium. With combined operation of the discharges, it is possible to produce an ion beam containing both gas and metal ions. The extraction system consists of three grids. The first one is a plasma grid being at the potential of the hollow anode. Two other grids made of metallic W-Re filaments stretched in parallel form an acceleration-deceleration system. The ion beam formed is transported onto a collector placed at a distance of 0.2–1.5 m from this system. We have developed two basic version, pulsed and dc, of the ion source.

(b) The pulsed ion source

For the pulsed version, the accelerating voltage in various ion sources varies from 10–60 kV to 20–100 kV and the beam cross-sectional area from 200 to 300 cm^2. The constricted arc and vacuum arc pulse duration is $\sim 400\ \mu s$ at a pulse repetition rate of 1–50 pps.

The peak current of gas and metal ion beams is 0.1–1 A depending on the constricted arc current (10–50 A) and vacuum arc current (20–200 A). The fraction of gas and metal ions in the ion beam was controlled by varying the constricted arc and vacuum arc currents. The control limits were found indirectly using RBS analysis of the irradiated target and for a Ta/Ar pair they were from 0.05/99.5 at.% to 90/10 at.%, respectively. Beams of He, Ne, Ar, Xe, Kr, N, C, Mg, Al, Ti, Cu, Nb, Cr, Fe, Co, Ni, Zn, Zr, Sn, Sm, Ta, W, Re, Y, Bi, Pb, and Mo ions were produced. This source version was used for high-dose implantation and ion-beam assistance.

(c) The dc ion source

We do not think that the best way to increase the average ion beam current is to increase the frequency and/or the peak pulse current since this would complicate the power supply system and involve additional problems with stable discharge initiation and an increase in the ion current density in the beam is limited by the capabilities of the extraction system used. The simplest method of increasing the average beam current is realization of the dc mode of operation of the ion source. We were able to realize the dc mode having modernized the discharge system of the ion source by making the construction more heatproof and using additional cooling. The accelerating voltage (10 kV) and the arc currents (10 A) were limited by the power (10 kW) of the power sources used for this ion source version. Beams of Ar, Xe, N, O, Mg, and Al ions have been produced with currents of 0.2–0.3 A, which is more than an order of magnitude higher than the average beam current for the pulsed version. We used the dc ion beam sources in experiments on surface sputtering and on thin-film deposition by reactive ion sputtering.

(d) The magnetic field effect

A magnetic field of up to 0.01 T produced by a solenoid, when applied to the discharge system of the ion source, increases the current extracted from the arc plasma. Measurement of the plasma parameters (n, T_e, φ) performed with the use of Langmuir and thermal emission probes have made it possible to find the mechanism for the effect of a magnetic field on the emission of ions. On application of a magnetic field, the plasma potential φ with respect to the anode and to the constricted and the vacuum arcs changes from positive to negative. Under these conditions the plasma ions are kept from going to the anode by the electrostatic field of the charged plasma.

For the gas ions of the constricted arc that go away to the anode or plasma electrodes, a potential barrier of negative anode fall $U = Ze\varphi$ appears. If the mesh size l of the emission grid is smaller than the thickness of the negative anode fall layer l_1, the barrier prevents the ions to go out beyond the grid, and the increase in ion current is insignificant. If $l > 2l_1$, the barrier can be partially eliminated by the field of the acceleration gap. When l is further increased, the emission of ions occurs from an open plasma surface; the ion current density reaches its maximum determined by the Bohm formula and becomes independent of l.

For the directed flow of the vacuum arc metal ions, a change in φ results in that some ions whose radial velocity is too low to overcome the potential barrier reflect from the latter. The condition that an ion of charge Z having escaped from the cathode spot with energy E_i at the angle α to the system axis travels through the anode cavity is $\alpha \leq \arcsin\sqrt{Ze\varphi/E_i}$. So, the ion flow is constricted by the action of the radial electric field in the plasma. The ion current onto hollow anode walls decreases, while the emission current correspondingly increases. Since for most of the ions emitted by the cathode spot which comply with the travelling condition the inequality $E_i \cos^2\alpha > Ze\varphi$ is valid, the effect of the l value on the ion emission current is not so strong. It should be noted that the applied magnetic field does not influence on the generation of ions in the cathode spot; it is responsible only for the changes in the anode plasma of the vacuum arc.

The magnetic field applied to the hollow anode region increases the densities of both the "gas" and the "metal" plasmas at the axis of the discharge system. In this case the condition that the plasma emission surface is stabilized by the grid,

$$d < \frac{2}{3}\left(\frac{\varepsilon_0}{0.4}\right)^{1/2}\left(\frac{2}{q_i k T_e}\right)^{1/4}\frac{U_{\mathrm{ac}}^{3/4}}{n^{1/2}}$$

can be violated, and the plasma will penetrate into the acceleration gap. The plane plasma boundary will transform into a convex boundary, and the accelerating field will become defocusing for the ion beam in its center. A partial defocusing of the ion beam makes the current density distribution over the beam cross section more uniform. The current density distribution can be varied, with the acceleration gap geometry and the accelerating voltage being fixed, by varying not only the discharge currents but also the magnetic field strength. Since the accelerating and the cutoff electrodes have a high geometrical transparency and the defocusing of the ion beam increases the ion losses at these electrodes only slightly, this effect can be harnessed to produce a more uniform distribution of the ion current density over the beam cross section.

III Transverse extraction of an ion beam from the anode cavity

The ion source described in Refs. 8 and 9 utilize axial extraction of a cylindrical ion beam from the anode cavity plasma. Being wide-spread, this technique for the formation of ion beams seems not to be the best. Cathode spots are "point" plasma sources; so the plasma density distribution near the emission boundary, and hence the ion current density distribution over the beam cross section, are nonuniform. Owing to the circular beam cross section, a nonuniformity in the embedded atom dose distribution appears in both the longitudinal and the radial scanning of the surface under treatment by the beam. These difficulties are also substantial for the extraction of a gas ion beam from the constricted discharge plasma, since the ionization occurs in the main near the constriction channel.

An alternate method is to fill the anode cavity with the plasma produced by several sources and to extract rectangular-cross-section beams through an emission window made in the side wall of the hollow anode. Preliminary experiments were carried out on a setup shown schematically in Fig. 3. Used as a plasma source was the discharge chamber of the source dc version. A rectangular emission window

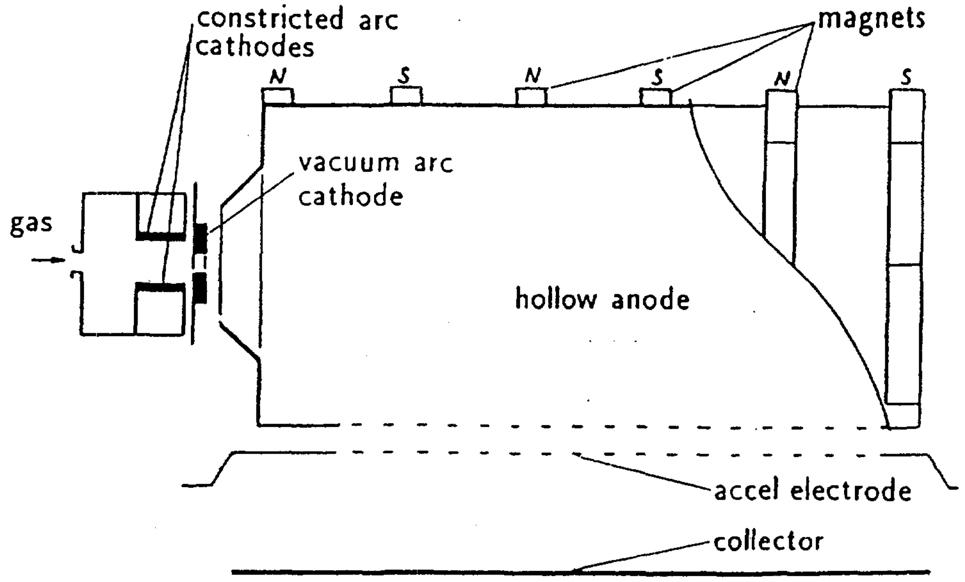

Fig. 3. The electrode system of the ion source with transverse extraction of the beam from the anode cavity.

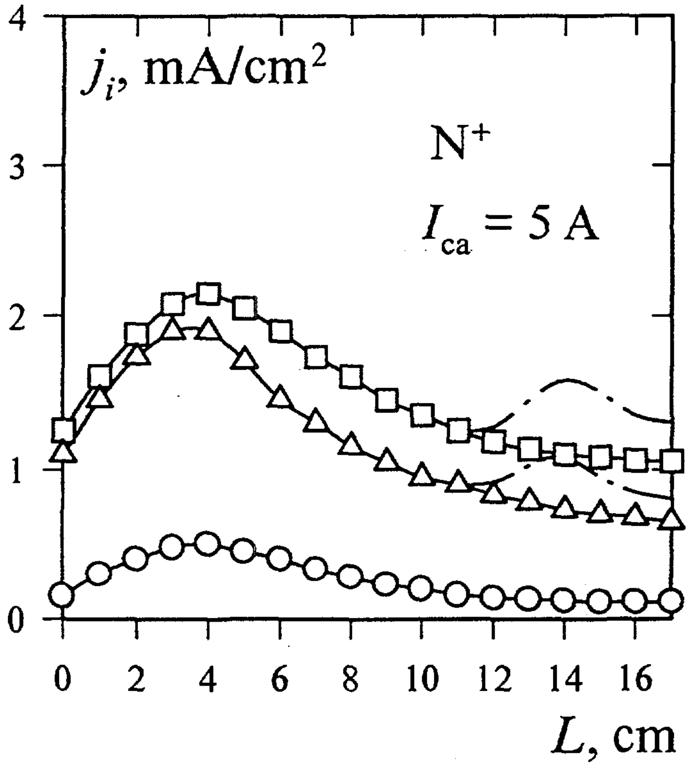

Fig. 4. The nitrogen ion beam current density profiles for constricted arc current of 5 A. o – zero magnetic field; △ – linear and □ – azimuthal configuration of magnets. Dashed lines – magnets at the anode end.

4×17 cm^2 in size was made in the anode side wall of length 19 cm and diameter 11 cm.

To keep the plasma charged particles from going to the anode cavity walls, a 0.2-T multipole magnetic field was used that was produced by Sm-Co constant magnets placed on the external side of the anode cavity. Two positions of the magnets on the anode cylinder were utilized: a linear position with evenly spaced 11 rows of magnets placed along the hollow anode cylinder and an azimuthal position with evenly spaced 6 rows of magnets placed in a circle around the hollow anode cylinder. 12 magnets were placed radially on the end of the hollow anode. The nitrogen ion current density distribution over the ion beam longitudinal section obtained for a constricted arc current of 5 A is given in Fig. 4. The use of a "magnetic wall" results in a 3–5 fold increase in ion current. The increase in ion current is a maximum for the azimuthal arrangement of magnets. Application of a magnetic field to the anode end results in the appearance of the second maximum in the ion current density distribution.

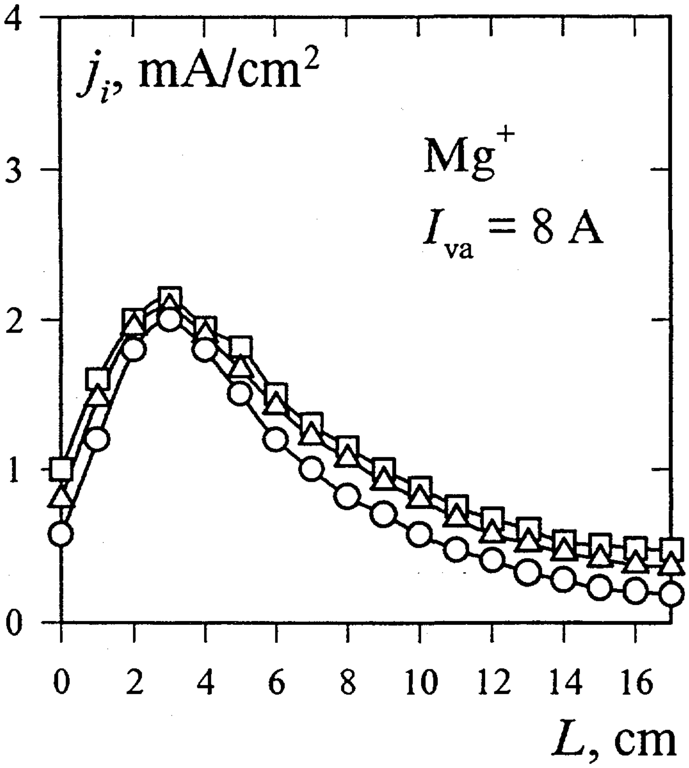

Fig. 5. The magnesium ion beam current density profiles for vacuum arc current of 8 A. o – zero magnetic field; △ – linear and ☐ – azimuthal configuration of magnets.

The magnesium ion current density distributions over the beam cross section measured for two configurations of the applied magnetic field and with no magnetic field at a vacuum arc current of 8 A are given in Fig. 5. The run of the $j = f(L)$ curves corresponds to the cosine curve that describes the density distribution for the plasma coming into the anode cavity from the cathode region of the vacuum arc. In this case, since the magnetic field is localized near the anode cavity walls, it would affect this distribution only slightly. This weak, compared to the case of a constricted arc, effect of the applied magnetic field on the beam current seems to

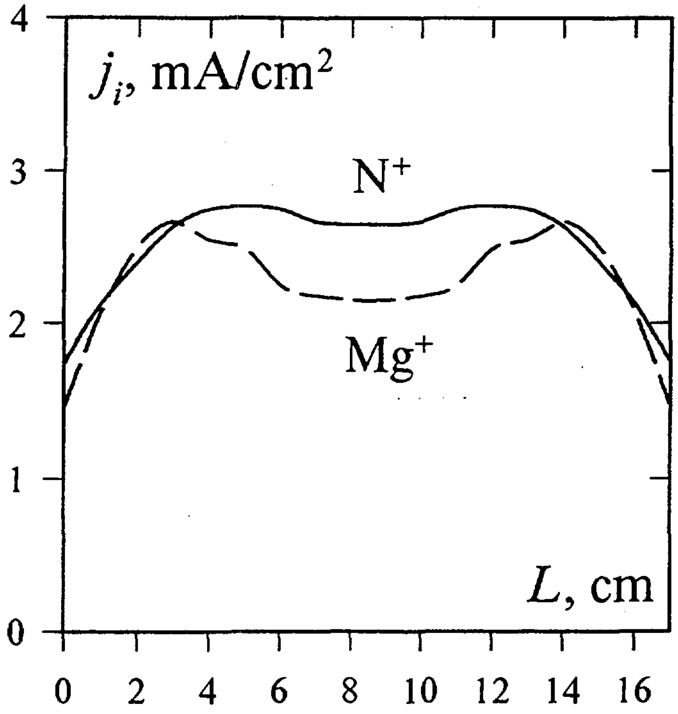

Fig. 6. Expected ion beam current density profiles for the discharge chambers used and the azimuthal configuration of magnets.

be due to the high velocities of the ions emitted by the cathode spots. According to estimates, for Mg$^+$ ions of energy $\sim$ 40 eV [6] the Larmor radius near the anode cavity walls is over 1.5 cm, while for a constricted discharge it is $\sim$ 0.1 cm. The slight increase in ion current on the application of a magnetic field is perhaps related to the reflection of only low-energy plasma ions from the potential barrier.

The obtained current density distributions for the ions extracted from the vacuum arc and constricted arc plasmas are substantially nonuniform; however, the cross-sectional uniformity of the ion beam can be improved by placing two discharge chambers at the ends of the hollow anode. In this case, owing to the superposition of the plasma flows, more uniform distributions are anticipated, such as those shown in Fig. 6. In view of the similarity laws, it is possible to obtain similar distributions for broader beams.

IV Gas-discharge plasma initiation of a vacuum arc

For stable operation of a pulsed ion source it is necessary to provide stable initiation of the vacuum arc cathode spots. The gas-discharge ignition of a vacuum arc in the TITAN ion sources has made the cathode lifetime as long as over 10^7 shots. We currently perform a research work aimed at the development of a mevva-type ion source with a gas-discharge-initiated vacuum arc. To ignite the initiating gas discharge at low pressures, a pulsed ($\tau = 1$ ms) magnetic field of up to 3 T is used.

In the experimental setup (Fig. 7) the Penning discharge cell is formed by a

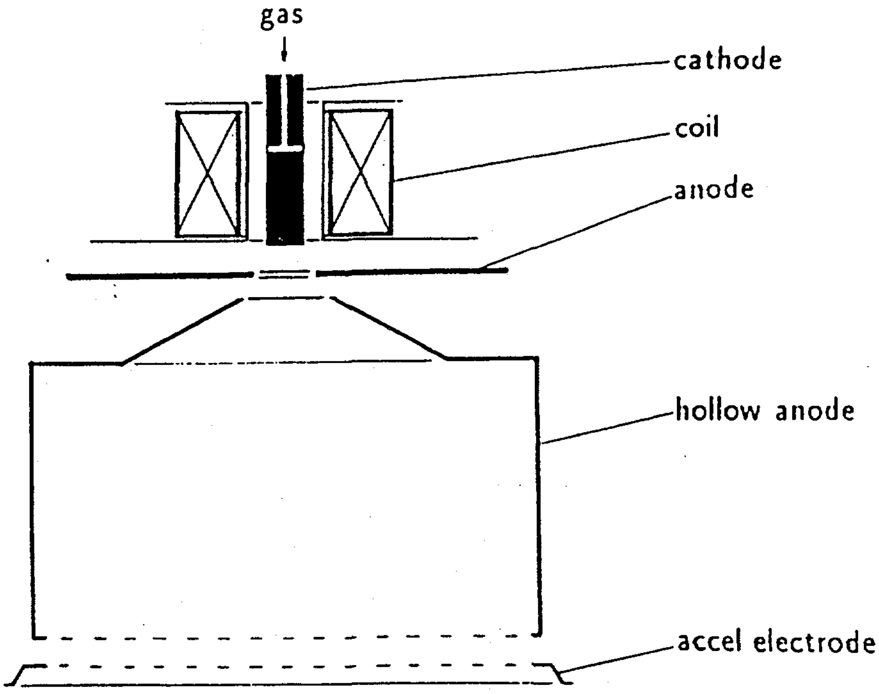

Fig. 7. The electrode system of the source with a vacuum arc initiated by a Penning discharge in a strong magnetic field.

titanium cathode, a hollow anode, and an anode. The first two electrodes serves as cathodes and the third one is the anode of the Penning initiating discharge powered from a dc voltage source producing 3–7 kV of voltage. A capacitor of capacitance 0.25 μF charged from this source is connected between the cathode and the anode. When the solenoid produces a magnetic field pulse and a 3-7-kV voltage is applied to the Penning cell, a Penning initiating discharge is ignited in the discharge gap. The Penning initiating discharge plasma fills the cathode-anode gap where the initiating arc discharge is ignited due to the discharge of the capacitor. The current therewith reaches 100–200 A, which exceeds the threshold current for the formation of cathode spots, in less than 1 μs. At the cathode end cathode spots appear, and the cathode material plasma produced by the cathode spots fills the cathode–hollow anode gap. This plasma in turn gives rise to the initiation between the cathode and the hollow anode, of a vacuum arc that is sustained for 150 μs by the discharge of the *LC* circuit. On ignition of an initiating arc discharge, stable initiation and operation of a vacuum arc with a current of 50–300 A is observed during the pulse. The vacuum arc initiation voltage is 100–350 V. The least gas pressure at which the vacuum arc initiation ensured decreases with increasing magnetic field. For $B = 3$ T the required gas pressure in the hollow anode can be reduced to $8 \cdot 10^{-5}$ Torr. This allows the conclusion that this technique for the initiation of vacuum arc cathode spots can be used successfully at lower, compared to the ion source, pressures. The beam current of Ti ions of all multiplicities extracted from the device was 0.2–1.5 A depending on the vacuum arc current. This research work is supported by the US

Department of Energy through Lawrence Berkeley Laboratory under the contract 4602410.

V A gas ion source based on a hollow-cathode discharge

A glow discharge with a hollow cathode can be used to produce broad beams of gas ions. However, the minimum pressure at which a discharge can still stably operate in the low-pressure mode is high enough ($\sim 10^{-3}$ Torr) in order that an intense ion beam could be produced and transported to a large distance.

Reducing the pressure results in that the primary electrons produced at the cathode as a result of ion-electron emission, oscillating in the cathode cavity, have no time to spend their energies in ionizing collisions with working gas atoms, and the discharge goes over into its high-voltage form. The decrease in anode area that increases the number of oscillations of the primary electrons in the cathode cavity is limited by the value of $S_a = S_c\sqrt{m_e/m_i}$ at which a double layer is formed near the anode[10]. It is possible to ensure the discharge operation at a lower pressure by providing an income of fast, capable of ionizing electrons from an external source into the anode cavity.

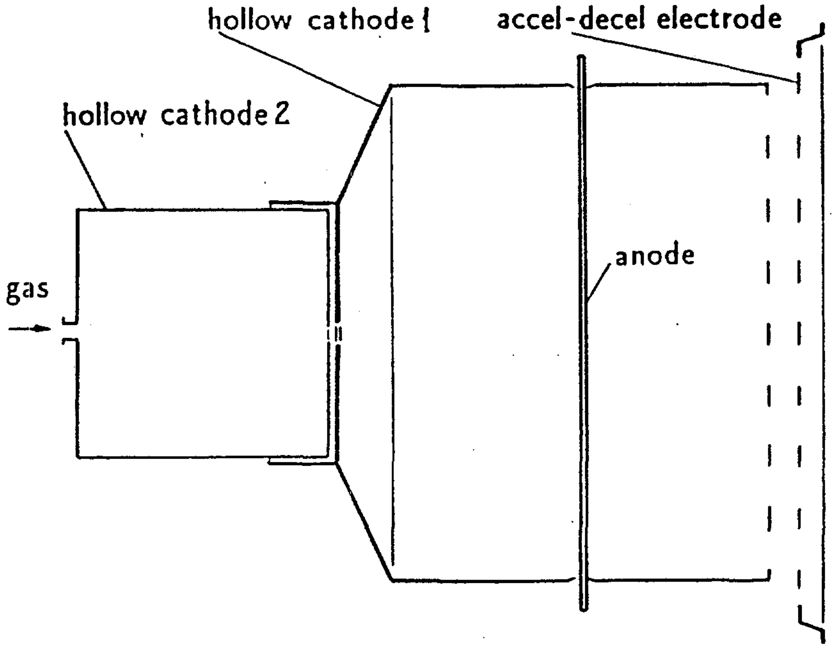

Fig. 8. The electrode system of the gas ion source based on a hollow-cathode discharge.

The design of the device is shown schematically in Fig. 8. The main discharge operated between cylindrical hollow cathode *1* and an anode. This discharge was

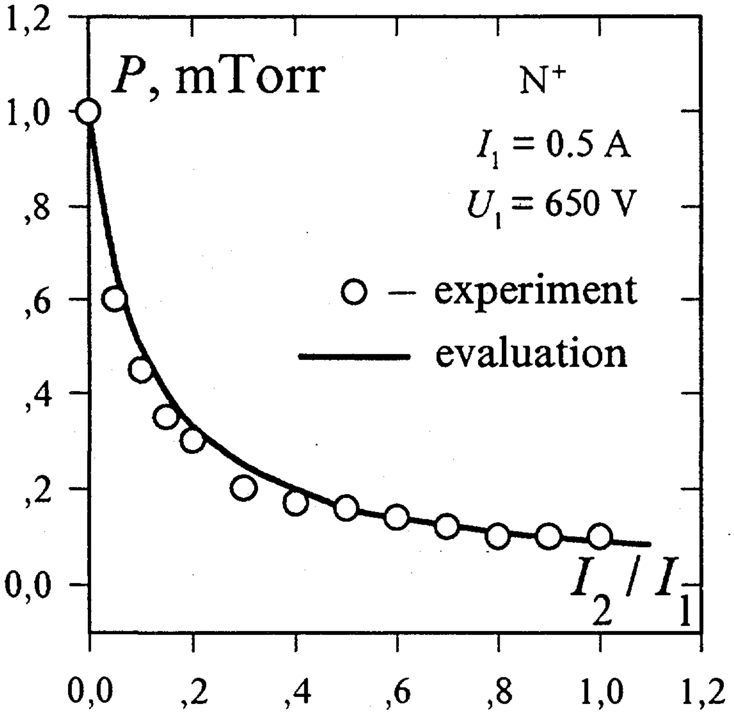

Fig. 9. Low limit pressure p of the hollow-cathode *1* discharge versus the auxiliary-to-main discharge current ratio I_2/I_1. The main discharge operating voltage $U_1 =$ 650 V and current $I_1 = 0.5$ A. Nitrogen.

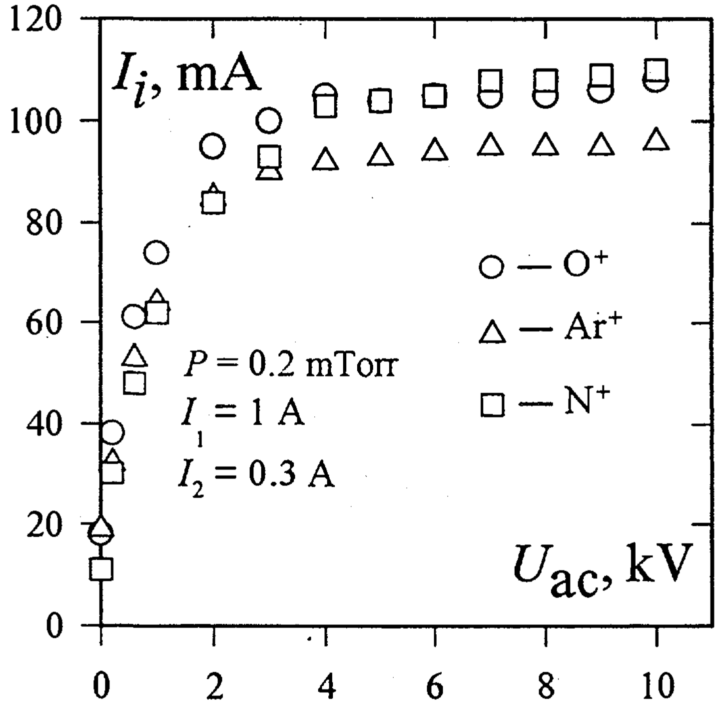

Fig. 10. Ion beam current as a function of accelerating voltage for ions of various gases.

initiated and sustained by an auxiliary discharge with hollow cathode *2*. Cathode *1* served as an anode for axiliary discharge. The working gas was fed into the cavity of cathode *2*. The gas pressure difference at the diaphragm separating the cathodes ensured an elevated pressure in hollow cathode *2* (over $5 \cdot 10^{-3}$ Torr) at which the auxiliary discharge was stably initiated and operated. The auxiliary discharge afforded the electron emission into the cavity of cathode *1*. In cathode *1* a gas-discharge plasma was produced from which an ion beam was extracted. The discharges were powered from two dc voltage sources (1 kV, 1 A).

As a rough approximation, it can be shown that the pressure at which the discharge operation voltage remains constant depends on the auxiliary-to-main discharge current ratio as $p \propto (\gamma + I_2/I_1)^{-1}$. The dependence of p on I_2/I_1 obtained in accordance with this estimation (for the secondary ion-electron emission coefficient $\gamma = 0.1$ electron/ion) and that measured for the main discharge operation voltage $U_1 = 650$ V and current $I_1 = 0.5$ A for nitrogen are given in Fig. 9. Thus, injection of additional electrons into the plasma of a hollow-cathode discharge reduced the working pressure from 10^{-3} to 10^{-4} Torr.

With the accelerating voltage of 2–10 kV, beams of various gases, oxygen included, with currents of up to 0.1 A have been produced (Fig. 10). The beam cross-sectional area was ~ 140 cm^2. The ion current from the plasma onto the whole surface of the hollow cathode is the Bohm current. So, the beam-to-discharge current ratio is proportional to the emission area to the total area of the hollow cathode, and the beam current can be increased by increasing the latter ratio. The highly simple design of the ion source and its stable parameters offer promise for its application in future.

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