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Plasma meniscus and extraction electrode studies of the ISIS H⁻ ion source[a)]

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In order to reduce the emittance and increase the transported beam current from the ISIS Penning-type H^- ion source, improvements to the extraction system are required. This ion source is currently being commissioned on the front end test stand at the Rutherford Appleton Laboratory, which demands higher extraction energies, higher beam currents, and smaller emittances. To facilitate this, the present geometry requires optimization. This paper details the experimental and simulation studies performed of the plasma meniscus and the possible electrode geometry modifications needed to extract the highest quality beam. © *2010 American Institute of Physics.* [doi:10.1063/1.3277139]

I. THE FRONT END TEST STAND

The front end test stand[1] (FETS) is being constructed at the Rutherford Appleton Laboratory in the U.K. to demonstrate a high intensity, chopped H^- beam for the next generation of high power proton accelerators. It will consist of a Penning H^- ion source, a three-solenoid magnetic low energy beam transport (LEBT), a 3 MeV radio frequency quadrupole (RFQ), a novel fast-slow chopper in a medium energy beam transport (MEBT) line, and a comprehensive suite of diagnostics including a laser profile monitor. The aim of FETS is to fully transport 2 ms long, 60 mA pulses of 3 MeV chopped H^- ions with transverse normalized rms emittances of 0.25π mm mrad. This paper details the investigations made on the ion source extraction system needed to fully understand the H^- beam and reduce the emittance enough to meet the requirements of FETS.

II. THE PENNING H⁻ ION SOURCE

A. Background

The H^- ion source used on FETS is identical to the highly successful Penning ion source used on the ISIS pulsed spallation neutron source. This source routinely produces 50–55 mA of beam current, but with a relatively large emittance. As such, the beam rapidly diverges and collimates on the first solenoid of the ISIS LEBT, leaving only about 25–30 mA of beam transported through to the rest of the accelerator. FETS requires much better transportation of the beam; so, although the ion source should be capable[2] of producing 60 mA, the optics of the extraction and beam transport need addressing to reduce losses.

B. Design features

A schematic of the ISIS ion source[3] is shown in Fig. 1. Hydrogen gas is injected through a hole in an anode via a piezoelectric valve, before a 55 A pulsed discharge is struck at 50 Hz between the jaws of a cathode. H^- ions are primarily formed by the surface effect, enhanced by the addition of caesium, on a covering plate anode (plasma electrode). This anode has a 0.6×10 mm slit aperture from which H^- ions and electrons are extracted with a ratio of approximately 1:10. The ions are accelerated by an extraction (puller) electrode before passing through a 90° sector dipole magnet housed in a "cold box." This system analyses out the coextracted electrons and traps caesium vapor, ensuring a clean beam and preventing contamination by caesium downstream. Additionally, the sector magnet is a combined function dipole, used to form the beam into a more uniformly round shape.[4]

The performance of the ion source has been improved significantly in recent times,[5] meaning 55 mA of beam should now reach the LEBT on FETS. However, high beam current is not the only important factor. The normalized emittance is still too high at about 0.6π mm mrad, so the beam will not currently fit into the acceptance of the RFQ. The modifications so far may have reduced emittance growth; but, ultimately, emittance is fixed at extraction from the ion source; so, to reduce it, the extraction system must be modified to get a perveance match, ensuring the beam has a minimum divergence upon entering the analyzing magnet.

III. ION BEAM EXTRACTION

A thorough experimental analysis of extraction optics for a single circular aperture is given by Coupland.[6] As shown in Fig. 2, the final divergence angle of a beam extracted from an aperture of radius r is a combination of initial focusing from a concave plasma meniscus with radius R_M, focusing

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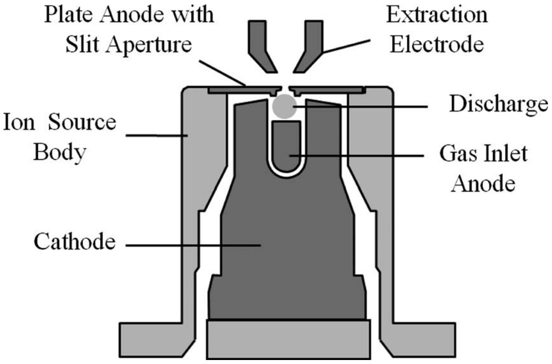

FIG. 1. Main ion source components.

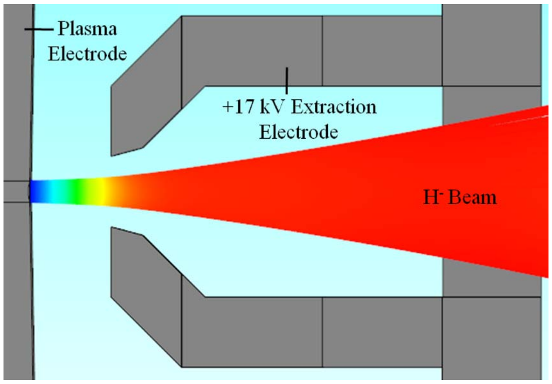

FIG. 3. (Color online) Standard ISIS extraction system.

from the plasma electrode inclined at an angle θ, defocusing from the gap g in the extraction electrode, and defocusing due to space charge.

The extraction potential, which tends to penetrate through the plasma electrode aperture, is repelled by the plasma sheath potential; so an equipotential is formed which defines a curved boundary: the plasma meniscus. The relative strength of the plasma and extraction potentials defines the radius of curvature of the meniscus. Particles that cross the meniscus see the extraction field and are formed into a beam. The initial focusing of the beam depends on the curvature of the meniscus and hence on the current density within the plasma. For uniform emission from an infinite plane, the Child–Langmuir law[7] gives the current density, J, of singly ionized hydrogen as

$$J=\frac{1.74}{d^2}V^{3/2}\ \text{mA mm}^{-2},\tag{1}$$

where V is the applied extraction potential in kilovolt and d is the separation between the aperture and the extraction electrode in millimeters. For emission from a concave surface with radius of curvature R_M, as in Fig. 2, for small values of d/R_M it can be shown that Eq. (1) is multiplied by a factor

$$[1-1.6d/R_M],\tag{2}$$

which is smaller than unity.

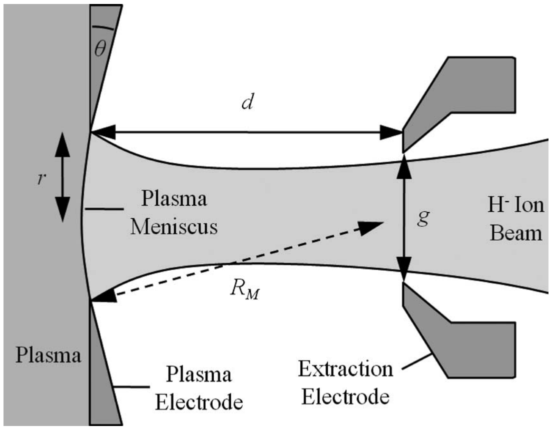

FIG. 2. Optical elements of an ion extraction system.

The total beam current is found by multiplying the current density by the area of the emission aperture. For the slit aperture of the ISIS ion source, the current is

$$I=Jrl=1.74\left(\frac{2rl}{d^2}\right)V^{3/2}\left[1-1.6\frac{d}{R_M}\right]\ \text{mA},\tag{3}$$

where $2r$ and l are the slit width and length, respectively. When l is much greater than $2r$, the extraction optics in the short direction (hereafter referred to as the horizontal direction) dominates, and hence Fig. 2 applies in the horizontal direction. The perveance, P, of an ion beam is defined as

$$P=\frac{I}{V^{3/2}}=\left[1-1.6\frac{d}{R_M}\right]P_0\ \text{mA kV}^{-3/2},\tag{4}$$

which, from Eq. (3), is a function only of the geometry of the system. The perveance (and hence current) of a beam from a concave surface is smaller than the planar perveance, P_0. However the concave meniscus focuses the beam, reducing its divergence. Therefore, a balance has to be made between a high extracted current and a low divergence by precisely shaping the plasma meniscus.[8] When this requirement is fulfilled, the extraction system is perveance matched. The overall divergence, ω, of the beam emerging from the extraction system is given by

$$\omega=290\frac{r}{d}\left(1-2.14\frac{P}{P_0}\right)\ \text{mrad},\tag{5}$$

which is zero—a perveance match—when $P=0.47P_0$. Inserting this into Eq. (4) implies that the perveance match occurs when $R_M=3.02d$. Using this value in Eq. (3) gives an expected beam current of 65 mA for the ISIS ion source. Since we typically see 50–55 mA of current at 17 kV extraction voltage, this suggests that the discharge current is set too low at the standard operating point of 55 A to create a meniscus with the optimum R_M.

IV. EXTRACTION SIMULATIONS

A. Present extraction system

Figure 3 shows a simple model of the standard ISIS extraction system, using a beam current of 60 mA emitted from a flat meniscus. The defocusing angle (in radians) of the extraction aperture, which contributes to the total beam divergence in Eq. (5), is given by the Davisson–Calbick[9] relation $g/3d$. Because g is large at 2 mm, the beam diverges

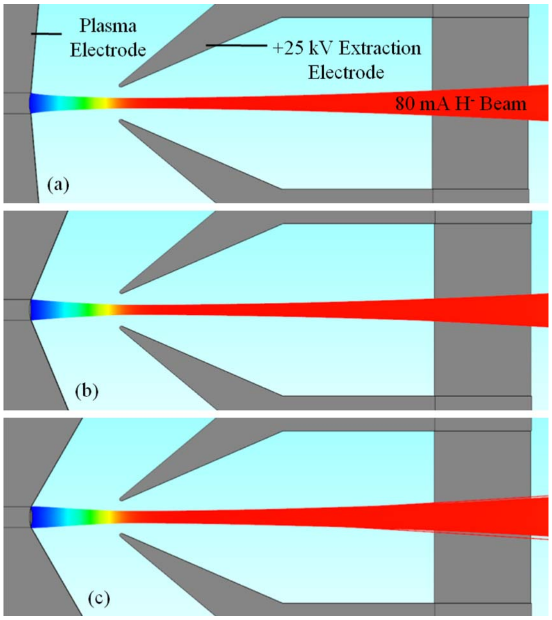

FIG. 4. (Color online) 25 kV extraction of an 80 mA beam from plasma menisci with different R_M. Plasma electrode inclination angles set to achieve minimum beam divergence: (a) Concave meniscus and 5° inclination. (b) Flat meniscus and 22.5° inclination. (c) Convex meniscus and 30° inclination.

rapidly upon passing through the extraction jaws. Equally, the separation d of 2.3 mm between the plasma and extraction electrodes likely does not provide the optimum electric field for the extraction voltage of 17 kV used. These large gaps are present to prevent electrical breakdowns and overheating due to electron and beam bombardment; however, there may be an improvement in the optics if they were reduced.

B. Plasma electrode inclination angle

A well known study by Pierce[10] found that a zero divergence electron beam can be extracted from either a slit or a cylindrically symmetric extractor if the plasma and extraction electrodes are shaped so as to match a Laplace solution outside to a Poisson solution inside the beam. The match demands the plasma electrode to have an inclination of 22.5°. H^- ion beams, however, are produced and subsequently behave very differently than electron and even proton beams, so it is not so clear what the optimum plasma electrode angle is. Various angles including 22.5°, 30°, and 45° have been used.[11,12] Figure 4 shows the ISIS extraction system simulated with varying plasma electrode inclinations. It was found that with a suitable inclination angle, the beam can be brought to a minimum divergence for any plasma meniscus shape—concave, flat, or even convex.

This being the case, to proceed further in the design of an optimum extraction system for the ISIS ion source, the shape of the plasma meniscus is needed to be determined experimentally.

V. PLASMA MENISCUS STUDIES

To vary the curvature of the plasma meniscus, one can either vary the extraction voltage or the plasma density. For a fixed extraction voltage, two main factors affect the plasma density: the gas pressure inside the plasma and the applied arc discharge current. In this study, the discharge current was varied and the transverse emittance and profiles recorded. Source temperatures were kept constant by varying the applied air cooling. Figure 5 shows a sample of horizontal phase space plots taken at 14 kV extraction voltage when the discharge current was varied.

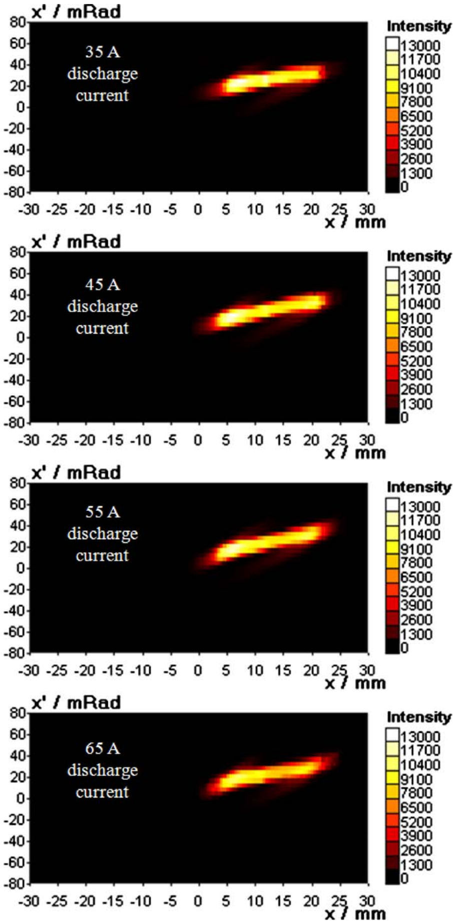

FIG. 5. (Color online) Changes in emittance with discharge.

The beam intensity can be seen to spread out and reduce as the discharge current is increased. Additionally, the beam's "S" shape becomes more prominent above about 55 A, indicating aberrations in the extraction system congruent with the meniscus becoming suboptimal. Qualitatively, therefore, the beam looks best at low discharge currents. However, the quantitative values of the horizontal divergence angle and normalized rms emittance are shown in Fig. 6. There is a local minimum for an extraction voltage of 14 kV when the discharge current is set to 55 A. The minimum moved to 60–65 A for 15 kV. Either side of this minimum, the plasma meniscus either under- or overfocuses the beam so the total divergence is increased. This suggests that when operating at higher extraction voltages, the discharge current should be increased to ensure a perveance match.

The beam profile, shown in Fig. 7, was measured using a quartz scintillator screen at the same plane as the transverse emittance scanners, 465 mm downstream from the cold box

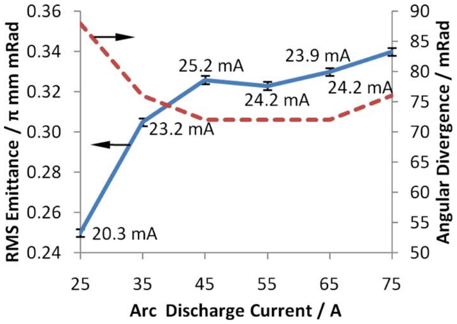

FIG. 6. (Color online) Variation of the horizontal rms emittance (solid line), divergence angle (dashed line), and beam current with the arc discharge current. The extraction voltage was 14 kV.

exit. The profile, too, was seen to change width when the discharge was varied, but there was little difference in the vertical spread. This was as expected because the meniscus is unlikely to vary in the long direction of the slit as much as in the short direction. The Penning magnetic field used to confine the plasma undoubtedly affects particle flow and hence the plasma meniscus in the short direction. The FETS ion source does not currently have a variable Penning field to test this; however, a previous study has shown that the magnetic field does slightly affect the emittance.[13]

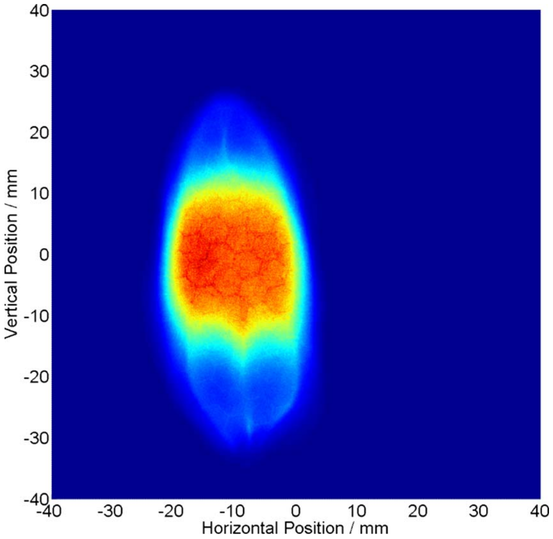

FIG. 7. (Color online) Profile of beam extracted at 14 kV and with total energy of 40 kV.

VI. DISCUSSION

With all other focusing elements kept constant, the changes in the beam emittance, divergence, and profile must be made by the varying discharge current and hence the plasma meniscus. The optimum discharge current increases with extraction voltage, as expected. When operating at extraction voltages above 14 kV, the plasma density is too low to achieve a perveance match when operating with a 55 A discharge. The meniscus is too concave, resulting in an overfocused beam. The plasma density needs to be increased, which is done either by running at a higher discharge current or by increasing the H_2 flow rate. However, experience has shown that operating at higher discharge currents for extended periods of time reduces the lifetime of the ISIS ion source. Also, high gas flow rates degrade the quality of the vacuum. Therefore, the best solution to achieve a beam with minimum divergence would be to operate at 14 kV extraction voltage and 55 A discharge, while reducing the extraction gap d and the extraction electrode jaw separation g in order to extract a higher beam current for that voltage. Results will be taken with said extraction geometry modifications shortly.

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