H$^-$ BEAM EMITTANCE MEASUREMENTS FOR THE PENNING AND THE ASYMMETRIC, GROOVED MAGNETRON SURFACE-PLASMA SOURCES*

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Summary

Beam-intensity and emittance measurements show that the H$^-$ beam from our Penning surface-plasma source (SPS) has twice the intensity and ten times the brightness of the H$^-$ beam from an asymmetric, grooved magnetron SPS. We deduce H$^-$ ion temperatures of 5 eV for the Penning SPS and 22 eV for the asymmetric, grooved magnetron.

Experimental Apparatus

As part of an accelerator development program at Los Alamos, we measured the H$^-$ beam intensity and emittance for our Penning SPS[1] and for the BNL Mark III magnetron[2] (called the asymmetric, grooved magnetron, or AGM, in this paper). Figure 1 shows a schematic of our experimental arrangement. The H$^-$ beam is extracted from the source emission slit (10 by 0.5 mm^2) with an extraction electrode at ~15 kV across an ~2-mm gap. The beam is transported through 90° by a dipole bending magnet having a field index n = 0.85. After exiting the dipole magnet, the beam drifts 17 cm (19 cm for the Penning source) to the two (orthogonal) emittance scanners.[3] Each emittance scanner has an acceptance of ±130 mrad in angle and ±8 cm in position. The mechanical angular resolution of the emittance scanners is ±1/4 mrad.

A Faraday cup (7 by 5 cm^2) is mounted on one of the emittance scanners for beam-current measurement (FC2 in Fig. 1). Comparison of the FC2 current with the FC1 current (FC1 is inserted just after the extraction electrode) determines the beam-transport efficiency through the dipole magnet to the emittance scanners. After correcting for stripping losses of the H$^-$ beam in the background hydrogen gas (a 1 to 2% correction), the transport efficiency is typically 90% for the Penning source and 70% for the magnetron.

The Penning[1,3] and AGM[2] source dimensions are contained in Refs. 1 and 2 respectively, with the exception that the AGM emission slit was changed from 45 by 0.6 mm^2 to 10 by 0.5 mm^2. The source operating parameters used to obtain our measurements are given in Table I.

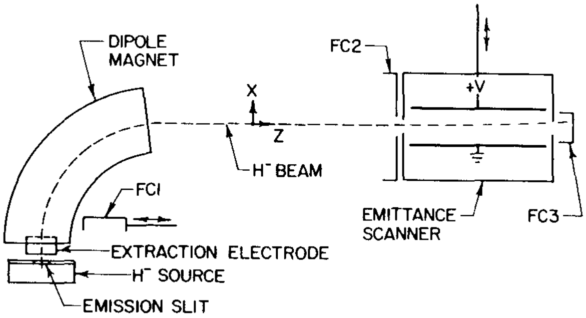

Fig. 1. Schematic showing the location of the H$^-$ ion source, 90° dipole magnet, Faraday cups (FC1, FC2, and FC3), and the emittance scanners. The x-direction is in the magnet bending-plane; z, in the beam direction; and y, perpendicular to x and z.

Emittance Measurements

Figure 2 shows the measured two-dimensional, normalized emittance ϵ as a function of the beam fraction F for the Penning and the AGM sources. The beam fraction $F = I_t/I_0$, where I_t is the beam current included in the brightness contour set by the threshold t, and I_0 is the total beam current measured at FC2. The normalized emittance is calculated from

$$\epsilon(F) = \beta\gamma A(F)/\pi \quad , \tag{1}$$

where A is the phase-space area of the beam and β and γ are the usual relativistic parameters. The normalized brightness values B(F x F) are calculated from

$$B(F x F) = 2I_0/[\pi^2\epsilon_x(F)\epsilon_y(F)] \quad . \tag{2}$$

The total H$^-$ beam current and the emittance at F = 0.63 are given for both sources in Table I. The I_0 values given in Table I are typical of the H$^-$ currents that routinely can be obtained in FC2. The maximum values for I_0 are 60 mA and

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*Work supported by the US Department of Energy.

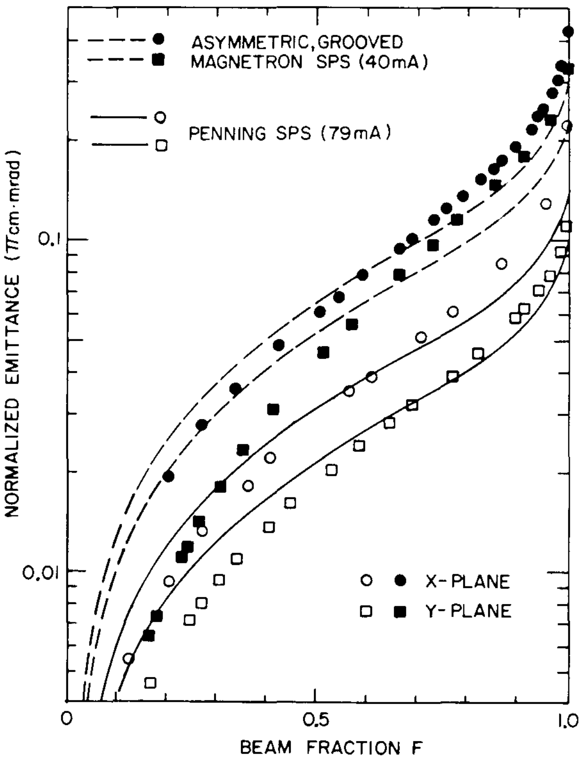

Fig. 2. Two-dimensional, normalized emittance ϵ versus the beam fraction F for a 79-mA, 17-keV H^- beam from the Penning SPS (open points, solid curves) and for a 40-mA, 14-keV H^- beam from the asymmetric, grooved magnetron SPS (solid points, dashed curves) in the x (circles) and y (squares) planes. The curves are calculated from Eq. (3) as discussed in the text.

130 mA for the AGM and Penning sources, respectively. Figure 3 shows the x,θ and y,ϕ phase-space areas for the Penning and AGM sources for F = 0.85.

Discussion

Recently, Allison[4,5] proposed a simple model of H^- ion beam emittance that allows calculation of the emittance as a function of the beam fraction. In this model, it is assumed that the H^- ions have a Maxwellian velocity distribution of temperature T and are emitted uniformly in space from the rectangular emission slit. The predicted functional dependence of beam fraction on emittance is

$$F = \mathrm{erf}[\pi\epsilon/\{4R(2kT/mc^2)^{1/2}\}] \qquad (3)$$

where R is the slit half-width and m is the ion mass. The curves in Fig. 2 were calculated using Eq. (3), normalized to the values of ϵ at F = 0.63. The resulting estimates of the H^- ion temperature are kT_x = 5 eV, kT_y = 840 eV for the Penning and kT_x = 22 eV, kT_y = 5650 eV for the AGM sources.

TABLE I

Operating Parameters and Measured Beam Quality for the Penning and AGM SPS Sources.

	Penning SPS	Asymmetric, Grooved Magnetron SPS
Discharge current, A	100	49
Discharge voltage, V	48	200
Discharge-voltage fluctuations (peak-to-peak), V	< ±0.5	±10
Magnetic field, T	0.25	0.20
Pulse length, ms	1.3	3.0
Duty factor, %	0.98	0.18
Beam energy, keV	17	14
H^- current (I_0), mA*	79	40
Emission-slit dimensions, mm^2	10 by 0.5	10 by 0.5
$\epsilon_x(0.63) \times \epsilon_y(0.63)$, $\pi^2 cm^2 mrad^2$	0.041 by 0.027	0.087 by 0.070
B(0.63 x 0.63), $A/cm^2 mrad^2$	14	1.3
kT_x, eV	5	22
kT_y, eV	840	5650

*Measured at the emittance-scanner Faraday cup (FC2 in Fig. 1) after magnetic analysis of the beam. Before magnetic analysis the H^- current (FC1 in Fig. 1) is 89 mA and 58 mA for the Penning and AGM sources, respectively.

Two second-order aberrations in the dipole magnetic field couple the x- and y-plane emittances,[6] resulting in the larger emittance of the x-plane masking the initially (far) smaller emittance of the y-plane.* This explains why the ratio of x- to y-plane emittances is 1.5:1 for the Penning SPS, instead of the 20:1 ratio of emission-slit length to width. The two second-order magnet aberrations cannot be simultaneously eliminated, their combined effect only can be minimized.[6] This x-y coupling results in spuriously large kT_y values for both sources; we therefore use the x-plane emittance values to estimate the H^- ion temperature in the source emission region, 5 eV and 22 eV for the Penning and AGM SPS sources, respectively. We observed oscillations in the discharge voltage of < ±0.5 V for the Penning SPS and ±10 V for the AGM SPS (1-MHz bandwidth on the oscilloscope amplifier used to measure the voltage fluctuations). These voltage fluctuations may indicate the presence of plasma instabilities that couple to the H^- ions in the discharge to increase their apparent temperature.

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*Our pepper-pot measurements (unpublished) for a 100-mA, pulsed H^- beam from a Penning SPS, similar to that of Ref. 7, show an x- to y-plane emittance ratio of ~10:1 after the beam has traversed ~2 cm in the dipole magnet.

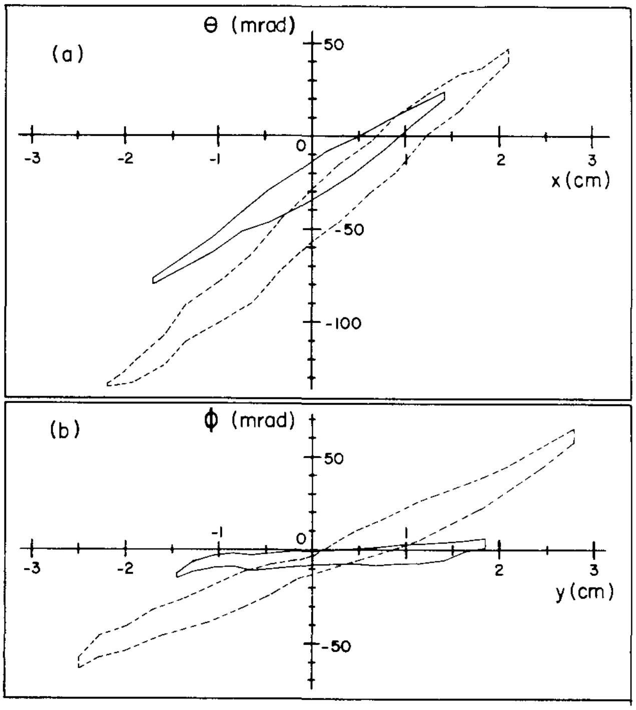

Fig. 3. Two-dimensional phase-space plots for the Penning SPS (solid lines) and the asymmetric, grooved magnetron SPS (dashed lines) for the a) x,θ and the b) y,ϕ planes. The displayed curves enclose 85% of the total beam.

Conclusions

We find that for a 10- by 0.5-mm^2 emission slit and beam transport through the same n = 0.85 dipole magnet, the H$^-$ beam from our Penning SPS[1] has 2 times the intensity and 10 times the brightness of the H$^-$ beam from the AGM SPS. The H$^-$ ion temperature, deduced from a Maxwellian model[4,5] and our emittance measurements, is 5 eV for the Penning SPS and 22 eV for the AGM SPS.

Acknowledgments

It is a pleasure to thank Th. Sluyters and J. G. Alessi for the loan of the Mark III magnetron source used in these measurements. The assistance of J. G. Alessi is gratefully acknowledged.

References

1. P. W. Allison, "A Direct-Extraction H$^-$ Ion Source," Proc. 1977 Particle Accelerator Conference, Chicago, Illinois, March 16-18, 1977, IEEE Trans. Nucl. Sci. 24, p. 1594 (1977).

2. J. G. Alessi and Th. Sluyters, "Regular and Asymmetric Negative-Ion Magnetron Sources with Grooved Cathodes," Rev. Sci. Instrum. 51, p. 1630 (1980).

3. P. W. Allison, "Experiments with a Dudnikov-Type H$^-$ Ion Source," Proc. Symp. on the Production and Neutralization of Negative Hydrogen Ions and Beams, Upton, New York, September 26-30, 1977, Brookhaven National Laboratory report BNL-50727, p. 119 (1977).

4. P. Allison, H. V. Smith, Jr., and J. D. Sherman, "H$^-$ Source Research at Los Alamos," Proc. 2nd Int. Symp. on the Production and Neutralization of Negative Hydrogen Ions and Beams, Upton, New York, October 6-10, 1980, Brookhaven National Laboratory report BNL-51304, p. 171 (1980).

5. P. Allison, J. D. Sherman, and H. V. Smith, Jr., "Comparison of Measured Emittance of an H$^-$ Ion Beam with a Simple Theory," Los Alamos National Laboratory report LA-8808-MS (June 1981).

6. J. D. Sherman and P. W. Allison, "A Study of a 90° Bending Magnet for H$^-$ Beams," Proc. 1979 Particle Accelerator Conf., San Francisco, California, March 12-14, 1979, IEEE Trans. Nucl. Sci. 26, p. 3916 (1979).

7. G. I. Dimov, G. Ye. Derevianki n, and V. G. Dudnikov, "A 100-mA Negative Hydrogen-Ion Source for Accelerators," Proc. 1977 Particle Accelerator Conf., Chicago, Illinois, March 16-18, 1977, IEEE Trans. Nucl. Sci. 24, p. 1545 (1977).