EXTRACTION OF HIGH-CURRENT LOW-EMITTANCE PROTON BEAMS FROM AN ECR PLASMA GENERATOR

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Abstract

Numerous electrode geometries were used to extract up to 125 mA of 50 keV hydrogen ions from a 2.45 GHz electron cyclotron resonance (ECR) plasma generator. The diameter of the plasma electrode was varied from 4.0 mm to 7.0 mm, while the width of the extraction gap was adjusted between 5.6 mm and 7.6 mm. The phase-space distribution of the beam was measured as a function of perveance for each extraction geometry. The matched perveance was consistently high and, in addition, the emittance, as well as the divergence, was relatively low at the matched perveance. A high-current ion beam of high quality can be extracted from a suitably designed ECR plasma generator.

Introduction

The emittance of the beam from a high-charge-state electron cyclotron resonance (ECR) ion source is invariably extremely large [1]. The enormous magnetic fields required to confine the ions, for literally seconds, and to satisfy the resonance condition at high frequencies, inevitably give rise to exceedingly high divergence. On the other hand, in an ECR ion source designed to produce a high-current beam of singly charged ions, axial confinement of the plasma is unnecessary [2]. Provided that the microwave frequency and, therefore, the magnetic induction corresponding to the resonance, is sufficiently low, the emittance of the beam is dominated by the optics of the extraction system rather than by the magnetic field.

This paper compares, for a wide range of extraction geometries, the quality of the beam from an ECR ion source, designed specifically to generate a high-current proton beam, with the quality of the beam from an arc discharge ion source.

Extraction Optics

The Child-Langmuir law implies that the space-charge limited perveance of an extraction system increases indefinitely with the square of the aspect ratio, S, given by

$$S = r/d \tag{1}$$

where r is the radius of the extraction aperture and d is the width of the extraction gap. Empirically, the perveance of the transported beam from an ion source saturates at a finite aspect ratio. An exhaustive study with a duoPIGatron [3] showed that the perveance, P, can be approximated by

$$P = \Pi \frac{S^2}{1+\alpha S^2} \tag{2}$$

where Π and α are empirical constants.

Assuming a Maxwellian velocity distribution characterized by an ion temperature, kT, the rms divergence of the extracted ion beam can be expressed as

$$x' = \left(\frac{kT}{2qeU}\right)^{1/2} \tag{3}$$

where q is the charge state and U is the extraction voltage.

The rms width of the waist of the extracted ion beam can be represented by

$$x = \delta r \tag{4}$$

where the proportionality constant, δ, depends on the radial distribution of the plasma as well as the details of the optics of the extraction system.

Then the normalized rms emittance at a modest ion velocity is given by

$$\epsilon_n = \beta\gamma x x' = \delta r\left(\frac{kT}{A m_u c^2}\right)^{1/2} \tag{5}$$

where A is the atomic mass number.

The ion beam from an ECR ion source is extracted in a substantial magnetic field. It is readily shown [1] that the normalized rms emittance, assuming a uniform emitter, is then limited by

$$\epsilon_n \geq \frac{1}{8}\frac{qeBr^2}{A m_u c} \tag{6}$$

where B is the magnetic induction.

Emittance Measurements

The emittance of hydrogen ion beams extracted from a 2.45 GHz ECR plasma generator [2] was measured with the two-slit system described in Ref. 4. The radius of the plasma electrode aperture was varied from 2.0 mm to 3.5 mm, while the width of the extraction gap was adjusted from 5.6 mm to 7.6 mm. The plasma electrode was shaped to increase the perveance.

The plasma generator parameters preferably remain unchanged during extraction geometry studies. A beam current density of 250 mA/cm^2 was selected. The proton fraction was fixed at 70%. The effective mass of the beam was then 1.25 amu. (The plasma generator can provide up to 500 mA/cm^2 with a proton fraction as high as 90%.)

The divergence as well as the emittance also depend on the residual gas pressure in the beam line because of space-charge neutralization, as shown in Figs. 1 and 2. A residual gas pressure of 4×10^{-5} Torr was maintained during the measurements by bleeding hydrogen gas into the beamline.

The phase-space distribution of the beam was mapped as a function of perveance for each of the extraction geometries.

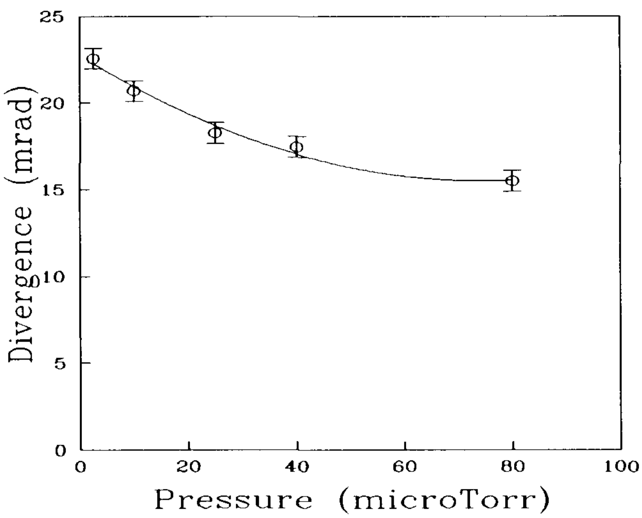

Fig. 1 Variation of rms divergence with pressure in beam line.

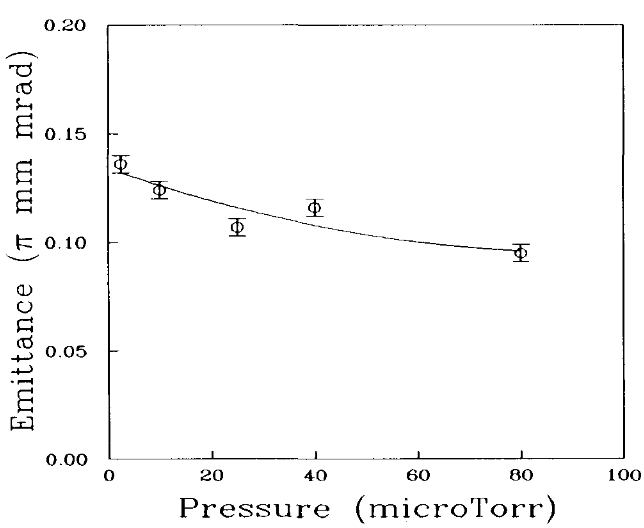

Fig. 2 Normalized rms emittance as a function of beam line pressure.

The data were processed as described in Ref. 4. Figures 3 and 4 show some typical results. Each data set was interpolated to determine the minimum divergence and the minimum normalized emittance as well as the perveance at the minimum divergence.

Analysis and Interpretation

The perveance at the minimum rms divergence is plotted against the aspect ratio of the extraction system in Fig. 5. The curve corresponds to Eq. (2) with Π = 1.9 mA/kV$^{3/2}$ and α = 1.7, the values recommended by Keller for "sophisticated" extraction systems [5]. The agreement is remarkably good.

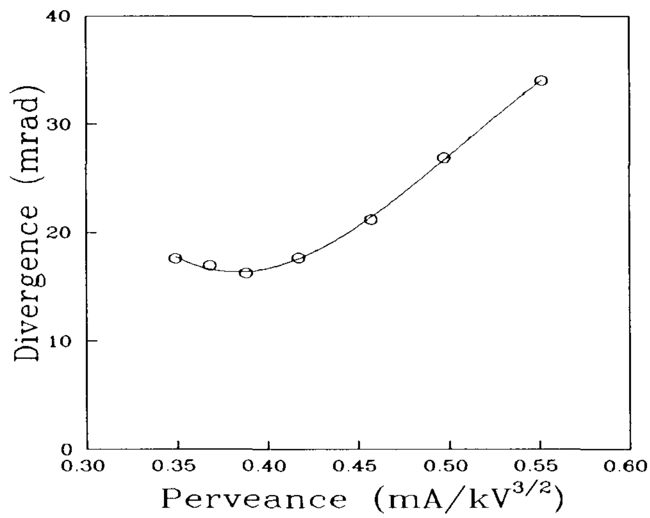

Fig. 3 Variation of rms divergence with perveance for 5.6 mm wide extraction gap and 3.0 mm radius extraction aperture.

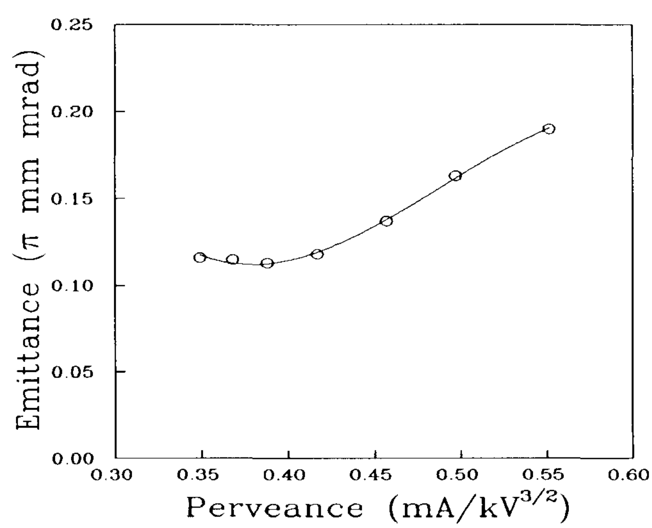

Fig. 4 Normalized rms emittance as a function of perveance for 5.6 mm wide extraction gap and 3.0 mm radius extraction aperture.

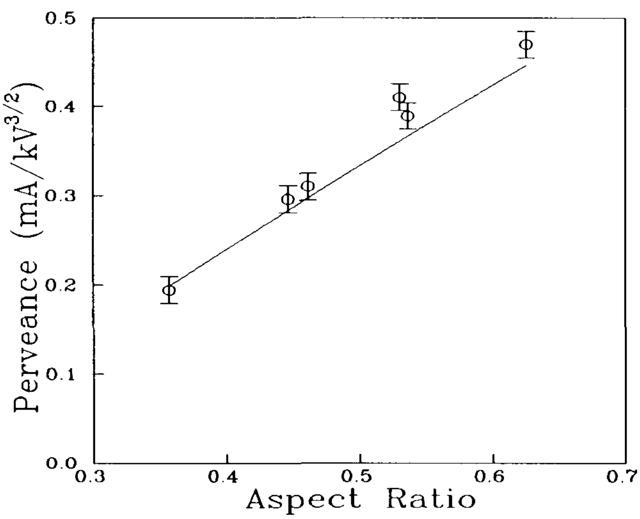

Fig. 5 Perveance at minimum divergence as a function of aspect ratio of extraction system.

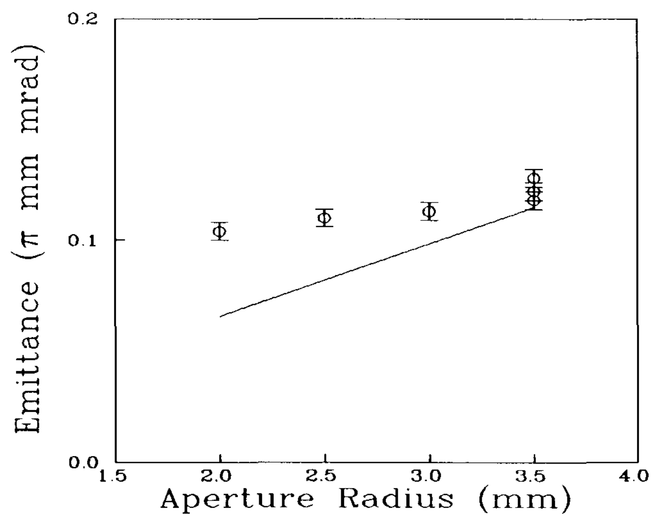

Fig. 7 Minimum normalized rms emittance as a function of extraction aperture radius.

Figure 6 shows the minimum rms divergence for each geometry versus the corresponding extraction voltage. The values are similar to those obtained with arc discharge ion sources under comparable conditions [4,5]. The commensurate ion temperature deduced from Eq. (3) is 20 eV. (The temperature of the ions in the plasma generator is, of course, much lower. The value reported here is primarily attributable to the optics of the extraction system.)

The minimum normalized rms emittance is shown as a function of the aperture radius in Fig. 7. At an ion temperature of 20 eV, the line conforms to Eq. (5) with a proportionality constant of 1/4, which, assuming a uniform emitter, is the value suggested in Ref. 5. The dependence of the emittance on the aperture radius appears to be somewhat smaller than expected.

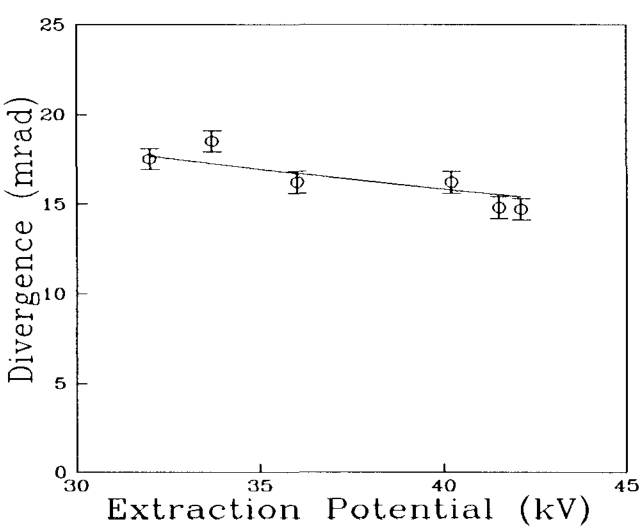

Fig. 6 Minimum rms divergence for various extraction geometries as a function of extraction voltage.

Conclusions

The magnetic induction at the ECR resonance is 875 G in the present case. Even for the largest extraction aperture used in the experiment described above, the contribution of Eq. (6) to the normalized rms emittance is only 0.03 π mm mrad, less than one third of the measured value. Provided that the frequency, and thereby the magnetic induction, is sufficiently low, the emittance of a high-current ECR ion source is virtually identical to that of a comparable arc discharge ion source. Furthermore, because the proton fraction of an ECR ion source is typically two and one half times the proton fraction of an arc discharge ion source [6], an ECR ion source can generate a proton beam with more than three times the brightness of an arc discharge ion source.

References

[1] W. Krauss-Vogt, H. Beuscher, H.L. Hagedoorn, J. Reich and P. Wucherer, Nucl. Instr. and Meth. **A268** (1988) 5.
[2] T. Taylor and J.S.C. Wills, Nucl. Instr. and Meth. **A309** (1991) 37.
[3] J.R. Coupland, T.S. Green, D.P. Hammond and A.C. Riviere, Rev. Sci. Instr. **44** (1973) 1258.
[4] T. Taylor, M.S. de Jong and W.L. Michel, 1988 Linear Accelerator Conference Proceedings, CEBAF Report 89-001, pp. 100-102.
[5] Roderich Keller, Nucl. Instr. and Meth. **A298** (1990) 247.
[6] G.M. Arbique, T. Taylor, M.H. Thrasher and J.S.C. Wills, 1991 IEEE Particle Accelerator Conference, IEEE Conference Record 91CH3038-7, pp. 842-844.