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TITLE: ECR ION SOURCE BEAMS FOR ACCELERATOR APPLICATIONS

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ECR ION SOURCE BEAMS FOR ACCELERATOR APPLICATIONS*

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Abstract

Reliable, easily operated ion sources are always in demand for accelerator applications. This paper reports on a systematic study of ion-beam characteristics and optimization of beam quality for production of light ion beams in a . ECR ion source. Of particular interest is the optimization of beam brightness (defined as ion current divided by the square of the emittance), which is typically used as a figure-of-merit for accelerator-quality beams. Other areas to be discussed include the measurement of beam emittance values, the effects of various source parameters on emittances, and scaling effects from operating the same ECR source at different frequencies.

Introduction

The electron cyclotron resonance (ECR) ion source has many desirable properties that make it an attractive prospect for accelerator applications. Among the most favorable aspects are the reliability, reproducibility, and relative simplicity of the source. As a result, a study was undertaken to examine the possibility of using an ECR source as a high-brightness hydrogen ion source.

Theory

The fact that an ECR source is superlative in creating high charge states of heavy ions at the sub-milliampere level is well accepted. Whether this source type can be extended to provide a multi-milliampere proton beam of sufficient quality for high-brightness applications was the general focus of these experiments. The general approach in the theoretical analysis of the ECR beam quality is to assume that any rotation of the beam due to extraction from a solenoid magnet will show up as a perpendicular energy term that increases the emittance. We used Lagrangian mechanics to derive the perpendicular energy

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term, which is

$$\frac{1}{2} m v_{\perp}^2 = \frac{Z^2 e^2 r^2 B^2}{8 m_i} \text{ (joules)} \qquad (1)$$

Using a previously derived equation for the emittance of a beam extracted from a plasma alone.[1]

$$\varepsilon = \frac{1}{2} r \sqrt{\frac{kT_i}{m_i c^2}} \qquad (2)$$

the perpendicular energy can be added (simply) to the ion temperature to give a composite emittance

$$\varepsilon_c = \frac{1}{2} r \sqrt{\frac{kT_i}{m_i c^2} + \frac{Z^2 e^2 r^2 B^2}{8 m_i^2 c^2}} \qquad (3)$$

where kT_i is the ion temperature. B is the magnetic induction in the extractor region, r is the radius of the aperture, and m_i is the ion mass

In this composite emittance, the perpendicular energy term (1) scales inversely with the ion mass, whereas the temperature term (2) scales inversely with the square-root of the mass. Hence, for heavy ions ($m_i \gg 1$) the emittance is generally dominated by the temperature term (except for large radii apertures). Consequently, at a given frequency, the emittance for a heavy ion beam should be less than it is for protons by the inverse square-root of the ion mass

To better relate the emittance to the actual merit of the transported beam, the concept of beam brightness was introduced as a quantitative measure of beam quality. The brightness is defined as the beam current (in milliamperes) divided by the product of the transverse emittances (equal to the square of the transverse emittance for the case of cylindrically symmetric beam). This, in effect, is a measure of the transportable ion current. If the composite emittance Eq. (3) is used in the brightness equation, with the ion current density derived from the plasma parameters,

$$j = e n u_{si} \qquad (4)$$

where n is the plasma density and u_{si} is the ion velocity at the sheath.

then the brightness is given by

$$\beta = \frac{I}{\epsilon^2} = \frac{j\pi r^2}{\epsilon^2} = \frac{4\pi n e u_0}{\dfrac{kT_i}{m_i c^2} + \dfrac{Z^2 e^2 r^2 B^2}{8 m_i^2 c^2}} \qquad (5)$$

From Eq (5), we can derive the following scaling rules for fixed power

with $$kT_i \gg Z^2 e^2 r^2 B^2 / 8m_i \qquad \beta \propto B \qquad (6a)$$

with $$kT_i \ll Z^2 e^2 r^2 B^2 / 8m_i \qquad \beta \propto B^{-1} \qquad (6b)$$

and for fixed magnetic field,

with $$P \gg P_{sat} \qquad \beta \propto P^{1/2} \qquad (7a)$$

with $$P \ll P_{sat} \qquad \beta \propto P^{3/2} . \qquad (7b)$$

where P_{sat} is the rf drive power required to bring the plasma density up to the saturation level determined by the electron plasma frequency

From Eq (6) we can deduce that at low B, the ion temperature dominates the emittance Increasing the magnetic field in the region of the extractor tends to enhance plasma confinement This purely geometric effect stems from the increased magnetic flux density passing through the extraction aperture This confinement effect gives a linear relation of brightness to B At higher B the perpendicular energy term dominates the emittance so that the brightness then scales with the inverse of B

From Eq (7) with rf power greater than the saturation power, the brightness scales as the square root of the drive power because ions entering the sheath have a velocity $u_0 > \sqrt{(kT_e/m_i)}$ (Ref 2) Therefore, beam current scales as the square root of P because the electron temperature scales linearly with power For rf power less than the saturation value level, this square-root scaling combines with the linear increase of plasma density with power to yield a brightness that scales as the power raised to the three halves

Experimental Setup

To test some of these ideas, we fabricated an ECR ion source and a low-energy beam transport and analysis line (Fig. 1). The ECR source consists of solenoid magnets providing an axial magnetic field. Microwave power at 10.46 GHz is injected axially into the source volume. A samarium cobalt sextupole is used to stabilize the plasma in the magnetic mirror confinement geometry. Ions are extracted axially from the end opposite the radio-frequency (rf) feed. Beam energy is restricted to values under 25 keV. This voltage enables us to use a freon jacket around the source volume not only to cool the source but also to insulate it from ground. The low voltage is also preferable from safety and feasibility standpoints.

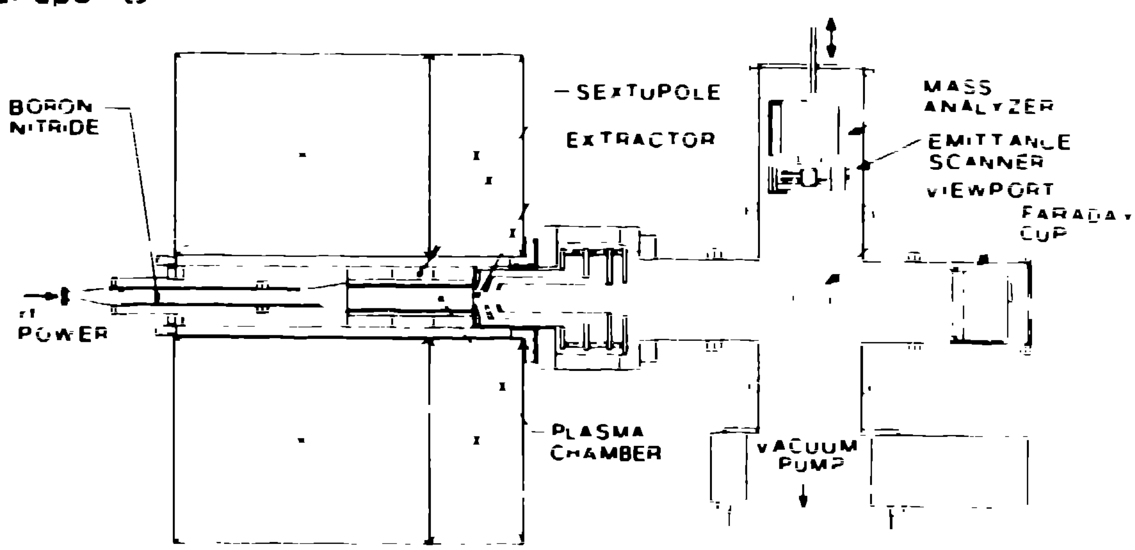

Fig. 1. Schematic cross-sectional view of ion source showing solenoid magnets, rf delivery, extractor, sextupole, and beam transport line.

To allow the rf power to pass through the first ECR resonance in the increasing magnetic field region, the delivery waveguide is completely filled with boron nitride to suppress plasma formation. The boron nitride also acts as a backstop for electrons backstreaming through the extractor and protects the rf window. Beam parameterization is done with four basic tools: the Faraday cup, the mass analyzer,[3] the emittance scanner,[4] (Fig. 2) and the video camera.

Results

During initial operation of the source, we observed that less beam could be transported to the Faraday cup than was expected. The measured ion current on the cup was around 10 mA, where 30-40 mA was expected. We observed early on that when multi-milliampere beams were extracted from the source, the

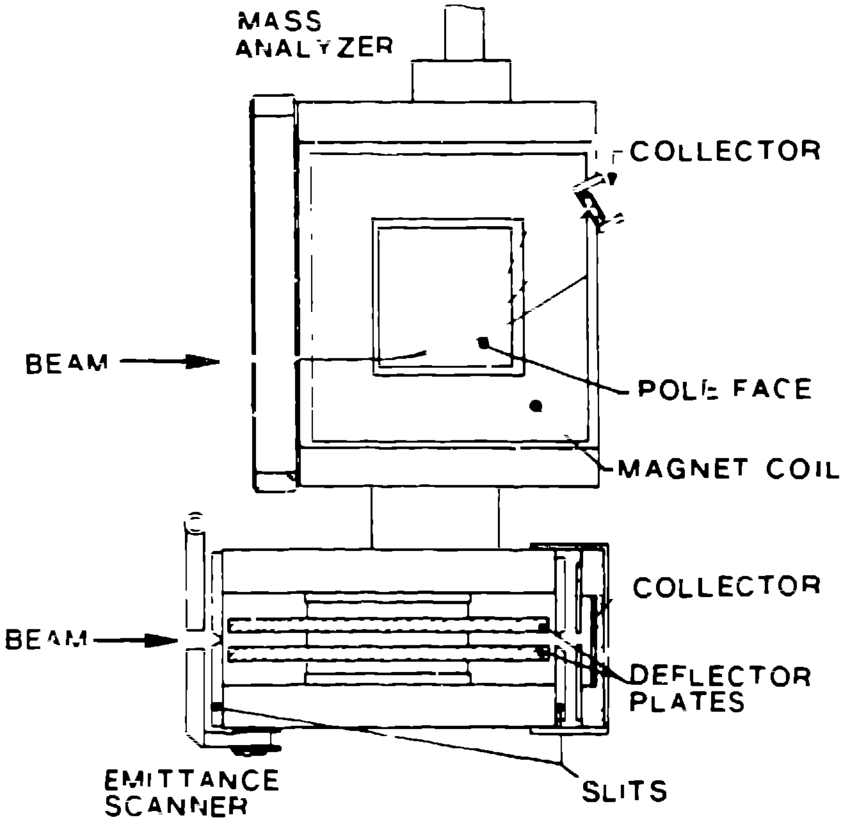

Fig 2 Schematic cross-sectional views of mass analyzer/emittance scanner package

extractor electrodes would routinely short together. We believe this was due to the high beam intensity creating a sufficient number of secondary electrons that would get trapped in the $\vec{E} \times \vec{B}$ fields in the extractor region and cause multiple ionizations and eventually a breakdown (Penning discharge)

Our belief was supported by the observation that the discharge would extinguish when either the plasma density was decreased, or the magnetic field was turned off

The present extractor design has operated well enough to allow data to be taken and analyzed Because of a computer failure, acquiring and analyzing emittance data has become a time-consuming, manual task As a result, only a few measurements have been analyzed and are available at this time

Data were obtained on transportable beam (related to brightness) versus rf power and B For the case of fixed rf power levels, the magnetic field scaling relations, Eq (6), appear to be supported by the data At low B, brightness scales directly with B, and at higher B, brightness goes as the inverse of B The data shown in Fig 3 generally support these results

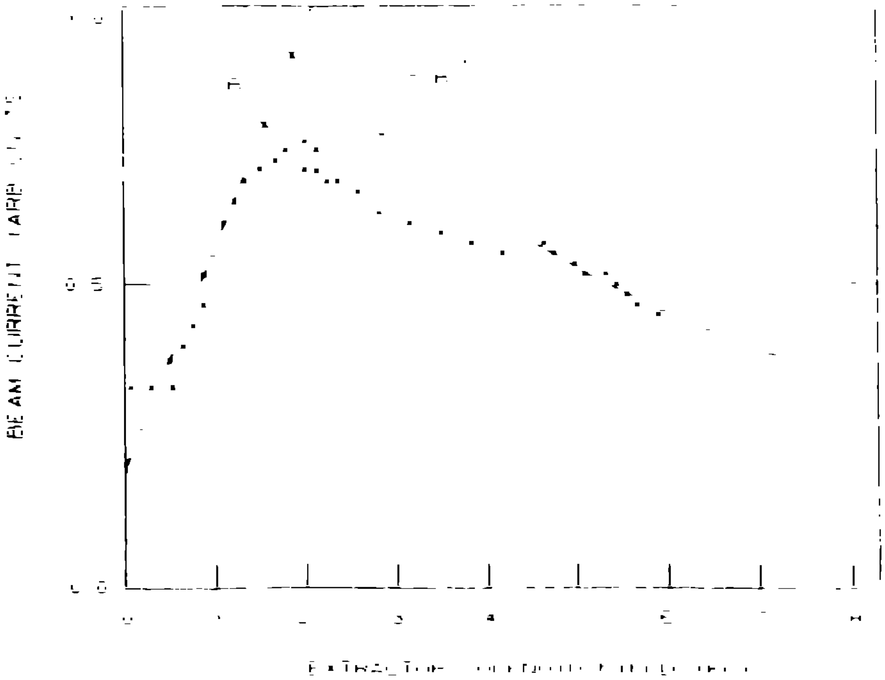

Fig 3 Experimental beam current at fixed rf power ($P = 477$ W) compared with the theoretical scalings of Eqs (6a) and (6b)

For the case where rf power is varied at fixed B, the scalings in Eq (7) indicate that brightness should go as rf power to the three halves for $P \ll P_{sat}$ and as the square root of power for $P \gg P_{sat}$. The data in Fig (4) reflect this behavior at the extreme ends of the plot, but the central region is not well described. The discrepancy observed in the central region is most likely caused by the fact that before reaching the saturation density, the rf power is heating the electrons that transfer energy to the plasma by ionizing neutral atoms, hence increasing the plasma density. Therefore, the ion current scaling would fall somewhere between the two extremes. The data generally support this conclusion by showing a constant slope over the transition region, which falls between three halves and one half. The constancy of the slope also indicates that a transitional mode is occurring; outside the transitional mode, behavior is dominated by the scaling rules in Eq (7). After saturation is achieved, the rf power goes into heating the electrons and driving plasma waves, rather than into increasing plasma density. For this reason, the brightness is only a function of the pre-sheath velocity, which scales as the square root of the electron temperature. In general, the coupling of rf power into a magnetized plasma is complex, and to properly characterize the behavior with scaling rules would be much more complicated than the above analysis suggests. However, the above rules seem to model the plasma behavior at the extremes of the power range

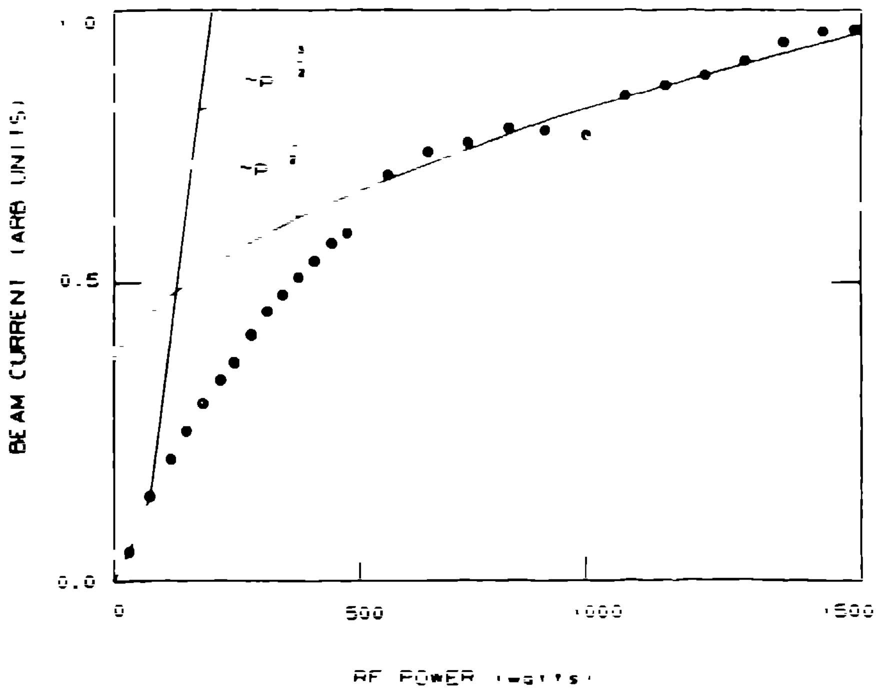

Fig 4 Experimental beam current at fixed magnetic induction in the extraction region (B = 1230 G) compared with the theoretical scalings of Eqs (7a) and (7b)

Discussion

Extraction of high-current proton beams from an ECR source continues to be challenging. The ways in which beam formation, plasma confinement, and beam quality are intertwined makes the sorting out of effects complex Our efforts are focused on getting the data acquisition computer working so a more thorough scan of emittance parameter space can be made Through this data, a better determination can be made as to the effects that low extraction energy, high beam currents, and magnetic field have on the beam emittance and, hence, on beam brightness

Another aspect to be addressed in our program is the scaling of source parameters with frequency Assembly has begun on a 14 5 GHz microwave system that will be used to compare frequency effects on the plasma in the identical source volume configuration

Acknowledgment

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