MULTI-BEAMLET INJECTION TO THE RFQ1 ACCELERATOR - A COMPARISON OF ECR AND DUOPIGATRON PROTON SOURCES

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Abstract

A 2.45 GHz electron cyclotron resonance (ECR) ion source, recently developed at Chalk River, was installed on the RFQ1 facility for comparison with the duoPIGatron source used previously. The proton fraction of the ECR ion source is 80 to 85 percent, much higher than the 30 to 35 percent of the duoPIGatron. Measurements of the beam transmission through the RFQ, as well as the emittance of the extracted and the accelerated beams, are reported. Four-aperture extraction columns were used on both sources.

I. INTRODUCTION

The original ion source for the RFQ1 cw proton accelerator [1] was a three-aperture duoPIGatron. Although the RFQ1 duoPIGatron [2] generates 320 mA/cm^2 at matched perveance, the proton fraction is low. A current density, as high as 450 mA/cm^2, is achievable with the source, but the required extraction gap, at matched perveance, is too small for reliable operation. In fact, the RFQ1 design current could only be achieved by increasing the number of extraction apertures to four [3]. In addition, the lifetime of the source is reduced by the periodic failure of the cathode, the efficiency of conversion of hydrogen gas to protons is very low and an extensive system of power supplies at high voltage is required.

A high-current low-emittance electron-cyclotron resonance (ECR) ion source with an exceptionally high proton fraction [4] has been developed as an alternative source for RFQ1. The source, shown in Figure 1, is driven by 2.45 GHz microwaves introduced to the plasma chamber via a dielectric window. The axial magnetic field, to satisfy the electron-cyclotron resonance condition and confine the plasma, is supplied by two solenoids. The duoPIGatron source extraction geometry is used, but with a larger extraction gap to lower the matched proton current to that required for the the RFQ.

This paper compares the performance of the duoPIGatron and the ECR proton sources. Measurements were made on the beams from the two sources immediately after extraction, following mass separation and after acceleration in the RFQ1 accelerator.

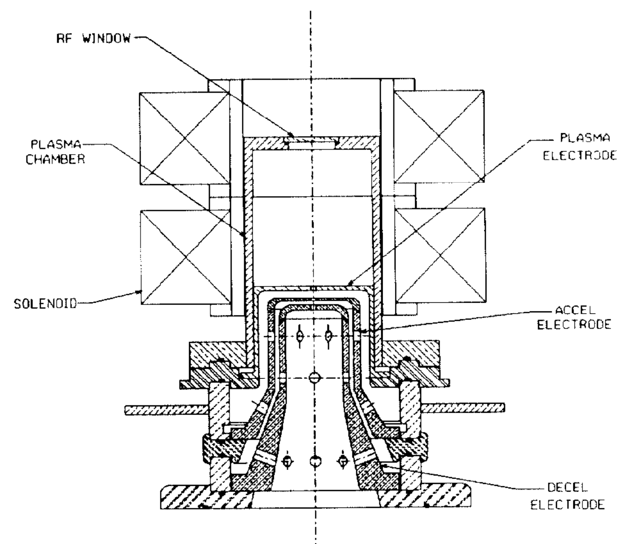

Figure 1. ECR proton source.

II. EXTRACTION FROM ION SOURCES

The duoPIGatron with a 0.64 cm acceleration gap and four 0.50 cm diameter extraction apertures, equally spaced on a 0.53 cm radius, generated a "matched" (i.e., minimum divergence) beam of hydrogen ions, for an extraction voltage of 50 kV, at a total beam current of about 250 mA. The proton fraction was typically 30 to 35 percent, resulting in an extracted proton current of between 75 and 90 mA. Some beam was lost in the low-energy beam transport line so that the required 90 mA could be supplied to the RFQ only by operating the source at higher than match current. On the other hand, the proton fraction of the ECR ion source is between 80 and 85 percent so that, even with the acceleration gap almost doubled to 1.2 cm, a proton current of 95 to 100 mA can be generated with a total matched current of only 120 mA.

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The normalized rms emittance of the unseparated beam from both the ECR and the duoPIGatron ion sources, measured on an ion source test stand, is less than 0.05 π-cm-mrad. In both cases, the emittance of the individual beamlets is typically 0.008 π-cm-mrad and the corresponding rms divergence is 12 mrad. However, the overall beam divergences are different because the individual duoPIGatron beamlets diverge from the beam centroid by about 10 mrad, while the beamlets from the ECR ion source are parallel. The cause for the misalignment of the duoPIGatron beamlets is under investigation.

The replacement of the duoPIGatron with the ECR ion source reduces the gas load on the injector vacuum system by about a factor of five. The ECR ion source operates stably with a hydrogen mass flow of no more than 5 std. cm^3/min, whereas the duoPIGatron usually operates at 25 std. cm^3/min.

The duoPIGatron, a mature design, is a reliable source and operates stably, without drift, over long periods; lifetime is limited by the oxide-coated cathode to about 200 h. The ECR ion source, which is still in early development, has at present a similar lifetime, limited here by dielectrics in the microwave window and plasma chamber liners. The microwave window is slowly degraded by electrons backstreaming from the extraction column, and the plasma chamber liners, introduced to enhance the proton fraction [4], are subject to contamination as well as catastrophic failure. These two factors may also contribute to drift and instability seen in the extracted beam from the ECR. Retuning the microwave line invariably restores the beam, and installation of a circulator improved stability. Nonetheless, the ECR source operated for over one-hundred hours before it was disassembled for repair of a dielectric liner.

III. INJECTION TO RFQ1

The 50 keV RFQ1 low-energy beam transport system (LEBT) is shown in Figure 2. The LEBT includes a 60° dipole magnet to separate molecular ions from the beam and solenoids after the ion source and at the entrance to the RFQ that match the beam to the acceptance of the RFQ. The beam is set up on a plunging beam stop (PBS) in the injector exit line, which is then raised to inject beam into the RFQ. Apertures in the LEBT, at the first solenoid and in the exit line, limit the size of the transported beam.

The current measured by non-intercepting beam-current monitors, at the exits from the injector and the RFQ, as well as the current on a beam-size-limiting aperture at the PBS, after the exit monitor, are shown as a function of the current from both the duoPIGatron and the ECR ion source in Figure 3. The solenoid fields were optimized for maximum accelerated current at each point.

The ECR ion source delivers a higher proton current than the duoPIGatron at less than half of the total source current. However, like the duoPIGatron, the ECR source can only achieve the 75 mA design current through the RFQ when it is operated at higher than matched perveance. Beam losses with

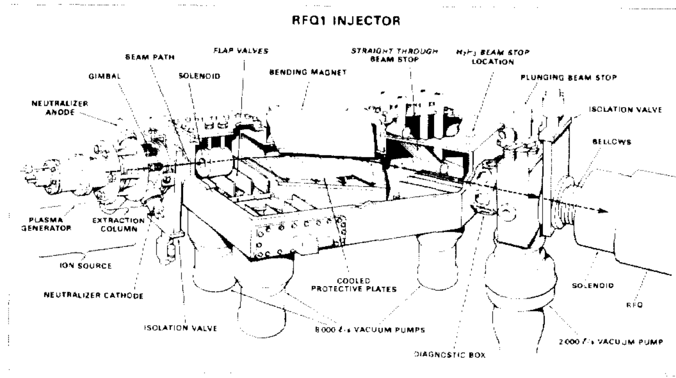

Figure 2. RFQ1 injector.

the ECR source are less at the start of the LEBT, but are excessive at the PBS aperture. At matched perveance, the RFQ transmission appears to be about 75% with the ECR ion source, slightly lower than the 80% achieved with the duoPIGatron. The output emittance of the RFQ, measured in the horizontal plane of the injector dipole, was 0.04 π-cm-mrad for a matched ECR beam, the same as for matched duoPIGatron injection [3]. RFQ output emittance trends are similar for the two ion sources.

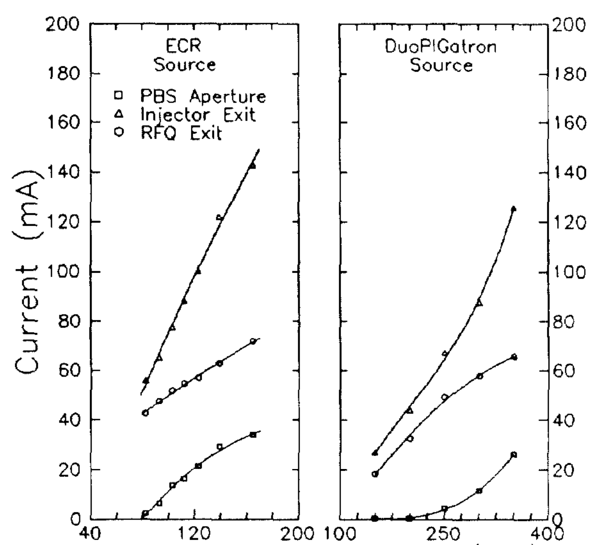

Figure 3. Injection and RFQ output currents for ECR and duoPIGatron ion sources.

The differences in the beam transport to the RFQ may be related to the variation in the beamlet-to-beamlet divergence of the two ion sources. The LEBT was designed so that a multi-beamlet beam with space charge would pass through a "gentle" waist between the solenoids. Calculations with the beam transport code TRANSOPTR [5] indicate a waist further downstream when beamlets diverge from the ion source. Parallel beamlet extraction results in a larger beam envelope at the PBS aperture. The increased beam loss on the PBS aperture at higher beam currents, with both ion sources, is also consistent with space-charge blow-up. This is probably the dominant effect, as losses at the PBS are similar for the two ion sources for given injector exit proton currents. Apertures in the injector exit line have yet to be optimized for ECR source operation (un-monitored beam losses in the exit line may be responsible for the lower RFQ transmission with the ECR source).

IV. DISCUSSION

The 75 mA design RFQ1 current was achieved with the ECR source. The ECR ion source consistently gives at least double the proton fraction of the duoPIGatron and, in almost every other respect, performs at least as well as the duoPIGatron. Reliability deficiencies will be addressed by a second-generation ECR ion source presently being fabricated.

The full potential of the high-current low-emittance ECR ion source has yet to be realized. The high-proton fraction opens up the possibility of direct injection, without mass separation, into the RFQ. The lower gas consumption reduces the injector pumping requirements. Proton current densities of up to 315 mA/cm^2 have already been demonstrated on a test stand so that the emittance may be dramatically reduced with beam current extraction from a single-aperture. The ECR source solenoids can be isolated from the plasma chamber, eliminating the need for dc power supplies at high voltage. A simple dc waveguide break already allows the microwave power supply to be at ground.

V. ACKNOWLEDGEMENTS

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VI. REFERENCES

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