A PULSED SYNCHROCYCLOTRON ION SOURCE USING A SINGLE COLD CATHODE*

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Summary

During a development program to improve the beam current accepted by the Nevis Synchrocyclotron, a new source using a single cold cathode was developed. The change to a single cold cathode has resulted in a marked improvement in the performance of the source compared to operation as a PIG source with the same chimney and extraction geometry. The extracted H^+ current was greater than 90% compared to about 70% for the PIG source, and the vertical emittance was improved by over a factor of 2. Pulsed beam currents of up to 80 mA were extracted from a slit of 1.6 mm by 6.25 mm high. Although the extracted current was less than the current from the PIG source ($\approx$150mA), the charge per pulse accepted by the accelerator (as measured by an internal probe at a radius corresponding to 30 MeV) increased from 20 to as high as 100 nanocoulombs/pulse.

Introduction

The modified Nevis synchrocyclotron [1,2] was operated for experiments at 150 pulses per second for much of the first half of 1977. This operation was marked by low beam currents and a major effort was mounted to improve the ion source, which was of a preliminary design.[2] A new ion source was developed in which hydrogen was fed into the source through the center of a single cold cathode. This source produced a large improvement in the beam accepted by the cyclotron, compared to operation as a PIG source. This report describes a series of measurements made using the cyclotron as the test bed, of DC source performance and cyclotron acceptance for both a conventional cold cathode PIG source and the new single cold cathode source.

Ion Source Designs

The original design of the ion source was a pulsed cold cathode Penning discharge source.[1,2] It was located at a radius of 1.3 cm on the ground side of the cyclotron and therefore could not extract directly into the rf. Ions were extracted by pulsing the ion source up to as high as 40 kv with respect to a grounded extraction electrode which was about 2 mm from the extraction slit.

Both the anode and cathode voltages were provided by separate taps on the pulse transformer. These were brought into the cyclotron using a freon insulated and cooled triaxial feed through the center of the yoke. The anode to cathode voltage could be varied over a nominal 1 to 5 kv range in 1 kv steps by switching taps on the pulse transformer. The arc current varied between about 6 and 18 amps for these voltages.

Details of several versions of the source are shown in Figure 1. The original version of the PIG source is shown in Figure 1a. The source body was made of 0.95 cm OD copper tubing with 0.79 cm ID. Tantalum cathodes, 0.64 cm diameter were mounted on stainless steel supports and insulated with boron nitride. An external wire was used to connect the two cathodes. For all source variations of Figure 1, gas was fed into the source via a small hole in the stainless steel support rod and through the center of the upper cathode. The beam was extracted through a 0.31 cm wide slot in the grounded extraction electrode. The DC output of the source was measured in its normal position in the cyclotron with a series of vertical copper strips on a printed circuit board, which was mounted at 180° from the source and used as a mass spectrometer. The source of Figure 1a produced adequate current ($\approx$100mA) but had a poor ratio of $H^+ : H_2^+$ (65%) and suffered from contaminant beams of boron and nitrogen which were likely caused by ion bombardment of the boron nitride insulators.

The source of Figure 1b was designed to remove the boron nitride from direct line of sight of the arc and to improve the extraction geometry. The source and puller aperatures were machined with an 82° tool to produce a 41° taper compared to the flat aperatures of Figure 1a. The source aperature was 7mm high by 2.3 mm wide and the extraction aperature was 6.25 mm by 1.6 mm wide. Beam currents of 150 mA with a ratio of $H^+ : H_2^+$ of 70% were measured with this source and the heavy ion contamination was substantially reduced. This source produced some improvement in the beam current accepted by the cyclotron but the improvement was not substantial.

The source shown in Figure 1c was the final design that worked much better than the PIG version. In this source the bottom electrode was electrically connected to the anode and only the top cathode was used. The extraction geometry was otherwise indentical to the source of Figure 1b.

Characteristics of the Single Cathode Source

The source of Figure 1c substantially improved the beam current accepted by the accelerator. However, the principle of operation was not understood for some time after the demonstration of improved beam performance. A series of experiments were performed in a test magnet (B $\approx$5 kG) to study the source, and the conclusion of these experiments was that the plasma originates inside the hollow cathode in a manner closely analogous to the hollow cathode arc (HCA) used in plasma physics (see Delcroix and Trindade[3] for a review of the properties of hollow cathode arcs). The single cathode source will therefore be referred to as a HCA source throughout the remainder of this paper. It is believed that the comparatively quiescent operation of a HCA plasma compared to a Penning discharge may be responsible for the marked improvements in the source operation.

Measurements reported in this paper (except the $H^+ : H_2^+$ ratio) were all made using the synchrocyclotron with typical accelerator operating parameters. Both DC source measurements with beam detectors mounted in the Dee, and acceptance measurements using a remotely moveable beam stop which moved radially from 4 to 38 cm, were used to check the source performance.

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Figure 2 shows several comparisons between operation of the same source in the HCA and PIG modes. The ordinate of this figure is the charge per pulse measured at 38 cm, which is a good measure of the acceptance of the cyclotron. The beam current of the HCA source is relatively independent of arc current but has a strong dependence on the throughput of the hydrogen. The PIG source shows similar dependences but with much poorer acceptance. The lower cathode current of the PIG source (for the same arc voltage and series resistance) reflects the higher source impedance of the PIG source compared to the HCA source. The DC source output was not measured as a function of hydrogen throughput, and this data may depend on other factors such as changes in emittance with current. However, it probably reflects the source output more than these other factors.

Figure 3 shows the increase in DC source current with extraction voltage. The solid curve is $I = P\ V^{3/2}$, normalized to the lowest data point. The perveance is $P = 1.2 \times 10^{-8}\ A/V^{3/2}$.

The percentage of the beam transmitted through a 1 mm horizontal slit at 1/8 turn from the source (part of the vertical emittance measurement apparatus) is also shown. The transmission increases to about 50%, which is very high considering the source aperature is over 6 mm high.

Cyclotron Performance

The vertical emittance was measured in the cyclotron by installing a mask with a 1 mm horizontal aperature at about 1/8 turn from the source. This could be moved vertically with good accuracy (≈1/4mm) from a remote drive below the cyclotron. The beam that passed through the 1 mm slit was measured at 180° with a printed circuit beam catcher with 10 horizontal strips, 1.25 mm wide separated by 0.25 mm. In this way, the mask could be moved vertically to measure the vertical profile of the beam and for each value of z, the angular divergence was measured using the 180° dectector. The mask was insulated and in a given measurement the sum of the beam current on the mask and on the 180° detector was nearly constant (± 5%).

Figure 4 shows vertical emittance diagrams measured for the three different source configurations that were shown in Figure 1. It is apparent from this data that the vertical divergences are fairly similar, but the height of the beam at the mask has been markedly reduced with the HCA source. The vertical emittance area A (z, z') is shown on Figure 4 for all three cases. The normalized emittance $E_n = \frac{1}{\pi} A(z, z') \beta\gamma$ is 1.1 mm - m rad for the HCA source at 80 mA. This compares favorably with the emittance, $E(r, r')$, of many high pulsed current duoplasmatrons, [4,5] and the ratio of $H^+ : H_2^+$ of ≈ 90% is significantly better.

The radial emittance could not be measured in the center of the cyclotron because of severe space restrictions. However, if it is assumed to be the same as the axial emittance, then the normalized brightness of the HCA source would be:

$$B_n = \frac{2\ I}{\pi^2\ E_z\ E_r} = 1.1 \times 10^{10} \frac{\text{amps}}{m^2\ \text{rad}^2}$$

which is also comparable to other high brightness proton sources [4,5]. Since it is unlikely that the radial emittance would be more than a factor of two larger than estimated, this number for brightness should be reasonable within that factor.

The remotely moveable beam stop was used to measure the beam current as a function of radius from 4 to 38 cm (38 cm corresponds to about 30 MeV). This beam stop was segmented into 5 sections to measure the vertical profile at any radius.

Figure 5 shows the vertical profile (F W H M) and the total charge per pulse as a function of radius for the HCA and PIG sources with the same extraction geometry. With the PIG source, the beam blows up vertically at a small radius, completely filling the gap in the magnet (1.9 cm) and only a small fraction of the beam survives. However, there is virtually no vertical blow-up of the beam from the HCA source.

The high beam current produced heavy beam loading of the rf immediately after injection, which enhanced a small dip in the rf pattern and produced losses from the phase bucket. This is demonstrated in Figure 6 which shows the beam loading as a function of the charge per pulse. The abscissa corresponds to the minimum rf voltage, resulting from beam loading. The beam current was controlled by inserting a vertically moveable beam stop at a radius of 7 cm to intercept part of the beam without changing ion source operating conditions. The accelerator transmission increases as the beam loading is reduced but the absolute beam current is lower, and therefore cyclotron operation was generally for the maximum input current.

Table 1 lists the optimum cyclotron performance recorded at 150 pps operation. The beam was measured at 38 cm and at various locations in the extraction system using secondary emission monitors (SEM's) calibrated with ^{27}Al foil activation. A toroid was used to measure the charge per pulse near the production targets. This data was recorded for fast extraction of the beam and was about 15% better than could be obtained using slow extraction.[6] The charge per pulse at 75 pps is also listed to show how the intensity scaled with repetition rate (there was no change for 75 or less pps). If this performance scaled to the design of 300 pps the internal beam would be nearly 30 μ amps. This agrees reasonably with the early calculations of the space charge limit of the modified Nevis synchrocyclotron.[7]

Summary

A new ion source has been developed which demonstrated substantial improvements over a PIG source. The performance of the HCA source with side extraction was comparable to other high brightness proton sources.

Because the principle of operation was not understood until much later than the original source development, no significant optimization program was undertaken to improve source performance. Some test bench experiments suggest that improvements may be possible in gas economy by changing the cathode to a thin walled tantalum tube. In view of the results obtained with the HCA source, it is felt that this source concept may be useful for other acceleration application.

TABLE 1

Position Measured	Charge/pulse (nanocoul/pulse) 75 pps	150 pps	Beam at 150 pps (μ A)	Current (μA) projected from 75 pps
38 cm	95	87	13.0	14.3
SEM 1 1/	57	50	7.5	8.6
SEM 2 2/	37	32	4.8	5.6
SEM 4 3/	37	32	4.8	5.6
TOROID 4/	31	26	3.9	4.6

1/ Entrance of extraction channel.
2/ Exit of extraction channel.
3/ Exit of cyclotron.
4/ Production targets.

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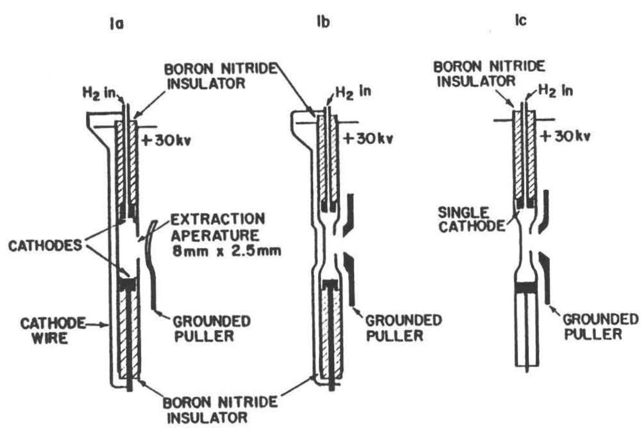

Fig. 1: Several versions of the ion source and extraction electrode. 1a was the original ion source using a flat aperature in copper tubing. 1b was machined from solid copper to produce the contours shown. 1c is identical to 1b except the bottom electrode is shorted to the anode.

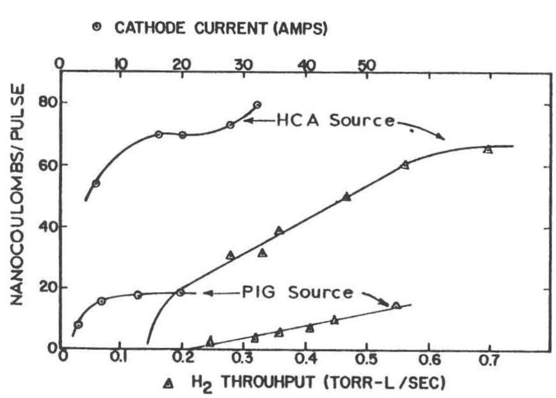

Fig. 2: The charge/pulse at 38 cm as a function of the cathode current (upper scale) and the hydrogen throughput (lower scale).

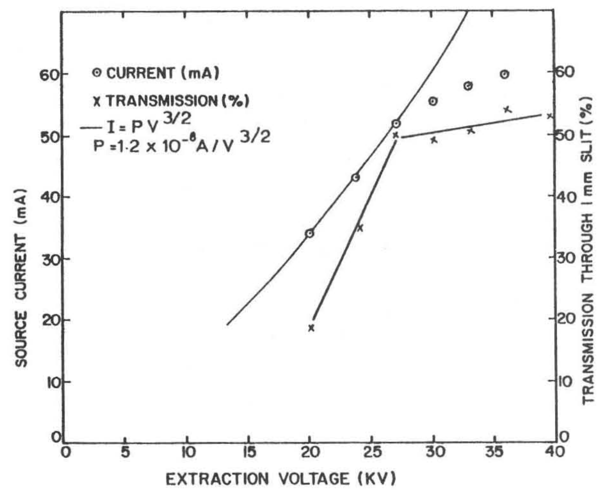

Fig. 3: DC source current as a function of extraction voltage for the HCA source. The right hand ordinate shows the transmission of the beam through a 1 mm high horizontal slit, about 10 mm from the source.

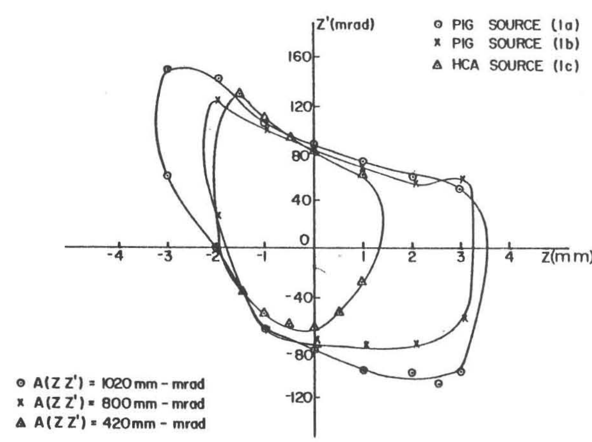

Fig. 4: Vertical emittance diagrams for the three source configurations of Fig. 1.

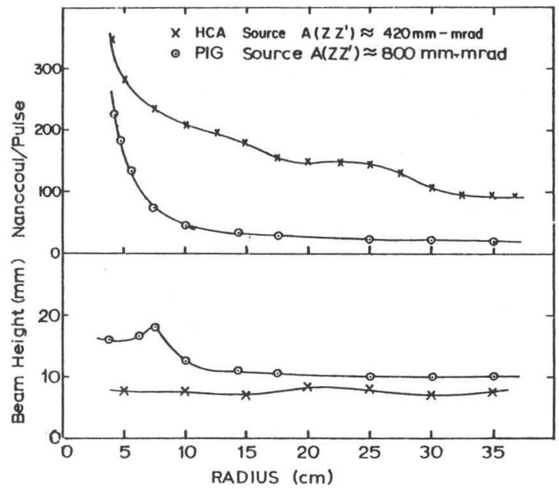

Fig. 5: Variation of the charge/pulse and the vertical profile of the ion beam as a function of radius.

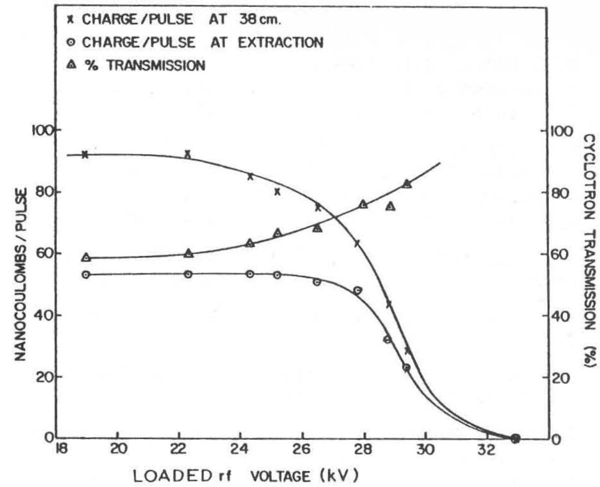

Fig. 6: The variation of the charge/pulse measured at 38 cm and the beginning of the extraction channel as a function of the loaded rf voltage. The accelerator transmission is indicated by the right hand scale.

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