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CYCLOTRON INTERNAL ION SOURCE WITH DC EXTRACTION*

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Summary

This paper describes a method for increasing the intensities for heavy ion beams accelerated in isochronous cyclotrons at high harmonics (h≥5) of the orbit frequency. Normally, only small intensities are obtained at high harmonics because of the low effective accelerating voltage between the ion source and the puller electrode. We have developed and tested a dc ion extraction system for the Oak Ridge Isochronous Cyclotron (ORIC). Use of the dc extraction system has increased beams of $^{40}Ar^{3+}$ on the 5th harmonic and $^{20}Ne^{1+}$ on the 7th harmonic from nanoamperes to microamperes.

Introduction

In existing isochronous cyclotrons, a variable frequency RF system allows acceleration of a large range of charge to mass particles. If the mass of the ion is large or if the charge is small the angular frequency of the ion may be less than the lowest angular frequency of the RF system. The RF angular frequency must be an integer multiple (harmonic) of the ion angular frequency. For 180° dees only odd harmonic values may be used. In the ORIC, ions have been accelerated using harmonics as high as the ninth.[1]

Experimentally it has been found that the beam intensity deceases as the RF harmonic is increased.[2] The beam current decrease has previously been ascribed to crossing of the 1st accelerating gap. In this paper a dc slit that accelerates the ions up to 15 kv before crossing of the 1st dee gap and operating experience obtained with its use is described.

Description of Experimental Hardware

A graphite dc accelerating slit was placed between the ion source and the RF dee (Fig. 2). During the tests described the slit was supported from an axially inserted tube. Motion of the slit was limited to rotation about the axis, and to translation along the axis. If a change in radial distance between the center of the cyclotron and the slit centerline was desired, a new slit of different dimensions was required. These constraints along with close clearances in the center region required operation of the source in an off centered position. It was, however, possible to compensate for this condition by adjustment of the harmonic and trim coils.

The mechanism used for supporting the slit and changing it from the configuration required for insertion, to the configuration required for operation, is shown in Fig. 3. Since the graphite is heated to incandescence by the beam the supporting mechanism must be capable of withstanding high temperatures. Both tantalum and stainless steel mechanisms have been used. The insulator is polyethylene and is protected from axial discharges by a stainless steel shield (Fig. 4). Voltages to -15 kV have been used.

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Experimental Results

The first successful runs with the dc slit were with the 5th and 7th harmonic beams and resulted in beam intensities larger than ever achieved before. However, the numerical value of the beam improvement due to the dc slit was uncertain because of problems of cyclotron operation (for example vacuum and ion source output). To reduce the uncertainty the following test was performed. A new ion source cathodes were installed and a $^{20}Ne^{1+}$ beam on the 7th harmonic was extracted with the dc slit and adjusted for maximum current over a 4 hour period. The ion source cathodes were then changed, the dc slit removed and again the extracted beam was maximized over a 4 hour period. A graph of the current as a function of radius, with and without the dc slit is shown in Fig. 5. The internal cyclotron beam with the dc slit is larger by a factor of ∿ 40. The extracted beam is larger by only a factor of ∿ 15. Gordon has shown that the extraction system for a cyclotron is a phase selection device.[3] Therefore the difference in the internal and extracted beam intensities can be attributed to an expected phase length increase due to dc extraction or possibly different centering conditions.

Another noticable effect is in the similarity in beam loss as a function of radius, and is suggestive of a common loss mechanism. Gas stripping is known to be a problem for heavy ions in ORIC.[4] The beam intensity vs radius curves can be fitted by the following equation:

$$I = I_o e^{\frac{-p K_1}{E}} . \qquad (1)$$

Where p is the pressure, K_1 a constant, I_o the source output current, and I the measured current. For a cyclotron, the energy (E) is related to the radius by equation (2),

$$E = \frac{q^2 r^2 B^2}{2m} . \qquad (2)$$

Substitutions of eq. 2 into 1 gives 3,

$$I = I_o e^{\frac{-p K_2}{r^2}} . \qquad (3)$$

A semi-log plot of the beam intensity with r^2 is linear (Fig. 5). Extrapolation back to the ion source (r=0) yields a current of ∿ 1 ma. About a factor of 1000 increase in intensity for $^{20}Ne^{1+}$ at ORIC's extraction radius can be expected for dc injection combined with improved vacuum.

The slope of the beam current vs radius curve of Figure 9 shows that the critical pressure area in ORIC is at the outer radius, where the particles spend most of the time. This is fortunate since this area is more accessible for vacuum pumping improvements.

Theoretical Calculation

The theoretical equations of Reiser[5] based on a uniform magnetic and electric field have been used in

calculating the transit angle (τ) during the first gap crossing as a function of RF harmonic. The transit angle is defined to be the number of RF degrees needed to cross the source to puller gap. The transit angle is related to a quality χ by the following equation:

$$\chi = \frac{1}{h+1}\left[\frac{2\sin(\frac{(h-1)}{2h})}{h-1} \times \sin\left(\theta_o + \frac{(h+1)\tau}{2h}\right) - \sin\theta_o \sin\frac{\tau}{h}\right] . \quad (4)$$

where h is the harmonic number and θ_o is the starting phase. Negative phase means the ions are ahead of the RF peak voltage.

$$\chi = \frac{\ell^2 B^2 q/m}{V} , \quad (5)$$

where B is the magnetic field (18 kG); V is the dee voltage (70 kV); q/m is the charge to mass ratio; ℓ is the effective distance of source to puller (1 cm). The equations were solved for various values of initial starting phase, RF harmonic, and transit angle. The dee crossing voltage, and hence energy gain, determines the starting phase necessary for acceleration in the cyclotron. First order approximation shows that the maximum energy gain will occur at the starting phase given by the following:

$$\theta_o = -h\sqrt{\chi} . \quad (6)$$

Any given RF harmonic in ORIC has a range of χ values and therefore a range of initial starting phases. For the 5th, 7th, and 9th harmonics the value of $\theta_o \sim -60°$ is a good approximation. The values of θ_o for the 1st and 3rd harmonics are considerably smaller. Figure 6 has a starting phase of -60° and gives the transit angle for the high harmonics in ORIC as a function of χ. The m/q values which correspond to χ are given at the left of figure 6. The parallel horizontal lines indicate the boundaries of the regions of harmonic operation for ORIC at maximum magnetic field excitation. The transit angle appears to be reasonable even up to the 11th harmonic and explains the success of 9th harmonic acceleration. The calculated energy gain is greater than 90% of the dee voltage for the above cases. However, it must be pointed out that the transit angle increases to unacceptably large values if the effective source to puller distance is increased to 2 cm.

Reiser has also discussed the expected ion source current density[5] as a function of voltage. The starting phase of the ions for high harmonics is such that Child's law is a good approximation. That is, the current density j will be given by the following equation:

$$j = \text{const}\sqrt{\frac{q}{m}}\ \frac{V^{3/2}\cos^{3/2}(\theta_o)}{d^2} . \quad (7)$$

A dc gain factor has been calculated where:

$$\text{dc gain} = \frac{j(dc)}{j(rf)} . \quad (8)$$

The results are shown in Figure 7 where the value of V = 70 kV, d = 1 cm and θ_o from (6) were used for j(rf). For dc injection the value of V = 10 kV, d = .1 cm and $\theta_o = 0$ have been used.

Experimental Application

The success of dc injection has made possible new types of experiments on cyclotrons. One is now possible because of the large beam currents and the other because of the acceleration at high harmonics.

The foil lifetime for stripping heavy-ions to a high charge state is of prime interest for various proposed accelerator concepts.[6] The charge state as a function of mass required to achieve an energy of 20 MeV from ORIC is shown in Fig. 8. This is the energy a negative ion would achieve from source to terminal in a 20 MV Van de Graaff accelerator where it would be stripped to a higher state. A life test on foils at 20 MeV will help establish whether foils can be used, instead of gas stripping and thus take advantage of the higher charge states.

An interesting speculative experiment conceivably possible with higher harmonic operation is indicated in figure 8 by 298^{7+}. In the search for super heavy elements the experimenters have primarily looked for a radioactivity signature. The experiments with mass separators[7] are plagued by background beams of molecular ions. In principle, an isochronous cyclotron is a "super" mass separator. However, a reasonable charge state for a superheavy ion must operate at a high harmonic (h=11 in ORIC). The operating point for 298^{7+} is shown in Figure 8. These harmonics are now possible with a dc extractor on the ion source. Atomic detection methods that are sensitive[1] and specific in yielding positive identification of the accelerated ion are already in use at ORIC for lower masses. However, the problem of selecting the ion source charge material is of course critical.

References

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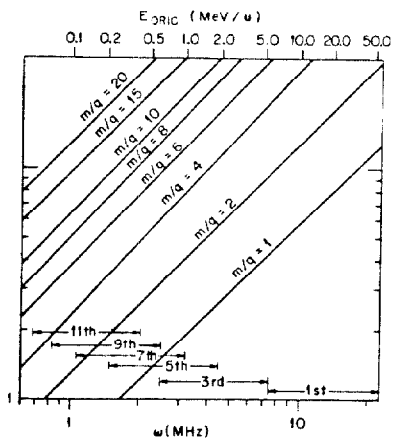


Fig. 1. Resonance conditions for various m/q ions on the ORIC. As the m/q value becomes larger, the RF frequency must operate on a higher harmonic and this range of harmonic operation is indicated by the 1st to 11th arrows.

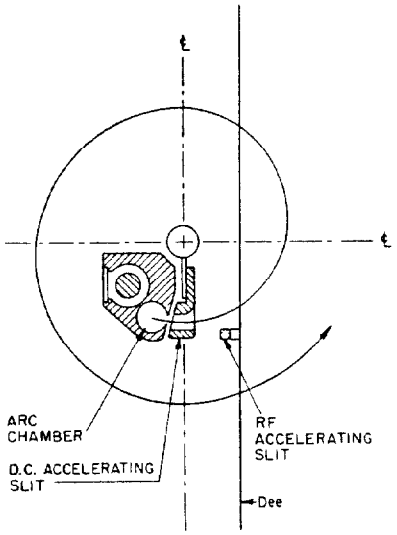


Fig. 2. Cross sectional view of the geometry in the center of the cyclotron. A particle starting from the ion source arc chamber is indicated by the circular orbit. The dc accelerating slit is position between the ion source and the RF accelerating slit and can hold up to 15 kV.

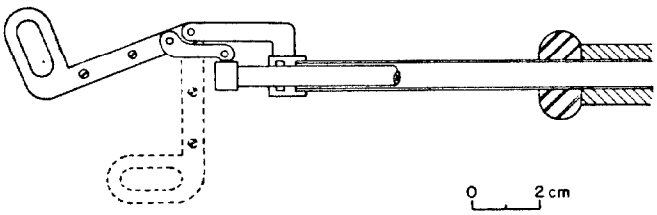


Fig. 3. Schematic drawing of dc slit mechanism. Solid lines indicate position of slit during insertion thru 1-1/2" diameter magnet axial hole. The dash lines indicate the position during operation in the center of the magnet.

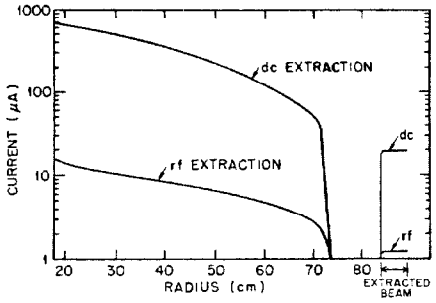


Fig. 5. The measured beam current as a function of radius with and without the dc slit for $^{20}Ne^{1+}$ beam on the 7th harmonic. The dc slit internal beam current is greater than the RF extracted beam by ∿ 40.

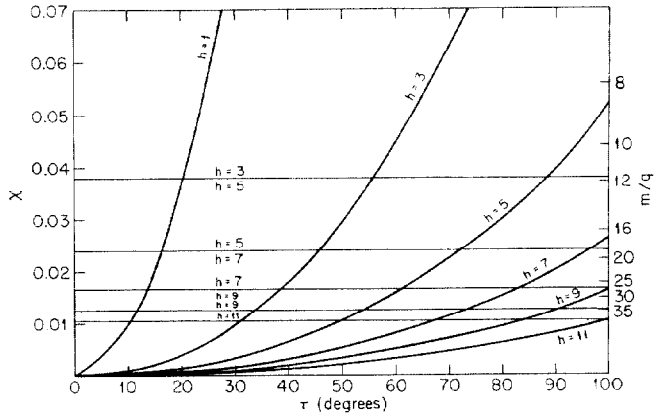


Fig. 6. The transit angle in RF degrees as a function of χ for an initial starting phase of -60° and for odd harmonic values. For a given geometry (see text) χ is related to a particular value of m/q. The harmonic operational boundry for ORIC are indicated by the light parallel horizontal lines. The transit angle are acceptable every up to the 11th harmonic and explains the successful acceleration of 9th harmonic on ORIC.

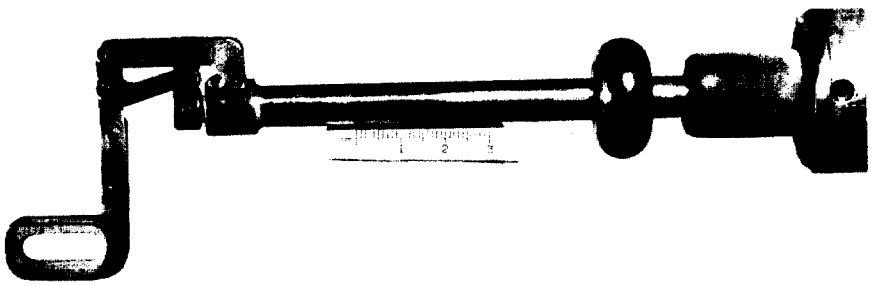


Fig. 4. A photograph of the dc slit in the operating position. The slit is made of graphite and mounted on a tantalum support.

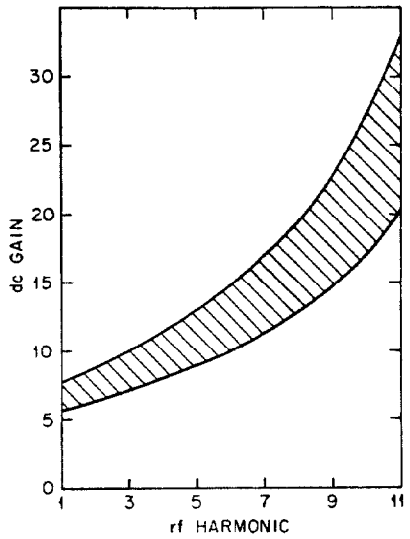


Fig. 7. The expected beam intensity gain as a function of harmonic with the dc slit. The variation in gain is due to the variable range of m/q for a given harmonic in ORIC.

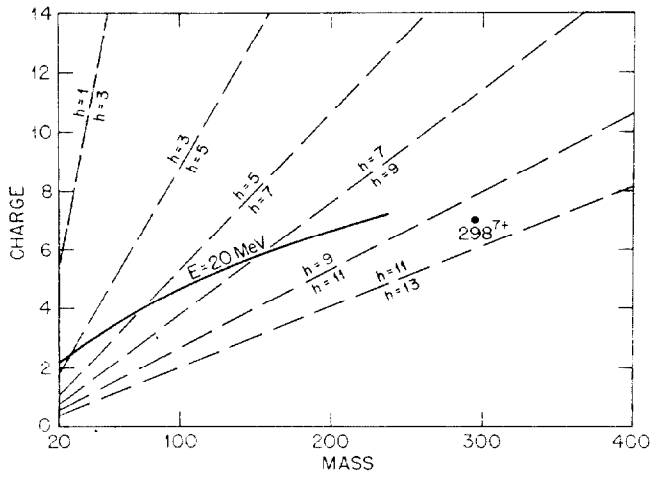


Fig. 8. The particle charge state as a function of mass for an energy of 20 MeV in ORIC. The necessary RF harmonic number for accelerating is indicated by the dashed lines. This energy is what a stripping foil will encounter in a terminal of a 20 MV Van de Graaff. The point at 298^{7+} indicate that ORIC would have to operate on the 11th harmonic in order to accelerate this charge to mass ratio.

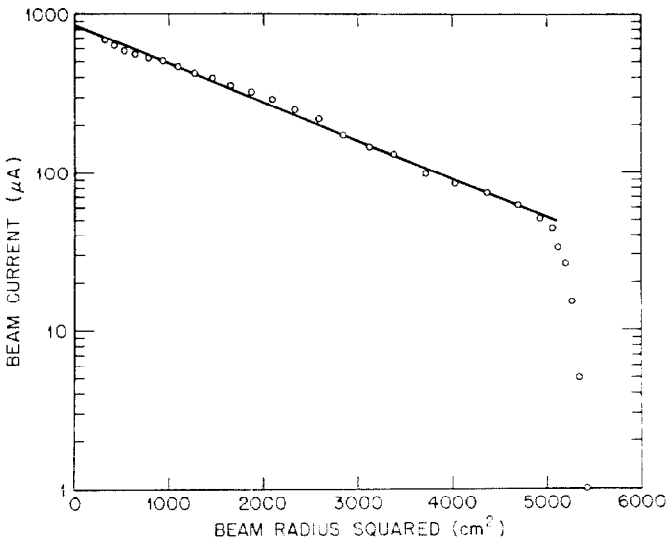


Fig. 9. The dc slit beam current plotted as a function of radius squared, indicating a beam loss mechanism that is consistent with poor vacuum.