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OPERATING CHARACTERISTICS OF THE ORIC BEAM EXTRACTION SYSTEM*

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Introduction

The ORIC extraction system was described previously in its component parts.[1] Several modifications have been performed and experience has been gained in the operation of the system. The system shown in Figure 1 consists of both electrostatic and electromagnetic elements. The electrostatic channel consists of an aluminum deflector electrode, water cooled, and operated at 60 to 70 kV across a gap of 1 to 1.5 cm to a graphite septum 0.8 mm thick. Both the septum and deflector curvature can be varied by a remote control system from the control room. The coaxial magnetic channel follows the electrostatic channel and provides a 4 kG maximum field reduction over a length of 22 cm. The third element of the extraction system, a compensated-iron channel, can provide up to 9 kG of field reduction along the path of the deflected beam.

To minimize the divergence of the extracted beam the pole tips are oriented so that the major portion of the fringe field is crossed at right angles to field contour lines, as shown in Figure 1. The radial divergence, as a result of this, is less than $\pm 0.6^{\circ}$.

The modifications to the above system include the incorporation of the curvature adjustments on the electrostatic channel, a remotely controlled motion adjustment for the exit of the compensated-iron channel, and improvements in the water cooling lead arrangements of the coaxial channel. The first two of these allow greater flexibility in the range of particles which can be extracted. The water lead modification remedied a propensity for leaking which caused a considerable loss of operating time.

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Operation

In operation, the system has provided extracted beams of protons from 18 to 65 MeV, deuterons from 22 to 40 MeV, alpha particles from 44 to 80 MeV, and ^{3}He particles from 25 to 55 MeV. Extraction efficiency is 60% for most particles but drops to ~30% for the highest and lowest energy protons. Lower energies for e/m = 1/2 particles could be obtained but no demand for these energies exists. Also, no program at present requires ^{3}He above 55 MeV, but no problem is anticipated in obtaining 100 MeV for this particle.

The initial decision to begin extraction at a radius where ν_r is still greater than 1.0 was made to avoid the loss of beam associated with passing through the outer resonances. It was found, while the extraction system was still under construction, that the introduction of a harmonic in the magnetic field by coils near the center region produces controllable and coherent oscillations about the magnetic center. These oscillations can provide good orbit separation at the entrance of the septum. The value of ν_r must remain relatively constant and be slightly greater than 1.0; the amplitude of the oscillations must remain within the stability limits of the phase-space region, and the phase width of the beam must be relatively narrow to prevent loss of coherence. If these conditions are available, controllable linear oscillations can be provided by use of the harmonic coils, and good extraction efficiency can be obtained. The effect of this oscillation is shown in Figure 2. For this case ν_r is about 1.05 in the region of the extraction radius. The variation of beam density vs radius is indicated by the current on probe 2 where the radial width exceeds 3/8 inch. The total current on probes 1 and 2 shows small dips where the beam density is highest. These dips result from increased scattering from the probe leading edge and provide a good indication of structure without the segmented probe. The radiation also indicates variation of density by the stepwise increases at regions containing many turns and high energy gain.

The choice of the combination of electrostatic and electromagnetic elements was made because of the desire to avoid the necessity for very high potential gradients and the resulting operational problems. The magnetic elements provide at these energies much stronger extraction forces than could possibly be obtained with an electrostatic system. The lower gradient requirement of the electrostatic deflector also allows the use of the graphite septum, which makes the radiation problems inside the cyclotron far more tractable. It is possible to go into the cyclotron and perform work for several hours within a short time (8 hours) after the cyclotron has been operated with 30 microamperes of 60 MeV protons for several days.

For values of ν_r greater than 1.0 the corresponding values of ν_z are small, hence the axial width of the beam is larger and the current density on the septum is smaller than they would be after $\nu_r = 1$. This reduces the problems associated with maintaining and cooling the septum. Axially, the beam is extremely well defined as it leaves the cyclotron, with a virtual source that appears to be located near the ion source.

External Beam Characteristics

Emittance Measurements

The radial and axial emittances, as calculated from measurements made on an extracted beam of 36.6 MeV H_2^+, are 55 millimeter-milliradians in the radial direction and only 14 millimeter-milliradians in the axial direction. The radial virtual source is in the middle of the compensated-iron channel and has an apparent size of 2.5 mm. The interesting possibility of compensating for the remaining field gradient in the region where the beam leaves the iron channel and eliminating the need for Quadrupole Number 1 by having an essentially parallel beam leaving the cyclotron has been considered.

Energy Spread

The energy spread of the beam from ORIC has been measured by two methods. Both systems utilize the 6-ft radius 153° analyzing magnet and the entrance-slit system. The first method scatters beam at 15° from a 1/2 mm wide plastic target at the image slit position of the analyzing magnet. The beam is prepared by the object slit to present a 1-mm wide beam to the magnet. A detector, carefully collimated, sees only the scattered beam. The primary beam is moved by the magnet so that first one edge of the analyzed beam is striking the target and then the other edge of the beam strikes the target. The peak separation of the two scattered beams is observed on a pulse height analyzer. Use of a plastic target containing carbon allows the 4.43-MeV excited state to be used as a calibration. It was found that this measurement was consistent with a method which simply uses the energy difference corresponding to a magnet current difference obtained by adjusting the two edges of the analyzed beam to the center of a phosphor screen. Alpha particles at full energy, 80 MeV, have an energy spread of 0.3% full width at half maximum. Protons are not so well defined, with an energy spread of 1% FWHM for 60 MeV. The probable reasons for this are discussed later.

Phase-Width Measurements

Both internal and external phase width of the beam have been measured. Results are very consistent for e/m = 1/2 particles, but some difficulty was encountered in resolving the differences in the proton cases. The development of a high-resolution system for measurement of the external pulse width has allowed an explanation for the differences in these measurements.

Internal Phase Width

The internal phase width of the beam has been measured using the method described by Smith and Garren.[2] Results of these measurements are shown in Figures 3 and 4 for 40-MeV protons and 68-MeV alpha particles. The phase width for both corresponds to Δ sine $\phi = 0.3$, or about 20° for isochronous conditions. The phase history shown is not particularly good but extraction efficiency for both beams is over 50%.

External Phase Width

To measure the width of the external beam pulse a 50-ohm constant-impedance Faraday cup was designed and constructed. This device is water-cooled and capable of collecting beam currents in excess of 25 microamperes. The signal generated in this device is delivered to a sampling oscilloscope with a 50-ohm input termination and a rise time of 0.35 nanoseconds. Typical pulse widths observed for 22, 40 and 60-MeV protons and 47, 68 and 80-MeV alpha particles are shown in Figure 5, with half maximum pulse widths of 36°, 33°, 30°, 18°, 23°, and 20° respectively. The time scale is 2 nanoseconds per division for all but the 47 MeV alpha particles, which is 5 nanoseconds per division.

Comparison of Internal and External Measurements

Within the limits of the resolution of the measurements, the results of the internal and external measurements for the alpha beam case are quite consistent. The protons at 40 MeV, with a nearly identical internal phase width, show a much wider external phase width than seems reasonable. It was decided to investigate the external pulse width of the 40-MeV protons in greater detail since this particular beam, partially because of better extraction efficiency and higher beam current available, displayed some structure in the external beam pulse. Some of the results of these tests are shown in Figure 6. The horizontal time scale for these pictures is 2 nanoseconds per division, and each represents the shape of the external beam pulse for the dee voltage as given. The dee voltage is adjusted for maximum extracted beam for each case and the extracted beam goes to zero between each value. This indicates that each picture represents extraction on a different precessional cycle and represents a condition of dee voltage for minimum beam density at the septum entrance. The pulse structure can be explained by referring to Figure 3 and noting that a rapid phase excursion occurs at the extraction radius so that if several turns are extracted each would have a different phase and would be spread in time in the external beam.

Conclusions

The extraction system for ORIC has proved to be stable, reliable, and easy to operate. The harmonic necessary to achieve the coherent oscillations is not easy to calculate but can be obtained in operation and optimized without difficulty.

Alpha particles have nearly ideal conditions for extraction and the extraction efficiencies and beam quality obtained indicate that this extraction method can be very successful.

The larger ν_r, typically 1.08, for higher energy protons and the smaller change in radius per turn compress the coherent oscillations so that it is more difficult to extract the beam with high efficiency. Reduction of the phase width of the beam by the incorporation of defining slits allows the possibility of improving extraction conditions for protons by increasing the coherence of the beam.

References

1. R. S. Lord, *et. al.*, CERN 63-19, 297 (1963).

2. A. A. Garren and Lloyd Smith, CERN 63-19, 18 (1963).

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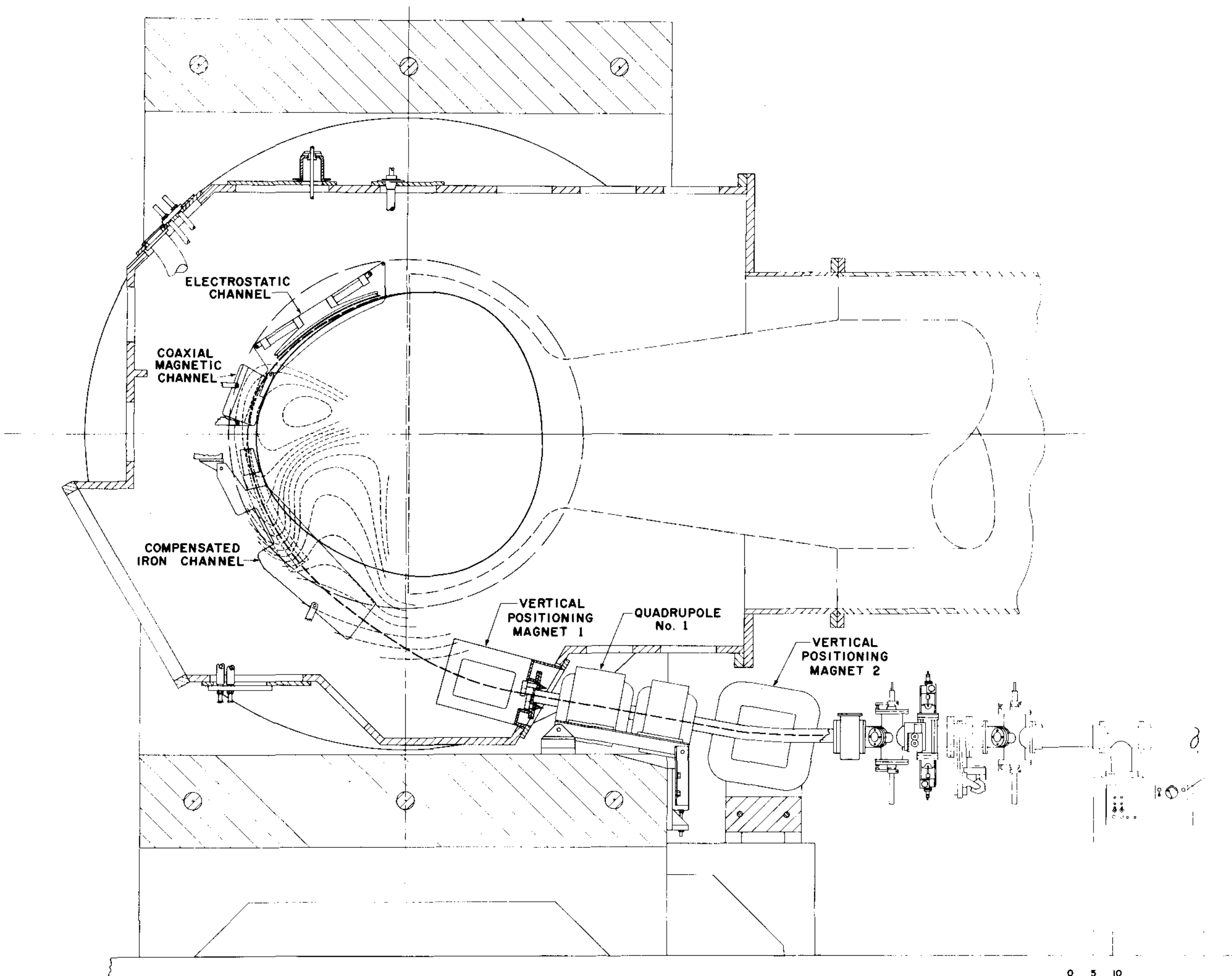

Figure 1. The Beam Extraction System in ORIC.

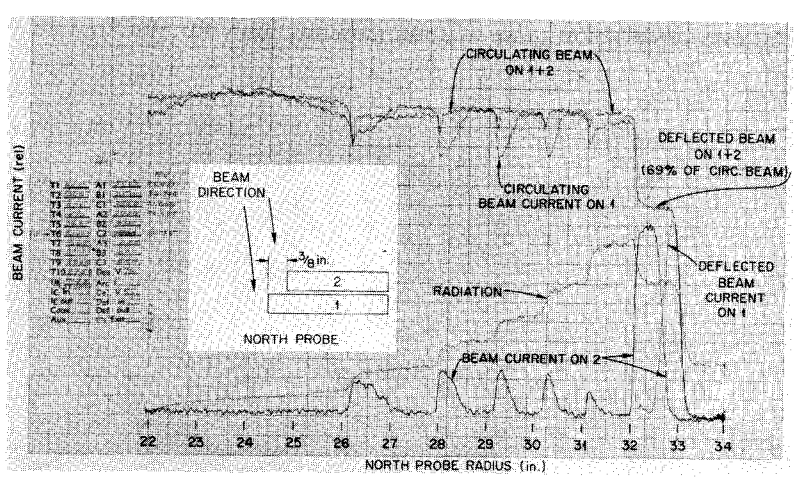

Figure 2.
Beam Current on the Movable Probe as a Function of Radius. Radiation was measured with a neutron detector located in the cyclotron vault.

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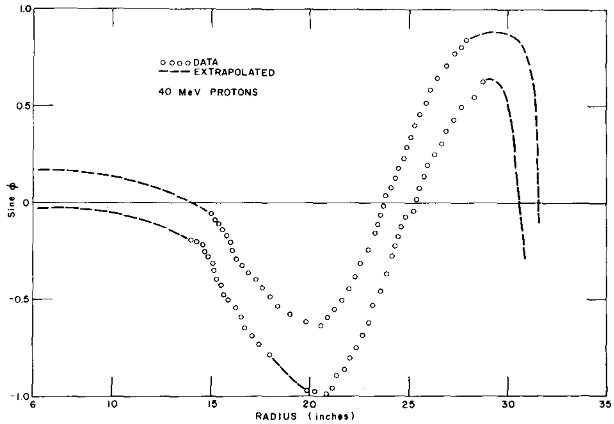

Figure 3. Phase vs Radius, Measured for 40-MeV Protons.

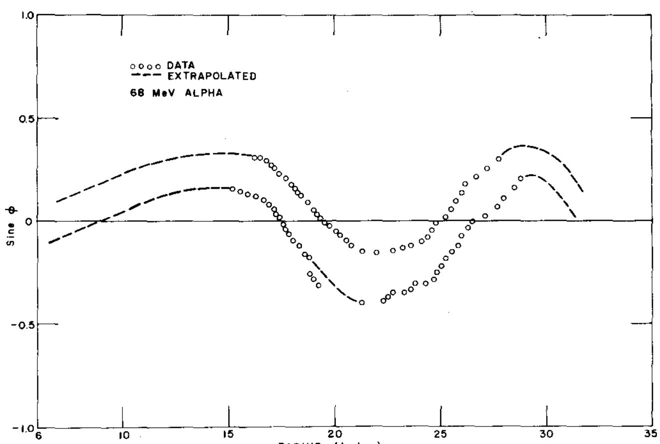

Figure 4. Phase vs Radius, Measured for 68-MeV Alpha Particles.

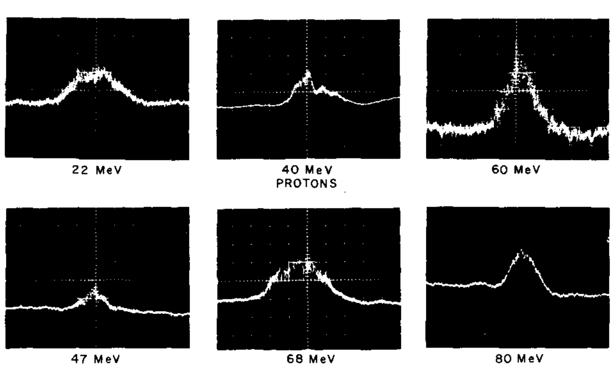

Figure 5. External Beam Pulse Widths for Protons and Alpha Particles of Various Energies. All horizontal scales are 2 nsec per division, except 47-MeV alpha particles, which is 5 nsec per division.

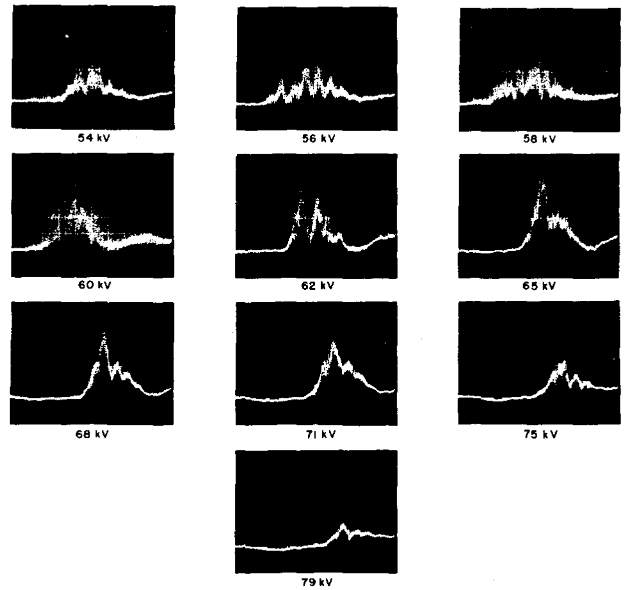

Figure 6. External Beam Pulse Shapes for 40-MeV Protons. Dee voltage is varied, each picture represents extraction on a different precessional cycle.

DISCUSSION

TENG: You get 60% efficiency by taking advantage of the coherent oscillation?

WHITE: Very definitely. The separation between turns is presented by the actual coherent radial oscillation of the beam; areas of high density are followed by areas where the radial gain is very large.

TENG: And the 40% loss is to the septum?

WHITE: Almost all of this is lost on the septum.

WEGNER: What did you mean by the statement that the virtual source of your beam was at the ion source?

WHITE: In the axial direction the beam comes out essentially parallel. The radial virtual source is at about the middle of the compensated-iron channel.

