ORIC BEAM ENERGY INCREASE

M. L. Mallory, J. B. Ball, D. T. Dowling, E. D. Hudson, R. S. Lord, and B. A. Tatum
ORNL,* Oak Ridge, TN, U.S.A.

Abstract

The detection of and solution to a beam interference problem in the Oak Ridge Isochronous Cyclotron (ORIC) extraction system has yielded a 20% increase in the proton beam energy. The beam from ORIC was designed to be extracted before the $\nu_r = 1$ resonance. Most cyclotrons extract after the $\nu_r = 1$ resonance, thus getting more usage of the magnetic field for energy acceleration. Attempts to increase the ORIC extraction radius over the past 40 years have failed. We determined that the electrostatic deflector septum in ORIC interferes with the last accelerated orbit, with the highest extraction efficiency being obtained near the maximum ν_r. This ν_r provides a rotation in the betatron oscillation amplitude that is equal to the same length as the electrostatic septum thus allowing the beam to jump over an interference problem with the septum. With a thinned septum we were able to tune the beam to the $\nu_r = 1$ resonance and achieve a 20% increase in beam energy. However, the method of extraction with $\nu_r > 1$ may be useful for very high field cyclotrons since it provides greater clearance at extraction than that obtained from dee voltage gain, thus allowing the possibility of utilizing a magnetic extractor.

INTRODUCTION

The Oak Ridge Isochronous Cyclotron (ORIC) has operated successfully for over forty years. During these years its mission has changed several times. Initially it was a light ion accelerator, then a heavy ion accelerator, then for many years a heavy ion energy booster accelerator, and today a light ion driver accelerator for a radioactive beam facility.[1] At the cyclotron's initial startup in the 1960's, the accelerator did not achieve its design extraction radius (31 inches) for protons. Instead, the operating extraction radius for protons was about 28½ inches, with a concomitant decrease in maximum proton energy. However, the changing of accelerator mission to heavy ions caused that problem to be set aside and the machine performed well in its new missions. In the late 1990's, with its mission changed back to light ion acceleration, the problem of reduced proton extraction radius reappeared. A new accelerator research program on ORIC has finally resolved this problem.

The clues to the solution of the lower energy problem came from the detection of several operational problems and the understanding of how these problems pointed to a common cause. Next we investigated the design calculations for beam extraction from ORIC and determined the theoretical cause of the problem. We also found that the ORIC operators had discovered a way, that has not been thoroughly studied, to successfully extract beam from the cyclotron. We modified ORIC's extraction system and achieved full extraction radius. In the last section of this paper, we discuss where the previous method of extraction may be useful for high energy cyclotrons.

* Oak Ridge National Laboratory is operated by UT Battelle LLC for the U.S. Department of Energy under contract number DE-AC05-00OR 22725

OPERATIONAL PROBLEMS

During the many years of operation of the cyclotron, it has been observed that the ion source radial support arms became radioactive and required shielding during ion source maintenance to prevent operator exposure. In particular, the induced radiation on the ion source arms was greatest after a deuteron beam run, and peaked at a radius of about 19 inches.

The position of the lower magnetic channel within the cyclotron is just beyond the ion source support arms. The graphite entrance shield to the lower magnetic channel shows an erosion pattern that is difficult to explain by the accelerated beam. The pattern on the slit has three components: a deeply eroded part on the medium plane of the cyclotron and near the accelerated beam side; two less eroded patterns located above and below the central eroded area, with a distinct uneroded area between them and the central eroded pattern.

Many orbit calculations, starting from the ion source radiation peak and tracing backwards were made and none seem to make sense until a proton coming from the breakup of the deuteron beam was assumed. It predicted a breakup collision point of the beam located at the exit end of the electrostatic deflector septum. This led to the hypothesis that the eroded pattern seen on the lower channel graphite shield was due to neutral particles coming from this same breakup collision point. Thus the assumption of both charged and neutral beams from a common breakup point could account for both the observed activation of the ion source supports and the observed erosion pattern on the lower channel shield.

These predictions of a beam collision point on the exit end of the deflector septum led to its removal and examination after a deuteron beam run. A visual examination clearly showed burn marks from beam striking along the last one-third of the length of the graphite septum, thus confirming the predicted source location for the induced radiation on the ion source support arms and the erosion pattern detected on the lower channel shield. We next undertook to understand the reason for the beam collision with the electrostatic septum. The explanation of this beam-septum interference provided the clue needed to solve the proton extraction problem.

ORIC EXTRACTION CALCULATIONS AND EXPERIMENTS

Measurements of the distance from the most intense burn spot on the electrostatic deflector septum to the septum beam entrance slot agreed with the calculated ν_r value for the deuteron beam at the deflector entrance radius (ν_r = 1.05). Thus the intense beam burn spot was identified with the last accelerated orbit before extraction. The separation distance between this next-to-last orbit and the extracted orbit was calculated. Figure 1 is the result of the calculations for extraction of a proton beam from ORIC. The distance between the next-to-last accelerated orbit and the extracted orbit, as a function of distance along the electrostatic deflector septum starting from the extraction slot, is shown for four different ν_r values. The

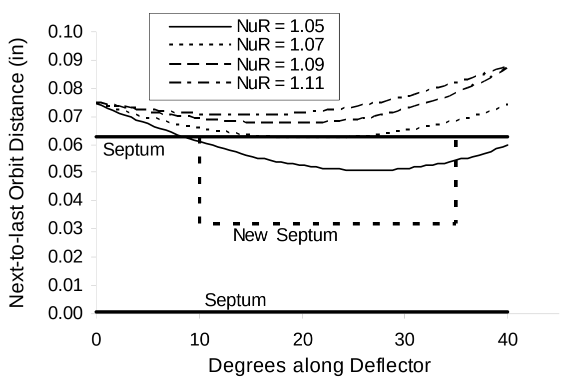

Figure 1: Separation distance of next-to-last orbit.

dee voltage and the electrostatic deflector voltage (kV/cm) were taken from ORIC's run sheet. A .030" increase at the entrance was assumed from the betatron term and a deflector septum thickness of 0.063 inches is also shown on the drawing. The calculated results predicted an interference of the deflector septum with the cyclotron beam for $\nu_r < 1.07$ for the proton beam. Similar results were obtained for the deuteron beam. Figure 2 is the calculated ν_r for ORIC using the latest magnetic field measurements and the cyclotron general orbit code. [2,3]

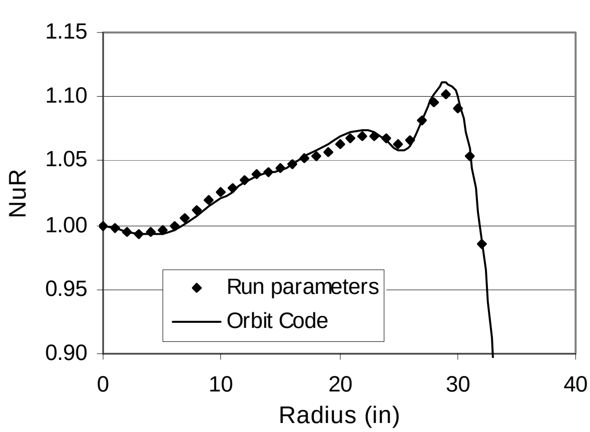

Figure 2: Calculated ν_r as a function of radius.

We note here that the cyclotron operators had found that maximum extracted proton beam intensity occurs at the radius where ν_r is a maximum. At this value of ν_r, the betatron rotation is greater than the length of the deflector septum, hence it becomes possible for the beam to jump over the septum interference in the last accelerated turn, but this requires extraction at an early radius, thus lowering the energy. Finally, we examined the original ORIC extraction calculations (1960's). These calculations used an analytical form of the cyclotron orbit to determine the engineering parameters for the extraction system.[4] We have compared this analytical orbit with an orbit obtained with the general orbit code and find they match quite well when using an amplitude of 1.45 for the 3 Θ term. Figure 3 shows a calculation of the orbits for a proton beam, with the operating ORIC energy gain per turn at a ν_r of 1.1 and a betatron amplitude of 0.2 inches.

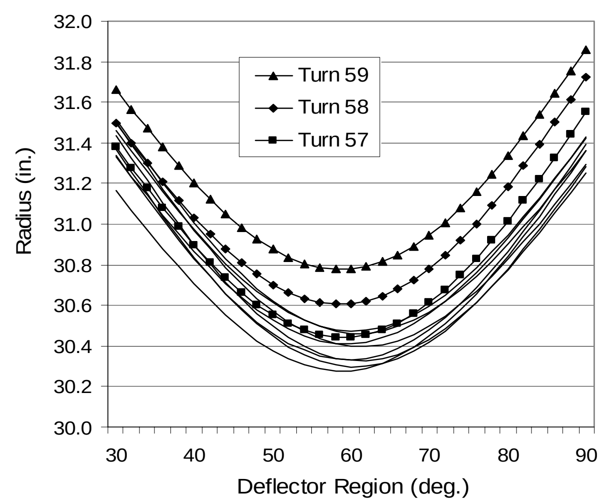

Figure 3: Turn separation at extraction with ν_r = 1.1.

The figure shows a complete betatron oscillation cycle (10 turns) before extraction with the last three turns highlighted. This shows the overlapping of earlier orbits and then the orbit separation at the end of the cycle that allows clean extraction of the beam. Lower values of ν_r require a somewhat higher value of betatron amplitude to achieve a similar separation.

A modified thinned graphite septum (as shown by the dotted line in Figure 1) was installed in ORIC and the results of tuning the cyclotron to a larger extraction radius are shown in Figure 4. The beam energy was increased from 43 MeV to 53 MeV. The maximum extraction radius was limited by the mechanical limit of the deflector entrance. The extraction efficiency as a function of the deflector entrance position is also shown in Figure 4, with the minimum in the extraction efficiency occurring when the betatron rotation angle equals the length of the deflector septum.

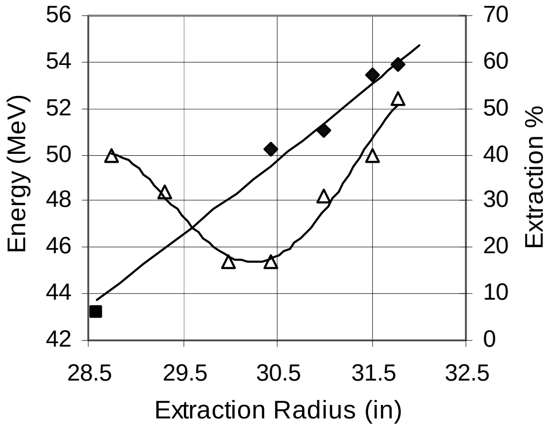

Figure 4: Extraction parameters vs. deflector entrance position. Closed points are the measured proton energy and open points are the measured extraction efficiency.

FUTURE USE OF THE $\nu_r > 1$ EXTRACTION METHOD

Superconducting cyclotrons are now reaching their technological limits when extracting beams using electrostatic deflector devices and extracting at $\nu_r < 1$. A recent proposal for a superconducting heavy ion medical cyclotron requires approximately 360° of the cyclotron orbit path length [5] before getting the beam extracted when using conventional electrostatic deflectors.

A more powerful extraction technique is magnetic extraction. The relative strength between a magnetic channel and an electrostatic deflector is such that a 5 kG magnetic field reduction applied to extract a 250 MeV proton beam would achieve approximately 10 times the separation distance of a corresponding 100 kV/cm electrostatic deflector.[6] In a recent use of magnetic extraction in a low energy proton cyclotron, a groove was machined in the pole tip of the cyclotron and the resultant magnetic field reduction of about 5 kG successfully aided in extracting the proton beam. This cyclotron demonstrated that magnetic extraction from cyclotrons is possible when provided with the proper clearance, which is easily obtained at low energy.[7] This cyclotron development also confirmed that the magnet field codes and the cyclotron orbit codes are in excellent working order to design magnetic extraction systems.

The electrostatic deflector provides two important properties. It is radially very thin and thus can fit between a small radial separation of the last accelerated orbit and the extracted orbit. Secondly, the electric field generated by the electrostatic deflector does not perturb the internal cyclotron beam orbits. High energy cyclotrons are opening two new parameters that may be exploited by ν_r >1 extraction. Namely, the ν_r values are increasing as the energy increases ($\nu_r \approx \gamma$) and the necessity to increase the pole tip sector number to higher values (3 to 4) to avoid accelerator focusing problems,[8] shortens the orbit path length over the pole tip region where the extraction devices are now located. The analytical expression used above for ORIC's extraction provides a fast method to survey the feasibility of using $\nu_r > 1$ extraction at high energy. Our calculations for a four sector machine show that a 0.2 inch clearance is easily obtained for such a high energy cyclotron with a $\nu_r = 1.25$. These preliminary results are encouraging enough to state that clearance greater than the dee voltage gain can be easily obtained and it appears that magnetic extraction at high energy may indeed be feasible. This method of extraction would also impact on the design of the cyclotron central region. Ion source or inflector clearance requirements and centering are important for $\nu_r < 1$. Betatron amplitudes are required for $\nu_r > 1$ extraction, thus acceptance of off centered orbit solutions in the central region would be allowed. Our studies indicate that there is an optimum betatron amplitude for this method. Finally we note that ORIC offers 40 years of proof of principle for the $\nu_r > 1$ extraction method.

ACKNOWLEDGEMENT

We greatly appreciate the cyclotron operation by Mike Dinehart and Cliff LeCroy in obtaining these results.

REFERENCES

[1] B. Alan Tatum, James R. Beene, Darryl T.Dowling, Sixteenth International Conference Cyclotrons and Their Applications, AIP Conference Proceeding 600, May 2001, 148-150.

[2] M. M. Gordon and T. A. Welton, ORNL Report 2765, Sept. 1959.

[3] J. P. Cleary, IEEE Trans. Nucl. Sci. NS-26, No. 3, (1979) 3907.

[4] Electronuclear Division Annual Progress Report, ORNL 3630, Dec. 1963, 38-62.

[5] J. Kim, F. Marti , and H. Blosser, Sixteenth International Conference Cyclotrons and Their Applications, AIP Conference Proceeding 600, May 2001, 324-326.

[6] E. D. Hudson and F. E. McDaniel, Fifth International Cyclotron Conference, London (Butterworth) 1969, 180-189.

[7] W. Kleeven, S. Lucas, S. Zaremba, W. Beechnon, D. Vandeplassche, M. Abs, P. Verbruggen, Y. Jongen, Sixteenth International Conference Cyclotrons and Their Applications, AIP Conference Proceeding 600, May 2001, 69-73.

[8] John J. Livingood, "Principles of Cyclic Particle Accelerators", D. V. Nostrand Company Inc., Princeton, New Jersey (1961) 219-266.

