AN OPTIMIZED MULTI-PARTICLE CENTRAL REGION FOR THE MICHIGAN STATE UNIVERSITY ISOCHRONOUS CYCLOTRON*

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ABSTRACT

Centered orbits are highly desirable in a cyclotron since problems with resonances are minimized and beam stability is greatly improved. The Michigan State University Cyclotron, as originally designed, produces accurately centered orbits in first harmonic operation and performs acceptably on second harmonic. Third harmonic operation, on the other hand, has never been adequate due to very large centering errors. The basic origin of these centering problems is the gap crossing resonance, and the effect of this resonance is highly sensitive to the angular width of the dees. Studies herein show that with a proper selection of both the central region geometry and the dee angle this centering problem can be effectively eliminated. Appropriate configurations have been worked out for harmonics H=1, 2, and 3, using 138°, 90°, and 60° dees respectively, and confirmed in electrolytic tank studies. To implement this new design, a major cyclotron improvement program has been initiated based on a system of interchangable dees. Basic features of this new design and computational results for the optimized geometries are discussed.

INTRODUCTION

In the Michigan State University Cyclotron, third harmonic operation (rf frequency three times the orbital frequency) is essential for producing the most important heavy ion beams, as well as very low energy protons and deuterons. Third harmonic operation has, however, thus far not been adequate for experimental needs due to large orbit centering errors. In view of this we decided some time ago to restudy and redesign the central region with the objective of improving third harmonic performance.

The advantages of centered orbits in a cyclotron have been widely discussed; problems with resonances are minimized, beam stability is greatly improved, and extraction is easier. The major problem in centering third harmonic orbits is the so-called gap crossing resonance[1] in which the acceleration process drives orbits off center as a result of a resonant interaction between the three sector magnet geometry and the basically two sector electric gap geometry. Moreover, when the orbits are off center, resultant rf phase deviations from gap to gap tend to drive the orbits still further off center. Since this latter effect increases with harmonic number, the centering problem is fundamentally more severe as the harmonic number increases.

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CENTERED ORBITS

Orbit centering problems can be easily studied with a computer program "Disport"[2] which calculates the displacement of an accelerated "closed" orbit from the static closed orbit with equivalent energy. Since it was expected that the gap crossing resonance could be reduced by changing the electric gap geometry, results were obtained from the Disport program for dee angles (angular width of the dee) from 60 to 180 degrees. Part of these results are shown in Fig. 1 where the magnitude of the center displacement

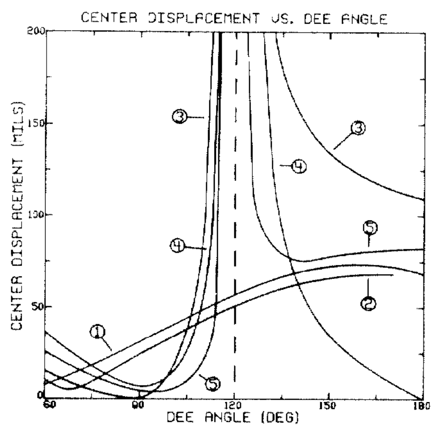

Fig. 1 Orbit center displacement vs. dee angle for 1) H=1 18 MeV protons, 2) H=2 9 MeV deuterons, 3) H=3 14 MeV C^{3+} ions, 4) H=3 14 MeV C^{3+} ions in a 4 sector magnet, and 5) H=3 14 MeV C^{3+} ions in a 3 sector magnet rotated by 30 degrees.

(in mils[3]) is plotted against the dee angle (in degrees) for one particular energy. The first harmonic curve (labeled 1) corresponds to 18 MeV protons, the second harmonic curve (labeled 2) to 9 MeV deuterons, and the third harmonic curve (labeled 3) to 14 MeV C^{3+} ions; in each case this energy is one-half the final energy of the ions at extraction. All curves in Fig. 1 represent an energy gain per turn $\Delta E=E/60$ at the given energy E, and the dee voltage is adjusted to make ΔE constant independent of dee angle. Under these conditions, the dee voltage would become infinite for third harmonic when the dee angle approaches 120 degrees, and for second harmonic when the dee angle approaches 180 degrees; consequently, the corresponding curves misbehave at these angles. Similar sets of curves obtained for different values of ΔE or of E indicate that the displacements are roughly proportional to $(\Delta E)/E$ at most energies.

In the case where the electric influence possesses two-fold symmetry, the contribution to the orbit center displacement from the gap crossing resonance should disappear in a four sector magnet geometry.[4] This is illustrated in the number 4 curve of Fig. 1 which is a Disport result with the three sector magnetic field replaced by an equivalent four sector field for the H=3 (third harmonic) C^{3+} ions. Minima near 90 and 180 degrees as well as reduced amplitude for dee angles greater than 120 degrees are clearly seen. The fact that the amplitude does not vanish can be attributed to the inherently asymmetric energy gain.

All of the above calculations assume that the two dees possess a reflection symmetry plane oriented so as to pass through the center of a magnetic field valley. For 180 degree dees this orientation minimizes the phase oscillation effect, due to the three sector magnetic field structure, while maximizing the coherent contribution to the displacement amplitude from the gap crossing resonance.[4] A change of this orientation by 30 degrees, on the other hand, places both gaps at points of equal magnetic field strength and hence minimizes this coherent contribution. This orientation effect was investigated by providing the Disport program with a three sector magnetic field which had been rotated by 30 degrees. These results are also presented in Fig. 1 (curve labeled 5) for comparison. The reduction in amplitude for dee angles greater than 90 degrees is clearly seen. This amplitude is, however, still several times larger than for dee angles in the neighborhood of 60 to 90 degrees.

DETAILED DESIGN

The final central region design procedure was as follows: 1) a family of accelerated closed orbits covering an energy range corresponding to the energy gain per turn was obtained with the Disport program near half extraction radius, 2) these orbits were tracked backward in time to find their origin using the general orbit code Goblin,[5] 3) since the source-puller geometry had previously been established[6] and the energy gain computed, the ray from the Goblin set which, at the first gap, matched the energy from the source-puller calculation was chosen as a tentative design ray and the source location determined by matching orbit parameters at this point, 4) next, an appropriate electrode configuration for this ray was designed and potentials were determined in an electrolytic tank model to an accuracy of about ±0.5%[7], 5) finally, a complete forward calculation in the measured electric and magnetic fields was performed with the orbit code Cyclone to either verify the design or determine corrections.

Examples of the designs obtained are presented with the corresponding design rays in Fig. 2; namely, an H=1 138 degree dee 210 turn geometry (original geometry in Fig. 2.1), an H=1 90 degree dee 300 turn geometry (Fig. 2.2), an H=2 90 degree dee 120 turn geometry (Fig. 2.3), and an H=3 60 degree dee 100 turn geometry (Fig. 2.4). To accomplish the implementation of these various designs, an interchangable central plug arrangement has been worked out along with a system of interchangable dees.

COMPUTER RESULTS

Results of the Cyclone program for the above designs are presented in the form of phase plots in Fig. 3.1 through 3.4

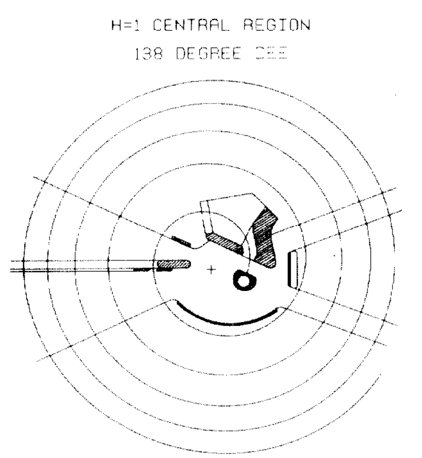

Fig. 2.1 H=1 138 degree dee 210 turn central region with 36 MeV proton design ray.

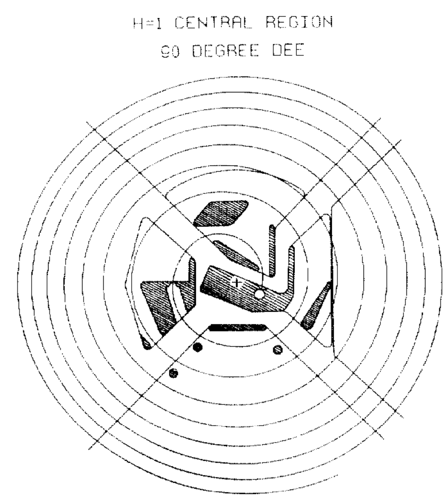

Fig. 2.2 H=1 90 degree dee 300 turn central region with 36 MeV proton design ray.

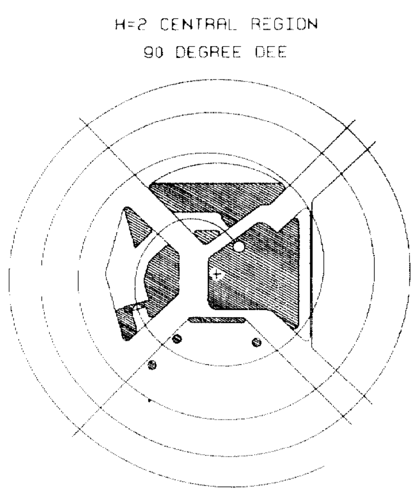

Fig. 2.3 H=2 90 degree dee 120 turn central region with 18 MeV deuteron design ray.

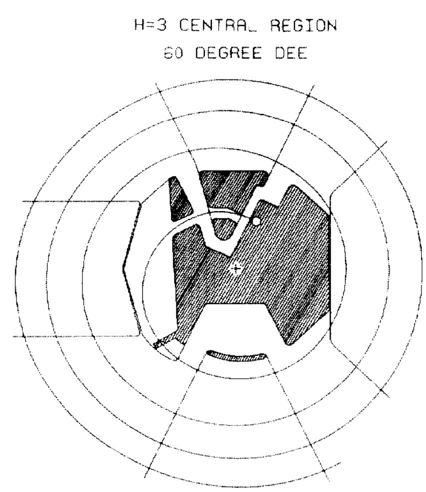

Fig. 2.4 H=3 60 degree dee 100 turn central region with 28 MeV C^{3+} design ray.

respectively. In each case, Px is plotted (ordinate) versus x (abscissa) for successive turns at θ=0 degrees, both quantities being expressed in mils $(Pr/(m_o\omega_o))$. Successive points are connected with a line to aid with identification. The approximate

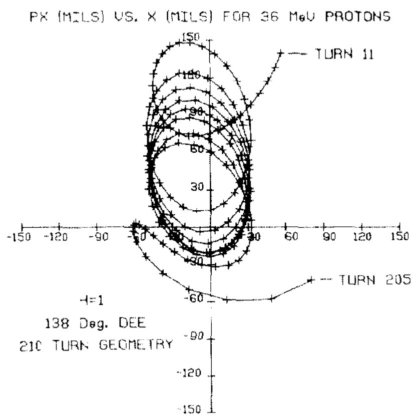

Fig. 3.1 H=1 138 degree dee 210 turn 36 MeV proton phase plot.

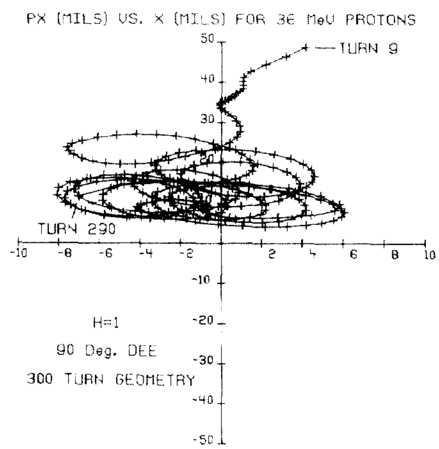

Fig. 3.2 H=1 90 degree dee 300 turn 36 MeV proton phase plot.

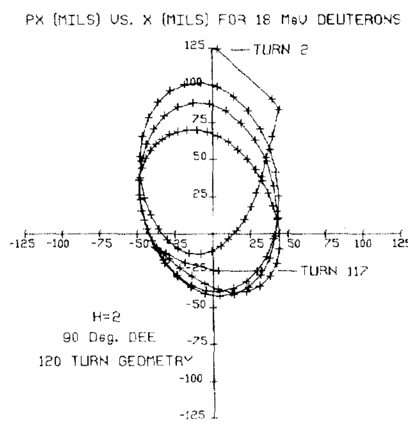

Fig. 3.3 H=2 90 degrees dee 120 turn 18 MeV deuteron phase plot.

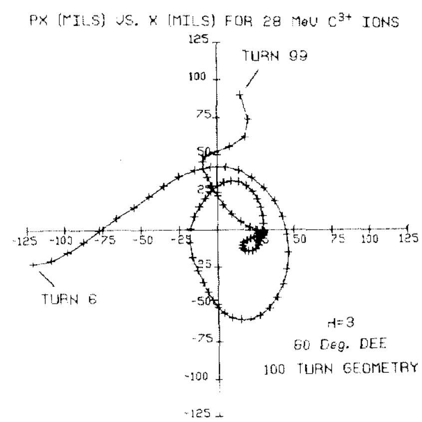

Fig. 3.4 H=3 60 degree dee 100 turn 28 MeV C^{3+} phase plot.

20 turn period corresponds to $\nu_r \sim 1.05$ over most of the acceleration range and the reversal of flow near extraction (most evident in Fig. 3.1 near turn 196) is brought about by passage through $\nu_r = 1$. When corrections are made for differing $(\Delta E)/E$, the center displacements (i.e. precession center) agree quite nicely with the results presented in Fig. 1.

As can be seen from the figure, the 90 degree H=1 geometry has a precession amplitude reduced by nearly an order of magnitude from the original 138 degree dee design, while the H=2 amplitude is comparable to that design. The new H=3 geometry has an amplitude of only a few mils over much of the acceleration range as compared to a best case amplitude of well over 200 mils for the 138 degree dee geometry on third harmonic. Furthermore, the sensitivity to small changes in starting conditions is not nearly as great for the 60 degree H=3 geometry as for the 138 degree dee geometry.

PHASE SELECTION

Phase Selection (limiting the beam phase width), which has been discussed elsewhere,[8] should be a consideration of any central region design. Briefly, this technique takes advantage of a phase dependent center displacement which can occur on the early turns to sharply limit the spread of the beam in rf phase. As this phase dependent center displacement precesses, it will present a maximum radial extent on some turn which is then the location of "maximum effectiveness" for a phase selecting slit. This phenomenon shows clearly in Fig. 4 which gives results from the Cyclone program for

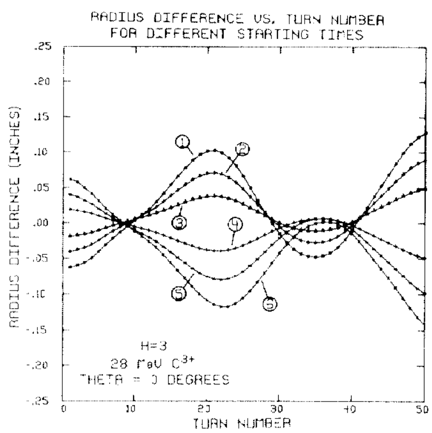

Fig. 4 Radius difference vs. turn number for different starting times (1-6 are -21, -19, -13, -11, and -9 rf degrees respectively) corresponding to $\Delta\tau=\pm6$, ±4, and ±2 rf degrees about the $\tau=-15$ degree design ray.

the H=3 C^{3+} beam previously discussed. Here we have plotted radial displacement (in inches) from the design ray (starting time $\tau_o=-15$ rf degrees) against turn number, at $\theta=0$ degrees, for a family of different starting times (-21, -19, -17, -13, -11, -9 rf degrees for the curves labeled 1-6 respectively, corresponding to $\Delta\tau=\pm6$, ±4, and ±2 rf degrees). It is evident that the phase width can be sensitively regulated by insertion of a slit near turn 21.

CONCLUSION

Results show that the gap crossing resonance can be effectively eliminated by choosing dee angles in the neighborhood of 60 to 90 degrees. An optimized multi-particle central region making use of this fact has been designed, and leads to a reduction of the third harmonic centering error from a present value of several hundred mils down to a few mils.

REFERENCES

1. M.M. Gordon, Nucl. Instr. and Methods, 18(19), 268(1962).
2. M.M. Gordon, IEEE Trans. Nucl. Sci., NS-13(4), 48(1966).
3. 1 millimeter = 39.37 mils.
4. R. Louis, Internal Report TRI-71-1, TRIUMF (1971).
5. T.I. Arnette, H.G. Blosser, M.M. Gordon, and D.A. Johnson, Nucl. Instr. and Methods, 18(19), 343(1962).
6. M.L. Mallory, Internal Report MSUCP-23, MSU(1966).
7. M. Reiser and J. Kopf, Internal Report MSUCP-19, MSU(1966).
8. H.G. Blosser, Proc. Fifth International Cyclotron Conference, (Oxford, AERE), Butterworths, 4, 257(1969).