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CROSSING THE ν_z = 1 RESONANCE IN THE IUCF MAIN STAGE*

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Abstract.-In the main stage of the Indiana University Cyclotron Facility, the axial focusing frequency is near the value 1.0 for protons having an energy between about 165 and 215 MeV. This resonance can lead to large axial deviations in the position of the beam if there is a lack of median plane symmetry.

By providing slightly different currents in the top and bottom coils of the four individual sector magnets, the beam is kept near the median plane, and moving the magnet yokes physically has not been necessary. The magnitude of the corrections necessary (a few percent) agrees roughly with those calculated from the observed axial beam excursions. Additional coils have also been provided to align the beam to the correct position and angle in the axial direction prior to extraction.

1. Introduction.-The Indiana University Cyclotron Facility (IUCF), became operational in 1975 and has accelerated a variety of light ions (up to ^{7}Li) over an energy range from 12 to 215 Q^2/A MeV. The accelerator system is made up of an external D.C. ion source pre-accelerator and two 4-sector variable energy isochronous cyclotrons, with transfer beam lines between them. The smaller cyclotron (~15 Q^2/A MeV) serves as an injector for the larger main stage machine. The accelerators and their performance have been previously reported[1,2,3].

Theoretical studies of the beam dynamics for a similar cyclotron, but having a sector angle of 38°,[4] and for the IUCF cyclotron (sector angle of 36°)[5] show that the most troublesome betatron oscillation resonance encountered is the ν_z = 1 resonance. This resonance is driven by small median plane field errors in the dipole magnets and is approached or crossed for all proton energies above 165 MeV. This paper describes the median plane field corrections needed to successfully accelerate high energy proton beams through this resonance, together with a comparison of the observed and calculated axial oscillation amplitudes.

2. Calculations and Predictions. To predict the axial excursions resulting from an error in the magnetic median plane, rays were traced through a measured main stage magnetic field that was isochronized to ±7° of RF phase. The initial beam starting conditions, as well as trim coil currents, RF dee voltages and dee phases were varied to assess their effect. For a field giving 200 MeV protons at extraction radius, and assuming an energy gain of 0.80 MeV per turn, the maximum axial oscillation amplitudes predicted were between 30 and 80 times the amplitude of the first harmonic of the median plane error. This is a few times larger than the predictions for an ideally isochronous field[4]. This difference may be due to the fact that ν_z does not go smoothly through the value 1.0 as radius increases in the actual cyclotron. Since the ideal relativistic radial field increase is only approximated by the strongly excited trim coils, the ν_z line oscillates with a period equal to the radial width of these coils, as is shown in figure 1. Similar wiggles due to the trim coils can be seen in the curves

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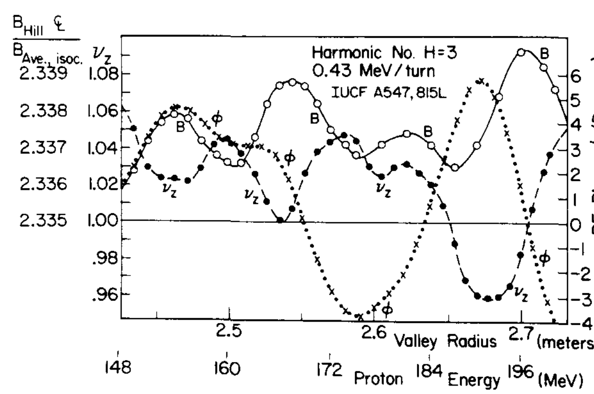

Fig. 1: "Mainstage field, ν_z and phase." The curve labeled B is the ratio of the hill field to the average isochronous field at that energy. The curve for ν_z rises at the largest radii since the field increases less rapidly with radius in order to facilitate extraction. The phase shown here is defined by $\phi = \omega_{RF}t - H\theta$, where ω_{RF} is 2π times the radio frequency and θ is the machine azimuth angle.

for the magnetic field and for the RF phase of the beam. The motion of the beam caused by this axial focusing when there is a median plane having a 0.11 mm amplitude first harmonic error is illustrated in figure 2. The only parameter changed between curves A, B and C was the Dee voltage; as the caption indicates, a small change in the energy gain per turn can cause a fairly large change in the axial beam excursions, although on the average the axial motion decreases as the Dee voltage increases. The curves labeled D and E show that an otherwise insignificant trim coil current change can lead to a sizable change in the coherent axial oscillation at large radii.

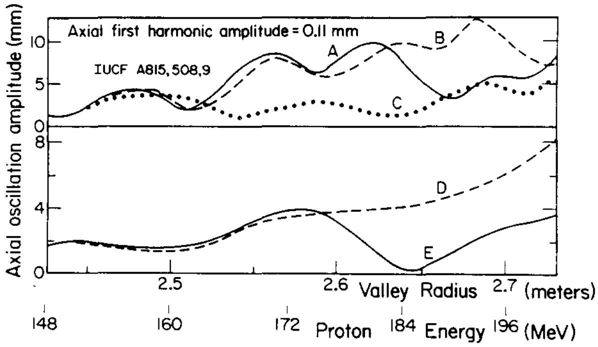

Fig. 2. "Axial excursions caused by a median plane error." The first three curves differ only in energy gain per turn: curve A, .37 MeV/turn; curve B, .43 MeV/turn; curve C, .61 MeV/turn. The last two curves, for which the energy gain was .96 MeV/turn, are the same except that the trim coils were set slightly differently; this caused a maximum RF phase difference or less than 6 degrees with H=4.

3. Initial Beam Diagnostic Measurements.- Beam disgnostic studies at IUCF have confirmed the results of these calculations. The internal beam of the large cyclotron is observed on a 25 mm square BeO scintillator mounted on the multi-purpose radial beam probe in the south valley, which has been previously described in the literature[6]. Large axial beam oscillations appear abruptly very near the extraction radius (2.73 m in the south valley) for 190 MeV protons, indicating that ν_z is close to 1 at this energy. Studies at a proton energy of 200 MeV made prior to correcting the median plane field errors observed that the axial ocillations began at a valley radius of 2.49 m and had an amplitude of over 10 mm. The orbit calculations described above show that this oscillation is consistent with a first harmonic median plane error of the order of 0.5 mm. The magnet gap at an equivalent valley radius of 2.67 m is constrained to 13 mm in magnet sectors C and D by vertical beam scrapers that protect the coils of the extraction D.C. kicker magnets. Transmission of this beam through the resonance was 10%, with the remainder of the beam appearing on the upper vertical beam scrapers in those magnet sectors. A plan view of the main stage cyclotron illustrating the locations of these devices is shown in figure 3. The problem of accelerating protons through the $\nu_z = 1$ resonance is aggravated by the temporary inability to operate the RF accelerating system on the 4th harmonic above 35 MHz. Proton energies above 195 MeV are presently accelerated on the 3rd harmonic where the effective accelerating voltage is 84% of the actual dee voltage. In this mode, the energy gain per turn is 270 keV at large radius and consequently over 1000 turns are required in the main cyclotron to accelerate protons to 200 MeV. In this case, ν_z is at or near 1.0 for about 120 turns. It was also observed that, like the transmission, beam stability at extraction was poor. Small main field, RF dee voltage or dee phase changes that normally do not affect the internal beam intensity cause large changes in the vertical position of the beam, causing more or less beam to be lost on the vertical scrapers. This, together with the relatively small turn separation (1.5 mm) at extraction caused by the low energy gain per turn, resulted in a transmission of beam from the inflection orbit through the extraction system of about 2 to 5%.

4. Median Plane Field Corrections.-Two kinds of median plane field corrections were applied to significantly reduce the axial oscillation amplitude of the high energy proton beams passing through the $\nu_z = 1$ resonance. First order corrections were made by selectively shunting small amounts of current away from either the top or bottom coils of individual magnet sectors. This was done empirically until the axial oscillation amplitude observed in the resonance region was reduced to about 3 to 4 mm. This allowed the acceleration of beam to the extraction radius with less than 10% losses on the vertical scraper slits. The configuration that produced the improvement was a reduction of the current in the upper coil of sector A of 1.9%, and in the lower coil of sector C of 0.4%,

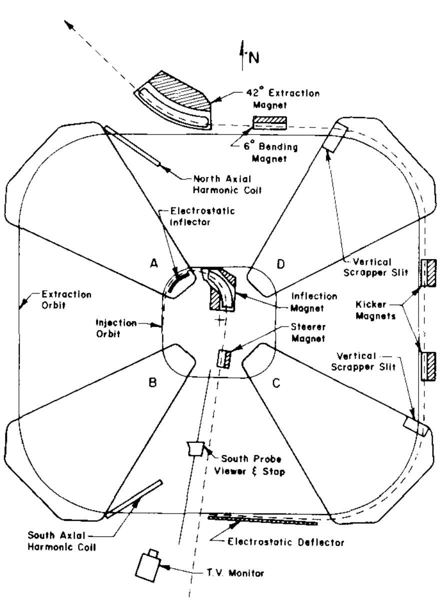

Figure 3

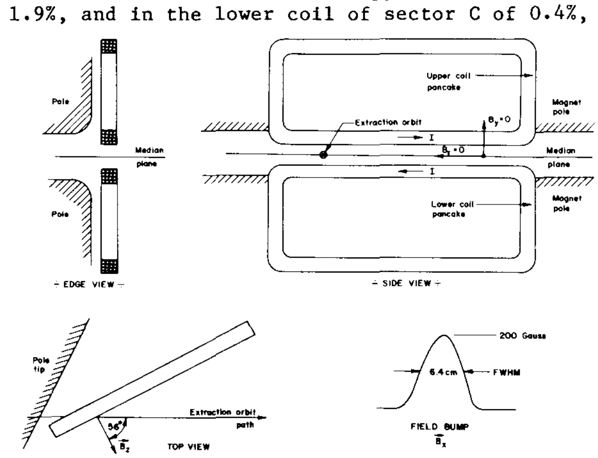

Figure 4

relative to the other sectors. This corresponds to a median plane 1st harmonic error amplitude change of about 0.5 mm. (This estimate could be off by up to a factor of two.) Fixed high power resistors, mounted on a water cooled base plate, are connected in parallel with these coils to reduce their current.

The effects of the $\nu_z = 1$ resonance were further reduced by the addition of two sets of axial harmonic coils, one set on the entrance edge of sector A in the north valley, and the other on the exit edge of sector B in the south valley, as shown in figure 3. The radial extent of these coils is from an effective valley centerline radius of 2.47 to 2.75 m, which completely spans the region of observed axial beam oscillations for proton energies up to 205 MeV.

The design of the axial harmonic coils is shown in figure 4. Two coil pancakes, constructed of twenty turns of 3 mm diameter hollow copper conductor, are mounted above and below the median plane and connected in series. The coils have a maximum current capability of 100 Amps and are mounted at an angle of 34 degrees to the beam path in the valley. At the maximum current of 100 Amps, the field bump produced by the coils, also shown in figure 4, is 1.27 kG cm parallel to the median plane at an angle of 56° degrees to the beam path. This produces a 0.5 milliradian axial deflection for 200 MeV protons, which is equivalent to a 0.3 mm first harmonic amplitude. The north coil has bipolar current capability while the south coil is unipolar.

Figure 5a

Figure 5b

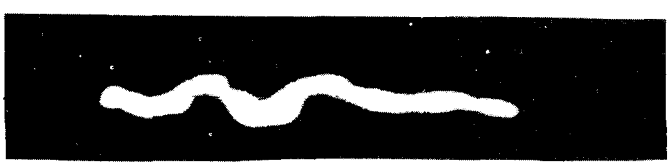

Figure 5c

5. <u>Results and discussions</u>. -The combination of these two median plane field correction measures routinely allows the axial oscillation amplitudes of 200 MeV protons accelerating through the $\nu_z = 1$ resonance region to be reduced to the order of 1 to 2 mm, as shown in figure 5. Figure 5a is a time exposure of a 200 MeV proton beam on the south probe BeO scintillator while being moved from 2.47 to 2.75 m, with the North and South harmonic coils adjusted to minimize the axial oscillation amplitude, which is of the order of the beam diameter, about 1.5 mm. Adjustment of the North and South harmonic coils by 40 Amps away from this solution produces a factor of 2 to 5 increase in the oscillation amplitude, as shown in figures 5b and c respectively. It is also observed that, as predicted by the calculations, small main field and trim coil changes can also affect the oscillation amplitude by as much as a factor of 3.

The final result of these median plane corrections is that now all of the beam inflected into the main cyclotron can be accelerated through the resonance to the extraction system, with no loss on the vertical scraper slits, up to an energy of 203 MeV. Extraction efficiencies as high as 90% have been achieved in spite of the small turn separation. The sign of the current in the harmonic coils is the same for all proton energies, with the current required increasing with energy until at 206 MeV, they are no longer strong enough to allow 100% transmission to extraction. This can be partially overcome by increasing the strength of the coils, but it is also probable that at the higher energies the $\nu_z = 1$ resonance effects become apparent at a smaller valley radius than covered by the present coils. Increasing the radial extent and current capacity of the axial harmonic coils are planned to remove all significant axial oscillations at energies up to 215 MeV.

6. <u>Acknowledgements</u>. The authors gratefully acknowledge the suggestion of Dr. R.E. Pollock on the calculation of the median plane error caused by unbalancing the current in the two coils of a sector magnet, and for his efforts and suggestions on how to reduce the effects of the resonance.

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