ORBIT STUDIES FOR THE INDIANA UNIVERSITY CYCLOTRON *

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ABSTRACT

The effects of a spiral isochronizing coil as an alternative to the use of a series of radial gradient coils for field isochronization of the Indiana University cyclotron are discussed. The calculations using measured magnetic fields indicate that such a coil yields improvement with regard to the betatron oscillation resonances encountered in this machine. Calculations involving the design of the inflector system and phase selection slits are also described.

INTRODUCTION

The betatron oscillation resonances intrinsic to our accelerator have been discussed in a previous publication.[1] The most troublesome of these is the error driven $\nu_z = 1$ resonance, which shows up strongly at proton energies between 170 and 200 MeV. Calculations show that accelerations through the resonance would be very difficult. In an attempt to raise the energy at which this resonance occurs, we are investigating the possible benefits of a spiral-shaped isochronizing trim coil.

SPIRAL ISOCHRONIZING COIL

The shape of the spiral was calculated to give an isochronous field for 200 MeV protons using a hard edge approximation of the magnetic fields (see figure 1). It was possible to design the coil such that the change in shape of the spiral for a range of proton final energies from 100 to 200 MeV was smaller than the physical width of the coil. The small amount of trimming required for isochronization can easily be accomplished with low power radial coils. A prototype set of spiral coils were constructed to fit in the 1/3 scale model magnet. The coils consisted of 6 turns of 1/4" o.d. water cooled copper tubing connected in series with the main coils. The ratio of the field inside the coil to that outside the coil was measured to be 1.290.

The magnetic fields of the spiral coil in the model magnet were measured on a .25" (0.2 magnet gap) by .25" rectangular grid. Lagrangian interpolation was used to convert the field data to polar coordinates for use by the orbit dynamics programs. Because radial dimensions of the main cyclotron sectors do not scale by the same factor as the gap of the main cyclotron relative to that of of the model magnet is was necessary to scale the gap to 4.0" rather

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than to the actual 3.0" gap of the main magnets. The result of this was to soften the field edges and lower the calculated vertical betatron oscillation frequencies.

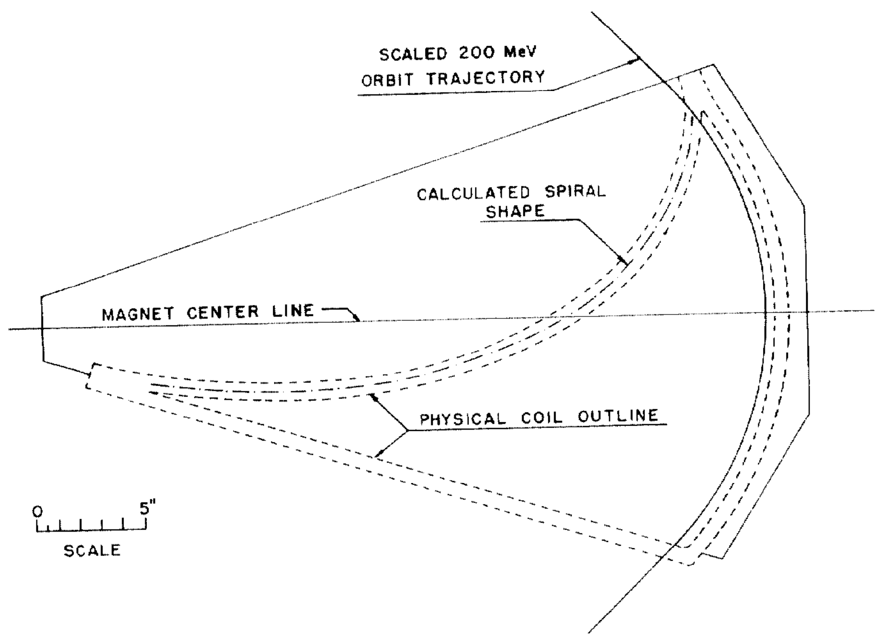

Figure 1. Layout of the prototype spiral coil design.

The raw data was modified to improve isochronism by a 15% reduction in the difference between the field inside the spiral coil and the field outside the coil. With this adjustment, equilibrium orbit times were constant to within 0.1% over the energy range 120 MeV to 200 MeV.

Figures 2 and 3 show the radial and vertical betatron oscillation frequencies respectively, as a function of energy for the spiral coil. For purposes of comparison the figures show the frequencies calculated assuming idealized radial gradient coils and a 4.0" magnet gap. The radial betatron oscillation frequencies do not show any significant differences except above 192.5 MeV where artifacts introduced by interpolating near the boundaries of the measured field make the calculation unreliable. No serious resonances are encountered for the radial motion. The $\nu_r = 4/3$ (nonlinear, intrinsic) and $\nu_r = 3/2$ (linear, imperfection) resonances have been studied in detail for the radial coils and found to be innocuous under reasonable acceleration conditions. The properties of these resonances for the spiral coil geometry appear to be very similar to the radial coil case.

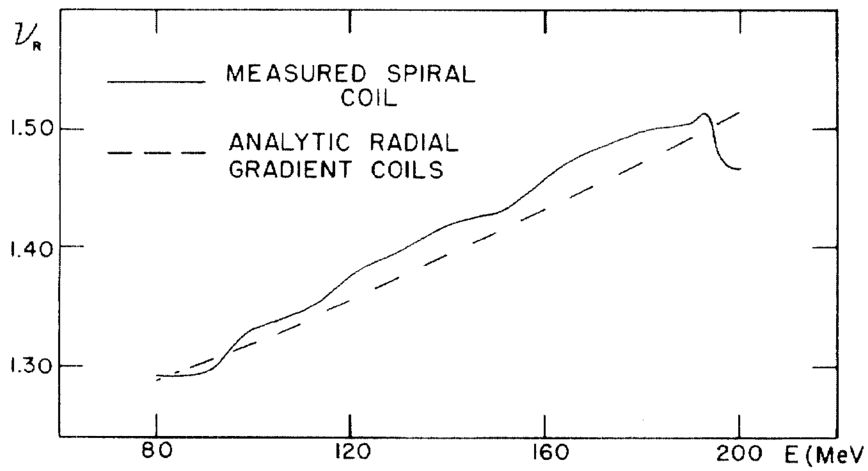

Figure 2. Radial betatron oscillation frequencies calculated using measured spiral coil fields.

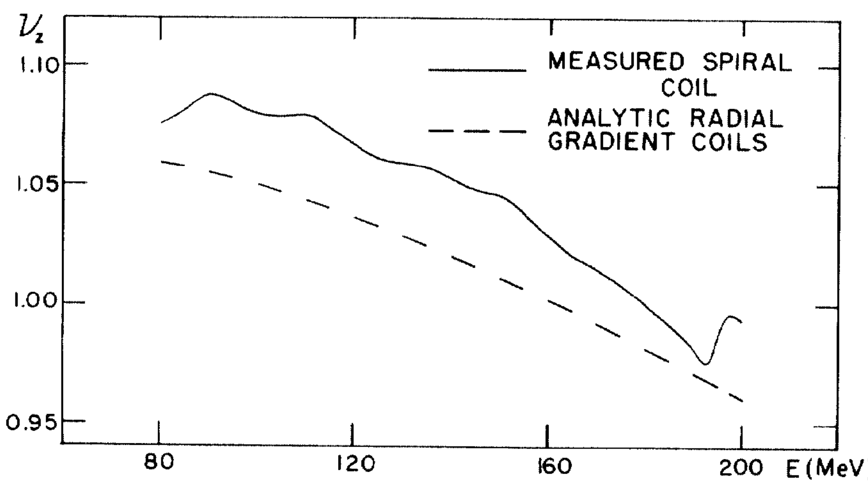

Figure 3. Vertical betatron oscillation frequencies calculated using the measured spiral coil fields.

Figure 3 shows that the energy at which $\nu_z = 1$ is approximately 20 MeV higher for the spiral coil than for the radial coils. The rise in ν_z above 192.5 is also a result of the interpolation problems mentioned earlier. The effect of performing the radial coil calculations with a 4.0" gap rather than the actual 3.0" gap of the main cyclotron magnet was to reduce the energy at which ν_z passed through unity by 30 MeV. A similar shift will occur in the spiral coil case, so that the energy at which this resonance occurs would be approximately 210 MeV.

For both cases, calculations of accelerated motion with an energy gain of 750 keV/turn indicated that the effects of the resonance begin to be seen approximately 10 to 15 MeV below the resonance energy if vertical driving terms are included. The rate of growth of the vertical oscillation amplitude is nearly the same in both cases. Calculations thus far have not indicated any effects on beam quality that would preclude further consideration of a spiral coil design.

Magnetic field measurements of the full size magnet[2] show a pronounced droop in the field at both ends of the magnet at high excitations. Consequently a set of radial coils capable of substantial field correction are necessary even for non-relativistic particles. Studies are being carried out to determine whether it is economically feasible to use a system encompassing both types of coil subject to the spatial limitations imposed by the 3.0" magnet gap. The spiral coil design will require appreciably more power than would the alternate radial coil design. Further investigation of these considerations as well as more detailed information about the main magnet fields are necessary before a decision about building a full scale prototype can be made. Additional studies of the effects of the spiral coil on beam quality are planned for the near future.

DETERMINATION OF INJECTION COORDINATES

In order to facilitate single turn extraction from the injector cyclotron, minimization of the amplitude of coherent radial betatron oscillation is desirable at extraction radius. By performing time reversed simulated acceleration, starting with an oscillation amplitude of zero, it is possible to determine the injection coordinates leading to a minimum oscillation amplitude at extraction radius. Such calculations have been carried out yielding optimal coordinates for the exit of the electrostatic inflector. Determination of the coordinates of the entrance to the inflector has been made by ray tracing through the fringe fields of the injector valley and matching those rays to the rays emanating from the last magnetic element prior to the cyclotron.

PHASE SELECTION SLITS

At the present time, a dc beam is injected into the first cyclotron stage. In order to make detailed studies of the properties of the accelerated beam, it is necessary to provide a method of selecting the phase of particles to be accelerated. Calculations have been carried out to determine the radial position on the injection valley center line for particles injected with different starting phases. The results of these calculations are shown in Figure 4. A slit system has been built to intercept particles outside the desired phase window after 1.5 revolutions in the machine. It can be seen from the figure that a single set of slits is not sufficient to select a unique phase group. Consequently a second set of slits at a larger radius has been included in the design to eliminate the unwanted phase group.

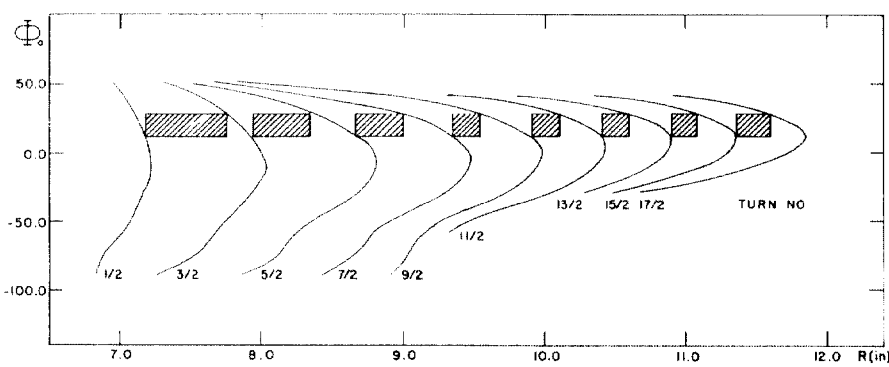

Figure 4. Radial position as a function of initial phase after n revolutions in the injector cyclotron. The shaded regions are those through which particles within ± 8° of the optimal injection phase do not pass.

ACKNOWLEDGMENTS

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REFERENCES

1. B. M. Bardin et al., IEEE Trans. Nucl. Sci. NS-16, 311 (1971).

2. R. E. Pollock, paper D1 presented at this conference.