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FIELD MAPPING RESULTS OF THE IUCF 200 MEV CYCLOTRON*

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Introduction

The Indiana University 200 MeV Isochronous Cyclotron is a separated sector (N = 4) machine whose design goals include the acceleration of both protons and heavy ions over a variable energy range up to a maximum energy of approximately 220 Z^2/A MeV. The large range in energy and particle mass requires that the radial profile of the magnetic fields be adjustable to match the relativistic mass increase of the accelerated particle. For the acceleration of protons to 200 MeV for example, an increase in the field from injection to extraction radius of about 22% is needed, whereas for heavier ions the field profile must rise approximately 2%.

The cyclotron magnet sectors have poletips without spiral and uniform gaps, each spanning an angular width of 36°. The four magnets are symmetrically positioned such that their effective field boundaries intersect at the machine center. The configuration is intrinsicaly almost isochronous[1] and allows a conceptualy simple design for the isochronization coils. We have chosen a set of 21 radial gradiant coils fabricated from .5 inch thick aluminum sheet and varying in radial width. The coil boundaries conform to the hard edge equilibrium orbit shape. The coil widths were determined from an iterated series of calculations based upon one-dimensional hill center-line magnetic field measurements of a prototype radial gradient coil set. The set could produce gradients about one half as large as the ultimate requirement. The number of coils and their widths were chosen to hold the maximum current in the coils below 1000 Amps with smooth changes from coil to coil, while keeping the resulting beam phase excursions during acceleration past any given coil to less than ±1° in a 300 turn pattern.

A set of gradient coils having the optimal geometry was fabricated for use in the field measurement program in one of the cyclotron sectors, with main magnet and trim coil excitations up to their full design values. An extensive series of two-dimensional field maps was obtained to verify the design of the coil set and to provide the data necessary to investigate the orbit dynamic properties of the cyclotron . The mapping procedure and orbit dynamic properties of the machine are the subject of two other papers presented in this journal.[2,3] This paper describes the results of the field data as they pertain to the trim coil design, and in particular, discusses those aspects of the fields other than the predictable relativistic shape changes which influence the coil design in this type of cyclotron. Some results illustrating the range of isochronous field profiles made available by the coil set are also presented.

Main Magnet Properties

Assuming the ideal case of a uniform hard-edged field in a cyclotron sector of infinite permeability, the trim coil design parameters (number, radial widths, resulting phase histories, etc.) may be readily determined and optimized for the various ions and energies considered. The radial linear current densities of the coils adjusted for isochronism then give a field which increases with the γ of the particle.[1] The complexity in the design of the isochronous coil configurations arises from the departures of the real fields from the simple model. Some of the basic properties of our main magnetic fields have been previously described.[4] Two of the dominant effects are reproduced in figure 1. Figure 1a gives the B vs I curve for magnet coil currents up to 1300 Amps. The magnet begins to saturate at 600 Amps, as is reflected in the dB/dI curve. The H field (30 Oersted Max) of

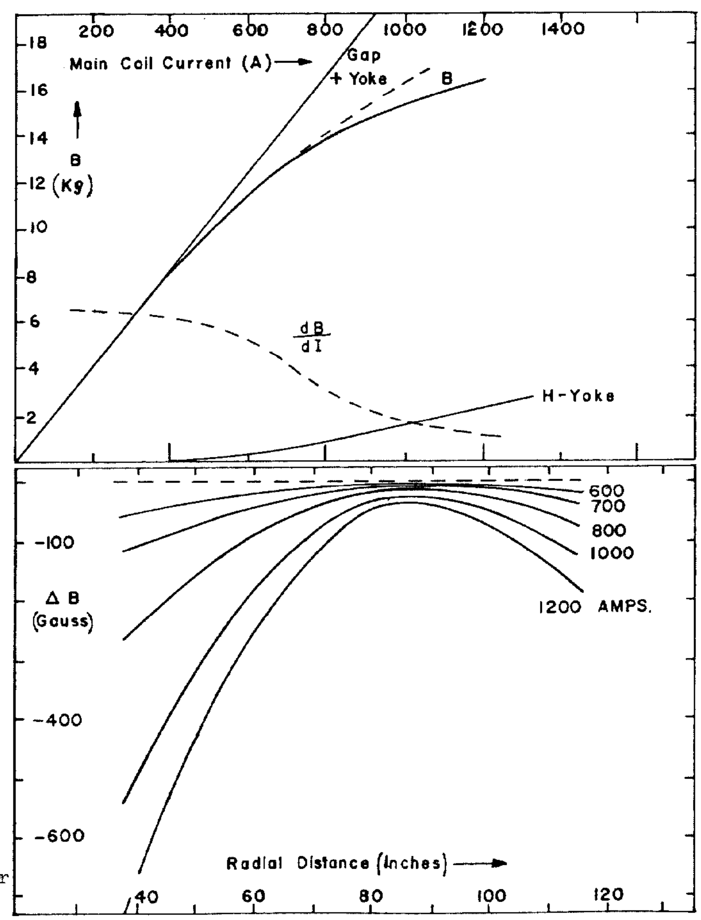

Figure 1a and 1b

the return yoke was measured and its contribution plus that of the gap field does not account for the B-I curve. This is because of an appreciable contribution from the saturation of the pole tips beginning at about 600 Amps. The resulting radial field profiles are shown as a function of magnet excitations in figure 1b. The gap field is uniform at currents up to 500 Amps and shows an increasing convex curvature as the pole tips saturate. The curvature is roughly parabolic and increase almost linearly

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with current above 600 Amps. This pole tip saturaton is found to be the largest single purturbation on the trim coil configuration. The coil currents required to flatten the convex curvature of the field are comparable to those needed for full energy proton isochronization. Figure 4 of reference 4 is based on an overly pessimistic extrapolation from this data and is superceded by the results presented below.

Trim Coil Effectiveness

The final coil configuration was affected by two other less significant effects related to magnet saturation. First, the effectiveness (strength and field profile) of the trim coils will vary with their radial position in the magnet and with magnet excitation. The measured effects are shown in figure 2. Figure 2a is a plot of the incremental field contribution of a typical trim coil at several magnet excitations, and is the difference of the magnetic field with the coil excited and the base field with no coils excited. The field step is reduced by only 6% at the highest saturation level, but it is superimposed on a radially decreasing field whose slope increases with magnet saturation until at high fields, the overall coil effectiveness is reduced by 30%. This effect was previously observed in a study of a similar model magnet and trim coil design at Oak Ridge[5] and may be explained by the finite reluctance of the pole tips and return yoke relative to the narrow gap. The increased reluctance of the yoke at high excitation causes a portion of the coils total flux to return through the magnet gap.

A second trim coil induced saturation effect observed is shown in figure 2b. Here, a full set of 21 coils was excited to produce approximately isochronous fields for protons of several energies. Selected trim coils at each isochronous field were individually de-excited. This figure is a plot of the difference fields for the several isochronous profiles, and illustrates the change in effectiveness of one coil when all the other coils are excited. Again, the field step height of the coil is only slightly reduced at high saturation levels. However, in this case the step is superimposed on a radially decreasing field whose slope increases with radius as well as with magnet excitation, resulting in a more substantial reduction of the trim coil effectiveness at large radii. The effectiveness of each of the 21 coils in the set was measured at several nearly isochronous proton fields. The radial profiles (one-dimensional sections along a hill centerline) of the measurements for the 223 MeV proton field are shown in figure 2C. The profiles are plotted on a common scale and the changing offset of each profile is a real effect. The observed decrease in trim coil effectiveness is interpreted as a result of an increase in pole tip saturation with radius induced by the radially increasing isochronous field. This would also explain the slight reduction of the coil step height with coil number.

Current Density Prediction with Central Shim

Figure 3 summarizes the predicted linear current densities required to isochronize the field for various energy ions. The curve labeled 1 is the predicted radial current density for an isochronous magnetic field for 220 MeV protons with the simplest assumpsions and no corrections. This should be contrasted with Curve 2 which is the 220 MeV isochronous proton prediction where the magnet saturation effects discussed above have been included. The orbit frequency at the injection radius is seen to be about 3% low, and is not due to an incorrect field in the

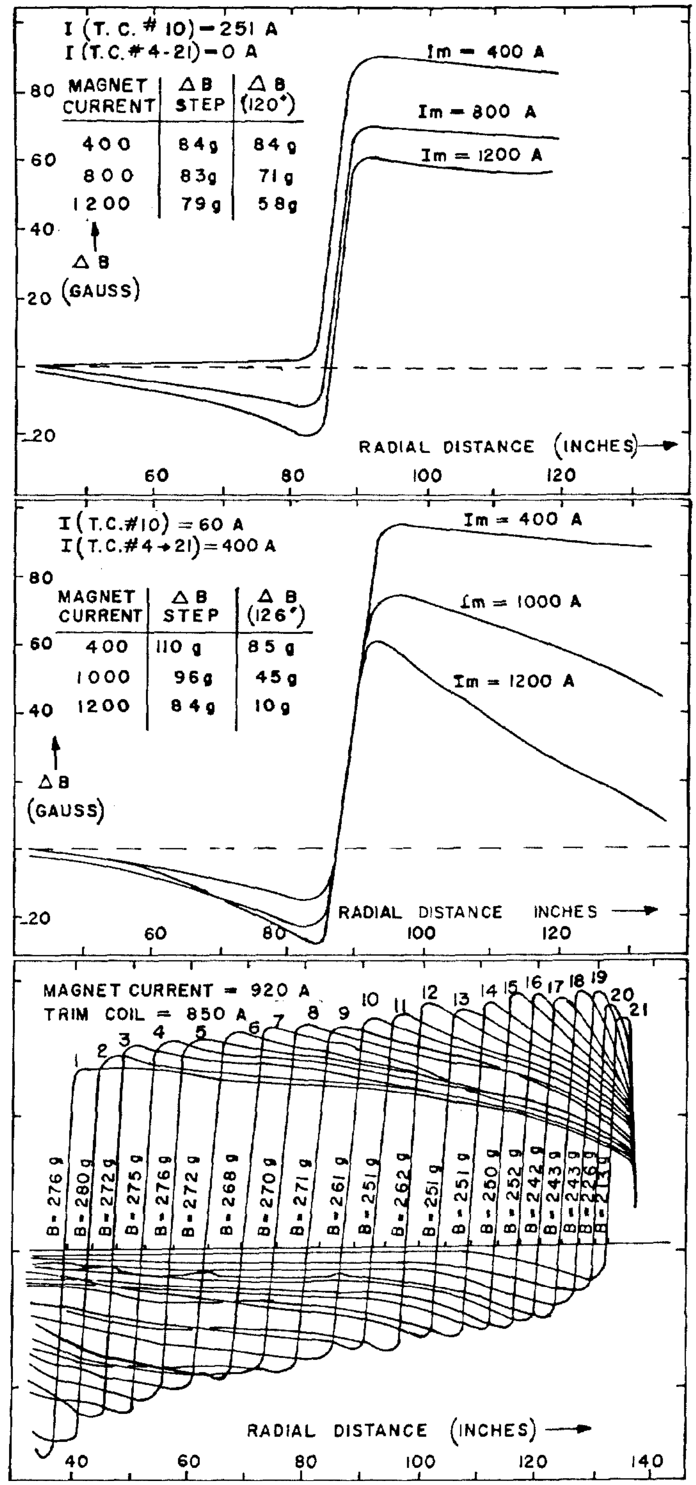

Figure 2a, b & c

sector gap. An additional contribution is the result of a superposition of the fringe fields of adjacent magnets at small radii. These fields add in the valley to give a maximum field of 2.4% of the gap field. The reduced gap field and increased valley fields combine to increase the orbit path length, requiring a field increase over the first few inches of field. Because the departure from isochronism scales with main field, the problem was corrected by the addition of a set of .0[illegible]2 inch thick shaped iron magnet shims to the pole tips. The shims reduce the field deficiency to about 0.[illegible]%, which may easily be corrected with the trim coils. The isochronous radial current density with these shims is given by the curve labeled 3. Curve 4 is the corresponding linear current density needed to produce an isochronous high energy heavy ion field, and is essentially the current density needed to flatten the convex curvature of the saturated magnet. Curves 3 and 4 were used to determine the parameters of the trim coil assembly.

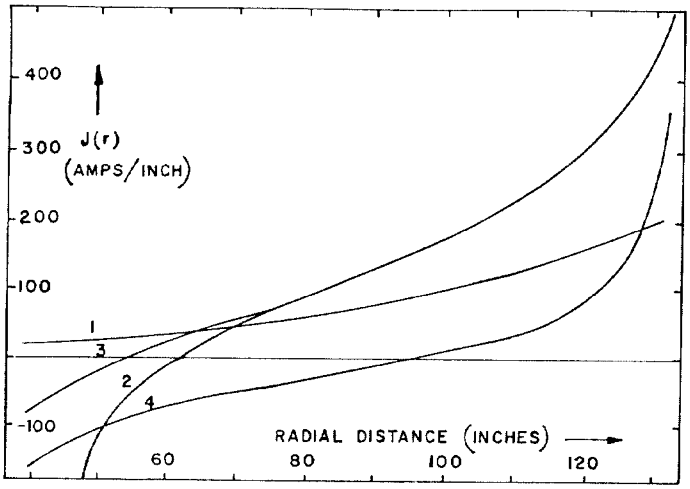

Figure 3

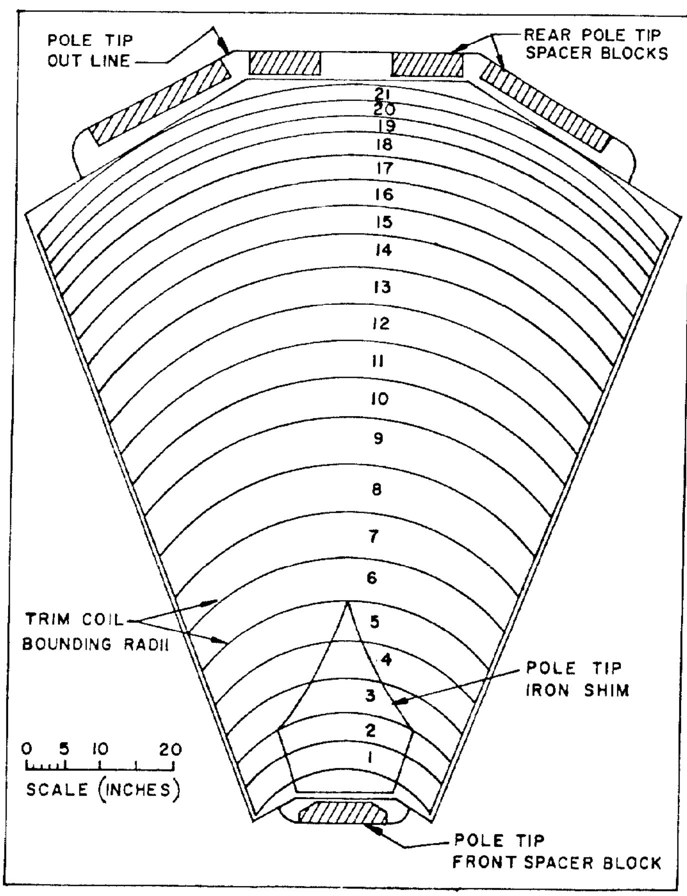

Figure 4

Coil Design and Typical Profiles

A plain view of the trim coil set and pole tip shims is given in figure 4. The trim coil radial widths vary approximately with the inverse of the absolute field correction required for the high energy protons. Table 1 lists the trim coil radial widths, along with the isochronous currents as ultimately predicted by full mapping with iterative adjustments for 225 MeV protons and for 53 MeV $^4He^+$. The latter current set is also a good approximation for the acceleration of heavier ions having higher charge states. The maximum design current for the trim coils was 1200 amps. All of the trim coils must return their current around the back of the pole tip for mechanical reasons. The result of this return path is that the saturation parabolic profile shown in figure 1b is flattened by reducing the high part rather than raising the rest. As a consequence the maximum energy of operation turns out to be just below $220Q^2/A$ for the heaviest ions, rising to about $225Q^2/A$ for $^3He^{++}$ and protons.

Table I

Trim Coil Number	Radial Width (Inches)	I (Amps) For 225 MeV $^1H^+$	I(Amps) For 53, 39MeV $^4He^+$
1	4.00	-471.6	-1125.7
2	4.28	-271.6	- 925.7
3	4.65	- [illegible]7.0	- [illegible]
4.	5.10	- 31.0	- 709.1
5	5.72	121.6	- [illegible]
6	5.95	246.2	- 513.5
7	6.25	411.[illegible]	- 390.2
8	6.45	55[illegible].0	- [illegible]
9	[illegible].13	[illegible].2	- [illegible]
10	5.72	754.5	- [illegible]
11	5.40	843.1	13.1
12	5.11	927.[illegible]	[illegible]0.3
13	4.[illegible]5	995.2	111.1
14	4.65	1074.4	150.5
15	4.11	105[illegible].1	19[illegible].2
16	3.70	1053.1	214.[illegible]
17	3.35	1074.2	254.[illegible]
18	3.03	105[illegible].4	274.5
19	2.72	10[illegible]3.1	313.3
20	2.35	1027.7	318.4
21	1.9[illegible]	1027.7	315.4

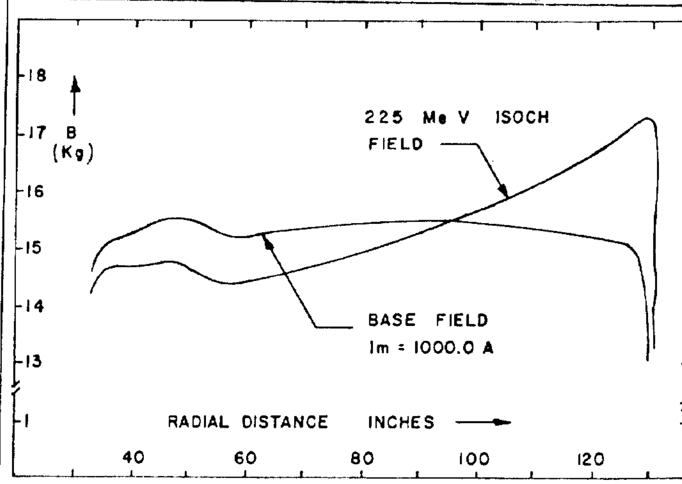

Figure [illegible]a

Figure 5 illustrates the range of isochronous field profiles made available by the trim coil assemblies. Figure 5a shows the isochronous radial field for 225 MeV protons and the corresponding saturated base field of the magnet. A subtraction of these two profiles gives the field contribution of the trim coil set. Figure 5b is a plot of the isochronous radial profiles for the various maximum energy ions we will be able to accelerate. The profiles for the protons and for the $^4He^+$ given in this figure were obtained with the currents quoted in table I. The absolute scale of each curve has been adjusted for ease of comparison .

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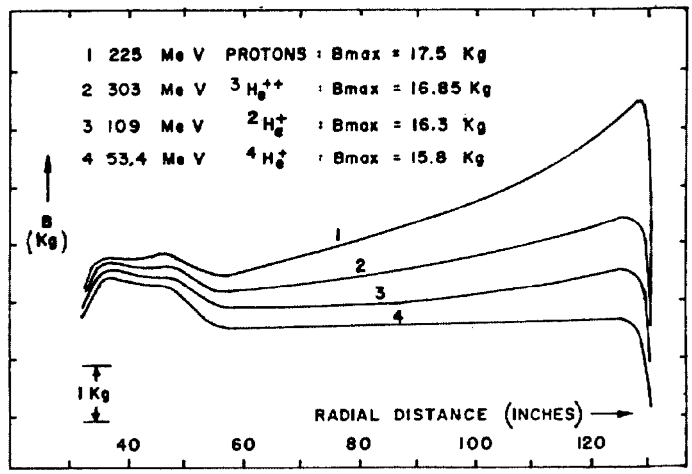

Figure 5 b