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INFLUENCE OF MAGNETIC ELEMENTS ON AN ISOCHRONOUS CYCLOTRON FIELD

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Summary

One of the main advantages of using magnetic field measuring equipment supported external to the cyclotron magnet is the ability to map the field before and after installation of the extraction elements. Field measurements with extraction elements in place are usually precluded by the size of internally mounted field mapping equipment (e.g., a wheel). The magnetic field of the NRL-isochronous cyclotron was measured to full radius before installation of extraction elements. After installation the influence on the magnetic field of each extraction element energized separately was measured. These measurements were used to determine the perturbation of the extraction channel on the isochronous field. Ion orbit calculations were then used to determine necessary field corrections to accelerate ions to the extraction radius. These field corrections are translated to currents needed in each of the various coils via a least squares fitting program.

Introduction

The use of magnetic channels in the extraction system of an isochronous cyclotron affords several advantages over electrostatic deflection alone. These advantages include a reduced azimuthal extent of the electrostatic deflector or "peeler" resulting in simple mechanical linkages; smaller operating voltages or gradients in the electrostatic channel which lessens the problem of electrical breakdown; large deflection angles achievable with magnetic elements; and ease in guiding the ions of greatly different energy along the extraction orbit by close control of the magnetic field along the trajectory. However, in realizing the advantages of magnetic extraction elements, there is always the danger that either the iron in the various components, or the leakage field of the current carrying coils, will perturb the magnetic field in the region of particle acceleration. This perturbation can result in field harmonics which introduce beam instabilities as well as destroying the desired field necessary for isochronism.

The object of this paper is to present data determining the extent of the perturbations produced by the extraction elements of the NRL cyclotron and show how these perturbations can be adequately corrected. The correction field is produced by compensating coils associated with the extraction channel, and by use of various harmonic and trimming coils located in the acceleration region of the cyclotron.

Extraction Channel

The various elements of the extraction channel closely parallel those of the Oak Ridge Cyclotron (ORIC).[1] The initial deflection of the accelerated beam is produced by an electrostatic deflector having an azimuthal extent of 55°. The nominal radial position of the septum is 29 inches which is 2 inches inside the $\nu_r = 1$ turn-over field and 2-1/2 inches inside the $\nu_r = 2\nu_z$ coupling resonance. The electrostatic deflector is immediately followed by an iron free magnetic channel (coax channel) 8.7 inches long. This channel depresses the confining magnetic field by 4 kilogauss along the extraction orbit. After the "coax" channel there is another magnetic deflector with an azimuthal extent of 60°. Field reductions up to 6 kilogauss are realized in this channel by the inclusion of an iron yoke (iron-channel). Finally, the beam is steered before leaving the cyclotron by a horizontal guiding magnet located in the fringe field (fringe-field-concentrator). Proper combinations of the currents in these last two elements and the position of the iron channel gives beam centering and directional control to the beam transport system. The geometrical configuration of these elements is shown schematically in Figure 1.

Magnetic Field Measuring Equipment

Accumulating and processing the large quantity of data necessary for an understanding of the cyclotron field requires a high degree of automation. Thus, an automatic tape controlled data logging assembly was selected that together with subsequent computer processing of the output provided the desired field information with a minimum of personnel attention.

A Hall-effect transducer was selected for measuring the magnetic field because of its reliability, usability in high gradients, and the ease of rapidly recording the Hall-voltage with a digital voltmeter (DVM).

Various techniques have been used to position Hall-plate apparatus. The most common is a polar device; that is, a wheel which selects an angular position of a radial arm which transports the Hall-plate in radial increments. This device has the disadvantage that it is not possible to use this device to measure the magnetic field when the extraction apparatus is in place. Moreover, a polar positioning device with fixed positioning increments has an undesirable distribution in its density of measurements which overemphasizes the central-field region, and takes inadequate measurements near the extraction radius, where the field gradients are largest.

At NRL the Hall-plate is mounted on one end of a nonmetallic boom, 116 inches long, and the other end of the boom is mounted to the saddle of a tape-controlled probe-positioning table[2] which occupies a space adjacent to the cyclotron magnet.

The cyclotron magnet, boom, and positioning table are shown in Figure 2.

The table is capable of performing independent and simultaneous motions in the x and y directions. The mechanism consists of a movable carriage (y axis) on which a saddle (x axis) is mounted. The entire assembly is mounted on a stationary base. The range of travel of both carriage and saddle is 81 inches. Lead screws with anti-backlash, ball-nut assemblies are used to convert the rotary motion of the drive motors to linear positioning motion. Direct-drive torque motors coupled to the lead screws provide a programmed velocity profile. Perkin-Elmer shaft encoders are used in conjunction with gear boxes to provide absolute digital feedback of carriage and saddle position. Stepping motors are used for final positioning, and clutches are used for locking of the table after agreement is obtained between the shaft encoders and the command position. This arrangement gives a positioning precision of ±0.002 inches. A detailed description of this apparatus has been given elsewhere.[3]

Results of Field Measurements

In order to ascertain the influence of the various extraction elements on the acceleration field, it is first necessary to know the detailed behavior of the unperturbed field. Accordingly, more than half a million data points were accumulated for the various current combinations needed to achieve an isochronous field. Since this paper is primarily concerned with the extraction channel, the analysis and subsequent use of the basic field data will be reported elsewhere. The parasitic first harmonics introduced by the iron and currents in the extraction channel can be compensated for by the contribution of the harmonic coils. These nine pairs of coils, located at three radii, in the three valleys, provide a means of close control as to amplitude and phase of the correction harmonic.

The currents in the three coils located at the same radius, but separated by 120°, are given by:

$$i_A = F + H \cos \Phi$$

$$i_B = F + H \cos (\Phi - 120°)$$

$$i_C = F + H \cos (\Phi - 240°)$$

where F, H, and Φ are helipot dial settings controlled by the operator. The harmonic coils are to a very good approximation air-core, thus the magnetic field generated is proportional to the current carried in a given coil. It is convenient to Fourier decompose the magnetic field into an average field and the harmonic contributions. For the contribution of each coil we thus have:

$$B^A(r,\theta) = i_A \left\{ Co(r) + \sum_{n=1} C_n \cos n(\theta - \varphi_n) \right\}$$

$$B^B(r,\theta) = i_B \left\{ Co(r) + \sum_{n=1} C_n \cos n[\theta - (\varphi_n + 120°)] \right\}$$

$$B^C(r,\theta) = i_C \left\{ Co(r) + \sum_{n=1} C_n \cos n[\theta - (\varphi_n + 240°)] \right\}$$

In this expression C_n is the amplitude of the nth harmonic in units of gauss/ampere. After substituting for the currents in the field equations, we add the contributions of the three coils. After some lengthly algebra we obtain for the contribution of the harmonic coils

$$\begin{aligned} B(r,\theta) = {} & 3F\ Co(r) \\ & + F \sum_{n=1} C_n \cos n(\alpha_n - 2\pi/3)(1 + 2\cos 2n\pi/3) \\ & + H/2 \sum_{n=1} C_n \cos (n\alpha_n + \Phi)[1 + 2\cos 2\pi(n+1)/3] \\ & + H/2 \sum_{n=1} C_n \cos (n\alpha_n - \Phi)[1 + 2\cos 2\pi(n-1)/3] \end{aligned}$$

where $\alpha_n = \theta - \varphi_n$.

Writing out the first few terms:

n	$B(r,\theta)$
0	$3F\ Co(r)$
1	$3/2\ H\ C_1 \cos (\theta - \varphi_1 - \Phi)$
2	$3/2\ H\ C_2 \cos [2(\theta - \varphi_2) + \Phi]$
3	$3F\ C_3 \cos [3(\theta - \varphi_3)]$

We see that the contribution of the harmonic coils to the first harmonic can be controlled in amplitude (H) and phase (Φ) as desired. The amplitude and change in phase by changing Φ is illustrated in Figures 3 and 4.

Fringe Field Concentrator

The final steering of the accelerated beam as it leaves the cyclotron is accomplished by the FFC. This magnet consists of a small quantity of iron for pole pieces and increases the field through the decreased reluctance. Fine control of this field is accomplished by varying the current in coils wrapped around the pole pieces. Since there is no yoke to contain the return field it can perturb the main field in the region of acceleration. This perturbation was determined by measurements before and after installation of the FFC, with various excitations of the main field. Field maps were obtained with 0,100 and 200 amperes in the FFC coils. Operating experience at the ORIC indicates that additional iron above and below the FFC allows more freedom in selecting the extraction orbit. Consequently, some iron was added and the measurements were repeated. A summary of these results for the main coil excited with 1500 amperes shown in Table 1.

Iron Channel

The major field reduction along the extraction orbit is accomplished by the iron channel. This

TABLE 1

The contribution to the amplitude of the first harmonic due to different currents in the fringe field concentrator.

FIRST HARMONIC AMPLITUDE IN GAUSS

RADIUS (INCHES)	ORIGINAL POLE PIECE			MODIFIED POLE PIECE		
	FFC 0 Amp	FFC 100 Amp	FFC 200 Amp	FFC 0 Amp	FFC 100 Amp	FFC 200 Amp
1	1.3	1.4	1.4	.6	.5	.3
2	1.5	1.4	1.5	.4	.3	.6
3	.6	.5	.6	.9	.9	1.1
4	.3	.3	.7	1.0	.2	.9
5	1.6	1.5	1.6	.7	1.2	.3
6	.9	.8	.5	.4	.6	1.4
7	.5	.9	.6	2.3	2.4	2.4
8	1.0	.6	.8	2.1	1.5	2.3
9	1.4	1.2	2.2	1.9	2.0	2.4
10	1.2	1.0	1.7	3.3	3.7	4.5
11	.0	.9	1.9	3.5	4.6	4.9
12	.6	1.1	1.2	5.0	5.8	7.0
13	1.2	.9	1.4	5.7	7.2	7.6
14	.8	.6	1.6	3.9	5.3	5.7
15	1.0	.8	2.2	5.3	6.3	7.0
16	.5	1.1	2.0	4.4	5.3	6.1
17	1.1	1.5	2.5	4.4	6.0	7.8
18	1.5	2.4	3.0	5.3	6.3	7.1
19	1.6	2.3	3.4	8.8	9.9	11.0
20	1.6	2.8	3.8	6.6	7.7	9.4
21	2.0	3.6	4.6	9.8	11.1	12.8
22	2.3	3.5	5.1	6.8	8.4	10.4
23	2.8	4.0	5.3	7.4	9.1	11.1
24	3.2	4.3	6.0	10.9	12.9	14.8
25	2.9	4.5	5.9	10.8	12.9	15.4
26	3.8	5.6	7.1	11.4	14.2	15.7
27	4.3	6.2	7.5	11.8	14.2	16.5
28	4.5	6.4	7.9	12.3	14.9	16.9
29	4.6	6.3	7.4	11.6	14.7	16.4
30	5.0	6.5	8.5	11.9	14.8	16.5
31	5.0	6.7	8.4			
32	3.3	6.8	8.5			
33	4.7	6.5	8.2			
34	7.7	9.3	10.8			
35	7.2	9.4	11.3			

channel is basically a rectangular iron pipe in which there are top and bottom coils that allow field control along the orbit and an external current sheath that partially corrects for the field perturbation in the acceleration region due to the iron and the "inside" current. The contribution of the inside and outside coils to the acceleration field at a given point is proportional to the respective currents, i.e., $B(r,\theta) = \alpha I_{in} + \beta I_{out}$.

The proportionality constants α and β will depend on the coordinates (r,θ) as well as the main field excitation. However, measurements such as those shown in Figure 5 revealed that their ratio is independent of both position and main field excitation, i.e., $\alpha = k\beta$. Consequently, any change in the extraction field can be realized without changing the acceleration field by constraining current changes to $\Delta I_{out} = -k\Delta I_{in}$. In other words, if the correct acceleration field has been achieved for realizing particles at the septum, then the iron channel field can be changed freely for best extraction conditions without destroying isochronism.

This feature is clearly demonstrated in Figures 6 and 7 where different combinations of I_{in} and I_{out} produce the same first harmonic as to amplitude and azimuth.

Coaxial Channel

The iron free coaxial channel allows the field to be altered very close to the acceleration region with a minimal leakage field. This is accomplished by a helical coil configuration which, if ideal, would produce no external field.[1] With 3,750 amperes in the coaxial channel the measured perturbation was limited to a few gauss at the outermost radii and can easily be corrected with the harmonic coils.

TABLE 2

A comparison of predicted and measured grand field tests at 3240 amperes main field excitation (72 MeV $^4He^{++}$). The constant 8 gauss difference corresponds to a 4 ampere correction in the main coil current.

RADIUS (Inches)	PREDICTED FIELD (Gauss)	MEASURED FIELD (Gauss)	DEVIATION (Gauss)
6	16,619.58	16,604.58	15.00
7	16,620.38	16,607.48	12.90
8	16,612.72	16,599.93	12.79
9	16,602.41	16,591.22	11.19
10	16,593.32	16,583.92	9.40
11	16,588.40	16,578.30	10.10
12	16,585.74	16,576.84	8.90
13	16,586.02	16,577.37	8.65
14	16,585.55	16,577.44	8.11
15	16,583.60	16,574.34	9.26
16	16,581.82	16,571.76	10.06
17	16,583.42	16,573.40	10.02
18	16,590.83	16,580.90	9.93
19	16,600.82	16,591.20	9.62
20	16,613.20	16,604.81	8.39
21	16,628.65	16,621.42	7.23
22	16,646.33	16,638.72	7.61
23	16,666.15	16,658.81	7.34
24	16,689.71	16,682.92	6.79
25	16,716.89	16,709.87	7.02
26	16,747.87	16,739.77	8.10
27	16,785.24	16,776.97	8.27
28	16,826.34	16,817.57	8.77
29	16,856.29	16,848.87	7.42
30	16,858.07	16,849.62	8.45

Conclusion

A test of the overall accuracy of the field measurements and the ability to produce a desired isochronous field through the linear combination of the various current carrying coils was made. These measurements were performed in the presence of the extraction channel excited close to actual operating conditions. The isochronous field was determined by codes developed by Professor M. M. Gordon and his colleagues at MSU. The trim coil currents necessary to correct the basic iron field (better than one kilogauss in the central region) were determined from a successive least squares technique. The calculated currents were dialed in and the measured deviation from the predicted field is displayed in Table 2. Because of a central magnetic hill for initial axial focusing, the isochronous condition is imposed only for radii larger than 5 inches. If the constant offset of 8 gauss is compensated for by the main field coils, the standard deviation from the predicted field is less than 2 gauss. The constant offset of 8 gauss corresponds to 4 amperes in the main coil and is due to different times of measurement.

Acknowledgments

Accumulating the magnetic field data involved around-the-clock operation for approximately three months. The authors would like to express appreciation to the entire cyclotron staff for the many man-hours contributed to this effort at considerable personal inconvenience. Much of the guidance for this program was due to Dr. Rollon O. Bondelid and is gratefully acknowledged together with the constant interest and support of Dr. John McElhinney.

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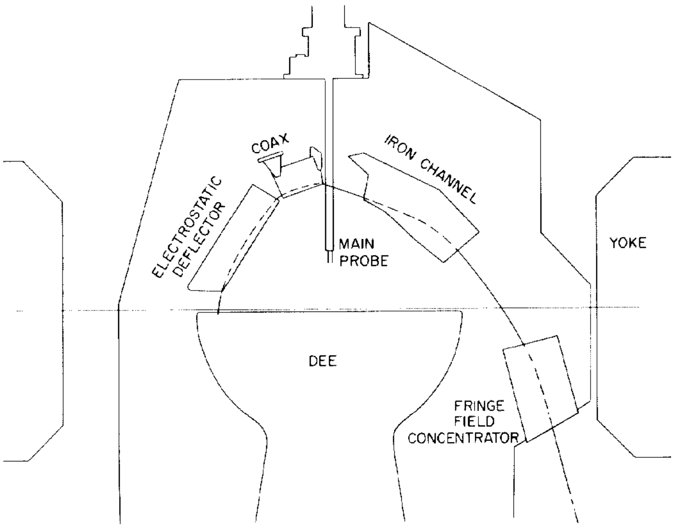

Fig. 1. Schematic representation of the extraction channel. The electrostatic deflector subtends an angle of 55 degrees and provides a gradient of 0.5 kilovolts/cm. The coaxial channel is mechanically linked to the exit of the deflector and reduces the field 4,000 gauss. The iron channel has compensating coils that approximately cancel the influence of the iron and primary coils. The final element is the fringe field concentrator which provides for horizontal steering of the beam into the external ion optic system.

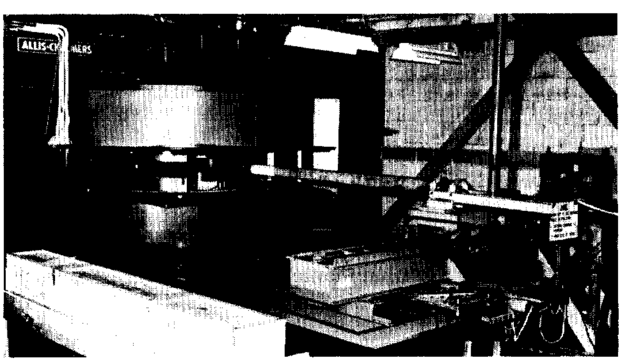

Fig. 2. Hall-probe positioning table. The probe boom extending into the cyclotron gap is fabricated of alumina ceramic. This particular nonconductor was used because of its high stiffness to weight ratio (the stiffness of this alumina is twice that of steel).

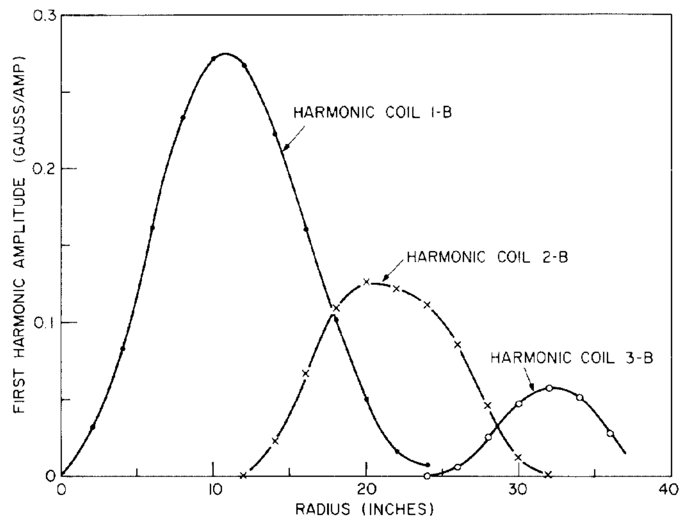

Fig. 3. Radial Dependence of the First Harmonic Amplitude due to the Harmonic Coils in Valley "B". The Excitation Current was 250 amperes.

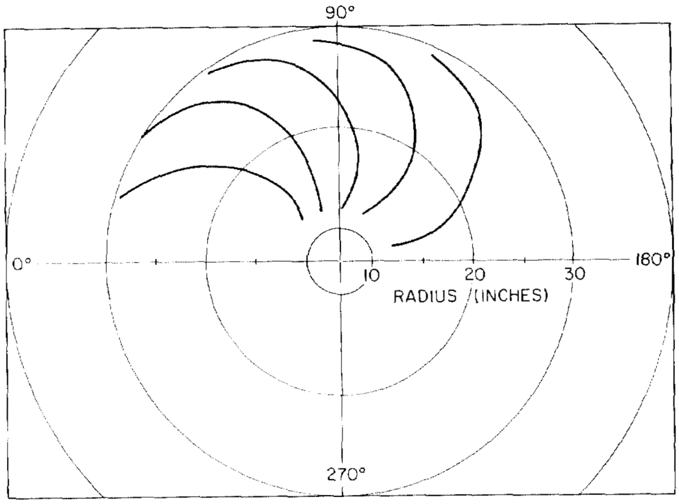

Fig. 4. The azimuth of the first harmonic due to excitation of the harmonic coils at the intermediate radii. The successive curves correspond to a change of 30 degrees in the Φ helipot dial.

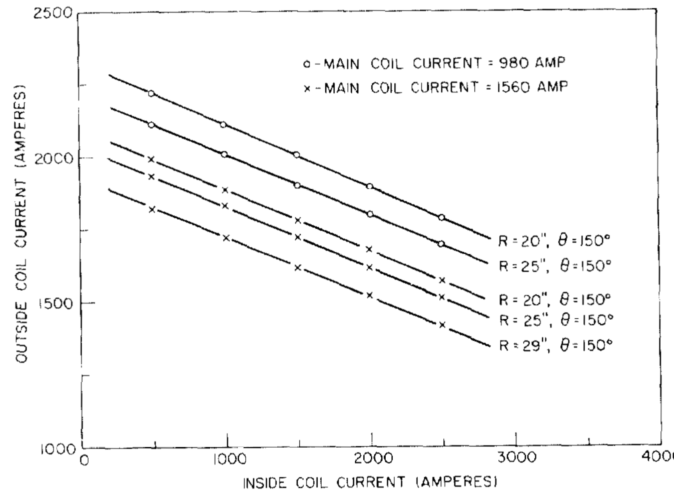

Fig. 5. The same magnetic field at any point exterior to the iron channel can be maintained by compensating a current change in the inside coil by a change in current of the outer coil so that $\Delta I_{out} = -k \Delta I_{in}$. Here we illustrate that k is a constant independent of main field excitation and position. Thus, the field inside the iron channel can be changed for best extraction without destroying isochronism.

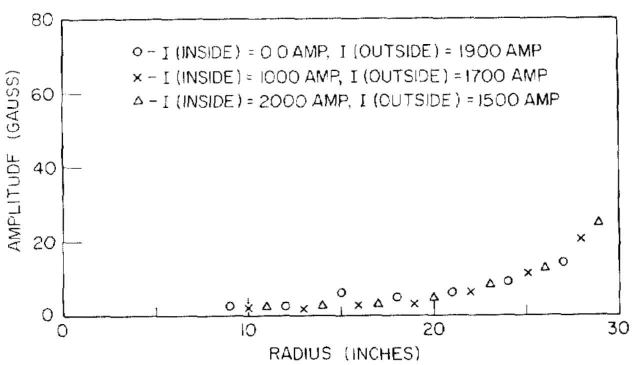

Fig. 6. Amplitude of the first harmonic for different current combinations in the inside and outside coils of the iron channel. The outside coil current was adjusted to compensate for changes in the first harmonic produced by changing the inside coil current. The initial current combination was chosen to get a measurable first harmonic to test the compensation feature of the outside coil on the inside coil. For clarity, only every third point for each current combination is shown. We notice that all points follow essentially the same curve.

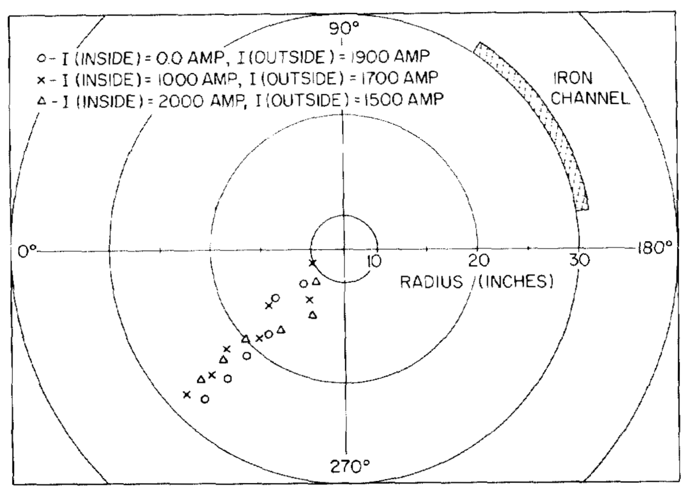

Fig. 7. Same Coil condition as Figure 6 with phases of the first harmonic rather than amplitude shown.