THE FOCUSING AIR-CORE MAGNETIC CHANNEL FOR THE M.S.U. 55-MEV CYCLOTRON †

R. E. Berg and H. G. Blosser
Michigan State University
East Lansing, Michigan

Summary. In variable-energy cyclotrons, saturation effects are always a problem; the use of air-core coils in lieu of iron as magnetic channels greatly reduces such difficulties. This paper describes the design of such a coil for the M.S.U. 55-MeV cyclotron. The coil includes the additional feature of incorporating a focusing gradient approximately equal in strength to a typical single-stage quadrupole.

Introduction

The extraction system for the M.S.U. cyclotron consists of a 45° electrostatic channel followed by a 30" magnetic channel. Specifications for the magnetic channel were obtained from computer orbit studies, and are as follows: (1) a field along the central ray of approximately 3.5 kilogauss, (2) a "small" external field, the first harmonic content of which should be less than one gauss at the radius of the adjacent $\nu_r = 1$ resonance, and (3) as large a radial focusing gradient as possible.

The desired channel current configuration was obtained thru a three-step process, namely: (1) the properties of various arrangements of infinitely long conductors were studied, to sort out arrangements having approximately the desired properties; (2) for promising current arrangements the fields of closed coils were calculated neglecting possible effects due to adjacent iron in the main cyclotron magnet; and (3) to determine the effect of this iron, a simplified test coil was constructed and installed in the cyclotron magnet, and a comparison made of the measured field and the computed air-core field.

Infinite Wire Calculations

An extensive series of calculations was performed computing the fields of various arrangements of infinitely long conductors. At all stages in the calculation, the current patterns were incremented in blocks corresponding to conductors of 0.200 by 0.225 inches in size, with the conductors placed to conform to constraints set by other structures in the cyclotron gap. The wire configuration with cross section shown in Fig. 1 was finally selected. The median plane field of such an arrangement of wires is given in Table I. As can be seen from Table I, this arrangement yields a focusing gradient of over 600 gauss per inch when the excitation is set to give the desired 3.5 kilogauss central field. In addition, the configuration has the desirable property of having a zero point in the external field at a distance roughly corresponding to the location of the $\nu_r = 1$ orbit. The 600 gauss per inch gradient distributed over the 30" length of the channel coil gives a focusing impulse approximately equivalent to that of a commercial 3" aperture, 6" long quadrupole magnet.

Closed Coil Calculations

To determine more accurately the amount of first harmonic produced at the $\nu_r = 1$ resonance, a second set of air-core calculations was performed with a realistic closed coil current arrangement. The final configuration retained the same cross-sectional arrangement given in Fig. 1, but approximated the curvature of the channel by considering the central ray to be a set of three straight lines joining the four coordinate positions listed in Table II. The conducting elements also made sharp bends along radial lines at each of the angles. At each end of the channel, currents were closed on each other by connecting wires in the manner indicated by the dotted lines in Fig. 1. The external field produced by this closed coil was calculated on a polar grid of points covering the region of interest and a Fourier analysis was performed. Resulting first harmonic data is shown in Table II. For comparison $\nu_r = 1$ occurs at a radius of approximately 27.5".

Mock-up Studies

Figure 2 is a photograph of a trial coil of form similar to the arrangements considered, which was constructed to determine the extent of errors resulting from the neglect of the adjacent iron structures in the magnet gap. Due to space limitations, it was necessary to use a rotating coil field measuring system with accuracy of approximately 10 gauss. To within this accuracy, no differences between measured field and calculations could be detected. A channel coil with cross-sectional form as shown in Fig. 1, is now in the process of design and construction, and will be installed in the cyclotron in future months. Inasmuch as the cyclotron is now operational, precise measurements of the stray field at the $\nu_r = 1$ position can be accomplished by observing the effect of the channel in displacing the beam.

† Work supported by National Science Foundation.

Table I. Internal and external median plane magnetic channel fields using infinitely long conductors of cross-section shown in Fig. 1.

Internal Field		External Field			
x(inches)	B_z(gauss)	x(inches)	B_z(gauss)	x(inches)	B_z(gauss)
0.9	3826.1514	0.0	-102.9768	- 7.0	2.0558
1.0	3751.9593	-0.5	- 85.3742	- 8.0	5.9676
1.1	3680.3352	-1.0	- 9.9784	- 9.0	8.4171
1.2	3612.5639	-1.5	19.4944	-10.0	9.8471
1.3	3549.1173	-2.0	15.9709	-11.0	10.5954
1.4	3489.5245	-2.5	1.8775	-12.0	10.8969
1.5	3431.9992	-3.0	- 10.0093	-13.0	10.9098
1.6	3372.5971	-3.5	- 15.9242	-14.0	10.7391
1.7	3304.1089	-4.0	- 16.7682	-15.0	10.4549
1.8	3219.3668	-4.5	- 14.6023	-16.0	10.1034
		-5.0	- 11.1082	-17.0	9.7154
		-5.5	- 7.3105	-18.0	9.3114
		-6.0	- 3.7312	-19.0	8.9045
		-6.5	- 0.5897		

Table II. First harmonic field of closed coil magnetic channel.

Central ray coordinates

r_1 = 31.2564" $\theta_1 = 45^\circ$
r_2 = 33.0524" $\theta_2 = 60^\circ$
r_3 = 35.6070" $\theta_3 = 75^\circ$
r_4 = 39.9813" $\theta_4 = 90^\circ$

First harmonic

r(inches)	B_1(gauss)	r(inches)	B_1(gauss)
0.0	0.00	23.0	1.93
1.0	0.11	25.0	0.79
3.0	0.34	25.5	0.46
5.0	0.57	26.0	0.42
7.0	0.81	26.5	0.66
9.0	1.06	27.0	0.78
11.0	1.32	27.5	0.60
13.0	1.59	28.0	0.29
15.0	1.86	28.5	0.67
17.0	2.11	29.0	0.51
19.0	2.30	29.5	1.97
21.0	2.32	30.0	4.23

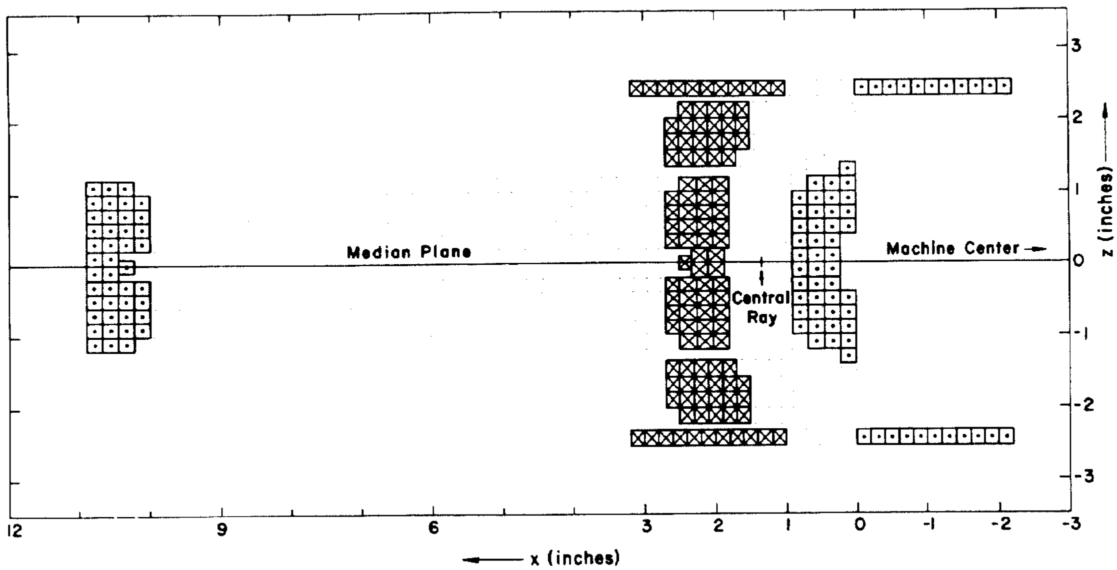

Fig. 1: Cross-section view of conductor arrangement. Dots and x's in blocks denote the two directions of current flow. Lightly dotted lines indicate the arrangement of end connections. Turn separation adequate to clear the group of conductors lying in the median plane and to the right of the central ray is produced by a previous 60° electrostatic deflector.

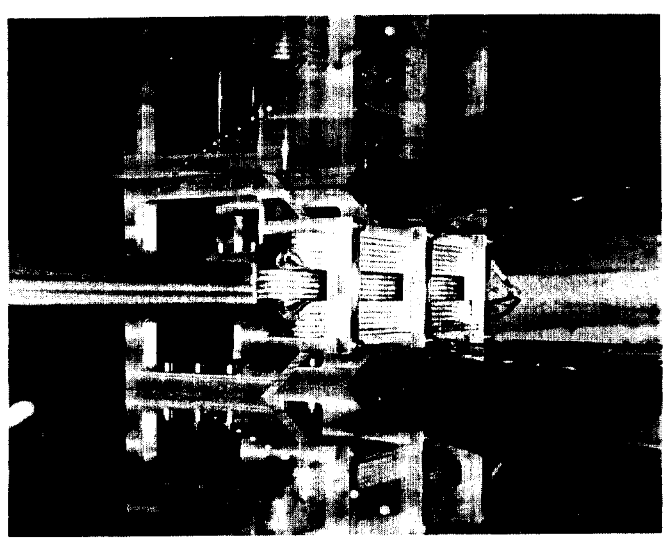

Fig. 2: View into the magnet gap of the M.S.U. cyclotron showing a test channel coil in position. The rotating coil field measuring device can be seen extending in from the left.