AIR-CORE MAGNETS FOR TRIMMING THE NAL BOOSTER SYNCHROTRON ORBIT

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Abstract

Forty-eight assemblies of four magnets each were provided for making orbit corrections at injection to the booster synchrotron. This assembly consists of both horizontal and vertical bending magnets as well as a quadrupole and skew-quadrupole. The magnets are 13 inch long and are concentric cylinders with the quadrupole which is innermost having an aperture of 4 3/4 inch. The differential form of Ampere's Law was used to calculate the field in three dimensions including ends. By adjusting the boundary defining parameters of the magnets the uniformity of the bending and gradient lengths were optimized. The dipoles provide a bending strength $\int B d\ell$ of 0.03 kG-m which is calculated to be uniform to within 1% over a 3-inch aperture. The quadrupole focusing strength $\int B' d\ell$ is 0.22 kG with calculated deviations in the order of 1% inside a 3-inch aperture.

General

The correction magnets for the booster synchrotron are located in each long and short straight section of the ring. In all there are 48 straight sections in the lattice where an identical assembly of four air core magnets is located.[1] Innermost in the assembly is a quadrupole, and going out in radius are found the skew quadrupole, a dipole for horizontal bends, and finally the outermost dipole for vertical bends. The quadrupoles were randomly wound in quadrants using light gauge round magnet wire. The dipoles were layer wound in halves with square magnet wire. The magnet sections were then vacuum impregnated with an unfilled epoxy resin.

The shape of the magnet sections are determined by using the differential form of Ampere's Law to calculate the field and optimizing the dimensions of the magnet to achieve satisfactory uniformity in the quantities $\int B d\ell$ for the dipoles and $\int B' d\ell$ for the quadrupoles. A cross section looking down the aperture of the four-magnet assembly is shown in Figure 1.

The criteria for specification of the correction magnets are based in part on magnetic measurement of the F and D booster magnets and partly on previous estimates of errors.[2] The trim magnets were designed primarily for dc corrections of the closed orbit, tuning, and suppression of horizontal-vertical coupling at the injection energy of 200 MeV.

The dipoles are designed to introduce a bend of 1.4 cm in 10 m (the distance separating successive trim magnet assemblies) at injection. This requires a bending length of 0.03 kG-m. This is based on the maximum aperture allowances made for closed-orbit errors, injection errors, and $\Delta\nu$ tuning range. A uniformity of 10% in the quantities $\int B d\ell$ and $\int B' d\ell$ over the booster aperture is considered satisfactory.

The quadrupoles are designed to provide for tune shifts of ±0.6. An integrated gradient of 0.220 kG is sufficient to provide this. The skew quadrupoles are designed to have an integrated gradient of 0.024 kG which is based on an estimate of the amount of twist within the booster magnets and rotation of the magnets about the beam direction due to alignment errors. Actually the strength of the skew quadrupoles is more than adequate to correct for these effects; the maximum focusing strength of the skew quadrupoles (approximately 0.05 kG at 500 A/in^2) is therefore a result of practical considerations relating to construction.

In addition to the field requirements the space limitations restricted the magnets to 13 1/4 inch long and a radius from beam center of 8 1/2 inch. It is also important that assembly of the magnet cluster could be performed without disturbing the integrity of the vacuum system. Air cooling was desirable and feasible in this case since the maximum current density present in any of the magnets at full excitation is 500 A/in^2. In addition air core magnets avoid problems of hysteresis and remanent fields.

Design

For infinite cylindrical magnets of cross section shown in Figure 1 analytic expressions have been developed for the

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two-dimensional field.[3] Using these expressions it was shown that certainly the maximum field requirements could be met without any special kind of cooling. Based on these two-dimensional calculations, preprototype magnets were wound in the coil shop at Argonne National Laboratory. Test results on these models showed that heating would be no problem even when all four magnets in the assembly were run at full power continuously. However magnetic measurements indicated that the field uniformity was less than what was desired.

In an attempt to achieve better field uniformity it was decided to calculate the field exactly. Following a suggestion by Halacsy[4] the differential form of Ampere's Law:

$$dB = \frac{I}{c} \frac{d\vec{\ell} \times \vec{X}}{|\vec{X}|} \qquad (1)$$

was programmed to add up the field due to current elements in the magnet. There are three different geometrical shapes to consider; namely, a circle segment, straight lines, and a curve connecting the first two. The dipole half core shown in Figure 2 typifies these curves. The field from the line was determined from an integrated form of equation (1) to reduce computer time. The fields from the circle segment and 3-dimensional curve connecting the line and circle were found by dividing these curves up into small straight line segments $d\vec{\ell}$ and adding up the field components due to each segment. As a check the calculated field was compared to results from two-dimensional calculations on a magnet that was long compared to the ends and also against a hand calculation at the center with good agreement (within 0.2%) in both cases. Of course maximum use was made of the symmetry of the magnets to minimize computer time. A typical run using the Argonne CDC 3600 computer for field values at 600 points and 450 turns in the half core required 4 hours of running time.

In order to minimize the variation in the quantities $\int B d\ell$ and $\int B' d\ell$ over the aperture, the sector angles (such as the one labeled in Figure 1 on the outer dipole) were adjusted. Also the radii of the various steps (a two-step dipole half core is shown in Figure 2) could be optimized, however the bending lengths are more sensitive to changes in the sector angles. An obvious starting choice for the sector angle of a one-step dipole is 60°, since this makes the sextupole field term zero (and certain other higher order terms as well) if the ends are neglected. The quadrupole required two steps with inner and outer sector angles of 12° and 35° respectively. The sector angle of the skew quadrupole (single step) is 27°. The inner dipole also required two steps with inner and outer sector angles of 60° and 45°. The outer dipole is a single step with a sector angle of 55.5°. The effective lengths at the center (x=0) and central field values are shown in Table 1. The measured central field in the inner dipole at 1A is 41.9 ± 0.2 G. The effective magnetic length of this magnet is 2/3 of the physical length.

TABLE 1

Calculated Fields for Correction Magnets

Magnet	Length (cm)	Central Field or Gradient at 1A	Effective Length at Center
Q	33	7.57 G/cm	28.3 cm
SQ	33	3.1 G/cm	29.0 cm
ID	33	42.2 G	22.0 cm
OD	33	26.7 G	20.0 cm

Using these three-dimensional calculations the final designs were completed. The calculated field uniformities are shown in Figures 3 and 4. It is noted that within the aperture occupied by the beam at injection (shown by the dashed lines in Figure 4) the calculated bending and gradient lengths are uniform to within 1% over most of the area. A comparison of $\int B d\ell$ between measurements and calculation in the horizontal plane is shown for the inner dipole in Figure 3. The error in the measured points is ±0.25%. The more rapid decrease in the measured $\int B d\ell$, (as the distance from the center increases) is consistent with one or both of the sector angles being larger than desired. A 2° to 3° increase in both section angles would account for the disagreement between the measured and calculated results. Since no such error could be found, the disagreement must be attributed to slight differences between the assumed and constructed shape of the current loops.

Construction

The quadrupole quadrants were random wound[5] using round magnet wire in a cylindrical fixture, and then vacuum impregnated while still on the winding fixture. After impregnation, two inner quadrupole quadrants were assembled together to form a half circle and one skew quadrupole quadrant was bonded to this assembly. Thus there were only four separate parts to the two-quadrupole assembly to be placed around the beam pipe. The beam pipes which were not always circular nor the right diameter were previously built up in two spots with thin strips of G-10 fiber glass and room cure epoxy to the inside diameter of the inner quadrupole. The leads in the quadrupoles were terminated with a 3/4 inch long x 1/4 inch diameter hex nut which was tapped for a no. 10 screw and impregnated as part of the quadrant.

The dipole halves were layer wound[5] with no. 13 and no. 11 square magnet wire for the inner and outer dipoles respectively. Actually two layers at a time were wound flat in such a manner that both leads came to the outside. Then the two layers were rolled to approximately the correct diameter (the inner dipole has 12 layers and the outer dipole 10 layers). Again the halves were fully vacuum impregnated to form a rigid structure. The technique of winding the layers and rolling them to a prescribed diameter required proper tensioning of the wire while winding and some taping to keep the windings in place.

The electrical properties and physical dimensions of the magnets are listed in Table 2 below. The magnets required from 12-15 volts to achieve full power except for the skew quadrupole which requires only 3 volts. This level of voltage was a determining factor in the selection of the wire size, mainly from the standpoint of economics. Actually the current density of 500 A/in^2 in these magnets corresponds to equal costs for copper and 10-year operating costs. All of the correction magnets (192 in all) are individually powered.

It is noted that between each successive magnet layer a space of approximately 0.1 - 0.2 inch has been left. This was done to allow for irregularities in construction. However it was necessary to build up each layer with thin strips of G-10 fiber glass and tape so that the magnets would fit tightly around each other.

A photograph of the magnet assembly installed in the Booster is shown in Figure 5. The cost of the 4-magnet assembly was approximately $1,600.

Conclusions

The initial capability of making corrections to the Booster orbit has been restricted to dc corrections at injection. Space is available for additional magnets should they be necessary. The magnets that were designed[7] met all the requirements previously stated. The dipoles have been used to correct the closed orbit at injection but neither the quadrupoles nor skew quadrupoles have received any extensive use as yet.

The correction dipoles in the 200 MeV transfer line between the Linac and Booster were designed and constructed in this same manner. They consist of an inner and outer pair for horizontal and vertical bends. Because of space limitations they are only 9 inch long. They provide a bending strength of .0255 kG-m at 5 A. Measurements on the inner dipole of this pair agreed with calculation to within 0.5% in the horizontal plane out to ± 1 inch from center (no measurements were made beyond 1 inch).

The cylindrical shape of these magnets facilitates surrounding them with iron to increase the field strength. Using an expression given by Halbach[6]

TABLE 2

Physical Dimensions and Electrical Properties of Correction Magnets

Magnet	Inner Radius	Middle Radius	Outer Radius	Wire Size	Turns/ Section	Total Resistance
Q	5.87	6.22	6.98	18RD	259	14.1
SQ	7.14	---	7.40	20RD	118	11.1
ID	7.62	8.81	10.0	13SQ	496	4.03
OD	10.16	---	12.57	11SQ	455	2.32

it was shown that the field strength increased by 80% for the outer dipole and 10% for the quadrupole with an iron cylinder around the 4-magnet cluster.

References

1. R. Billinge, FN-118 March 12, 1968.
2. NAL Design Report pp. 9-14, July, 1968.
3. A. Asner and C. Iselin, Proceedings of International Conference on Magnet Technology 1967 pp. 32-39.
4. A. A. Halacsy, G. Clark, and V. Dunks, Proceedings of International Conference on Magnet Technology 1967 pp. 61-77.
5. Magna Tek Systems, Inc. Hayward, California.
6. K. Halbach, UCRL-18947, July 1969.
7. Technical Specifications #0326-ES-2769

Quadrupole	#0326-MD-2768
Skew Quadrupole	#0326-MD-2764
Inner Dipole	#0326-MD-2767
Outer Dipole	#0326-MD-2763

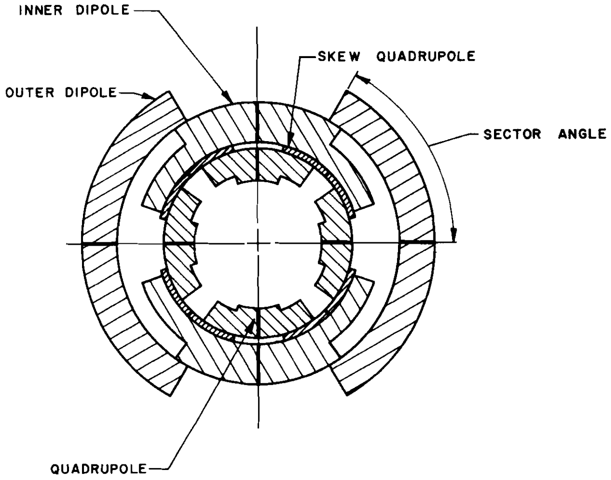


FIG. 1

CROSS-SECTIONAL VIEW OF A TYPICAL ASSEMBLY OF FOUR TRIM MAGNETS

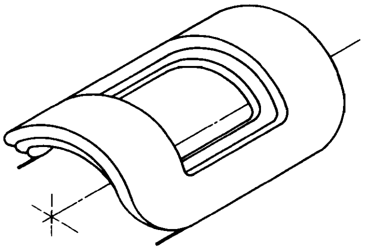


FIG. 2

TOP COIL OF AIR CORE DIPOLE TRIMMING MAGNET.

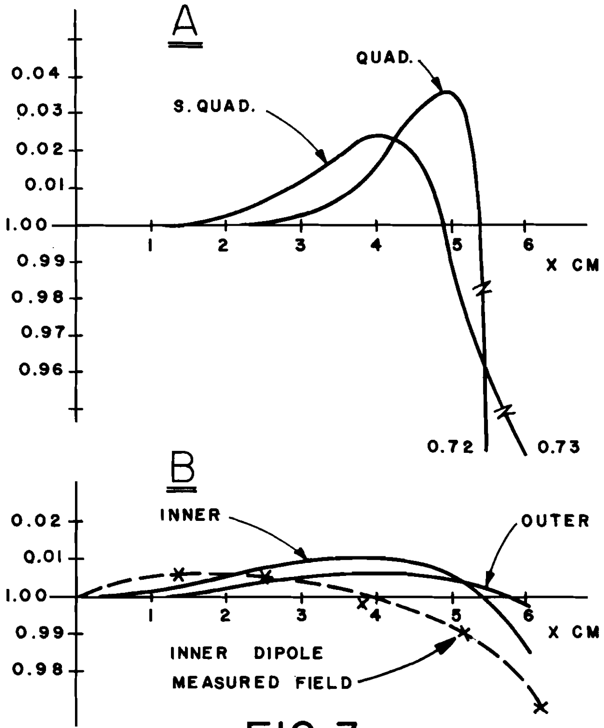


FIG. 3

A) $\int B'(x,0)\,dz / \int B'(0,0)\,dz$ FOR THE QUADRUPOLES.

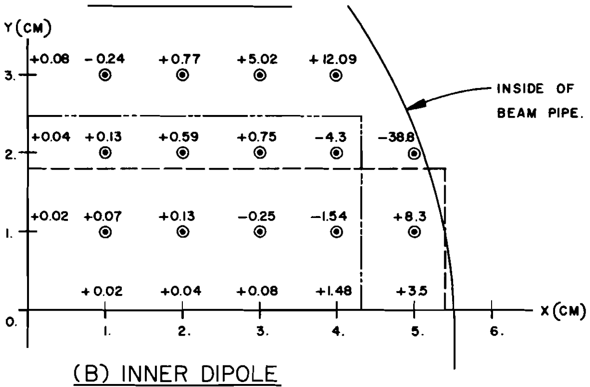
B) $\int B(x,0)\,dz / \int B(0,0)\,dz$ FOR THE INNER & OUTER DIPOLES

REQUIRED GOOD FIELD AREAS AT INJECTION IN BOOSTER

D —·—·—·—

F — — — — —

(A) QUADRUPOLE



(B) INNER DIPOLE

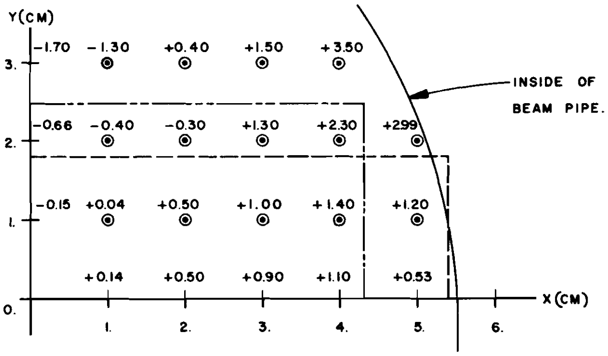


FIGURE 4

THE PERCENTAGE DIFFERENCE IN THE CALCULATED VALUES OF GRADIENT LENGTH & BENDING LENGTH FOR THE TRIM QUADRUPOLE & INNER DIPOLE.

A) $\left[\left|\int B'(X,Y)\,dz - \int B'(0,0)\,dz\right| / \int B'(0,0)\,dz\right] \times 100$

B) $\left[\left|\int B(X,Y)\,dz - \int B(0,0)\,dz\right| / \int B(0,0)\,dz\right] \times 100$