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ANALYSIS AND DESIGN OF SHORT, IRON-FREE DIPOLE MAGNETS

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SUMMARY

Iron-free, dipole magnets are used extensively as steering magnets to correct for the bending, induced by extraneous magnetic fields, of particle beams that are being transported in vacuum. Generally, the dipoles are long enough that the space occupied by the end conductors is small compared to the overall magnet length. In a recent application, however, this criteria did not apply. This has motivated a reanalysis of the characteristics of a system of small aspect ratio (length/diameter) dipoles that are spaced at relatively large axial distances. The following observations and conclusions resulted from this analysis:

1. The effective magnet length is a simple function of the axial conductor lengths, their relative orientation, and the magnet diameter.

2. The overall magnet strength is a function of axially parallel conductors only.

3. End conductors should be placed in a single plane normal to the axis at each end of the magnet.

4. Flat wound and formed magnets lead to considerable cost reductions over more conventional winding methods.

5. Increasing the number of turns yields more favorable power supply matching, better field uniformity, and more favorable heat dissipation.

6. Increasing the number of and upturning the end conductors provide a more favorable field profile at the ends of the magnet.

The above points are discussed in this report. Some fabrication techniques which are being developed in a prototype magnet are also discussed.

NOTES ON EQUATIONS AND SYMBOLS

I have used pseudo-fortran line style equations throughout this report for ease of reproduction on standard word processing equipment. Integrals and summations, followed by their limits, are spelled out. Constants such as MUO and PI are phonetic spellings of their greek counterparts. I is universally designated as current and N as turns. Indexed quantities are enclosed by parenthesis and paired by the letter J. Magnetic fields are prefaced with B and all incremental values are prefaced with D. Directional quantities are suffixed with the letters Y or Z. Z is universally designated to be the beam axis. Mathematical notations, with the above exceptions, are as defined in fortran. Although no specific units are expressed, consistent units are implied.

FIELD ANALYSIS

Fig. 1A is a graphical representation of a cross-section of the upper half of a classical dipole magnet. The conductor profile is shaped such that, if filled with many uniform current density elements the following relationship holds.

(1) N(THETA)*I=N(O)*I*COS(THETA)

FIGURE 1A

CLASSICAL DIPOLE

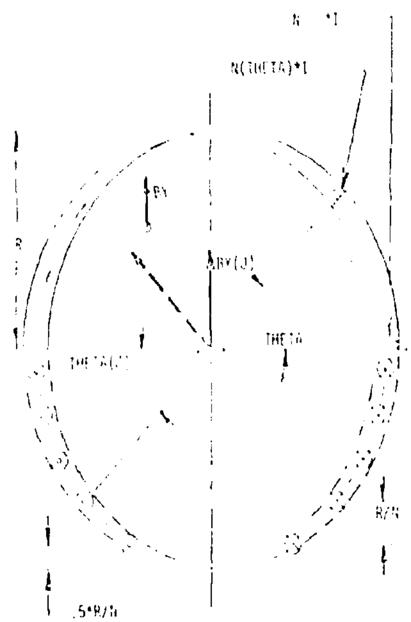

FIGURE 1B

"COSINE" APPROXIMATION

This current distribution produces a uniform transverse field at any location within the magnet bore.

(2) BY=MUO*NI/(2*R)

Where NI is the integrated sum of the ampere-turns.

In practice this winding configuration is difficult to achieve. A typical winding approximation is shown in figure 1B. The transverse field contribution at the center bore for an infinitely long current element would be:

(3) BY (J)=MUO*COS(THETA(J))/(2*PI*R)

The net field for all of the elements would be:

4) BY (TOTAL)=2*MUO*I/(PI*R)*SUM
(J=1 TO N)COS(THETA(J))

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Where N is the number of current elements per quadrant. Several ratios of B(N)/B(COSINE) are:

N	10	20	30	40	60
B(N)/B(COS)	.9966	.9988	.9993	.9996	.9998

Thus a reasonable approximation (for at least the center field) may be obtained with a relatively small number of turns. Clearly, the field uniformity will improve as the number of turns increases approximating the classical distribution in the limit. Further, increasing the number of turns will provide a larger surface area for a given power input and improve the ohmic heating dissipation.

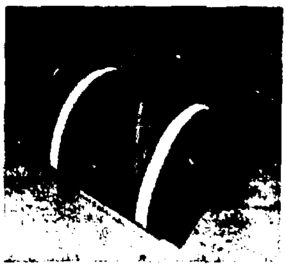

FIGURE 2
EXISTING DIPOLE

Fig. 2 is a photograph of one half of an existing dipole. Note how the conductors at the ends are treated (we will refer to overall construction later in the report). For this magnet, the end conductors utilize a considerable amount of axial space. We currently have an application where the magnet diameter is approximately 14 in. and the length 16 in. and it is formed from 60 to 70 turns of #12 AWG (.0856) magnet wire. If the magnet were *monolayer wound we would end up with axial current* elements ranging from 5 to 16 in. in length. Clearly, the cosine current distribution would not hold for the majority of magnet. For this application, we have had to analyze the effects of the components--finite length axial elements and their end returns.

EFFECTIVE MAGNET LENGTH

In this section we will derive equations to define an effective magnet length for steering magnets used to guide a beam on an axis only. The following discussion does not apply to dipoles used for large scale bending of particle beams!

For the purpose of this discussion, we *shall define* "axial turns" to mean current elements parallel to the beam axis and "end turns" as current elements *contained within a plane perpendicular to the beam* axis. In general, end turns as defined here, will be considered to be in mirror pairs folded about the mid-plane axis, but not necessarily in any particular path configuration.

END TURNS

Simple symmetry arguments demonstrate that on a line perpendicular to the midpoint of a plane containing a mirror pair of current elements, the magnetic field on one side of the plane is equal and opposite to that on the other. Therefore:

(5) Integral (-INF to +INF)B*DZ =0

For steering magnets, where the entire integrated field lies on the line of action, the end turns have no net affect on the overall magnetic rigidity of the beam. This does not, however, discount the regional *field excursions near the end turns.*

Further current elements at radii distant from the beam axis exert less influence on off axis particles than those less distant.

The above implies that the end turns should be brought up and away from the magnet, if possible.

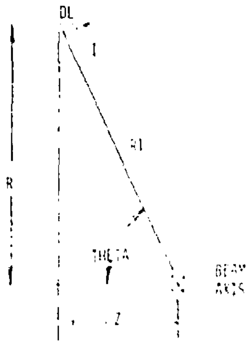

FIGURE 3
INFINITESIMAL, AXIAL LINE ELEMENT

AXIAL TURNS

Since end turns have no overall affect on the *magnetic rigidity, axial turns must provide the total* magnet strength. This considerably reduces the complexity of the problem, since the number of productive ways that axial turns may be placed is minimal. Fig. 3 represents an infinitesimal line element located at a radius, R, from the beam axis. Using the Biot-Savart law to integrate the B*DZ product along the beam axis from -INF. to +INF., the *following equations apply:*

(6) DB=MUO*I*DL*SIN(THETA)/(4*PI*R1**2)

where

(7) R1=SQR(R**2+Z**2)

*substituting for Z=J*DL, SIN(THETA)=R/R1,* and *P=DL/R*

(8) DB(J)=MUO*I*P/(4*PI*R**2(SQR(1+(J*P)**2))**3)

integrating

(9) Integral (J=-INF to +INF)DB*DZ=I1

(10) I1=MUO*I*DL/(2*PI*R**2)

For a given line length, L, the number of infinitesimal line elements = L/DL. The integrated field for the line becomes

*(11) Integral (B*DZ)=MUO*I*L/(2*PI*R**2)*

The field at the axis on the perpendicular bisector of the line is

(12) BO=MUO*I*L/(4*PI*R*SQR(R**2+L**2/4))

The effective length of a magnets LEFF is defined by

(13) LEFF=INTEGRAL(B*DZ)/BO=2*SQR(R**2+(L**2/4))

Thus the effective length of a line element is simply twice the hypotenuse of a triangle formed by the radius to the axis and half the axial length.

Since the dipole magnet is composed of a number of finite lines, the effective dipole length is nothing more than the summation of the product of the individual lines and their contribution factors divided by the number of elements. The maximum strength magnet contains elements of the same length, and this is possible only if the ends are turned up. The cosine approximation is maintained for the full length of the magnet in this case. Increasing the number of turns improves the impedence matching for power supplies, since higher voltages and lower currents are desireable in most power supply applications.

MAGNET FABRICATION

Referring to the conventional style magnet shown in Fig. 2., a number of fabrication features used for this magnet are worth consideration for improvement.

1. The conductors are placed in grooves which are machined in half of a prefabricated tube.

2. The end turns are placed in bunched clusters in a manner which is ordered as well as one could expect from a hand wound magnet.

3. The options for the tube used are limited. Either the tube was machined from a stock size or purchased by special order.

4. The lands between machined grooves becomes extremely narrow (hence fragile) for turns near the edge. *This becomes much more pronounced* as the number of turns increase.

5. It is difficult to conceive of any simple mechanized way to wind this magnet as it is now constructed.

Each of the above contribute to the relatively high cost for this magnet. A proposed winding technique which simplifies the magnet fabrication and eliminates these problems is described below.

FLAT-WOUND, FORMED, AND EPOXY STABILIZED DIPOLE MAGNET

One method of constructing the dipole magnets would be to wind the magnet flat on a winding table, maintaining the winding spaces by means of grooved bars. The end turns could be wound around properly spaced pins. The winding could then be rolled to the proper radius, sandwiched between two fiberglass-epoxy sheets with an epoxy-fiberglass paste filling the remainder of the void between the sheets. The assembly could then be cured to form the final rigid shape.

One very difficult problem is encountered. How can the proper relationship between the windings be maintained, once the fixture is removed? We have *resolved this problem by encapsulating the conductors between glass tapes saturated with a semi-flexible,* fast cure epoxy at critical locations before the fixture parts are removed. The tape encapsulated *sections are kept to a minimum thickness by pressing* them between rubber faced bars during the rapid cure.

This system works well if the end turns are "unfolded" (not turned up). For this case, two problems are encountered;

1. The end turn configuration must be defined.

2. A flat winding scheme must be developed to allow for the increased winding lengths required.

FIGURE 4
DIPOLE END TURNS

FOLDED END TURNS

Fig. 4 is a photo of how the turns might look at the *end of a dipole (this photo allows approximately half* of the turns to be "folded", i.e. turned up). These turns were formed, in the flat, folded about a break line, and subsequently rolled about the cylinder as *shown. The peaks and gaps were introduced by the* manner in which we did that flat forming.

FIGURE 5
FLAT WINDING TURNS

Fig. 5 is a photo of a flat winding which we feel will give us better control over the final form of the end turns. The winding length for each turn is controlled by the previous turn and two appropriately spaced pins. I have since defined the pattern for the location of the pins, which lie on arcs (they very nearly lie on arcs in the photo). This arrangement allows for placement of an encapsulating tape at the *center of the arcs for greater handling* stability during forming to the final configuration.

CONCLUSION

Short steering magnets, utilizing the maximum *available length for axial turns may be fabricated,* at reasonable cost, provided that the ends are folded and the turns are increased to compensate for the reduced overall length. The larger number of turns *further enhance the field quality* and provide for better impedence matching of power supplies.

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