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END FIELDS OF CBA SUPERCONDUCTING MAGNETS*

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Abstract

Measurements of the two dimensional harmonic content of the end fields generated by the Brookhaven CBA dipole and quadrupole superconducting magnets are presented. Both the local longitudinal structure and the integrated end effects are examined.

Introduction

Whereas the two dimensional structure of the magnetic field within the straight section of a magnetic can be easily modeled, the determination of the harmonic content of the magnetic fields at the ends of a magnet is a much more sophisticated problem requiring three dimensional modeling and rather elaborate calculations. It is therefore of great interest to determine experimentally the nature of these end fields.

The measuring coil used for obtaining our data consists of a revolving cylinder[1] (76.2 cm long × 3.5 cm radius) upon which wire loops have been wound so as to measure directly various multipoles (typically up to and including 14-pole). By drawing the coil through the end region of our superconducting dipole and quadrupole magnets[2] and taking data at regular intervals, we obtain the two dimensional equivalent of the end fields as a function of the longitudinal position along the axis of the magnet.

The analysis of the magnetic field is based on its decomposition into its harmonic components such that

$$B_y(x) = B_0 + B_1 \left(\frac{x}{4.4}\right) + B_2 \left(\frac{x}{4.4}\right)^2 + B_3 \left(\frac{x}{4.4}\right)^3 + \ldots$$

$$B_x(x) = A_0 + A_1 \left(\frac{x}{4.4}\right) + A_2 \left(\frac{x}{4.4}\right)^2 + A_3 \left(\frac{x}{4.4}\right)^3 + \ldots$$

where B_n and A_n express the normal and skew multipole components of the field (n=1 for quadrupole, n=2 for sextupole, etc.). All fields will be expressed as Gauss at 4.4 cm. This number has been chosen since it corresponds to the radius of the beam aperture of our magnets.

Local Fields

The longitudinal structure of the field is deduced by comparing measurements at adjacent longitudinal positions. The local two dimensional field is obtained by subtracting contiguous measurements of the integral fields. In Figure 1 we show the results for the first three higher allowed harmonics of a dipole magnet. Depicted on this figure are the locations of the end of the iron yoke and the effective end of the magnetic field where the effective length is defined as

$$L_{eff} = \frac{\int_{-\infty}^{+\infty} B_0 \cdot d\ell}{B_0^{max}} .$$

B_0^{max} corresponds to the dipole field generated in the straight section of the magnet.

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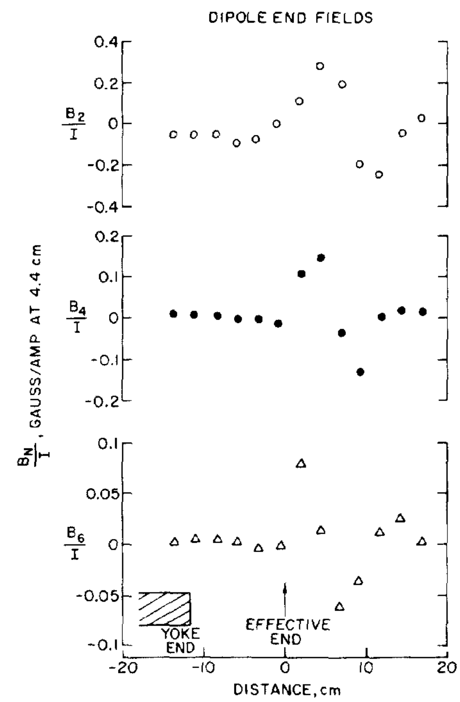

Figure 1. The end field structure of the first three higher allowed harmonics of a dipole magnet.

For the case when the measuring coil completely contains an end field, i.e., extends from zero field to the magnetic field of the straight section, then that portion of the effective length, Z, contained within the longitudinal dimensions of the measuring coil is given by

$$Z = \frac{\int_{meas\ coil} B_0 \cdot d\ell}{B_0^{max}} .$$

Note the self-correcting nature of these end harmonics. This is in contrast to our quadrupole magnets in which the higher allowed field harmonics (B_5, B_9, etc) are not self-correcting and therefore the ends contribute significantly to the higher allowed harmonics of the total field. In Figure 2 we show, as an example, the longitudinal structure of the B_5 field for a quadrupole.

Integrated End Fields

The total magnetic field consists of end field components plus a contribution due to the straight section of the magnet. If we model the magnetic field as containing a straight section over the entire effective length of the magnet, then

$$\int_{-\infty}^{+\infty} B_n \cdot d\ell = \int_R B_n \cdot d\ell + \int_L B_n \cdot d\ell + B_n^{ST} \cdot L_{eff}$$

where the indices R,L, and ST correspond to return end, lead end and straight section respectively. B_n^{ST} represents the field harmonics generated by the magnet straight section, unperturbed by the magnet ends.

If we place the measuring coil so as to completely contain the field generated by one end, then a vari-

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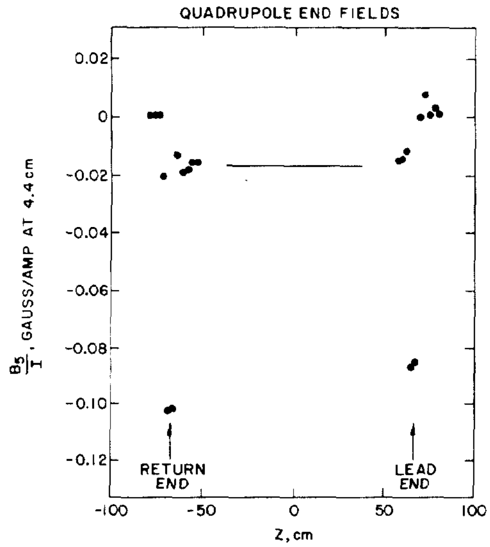

Figure 2. The longitudinal structure of the allowed harmonic B_5 in a quadrupole magnet. The line represents the measured B_5/I in the straight section of the magnet.

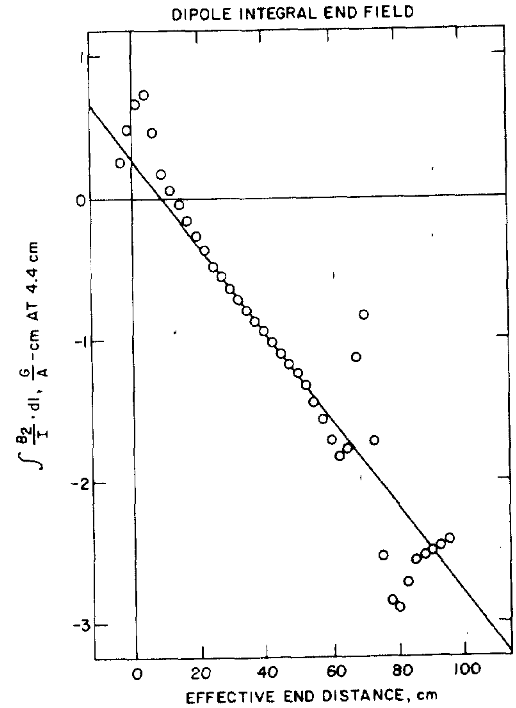

Figure 3. The integral sextupole field contained within the 76.2 cm length of the measuring coil.

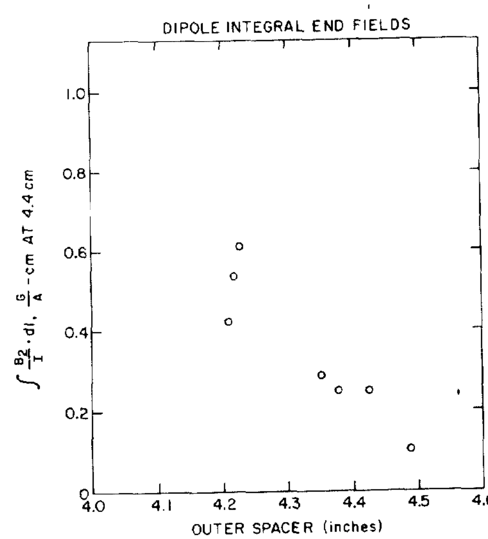

Figure 4. The integral sextupole field as a function of end spacer width.

ation of the measured integral field strength found by moving the measuring coil in incremental steps can be attributed to the change of the straight section length contained within the dimensions of the measuring coil. Further the residual field found by extrapolating to Z=0 (the effective end) can be identified as the end field contribution to the total integrated field. Note that this extrapolation procedure allows for end effects to extend both within and outside the effective length of the magnet.

In Figure 3 we see the results of measuring the integral sextupole at the lead end of a dipole magnet. The effective end distance, Z, is the distance from the effective end of the magnetic field to the end of the measuring coil nearest the longitudinal center of the magnet. We see linear behavior in the region 24 cm $< Z <$ 52 cm. The departure from linear behavior beyond this region leads us to deduce that the end fields extend ± 24 cm from the effective end of the magnetic field.

The results of the integral end field measurements, corresponding to the intercepts at Z=0, are given in Table I for the lead end of a series of seven dipole magnets and in Table II for both ends of two quadrupole magnets. Also given in these Tables are the magnet-to-magnet RMS tolerances necessary to achieve design field quality for a 400 GeV × 400 GeV proton storage ring.

Note that only for the quadrupole are the generated end fields greater than the RMS tolerance and therefore in need of careful control. However, the generated end field harmonics of both the dipole and quadrupole magnets satisfy the RMS variation allowed for the successful operation of the storage ring.

It is interesting to note that the sextupole end fields in dipole magnets correlate well with changes in end spacer dimensions. This result is shown in Figure 4 where the horizontal axis represents the sum of the widths of the last end spacers of the inner and outer coils in the two layer magnets.

TABLE I
Dipole End Fields
$\int B_n \cdot d\ell$, $\frac{G}{A} \cdot$ cm at 4.4 cm

Dipole	n = 2	4	6
CM03	0.25	0.06	
LM01	0.28	0.22	
LM02	0.25	0.15	
LM03	0.10	0.04	-0.01
LM05	0.54	-0.02	0.14
LM06	0.42	0.18	0.05
LM07	0.61	-0.03	0.21
RMS TOL	1.10	0.51	0.24

TABLE II
Quadrupole End Fields
$\int B_n \cdot d\ell$, $\frac{G}{A} \cdot$ cm at 4.4 cm

Quadrupole	n = 5	9
QM1 Lead	-0.32	-0.007
QM1 Return	-0.54	-0.046
QM2 Lead	-0.52	-0.031
QM2 Return	-0.53	-0.057
RMS TOL	0.11	0.024

Conclusions

With our revolving coil measuring system we can reliably measure the contributions of each magnet end to the total integral field.

The self-correcting nature of end fields of a dipole magnet results in harmonic field fluctuations which are well within specified tolerances. The end fields of quadrupole magnets are a more important contribution to the total integral field of the magnet and therefore require more attention as to how the superconducting conductor is arranged in the end sections of the magnet.

References

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2. R.B. Palmer, et al., Proc. of 1982 Applied Superconductivity Conference, Knoxville, TN. To be published.