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Some Uses of REPMM's in Storage Rings and Colliders*

J. E. SPENCER

Stanford Linear Accelerator Center
Stanford University, Stanford, California, 94305

Abstract

Improvements for existing rings and techniques for building new rings composed entirely of passive, Rare Earth Permanent Magnet Multipoles (REPMM's) are considered using circular dipoles, quadrupoles and sextupoles. Over the past few years we have made such magnets using a single size $SmCo_5$ block with up to five easy-axis orientations. The final production scheme is modular in that magnets are built-up from quantized layers. All multipole layers are made in exactly the same way using algorithms differing only by the desired multipole symmetry. The method is simple, efficient and inexpensive and allows a "do-it-yourself" approach to constructing new magnetic elements. For rings these might include focusing optical klystrons, rotatable multipoles for diagnostics, correction or extraction, or possibly combined function systems for the unit cells. A high quality, low-beta, PMQ insertion which can change beta, tune and energy is described as well as the PMS's for the SD and SF elements of the North SLC damping ring. Because these sextupoles will be the first optical use of PM's in storage rings they are discussed in detail together with the advantages, problems and requirements of such applications.

Introduction

A good overall introduction to the many aspects of this subject can be found in Holsinger's work on PMQ's[1]. The initial interest in our lab was the *possibility* of compact, high gradient, high quality quadrupoles that could be used in the high solenoidal fields of particle detectors without seriously perturbing either the solenoid or the quads. The advantages of high coercive force permanent magnets over superconducting or conventional, iron-dominated magnets for such applications are obvious. However, because these kinds of magnets had only recently come under development, it was decided to build and study a 20 cm long prototype with a nominal gradient of 100 T/m at a bore radius of R_b=1.05 cm. If sufficient strength and field quality could be achieved for the required apertures, one would have all the necessary tools for an optimal design of low beta insertions and also an optimal way to upgrade existing rings like PEP and SPEAR as well as the SLC final focus.

The techniques for a tunable, low beta insertion can also be carried over to the cells. The situation is straightforward for sufficiently low, fixed energy rings whose advantages and industrial potential were discussed in the last conference[2]. We have built the kinds of magnets required for such rings in a way that extends their applicability to much higher energies. The main criteria of multipole strength, harmonic quality and costs are discussed. For small enough apertures, split-ring multipoles compare favorably in strength and quality to conventional cell magnets at comparable or lower capital, installation and operating costs.

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Comparison of Quad Types

Figure 1 *predicts* gradients for a variety of good quality quadrupoles based on theoretical models consistent with what has actually been achieved. The figure is more revealing when one observes that there are few, if any, gradients larger than 100 T/m *e.g.* virtually all superconducting magnets made so far have radii larger than 3-4 cm with data points from many labs clustering around the flatter portion of the λ=1/20 line. When one realizes that the 50 GeV, SLC beam is supposed to travel nearly one kilometer in a 1.3 cm beam pipe the goal is obvious. Apertures should be lowered into the more steeply rising regions of Fig. 1 and field quality improved to maintain harmonic content at the beam radius. An important aspect of Fig. 1 is that the PMQ curves are steepest. We show that REPMM's are more easily scaled to smaller radii because their fabrication needs fewer steps, is intrinsically more accurate, the parts can be accurately pretested and the "final" assembly can be easily tested and corrected. This is not the case for the other magnet types so that scaling to smaller apertures and the required improvement in tolerances may well require new fabrication techniques if costs are to be maintained.

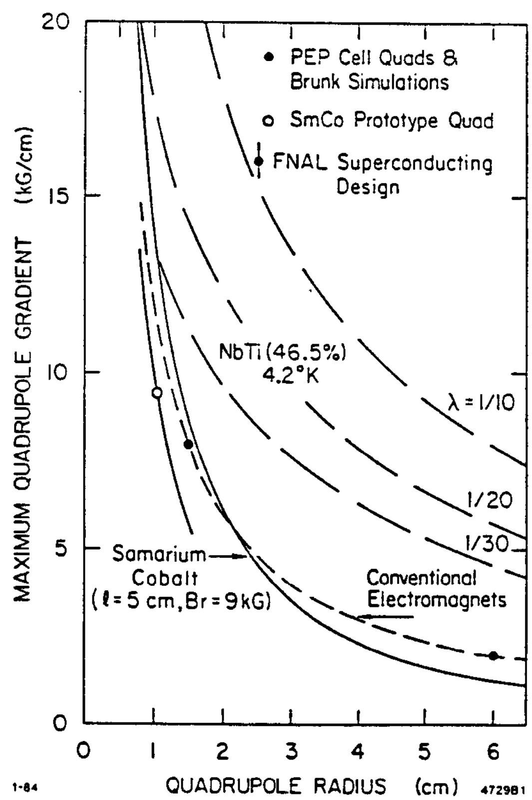

Fig. 1: Comparison of achievable gradients in conventional, superconducting and permanent magnet quads as a function of aperture radius. λ is the superconductor packing fraction.

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Calculations for conventional, iron-dominated magnets have repeatedly shown that pole tip fields exceeding $B_p \approx 12$ kG are inefficient, difficult to achieve, nonlinear, often expensive and seldom satisfactory. This is because the field near the pole root exceeds 20 kG. Many magnets have verified the calculations. For the PEP magnets, shown in the figure at R=6 cm, this is the peak operating point and although improved coils and pole contours could make this an acceptable operating region, it would be better to add PM material in a modified pole and coil design which is not marginal and gives conventional tunability. Halbach has suggested an iron hybrid for tunability where the iron acts as a variable flux shunt[3]. In the same paper he discusses the limitations of scaling current carrying magnets to smaller dimensions based on coil cooling constraints. While one wants to evade this "mortal coil", such constraints are probably not limiting above $R_p = 1$ cm *i.e.* over the range covered in Fig. 1.

The iron-free, superconducting magnets represented by the three, long-dashed lines have elliptical coils with a gradient[4,5]

$$G = -\mu_o \lambda J \left(\frac{a}{a+b} - \frac{a'}{a'+b'}\right) \stackrel{\epsilon=\epsilon'}{\longrightarrow} \mu_o \lambda J \left(\frac{\epsilon - 1}{\epsilon + 1}\right)$$

where λJ is the average current density and $\epsilon (\equiv \frac{a}{b} = \frac{a'}{b'} > 1)$ is the aspect ratio of the coils. For any chosen gradient, there will be a limiting radius (b) which depends on the quad design *i.e.* coil geometry, material and packing fraction. The relationship between these parameters, for elliptical coils, is[5]:

$$\lambda b = \left(\frac{B_{max}(T)}{J_c(A/m^2)}\right)\left(\frac{1}{\sqrt{2}\mu_o}\right)\frac{\epsilon+1}{\epsilon-1}\sqrt{1+\frac{1}{\epsilon^2}} \stackrel{\epsilon\to\infty}{\longrightarrow} k\frac{B_{max}(T)}{J_c(kA/mm^2)}$$

with b in cm and k=1/17.8. With a maximum, fixed coil size of a=12 cm and a knowledge of the peak field point in the coil, one finds G_{max} given a material curve of B_{max} versus J_c.

The PMQ's, shown by the solid lines in Fig. 1, are based on using trapezoidal blocks with a maximum length $r_o - r_i = l = 5$ cm and $B_r = 9$ kG. The equivalent pole-tip field is then given by the expression[1]:

$$B_p(n, r_i) = \left(\frac{n}{n-1}\right) B_r \cos^n\left(\frac{\pi}{m}\right) \frac{\sin\frac{n\pi}{m}}{\frac{n\pi}{m}} \left[1 - \left(\frac{r_i}{r_o}\right)^{n-1}\right] .$$

m=16 is the number of blocks and n is the fundamental of the multipole *i.e.* $n = 2$ for quads etc. The SLC prototype magnet, shown by the open circle, uses the smaller block shown in fig. 2 which scales as shown.

Assembly Procedure and Results

The prototype proved to be an unredeemable disaster for several reasons *e.g.* tolerances were essentially determined by the block manufacturers who neither guaranteed nor complied with them due to inability to measure easy-axis angles. Bids were made on a "best effort" basis implied to be ±3° which measurement later showed to be as high as ±10° for some manufacturers. Thus, a single block could cause harmonic errors in all of the low-lying harmonics of a percent or more in an otherwise perfect layer. Table I gives some two-dimensional calculations for this and a number of other errors and multipole types based on the same block shape shown in fig.2.

Fig. 2: Photograph of one-layer and seven-layer quads and a one-layer, split-ring sextupole made with blocks of nominal dimensions $l \times w \times h = 2.10 \times 0.64 \times 1.27$ cm.

Because the properties of the multipoles shown in Fig. 2 are determined by the characteristics of the single block *and* how well it can be positioned relative to the others, it was decided not to vary the R_{pi} of the blocks, because they could be very accurately positioned about a precision mandrel. Having traced the discrepancies between predictions and measurements to large block errors we then began interacting with manufacturer's to obtain precise measurements of the easy-axis angles(transverse and longitudinal relative to the desired B_r direction) just as for B_r. The results of this work and how we use such measurements will be discussed in detail in a joint report[6]. We believe it is now possible to achieve measurements with errors of $\lesssim \pm 0.1°$ for the easy axis and $\lesssim \pm 0.2\%$ for B_r. Figure 3 shows one of five block types we designate as "A". There are 385 blocks plotted in 0.2° angle bins and 28 G field bins with mean values:

$$< \alpha_i > = -0.04 \pm 0.58°$$
$$< \beta_i > = 0.01 \pm 0.64°$$
$$< B_{ri} > = 9401.7 \pm 84.4G .$$

Thus, rather than globally correcting errors by adjusting the R_{pi} of block rows based on magnetic measurements we assemble individual layers based on block measurements of $\vec{B}_{ri}$ and only use magnetic measurements to check assembly.

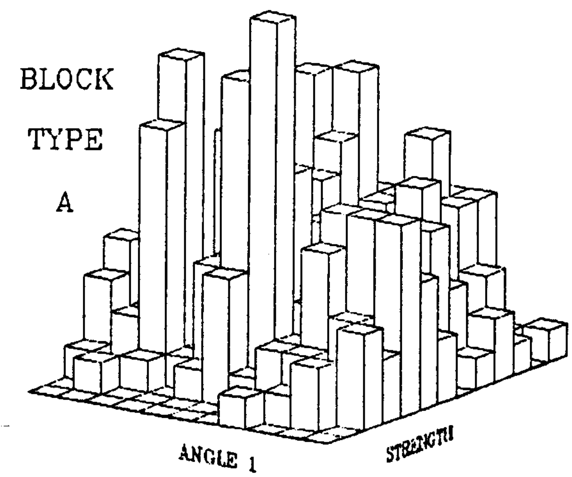

Fig. 3: Typical 3-D plot of the transverse error matrix showing block distribution as a function of B_r-values and transverse, easy-axis angle errors in bins of 0.2°.

The primary assembly algorithm for any multipole and a golden rule for any magnet type is: ***maintain basic multipole symmetry whenever possible.*** Table I shows how small, single-block errors make big harmonic errors which become worse with smaller m. Multiple errors in a single block only worsen things *i.e.* cannot cancel one another. However, when opposing blocks in an otherwise perfect assembly have identical errors, half the harmonics remain zero. Furthermore, when we arrange multiple pairs as shown in the table, we eliminate successively higher harmonics. This is true for any error or any combination of multiple errors in the block *and* remains true regardless of the magnitudes of the errors. Figure 4 demonstrates this for two blocks with large but identical errors.

Defining the integral strength of the REPMM'S in Fig.2 as

$$\int B_y(x,o,z)dz \equiv (\frac{B\rho}{(n-1)!}) \sum_n k_{n-1}x^{n-1},$$

gives, for the sextupole, $(B\rho)k_2 = 110$ T/m and for the quad, $(B\rho)k_1 = 1.30$ T. Such magnets are easily added to existing rings. The longitudinal force from adjacent B-fields, is then

$$F_l = -\sum_{i=1}^{m}(M_{zi}\bar{B}_{zi} + M_{yi}\bar{B}_{yi}) \approx -\sum M_{yi}\bar{B}_{yi}$$

where $\bar{B}_i$ is the normalized volume integral of the field over the ith block and the approximation is for a sector dipole. With no misalignments, F is zero for PMQ's and very small for PMS's. Similarly, the transverse force is zero.

It is simpler to build, measure and operate these magnets and often less expensive. Their use in the damping ring makes it easier to model and should bring model and measurement closer together. Aging effects in the damping ring environment are easily monitored by simply removing a few and measuring them occasionally. Different methods for varying REPMM's are described in ref's. 1,3,7. The latter describes a low-beta(β^*=0.5 cm) PMQ system for 50 GeV electrons. The use of the sextupoles is discussed in ref. 8.

Table I: 2-D calculations of harmonics at the pole radius for the block in Fig. 2 where $B_r = 9250$ G and α_i is the easy-axis angle of block i and θ_i is its location.

Description	$n=1$	2	3	4	5	6
Perfect Quad	0.0	100.0	0.0	0.0	0.0	0.0
$\delta\alpha_2 = 1°$	0.088	100.0	0.108	0.101	0.091	0.081
$\delta R_{p2} = 0.01R_p$	0.062	99.87	0.171	0.205	0.227	0.237
$\delta B_{r2} = 0.01B_r$	0.050	100.1	0.062	0.058	0.052	0.046
$\delta\alpha_2 = \delta\alpha_{10} = 1°$	0.0	100.0	0.0	0.202	0.0	0.162
$\delta\alpha_2 = -\delta\alpha_{10} = 1°$	0.176	100.0	0.216	0.0	0.182	0.0
$\delta\alpha_{2,6,10,14} = 1°$	0.0	100.0	0.0	0.0	0.0	0.324
Perfect SD	0.0	0.0	100.0	0.0	0.0	0.0
$\delta\theta_2 = 1°$	0.216	0.423	99.98	0.698	0.778	0.831
$\delta\alpha_2 = 1°$	0.108	0.141	100.0	0.139	0.130	0.119
$\delta R_{p2} = 0.01R_p$	0.080	0.165	99.76	0.291	0.332	0.359
$\delta B_{r2} = 0.01B_r$	0.062	0.081	100.1	0.080	0.074	0.068
$\delta\alpha_2 = \delta\alpha_8 = 1°$	0.215	0.0	100.0	0.0	0.259	0.0
$\delta\alpha_{2,5,8,11} = 1°$	0.0	0.0	100.0	0.0	0.0	0.0

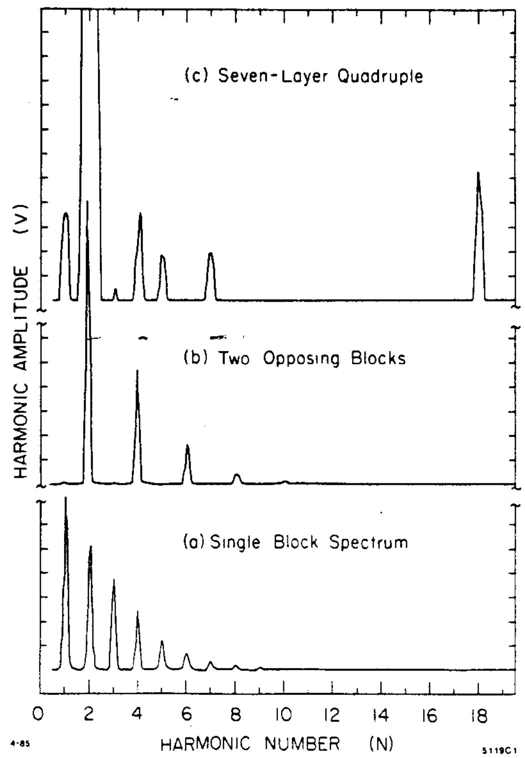

Fig. 4: FFT spectra for magnet development of Fig.2 showing: (a) a single block with all harmonics, (b) two matched, opposing blocks making an elementary quadrupole with all even n harmonics, and (c) a seven-layer quad with the first symmetry allowed harmonic of n=18 and A_{18}/A_2=0.08%.

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