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Comparison of SmCo and NdFeB in PM Multipoles*

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Abstract

We study the use of such compounds in the strong, permanent magnet multipoles required for handling high energy, charged particle beams. We have made a number of $SmCo_5$ multipoles which have been used in a variety of ways e.g. sextupoles for chromatic correction of the SLAC damping rings and quadrupoles for matching their associated injection and extraction lines. For applications in high radiation areas, we have used VACOMAX 170 thermally stabilized at 80° C. Because our fabrication method uses measured characteristics of individual blocks in isolation, linearity over the operating range of the B-H curve is important. Stronger PM materials or multipole magnets increase the operating range which decreases linearity and increases unwanted harmonics. To study such effects, multipole magnets of VACODYM 370 are being made at different radii to emphasize high field effects which can drive parts of a magnet well into the third quadrant of the B-H curve. The results are compared to calculations based on various assumptions and our previous results for SmCo.

Introduction

The development of new magnetic materials is a lively area of current research. Mechanisms and materials producing high coercivity, Curie temperature, linearity and their interplay are not understood. Furthermore, reduced temperature operation at the opposite extreme of the Curie point (usually in high field environments) has been ignored until recently[1] even though relevant for many applications – probably because this reduces the attractive self-sustaining, zero maintenance characteristics of these devices. Other important studies for high energy physics include radiation effects and their relation to local thermal effects and the possibility of annealing and/or thermal cycling. In the following SmCo always refers to $SmCo_5$ and NdFeB to $Nd_2Fe_{14}B$ near 20° C.

Description of Rare Earth Multipoles (REPMM's)

Ideally, blocks used for REPM's should have a homogeneous distribution of magnetic polarization $\vec{J}(\equiv J_r e^{i\alpha})$ with small block-to-block variations in both magnitude(remanent field strength) and direction(easy-axis). The desired easy-axis direction, specified by a unit vector $\vec{r}$, varies around the magnet aperture to provide a piecewise linear approximation to the continuous distribution. Figure 1 shows some examples of split-ring, circular multipoles. These are compared to the corresponding iron-dominated electromagnets and a "combined function" or "edge-effect" magnet.

The easy-axis arrow and corresponding block type designation(A,B,C,D,E etc.) are scribed on only one side of each block so that all reference surfaces can be specified and used unambiguously. A library of blocks with five easy-axis orientations has proven adequate for most applications. The 8-block dipole is compounded of two, 4-block dipoles which are both compounded of two elementary 2-block dipoles. This is the basis of our multipole construction algorithms discussed elsewhere[2,3].

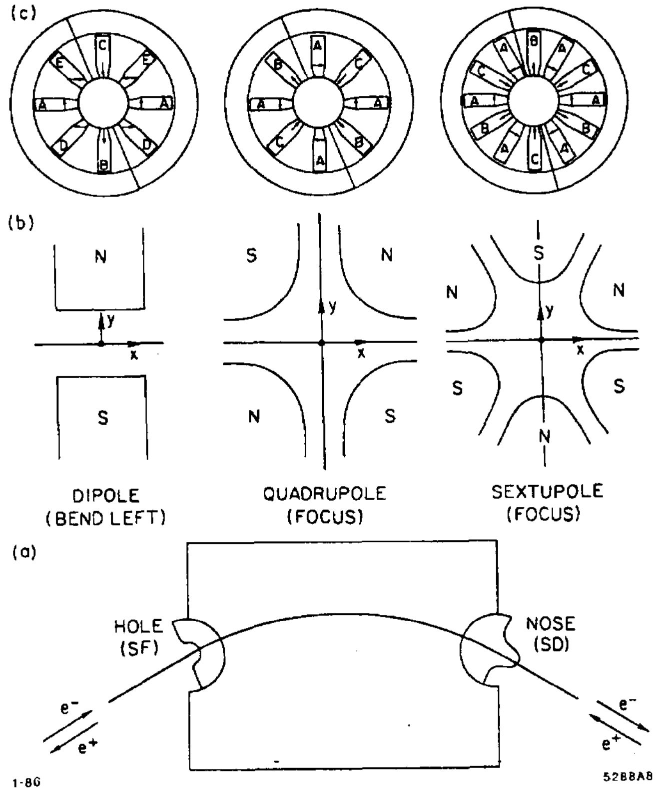

Fig. 1: Some different ways of obtaining dipole, quadrupole and sextupole fields using: (a) "combined function" systems with rotatable end shims; (b) conventional, iron-dominated electromagnets and (c) permanent magnets. The magnetic midplane is defined by y=0 and polarities are all positive with respect to one another except as noted by SD.

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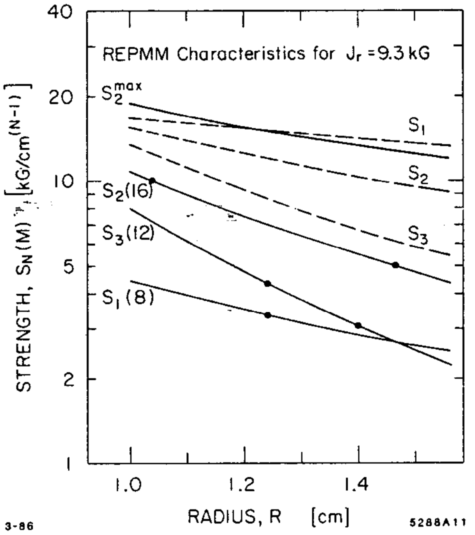

Fig. 2: Strengths of multipoles shown in Fig. 1 for $SmCo_5$ blocks with J_r = 9.3kG. The 8-block quad in Fig. 1 has strength $2S_2(8) = S_2(16)$. The dots represent magnets that have been made for the SLC damping rings, their injection and extraction lines and the final focus as shown in Fig. 2.

From the desired distribution of magnetic polarization for the 2N-multipoles in Fig. 1 where 2N=2=dipole etc., it is clear that:

$$\vec{J}_N = J_r e^{i[\frac{\pi}{2}+(N+1)\theta]} \qquad (1)$$

for a continuous variation of the easy-axis, in which case one gets a pure multipole i.e. a central field with no higher-order, symmetry-allowed error harmonics so long as J_r remains constant. The goal is to obtain this distribution as closely as practicable with as high a J_r as possible.

Approximating $\vec{J}_N$ as in Fig. 1 with a set of M discrete blocks distributed uniformly around the magnet aperture in angular steps $\Delta\theta = 2\pi/M$, the desired easy-axis varies in steps of $(N+1)\Delta\theta$ so that

$$\alpha_m = (\alpha'_o + \theta_o) + m(N+1)\frac{2\pi}{M} \qquad (m = 0, 1, ...M-1) \qquad (2)$$

where α'_m is the easy-axis orientation relative to the block axis(θ_m) and α_m is relative to the horizontal axis.

Minimizing the number of block types by using symmetric, complimentary angles for α'_m and imposing median plane symmetry for the fields$(B_y(x,y) \equiv B_y(x,-y))$ fixes θ_o and α'_o. From this one sees that systematic errors in either θ_m, α_m or both don't change the magnet but only its optical effects and can be corrected by simple complimentary rotations of the magnet as a whole e.g. $\delta\theta_o = -\delta\alpha_m$. Similar arguments imply that systematic errors in either strength or easy-axis angles are not as important as relative errors or the precision with which we know the characteristics of the individual blocks. For a perfect set of M-blocks which are not driven into the third quadrant from their mutual fields, the allowed harmonics will be $N + nM$.

The multipole strength is directly proportional to the number of blocks, their remanent magnetization and a function that depends on the size, shape and location of the blocks. The field distribution follows directly from Fig. 1:

$$\vec{B}_N(\vec{z}) = B_{PT}\,(\frac{r}{R})^{N-1}\, e^{-i[\frac{\pi}{2}+(N-1)\theta]} \qquad r \leq R \qquad (3)$$

where $\vec{z} = re^{i\theta} = x + iy$. One can show that the maximum strength occurs when $M \to \infty$ and blocks completely fill the space between two concentric cylinders with radii $R_i \leq r \leq R_o$, in which case, the optical strength of any multipole is:

$$S_N \equiv \frac{B_{PT}}{R_i^{N-1}} = \frac{J_r}{R_i^{N-1}}\frac{N}{N-1}\Big[1-(\frac{R_i}{R_o})^{N-1}\Big] \longrightarrow \frac{J_r}{R_i^{N-1}}\frac{N}{N-1} \qquad (4)$$

and $S_{N=1} = J_r\, ln(\frac{R_o}{R_i})$. Such expressions have been derived by Blewett as early as 1965 and by Halbach[4]. Figure 2 compares this limit to detailed calculations for the multipoles of Fig. 1 on the assumption that $\mu = 1$ everywhere.

One understands the slopes and magnitudes in Fig. 2 from this expression which is also shown for $R_o - R_i = 5$ cm which is consistent with current manufacturing capabilities. The limit $R_i/R_o \to 0$ in Eq. (4) is designated S_N^{max} in Fig. 2. Dipoles with $S_1 \geq B_{PT} \geq 2$ T could be made using Nd-Fe-B and this number is expected to grow significantly. The value $J_r = 9.3$ kG corresponds to the $SmCo_5$ blocks which we have used for several years. High quality quadrupoles with gradients $S_2 \geq 1$ T/cm are good design benchmarks[3] for SmCo. While this depends on the radius, trends toward low emittance beams favor[3,5] REPMM's in many cases over the alternatives – especially if they can be made with good stability (or hardness) and low harmonic errors. The problem is that the magnets are increasingly driven toward the highly nonlinear regions of their B-H characteristics where they become increasingly vulnerable.

High Field and Hysteresis Effects

High field applications are examples of 'life on the edge' — always interesting and seldom successful except for the lessons. Permanent magnets are no different than other magnets in this respect. They are characterized by hysteresis loops, as shown in Fig. 3 for the materials used here, which define 'high' for each material. They normally operate mostly in the second quadrant and stability is achieved by 'fixing' magnetization thermally and with external fields consistent with the intended use analogous to other kinds of magnets[6]. This is a literal example of how research tastes affect change and impermanence.

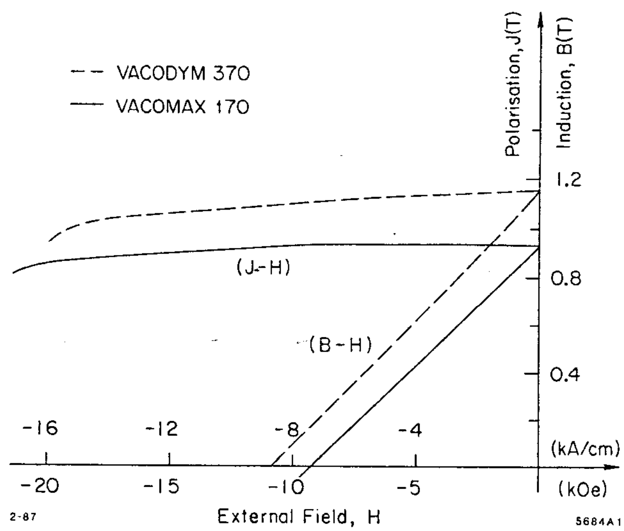

Fig. 3: Demagnetization quadrants of the hysteresis curves for both kinds of rare earth permanent magnets studied. The upper curves give the polarization J=B-H and the lower ones give B.

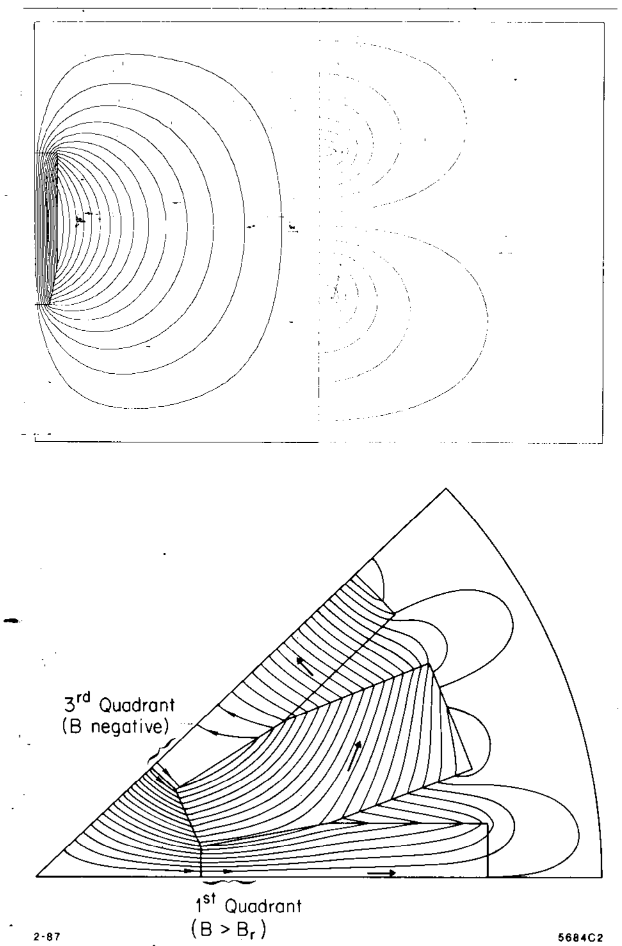

Fig. 4: Field plots of single and multi-block combinations showing the range of operation in different conditions. Calculations were done with the code PANDIRA.

The higher the induction, B_r, the higher the external energy density available for applications as well as self and mutual perturbations. Among other things, this usually results in a more nonlinear B-H characteristic and a smaller intrinsic coercive force, H_{ci}, or demagnetizing field, H_k. These, in turn, are are expected to result in worse stability, error harmonics and a somewhat lower than expected strength in the final magnet[7]. Several methods have been suggested[2,3,6,7] to deal with this. Figure 4 shows such effects for single blocks and a quadrupole arrangement. When the easy-axis is oriented perpendicular to the long axis(labelled A in Table I & Fig.1), the self excitation $H \to -J_r$ near the 'pole-tip' and clearly exceeds it in the quad. In contrast, the blocks with J_r parallel to the long axis(labelled B/C) should be augmented and made somewhat stronger depending on the permeability.

Table I: Comparison of SmCo(Vacomax170) and NdFeB(Vacodym370)

Block	SAMARIUM		NEODYMIUM		#
Type	n=1	n=3	n=1	n=3	Blocks
A	4798 ± 19	2116 ± 12	5898 ± 24	2623 ± 22	1
B/C	5001 ± 21	2141 ± 17	6002 ± 47	2578 ± 28	1
A	9662 ± 18	4240 ± 20	11836 ± 39	5243 ± 37	2
B/C	10055 ± 38	4335 ± 21	12068 ± 63	5208 ± 35	2
A		12773 ± 66		15586 ± 122	6
B/C		12985 ± 48		15637 ± 74	6
A/B/C		25938 ± 100		31516 ± 98	12

Based on this, our first test used a 12-block sextupole[2,3] composed of only A,B&C blocks as shown in Fig.1. Some of the data for the SmCo example in Table I is shown in Fig. 5. Although we selected stronger A blocks, the B/C's were still strongest. This resulted in the major error harmonic at n=9. Similar quality results were observed for NdFe. The ratio of the B/C blocks remained constant for the two materials, independent of the number used, while the A's for NdFe grew significantly weaker as expected.

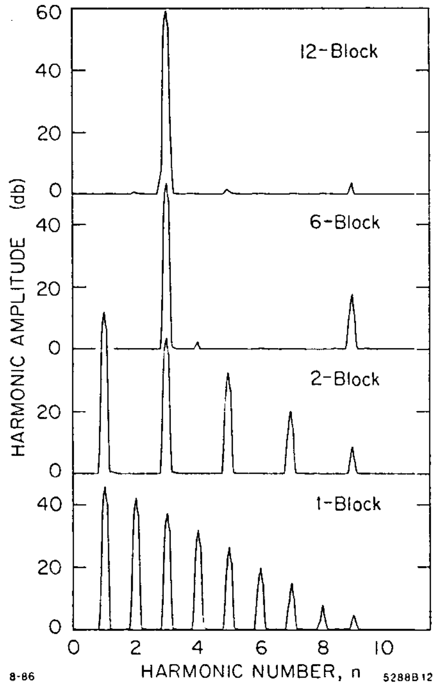

Fig.5: FFT spectra of amplitude versus frequency for a damping ring sextupole as shown in Fig's. 1-2 indicating the basic construction technique. For the 12-block system all error harmonics are down more than 55 db. This particular spectrum is for $SmCo_5$.

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