Magnets for High Energy Colliders*

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Abstract

The problem of producing, preserving and stably colliding low emittance bunches for long periods of time is a formidable problem involving questions of jitter, dynamic alignment and reproducibility associated with magnetic and mechanical hysteresis. Permanent magnets provide ideal solutions for lower capital and operating costs. Because they are light in weight, compact and require no power or cooling they are easy to use, stable and uniquely reliable. With their low permeability, this implies a minimal impact on the surrounding environment and vice versa. For example, they are ideal for final focus systems embedded in particle detectors with strong solenoidal fields while their strength and compactness minimizes the solid angle they subtend around the interaction point(IP) as well as their target thickness along the beam line. We discuss calculations where $\vec{B}$ is a nonlinear, anisotropic function of $\vec{H}$. The results explain discrepancies observed between measurement and calculation of permanent magnet systems and indicate good multipoles are possible with far higher strengths than previously obtained. We extend previous calculations on the obtainable gradients for different types of quadrupoles down to 1 mm bore radii where 2000 T/m appears possible with conventional designs and available materials. We discuss why much higher gradients are possible by the same means. Additional specifications for PM manufacturers are recommended.

1. Introduction

As beam energies have increased logarithmically with time so has the complexity of accelerators and their control systems. Without new technology one expects corresponding cost increases. While new approaches like the SLC are justified on such grounds, they often use old technology unless there is no alternative. The PM multipoles used in the SLC damping rings and their injection and extraction lines[1, 2] are examples where conventional electromagnets couldn't provide the needed strength in the available space. It has been argued that such magnets might also be used in the next generation linac[3, 4] as well as the final focus system(FFS)[5]. This has been the area of most interest because it requires the highest fields. Of course, there are many other possibilities and approaches. At CERN, Sievers has considered low-inductance, high-current, pulsed quads, Riege et al. are studying plasma devices and Egawa and Taylor consider 'recorder-head' magnets in another paper in these proceedings[7].

If one considers only 'linear' colliders i.e. colliding linacs it is possible to confine the discussion primarily to quadrupoles. Because linac accelerating gradients require shorter wavelengths and higher luminosity requires smaller emittance, a new scale is possible for magnets which allows higher magnetic gradients via smaller apertures. The problem is to maintain relative field quality as a function of radius. We compare the strengths of conventional quadrupole designs based on coil, steel and PM dominated systems. In each case, detailed 2D-calculations were made for a range of radii consistent with known constraints. The results provide a straightforward comparison of the limiting gradients achievable as a function of radius and so provide useful guidelines for various magneto-optical calculations as well as benchmarks for magnet designers - including those interested in alternative approaches. They also indicate where improvements in the materials and their specifications would be useful[6, 2]. The underlying models and the results for quadrupoles can be used to infer the limiting strengths for other multipoles.

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2. Description of the Problem

Figure 1 shows a plan view beginning at the IP that includes the last telescope and part of a chromatic correction cell(C^3) for a CLIC FFS[8]. While the C^3 includes several multipolarities, all dipoles such as B1 are soft and require no discussion. The first quad(QD1) is almost completely immersed in the superconducting solenoid field assumed for the detector. Other quads such as QF1 may be outside the solenoid and are also weaker. Depending on the gradient one achieves for QD1 compared to a nominal value of ≈750 T/m, there can be more than 2m of free space on either side of QD1. In this case, the optics were constrained by the gradients that were believed possible for a 5 mm aperture but other FFS designs usually assume higher gradients[9] i.e. smaller radii that are located closer to the IP because this significantly simplifies the non-linear optics.

3. Comparison of Quadrupole Types

Figures 2–3 show the various magnet models that were used and the maximum gradients expected in each case. The predictions are based on conservative parameters such as chose of materials and characteristic dimensions. As far as we know, the results are consistent with what has actually been achieved. The figure becomes interesting when one observes that there are no gradients larger than 200 T/m currently operating[10] e.g. virtually all superconducting magnets have radii larger than 2-3 cm with gradients from many labs clustering below the curve in Fig. 3.

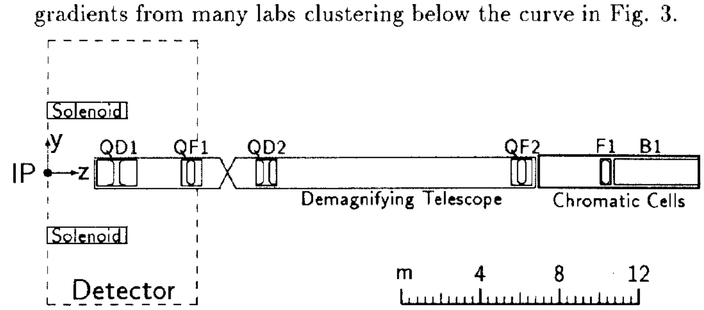

Figure 1: Layout of a final focus system for a TeV linear collider.

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3.1 Iron-Dominated Magnets

The curve for iron-dominated magnets in Fig. 3 has been given previously[1]. Results for conventional electromagnetic quads have repeatedly shown that pole tip fields exceeding $B_p \approx 12$ kG become increasingly inefficient and nonlinear with excitation; difficult to calculate or predict accurately; difficult to realize and use and usually expensive because special steels, heat treatment and permeability measurements are often necessary. The magnet of Ref.[11] with R=5 mm was 76% efficient with $B_p = 12.4$ kG.

Because the field near the pole root approaches 20 kG, one must generally design the whole volume of the magnet and not just the pole surface with $\mu = \infty$ throughout. One can achieve a nearly perfect magnet with finite μ by exciting it with PM material so the pole shape need not accommodate coils. This can also improve the internal field 'bottleneck' at the pole root but can't make the magnets stronger than pure PM quads.

Fig. 4 shows some results for the 1.27 cm aperture magnet of Ref.[11] calculated with POISCR[12]. This design was scaled to different radii with similar results indicating that saturation effects saturate leaving a reasonably good magnet regardless of excitation method or level. Fig. 5B shows an extreme limit with similar results. Thus, one expects the straight line in Fig. 3 to extrapolate to smaller radii – perhaps until the radius approaches the domain size while its intercept is probably good to 20%.

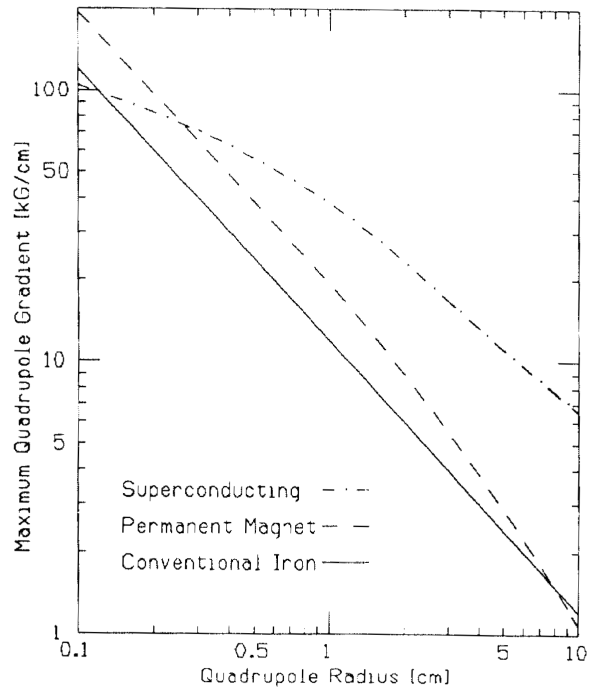

Fig. 3: Strengths obtainable for the different quad types in Fig. 2 based on a peak pole-tip field B_p=12 kG for the iron, a maximum remanent field B_r=11.5 kG for the PM material and NbTi wire with J_c=2kA/mm^2 at 5T and 4.2°K.

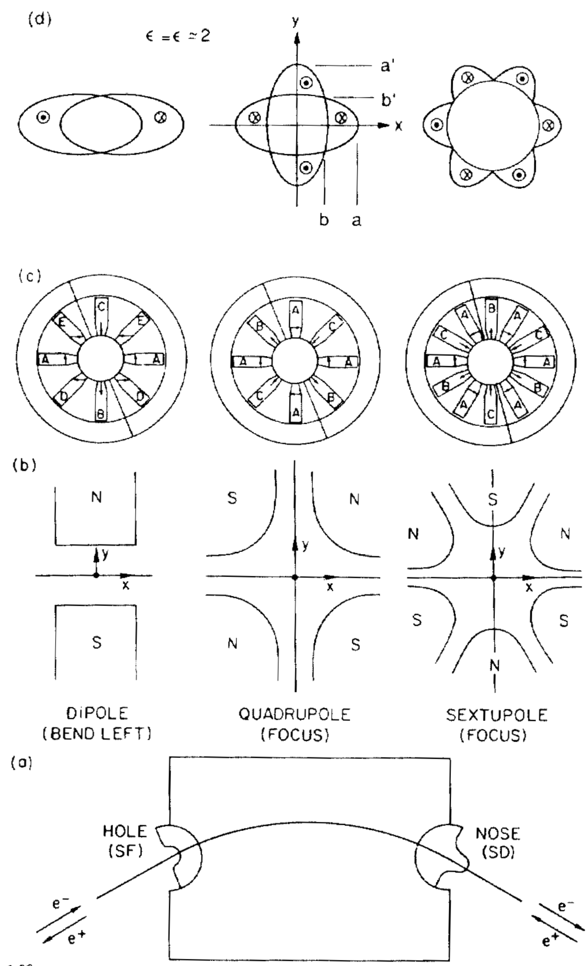

Fig. 2: Some different ways of obtaining dipole, quadrupole and sextupole fields using: (a) variable edge rotations and curvatures; (b) conventional, iron-dominated electromagnets; (c) permanent magnet- and (d) coil-dominated systems. The magnetic midplane is defined by y=0 and polarities are all positive with respect to one another except as noted by SD.

3.2 PM-Dominated Magnets

The PM curve in Fig. 3 assumes 16-block NdFeB quads with B_r=11.5 kG[2]. It parallels the iron curve out to 1 cm because we increased the radial size of blocks to maintain R_i/R_o = 90% up to a maximum block length of 10 cm. This implies a crossover between iron and PM around 5-10 cm depending on materials. Even here one may prefer to use pure PM inside solenoids but a hybrid should also be considered since PM provides a stable, strong excitation B_r/μ. As with iron, nonlinearities need to be considered as well as the possibility of depolarization. Detailed calculations were done[5] with POISCR for various configurations using a nonlinear, longitudinal permeability μ_l[2] supplied by the manufacturer and a transverse permeability assumed to be $\mu_t = 1.1\mu_o$. Fig. 5C shows an example where the calculated gradient implied $\overline{\mu} = 1 + 2\delta G/G$=1.05. Because this agrees with analytic calculations to a few percent, one expects gradients G$\approx 2 \times 10^4$T/m for bore radii of 1 mm. Further, the straight line portion of the curve in Fig. 3 should extrapolate to smaller radii with similar caveats as for iron.

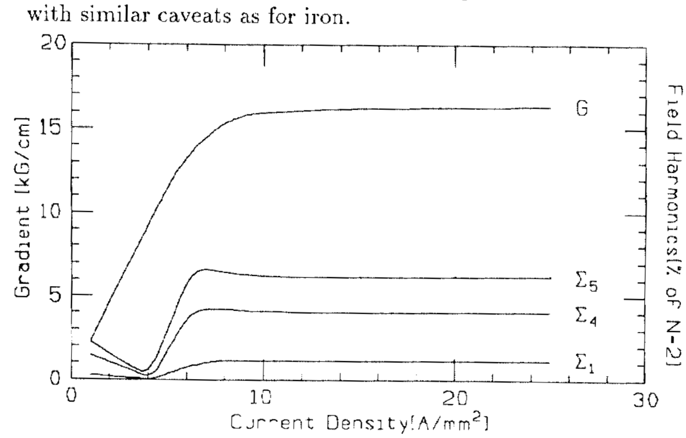

Fig. 4: Harmonic content at the pole radius R=6.35 mm as a function of current density for the magnet of Fig. 5b.

3.3 Coil-Dominated Magnets

The curve in Fig.3 is for the iron-free, superconducting, elliptical coil quad of Fig. 2. Beth[13] showed such coils could produce a pure 2D multipole field. It has been studied in detail[14] with an analysis for wire placement errors and a variety of POISSON calculations such as shown in Fig. 5D. The gradient is:

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

where λJ is the average current density and the aspect ratio $\epsilon = a/b$ as shown in Fig. 2D. A value of $\lambda = 1/5$ with variable $\epsilon = \epsilon'$ with a_{max}=12 cm is consistent with the superconducting quad for SLC[10] which allows us to extrapolate to other radii. The method for determining the gradient is described in Ref. 1.

4. Conclusions

We have shown why both iron and PM magnets may be extended to very small radii $\ll$1 mm. This is simplified for iron by using PM material. While the nonlinearities assumed for different materials degrade both quality and strength, the results are generally good for such strong magnets. In most cases the first allowed harmonic was $n_6/n_2 \leq 1\%$ at the bore radius. Comparing the strengths shows that superconducting magnets are clearly best above 1 cm but PM have advantages for sufficiently small bore sizes where coil real estate becomes increasingly scarce. One expects such advantages to improve with increasing multipolarity N as seen in Fig. 2. While the relative strengths required for multipoles usually decrease with increasing N so does quality.

Pure permanent magnets provide advantages when scaling to smaller radii because their fabrication is intrinsically precise, the parts can be pretested and "final" assembly can be tested *and* corrected. We also believe there are a number of different optics schemes and mechanical designs for them which allow variability of both energy and beta function(β^*).

The question of how one should represent these materials in calculations is still an open question i.e. we have assumed that the magnetic susceptibility χ_M depends nonlinearly on only the component of H parallel to the polarization $\vec{P}_M$ but the situation is more complicated. Measurements of the full susceptibility tensor for both iron and PM for different temperatures at such size scales would be very interesting and relevant to many applications. A project for building and measuring a PM and PM hybrid with a nominal radius R≈1-2 mm to study effects of mechanical tolerances, easy-axis errors, remanent field strengths and magnetic susceptibilities $\chi_{l,t}$ on gradients seems warranted.

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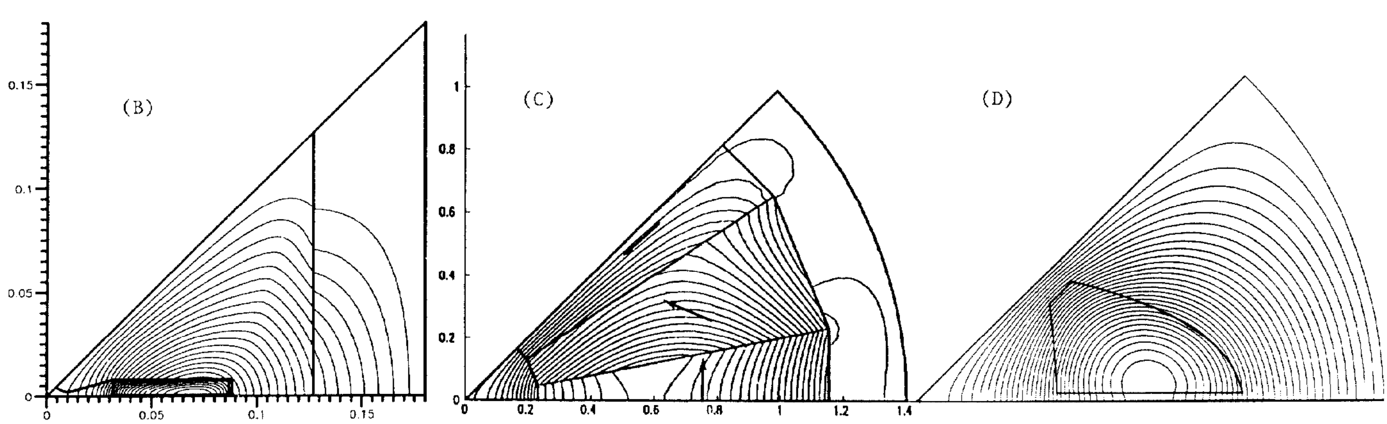

Fig. 5: Field plots for the various quadrupole types(or their variants) shown in Fig.2 for (b) fully saturated iron at 2 kA/mm^2, (c) PM quad with G=726 T/m at R=2.3 mm and (d) superconducting quad with mandrel and synchroton radiation cutouts at 0° and 45° where the coil field is highest.