Questions on Criteria Used for Magnet Field Quality* DOE/ER/40374--59

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Abstract

Questions are raised here, without providing any answers to them, regarding the standard way of specifying the tolerances on various multipole components in superconducting dipoles. They are: 1. Dependence of systematic b_6 (normal 14-pole) and b_8 (normal 18-pole) on the required momentum aperture, 2. Importance of resonance width (and its precise meaning) for specifying random low-order multipoles, and 3. Understanding tracking results in terms of multipole components.

1.0 Introduction

The primary purpose of raising a few questions here on the subject of criteria which are customarily used to specify the field quality of superconducting magnets, especially dipoles, is to solicit answers during this workshop from those who are actively engaged in the planning or construction of large hadron colliders. These questions have been nagging me for many years, ever since I had to compose a (quasi-official) Fermilab answer to the question

"Are the present best magnets (or magnet) suitable as is for the pp collider at luminosity = 10^{30} ?" which was presented to Fermilab management in May 1980 by HEPAP.¹

There are, of course, many factors affecting the stable operation of superconducting colliders, the field quality of magnets being just one of them. For example, one might randomly list lattice, beam monitors, power supply ripples, correctors of all kinds, feedbacks, magnet sorting, and the empty space in the ring. Of these, the last item may turn out to be one of the most important, particularly if it is "warm."

In raising questions on criteria for the magnet field quality, one must also ask whether "reality" should play any role in the discussion during a workshop such as this one or in the study of real projects (SSC, LHC, RHIC, ...). I mention here a few items of "reality" which we could not ignore during the energy doubler project:

1. compromises to be made between magnet builders and accelerator builders,
2. reliability of measurements, especially if "warm" results are the only ones available,
3. acceptance-rejection guidelines (which may be different from criteria) for magnets and their implementation, and
4. question of long-term stability of the field quality.

The motivation for raising the questions at this time came from the following developments at the Texas Accelerator Center (TAC):

- 1) TAC is considering a proposal to DOE to develop two-in-one magnets which will be suitable for the energy doubling (from 20 TeV to 40 TeV) in the SSC tunnel.
- 2) Development of high-field superferic magnets for SUPERLEAR² at CERN.

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2.0 Questions - General

In any design of accelerators or storage rings, one must of course be reasonably sure of the aperture that will be available to the beam for its manipulation (including acceleration) and its storage with a desired lifetime. Different types of aperture have been introduced with not-always-common definition for each, namely dynamic aperture, momentum aperture, and linear aperture in addition to the obvious physical aperture. For whatever definitions one chooses for them, the tracking of individual particles through magnets of assumed field quality must eventually be performed to find the apertures. Since trackings must be done for many different arrangements of magnets even with a specific sorting scheme in mind, they are generally quite time-consuming and the end results are often hard to understand ("Why is the dynamic aperture so small with this seed number compared with the one with that seed number?"). It is therefore customary to express the magnetic field in terms of the multipole components (a_n, b_n):

$$B_x(y=0) = \sum a_n x^n, \quad B_y(y=0) = \sum b_n x^n \quad (1)$$

and calculate the quantities such as the dependence of tunes on the momentum deviation ($\Delta p/p$) and on the betatron oscillation amplitudes (A_x, A_y), width of various resonances up to whatever order one cares to consider, and the quantity called "smear" which was originally introduced as a measure of nonlinearity when many weak resonances contribute more or less equally without any one of them dominating.

In order to set the criteria on each multipole component, it is then necessary to say something quantitative on each quantity just mentioned (Δv vs. $\Delta p/p$, etc.) and this inevitably involves a certain degree of arbitrariness since one cannot express the absolute value of aperture as a function of these quantities (unless, of course, it is simply a definition). The general question is:

"Is this still the best way to set up the criteria for the field quality of magnets, or are we doing this simply because we do not know what else to do?"

3.0 Specific Questions

3.1 Systematic High-order Multipoles

In designing a superconducting dipole, one tries to eliminate a few low-order multipoles, usually b_2 (sextupole) and b_4 (decapole), by adjusting coil angles or some other free parameters. As a consequence, the remaining high-order multipoles ($b_6, b_8, \dots$) can be rather large. For example, in the Tevatron dipoles, we find b_6 (average) = $5.5 \times 10^{-4}/\text{in}^6$; b_8 (average) = $-12.5 \times 10^{-4}/\text{in}^8$. For 3T superferric dipoles developed at TAC for the SSC,³ three independent currents were used to control dipole, sextupole and decapole components with the resulting $b_6 = 1 \times 10^{-4}/\text{cm}^6$. This was considered to be unacceptably large compared with the expected (but not fully demonstrated) performance of Design D dipoles: $b_6 = -0.03 \times 10^{-4}/\text{cm}^6$.

According to the standard formulas derived by many people, the dependence of tunes on the momentum (and, sometimes, on the betatron oscillation amplitudes as well) dictates the acceptable values of systematic b_6 and b_8 . Indeed, one finds a statement that the momentum aperture of the superconducting ring will be limited ultimately by high-order multipoles which in effect form an "edge" to the godd-field region. Aside from a real problem of how well one can measure such high-order multipole components, the difficulty inherent in this approach is the appearance of very high power in $(\Delta p/p)$. When the betatron oscillation amplitudes are ignored, one finds $\Delta v \propto b_6 (\Delta p/p)^5$ and $b_8 (\Delta p/p)^7$. If, for whatever reasons, the required $(\Delta p/p)$ is reduced to 60% to 70% of the original value, the allowed values of b_6 and b_8 will be more than an order of magnitude larger for the same value of Δv .

How well can one specify the required magnitude of $(\Delta p/p)$ for a stable operation of a particular accelerator? Some of the factors influencing the specification are

1. injection energy errors,
2. beam energy spread (how many σ 's?)
3. collective instabilities,
4. intra-beam scattering.

None of these are precise enough to specify the required $(\Delta p/p)$ with the uncertainty of less than, say, 30%. How can we then tell the magnet designers and builders to limit b_6 and b_8 to a certain value without introducing an uncertainty of factor five or even more?

Is it at all conceivable to abandon the specification of b_6 and b_8 , using instead some criteria based on the field flatness?⁴ If we use the field flatness, how do we come up with the allowed deviation of the magnetic field within a given physical aperture?

3.2 Random Low-order Multipoles

In principle, it is possible to calculate all the effects arising from the random quadrupole components b_1 and a_1 in a linear machine once the magnet arrangement is specified. There is no need to perform trackings to find the apertures, dynamic or momentum. It is emphasized here that this is possible in a linear machine. When nonlinear components such as b_2 and a_2 are introduced in addition to b_1 and a_1 , there are no unambiguous ways to find the apertures without extensive trackings.

How should we specify the allowed random multipole components, that is, $\sigma(b_n)$ and $\sigma(a_n)$?

It is claimed by some people that, more or less independent of the total number of magnets involved, the average value of a multipole component is somewhere around one-third of its σ . This seems to have come from the experiences from at Tevatron and HERA where less than one thousand dipoles are used. Whether we should apply this rule-of-thumb to the SSC collider or the LHC is certainly debatable but it can put a limit to the allowed value of σ . Another approach may be a purely pragmatic one. Based on the result from a dozen or so magnets, one may get a "feeling" as to what to expect from the mass-produced magnets. One can then say, "We will reject a magnet if any of its multipoles exceeds $\pm 3 \sigma$," and specify σ such that the expected rejection rate is within a reasonable bound. In many cases, this may very well be the most convenient way to set the criteria on magnet field quality provided one knows how to take care of its consequences. It is also stated (for example Tom Collins, among others) that the allowed value of σ 's should be determined by its "correctability." According to this approach, anything that "cannot be corrected" by practical correction schemes must be rejected. The difficulty here is again how to answer the question of "can or cannot be corrected" without the eventual recourse to trackings.

For the discussion of the allowed value of σ 's, what we usually find in design reports are the "smear" and the "resonance width." In principle, one can estimate analytically the amount of smear resulting from each multipole component with some approximations. There are many unresolved questions on the usefulness of the concept of smear and the definition of linear aperture in terms of a certain absolute value assigned to it is simply a matter of convenience. Smear alone cannot dictate the allowed value of σ 's.

As for the resonance width, the situation is even more confusing because of an illusion most of us share.⁵ There are at least two entirely different definitions of the width^{6,7} and, in somehow trying to relate them to the criteria of magnet field quality, we go through arguments which are at best ambiguous and often devoid of any significance for the problem at hand. Thus we are back to the question: How should we specify the allowed random multipole components, $\sigma(b_n)$ and $\sigma(a_n)$?

3.3 Understanding Tracking Results (or "Can We Learn Anything?")

Finally, the tracking.

After seeing so many questions but no answers to them, one might be tempted to resort to a familiar statement: "Give me the bottom line only. Just track and find the aperture, dynamic or whatever, everything else is immaterial." This is understandable when literally billions of dollars can be added or subtracted from the estimated cost of large accelerator projects if some results from tracking are used to justify the action. If the brute-force, number-crunching trackings by computers are the only way to find the apertures AND if there is no way to understand why some random seed numbers give much larger apertures than other seed numbers, we abandon the usefulness of any concepts such as resonance and harmonic components. We also lose the theoretical underpinnings of the sorting procedures.

The question raised here is: Is it really hopeless to try to understand why some arrangements are so good and why others are so bad? More specifically, do we have any answers to straightforward questions such as:

- 1) Is the skew quadrupole component a_1 important in limiting the aperture even in the presence of a correction system? If yes, are all tracking results done with the assumption $a_1 = 0$ suspect?
- 2) Is it true that, aside from the factor two or so in $\sigma(a_3)$ relative to $\sigma(b_3)$, the skew octupole a_3 is more damaging to the aperture than the normal octupole b_3 ? If so, do we know why?

Finally, as one who has never done (and most likely never will engage in) a large scale tracking calculation, do I have the right to appeal to those active in such endeavors: "Please try to understand your results in terms of a few multipole components and a few of their harmonic components"?

4.0 References

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