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CORRELATIONS IN THE FIELD ERRORS OF SUPERCONDUCTING MAGNETS FOR PARTICLE ACCELERATORS

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Abstract

Random errors in the field of superconducting magnets are mainly due to mechanical tolerances; consequently, multipolar components of different orders can be correlated amongst themselves. A detailed analysis of the data relative to the field measurements, executed on the superconducting magnets of some existing particle colliders, has been performed, and correlations between the multipolar errors have been looked for. The results of this study for the cases of the HERA and of the TEVATRON magnets are reported. Correlations between the different multipolar field components have been found. Unfortunately, their dependence on the specific design, and, often, also on the particular manufacturing and assembling process, does not allow us to use the existing data to make predictions for the superconducting magnets of the future large hadron colliders.

1 Introduction

Spurious multipolar components are inevitable in the field of the superconducting magnets for modern particle accelerators.

The magnetic field can be expressed by

$$B_y + iB_x = B_o \sum_{i=1}^{\infty}(b_n + ia_n)\left(\frac{x+iy}{R_r}\right)^{n-1}, \quad (1)$$

where B_o is the dipole field in the vertical direction, R_r is the reference radius, b_n and a_n are the normal and skew multipolar coefficients, $2 \times n$ is the number of poles.

Since random multipolar errors are mainly due to mechanical tolerances, correlations between different field components should be expected. In order to test this assumption, and to evaluate if and how much collider performances can be affected, the databases containing the field measurements performed on the magnets of several of the present machines, have been analyzed systematically [1], and all possible correlations between the different multipolar components of the magnetic field have been checked. Here we will give a qualitative summary of the results of this study, with emphasis on the results from the HERA and TEVATRON magnets, referring the reader to Ref. [1] for more details.

2 The HERA magnets

The magnetic system of the arcs of the HERA proton ring is entirely made of superconducting magnets. All of the magnets have been measured, and the normal and skew components of the field up to the 16^{th} order are recorded.

A database [2] containing the measurement data of 215 dipoles built in Italy, 221 dipoles built in Germany, 119 quadrupoles built in France, and 125 quadrupoles built in Germany has been analysed.

2.1 Dipoles

The two groups of HERA dipoles have been manufactured by different firms on the basis of the same design, but with slightly different technical solutions; they have therefore been analysed separately. Correlations between the normal multipolar components of the field, between the skew components, and between mixed normal and skew multipolar components, have been investigated.

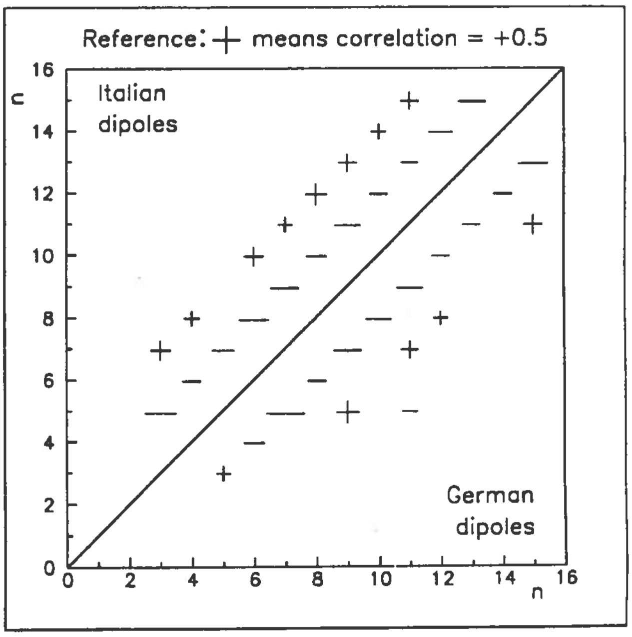

Figure 1: Correlations between the *normal* multipolar components, b_n's, of the magnetic field of the HERA dipoles

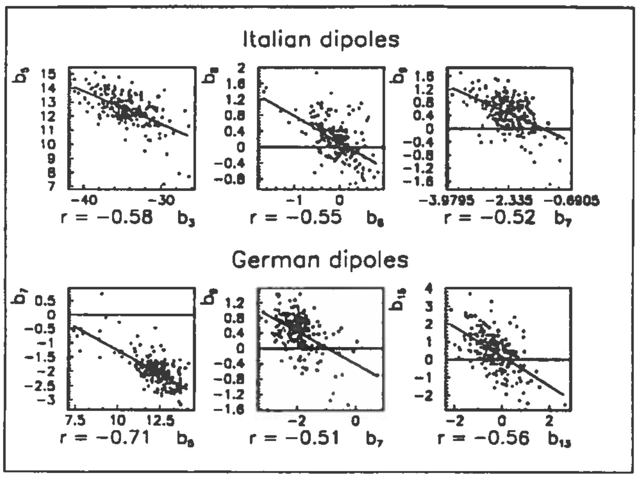

Figure 2: Large correlations between *normal* multipolar fields in the HERA dipoles (b_n are given in units of 10^{-4} at R_r = 25 mm)

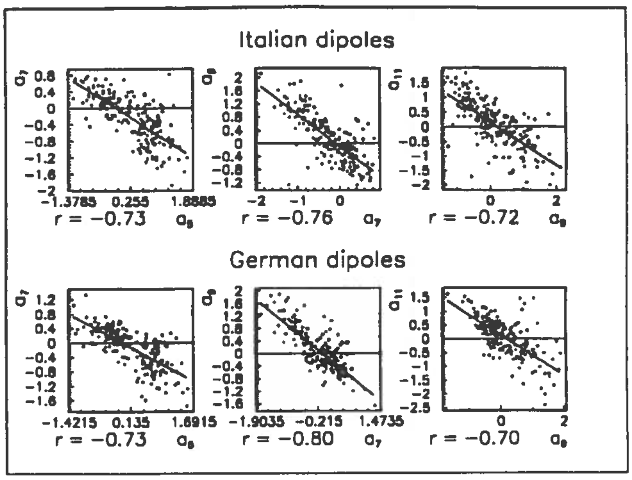

Figure 3: Large correlations between *skew* multipolar fields in the HERA dipoles (a_n are given in units of 10^{-4} at R_r = 25 mm)

The correlations found amongst the normal components of the field are summarised in Fig. 1 for both sets of magnets: the upper part of the graph refers to the dipoles built in Italy, the lower part to those built in Germany; the symbol and its size give information about the sign and the magnitude of the correlation coefficient r (as a reference, the symbol size for $r = +0.5$ is shown).

A quite general behaviour can be observed: every b_n correlates with b_{n-4}, b_{n-2}, b_{n+2} and b_{n+4}, i.e. with its two first neighbours of the same parity on both sides; the correlation with the first neighbour is negative, while the correlation with the second neighbour is positive. This systematic feature has been found in both groups of magnets, with the exception only of the correlation between b_3 and b_5 in the German dipoles, which, although small, shows a sign opposite to the 'rule'.

The scatter plots relative to the cases with the largest correlations are shown in Fig. 2: the corresponding values of the correlation coefficient r are indicated on the single plots. Although the correlations between the different multipolar fields are clearly evident in the scatter plots, the distributions still look 'random enough', so that the performance of the collider should not depart significantly from that estimated for random uncorrelated errors. In addition, the b_n's first neighbours of the same parity, which are more likely to overlap in the composition of the magnetic field, correlate negatively, so that we can even hope for a partial compensation of their effects.

Also in the case of the correlations between the skew components of the magnetic field some general behaviours can be observed: for n odd, a_n correlates with at least three first neighbours of the same parity on each side, whilst for n even, it correlates with one or two first neighbours of the same parity on each side, with the exception of a_2, which correlates with a_4, a_6 and a_8; again, the correlation is generally negative between first neighbours, and positive between second neighbours. Quite strong correlations, even exceeding $|r| = 0.70$, have been found between a_5 and a_7, between a_7 and a_9, and between a_9 and a_{11} in both group of magnets: the corresponding scatter plots are shown in Fig. 3.

Finally, not much correlation has been found between the normal and the skew components of the magnetic field. The German dipoles show slightly more correlations than the Italian ones, in particular b_5 and b_7 of the German group correlate with almost all odd a_n's. Furthermore, for large n's, some correlation is found between b_n and a_{n-1}, and, in some cases, also between a_n and b_{n-1}; this unexpected feature could have also been introduced artificially by some systematic error in the measurement system: the measurement of the small higher-order components of the field is indeed more difficult and can be affected by larger errors.

2.2 Quadrupoles

Also the two groups of HERA quadrupoles have been analysed separately.

Only a few cases of weak correlation have been seen amongst the normal components and amongst the skew components of the field, with the exception of a_6, a_{10} and a_{14}, which correlate quite strongly amongst themselves in the French set of quadrupoles.

Several quite strong correlations are found, instead, by mixing normal and skew multipolar components.

3 The TEVATRON magnets

A similar analysis was conducted for the TEVATRON superconducting magnets. The data relative to 774 dipoles and 228 quadrupoles were available[3].

3.1 Dipoles

The TEVATRON superconducting dipoles were all built at Fermilab; they could therefore be analysed all together.

In the search of correlations amongst the TEVATRON magnets, we can clearly distinguish between two different situations: for $n < 7$ and for $n \geq 7$.

In the case of $n < 7$, only weak positive correlations between b_n's, and between a_n's which are first neighbours of the same parity are observed, whilst no correlation at all is found mixing normal and skew components. It should be noted, however, that b_3 correlates also with all odd b_n's with $n \leq 11$.

For $n \geq 7$, large negative correlations between first neighbours of the same parity, and medium positive correlations between second neighbours of the same parity can be found, both amongst the normal and amongst the skew multipolar components of the field. Furthermore, almost all b_n's of the same parity, as well as all a_n's, correlate more or less amongst themselves, and some of the a_n's even correlate with other a_n's of different parity. Finally, many weak- or medium-strength correlations are found by mixing normal and skew multipolar fields with $n \geq 7$, with the exception of the couples b_{11}–a_{10} and b_{14}–a_{13}, whose correlation is larger.

3.2 Quadrupoles

Not many correlations can be found amongst the normal components and amongst the skew components of the magnetic field; a peculiar feature is that, although weak, correlations appear frequently between second neighbours of the same parity, but do not appear between first neighbours. The only noticeable correlations are between b_{12} and b_{14}, and between a_{13} and a_{14}.

Mixing normal and skew components, a few stronger correlations are observed, expecially at large n: in particular, large positive correlations between b_n and a_{n-1}, and large negative correlations between b_n and a_{n+1} can be detected.

4 Summary

Correlations of different levels and between different spurious multipolar components of the magnetic field have been found in all the analysed sets of superconducting magnets.

Within certain ensembles of magnets some sort of 'rules' can be found, dominating the existing correlations. It is impossible, however, to try to derive general rules in order to make predictions about the magnets of future superconducting machines such as LHC, SSC, or RHIC.

In fact, random multipolar errors in superconducting magnets are mainly due to mechanical tolerances of the conductor positioning and it may well happen that during the assembly of the magnets there are particular directions in which mispositionings tend to occur, thus yielding correlations between the consequent multipole errors.

These 'preferred' directions can, of course, vary from one design to another: for example, whilst both the HERA and the TEVATRON quadrupoles have mainly shown correlations mixing normal and skew components, the LEP superconducting quadrupoles have shown only correlations amongst the normal components, and the TRISTAN quadrupoles only amongst the skew components (see Ref. [1]).

Furthermore, the 'preferred' directions can also differ from one manufacturing and/or assembling technique to another, giving rise to different kinds of correlations, as it is often found in the analysis of the HERA magnetic measurements. As an example of this, it is enough to look at Fig. 1. The correlations having roughly the same strength and the same sign in both Italian and German magnets are most probably due to some design characteristics, but those which are different in the two sets, or arise only in one of them, are much more likely to be due to the manufacturing or to the assembling process.

5 Conclusion

Correlations have been found in the multipolar errors of the magnetic field of the existing superconducting machines.

The analysis of different sets of magnets has shown that the kind of correlations developed can vary not only from one design to another, but also from one assembling procedure to another. Thus no predictions, based on the existing data, can be made about correlations in the magnets of future superconducting colliders; in particular, there is no way to include realistic, meaningful distributions of correlated field errors in the computer simulations for the evaluation of the long-term behaviour of these machines. One will have to wait until mass production starts; only then, after measurement of a first ensemble of magnets, it will be possible to individuate the dominating correlations to be possibly included in the simulations, and, if necessary, compensated in the rest of the magnets.

Acknowledgements

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