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SUMMARY OF THE WORKING GROUP ON ERRORS

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The errors working group discussed various aspects of errors in superconducting storage rings: their measurement, their phenomenological behaviour, minimising them during fabrication, compensating for them, and diagnosing their effects. Accelerator performance of the Fermilab Tevatron and HERA at DESY, accelerator construction of RHIC at BNL, and projections for LHC at CERN were emphasised.

Keywords: Accelerators:superconducting; errors:minimisation; errors:compensation; errors:diagnosis.

1 INTRODUCTION

This report, like the deliberations of the working group, concentrates on four topics: measured behaviour of magnets; feedback from magnetic measurement and accelerator physics to improve magnet construction; error compensation; and error diagnosis. Most of the discussion was specific to errors in superconducting magnets; that which was not has been inserted where it seems most relevant. This report attempts to give no more than the flavour of the presentations; where possible, reference is made to more complete descriptions in these proceedings. I have made no effort to review plenary talks, which tended to be summaries themselves. The plenary talks that most closely related to this working group were given by D. Ritson,[1] and S. Peggs.[2]

One can scarcely imagine a topic less likely to captivate an audience than "magnet errors". And yet, considerable interest was generated at this workshop. Perhaps it was because of the large spectrum of backgrounds represented. There were blasé "old hands" recalling problems from the distant past at the Tevatron, heroes of the recent, successful, HERA campaign, workers from RHIC marshaling strength for their imminent commissioning efforts, and designers from LHC, luxuriating in their not-yet-urgent future challenges. With all phases represented, everyone was both anxious to convey their experience and enthusiastic to learn from others.

Participants in the Errors Working Group were: Y. Cai, A. Faus-Golfe, R. Gupta, B. Holzer, J. Koutchouk, F. Meot, S. Mishra, S. Peggs, Q. Qin, D. Ritson, T. Sen, R. Talman (chairman), G. Tsironis, A. Verdier, L. Walckiers, J. Wei, S. Weisz (secretary), R. Wolf, and V. Ziemann.

2 BEHAVIOUR OF SUPERCONDUCTING MAGNETS

It is well known that there are serious time-dependent and current-dependent effects that cause superconducting magnets to exhibit hysteretic dependence on recent excitation history. Of these the one that has probably received the greatest attention (because it is expected to have the most deleterious effect on accelerator operations) is the time-dependent sextupole field non-uniformity due to persistent superconducting currents. Since these currents circulate within individual filaments and do not conform to the design current symmetry, they cause field non-uniformity; it is predominantly in the next highest multipoles with compatible symmetry, sextupole in this case. The sextupole multipolar coefficient (call it $b_{2,3}$ because the European convention is b_3 and the American convention is b_2) is traditionally measured in parts per 10^4 at a reference radius r_{ref}, chosen (arbitrarily) to be about 2/3 of the coil radius. For LHC take $r_{\text{ref}} = 1$ cm.

The importance of this sextupole field perturbation can be estimated as follows, dropping numerical factors such as 2. The sextupolar component in a dipole magnet that bends particles through angle θ_D causes an unwanted extra bend of magnitude

$$\Delta x' \approx b_{2,3}(x/r_{\text{ref}})^2\, \theta_D \approx b_{2,3}(\text{"units"})\, \theta_D\, x^2\, (\text{m}^2),$$

where (x, x') are the displacement and slope of the particle at the dipole location (For this particular multipole, two conventional factors, 10^{-4} and conversion from centimetres to meters, happen to have cancelled). The leading effect of this deflection is to cause chromaticity $\Delta\chi = \Delta Q/\delta$

where δ is the fractional momentum offset, and ΔQ is the tune shift caused by that momentum offset and the sextupole perturbation. Substituting $x = x_{\text{betatron}} + \eta\delta$, the part of the extra deflection that gives linear focusing is $\Delta x' \approx b_{2,3}\ \theta_D\ \eta\ \delta\ x_{\text{betatron}}$, where η is the dispersion. Applying the well-known formula for tune shift due to a quadrupole perturbation yields the estimate

$$\Delta\chi \approx \frac{1}{4\pi} b_{2,3}(\text{``units''}) \sum \beta\eta\theta_D \approx b_{2,3}(\text{``units''}) \frac{R^2}{Q^3} \approx 100\, b_{2,3}(\text{``units''}),$$

where "typical" values, $\beta \approx R/Q$ and $\eta \approx R/Q^2$ have been substituted as well as $R \approx 4.2 \times 10^3$ m and $Q \approx 63$. Because factors have been dropped, the coefficient 100 has only semi-quantitative validity, but it should be clear that chromaticity from this source is an increasingly important problem as R increases. Since chromaticity changes of order 1 can have a noticeable effect on accelerator operation, it can be seen that 1 unit of $b_{2,3}$ may require compensation at approximately the 1% level.

Effects of cable design on magnetic field quality for LHC prototype magnets were described by R. Wolf, and measurements of these magnets were described by L. Walckiers. The most critical point is expected to occur at the instant the magnetic field resumes ramping up after it has been held constant at the (low) injection field. For the prototype magnets measured, this step was about 1.5 units after a 1 hour injection plateau and was roughly proportional to the length of the plateau. An effect of this magnitude was judged acceptable, but only because the injection phase is projected to last only 15 minutes. It was also found that a ramp rate of 50 A/s caused an unacceptably great rate of change of $b_{2,3}$, though 20 A/s was manageable. A. Faus-Golfe[3] described a procedure for optimising the ramp sequence for these and other effects. The result is that the low ramp rate will need to be maintained for an acceptably small fraction of the overall fill cycle. Concerning the dependence on the multipole order n, L. Walckiers emphasised three different aspects: magnitude of the field error, accuracy of its measurement, and reproducibility of the measurement. Fortunately, when plotted on semi-log paper, all three of these effects tend to lie on parallel straight lines, falling by about one order of magnitude as n increases by 3 units. Another effect that will require care is that the twisting of a long dipole rotates the magnetic field axis by as much as 10 mrad over the length of a dipole. By careful magnet orientation the unwanted vertical deflection from this effect can be held to tolerable levels.

Magnetic field imperfections and their effects on the operation of HERA were described by B. Holzer, from DESY. He showed that, if uncorrected, the chromaticity due to persistent current (as described above) causes chromaticity variation $\Delta\chi_y \approx -\Delta\chi_x \approx 20$ as HERA ramped from 39 GeV to 50 GeV, and returned more-or-less to the starting values as the energy continued ramping up to 70 GeV. B. Holzer described a servomechanism based on "reference magnets" external to the lattice, with magnetic probes whose output could be fed back to reduce deviations. Because the magnets from two different manufacturers were noticeably different, it was necessary to have two reference magnets. Also there are various, somewhat unpredictable, hysteretic effects causing lack of reproducibility of order 1 "unit" of $b_{2,3}$ and other multipoles. B. Holzer presented what was perhaps the most satisfactory result in this particular working group — a graph showing that the control circuit regulates the r.m.s. chromaticity variation to well below ± 1. (It can be noted that CESR uses a similar external reference magnet for the slightly different purpose of improving the energy calibration of its room temperature iron magnets.) Another observation: as indicated above, though χ_x and χ_y vary greatly due to persistent currents, their sum does not, and this suggests that storage rings modified for Möbius operation[4] may be insensitive to persistent currents, since they exhibit a single chromaticity, $\chi_x + \chi_y$.

S. Peggs suggested that the ratio $\Delta\chi/\chi$ be regarded as a quantitative figure of merit for estimating the degree of operational seriousness of hysteresis in superconducting storage rings. He further indicated how to make allowance for minor variations of parameters as shown in Table I. His estimates of correction factors to account for variation of filament size, injection field, top field and temperature are shown. By this performance predictor, LHC is "more conservative" than HERA, and RHIC is more conservative yet.

3 FEEDBACK FROM MAGNETIC MEASUREMENT AND ACCELERATOR PHYSICS TO IMPROVE MAGNET CONSTRUCTION

Detailed and clear descriptions of the refinement of all phases of magnet construction of RHIC magnets were given by R. Gupta from BNL. Special attention was paid to responding rapidly to the results of both magnet measurements and simulation of resultant accelerator performance. One specially pleasing success story relates to high field saturation that has

TABLE I Comparison of different storage rings on the basis of hysteretic chromaticity. The final two columns are estimated multiplicative correction factors for the ratio of ratios $\Delta\chi/\chi$

Variable	*unit*	*HERA*	*LHC*	*RHIC*	*HERA/LHC*	*RHIC/LHC*
Filament	μ	10	6	6	1.7	1
Injection field	T	0.22	0.58	0.4	2.6	1.4
Temperature	°K	4.2	1.8	4.2	0.6	0.6
Top field	T	4.7	8.5	3.5	0.6	0.4
Total					1.6	0.34

improved by more than an order of magnitude over 10 years. Remarkably, in this case, saturation was improved by *removing* iron from "under-saturated" regions of the magnet yoke. R. Gupta also described procedures that could be used to trim unwanted multipoles ($b_{2,3}$ and $b_{4,5}$ together) by adding insulating shims without interrupting the magnet production line. Some seven independent examples were given of rapid turn-around in which field uniformity was improved by making small production changes like this that did not slow down delivery schedules.

An extremely informative, and to me novel, way of presenting RHIC field quality statistics, both random and systematic, was also part of this presentation. On one of the plots, colour coded contours of equal r.m.s. field deviations from nominal are plotted on a transverse plane; the other plot has contours of constant systematic deviation plotted. These plots support the identification of "(old fashioned) good field regions" rather than the more "modern" emphasis on multipolar field expansions. While the multipole coefficients have the dual advantages of being directly measurable and directly applicable to accelerator theory, they are susceptible to being assigned unjustified weight in assessing magnetic field quality. A. Verdier stressed the unreliability of extrapolating fields to radii greater than the coil radius of the magnetic measuring apparatus used to measure the coefficients.

V. Ziemann[5] described scaling rules by which dependencies on multipole order could be correlated and resultant accelerator performance predicted. These scaling laws were based partly on dimensional analysis and partly on use of Hénon-like maps to estimate dynamic aperture in the presence of random errors. Q. Qin, with S. Weisz, applied a similar model in order to project various LHC field quality scenarios.

A topic eliciting much discussion was magnet errors that are neither completely random nor completely systematic. It was universally agreed that, though such effects influence accelerator performance in serious ways, there is not even an established vocabulary to describe them. This may be inevitable because different problems are faced by different projects. Unfortunately, these effects tend to show up during hectic installation, when the least amount of time is available for reacting to them. With rejection typically not an option, attempts to ameliorate such variability tend to use *ad hoc* sorting procedures.

4 ERROR COMPENSATION

As an attempt at levity, the chairman introduced the subject of error compensation by defining its four "schools", with their guiding principles:

- The French School: "With errors known, an accelerator can be compensated arbitrarily well with at most two families of correctors. With unknown errors it is impossible."
- The German School: "With enough reference magnets, a servomechanism can be designed to compensate any error."
- The American School: "Since it is impossible to correct magnet errors, it is necessary to build perfect magnets."
- The Pangloss School. "If an error is big enough to harm operations it is big enough to measure and compensate."

Needless to say, most of these schools are well represented at most laboratories.

The special compensation topics that attracted greatest attention were the correction of coupling effects and the special problems associated with correcting field errors in magnets situated near low β intersection points.

Coupling effects anticipated in the LHC and plans for their compensation were described by J.-P. Koutchouk,[6] with T. Risselada, S. Weisz, and V. Ziemann. Some effects, such as detector solenoids and vertical closed orbit displacements in sextupole (chromaticity correcting or random) are small enough to be neglected. Others, such as quadrupole tilts, are large enough to need compensation but small enough to be manageable without further discussion. This leaves a single dominant concern: skew quadrupole components in the superconducting dipoles. Two natural questions arise:

TABLE II Fractional constancy of skew quadrupole error required for stable operation

Storage ring	$\|C\|$	$\|Q_x - Q_y\|$	$\|Q_x - Q_y\|/\|C\|$
ISR	0.01	0.025	250%
SPS	0.01	0.005	50%
LEP	0.025	0.1	400%
HERA	0.06	0.01	17%
LHC (version 4)	0.5	0.01	2%

can the coupling be compensated with a small number of correction elements? and how dynamically stable must the errors remain in order to maintain adequate compensation? The answer to the latter question can be used to compare the LHC with other storage rings as regards the seriousness of coupling. The results are shown in Table II as a ratio of appropriately-normalised, as-yet-uncorrected, coupling error $|C|$, to operationally-intended deviation from coupling resonance $Q_x - Q_y$. The requirement, for example, that $Q_x - Q_y$ does not drift by more than 1% places a requirement that C be stable to an accuracy 100 times smaller than the entry listed in the final column of Table II. Evidently this requirement is harder for LHC to meet than has been true of previous accelerators. J.-P. Koutchouk also answered the former question. Compensation of early versions of the LHC had seemed to entail serious β-beats but this was traced to nearness to the sum resonance. When this was remedied, global decoupling with a small number of skew elements became possible. Even so, displacing the horizontal integer tune from the vertical integer tune strongly improves the situation. Since the two-in-one magnet design complicates such a shift, this has become an important issue being studied for the next iteration of the LHC design.

Detailed description of the special problems of refining intersection region optics at RHIC was given by J. Wei.[7] Emphasis was placed on warm/cold magnetic field correlation (very good) and on the effectiveness of rapid feedback from measurement and performance simulation to magnet production. Procedures for trimming as many as eight multipoles with eight shims were described. With alignment of intersection region quadrupoles being so critical, minor alteration of the production line after production of the first few magnets has yielded more nearly ideal magnet assemblies. Various end effects were also discussed. Field non-uniformity due to the "dressing" of external leads was larger than some end field multipoles. Concerning longitudinal fringe fields a theorem was proved showing that the effect of longitudinal field at one or both ends of any non-solenoidal magnet are (essentially) always negligible.[8] This validates the (universally assumed) multipole expansion formalism, even as it is applied to a single end of an ordinary accelerator magnet. A technical procedure found by J. Wei to be effective is to minimise "action kicks" over triplets, rather than compensating individual quads. Also sorting schemes, based on "golden magnets" with small measured field errors and "silver magnets" with bigger, but still small field errors, have been effective. "Effectiveness" in this case is determined by particle tracking simulation. After applying the compensation algorithms the tune "footprint" is brought well within specifications.

An interesting analytical analysis of end field deflections in LHC magnets was presented by F. Meot.[9] Compensation schemes for Main Injector magnets at Fermilab were described by C. Mishra.[10] Since these are conventional warm magnets the results are not further reviewed here.

5 ERROR DIAGNOSIS AND OTHER RESULTS

V. Ziemann[11] described a "wobbling method" for empirical diagnosis of nonlinear deflection errors. With the storage ring represented in Hamiltonian terms, and making conservative assumptions about degradation of beam position measurement by noise, he showed that Hamiltonian coefficients could be realistically extracted for LHC. Though only tested so far in simulation, this approach appears promising. If it could be trusted to compensate nonlinearity operationally it might permit loosening of field quality specifications, thereby reducing cost or improving quality.

S. Mishra, with Assadi, presented a novel, and seemingly powerful frequency-domain analysis procedure for identifying resonances. Though applied so far only to simulation of beam-beam parasitic collisions in the Tevatron the method seems likely to be effective in analysing operational turn-by-turn beam position data.

Some other results were presented analysing the "conspiracy" of field non-uniformity and tune modulation to cause beam degradation in high energy proton rings. G. Tsironis, with B. Cole,[12] described long term simulation analysis of such effects. T. Sen, with J. Ellison[13] described similar phenomena analytically.

6 SUMMARY

High energy hadron colliders are large and expensive and their performance will surely be limited by field errors. This reminds me of an earlier era in accelerator physics, when statistical analysis was applied to "the ensemble of accelerators of the sort being built". A typical design requirement was that some acceptably small fraction, such as 2%, would fail because the closed-orbit intercepted the wall of the vacuum chamber. Technological advances (beam position monitoring and orbit smoothing) have by now rendered that analysis silly — without orbit measurement and active beam steering most modern accelerators would not work at all. It seems then, to repeat the successes of the earlier era, that a leading challenge facing accelerator physicists is to make reliable technological advances that best make use of imperfect accelerator components. Modest progress in that direction occurred at the workshop.

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