Particle Accelerators, 1996, Vol. 54, pp. 93–105
Reprints available directly from the publisher
Photocopying permitted by license only

ERRORS AND HOW TO DEAL WITH THEM

D. RITSON

Stanford Linear Accelerator Center, Stanford University,
Stanford, CA 94305, USA

(Received 21 February 1996; in final form 21 February 1996)

Optimization of the design of the LHC requires an understanding and correction of errors throughout the collider cycle. The purpose of this paper is to discuss a number of unsolved or only partially understood problems that are likely to affect the final operational performance of the LHC.

Keyword: Errors.

1 INTRODUCTION

The LHC compared with previous accelerators will be qualitatively larger than any previous hadron collider and to achieve its objectives will aim for qualitatively higher luminosities. The aim of this talk will be not to dwell on previous successes but to outline a number of significant problem areas which are only partially understood at this time. The talk divides into a number of topics. The first section is intended to provide a framework for the later sections outlining specific problem areas. It will provide some brief reminders on notation, the classification of errors, and their diagnosis. Subsequent sections will deal with specific problem areas.

2 REMINDERS ON ERRORS

This section is intended to provide a quick overview of errors and their effects.

2.1 Multipole Field Expansion of Magnetic Field Errors

The basic physics is completely understood, but unfortunately there is a definitional difference between US and European notation.

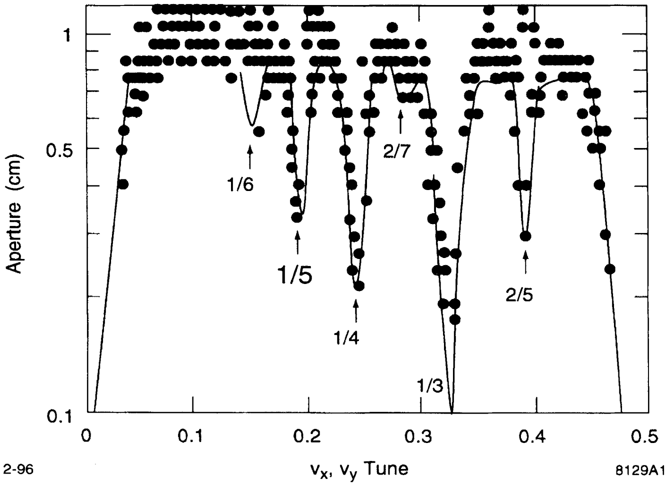

FIGURE 1 Typical SSC dynamic aperture versus tune at injection.

In the US the magnetic field expansion is written as

$$B_y + iB_x = B_0 \sum_{n=0} (b_n + ia_n) \left(\frac{x + iy}{r_0} \right)^n .$$

A skew quad error is characterized by the a_1 coefficient.

In Europe the field expansion is written as

$$B_y + iB_x = B_0 \sum_{n=1} (b_n + ia_n) \left(\frac{x + iy}{r_0} \right)^{n-1} .$$

A skew quad error is characterized by the a_2 error in Europe, but is identical in magnitude and significance to the a_1 errors of the US.

This paper will use the European notation. It is the author's hope that a common definition could be adopted to avoid the current confusion.

2.2 Error Effects

Field errors in repetitive components of an accelerator, such as dipoles or quadrupoles, can be divided into the averaged error or systematic error and the rms deviation from the average or random error. An example of the effects of errors is illustrated in Figure 1 which shows a typical simulated 'long-term dynamical aperture sweep' from the SSC at injection. Plotted are the apertures determined from five seeds for runs of one hundred thousand turns for tunes along the $\nu_x = \nu_y$ diagonal. The figure shows the individual resonances, with effects decreasing with resonant order, and a 'ceiling' aperture set by the overall 'off-resonant' onset of chaotic motion.

2.2.1 Systematic errors Even multipole systematics (quadrupole, octupole, etc., errors) will cause tune shifts, and odd multipoles (sextupole, decupole,etc., errors) will cause beta beat and chromatic tune shift.[1]

In general, systematic errors do not excite resonances. In the absence of appropriate supersymmetry, however, resonance excitation by systematics may become important. In contrast to a 60° phase advance FODO lattice, systematic octupole errors in a 90° phase advance add coherently to excite fourth-order resonances, and, in the absence of appropriate cancellation, may be troublesome.

2.2.2 Random errors In contrast to systematics, random errors predominate as the source of resonance excitation. To excite a resonance requires both given multipole orders and the appropriate Fourier components of the multipole order around the lattice.

2.2.3 Systematic power supply modulation In the presence of chromaticity, high-frequency power supply modulation will produce side band structure to the already present resonances. The result is decreased operating space between resonance lines and enhanced chaotic motion.

Low-frequency modulation of power supplies causes adiabatic modulation of the rotation frequency around the machine, and can result in resonance crossing or approach.

2.2.4 Noise in power supplies, mechanical magnet movement, etc. Stochastic noise causes the machine emittance to grow, thus shortening beam lifetimes and increasing beam losses around the ring.

2.3 Errors in Combination

Simultaneous occurrence of errors, such as chromaticity, skew-coupling, modulation, etc., will increase the 'dimensionality' of the motion and enhance the chaotic motion. The effect of errors in combination can be substantially greater than in isolation, and can cause damage that is 'multiplicative,' not additive.

3 REMINDERS ON THE LHC MACHINE CYCLE

The LHC collider rings will proceed via a complicated set of steps, from injection at 400 GeV through to luminosity running at full 7 TeV energy.[2] Each step has its own unique problems and each step must, of course, meet specifications. We now summarize this sequence of steps.

3.1 Initial Injection at 400 GeV

Imperfect matching of the injection-line to the accelerator rings will cause coherent betatron and synchronous phase motion. These oscillations will be damped out by feedback over approximately 1,000 turns. During these thousand turns, all particles outside a 'short-term' dynamic aperture will be lost. Thus, the short-term dynamic aperture and injection-line to ring matching must be adequate to contain the necessary emittance in the presence of the induced coherent motions.

3.2 Coasting of the Injected Beam

After the damping out of the coherent motion, subsequent to the first thousand turns, individual bunches may have to coast for up to ten minutes ($\sim 1 \times 10^7$ turns) until both rings are fully filled. Thus, the 1×10^7 turn or 'long-term' dynamic aperture must be adequate. The penalty for an inadequate dynamic aperture is smaller emittance acceptance and ultimately, poorer luminosity.

3.3 Beams Ramped to 7 TeV

The beam emittance is strongly adiabatically damped by the ramp cycle and by 7 TeV, it is $\sim$ 4 times smaller. Therefore, in theory, there should not be problems. In practice, superconducting magnets have time-varying persistent field hysteretic effects and the changes in these field errors at the onset of the ramp (snap-back effect) pose worrisome problems. At the end of the ramp cycle, the magnitude of the systematic allowed errors will be qualitatively different from those at injection.

3.4 IR β Squeeze Prior to Luminosity Running

To prepare the collider rings for luminosity running, the β^* at the IP is reduced from the injection value of 15 m to the final value for luminosity running of

0.5 m. During this process, the βs at the first IR triplet quads (the 'high-beta' quads) is increased by a factor 30. The errors in the high-beta quads cause strong non-linear chromaticity, lattice mismatches, and skew-coupling errors. The errors in the high beta triplet region of the IR and the long-range effects from the satellite beam-beam collisions will now be very strongly enhanced, and will dominate the lattice behavior. Even with the small adiabatically damped emittances at full machine energy, long-term dynamic aperture is again an important consideration.

3.5 Luminosity Running

Finally, the beams are brought into interaction, and may be required to coast for periods up to 24 hours. The beam dynamics are now dominated, in order of decreasing importance, by the head-on beam-beam collisions, the long-range satellite collisions, the high-beta quad errors, and the lattice errors. As has been previously noted, damage from individual errors can add non-linearly.

4 REMINDERS ON DIAGNOSTICS

The design and construction of a machine proceeds through a number of stages. Initially in the design phase, there are only a few prototype components available and experience gained from previously constructed machines. At this time, designs are evaluated largely through simulation studies. Later, when production runs of components become available, a sector of the machine can be completed and tested. Finally, the full machine is completely installed and tested, first on a single-turn and then sequentially, through to full luminosity running. One must always remember that WHAT CANNOT BE DETECTED CANNOT BE CORRECTED. The following are diagnostics available through design, construction, and operation.

4.1 Simulation Studies of Accelerators

Prior to about 1992, brute force 'element-by-element' simulation studies for the large hadron colliders (LHC and SSC) were restricted by available computer power. To overcome this problem, it was suggested that the use of 'one-turn' maps would provide a magic fix.

In reality, element-by-element tracking uses a very simple map to proceed from one element to the next. The trade off involved is either to use many very simple maps or one very complex map per turn.[3] The computer time required for element-by-element tracking increases only linearly with maximum multipole order considered. The number of terms in a single-turn map rises as a high power of the maximum multipole order, so there is a very non-linear dependance of computer time on maximum order. In studies at the SSC, the crossover in required computer time; i.e., the point for which element by element tracking became faster than single turn mapping, was roughly for multipole orders above eighth.

Currently, computer speeds and memory capacity are now so readily available that the determination of long-term dynamic aperture, either by element-by-element tracking or by single-turn maps, is no longer a critical problem. The real challenge lies in the ability to set up and evaluate realistically corrected lattices in the presence of the full range of physical errors, including tunes, skew-coupling, feedback systems, noise, beam-beam physics, etc.

To introduce correction schemes into simulations, 'machine based corrections' may be used where the code simulates what an operator would do. At other times, it may be more convenient to use the very powerful Lie algebra normal-form correction techniques to determine corrector settings. Alternatively, some problems are more easily tackled with traditional perturbation techniques that set the corrrectors to zero-out appropriately weighted Fourier integrals around the ring. There is no very strong reason to prefer one method over the others, and whatever works is fine. However, machine-based correction techniques have the advantage of forcing you to be 'honest'.

4.2 Pre-operation Diagnostics

This set of 'diagnostics' comprises the full range of experimental component and site tests, and includes magnetic measurements, simulations, survey precision, etc. An important component of this testing are experiments on beam dynamics at existing accelerators designed to evaluate the effects of power supply modulation, correction strategies, and optimal operating points in tune space.

4.3 Operational Diagnostics

A new, and obviously the most important, phase starts with commissioning through to operations. The available techniques can be roughly categorized as either ‘intrusive’ measurements where the beam is either destroyed or degraded in quality, and thus is useful only for exploratory set up, and ‘non-intrusive’ measurements that do not affect the beam quality and are used to optimize luminosity running.

4.4 Intrusive Measurements

A multiplicity of intrusive diagnostics are available, and we shall mention typical examples of intrusive measurements.

The simplest is to directly view the beams on fluorescent screens during initial single-turn setup. Collimators can be moved into the beam line to measure beam haloes. Beams can be coherently excited, and their subsequent motion can be followed with BPMs or Fourier analysed. The tune of the machine can be changed to sweep across resonances, or errors can be deliberately introduced into the lattice.

4.5 Non-intrusive Measurements

Some typical techniques of non-intrusive diagnostic procedures now follow. BPMs are used to measure beam centroid positions at many points around the ring. Very often the beams will be bumped in position, or energy and difference measurements will be made to eliminate systematic inaccuracies from BPM placement. Another very powerful family of techniques involve frequency analysis of BPM or pick-up signals. The frequency analysis of the Schottky noise in the beam can be used both with unperturbed and perturbed orbits to provide a wealth of information on resonance behavior and driven resonant motions. Frequency analysis of BPM information on successive turns can be used to analyse the eigenvectors and planes associated with skew-coupled motion. Flying-wire beam profile measurements can be used to measure emittances and beam halos.

Finally, measurements of luminosity, loss monitors, beam intensity, detector backgrounds, etc., provide both the ‘bottom line’ to machine performance and, via a skilled operator or through feedback devices, can provide unique tools to diagnose and optimize machine performance.

5 REPRESENTATIVE PROBLEM AREAS

We now discuss a number of areas of error correction that are only partially understood but are important if the LHC is to be an easily controllable high luminosity collider.

5.1 Lumped Versus 'Local Correction'

The LHC will be a tightly designed machine. A central problem is to ensure adequate short-term and long-term dynamic aperture. It is always true that larger dynamic apertures can be provided by correcting ever higher order multipole errors. There is, however, a point of diminishing returns; corrections above fourth- or fifth-order do not on their own provide substantial aperture gains. In principle, based on magnetic measurements, full element-by-element corrections could be provided. In practice, this becomes prohibitively expensive and complicated if applied to many multipole components. The Neuffer Simpson rule technique[4] provides some simplification of the number of correctors required for individual cells. Correction schemes can be further simplified if corrections are not made locally at every cell, but are 'lumped' together and applied every few wavelengths. The use of such lumped or 'semi-local' correction schemes has generated substantial controversy. If the required lumped corrections are too large, the machine will be very sensitive to steering errors. Further large correction strengths for a given multipole order will generate higher order multipole components by 'feed up' effects.

The following questions should therefore be answered:

1. What random and systematic multipoles require correction?
2. How should corrector strengths be determined by magnetic measurements, perhaps?
3. How coarse can 'lumping' be and still be effective?

5.2 Correction via Sorting

In a very large machine such as the LHC, random errors accumulate and can become excessive as one proceeds around the ring. However, if instead of installing components as they arrive on site, the installation sequence is determined by field measurements to minimize buildup of random errors, the effects of random errors can be reduced by up to an order of magnitude.[5] This derandomization process is known as 'sorting'. Sorting can only work efficiently to reduce resonant excitation effects for perhaps two to three multipole resonances.

The questions that need to be answered are:

1. What are practical sorting strategies and how many multipoles can indeed be simultaneously minimized?
2. Which multipoles should be targeted for reduction?

5.3 Removal of Skew-coupling

The removal of linear skew-coupling or a_2 errors is important to achieve good dynamic aperture, optimum luminosity, and simple orbit diagnostics and corrections. Conventional wisdom is that the coupling of horizontal to vertical motion should be kept below 10% around the lattice. Working close to the coupling resonance $\nu_x = \nu_y$ is usually regarded as optimum for optimizing luminosity, but at the same time, results in great sensitivity to skew coupling. Systematic skew errors are removed by local spool correctors, and by integer splitting of the horizontal and vertical tunes. However, even after correcting for systematics, random error effects must also be minimized. The simplest correction scheme at current hadron accelerators is to use two global skew quadrupole families located in regions that approximately differ by 90° in the phase differences between horizontal and vertical motion. A two-family correction scheme can eliminate the difference $\nu_x - \nu_y$ resonance excitation, but does not eliminate the effects of the sum $\nu_x + \nu_y$ excitation.[6]

For a large machine like the LHC, it is certainly required to fully eliminate skew-coupling growth for both the sum and difference resonances. This can be accomplished with four families. Four suitable families of skew quad correctors can zero-out coupling at any specified reference point in the lattice for every turn. This is all that is required to eliminate the effects of the sum and difference resonances at this specified point. For all other locations around the ring, there will be skew-coupling calculable directly from the 'single turn' transfer matrix from the reference point to the point in question. Unfortunately, for a large machine such as the LHC, if random a_2 errors are $\sim 1.4 \cdot 10^{-4}$ at 1 cm, it will be necessary to correct coupling to zero at several points around the machine if coupling below the 10% level is to be maintained around the machine. Similar problems are associated with the vertical dispersion in the lattice generated by skew coupling. To remove this anomalous dispersion requires an additional two skew families to correct at a specified point and may require additional families to control it all around the lattice.

At the SSC,[7] there was considerable discussion and controversy as to the needed complexity for good skew-coupling correction. The most desirable solution is to fabricate magnets of sufficient quality that a four global family correction is sufficient. A second approach might be to use sorting to reduce the effects from the a_2 error build-up in the lattice.

Therefore, issues relative to skew-coupling are:

1. What is tolerable coupling in a lattice? Is $<10\%$ coupling the right criterion?
2. How far can fabrication procedures be used to lower a_2 errors?
3. What is an optimum configuration for skew correctors around the lattice?
4. Should one choose random skew errors for sorting on, or is the correction of other multipoles more important.

5.4 - Persistent Current Hysteretic Effects

An ugly effect for superconducting magnetic components passing through a ramp cycle is the presence of persistent currents.[9] The magnitude of these hysteretic currents depends both on the excitation cycle and on fabrication. Different batches of magnets or magnets from different manufacturers may have very different hysteretic properties. The persistent currents will cause systematic 'allowed' multipoles errors. For dipoles, the 'allowed' errors are sextupole and decupole, etc. Figure 2a from Rossbach[9] shows the anomalous sextupole field in the HERA dipoles for increasing and decreasing main field excitation current. Figure 2b shows the corresponding time decay of the anomalous sextupole components at the 250 A excitation level for peak ramp fields of 3,000 and 6,000 A. Injection conditions are significantly impacted and there is a very significant 'snap-back' effect at the start of the ramp cycle. DESY implemented a dynamic correction scheme based on measuring fields in external magnets undergoing identical excitation to the main accelerator to control the corrector strengths. This worked very well. There was much discussion at the workshop on how to minimize these effects. Possible solutions ranged through fabrication improvements to optimizing the ramp cycle.

5.5 Field Quality and Corrections for High Beta Quads

Subsequent to the beta squeeze, the high betas magnify the effects of the field errors in the high-beta region. This results in their being more important

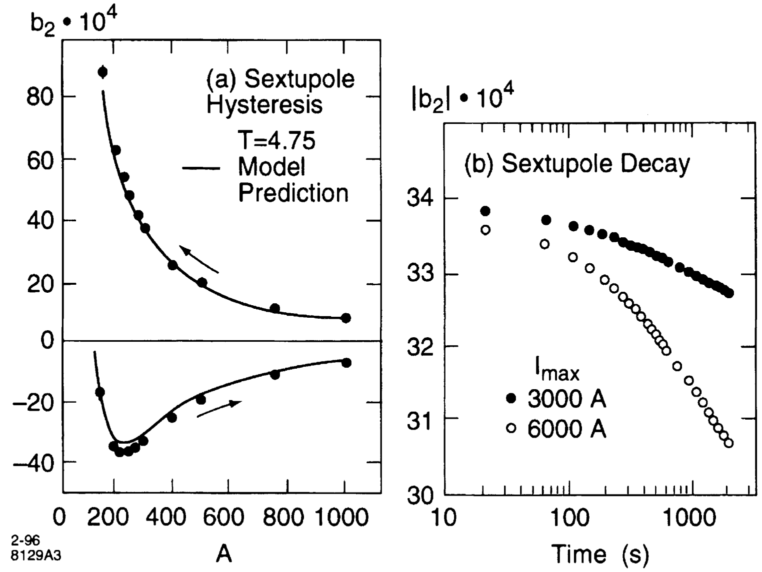

FIGURE 2 Anomalous hysteretic sextupole fields observed in the HERA superconducting dipoles shows: (a) the dependance on ramp cycle and (b) the decay with time at injection time at 250 A excitation.

than overall lattice errors. The counter-circulating beams cross at the IP with finite angles, and then pass off-center through the shared first high-beta quad triplet. This off-centering places the beams in the bad field regions close to the magnet edges and further substantially increases mutlipole errors, evaluated on the equilibrium orbits, by feeddown from higher multipoles. Because the counter-circulating beams are oppositely off-centered, half the feeddown terms are of opposite sign for the two beams, and cannot be locally cancelled. Local corrections of the intrinsic lower-order multipoles is easy, but full removal of the feeddown components requires complicated non-local corrections. Simulations at the SSC found that feeddown from multipole orders above sixth order contributed substantially to the reduction of the dynamic aperture. Two questions therefore arise:

1. How serious are the errors in the high beta region compared with the head-on and satellite beam-beam effects? How necessary is it to correct them?
2. If they are to be corrected how should this be done?

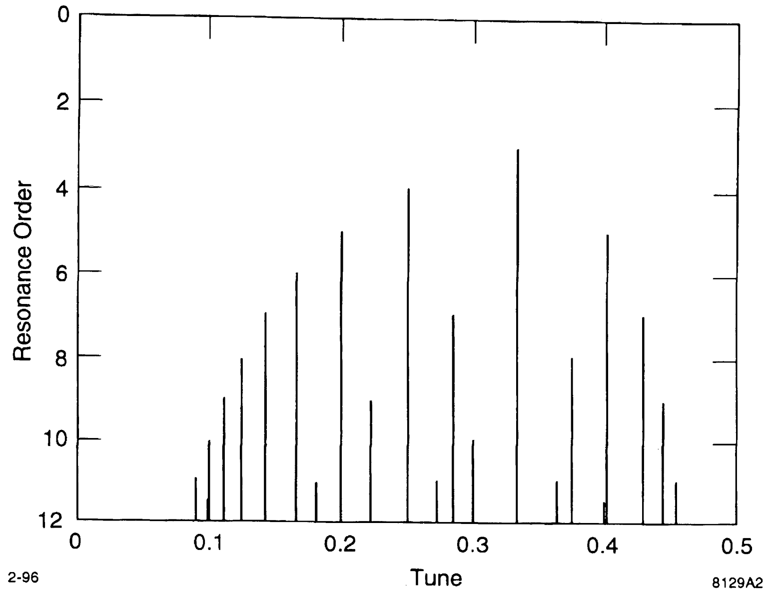

FIGURE 3 Order of resonances up to 11th order plotted at their resonant tune value for $\nu_x = \nu_y$.

5.6 Luminosity Running

It is a well established rule that for luminosity, running beam-beam tune shifts sufficient to move the tune to an 11th or lower-order resonance will cause serious beam loss. Figure 3, dubbed a 'bed of nails' plot, shows a plot of resonance orders, up to eleventh, versus tune for the diagonal in tune space with $\nu_x = \nu_y$. The height of the vertical bars is the resonance order at the appropriate resonance. The operating space is then confined to the regions between the vertical bars, giving a best total allowed tune-spread of ~0.025.

This allowed tune-spread can be degraded by skew-coupling and power supply modulation, which broaden resonances and produce resonance side bands. Anomalous dispersion also causes synchrobetatron coupling and side band structure. However, such coupling is already irreduceably present from the combination of longitudinal synchrotron motion and the IP crossing angles. The level at which additional damage from anomalous dispersion at the IP and machine chromaticity would substantially affect luminosity is presently uncertain.

The following are still unresolved, or only partially resolved questions:

1. What are permissible tolerances for skew-coupling, anomalous dispersion and chromaticity during luminosity running?
2. What are tolerances and sensitivities to tune and orbit modulation?

6 CONCLUSIONS

There are a large number of complex, difficult, and unresolved questions for the LHC if it is optimally to balance the need to be simple and inexpensive against the need to be conservative, with a high certainty of meeting design goals. Of course, this is why we needed this Montreux workshop.

References

[1] Jackson, A. (1987). SSC-107.
[2] Gareyte, J. *An overview of the LHC at this workshop.*
[3] Forest, E. (1991). *AIP Advanced Beam Dynamics Workshop*, Corpus Christi, 316 has interesting comments on 'mapping.'
[4] An interesting summary and earlier references can be found in Neuffer, D. *AIP Advanced Beam Dynamics Workshop*, Corpus Christi, 215 (1991).
[5] For earlier references, see Scandale, W. *et al.*, *16th Biennial Particle Accelerator Conference (PAC 95)*, Dallas, TX, USA, 15 May 1995.
[6] For discussion of coupling effects, see Peterson, J. *AIP Advanced Beam Dynamics Workshop*, Corpus Christi, 212, (1991).
[7] Pilat, F. and Bourianoff, G. (1991). *AIP Advanced Beam Dynamics Workshop*, Corpus Christi, 36, 299.
[8] Brandt, D. *et al.* (1990). *Nice EPAC Conf.*, 1438–1440.
[9] Rossbach, J. (1991). *AIP Advanced Beam Dynamics Workshop*, Corpus Christi, 36.