WISE: AN ADAPTIVE SIMULATION OF THE LHC OPTICS

P. Hagen, M. Giovannozzi, J.-P. Koutchouk, T. Risselada, S. Sanfilippo, E. Todesco, E. Wildner
CERN, Geneva, Switzerland

Abstract

The beam dynamics in LHC requires a tight control of the field quality and geometry of the magnets. As the production advances, decisions have to be made on the acceptance of possible imperfections. To ease decision making, an adaptative model of the LHC optics has been built, based on the information available on the day (e.g. magnetic measurements at warm or cold, magnet allocation to machine slots) as well as on statistical evaluations for the missing information (e.g. magnets yet to be built, measured, or for non-allocated slots). The uncertainties are included: relative and absolute measurement errors, warm-to-cold correlations for the fraction of magnets not measured at cold, hysteresis and power supply accuracy. The pre-processor WISE generates instances of the LHC field errors for the MAD-X program, with the possibility of selecting various sources. We present an application to estimate the expected beta-beating

INTRODUCTION

The Large Hadron Collider (LHC) ring consists of some 8000 superconducting magnets and some tens of normal conducting magnets [1]. The control of the beam shall be tight in the LHC, as the beam energy is very much above the quench and even damage levels of the magnets. The production must be backed by a tight quality control of the magnet field and geometry to minimize beam losses and maximize performance. As far as possible, the magnets are sorted for installation in the ring (slot allocation) to further reduce the impact of the field imperfections [2].

Magnetic field measurements are carried out in the industry for all magnets, with a low excitation current, the so-called “warm” measurements. The superconducting magnets are cryostated and tested in operational conditions after delivery to CERN. The magnetic field is measured in these conditions over a sample of magnets, and correlations between “warm” and “cold” magnetic data are evaluated. For the magnets that are not measured in operational conditions, warm measurements are extrapolated using the appropriate correlations.

Up to now, beam dynamics simulations have been carried out using field errors extracted by Gaussian distributions based on the expected or target values, and, more recently, on the statistics given by the measurements. Indeed, with much more than half of the magnet production completed and tested, one can imagine building a field error file of the machine where each slot has the measured harmonics of that magnet, thus generating a complete field model of the installed machine.

In this paper the main features of a code that builds an input file with the best estimates of the field errors of the magnets in the LHC lattice are presented. At the present stage of the production and installation, only partial information is available as not all the magnets have been produced and measured, and only a fraction of them has been assigned to a slot in the lattice. The code completes the missing data by drawing them from Gaussian distributions whose parameters are evaluated on the basis of the acquired experience.

The code is adaptive since new measurements and allocations can be automatically downloaded from the official databases. Moreover, it is based on a MonteCarlo method, since it randomly generates several instances of the machine whenever the information is incomplete. It is worth noting that at the end of the production and of the installation, a non-deterministic part will be anyway present, due to the uncertainties associated to measurements, power supply, warm-cold correlations (80% of the main magnets will not be measured in operational conditions), and powering history.

THE WISE SIMULATION TOOL

The output of the simulation tool Windows Interface to Simulation of Errors (WISE) is a MAD input file [3] with magnet imperfections, expressed in units (10^{-4}) of the magnet main field. The tool has been implemented as Visual Basic code inside Excel to allow a quick implementation and debugging. Spreadsheets allow the code to be data driven, making it easier for data validation as the results from intermediate calculations can easily be read and analysed. The trade-off is that the code is mainly interactive and therefore ill-suited for integration into a server application, like being called from a web interface. However, it was felt that the first priority is to produce a reliable simulation within a tight schedule, leaving to a second phase the transition to a more stable and professional software environment.

Slot Allocation

The slot allocation of each magnet, when already attributed, is extracted from the database. In addition, pre-allocations are also taken into account. The slots which are not yet known have to be drawn in a realistic way, matching a few criteria.

- Main dipole allocation has to satisfy the sector type (L and R given by diode polarity) as well as spool piece corrector type. A pre-selection by sector of the main dipoles exists and has been taken into account.

As for beginning of June 2006, 75% of the dipoles have been allocated.

- Main quadrupoles allocation has to satisfy the type of corrector magnets embedded in the cold mass since there are about 40 variants of short straight sections due to differences in cryogenics and electric connections [4]. The slot allocations of most quadrupoles are already known as of June 2006.
- Pre-allocations exist for most of the matching magnets, except the low beta focusing quadrupoles and some normal conducting magnets.

All pre-allocations made before delivery at CERN can change in case of a rejection of the magnet during cold test. The code has an option to periodically update the slot allocation.

Measurement Data

In Table 1 we list the number of measurements at room temperature and in operational conditions. In June 2006 we have room temperature measurements of about 90% of the main dipoles and all quadrupoles in the arcs. The fact that sometimes more magnets are measured than needed for filling the LHC ring is due to spare magnets.

Table 1: Magnet types and number of measurements at room temperature and in operational conditions

			Measured	
		Total	room temperature	operational conditions
Arc dipole	MB	1232	1123	193
Separation dipoles	MBR MBX	60	0	18
Main quads	MQ	392	390	25
Matching quads	MQM	76	98	6
Matching quads	MQY	28	0	8
Matching quads	MQW	48	0	55
Low beta quads	MQX	32	0	33

Field Quality Estimate

Let E be either the transfer function or a multipole. We have

$$E(i) = E_t(i) + \Delta E_m + \Delta E_h(i) + \Delta E_p(i) \qquad (1)$$

i.e. E is a sum of the "true" value plus errors coming from the measurement system, the history of the magnet, and the power supply as a function of electric current.

- Calibration errors of the measuring system have been estimated: the measurement system uncertainty is assumed to be Gaussian and is drawn once in a run for each magnet type.
- The reproducibility of the magnet behaviour is limited by the powering history. An uncertainty is drawn for each magnet from a rectangular distribution, whose parameters are evaluated on the basis of the available measurements.
- The influence of the power converters have been taken from [1]. These are absolute errors, having a stronger effect at injection (~16 times more than in collision). They are only added to the main field component of the magnet, since the effect on field harmonics is negligible.

The "true" value is computed according to the following equations

- If the slot has been already assigned and the corresponding magnet has been 'cold' measured, E_t is set to the measured value E_c

$$\boldsymbol{E_t = E_c} \qquad (2)$$

- If the slot has been already assigned, and the corresponding magnet has been only 'warm' measured, that value E_w is used and the correlations are added

$$E_t = E_w + E_{c-w} + \Delta E_{c-w} \qquad (3)$$

- where the average offset E_{c-w} and the spread ΔE_{c-w} are computed over all magnets that have been measured both at room temperature and in operational conditions.
- If the slot has not been assigned, but a magnet measured at room temperature is compatible with that slot, Eq. (3) is used.
- If the slot has not been assigned and no measured magnets are available (since they have not yet been produced), a value E_w is drawn from a distribution whose average and sigma are computed from the produced magnets. Warm-cold correlations are then added as in Eq. (3):

It must be noted, however, that the errors computed are relative to the average calculated over all magnets of the same type. In reality, only a subset of the magnets is on the same power supply. Furthermore, most of the insertion quadrupoles have an individual power supply. Therefore, the power converter can be adjusted so to remove a systematic known error common to the subset of the magnets. This can be taken into account in WISE.

Flexibility and Limitations

The demand for software flexibility grows as the software evolves: the data-driven nature of the code makes it possible to do many "what-if" scenarios by editing statistical tables. In addition, a few options have been added to the user-interface. For example, there is an option to ignore all measurements: in this case values are drawn statistically and we get the same results as assigning statistical errors inside MAD-X. Another option consists in ignoring all uncertainties, thus giving the deterministic part as in the magnet "id-cards" [5] used for slot allocation. These two options can be used for validating some parts of the simulation.

The parts relative to slot allocation, warm-cold correlations, and measurements download are completely independent: this gives a wide flexibility, allowing for instance to see the effect of sorting in the machine by manipulating the slot allocation table.

WISE can only be used to generate simulation of static errors. Therefore, different sets of errors can be generated depending on the stage in the LHC beam cycle, e.g. injection, collision and some special ones for commissioning.

BETA-BEATING ESTIMATES

As an application, we give an estimate of the β-beating based on the present best available knowledge of the machine. Results are summarized in Tables 2-3, where the average β-beating plus two sigma is given from each family of magnets. In Table 4 we give the hypotheses on the field quality that are used in simulation, based on the measurements carried out in the last years. We point out a large error in the calibration associated to MQM and MQY, and a very small spread observed in cold measurements for the MQXA. A quadratic sum is used to add up the different sources of β-beating.

Table 2: Estimated β-beating at injection

	$\Delta\beta_x/\beta_x$ (%)			$\Delta\beta_y/\beta_y$ (%)		
Magnet type	μ	σ	μ+2σ	μ	σ	μ+2σ
MB arc	6	1	8	7	1	10
D1-D4	2	1	3	1	0	2
MQ arc	7	2	11	8	2	12
MQM	5	4	12	4	3	10
MQW	1	1	3	1	0	2
MQY	2	2	5	3	2	6
MQX	2	2	5	1	2	5
Total	11	5	20	12	4	20

Table 3: Estimated β-beating at collision

	$\Delta\beta_x/\beta_x$ (%)			$\Delta\beta_y/\beta_y$ (%)		
Magnet type	μ	σ	μ+2σ	μ	σ	μ+2σ
MB arc	6	2	9	8	2	11
D1-D4	1	0	1	1	0	1
MQ arc	6	2	10	8	2	13
MQM	6	4	15	5	3	12
MQW	1	1	3	1	0	1
MQY	5	3	12	3	3	10
MQX	35	31	98	30	20	71
Total	37	32	101	33	21	74

Table 4: R.m.s. uncertainty values for the LHC superconducting quadrupoles used in the simulation

		warm-cold		cold			
	warm	Inj	Coll	Inj	Coll	Calib	Hist
MQ arc	12	8	8	-	-	5	2
MQM	12	8	8	-	-	25	10
MQY	-	-	-	12	12	25	10
MQXA	-	-	-	6	4	5	10
MQXB	-	-	-	7	11	5	10

At injection the estimated β-beating is within the 21% budget, MQ and MQM being the dominant sources (10-12% for each magnet class). The large contribution of the MQM mainly derives from the estimated 25 units of calibration error. At collision the triplet quadrupoles MQX are obviously dominating the β-beating, due to the large values of the beta function. The expected out-of-target β-beating (100%) build up progressively during the β squeeze and will thus require measurements and corrections.

The small change in the estimated β-beating with respect to values reported in Ref. [6] is due to:

- MQM and MQY were driven by statistical estimates. Many measurements are now available.
- Reassessment of measurement uncertainty for the same magnets

CONCLUSIONS

We presented a tool that allows generating a MAD-X input file including magnetic errors based on measurements, both at room temperature and in operational conditions. The code gradually adapts to the increased quantity of information available from production, measurements at CERN, and allocation in the machine lattice. Missing information is generated on the basis of the experience acquired during the production, i.e. by drawing from statistical distributions derived from magnetic data.

The modules of the code (slot allocation, measurement download, warm-cold correlations) are independent, thus allowing a large flexibility to carry out studies on different scenarios. Moreover, one can analyse the dependence on uncertainties associated to the measurements which are difficult to estimate.

Even at the end of the installation, the knowledge of the lattice errors will not be totally deterministic, mainly due to the uncertainties associated to warm-cold correlations, to the calibration of measurement systems and to the power supply. The code can generate several instances of the possible field errors, thus allowing the calculation of the main quantities relevant for beam dynamics and of their allowed ranges.

A first application to the estimate of the β-beating has been presented here. The code has also been used to devise and assess the possibility of correcting the β-beating in the LHC machine according to the specifications. These results are presented in Ref. [7].

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