WISE: A SIMULATION OF THE LHC OPTICS INCLUDING MAGNET GEOMETRICAL DATA

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Abstract

The beam dynamics in the LHC require a tight control of the field quality and geometry of its magnets. At the EPAC06 we presented the simulation tool WISE which generates magnetic field errors to be used as input to the MAD-X program. This paper describes the evolution in the WISE software since EPAC06. The allocation of magnets to lattice positions is completed, and therefore there is no more need for simulated allocations. Geometric axis measurements are now available for all cryostats. Furthermore, survey data is available to estimate the precision of the magnet installation (alignment). This paper discusses how the new data is used in connection with MAD-X simulations to give the most recent figures for beta-beating at injection (450 GeV) and collision energy (7 TeV).

INTRODUCTION

The Large Hadron Collider (LHC) ring consists of some 8000 superconducting magnets and around 100 normal conducting magnets [1]. The control of the beam will be tight, as the beam power is very much above the quench level. Therefore good knowledge of field quality and alignment errors is needed in order to optimize machine performance, like beam life-time and integrated luminosity.

During the initial beam commissioning the knowledge of the machine in terms of optics and beam dynamics will progressively be established. Real-time feedback from instrumentation will be used to calculate linear optics parameters and to optimize the machine settings. Inevitably some sources of errors cannot be totally compensated by tuning the main magnets or the usage of corrector magnets. For example, 1/8 of the bending arc dipoles in the machine share one power supply. Likewise the arc quadrupoles are connected in series, with one power circuit for focusing and one for defocusing per sector. The very best case is that the powering of the main magnets will give the correct average field integral in addition to some undesired multipoles. Geometrical alignment errors in the positioning of magnets during installation and subsequent movements over time must be compensated by the online control system.

At the EPAC06 we presented the simulation tool WISE [2] which generates magnetic field errors from measurements of the LHC magnets. This serves as input to the MAD-X [3] LHC model which is used for commissioning of the machine. In this way we can use more realistic estimates of magnetic field errors based upon individual measurements and estimates of uncertainty as compared to a more general statistical approach using random generators driven by expected Gaussian distributions of field errors.

This paper describes the evolution in the WISE simulation software [4] since the results presented in [2]. First we briefly recall the EPAC06 figures concerning β-beating driven by magnetic field errors, then we present data of the alignment (usually called geometric errors) and lastly we give figures for β-beating when these error sources (magnetic and geometric) are combined. The β-beating is usually a limiting factor of the machine performance in the initial phase of commissioning as it generates aperture bottlenecks at injection.

FINAL ESTIMATE OF BETA-BEATING DRIVEN BY MAGNETIC FIELD ERRORS

For comparison the peak β-beating estimates presented in [2] are shown here again in Table 1 and 2. The average β-beating plus two σ is given for each magnet family. The error sources are magnetic field errors due to variations in the main field, undesired multipoles and power supply errors. The uncertainty hypotheses wrt measurement calibration and powering history are the same as in Ref. [2]. In the meantime more magnets have been measured. The statistical distributions did not change much beyond some small adjustments of σ in warm-to-cold correlations.

Table 1: Estimated β-beating given in [2] at injection, beam 1, driven by field errors, no corrections

	$\Delta\beta_x/\beta_x$ (%)			$\Delta\beta_y/\beta_y$ (%)		
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 2: Estimated β-beating given in [2] at collision, beam 1, driven by field errors, no corrections

	$\Delta\beta_x/\beta_x$ (%)			$\Delta\beta_y/\beta_y$ (%)		
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

The allocation of magnets to each slot in the lattice is now completed. This process was based upon sorting of the dipoles to maximize the mechanical aperture and to reduce the resonant terms driven by b_3 and a_2. For the quadrupoles, the installation strategy aimed at reducing the spread of the integrated gradient: therefore one should expect a reduced β-beating as well as reduced spread in the simulation itself. These simulations represent uncorrected optics corresponding to running the machine without powering the corrector magnets.

Table 3: Updated estimate of β-beating at injection, beam 1, driven by field errors, no corrections

	$\Delta\beta_x/\beta_x$ (%)			$\Delta\beta_y/\beta_y$ (%)		
Magnet type	μ	σ	μ+2σ	μ	σ	μ+2σ
MB arc	5	1	7	7	1	9
D1-D4	1	0	1	1	0	1
MQ arc	6	2	9	6	2	9
MQM	3	1	6	3	1	4
MQW	1	0	2	1	0	2
MQY	1	1	3	2	1	3
MQX	2	1	3	2	1	3
Total	9	2	14	10	2	15

Table 4: Updated estimate of β-beating at collision, beam 1, driven by field errors, no corrections

	$\Delta\beta_x/\beta_x$ (%)			$\Delta\beta_y/\beta_y$ (%)		
Magnet type	μ	σ	μ+2σ	μ	σ	μ+2σ
MB arc	5	1	7	3	1	5
D1-D4	2	1	5	1	0	2
MQ arc	6	2	9	6	2	10
MQM	4	1	6	3	1	5
MQW	1	0	1	1	0	1
MQY	2	1	4	2	1	3
MQX	18	14	47	22	12	46
Total	21	15	49	23	12	47

Table 3 and 4 show the updated β-beating estimates taking into account the final installation sequence. For the arc dipoles (MB) we have suppressed errors due to variations of the main field as this would strongly perturb the closed orbit in the x-plane and the β-beating would no longer be driven by quadrupole errors. The conclusion is that β-beating goes down and remains well below the 21% budget at injection. The 50% at collision, dominated by the MQX inner triplet needs further correction [5].

PROCESSING OF GEOMETRY DATA

The alignment errors are driven by two main error sources. Typically one main magnet, some correctors and a beam position monitor are assembled into a cryostat. The mechanical and magnetic axes were measured after cold test at CERN. The axis of the main magnet is used as the reference, and the position of the other elements is given relative to this axis. This gives the alignment errors for individual magnets, which is the first error source in the alignment.

The second error source is the positioning of the cryostat in the tunnel. Survey measurements are done for all assemblies by measuring the position of external points and using fiducialisation data to relate these to the position of the theoretical magnetic axis as required by the MAD-X model of the magnetic lattice. Sometimes the cryostat is installed with a known shift to maximise the available mechanical aperture. In other cases (for instance the MQX), a longitudinal shift with respect to the nominal position has been necessary for the magnet installation. These values are added to the cryostat positioning error.

For the normal conducting magnets we do not have any individual axis measurements and therefore we assume that mechanical and magnetic axis coincide. We consider these to have only positioning errors as installed in the tunnel, which are measured during the magnet installation by the survey group.

The interface to the MAD-X is via the *Ealign* function. It takes a spatial error vector of displacement and rotations in 3D expressed in a local coordinate system and evaluated at the theoretical magnetic axis, at the middle of the magnetic length. The two error sources are added geometrically, using the fact that we are only dealing with rotations through small angles.

Table 5 shows the σ in the survey alignment data, converted into the MAD-X local coordinate system. The coordinate symbols represent: dx horizontal, dy vertical, ds longitudinal, and ψ is the rotation about the s-axis. On the other hand, the rotations about the x and the y-axis are so small that they can be neglected.

Table 5: measured survey alignment errors (rms)

	Alignment error (mm, mrad)			
Magnet type	dx	dy	ds	psi
MB arc	0.53	0.41	0.26	0.05
D1-D4	0.58	0.23	0.95	0.06
MQ arc	0.21	0.39	0.51	0.05
MQM	0.24	0.35	0.16	0.06
MQW	0.16	0.13	0.11	0.05
MQY	0.30	0.30	0.97	0.12
MQX	0.27	0.25	6.32	0.14

In Table 5, we see that the MQX magnets have important errors in longitudinal positioning. These alignment errors did increase after the magnets were reinstalled into the tunnel following a change of the design to withstand the asymmetric forces.

The only data generated by WISE simulation is to add uncertainty related to the measurements and the fact that magnets and assemblies might move inside the tunnel over time. See Table 6 for the σ used in current simulations. Evidently these tables need to be updated with different working hypothesis in the future. Currently they add only a modest random contribution compared to the deterministic part of the errors.

Table 6: Alignment uncertainty for assemblies (rms)

	Alignment error uncertainty (mm, mrad)			
Source	dx	dy	ds	psi
Initial positioning	0.15	0.15	0.10	0.05
Movements until new survey	0.20	0.20	0.00	0.10

ESTIMATE OF BETA-BEATING DRIVEN BY FIELD AND ALIGNMENT ERRORS

Next to study are the geometric positioning errors together with the magnetic field errors to produce a final estimate of the β-beating.

The error sources, when combined, produce significant perturbation of other optics parameters, like closed orbit. This in turn strongly influences the β-beating estimate due to feed-down effect from the b_3 multipoles in the MB arc dipoles as well as lattice sextupoles. Therefore we need to add some simple simulation of global corrections.

The correction need for the b_3 multipole from the MB arc magnets is shown in Table 7. WISE builds the table during simulation of MB field errors. Only the systematic effect per beam and per sector can be corrected.

All other corrections are done inside MAD-X itself, driven by the simulation script. The closed orbit error is minimised letting MAD-X handle the orbit correctors. The tunes are adjusted to the nominal design values by adjusting the power of the MQ lattices quadrupoles. During machine runs the trim MQT quadrupoles will be used as well for this purpose. The linear chromaticity is corrected to the nominal value by the lattice MS sextupoles.

Table 7: b_3 systematic error for MB arc dipoles (units)

	b3 injection		b3 collision	
Sector	beam 1	beam 2	beam 1	beam 2
1-2	-4.6	-4.6	2.6	2.5
2-3	-4.5	-4.5	2.6	2.7
3-4	-5.7	-5.8	1.4	1.4
4-5	-4.6	-4.6	2.5	2.6
5-6	-5.1	-5.0	2.1	2.1
6-7	-4.2	-4.2	3.0	2.9
7-8	-2.5	-2.5	4.7	4.7
8-1	-4.7	-4.8	2.4	2.3

We recorded global optics parameters before and after corrections by saving the Twiss optics tables. In addition we evaluated the betatron coupling strength $|c|$ by adjusting the optics to the same fractional tune for both planes. Correction of linear coupling was not done. It is negligible at injection but it can become large at collision, i.e. of the order of 0.1.

We simulated classes of magnets and summed the errors quadratically. The final β-beating estimates, after corrections, are shown in Table 8 and 9.

The simulated, non-correctable, errors at injection are well below the 21% budget for field errors alone. The MQX inner triplet is by far the dominating source at collision. The local multipolar correction of the triplet system has not been applied so we should expect that these figures will be significantly reduced during operation.

Table 8: Final estimate of β-beating at injection, beam 1, driven by field and alignment errors, after corrections

	$\Delta\beta_x/\beta_x$ (%)			$\Delta\beta_y/\beta_y$ (%)		
Magnet type	μ	σ	μ+2σ	μ	σ	μ+2σ
MB arc	6	1	8	7	1	9
D1-D4	0	0	1	1	0	1
MQ arc	6	2	10	5	1	8
MQM	4	1	7	3	1	4
MQW	1	0	2	1	0	2
MQY	2	1	3	2	1	4
MQX	2	0	3	2	1	3
Total	10	3	15	10	2	14

Table 9: Final estimate of β-beating at collision, beam 1, driven by field and alignment errors, after corrections

	$\Delta\beta_x/\beta_x$ (%)			$\Delta\beta_y/\beta_y$ (%)		
Magnet type	μ	σ	μ+2σ	μ	σ	μ+2σ
MB arc	6	1	9	4	1	6
D1-D4	1	0	1	0	0	1
MQ arc	9	3	14	6	7	2
MQM	4	2	7	3	1	6
MQW	1	0	2	1	0	1
MQY	2	1	4	2	1	3
MQX	47	25	97	48	33	115
Total	48	25	99	49	34	116

CONCLUSIONS

We have demonstrated that WISE can now provide measured field and geometry errors ready for use in MAD-X optics and commissioning studies [6].

The β-beating at injection and collision are compared with preliminary results from EPAC06.

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