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β -BEATING IN THE EFFECTIVE MODEL OF THE LHC USING PTC

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THE EFFECTIVE MODEL

The high intensity and energy of the LHC proton beams requires accurate control of the transverse beam dynamics in order to guarantee machine protection. This imposes tight tolerances on the optics errors. Geometric and magnetic field errors affect the optics and have to be corrected for safe operation.

An effective model of the optics of the LHC has been built based on measurements of the alignment and magnetic errors. The aim is to have a realistic model including the maximum knowledge available from the machine at present. This model has been performed using MAD-X [1] and the Polymorphic Tracking Code (PTC) [2] which allows treatment of the magnetic errors up to an arbitrary order in the thick elements lattice. After introducing these errors, correction of the beam orbits, tunes, chromaticities and transverse coupling are performed to retrieve the nominal settings of the machine. The resulting β-beating from the remaining errors after all the corrections is calculated along the machine [3]. The results of the model at injection optics and at 3.5 TeV squeezed to 3.5 m β-function at the interaction point (β^*) are presented in this paper, and are compared to the measured β-beating after the correction of local errors performed during the 2010 run [3, 4].

ALIGNMENT AND MAGNETIC ERRORS

The magnet errors introduced in the effective model come from the simulation tool Windows Interface to Simulation Errors (WISE) [5, 6].

Magnetic field errors are generated by WISE based on the so-called "warm" measurements (performed with a low excitation current) of the LHC magnets and the so-called "cold" measurements (performed under operational conditions). Only a fraction of the magnets are measured at "cold". For the rest of the magnets warm-to-cold correlations are introduced in the modeling of the field. In addition to this uncertainty, relative and absolute measurement errors or hysteresis and power supply accuracy are included in WISE for all magnets [6, 7]. 60 different 'seeds' are available containing harmonics until 15^{th} order for bending and quadrupole magnets. It is worth noting that the uncertainty from the warm-to-cold correlation for the quadrupolar (b_2) component is not negligible in the case of the quadrupole magnets.

Alignment errors are also generated by WISE based on measurements of the mechanical and magnetic axis [6, 8].

The errors introduced in the simulations presented in this paper were generated using the magnetic measurements and the magnets sequence in the machine after the repair performed following the September 2008 incident.

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MAD-X AND PTC MODELS

In the modeling of the optics the PTC code has been used as an extension to the MAD-X program. PTC is a code dedicated to beam dynamics calculations in the nonlinear regime. In MAD-X only normal quadrupolar and sextupolar errors in the bending magnets can be assigned into the thick elements. Both codes are in perfect agreement when introducing such errors, but in PTC all other components (normal and skew) can also be assigned to thick elements.

THICK ELEMENTS MODEL INCLUDING DIFFERENT MAGNET ERRORS

Different models of the LHC optics have been performed with PTC introducing progressively different magnetic or alignment errors in order to evaluate their effect on the β-beating. It should be noted that when introducing any error, the corresponding correction is performed to retrieve the nominal settings of the machine [3].

The biggest effect on the β-beating comes from the quadrupolar errors, as can be seen in Table 1. This table shows the peak and standard deviation β-beating along the machine for the different models studied for the LHC Beam 1, seed 1 from WISE. The β-beating when introducing the quadrupolar errors in the bending magnets is of the order of 7 or 10%. The contribution of the quadrupolar errors in the quadrupole magnets is of the same order of magnitude as in the bending magnets, but in the former, the uncertainty from the warm-to-cold correlation is non-negligible and the shape of the β-beating along the longitudinal axis changes significantly for the 60 different seeds of the most likely LHC machine created by WISE.

Table 1: Summary of the peak and standard deviation (std) β-beating for the different models: introducing b_2 errors in the bending magnets (MBs), adding b_2 errors in the quadrupole magnets (MQs), introducing all the harmonics in the MBs and MQs, adding to them the alignment errors and correcting the orbit to zero or to the measured one. The results correspond to the LHC Beam 1 seed 1 from WISE, and in two of the models the std and peaks of the averaged values over the 60 seeds are also shown. The results are representative of the LHC Beam 2.

Model	$\Delta\beta_x/\beta_x$ (%)		$\Delta\beta_y/\beta_y$ (%)	
	std	peak	std	peak
Injection optics				
b_2 in MBs	4.0	11.6	4.7	14.2
b_2 in MBs & MQs	7.5	-16.8	5.0	19.8
All harmonics	7.4	-16.8	5.0	19.7
+Misalign, zero orb.	8.1	17.5	5.4	20.3
(60 seeds average)	(6.2)	(16.9)	(4.3)	(14.3)
+Misalign, meas orb.	8.2	17.4	5.8	21.4
3.5 TeV 3.5 m β^* optics				
All harmonics	6.9	18.1	3.9	13.2
+Misalign, zero orb.	6.7	18.4	5.0	15.1
(60 seeds average)	(6.2)	(16.0)	(3.2)	(12.1)

The contribution to the β-beating when adding to the model all the harmonics (skew and normal components), from 2^{nd} to 15^{th} order, in all bending and quadrupole magnets (and the corresponding correction to the errors), compared with the case where only quadrupolar errors were introduced, is very small. The maximum difference along the machine is about 1%. The feed-down multipoles are negligible as the closed orbit is small.

Going one step further in the modeling of the optics, the alignment errors have also been added together with all the magnetic errors, and the orbit has been corrected to zero. The effect of introducing the alignment errors and corrections is small, but not completely negligible, as can be seen in Table 1. The effect is slightly bigger for the 3.5 TeV case than for injection as expected due to the stronger sextupoles, but it remains maximum at about 4%.

The impact of the closed orbit has also been studied. With this purpose, the optics has been modeled including all the magnetic and alignment errors, but correcting the orbit to the measured one during the LHC run instead of correcting it to zero. The difference in β-beating between these cases is very small, with a maximum of about 1 or 2%. The impact of the closed orbit is almost negligible.

EFFECTIVE MODEL *VS* MEASURED β-BEATING

The effective model has been studied for all the different instances of magnetic errors generated by WISE (60 seeds) at injection and at 3.5 TeV squeezed to 3.5 m β^*. The 60 seeds correspondig to the errors at injection include the statistical error generation component for both quadrupolar and higher order errors. In the case of 3.5 TeV, the 60 seeds include the statistical error generation in the quadrupolar errors, but not in the higher order components, for which all the seeds include the same instance of the machine. This does not affect the results as the effect of the higher order multipoles is negligible after the due corrections. The alignment errors have also been added and the orbit has been corrected to zero. The corresponding corrections to the magnetic errors have been performed for each seed. The average over the 60 seeds of the β-beating obtained at each location along the machine are shown in Figs. 1 and 2 for Beam 1 at injection and 3.5 TeV squeezed to 3.5 m β^* respectively. The model is compared to the corresponding measurements of the β-beating at injection and 3.5 TeV after the correction of the local errors[1] [9, 4]. It has been observed that the β-beating at injection, measured in the same conditions, fluctuates of about 8% between periods of a few months [4], while the variations at 3.5 TeV are about a factor of two smaller.

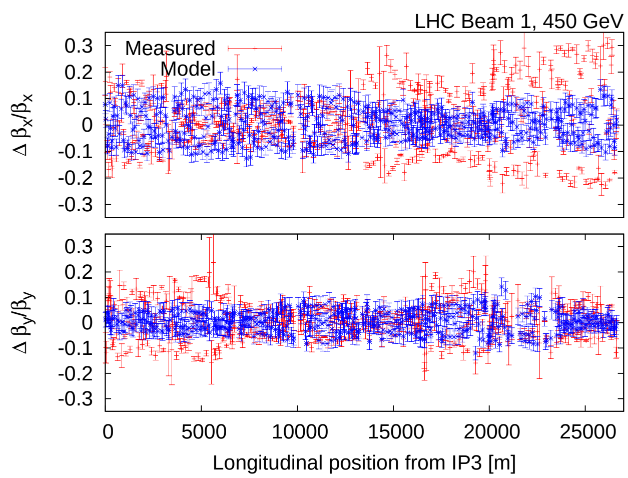

Figure 1: Modeled β-beating together with measurements from the 12^{th} of August 2010 for Beam 1 at 450 GeV.

The results for Beam 2 are shown in Figs. 3 and 4 at injection and 3.5 TeV squeezed to 3.5 m β^* respectively.

The β-beating obtained from the effective model is in good agreement, between the errors, to the measured data after correcting the local errors. From this model, which includes the best knowledge that we can have at present from the machine, one can conclude that the effect on the β-beating of the residual errors after all corrections is of the same order of magnitude as the measured effect. At 3.5 TeV there is a remarkable agreement between the model and the measurements, except for Beam 2 in the horizontal plane where some errors in IP8 could still remain. In general, this indicates that no significant errors, as for example cable swaps in strong magnets, remain in the

[1] Measurements performed by the β-beating group (R. Tomás *et al.*) during the 2010 LHC run.

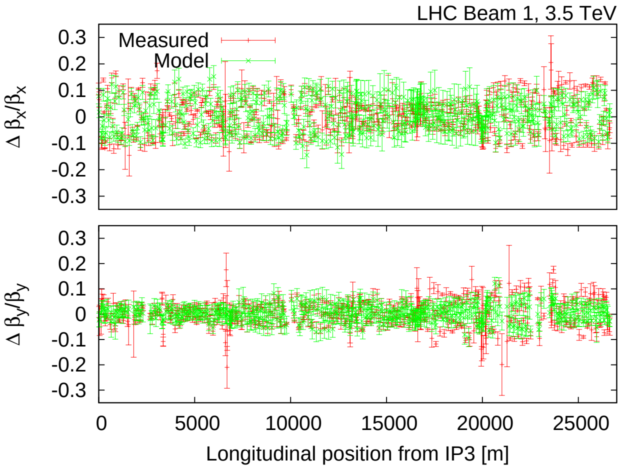

Figure 2: Modeled β-beating together with measurements from the 4^{th} of September 2010 for Beam 1 at 3.5 TeV.

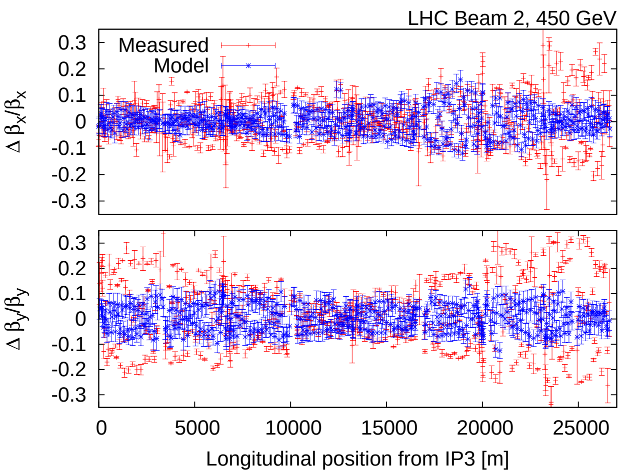

Figure 3: Modeled β-beating together with measurements from the 19^{th} of August 2010 for Beam 2 at 450 GeV.

machine after correction of main errors at the begining of the commissioning and after the local error correction was performed in the collimation sections and the IRs.

SUMMARY AND CONCLUSION

An effective model of the LHC optics has been built based on the best knowledge presently available concerning alignment and magnetic field errors. The model has been performed with the MAD-X code together with PTC to allow the treatment of the magnetic errors up to an arbitrary order in the thick elements lattice. After introducing the errors, the corresponding corrections are performed.

The main effect on the β-beating arises from the quadrupolar errors. There is a non negligible uncertainty of this component in the quadrupoles due to the high warm-to-cold correlation uncertainty for magnets that were not measured at "cold". Higher order multipoles have a negligible contribution. The feed-down multipoles are very small due to the small closed orbit. A small effect on the β-beating,

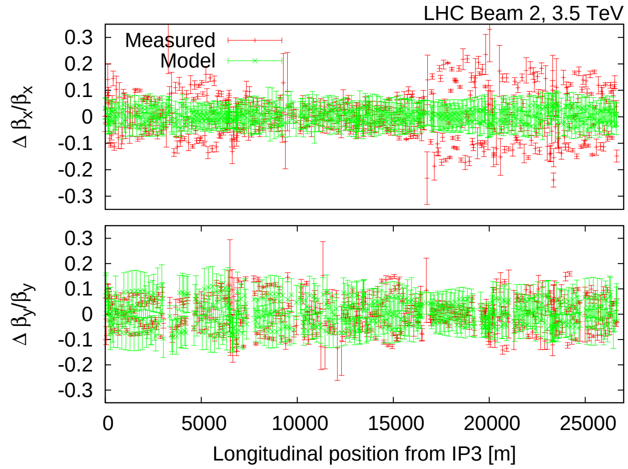

Figure 4: Modeled β-beating together with measurements from the 4^{th} of September 2010 for Beam 2 at 3.5 TeV.

maximum about 4%, arises when the alignment errors are included and the orbit is corrected to zero. The effect of the closed orbit is almost negligible, about 1 or 2%.

The effective model has been studied for all the different instances of magnetic errors generated by WISE (60 seeds) at injection and at 3.5 TeV squeezed to 3.5 m β^*. The results have been compared to the measurements of the β-beating performed after the correction of local errors during the 2010 run and show a remarkable agreement, especially at 3.5 TeV, which indicates that no significant errors remain in the machine. Some errors may still be corrected in certain IRs, mainly at injection optics.

The effective model is being implemented into the LHC online model for general use[2] [11].

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REFERENCES

[1] MAD-X Home Page, http://www.cern.ch/mad.

[2] E. Forest and F. Schmidt, http://frs.web.cern.ch/frs/PTC_reference_manual/PTC_reference_manual.html.

[3] C. Alabau *et al.*, "β-beating in the effective model of the LHC using PTC". To be published, submitted to PRSTAB.

[4] R. Tomás *et al.*, CERN-ATS-Note-2011-017.

[5] WISE Home Page, http://www.cern.ch/wise.

[6] P. Hagen, CERN-LHC-PROJECT-Report-1056 (2008).

[7] P. Hagen *et al.*, *Proceedings of the EPAC'06*, p. 2248.

[8] P. Hagen *et al.*, *Proceedings of the EPAC'08*, p. 1744.

[9] R. Tomás *et al.*, Phys. Rev. ST AB 13, 121004 (2010).

[10] R. Tomás *et al.*, Phys. Rev. ST AB 12, 081002 (2009).

[11] S. Redaelli *et al.*, *Proceedings of the IPAC'10, p. 480.*

[2] Implementation performed by G. Müller and K. Fuchsberger.