LHC OPTICAL MODEL AND NECESSARY CORRECTIONS

M. Aiba, C. Alabau, R. Calaga, J. Cardona, O. Dominguez, S. Fartoukh, M. Giovannozzi, V. Kain, M. Lamont, E. Mcintosh, R. Miyamoto, G. Mueller, S. Redaelli, F. Schmidt, R. Tomás*, G. Vanbavinckhove, J. Wenninger, S. White and F. Zimmermann

Abstract

The 2009 LHC run has made it possible to collect an extensive set of beam-based measurements. A good fraction of the LHC magnets, aperture and optics models has been validated with these measurements. However, a few localized optical errors remain. Appropriate corrections are necessary to reach machine specifications and to safely operate the LHC at higher intensities. The measurements, model predictions and proposed optics corrections are summarized.

LHC STATUS

The first optics measurements during the 2009 run made it possible to compare β-beating with and without precycling the LHC magnets. Figure 1 shows large variations of the β functions between these two cases. This clearly indicates the importance of operating the machine with a reproducible magnet cycle. However, due to technical problems it was not possible to pre-cycle the Q6 quadrupoles in IR3 and IR7.

Extensive optics measurements were made at two energies, 450 GeV (injection) and 1.18 TeV, throughout the run. The β functions proved to be reproducible even in the changing daily commissioning scenario. The largest optics change was found to be a 5% variation of the vertical β function of Beam 1 within a period of 4 days. It is expected that this sort of dynamic β-beating will be even lower when the machine operates in the more stable production mode. A summary of the peak β and dispersion beatings during 2009 is shown in Table 1 together with the tolerances presented in Ref. [1]. It is remarkable that the horizontal and vertical dispersions are within tolerances for both beams and for the two energies used during the 2009 run. Figure 2 compares the Beam 2 peak β-beating to simulations, tolerances and the measurement from 2008 [2]. While there is a considerable improvement between 2008 and 2009, as a result of fixing a cable swap between the two apertures of a trim quadrupole in the insertion region (IR) 3, the β-beating at injection is still well out of tolerance and out of the range expected from simulations.

For the first time in 2009 aperture measurements with circulating beam were performed in the LHC. The measured aperture tolerance expressed in beam sigmas is below the specification due to the large β-beating. Yet, no unforeseen mechanical aperture bottlenecks have been observed.

* rogelio.tomas@cern.ch

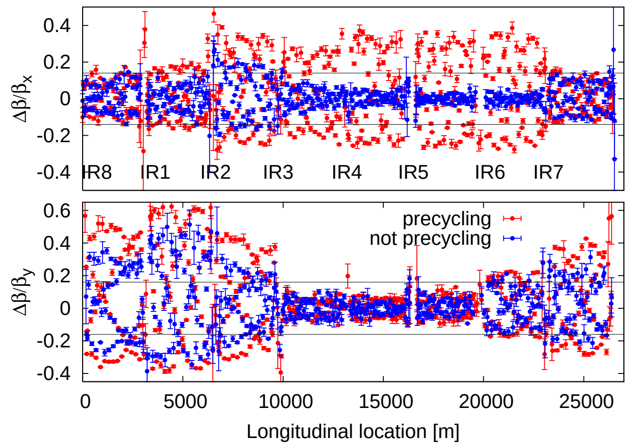

Figure 1: Measured horizontal (top) and vertical (bottom) β-beating for LHC Beam 2 with and without magnet precycling.

Table 1: Measured peak horizontal and vertical β and dispersion beatings for the two LHC beams and for two energies during the 2009 run. The tolerances as presented in [1] are displayed in the last column.

		Beam 1		Beam 2		Tol.
E	[TeV]	0.45	1.18	0.45	1.18	
$\frac{\Delta\beta_x}{\beta_x}$	[%]	35	20	40	15	14
$\frac{\Delta\beta_y}{\beta_y}$	[%]	50	16	55	20	16
$\frac{\Delta D_x^{qf}}{D_x^{qf}}$	[%]	19	11	16	-	30
$\frac{\Delta D_y^{qd}}{D_x^{qf}}$	[%]	8	12	11	-	28

The details of all the above beam-based measurements are presented below. The most relevant local optics errors are identified and effective corrections are proposed. The aperture bottlenecks and a few candidate locations which might have an aperture non-conformity are described.

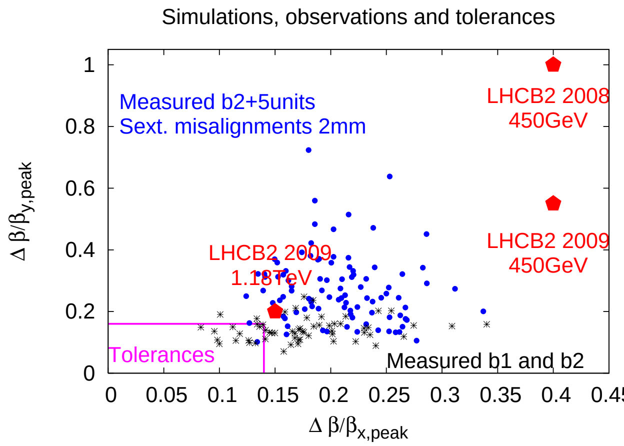

Figure 2: Peak vertical versus horizontal β-beating from simulations, tolerances and measurements during 2008 and 2009.

Table 2: Estimated peak β-beating in percent generated by the identified quadrupolar errors at injection energy (ordered by size).

	Beam 1		Beam 2	
	$\frac{\Delta\beta_x}{\beta_x}$	$\frac{\Delta\beta_y}{\beta_y}$	$\frac{\Delta\beta_x}{\beta_x}$	$\frac{\Delta\beta_y}{\beta_y}$
IR3	15	10	15	10
IR7	15	6	12	8
IR2	6	9	6	10
IR8	8	8	8	8
dip. b_2	6	7	5	9

IDENTIFIED ERRORS

Applying the segment-by-segment method [2] to the optics measurements from 2009 at injection energy has made it possible to identify the sections with the largest error sources. Table 2 shows a summary of these findings together with the estimated impact they would have in the ideal lattices of the two beams. The last entry of the table, the dipole b_2, is not a local error but the known systematic quadrupolar component of the LHC superconducting dipoles. All the identified errors affect both beams and cause between 5% and 15% β-beating in the design lattice. The sections with the largest error source seem to be the warm IR3 and IR7 regions, dedicated to collimation. These are followed by the triplets in IR2 and IR8. A detailed examination of all these errors follows.

The warm sections IR7 and IR3

IR7 and IR3 have the largest optics errors at injection energy while at 1.18 TeV almost no trace of these errors remains. This is illustrated in Fig. 3 by comparing the local horizontal and vertical phase-beatings between the measurement and the propagated model using as initial conditions the measured β, α functions at the 11^{th} quadrupole location to the left of the interaction point (IP) 7. The accumulated vertical phase-beat at the exit of the section is 0.03 2π radians at injection energy and 0 at 1.18 TeV. In the horizontal plane the situation is slightly worse as can be seen in Fig. 3. The optics errors are estimated by matching the propagated model optics to the measured β functions

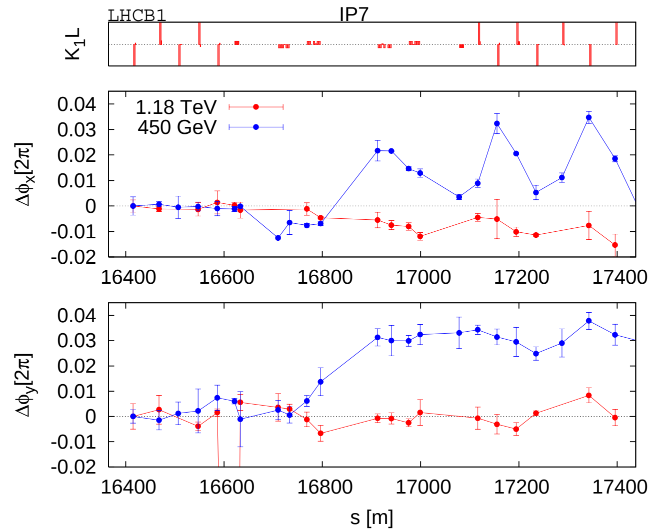

Figure 3: Beam 1 IR7 local error at 450 GeV and 1.18 TeV. Horizontal and vertical phase-beating between measurement and the propagated model are plotted versus longitudinal location. The top plot shows the lattice quadrupoles in the same region.

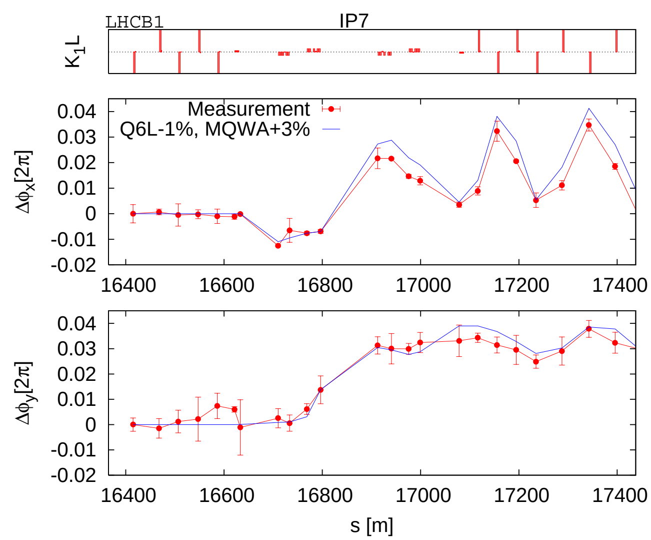

Figure 4: IR7 proposed local error source at injection energy. Reducing the strength of Q6L7 by 1% and increasing the strength of all MQWA modules by 3% reproduces the measured phase-beatings.

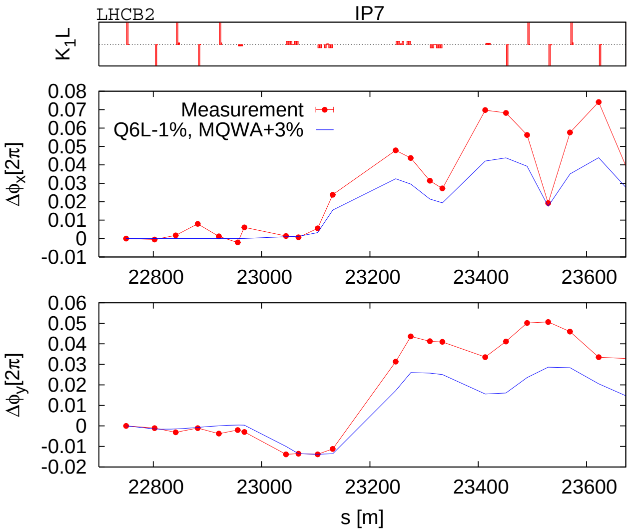

Figure 5: Impact of the IR7 Beam 1 identified local error sources on Beam 2.

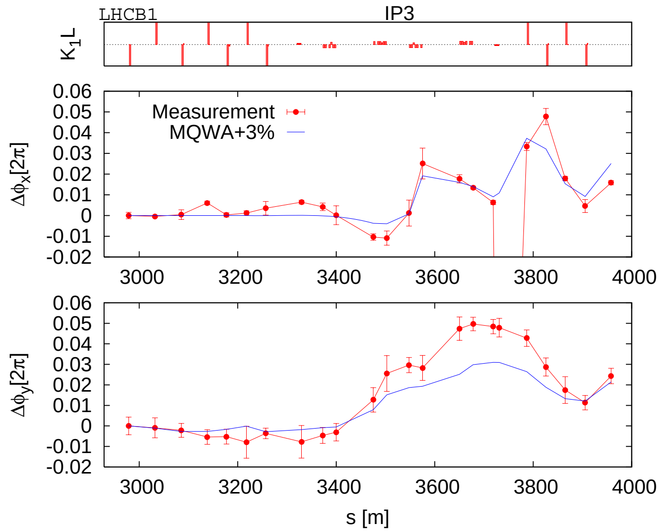

Figure 6: Effect of increasing the MQWA magnet strength by 3% in IR3 for Beam 1.

or, equivalently, phase advance within the segment under study. The variables used in the matching are the strengths of the quadrupoles within the section. Figure 4 illustrates the local error source in IP7. A matched model is found by reducing the strength of Q6L7 by 1% and increasing the strength of all MQWA modules by 3%. Previous attempts using only the trim quadrupoles (MQWB) were not as successful. Note that, as mentioned above, the Q6 magnets in IR3 and IR7 were not pre-cycled during 2009 for technical reasons and therefore some important error in Q6 can be expected. The impact of this Beam 1 correction on Beam 2 is shown in Fig. 5. A good fraction of the Beam 2 error is reproduced by the Beam 1 correction. Various iterations will be required to completely correct the errors for Beam 1 and Beam 2 in IR7 using all the available degrees of freedom. The situation in IR3 is very similar to that in IR7. An increase of the MQWA by 3% seems to reproduce a good fraction of the phase-beat in this region (see Fig. 6). Therefore the same iterative approach will be undertaken once the Q6 have been pre-cycled. It is worth pointing out that when the IR3 and IR7 estimated errors are used in the design optics the tunes for each beam in both planes are increased by about 0.05.

The IR2 and IR8 triplets

Applying the segment-by-segment technique to IR2 suggested using Q2 left and right triplet magnets with correction strengths corresponding to 50 and -70 units respectively, see Fig. 7. This correction was applied to the machine. Figure 8 compares measurements before and after the IR2 correction. Although error bars are rather significant an improvement in the horizontal and vertical phase-beat is observed. A similar situation is observed in IR8 with the required triplet corrections at the level of 50 units.

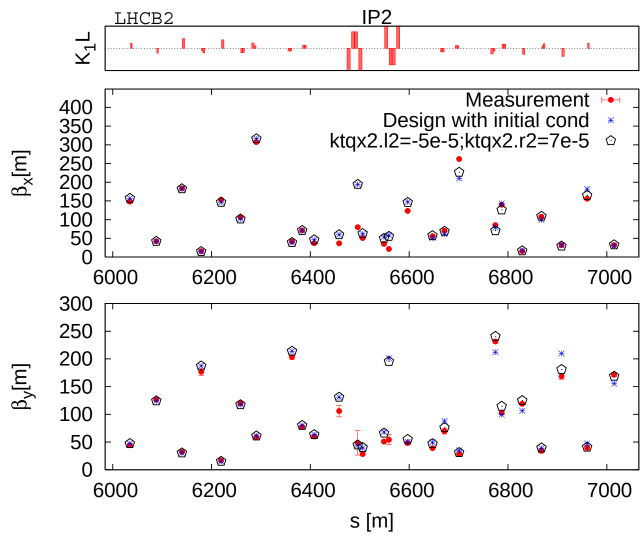

Figure 7: Predicted Beam 2 IR2 triplet correction. Horizontal and vertical beta functions from measurement and two propagated models. The model closest to measurements includes the Q2 correction.

These corrections should be reviewed in 2010 with a view to trying other possible configurations when better measurements are available.

The dipole b_2 component

The systematic quadrupolar component of the LHC dipoles has been determined from magnetic measurements [3, 4]. This quadrupolar error is corrected arc-by-arc using the MQT magnets to cancel the betatron phase shift. Figure 9 shows the measurements of the horizon-

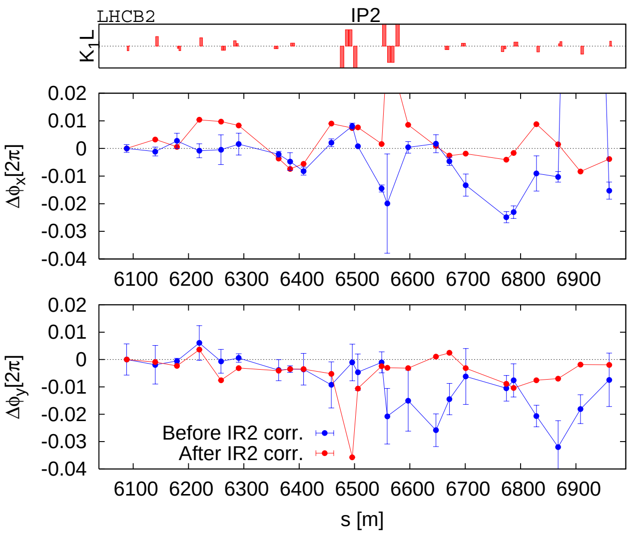

Figure 8: Horizontal and vertical phase-beat before and after IR2 correction using the Q2 left and right magnets.

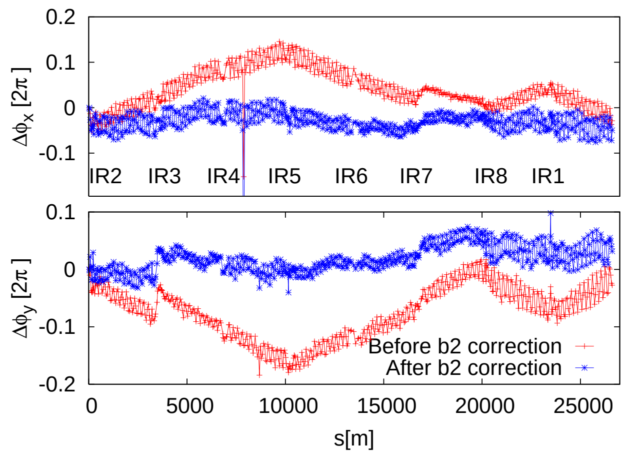

Figure 9: Horizontal (top) and vertical (bottom) phase-beat before and after the dipole b_2 component correction.

tal and vertical phase-beating before and after implementing the MQT strengths to correct the systematic dipole b_2. The correction is outstandingly successful in removing the systematic phase shift along the arcs. This was also observed during the 2009 injection tests, see Fig. 10, where difference orbits revealed the need to introduce the dipole b_2 and b_3 components in the model to perfectly reproduce the measurements.

IR2, IR8 and dipole b_2 measured correction

The error sources within IR3 and IR7 could not be identified during 2009 and the effective correction proposed above (increase strength of MQW by 3%) was found only towards the end of the run, too late to perform further beam

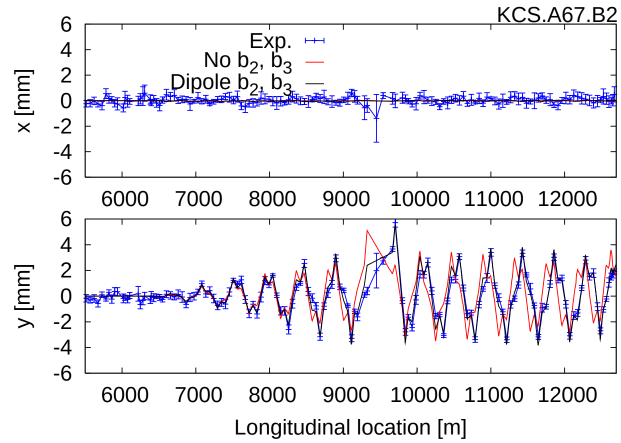

Figure 10: Measured off-momentum horizontal (top) and vertical (bottom) difference orbits compared to model predictions with and without the dipole b_2 and b_3 components from injection tests.

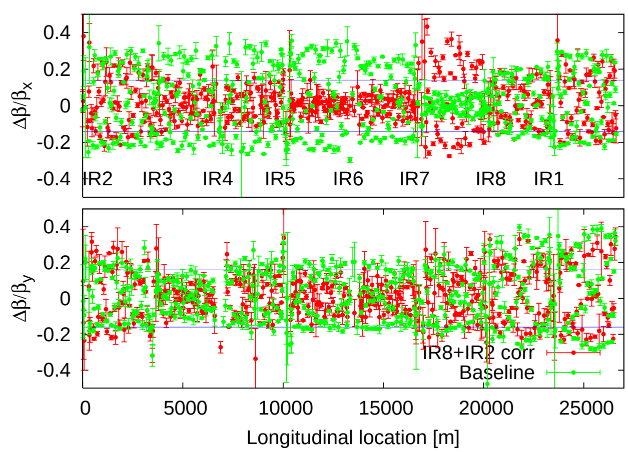

Figure 11: Beam 1 measured beta-beating before and after the simultaneous correction of IR2, IR8 and the dipole b_2 component.

tests. Therefore the largest correction applied was for IR2, IR8 and the dipole b_2. The measurements were done for Beam 1, only. Figure 11 shows the measured beta-beating before and after the simultaneous correction of IR2, IR8 and the dipole b_2 component. A considerable improvement of the horizontal β-beating is observed, leaving one single large jump of the β-beating wave amplitude at IP7. The improvements in the vertical plane are moderate. The largest jumps of the vertical β-beating wave amplitude occur at IR3, IR7 and IR8. The latter indicates the need for further iterations of the IR8 correction.

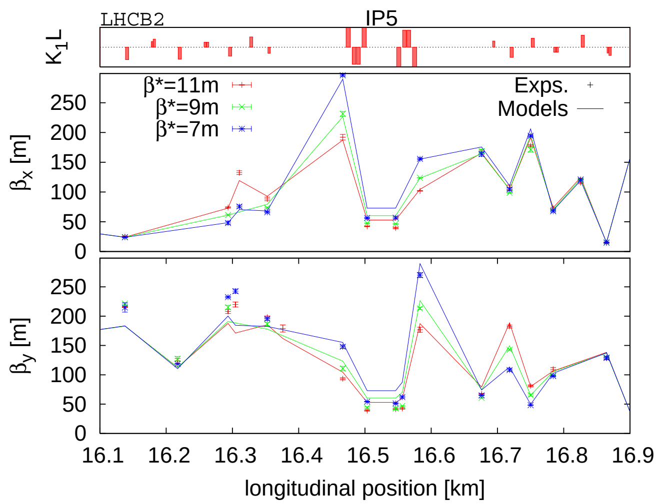

Figure 12: IR5 β functions from design models (lines) and measurements (points) for three steps of the β^* squeeze between 11 m and 7 m β^* at 1.18 TeV.

FIRST SQUEEZE IN IR5

A partial squeeze of β^* in IP5 was exercised during 2009 from 11 m to 7 m at 1.18 TeV. Optics measurements were performed at the nominal matching steps of 11 m, 9 m and 7 m. Measured and model IR5 β functions are shown in Fig. 12. The good agreement between model and measurement confirms the success of the first squeeze of the LHC. Further details of this first squeeze can be found in [5].

β^* KNOBS

In the event of mismatched IP beam sizes, the beam-beam interaction could cause emittance blow-up. β^* knobs are therefore not only valuable for optics corrections but might turn out to be essential for the optimization of beam lifetime. β^* knobs have been implemented and successfully uploaded into the control system. A dry run was performed in IR5 where it was possible to drive all the insertion quadrupoles simultaneously. All tools are ready for the commissioning with beam. Figure 13 shows the evolution of the β-function in both planes as a function of the knob value (a value of 1 corresponds to a change of 10 % of β^*). The behaviour is rather linear in the ± 20 % range with reasonable tune variations (few 10^{-3}). An early commissioning with optics measurement to characterize the performances of these tools is therefore recommended and could also help understanding the hysteresis effects in the main insertion quadrupoles. Detailed analysis and measurements will be presented in [6].

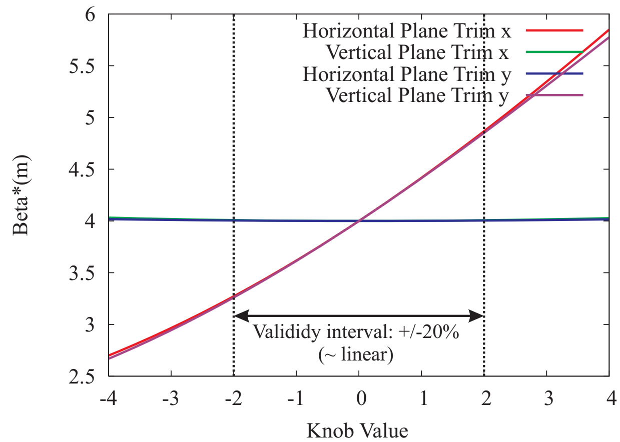

Figure 13: Behavior of β^* knobs for the 4 m optics in IP5 using all insertion quadrupoles.

APERTURE MODEL AND BEAM-BASED MEASUREMENTS

It is customary to express the aperture of the LHC machine using the so-called n_1 parameter (see Ref. [8] for a detailed description of its definition and computation). Such a quantity is linked to the available machine aperture. Its computation requires the knowledge of a number of relevant optical and beam parameters and it also takes into account the tolerance budget on a number of quantities, such as: i) mechanical alignment of the apertures; ii) closed orbit of the machine; iii) beta-beating in the machine; iv) spurious dispersion. All this with a view of providing the most realistic estimate of the available aperture taking into account all known uncertainties. It is also worth mentioning that over the years, the aperture model has been improved in order to incorporate, as far as possible, all the measurement data, such as the information concerning the axis position of the cold bore of the cold magnet, which is used to define a displacement of the beam screens in the aperture model.

It is also worth mentioning that n_1 is crucial as it is used to define the positioning of the collimators in the LHC machine, its nominal value is 7.

One of the first things investigated after the optics measurements, was the evaluation of n_1 using the most accurate experimental data in order to derive information about the actual tolerance budget on, e.g., beta-beating and closed orbit. This would enable estimating whether ramp and squeeze can be performed without endangering the whole machine due to, e.g., lack of mechanical aperture. In Fig. 14 the n_1=7 level curves for the measured optics are plotted as a function of the beta-beating and the closed orbit budget for Beam 1 (left) and Beam 2 (right). The optics used for these computations are the measured values, while the aperture model is the nominal one including the measured profiles. For each beam the curve corresponding to $n_1 = 7$ is computed in the space beta-beating/closed

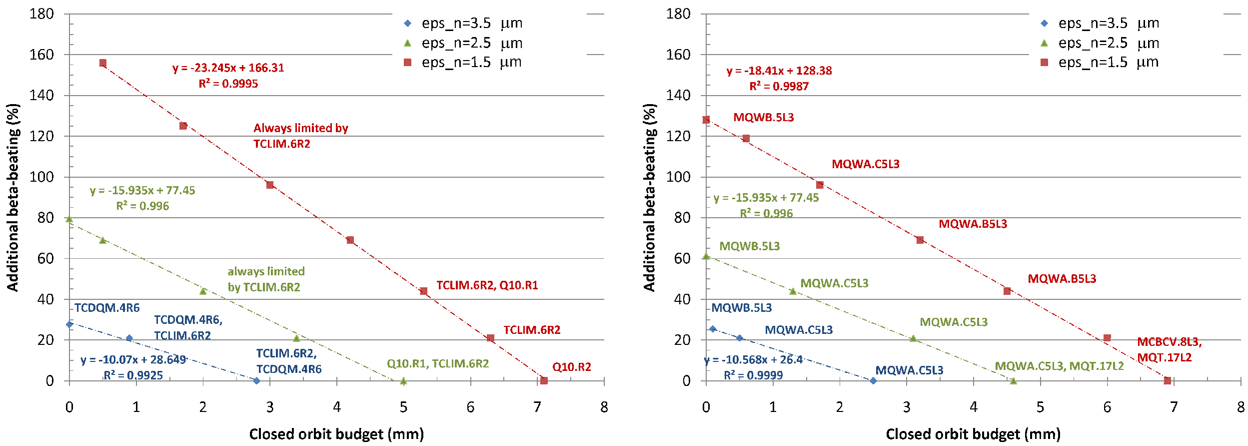

Figure 14: Available aperture as a function of the beta-beating and closed orbit budget for Beam 1 (left) and Beam 2 (right).

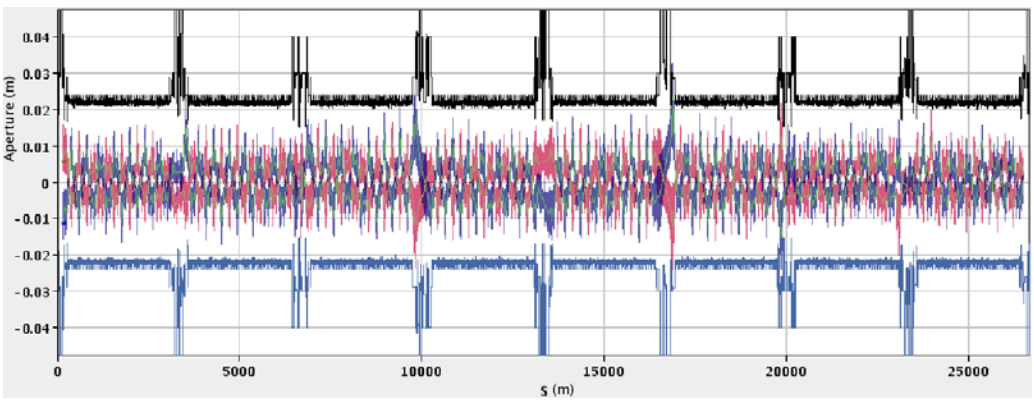

Figure 15: Example of horizontal aperture measurement with circulating beam. Two closed orbit distortions with same amplitude and dephased by 180 degrees are shown together with the beam envelope. The entire Beam 2 is reported.

orbit. It is worth stressing that the beta-beating here is additional to that of the measured optics. The three curves correspond to three values of the transverse emittance. The curves identifying the nominal n_1 value are straight lines covering a different surface in the beta-beating/closed orbit space depending on the emittance value. The information concerning the limiting elements has been added. Figure 14 gives a good indication of the link between beta-beating and closed orbit and provides a way to find a balance between the two. There is no fundamental difference between the two plots for the two beams, apart from the fact that less aperture is available for Beam 2 and a tighter control of optics and closed orbit is required. Of course this should not be a surprise, given that the beta-beating is indeed larger for Beam 2 as reported in Table 1.

This first check of the aperture provides better information with respect to the standard computation of n_1 based on nominal parameters as it takes into account the measured optics. Still, it assumes a perfectly nominal aperture model. Therefore, detailed aperture measurements were performed both during the numerous injection tests [9] as well as during the beam commissioning period, this time using circulating beam.

The idea is to generate closed orbit distortions with two orbit correctors: the beam loss monitors (BLMs) allow the determination of the location of the losses and hence the smallest aperture in the machine. Specifically, during 2009 the following couples of orbit correctors were used: (MCBH.14R2.B1, MCBH.16R2.B1), (MCBV.13R2.B1, MCBV.15R2.B1), (MCBH.16L8.B2, MCBH.18L8.B2) and (MCBV.17L8.B2, MCBV.19L8.B2). This approach is repeated by changing the betatronic phase of the bump in order to provide appropriate coverage of the betatron space. Horizontal and vertical scans for both beams were performed. The measured aperture in millimeters is determined by the bump amplitude at the location where the beam loss is detected plus the size of the beam envelope evaluated at three sigma. An example of the measurement results is reported in Figs. 15 and 16. It is clear that this method relies heavily on an accurate emittance

Table 3: Selected results of aperture measurements for Beam 1.

Plane	$\epsilon*$ (H/V) [μm]	Phase [degrees]	Amplitude [σ]	Element name	Type	Nominal aperture [mm]	Measured aperture [mm]
H	3.3/3.3	30	7	MQM.6R2	F	21.1	12
	3.3/3.3	30	7	MQM.6R8	F	21.0	17
	4.2/4.2	270	7	MQY.4R6	F	27.4	24
V	9.2/9.2	90	7	MQY.4L6	D	27.7	25
	9.2/9.2	270	7	MQML.10R1	D	15.7	17

Table 4: Selected results of aperture measurements for Beam 2. The analysis of the vertical plane data is still in progress.

Plane	$\epsilon*$ (H/V) [μm]	Phase [degrees]	Amplitude [σ]	Element name	Type	Nominal aperture [mm]	Measured aperture [mm]
H	15.0/10.7	300	7	MQY.5R6	F	27.3	27
	15.0/10.7	150	8	MQ.11R6	F	20.4	13
	15.0/10.7	270	7	MQY.4L6	F	27.4	28
	15.0/10.7	270	7	MQM.6L8	F	20.8	21

measurement and a continuous monitoring of the beam size to exclude growth of the emittance during the aperture scans, which would otherwise affect the final aperture estimate. It is also clear that a certain degree of arbitrariness is involved in choosing the number of sigmas to be used in estimating the beam envelope. For all these reasons and depending on the emittance value, the error on the measured aperture should be of the order of few/several millimeters. During the aperture scans the amplitude was increased until the same level of losses, as measured by the BLMs, were recorded. This is also important to ensure that the number of sigmas assumed for the beam envelop is roughly the same in all measurements.

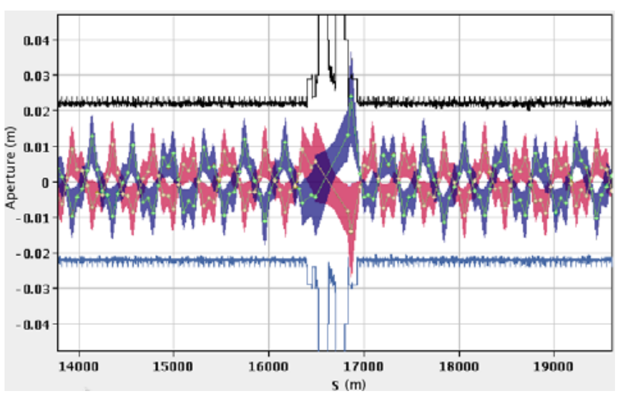

Figure 16: Example of horizontal aperture measurement with circulating beam corresponding to the IR6 zoom of Fig. 15.

In Tables 3 and 4 a selection of the measurements analyzed so far is reported. Some explanations on the quantities reported in the columns and the approach used for the analysis are given in the following:

- The emittance values used for the computation of the beam envelope are quoted in the summary tables. These values are derived from flying wire measurements. Such an instrument provides the beam size, and the resulting emittance value is obtained by using the values of the measured optical parameters at the location of the instrument.
- The phase of the bump as well as its amplitude in nominal sigmas is given. The bump is computed using the nominal LHC optics. Hence a distortion with respect to the nominal shape is always observed.
- The nominal aperture is inferred from the nominal mechanical aperture reduced by the standard tolerances (mechanical and alignment). The data from the measured aperture profiles are also taken into account in the computations.
- The measured aperture is given by the beam position as measured by the beam position monitor (BPM) at the location of the loss plus the three sigma envelope. The beam envelope is obtained by using the measured emittance value and the measured optics.

From the arguments above and Tables 3 and 4 it is clear that a larger error is to be expected for the measurements for Beam 1 (V-plane) and Beam 2 (H-plane) due to the large emittance value. While in general there is a reasonable agreement between nominal and measurement aperture, a few cases are controversial, namely MQM.6R2.B1 and MQ.11R6.B2. The data available do not permit clarification of the situation and additional measurements will be required during the 2010 re-commissioning period.

CONCLUSIONS

Important optics errors have been localized in the IR3 and IR7 warm sections at injection. It has been confirmed that the error sources within these sections vanish at 1.18 TeV. An effective first order correction has been proposed by reducing the strength of all the MQWA magnets by 3%. Further measurement and correction iterations using all available quadrupoles in these sections should take place in 2010 after the Q6 magnets have been pre-cycled.

The IR2 and IR8 triplets were identified as secondary error sources. First correction iterations in these regions proved successful. The optics deviations caused by these triplet errors are comparable to the error of the measurement. Therefore higher precision measurements should be performed in 2010 by using the aperture kickers to excite large betatron oscillations.

The lattice models including the systematic arc dipole b_2 and b_3 components from magnetic measurements were found to reproduce the beam-based measurements with a remarkable agreement. The foreseen corrections of these multipolar errors should be implemented from the restart of the LHC commissioning in 2010.

For the 2010 run it will be desirable to commission as early as possible the β^* knobs and the AC dipole. β^* knobs might become fundamental in the optimization of beam lifetime. The AC dipole provides safe and non-destructive large betatron oscillations at all energies and it is the only functional exciter at high energies.

In Ref. [7] it was suggested that the β-beating corrections should be aimed at achieving the 10% level (below the current tolerances between 14% and 16%) in order to minimize the detrimental effects coming from head-on and long-range beam-beam interactions. This challenge seems to be at hand once the measurement resolution has been increased by exciting larger betatron oscillations either with the aperture kickers or the AC dipoles.

As far as the aperture scans are concerned, a number of unambiguous observations indicate that no unforeseen aperture bottleneck should be expected. However, a number of unclear measurements indicate that another detailed campaign of aperture measurements should be foreseen during the 2010 commissioning period. Such a campaign should be repeated also in view of the optics corrections to be performed on the basis of the observations made in 2009. It will be vital to improve the control of the experimental conditions, such as the beam emittance and its evolution during the scans. A clear improvement with respect to the 2009 run will be the availability of the synchrotron radiation monitors to control the emittance evolution.

ACKNOWLEDGMENTS

We would like to warmly thank P. Hagen and E. Todesco for their feedback and many stimulating discussions concerning the magnetic field quality and magnet modeling of warm quadrupoles and triplet quadrupoles. R. de Maria provided invaluable help with Python codes. We are grateful to O. Bruning for continuously supporting these beam experiments.

REFERENCES

[1] S. Fartoukh and O. Brüning, “Field Quality Specification for the LHC Main Dipole Magnets”, CERN LHC-Project-Report-501 (2001).

[2] M. Aiba, R. Calaga, S. Fartoukh, A. Franchi, M. Giovannozzi, V. Kain, M. Lamont, R. Tomás, G. Vanbavinckhove, J. Wenninger, F. Zimmermann and A. Morita, “First β-beating measurement and optics analysis for the CERN Large Hadron Collider”, Phys. Rev. ST Accel. Beams **12**, 081002 (2009).

[3] P. Hagen, M. Giovannozzi, J.-P. Koutchouk, T. Risselada, S. Sanfilippo, E. Todesco, E. Wildner, “WISE: An Adaptative Simulation of the LHC Optics”, in Proceedings of Tenth European Particle Accelerator Conference, ed. by J. Poole and C. Petit-Jean-Genaz, Institute of Physics UK London, p. 2248 (2006).

[4] P. Hagen, M. Giovannozzi, J.-P. Koutchouk, T. Risselada, F. Schmidt, E. Todesco, E. Wildner, “WISE : A Simulation of the LHC Optics including Magnet Geometrical Data”, in Proceedings of Eleventh European Particle Accelerator Conference, ed. by C. Petit-Jean-Genaz, Institute of Physics UK London, p. 1744 (2008).

[5] S. Redaelli, “Squeeze: strategy and issues, including machine protection”, these prodeedings.

[6] S. White *et al.*, 1^{st} International Particle Aceelerator Conference 2010, Kyoto, Japan, in preparation.

[7] W. Herr, “LHC beam behaviour”, these proceedings.

[8] J.-B. Jeanneret, R. Ostojic, “Geometrical Acceptance in LHC Version 5.0”, CERN LHC-Project-Note-111, 1997.

[9] S. Redaelli *et al.*, “First Beam Based Aperture Measurements in the Arcs of the CERN Large Hadron Collider”, in Proceedings of Twenty-third Particle Accelerator Conference, in press.