LHC OPTICS MODEL, MEASUREMENTS AND CORRECTIONS

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Abstract

Optics stability during all phases of operation is crucial for the LHC. The optical properties of the machine have been optimized based on a detailed magnetic model of the SC magnets and on their sorting. Tools and procedures have been developed for rapid checks of beta beating, dispersion, and linear coupling, as well as for prompt optics correction. Initial optics errors, correction performance and optics stability from the first LHC run will be reported, and compared with expectations.

INTRODUCTION

LHC is the first hadron collider with tight design tolerances on optics errors to guarantee the machine protection during operation with beam. This called for a quest of the most convenient optics measurement techniques [1, 2, 3, 4] and instruments [5, 6]. Several measurement and correction algorithms were tested in SPS [7, 8], RHIC [9] and SOLEIL [10]. The first optics measurement of the LHC [11] revealed an unexpectedly large β-beating. The leading source of this error was identified as a cable swap between the two beam apertures of a trim quadrupole. This finding was only possible thanks to the development of a new optics correction method, the Segment-By-Segment Technique (SBST). This technique has evolved to include the full set of linear optics parameters in the general case of a coupled lattice (see next section). Figure 1 shows the peak β-beating (top) and the rms orbit (bottom) of the LHC Beam 2 at injection energy versus the number of days in commissioning with circulating beam. Until April 2010 LHC had accumulated 60 days of operation with circulating beam. During this period the dominant optics errors were identified and corrected at injection, considerably reducing the β-beating to values close to design tolerances. The evolution of the rms orbit shows a clear correlation with the β-beating since the orbit correction uses the orbit response matrix from the ideal model. Figure 1 also shows the relevant events that affected the optics quality. A very good stability of the optics is observed in periods over 10 days when the machine was unchanged.

The optics corrections at injection are smoothly zeroed along the ramp, between 450 GeV and 1.2 TeV. The measured β-beatings at injection, 1.2 TeV and 3.5 TeV are shown in Fig. 2. The AC dipole [5] is a fundamental instrument for the optics measurement at high energies [6]. Optics corrections might be required at intermediate energies.

At 3.5 TeV the IPs β^* are squeezed to 2 m to increase the luminosity. The commissioning of the four IPs β^* squeeze
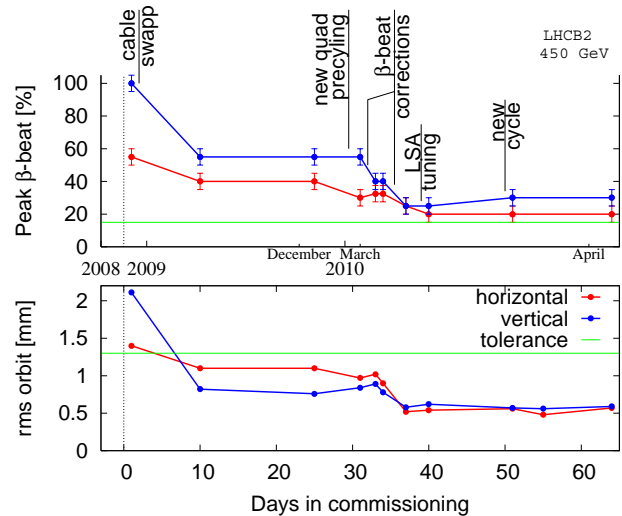

Figure 1: Measured peak β-beating (top) and rms orbit (bottom) of Beam 2 versus the number of days of LHC operation after circulating beam was established in 2008. Relevant events affecting the LHC optics are also displayed. LSA stands for LHC Software Architecture [12].
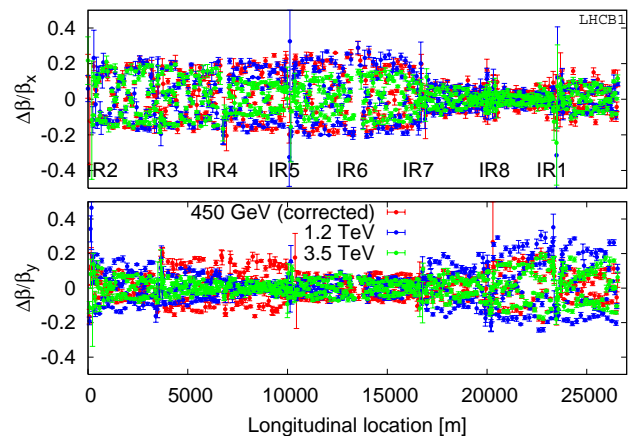

Figure 2: LHC Beam 1 horizontal (top) and vertical (bottom) β-beating for 3 energies as measured during 2010.

is summarized in Fig. 3 showing the peak β-beat and the four β^*s versus time. About 15 days were used to achieve 2 m at all IPs. Large optics errors became evident in the IRs as β^* was being reduced. Local optics corrections were computed on-line and fully implemented in the squeeze procedures. After the squeeze a rather poor reproducibility of the β-beating in Beam 2 has been observed.
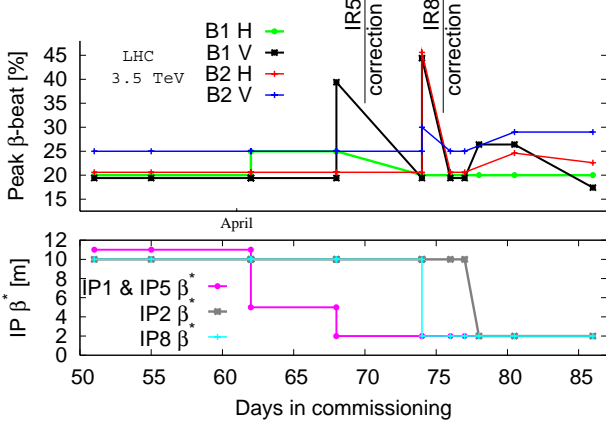
Figure 3: Measured β-beating (top) and IPs β^* (bottom) versus the number of days of LHC operation during the β^* squeeze commissioning.
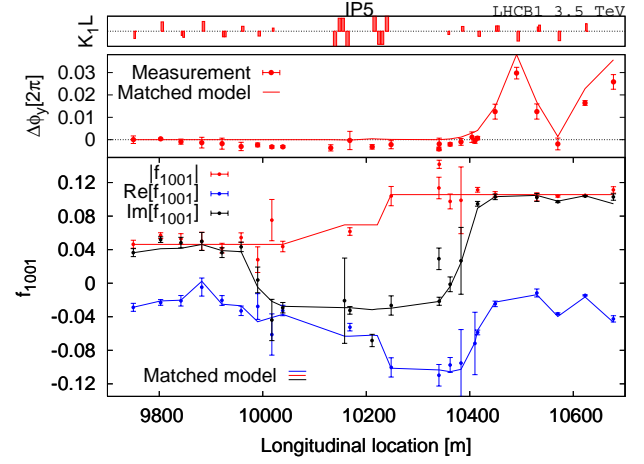

Figure 4: Example of the full SBST applied to the correction of the IR5 normal and skew optics errors. The IR quadrupoles (top), the vertical phase advance error (medium plot) and the difference resonance f_{1001} are shown. The lines represent the matched model with normal and skew errors only in the triplets.

FULL SBST

In [11] the SBST was introduced to identify the dominant optics error in the LHC. This error was responsible for about 50% β-beating in the vertical plane of Beam 2, see Fig. 1. Since then the SBST has been extended and improved to localize and correct linear optics errors, both normal and skew. The basic concept of the SBST is to split the machine into various sections and treat them as independent beam lines using the measured values as initial optics conditions. This was first applied to β and α functions, which are measured from the phases between three BPMs [13]. The phase advance within the segment proved to be a more precise and local observable. The horizontal and vertical dispersions can also be incorporated in the SBST by computing the dispersion angles ($D'_{x,y}$) at the start of the section using the dispersion measurement at the first two BPMs and assuming the ideal model between them. A more delicate and innovative addition to SBST is the transverse coupling. All the coupling parameters need to be measured at the start of the segment and translated into the MADX [14] formalism for the model propagation. The real and imaginary parts of the difference (f_{1001}) and sum (f_{1010}) resonance terms are extracted from the measured spectrum of the normalized complex signal [15, 16], $h_x = \hat{x} - i\hat{p}_x$, which is parametrized to the first order as

$$h_x(N) = \sqrt{2I_x}e^{i\phi_x(N)} -$$
$$i2f_{1001}\sqrt{2I_y}e^{i\phi_y(N)} - i2f_{1010}\sqrt{2I_y}e^{-i\phi_y(N)}$$
$$h_y(N) = \sqrt{2I_y}e^{i\phi_y(N)} - \qquad\qquad (1)$$
$$i2f^*_{1001}\sqrt{2I_x}e^{i\phi_x(N)} - i2f_{1010}\sqrt{2I_x}e^{-i\phi_x(N)}$$

where $I_{x,y}$ are the action invariants and $\phi_{x,y}(N) = 2\pi N Q_{x,y} + \phi_{x0,y0}$ describe the turn-by-turn phase evolution. The LHC double plane BPMs allow the measurement of $\phi_{x0,y0}$ from the horizontal and vertical tune spectral lines. With these phases the real and the imaginary

parts of f_{1001} and f_{1010} can be measured from both the horizontal and vertical spectra as shown by Eqs. (1). In order to achieve a measurement independent of BPM calibration and beam decoherence, the values obtained from the horizontal and vertical planes are geometrically averaged as done in [17]. The measured f terms are translated into the MADX coupling formalism at the start of the segment as described in [18]. An illustration of the full SBST applied to the correction of IR5 normal and skew gradient errors in the triplet is shown in Fig. 4. The lines represent the propagated model matched to the measurement. The normal gradient errors generate the vertical phase-beating and the skew gradient errors cause the jumps of $|f_{1001}|$, which would stay constant in the absence of coupling sources.

AC DIPOLE

AC dipoles force long lasting betatron oscillation without emittance growth when ramped up and down adiabatically. The long lasting oscillations are ideal for transverse beam dynamics measurements. The slow increase of the oscillation amplitude guarantees the effective response of the machine protection devices in case of a mishappening [6]. This makes the AC dipole the perfect transverse exciter for the LHC. Dedicated measurements were performed in the LHC to verify the safe operation of the AC dipole and to confirm the predictions in [6]. Figure 5 shows the measured and simulated beam excursion while ramping the AC dipole to 20% of its maximum strength in 2000 turns with a frequency equal to the tune. At the turn 290 the beam was cleanly extracted by the machine protection system after having detected losses in the primary collimators (with a half gap of 6σ). This, together with the good agreement between measurement and simulation, validated the AC dipole as a safe instrument.
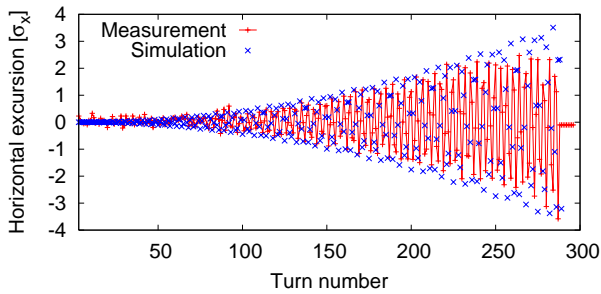
Figure 5: Measured and simulated horizontal beam excursions with the AC dipole ramping up on the tune resonance.

Figure 6: β-beating for Beam 1 before and after corrections at injection.

Figure 7: Illustration of the local optics correction in IR3.

However forced oscillations differ from free oscillations proportionally to the distance between the driving tune and the machine tune [19, 20, 21, 22]. In presence of an AC dipole the measured β functions differ from the machine β functions as if there was a quadrupole error in the location of the AC dipole [23]. This equivalence allows to apply exactly the same analysis to all experimental data but using a modified reference model which includes the quadrupole error according to the AC dipole settings. The measured difference resonance term f'_{1001} also differs from the machine f_{1001} as follows [22, 24],

$$f'_{1001} = \frac{\sin(\pi(Q_x - Q_y))}{\sin(\pi(Q_{ac} - Q_y))} f_{1001}(1 + O(2\pi\delta)) \qquad (2)$$

assuming a horizontal AC dipole with driving tune Q_{ac} and $\delta = Q_x - Q_{ac}$. The fraction on the r.h.s is a global factor easily taken into account. However it is not possible to estimate the residual $O(2\pi\delta)$ from the measurement. Therefore a good coupling measurement needs to drive as close as possible to the machine tune. In the LHC it is customary to excite at $|\delta| = 0.005$ without significant emittance blow-up, yielding a systematic error of about 3% in f_{1001}.

OPTICS CORRECTIONS AT INJECTION

Optics measurements during 2009 at injection energy allowed to identify the sections with the largest error sources [25]. 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 are the warm IR3 and IR7 regions, dedicated to collimation, followed by the triplets in IR2 and IR8 and by the quadrupolar error in the main dipoles (the b_2 component). The error sources in IR3 and IR7 vanish at higher energies [25]. This findings allowed magnet experts to identify a wrong magnetic pre-cycle in the main quadrupoles of IR3, IR7 and the triplets [26]. The magnetic pre-cycle was corrected in 2010, see Fig. 1, improving the horizontal β-beating in the Beam 2. Nevertheless optics corrections were still required. Figure 6 shows the β-beating before and after correction for Beam 1. All the corrections were computed via the SBST to ensure their locality. Figure 7 illustrates the local optics correction in IR3. IR3 and IR7 insertions are
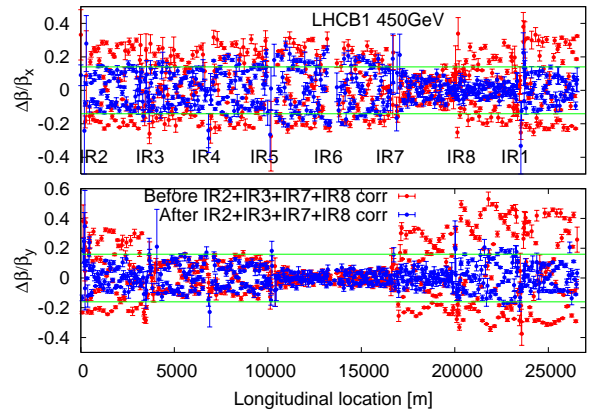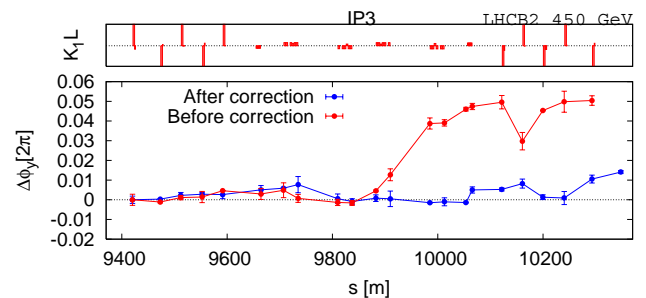
particularly constrained for optics correction since the main warm quadrupoles are powered in series on both sides and for both beams and trim quadrupoles are powered in series for both beams. The size of the required relative corrections is in the 1% level for the main IR3 and IR7 quadrupoles and between 10% and 250% for the trim magnets. The latter are nominally set to a very low field in IR7, this explaining the large corrections needed. Presently new magnetic measurements of IR3 and IR7 quadrupoles using the same pre-cycle as in operations reveal that the calibration errors are in agreement with the optics measurements [27].

Further corrections could be applied, being IR1 the next leading source, but the β-beating level is considered to be acceptable for the existing aperture (thanks for a lower than expected rms orbit).

The systematic quadrupolar component (b_2) of the LHC dipoles has been determined from magnetic measurements [28]. This quadrupolar error is corrected arc-by-arc using the arc MQT magnets to cancel the betatron phase shift [29]. Figure 8 shows the measurements of the horizontal and vertical phase-beats before and after implementing the corrections. An excellent correction is achieved removing the systematic phase shift along the arcs.

OPTICS DURING β^* SQUEEZE

At 3.5 TeV the IPs were first squeezed sequentially (IP1&IP5, IP8 and IP2) allowing for local optical correc-

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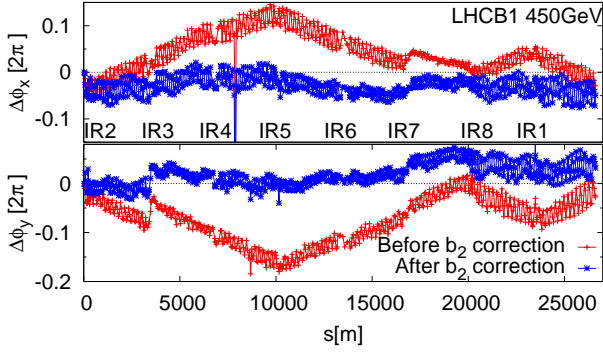
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Figure 8: Beam 1 horizontal (top) and vertical (bottom) phase-beat before and after the dipole b$_2$ component correction.
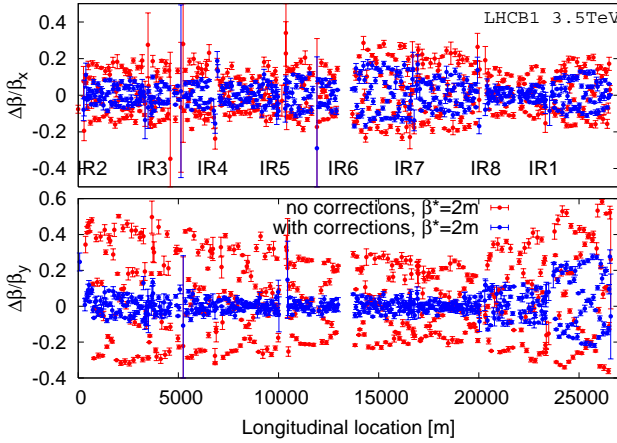

Figure 9: Beam 1 horizontal (top) and vertical (bottom) β-beating before and after correction with all IPs at 2 m at 3.5 TeV.

tions after each IP reached 2 m, as shown in Fig. 3. All IPs were finally squeezed simultaneously. Measurements with and without local IR corrections at β*=2m reveal unexpectedly large optics distortions as shown in Fig. 9. Up to 60% β-beating is observed in the vertical plane of Beam 1. Table 1 shows the magnets used for this correction. For IR5 it was possible to find a triplet correction that would correct both beams. Figure 10 illustrates the simultaneous two-beam correction showing the local IR5 phase-beating before and after correction for the vertical and horizontal planes of Beam 1 and Beam 2, respectively.

The dominant optics error source appears in IR8. In this IR it was not possible to find a local correction for both beams using only the common triplet magnets. The pragmatic approach was to use the independent magnets nearby, resulting in the large relative corrections in Table 1. The triplets in IR8 have known relative calibration errors in the order of 13×10^{-4}. After the corrections were applied it was checked that the magnetic errors explain about 30% of the vertical phase-beating for Beam 1, see Fig. 11. Up-

Table 1: Magnets used to correct the β-beating at 3.5 TeV with the IPs β* at 2 m.

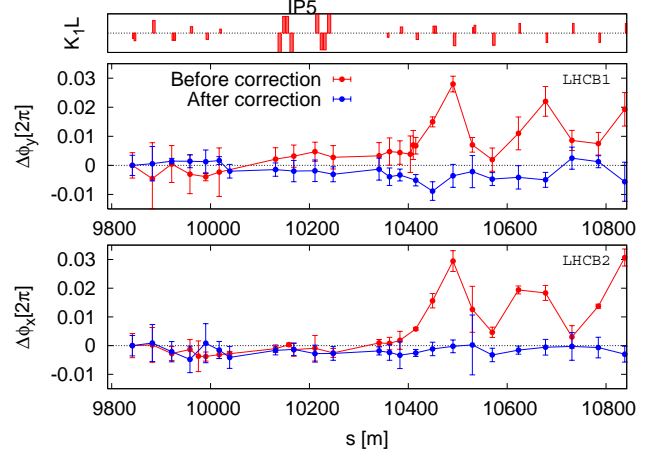| Magnet	Value[m^{-1}]	Max[m^{-1}]	Correction[%]
MQXB2.R5	-0.0087	0.018	-0.15
MQXB2.L5	0.0087	0.018	0.12
MQ5.R8B1	-0.0029	0.013	5
MQ6.L8B2	0.0056	0.013	1.8

Figure 10: Illustration of the two-beam β-beat correction using the IR5 triplets.

dating the calibration of the IR8 triplets would reduce the required correction from 5% to 3.3%.

A lack of reproducibility of the β-beat in the 10% level was observed for the first time with the squeezed β*. Figure 12 shows the difference of the vertical β-beat between two measurements separated by 5 days. One measurement was performed right after the squeeze while the second was done at the end of a 30 hours physics fill. The figure shows abrupt jumps at IR8 and IR2. More measurements are needed to better understand the level of reproducibility
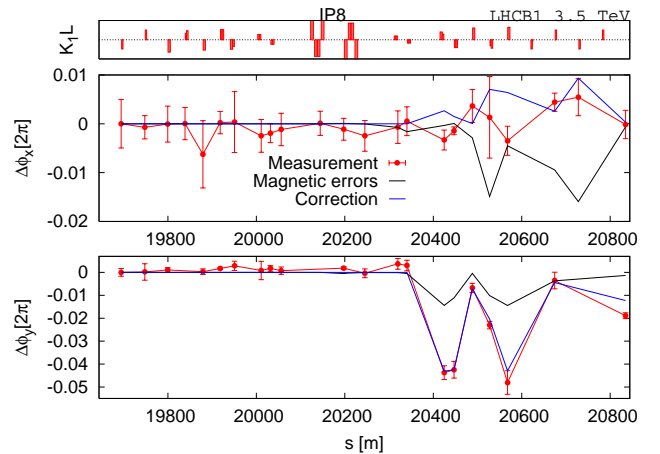

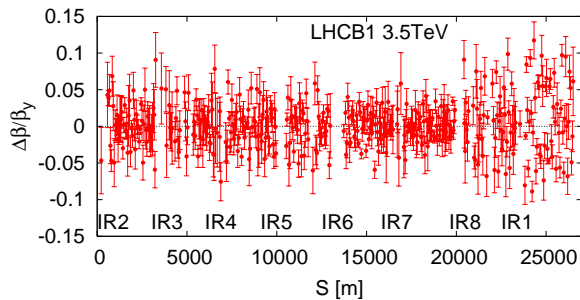Figure 11: Local Beam 1 IR8 correction increasing by 5% the fifth quadrupole to the right of IP8.

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Figure 12: Difference of the Beam 1 vertical β-beating between 2 measurements at β^*=2m separated by 5 days.
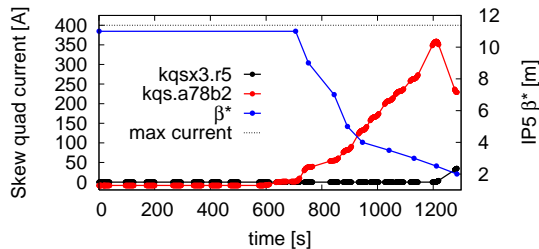

Figure 13: Skew quadrupole current along the squeeze.

and the "dynamic" error sources.

COUPLING CORRECTION

The transverse coupling is generally corrected on-line [30] by using two orthogonal global knobs of skew quadrupoles, for the real and imaginary parts of f_{1001}. During the squeeze these global knobs need to be stronger as the β functions increase in the IRs as shown in Fig. 13. With all the IPs at β^*=2m the global knobs were not strong enough to correct the coupling and the IR local coupling correction was mandatory.

The full SBST was applied to all IRs, as shown in Fig. 4, to compute the required strengths of the inner triplet skew quadrupoles in order to reproduce the measured f_{1001}. A considerable reduction of the required strengths of the global knobs was achieved after the local coupling correction.

SUMMARY AND OUTLOOK

Unexpectedly large optics errors have been observed in the LHC at injection energy and at 3.5 TeV after the β^* squeeze down to 2 m. The dominant errors have been locally corrected by applying the full SBST. New magnetic measurements agree with the predictions from the measured optics errors at injection and an update of the magnet calibration curves is presently under consideration to avoid the use of corrections.

At 3.5 TeV and β^*=2m the error sources are not fully understood. If we assume these errors to be the same at 7 TeV with the nominal collision optics a β-beating over 120% would arise in the horizontal plane of Beam 2, Fig. 14.

The use of the inner triplet skew quadrupoles to correct the local coupling with moderately low strength is mandatory at β^*=2 m (3.5 TeV). The required triplet quadrupole
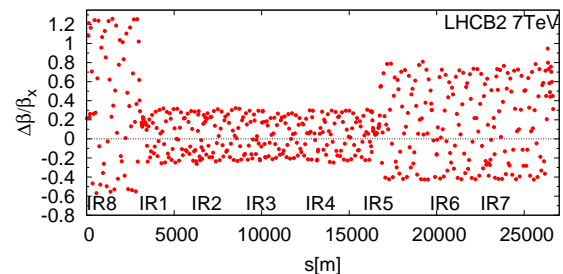

Figure 14: Extrapolation of the 3.5 TeV identified optics errors to 7 TeV with nominal optics.

tilts to reproduce the observed local coupling range between 0.5 mrad and 2.0 mrad for different error distributions.

An effort should be put in understanding the poor reproducibility of the LHC optics after the squeeze. Improvements in this area combined with further optics corrections, both local and global, could allow to reduce the current aperture margins and therefore push the machine performance by further reducing the β^*.

ACKNOWLEDGMENTS

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