Record low β beating in the LHC

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The LHC is currently operating with a proton energy of 4 TeV and β^* functions at the ATLAS and CMS interaction points of 0.6 m. This is close to the design value at 7 TeV ($\beta^* = 0.55$ m) and represented a challenge for various aspects of the machine operation. In particular, a huge effort was put into the optics commissioning and an unprecedented peak β beating of around 7% was achieved in a high energy hadron collider.

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I. INTRODUCTION

High energy colliders have not traditionally required high precision control of their optics. The maximum relative deviation of the β function with respect to the model (β beating) is an appropriate figure of merit to compare different colliders. An illustration of the achieved peak β beating in various high energy colliders is shown in Table I as collected during the "Optics Measurements, Corrections and Modeling for High-Performance Storage Rings" workshop [1]. References for the various machines on the table are: PEP II [2], LEP [3], KEKB [4], CESR [5], HERA-p [6], Tevatron [7], and RHIC [8]. The record low beta beating is held by CESR, the smallest of these colliders with a 768 m circumference. The achieved peak β beating in these machines is far from the 1%–2% in modern light sources such as DIAMOND [9], SOLEIL [10], and ALBA [11].

The CERN LHC is the first high energy collider with tight design tolerances on optics errors to guarantee the machine protection during operation with beam. The β functions are usually squeezed to the minimum possible value in the two interaction points (IPs) where the ATLAS and CMS detectors are placed. The β functions in these interaction regions (IRs) are as large as 4 km for $\beta^* = 0.6$ m (see the layout and optics in Fig. 1). The quadrupole triplets next to the IP host the two LHC beams. A peak β beating below 15% and 19% is required during collisions for the horizontal and vertical planes, respectively [12].

The first optics measurement of the LHC [13] revealed an unexpectedly large β beating of 100%. The leading source of this error was identified as a cable swap between the two beam apertures of a quadrupole. In a machine as large as LHC, this finding was likely only possible with the aid of a new approach for optics correction, the segment-by-segment technique [13]. This technique has evolved to include the full set of linear optics parameters in the general case of a coupled lattice [14]. The time evolution of the LHC peak β beating at injection energy is shown in Fig. 2 together with specified tolerances and rms orbit. A clear correlation between β beating and rms orbit is observed in the figure. This is due to the fact that the orbit correction algorithm uses the design optics. Therefore, correcting the β beating benefits not only machine protection and luminosity production but also a wide range of machine parameters and operational aspects. For the first time in 2012, the injection optics was corrected to be within design tolerances (the rms orbit was low enough to allow for the larger β beating in previous years).

A 10% peak β beating at top energy was already demonstrated in the LHC in 2010 [15]. However, owing to the change in the hysteresis branch of some quadrupoles involved in the correction, during regular operation it was not possible to keep this 10% β beating. In 2011 this technical obstacle was solved [16] and a β beating near 10% became operational [17,18]. 2011 started with a $\beta^* = 1.5$ m and intensive optics corrections following the same strategies as in [15]. In August a beta squeeze down to $\beta^* = 1$ m was successfully commissioned [18], apparently without requiring further optics corrections, although precise β^* measurements were not performed. Between these two periods of different β^*, the luminosity imbalance between the ATLAS and CMS experiments increased from roughly 5% to 10% [19] (providing more luminosity for CMS). Squeezing further down to 0.6 m in 2012 could increase the luminosity imbalance to intolerable levels. It was therefore decided to place special attention to the optics commissioning following the procedure below: (i) Measure the machine in the absence of any beam-based corrections (*virgin* machine)

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TABLE I. Peak β beating of various high energy colliders as collected during the Optics Measurements, Corrections and Modeling for High-Performance Storage Rings workshop [1].

Lepton collider	Circumference [km]	Peak $\Delta\beta/\beta$ [%]	Hadron Collider	Circumference [km]	Peak $\Delta\beta/\beta$ [%]
PEP II	2.2	30	HERA-p	6.3	20
LEP	27	20	Tevatron	6.3	20
KEKB	3	20	RHIC	3.8	20
CESR	0.8	7			

throughout the entire magnetic cycle. (ii) Reduce the measurement uncertainty compared to previous years by increasing the excitation amplitude of the ac dipole. (iii) Compute new local IR corrections, which can remain constant throughout the beta squeeze process. (iv) Compute global corrections to minimize β beating and dispersion beating simultaneously. (v) Use local β^* and IP waist knobs to equalize luminosities if required. These knobs must use independently powered quadrupoles excluding the triplet quadrupoles as these act on both beams.

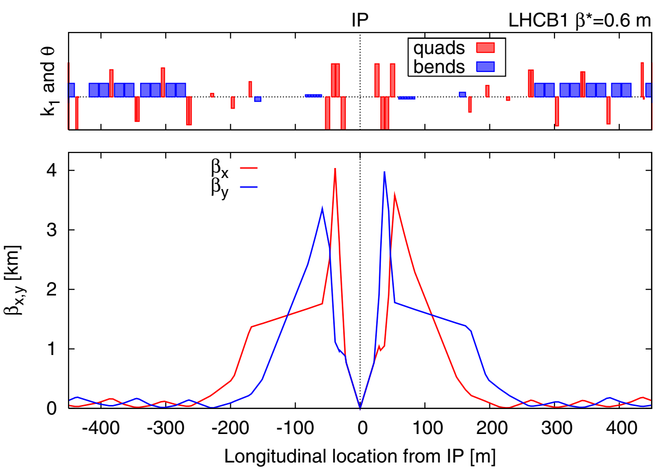

FIG. 1. Layout of the main interaction region (top) and β functions (bottom) versus longitudinal location from the IP for $\beta^* = 0.6$ m.

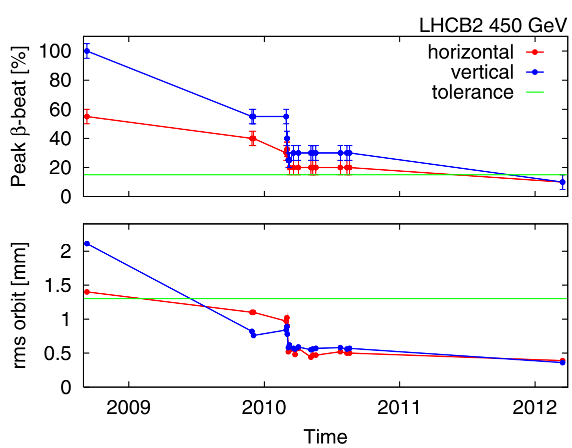

FIG. 2. Measured peak β beating (top) and rms orbit (bottom) at injection for beam 2 versus time.

The various steps during the 2012 optics commissioning down to $\beta^* = 0.6$ m are described in the following sections. Section IV explains why it was not required to resort to point (v). Section V describes the off-momentum optics measurements.

II. MEASURING THE VIRGIN MACHINE

All β beating and coupling corrections prior to 2012 were removed all along the LHC magnetic cycle. The global coupling correction knobs were slightly improved for 2012 [20]. The LHC ac dipoles [21] were used to measure the β functions along the β^*-squeeze process. A subset of the measurements are shown in Fig. 3 versus the longitudinal position for beam 1 and beam 2. A peak β

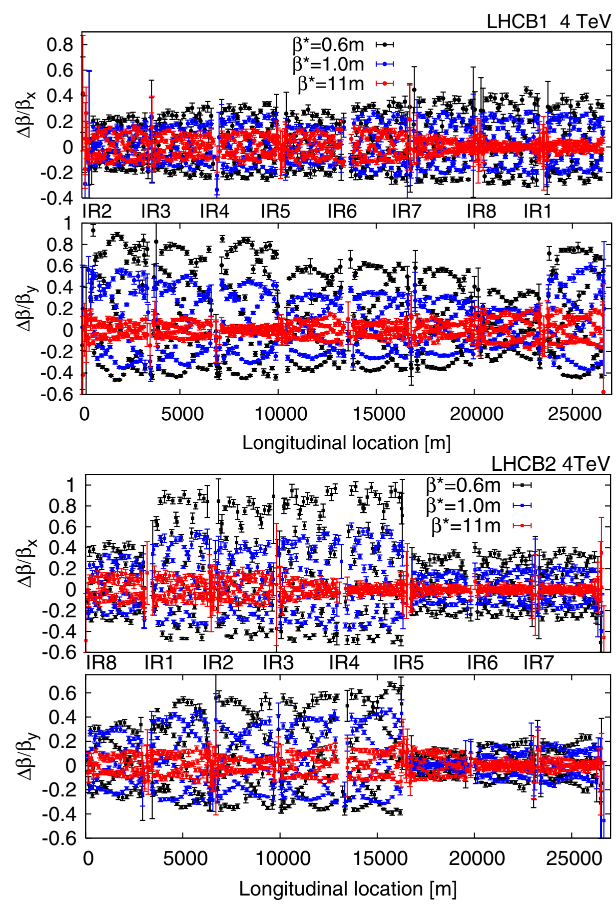

FIG. 3. Beam 1 (top) and beam 2 (bottom) β beating at three IP1 and IP5 β^* values during the squeeze of the virgin machine.

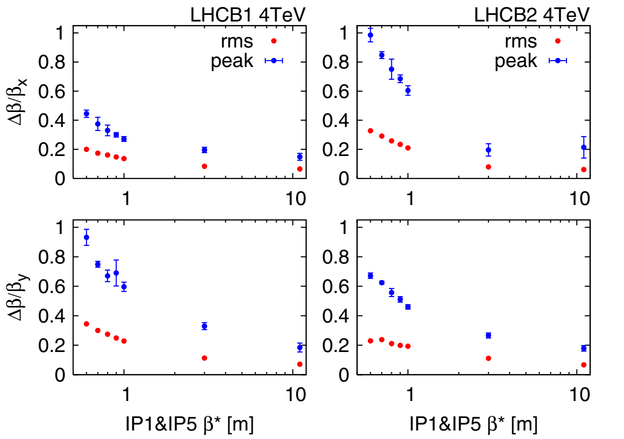

FIG. 4. β beating of the virgin machine along the squeeze. Beam 1 (left) and beam 2 (right), horizontal (top) and vertical (bottom) plots showing the peak and rms β-beating values versus β^*.

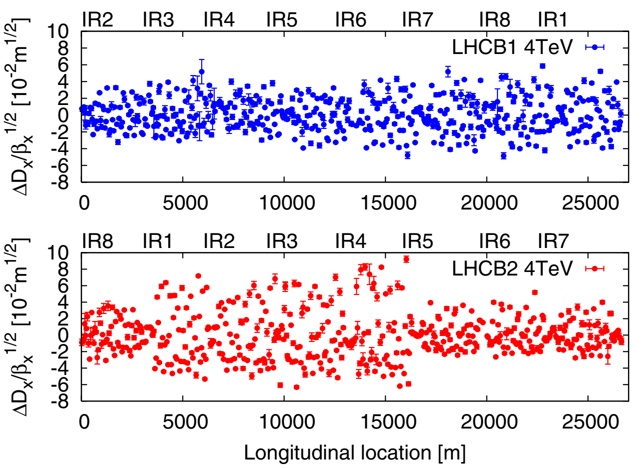

FIG. 5. Normalized dispersion beating for beam 1 (top) and beam 2 (bottom) for the virgin machine at $\beta^* = 0.6$ m.

beating of about 100% is reached for $\beta^* = 0.6$ m. The β beating rms and peak values corresponding to all measurements during the β squeeze are shown in Fig. 4. A monotonic increase of the peak and rms values is observed while reducing β^*, suggesting the need of local optics corrections in the interaction regions (IRs).

The normalized horizontal dispersion $(D_x/\sqrt{\beta_x})$, which is independent of beam position measurement (BPM) calibration errors [22], was measured only at $\beta^* = 0.6$ m since this requires extra time for the measurements at different relative momentum deviations. Figure 5 shows the deviation of $D_x/\sqrt{\beta_x}$ with respect to the model (normalized dispersion beating) for both beams. The measured deviation of $D_x/\sqrt{\beta_x}$ clearly exceeded the $1.25 \times 10^{-2}\sqrt{m}$ tolerance specified in [12] and required attention in the following corrections.

III. LOCAL AND GLOBAL CORRECTIONS

Local corrections are best suited for the IRs where the β functions are large and there are independently powered quadrupoles. However, the small phase advance between quadrupoles introduces some degeneracy in the possible corrections. To minimize the level of degeneracy multiple optics were corrected simultaneously for both beams in 2012. Figure 6 shows an illustration of a simultaneous correction for six different optics (three per beam) using the segment-by-segment technique for IR5. The errors are assumed to be independent of the magnet strength. This approach gave considerably different results than for 2011. A comparison between the 2011 and the 2012 correctors is given in Table II. It is observed that more correctors are required when considering all the optics together. The good quality of the corrections, as illustrated in Fig. 6, in this tightly constrained scenario provides confidence in this approach.

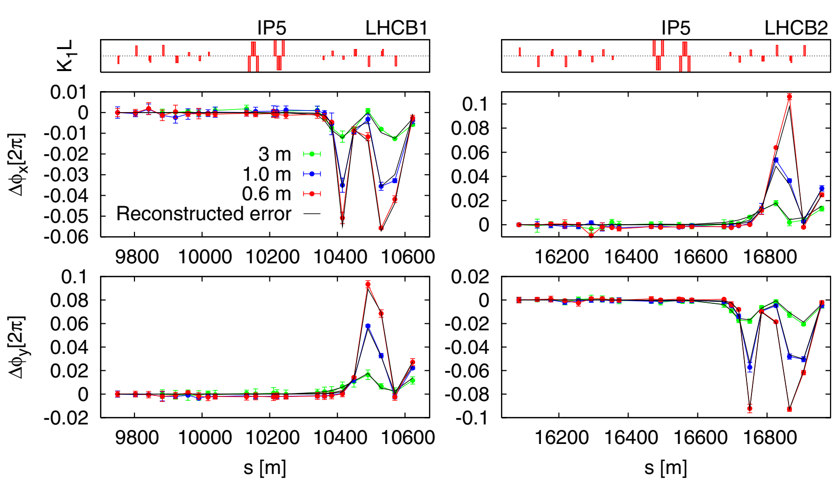

FIG. 6. Illustration of the segment-by-segment technique applied to IR5 simultaneously to the two beams and three different β^*. The black lines show the reconstructed error model.

TABLE II. Strength of local corrections used in 2011 and 2012. Relative values for the 2012 case are also shown.

	Δk [10^{-5} m^{-2}] 2011	2012	Relative [%] 2012
ktqx2.r1	−0.8	−1.4	0.16
ktqx2.l1		1.0	0.11
ktqx1.r1		1.0	0.11
kq4.l1b2		−0.5	0.13
kq9.l1b1	3.8	1.5	0.23
ktqx2.r5	1.3	1.05	0.12
ktqx2.l5	1.0	0.70	0.08
kq4.l5b2		3.80	1.00
kq5.l6b1		−3.9	0.6
kq5.r6b1		0.9	0.1
kq5.l6b2	4.6	4.8	0.7
kq5.r6b2		1.0	0.1
ktqx2.r8	−0.5		
ktqx2.l8	−2.3		
kq4.r8b2		−10.0	2.4
kq5.r8b2		−3.0	0.8
kq6.l8b2		−3.0	0.5
kq4.l8b1		4.0	1.0
kq5.r8b1		8.0	2.7
kq6.l8b1		2.0	0.4

Global corrections are required to take care of the optics errors in the arcs and the residuals from the IR local corrections. All available singly powered quadrupoles were used to minimize the β beating and the normalized dispersion beating at all BPMs in an inverse response matrix approach. In 2011 only the β beating was corrected, regardless of the dispersion. The 2012 global corrections required approximately twice larger correction strength than in the previous year. Figures 7 and 8 show the unprecedented low β beating and normalized dispersion beating achieved after the global corrections. Figure 9 shows the evolution of the β beating along the squeeze after local and global corrections. This figure is to be compared to Fig. 4. Table III shows the evolution of the peak and rms values during the correction process. The normalized dispersion was within tolerance already after the local corrections. The global corrections further reduced its deviation by a factor of 4 for beam 1. Similarly the β beating is already within specifications after the local corrections. After global corrections the record peak β beating of $(7 \pm 4)\%$ is achieved for the first time in a high energy hadron collider. This value matches the current record for high energy lepton colliders held by CESR.

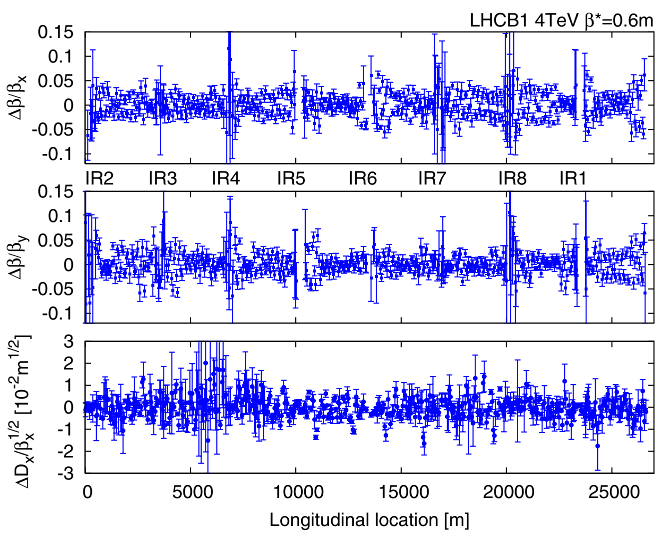

FIG. 7. Beam 1 β beating and normalized dispersion beating after global correction at $\beta^* = 0.6$ m.

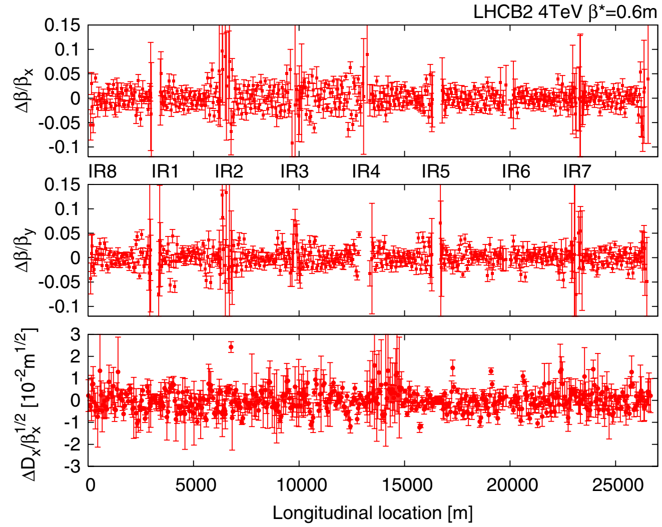

FIG. 8. Beam 2 β beating and normalized dispersion beating after global correction at $\beta^* = 0.6$ m.

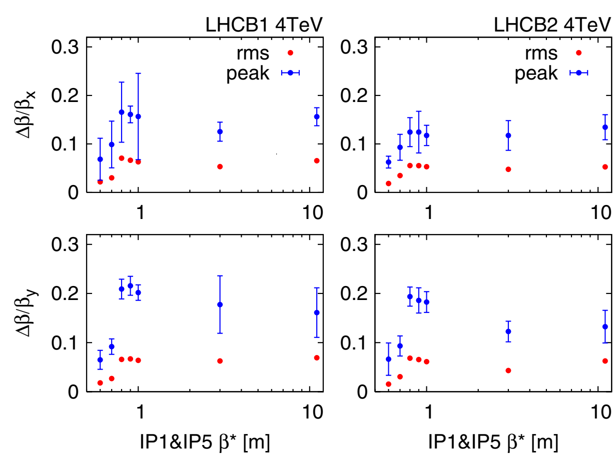

FIG. 9. β beating after global correction for $\beta^* \leq 0.7$ m and after local correction for $\beta^* \geq 0.8$ m. Beam 1 (left) and beam 2 (right), horizontal (top) and vertical (bottom) plots showing the peak and rms β-beating values versus β^*.

TABLE III. rms and peak β- and $D_x/\sqrt{\beta_x}$-beating values at $\beta^* = 0.6$ m for the virgin machine and after local and global corrections.

	Beam 1						Beam 2					
	$\Delta\beta/\beta$ [%]				$\Delta D_x/\sqrt{\beta_x}$ [$10^{-2}\sqrt{\mathrm{m}}$]		$\Delta\beta/\beta$ [%]				$\Delta D_x/\sqrt{\beta_x}$ [$10^{-2}\sqrt{\mathrm{m}}$]	
	H		V				H		V			
	rms	peak	rms	peak	rms	peak	rms	peak	rms	peak	rms	peak
Before corrections	20	44 ± 2	34	93 ± 5	1.8	5.8 ± 0.2	33	99 ± 5	23	67 ± 2	2.1	9.2 ± 0.4
Local corrections	6.2	15 ± 2	7.9	19 ± 2	1.2	3.2 ± 0.1	4.1	10 ± 2	3.9	12 ± 2	0.7	2.6 ± 0.2
Global corrections	2.2	7 ± 4	1.8	6 ± 2	0.3	1.5 ± 0.7	1.8	6 ± 2	1.5	7 ± 3	0.4	2.4 ± 0.2

This achievement owes to many actions during the design and construction of the machine. Some notable illustrations of these are: (i) the meticulous magnetic field quality specification [12], (ii) a careful installation strategy [23,24], (iii) an elaborate magnet model [25], (iv) the installation of an AC dipole [26] to excite transverse oscillations adiabatically [27], (v) an excellent BPM system [28] (less than 1% BPM failure as shown by singular value decomposition and fast-Fourier-transform analyses [29]), and (vi) an elegant approach for the cancellation of the spurious effects of the AC dipole on the optics measurements [30,31].

IV. β MEASUREMENTS FROM K MODULATION AND LUMINOSITY IMBALANCE

The low phase advance within the triplets of the IRs makes it impossible to measure the β functions in this region using the three BPM method [3]. Changing the strength of the quadrupoles and determining the average β at the quadrupole via the measured tune shift is the appropriate approach for the triplet. This measurement was conducted in the four quadrupoles next to the ATLAS and CMS IPs (Q1s). Figure 10 shows the measured β beating at Q1 for the two beams, planes, and IPs. All the measured values are below 5%, confirming the good quality of the correction. These measurements are typically used to infer the β^*, however the error propagation to the IP for this particular measurement yields a too large uncertainty on the β^*. At this point during the optics commissioning it was decided that no further corrections would be needed, awaiting for the ultimate confirmation: the luminosity imbalance. After the precise calibration of the luminosity from the experiments in April 2012 [19] the imbalance between the published values from the two detectors was below 3% [32,33]. This is the lowest imbalance reached so far in the LHC.

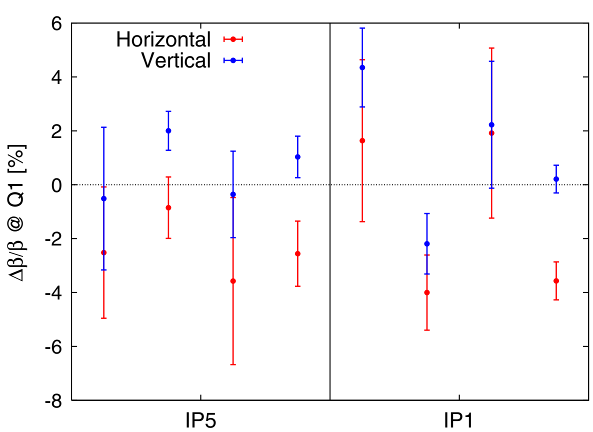

FIG. 10. β beating from K modulation at the first quadrupoles by IP1 and IP5.

V. MEASUREMENTS OF CHROMATIC β BEATING

Nonlinear effects play an important role when energy and intensity are pushed to the limits. If the chromatic aberrations are not under control, the end result may be a larger tune footprint, reduced aperture, and beam lifetime. In [34] first LHC measurements of the chromatic functions were reported.

The Montague functions [35] are used to describe the chromatic aberrations. The chromatic A and B functions are defined as

$$B = \frac{1}{\beta}\frac{\partial\beta}{\partial\delta_p}, \tag{1}$$

$$A = \frac{\partial\alpha}{\partial\delta_p} - \alpha B, \tag{2}$$

where δ_p is the relative momentum deviation. The derivatives of the Twiss functions are then evaluated at each beam position monitor by making a measurement for at least three different values for δ_p. The Montague function is defined as

$$W = 0.5\sqrt{A^2 + B^2}. \tag{3}$$

The Montague function is invariant in achromatic regions. As a result, by looking at the derivative of the Montague function, one can see the most critical regions for chromatic imperfections.

Figures 11 and 12 show the comparison between the model and measurement for the 0.6 m β^* optics at 4 TeV before and after correction, respectively. ALICE is at the

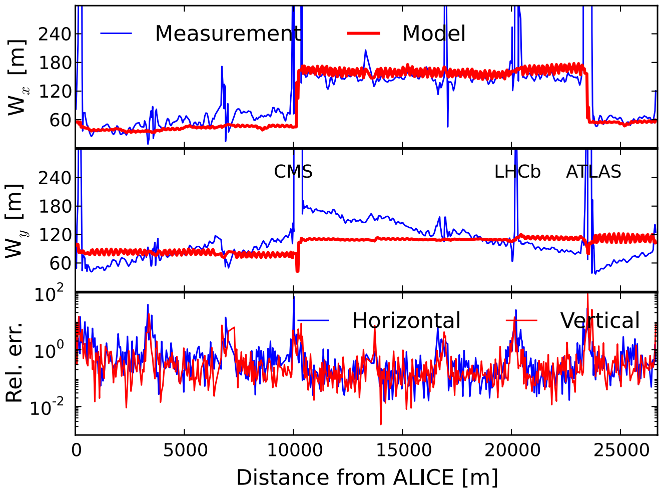

FIG. 11. Beam 1 horizontal (upper) and vertical (middle) Montague functions as defined in Eq. (3). The model function is shown in red, and the measurement in blue. The relative error of the measurements is shown in the lower plot. The figure shows the case for 0.6 m β^* optics at 4 TeV beam energy, before corrections.

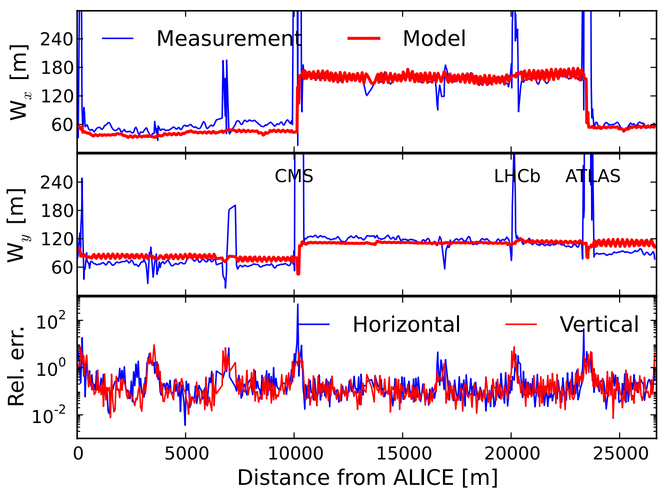

FIG. 12. Beam 1 horizontal (upper) and vertical (middle) Montague functions as defined in Eq. (3). The model function is shown in red, and the measurement in blue. The relative error of the measurements is shown in the lower plot. The figure shows the case for 0.6 m β^* optics at 4 TeV beam energy, after corrections.

origin of the horizontal axis, while the location of the other three experiments are shown. Similarly to the β functions the measured Montague functions feature large error bars in the IRs. A large discrepancy between measurement and model is observed for the vertical Montague function before the optics correction. Simulations including quadrupolar errors in the triplet reproduce the linearly varying Montague functions in the arcs. After correction a good agreement with the design model is achieved, showing a Montague function which is flat in the arcs. This is yet another confirmation of the good quality of the optics corrections.

VI. CONCLUSIONS

At 4 TeV the LHC optics has been successfully commissioned almost to its 7 TeV design β^*. The strategy was to measure the virgin machine with the best possible accuracy and compute corrections compatible with a large set of different optics for both beams. For the first time β functions and normalized dispersion were corrected simultaneously. All this resulted in a record low peak β beating of $(7 \pm 4)\%$ for high energy hadron colliders and matches the current record for high energy lepton colliders held by CESR. No dedicated IP corrections were required to achieve the lowest (so far) luminosity imbalance between the two main detectors in the LHC.

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[1] Optics Measurements, Corrections and Modeling for High-Performance Storage Rings, 2011, CERN [https://indico.cern.ch/conferenceDisplay.py?confId=132526].

[2] Y. T. Yan, Y. Cai, F-J. Decker, J. Irwin, J. Seeman, S. Ecklund, M. Sullivan, J. Turner, and U. Wienands, Report No. SLAC-PUB-10369, 2004.

[3] P. Castro, *Proceedings of the 1999 Particle Accelerator Conference* (IEEE, New York, 1999).

[4] A. Morita, H. Koiso, Y. Ohnishi, and K. Oide, Phys. Rev. ST Accel. Beams **10**, 072801 (2007).

[5] D. Sagan, R. Meller, R. Littauer, and D. Rubin, Phys. Rev. ST Accel. Beams **3**, 092801 (2000).

[6] F. Brinker, H. Burkhardt, W. Decking, K. Ehert, W. Fischer, M. Funcke, E. Gianfelice, S. Herb, G. H. Hoffstaetter, U. Hurdelbrink, W. Kriens, C. Montag, F. Schmidt, F. Stulle, R. Tomás, E. Vogel, M. Werner, and A. Xiao, Report No. DESY HERA 00-07.

[7] A. Jansson, P. Lebrun, and J. T. Volk, in *Proceedings of PAC 2005, Knoxville, Tennessee* (IEEE, Piscataway, NJ, 2005).

[8] G. Vanbavinckhove, M. Bai, and G. Robert-Demolaize, in *Proceedings of IPAC 2011, San Sebastián, Spain* (EPS-AG, Spain, 2011).

[9] I. P. S. Martin, R. Bartolini, R. Fielder, E. Longhi, and B. Singh, in *Proceedings of PAC07, Albuquerque, New Mexico, USA* (IEEE, New York, 2007); in *Proceedings of EPAC08, Genoa, Italy* (EPS-AG, Genoa, Italy, 2008).

[10] L. S. Nadolski, in Proceedings of EPAC08, Genoa, Italy (Ref. [9]).

[11] G. Benedetti, D. Einfeld, Z. Martí, and M. Muñoz, in Proceedings of IPAC 2011, San Sebastián, Spain (Ref. [8]).
[12] S. Fartoukh and O. Brüning, CERN-LHC-Project-Report-501, 2001.
[13] 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, Phys. Rev. ST Accel. Beams **12**, 081002 (2009).
[14] R. Tomás, O. Brüning, M. Giovannozzi, P. Hagen, M. Lamont, F. Schmidt, G. Vanbavinckhove, M. Aiba, R. Calaga, and R. Miyamoto, Phys. Rev. ST Accel. Beams **13**, 121004 (2010).
[15] R. Tomás, M. Aiba, C. Alabau, O. Brüning, R. Calaga, M. Giovannozzi, V. Kain, P. Hagen, M. Lamont, R. Miyamoto, F. Schmidt, M. Strzelczyk, and G. Vanbavinckhove, Report No. CERN-ATS-2011-017.
[16] L. Deniau, N. Aquilina, L. Fiscarelli, M. Giovannozzi, P. Hagen, M. Lamont, G. Montenero, R. Steinhagen, M. Strzelczyk, E. Todesco, R. Tomás, W. Venturini Delsolaro, and J. Wenninger, in Proceedings of IPAC 2011, San Sebastián, Spain (Ref. [8]).
[17] G. Vanbavinckhove, M. Aiba, R. Calaga, R. Miyamoto, and R. Tomás, in Proceedings of IPAC 2011, San Sebastián, Spain (Ref. [8]).
[18] R. Assmann, R. Bruce, M. Giovannozzi, M. Lamont, E. Maclean, R. Miyamoto, G. Mueller, G. Papotti, L. Ponce, S. Redaelli, R. Tomás, G. Vanbavinckhove, and J. Wenninger, Report No. CERN-ATS-Note-2012-005 MD.
[19] E. Meschi, at the 129th LHC Machine Committee meeting held on 18 April 2012.
[20] R. Tomás, Report No. CERN-ATS-Note-2012-019 MD.
[21] J. Serrano and M. Cattin, Report No. CERN-BE-Note-2010-014 (CO).
[22] R. Calaga, R. Tomás, and F. Zimmermann, in *Proceedings of the 2007 Particle Accelerator Conference* , edited by C. Petit-Jean-Genaz (Institute of Physics, London, 2007), p. 3693.
[23] S. Fartoukh, in *Proceedings of the 9th European Particle Accelerator Conference, Lucerne, 2004* (EPS-AG, Lucerne, 2004).
[24] S. Fartoukh and M. Giovannozzi, Nucl. Instrum. Methods Phys. Res., Sect. A **671**, 10 (2012).
[25] E. Todesco, N. Aquilina, B. Auchmann, L. Bottura, M. Buzio, R. Chritin, G. Deferne, L. Deniau, L. Fiscarelli, J. García Perez, M. Giovannozzi, P. Hagen, M. Lamont, G. Montenero, G. Muller, M. Pereira, S. Redaelli, V. Remondino, N. Sammut, F. Schmidt, R. Steinhagen, M. Strzelczyk, R. Tomás, W. Venturini Delsolaro, J. Wenninger, and R. Wolf, in *Proceedings of the International Particle Accelerator Conference, Kyoto, Japan* (ICR, Kyoto, 2010).
[26] J. Serrano and M. Cattin, Report No. CERN-BE-Note-2010-014 (CO).
[27] R. Tomás, Phys. Rev. ST Accel. Beams **8**, 02440 1 (2005).
[28] O.R. Jones, in *Proceedings of DIPAC'09, Basel, Switzerland* (PSI, Basel, 2009).
[29] R. Calaga and R. Tomás, Phys. Rev. ST Accel. Beams **7**, 042801 (2004).
[30] R. Miyamoto, S.E. Kopp, A. Jansson, and M.J. Syphers, Phys. Rev. ST Accel. Beams **11**, 084002 (2008).
[31] R. Miyamoto, BNL C-A/AP Note No. 410.
[32] ''LHC performance and statistics'' [http://lhc-statistics.web.cern.ch/LHC-Statistics/].
[33] B. Gorini and E. Meschi (private communication).
[34] G. Vanbavinckhove, M. Aiba, R. Bartolini, R. Calaga, M. Giovannozzi, E. Hamish Maclean, R. Miyamoto, F. Schmidt, and R. Tomas, CERN, Geneva Report No. CERN-ATS-2011-160, 2011.
[35] B.W. Montague, CERN Report No. CERN-LEP-Note-165, 1979.