NEW LHC OPTICS CORRECTION APPROACHES IN 2017

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Abstract

The optics commissioning strategy for low-β^* operation of the LHC underwent significant revision in 2017 [1]. The beam-based correction strategy transitioned from being concerned exclusively with linear optics errors, to a combined linear and nonlinear optics commissioning, with the traditional optics corrections at flat-orbit being both preceded and followed by corrections for the effect of nonlinear errors in the ATLAS and CMS insertions.

CHANGES TO COMMISSIONING STRATEGY

Traditional optics commissioning strategy in the LHC is concerned exclusively with linear optics [2, 3, 4]. Commissioning is normally performed in two stages. Local corrections for the quadrupole errors in the IRs are applied to the machine first, with all beam based correction removed (virgin optics). This is then followed by a global optimization of the optics using all available circuits around the ring. Since the ATS optics [5, 6] was already commissioned in late 2016 it was decided to re-use the existing corrections [7]. Local correction quality had deteriorated during the winter shutdown, as seen in Fig. 1, which shows the outcome of segment-by-segment measurements of the propagated phase error through IR5. The quality of the local corrections was still sufficient however, for global corrections to compensate the additional β-beat generated. This is seen in Fig. 2, which shows the β-beat in LHC Beam 1 before and after application of global optics correction at flat-orbit in 2017. The local jumps in optics quality around the IRs were considerably reduced, and the RMS β-beat after linear optics corrections was comparable to that obtained in 2016 (Table 1). While this change to optics commissioning strategy was viable in 2017, it should be noted that further deterioration is likely to require an iteration of the local corrections in the future.

In 2017 this *linear optics commissioning at flat-orbit* was incorporated into a much broader *combined linear and nonlinear optics commissioning*. Figures 3 and 4 show a simplified schematic of the main components of low-β optics commissioning performed in 2016 and 2017. Linear optics commissioning at flat-orbit is shown in blue.

In 2017 the first optics measurement / correction (OMC) action taken was to apply corrections for the normal octupole errors in the ATLAS and CMS insertions. At low-β^* these errors dominate the contribution of nonlinear errors to the unwanted tune-spread in the LHC. As they are generated in the squeezed IRs, the contribution to the amplitude detuning also increases through the squeeze, be-

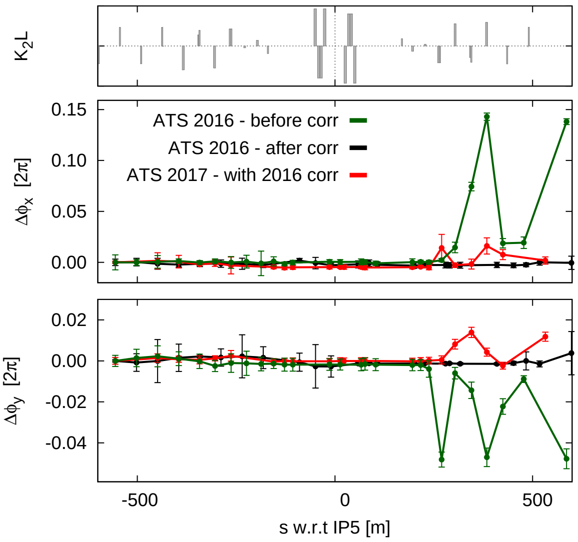

Figure 1: Propagated phase error through IR5. Measurements for ATS optics in 2016 are shown before correction (green) and after correction (black). The optics quality obtained in 2017, with the 2016 correction applied, is shown in red.

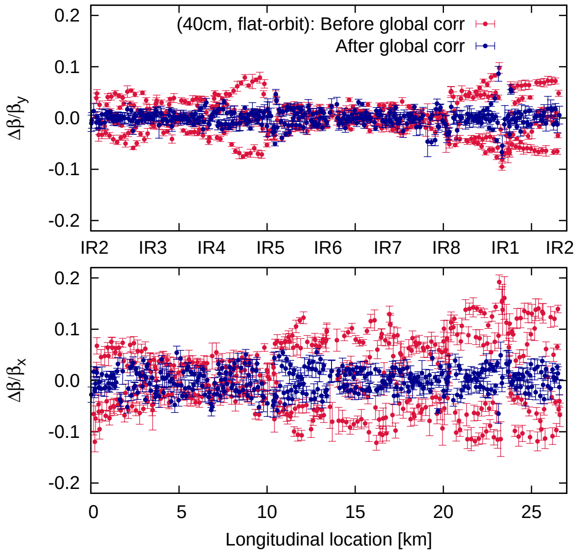

Figure 2: β-beat in LHC Beam 1 before and after application of global optics correction at flat-orbit in 2017.

Table 1: Comparison of linear optics quality obtained with flat-orbit for the 2017 ATS optics at $\beta^* = 0.4\,\mathrm{m}$, to that obtained with flat-orbit in 2016 for the nominal $0.4\,\mathrm{m}$ optics. Values for 2016 were taken from [4].

	2017 ATS		2016 Nominal	
	Beam 1	Beam 2	Beam 1	Beam 2
$\beta_x\vert_{\mathrm{RMS}}$ [%]	2.3	2.6	1.4	1.4
$\beta_y\vert_{\mathrm{RMS}}$ [%]	1.5	1.5	1.8	1.4
$\beta_x\vert_{\mathrm{peak}}$ [%]	5.5	10.9	7.7	4.5
$\beta_y\vert_{\mathrm{peak}}$ [%]	8.6	7.6	5.8	4.9
$\frac{\Delta D_x}{\sqrt{\beta_x}}\vert_{\mathrm{RMS}}$ $[10^{-2}\mathrm{m}^{-\frac{1}{2}}]$	0.45	0.58	0.52	0.62
$\vert\frac{\Delta D_x}{\sqrt{\beta_x}}\vert_{\mathrm{peak}}$ $[10^{-2}\mathrm{m}^{-\frac{1}{2}}]$	1.2	4.3	1.9	1.8

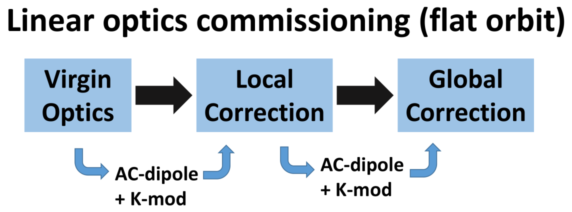

Figure 3: Main steps of optics commissioning in 2016.

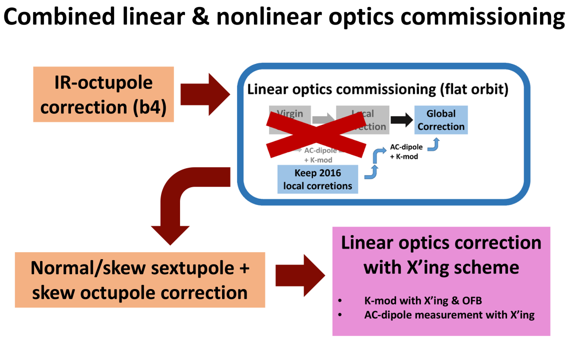

Figure 4: Main steps of optics commissioning in 2017.

coming comparable to the tune-spread purposefully introduced by the Landau octupoles (MO), and creating significant distortions of tune-footprint while β^* is being reduced. This is illustrated in Fig. 5 which shows the contribution of the ATLAS and CMS IRs to direct vertical detuning of Beam 2, expressed in units of the equivalent Landau octupole strength in Ampere (at $6.5\,\mathrm{TeV}$) required to generate the same detuning. We note that the typical operational powering of the Landau octupoles is in the range of $300 - 400\,\mathrm{A}$, compared to which the role of the IR-b_4 cannot be neglected. The distortion of the tune-footprint evolves particularly fast at end-of-squeeze, where the IR-octupole errors generate a change in the amplitude detuning equivalent to $150\,\mathrm{A}$ of the MO during the final $10\,\mathrm{cm}$ of the β^*-squeeze. The distortion of the tune-footprint generated by the IR-octupole errors is expected to be detrimental to instabilities [8, 9], motivating b_4 compensation in order to provide a stable baseline upon which to implement Landau damping with the MO.

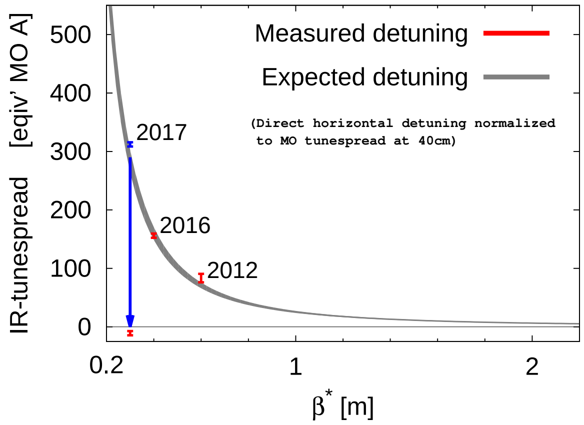

Figure 5: Direct vertical detuning of Beam 2 expressed in equivalent amps of the Landau octupole circuits

Octupole corrections in IR1 and IR5 were performed based upon measurements of the AC-dipole detuning [10], and significantly reduced the direct detuning terms (cross-terms were already negligible), as seen in Fig. 6 and Table 2.

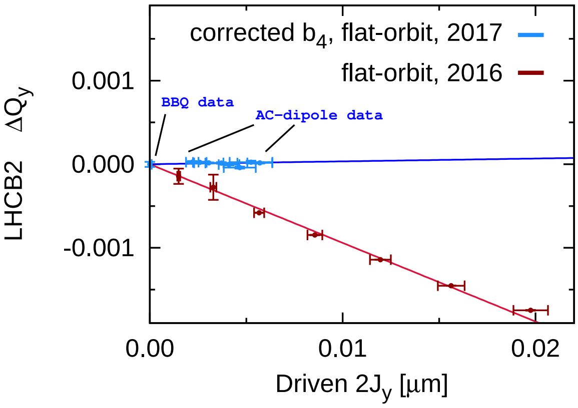

Figure 6: Example of amplitude detuning measurements at $\beta^* = 0.3\,\mathrm{m}$ after IR-octupole correction (blue), and $\beta^* = 0.4\,\mathrm{m}$ before correction (red).

In compensating the amplitude detuning, the IR-octupole correction also significantly improved the performance of the online tune measurement (BBQ) at low-β^*. Figure 7 shows the reduction in noise in the BBQ measurement upon application of the IR-b_4 correction. A significant improvement was also seen to the online measurement of linear coupling. The improved performance of the LHC BBQ upon correction of normal octupole errors in the ATLAS and CMS IRs provides a first example of the intrinsic links between commissioning of the nonlinear and linear optics which are imposed at low-β^* in the LHC: correction of the β^* imbalance relies on K-modulation, which in

Table 2: Amplitude detuning coefficients at $\beta^* = 0.4\,\mathrm{m}$ without IR-b_4 correction, and at $\beta^* = 0.3\,\mathrm{m}$ after correction.

Detuning coefficients $[10^3\,\mathrm{m}^{-1}]$		$\beta^* = 0.4\,\mathrm{m}$ (no correction)	$\beta^* = 0.3\,\mathrm{m}$ (with correction)
LHCB1	$\frac{\partial Q_x}{\partial \epsilon_x}$	43 ± 1	-3 ± 1
	$\frac{\partial Q_x}{\partial \epsilon_y} = \frac{\partial Q_y}{\partial \epsilon_x}$	0 ± 1	5 ± 3
	$\frac{\partial Q_y}{\partial \epsilon_y}$	-50 ± 1	No measurement
LHCB2	$\frac{\partial Q_x}{\partial \epsilon_x}$	38 ± 1	-2 ± 1
	$\frac{\partial Q_x}{\partial \epsilon_y} = \frac{\partial Q_y}{\partial \epsilon_x}$	1 ± 1	-3 ± 2
	$\frac{\partial Q_y}{\partial \epsilon_y}$	-44 ± 1	2 ± 1

turn relies on high precision measurement of the betatron tunes. Without the improved tune measurement quality obtained through octupole correction, linear optics commissioning for the ATLAS/CMS luminosity imbalance would have been severely inhibited at $\beta^* \leq 0.4\,\mathrm{m}$.

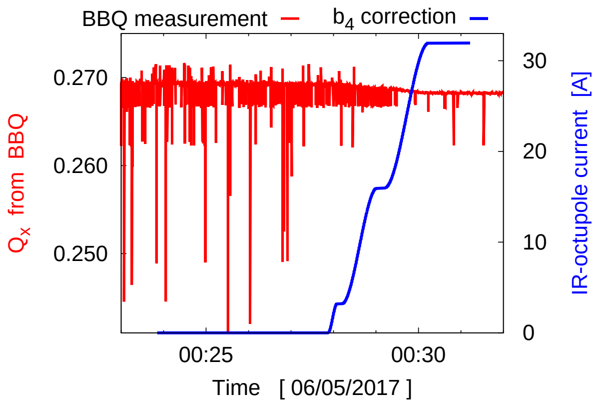

Figure 7: Improvement in online tune measurement quality upon application of corrections for normal octupole errors in the ATLAS and CMS insertions.

A further example of the intrinsic links between linear and nonlinear optics correction quality can be seen through normal sextupole corrections implemented in the CMS insertion. Non-negligible changes to the measured β were observed as function of the crossing angle in IR5, resulting from feed-down of nonlinear errors in the insertion to generate additional linear optics perturbations. These additional errors would be present during regular LHC operation with a crossing scheme, but were not considered in previous years commissioning and are not corrected by the traditional linear optics commissioning which is only performed at flat-orbit. Figure 8 shows histograms of the differential β-beat obtained between $\pm 150\,\mu\mathrm{rad}$ crossing angles in IR5 at $\beta^* = 0.4\,\mathrm{m}$. Corrections for the normal sextupole errors in IR5 were obtained by minimizing the linear component of the tune-shift with crossing angle. After corrections were applied the distribution of the differential β-beat in Fig. 8 (blue) shows a significant improvement, corresponding to an improved stability of the linear optics as a function of crossing angle.

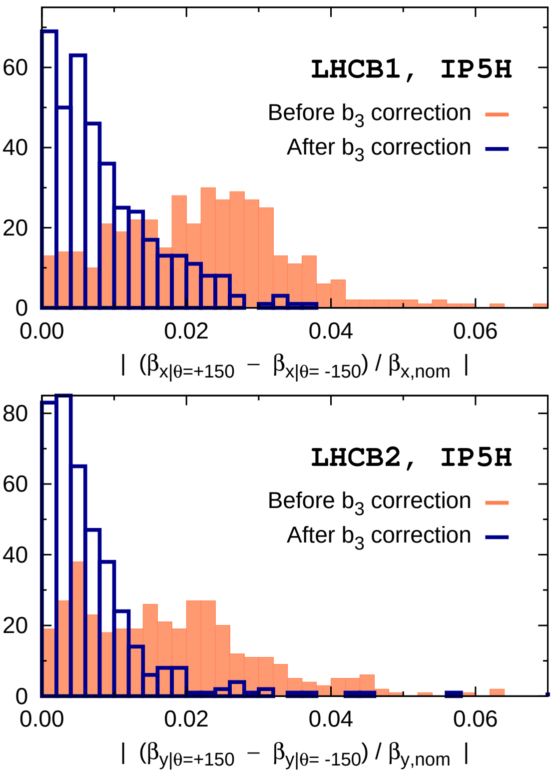

Figure 8: Histograms of Beam 1 (top) and Beam 2 (bottom) β-beat measured at LHC BPMs, before (blue) and after (red) normal sextupole compensation in IR5.

Feed-down to tune and coupling as a function of crossing angle in the low-β insertions are also of considerable concern due to the introduction of the crossing angle luminosity levelling into regular LHC operation in 2017. Landau damping is critically dependent on the size of the linear coupling compared to the tune separation, since coupling which is too large in comparison to ΔQ can lead to significant distortions of the tune-footprint [11, 12, 13]. Corrections for normal and skew sextupoles, and for skew octupoles, were also performed in IR1 in 2017. These corrections helped improve the stability of linear coupling and tune separation during crossing angle levelling. While the expected coupling shifts during levelling depend on the initial amplitude and phase of the coupling RDTs, Table 3 details the maximum possible changes to $|C^-|$ which could be generated by feed-down from nonlinear errors in IR1 before and after application of corrections to the relevant multipole errors. The level of coupling introduced during levelling before correction could be significant, $\Delta|C^-| \leq 2\times10^{-3}$ from a $50\,\mu\mathrm{rad}$ change in crossing scheme, which is potentially up to $50\,\%$ of the minimal tune separation used during 2017 operation. After correction the potential coupling feed-down is reduced to far more tolerable levels, significantly reducing the risk that crossing angle luminosity levelling would cause a loss of Landau damping during operation. In this case it is possible to observe an instance where the nonlinear errors in the low-β^* IRs have the potential to generate perturbations to the linear properties of the machine, which can then in turn influence other nonlinear properties of the lattice such as tune-spread and Landau damping. This once more motivates the transition to a combined linear and nonlinear approach to LHC commissioning at end-of-squeeze.

Table 3: Maximum possible changes in linear coupling which can be generated due to normal sextupole and skew octupole feed-down from the IR1 insertion during crossing angle levelling of LHC luminosity. Values for $\beta^* = 0.3\,\mathrm{m}$ are based on the expected scaling of the feed-down with β^*.

	$\Delta\lvert C^-\rvert\ [10^{-3}]$		$\frac{\Delta\lvert C^-\rvert}{Q_{x,\mathrm{frac}}-Q_{y,\mathrm{frac}}}$
	$\beta^* = 0.4\,\mathrm{m}$	$\beta^* = 0.3\,\mathrm{m}$	$\beta^* = 0.3\,\mathrm{m}$
No correction	≤ 1.5	≤ 2.0	$\leq 50\,\%$
After correction	≤ 0.4	≤ 0.6	$\leq 15\,\%$

While sextupole correction in IR5 did help improve the stability of the linear optics as a function of crossing angle, when the full operational crossing scheme was applied in all IRs some deterioration of the linear optics could still be observed. Normalized dispersion also became notably worse. This is illustrated in Fig. 9. The final stage of the new combined linear and nonlinear commissioning strategy was to perform a re-iteration of the linear optics corrections, no-longer at flat-orbit, but with the full crossing scheme applied. Table 4 shows the RMS β-beat and normalized dispersion measured at various stages of the 2017 optics commissioning, as well as the values obtained at flat-orbit in 2016.

The final optics quality obtained for the true operational configuration of the LHC after all linear and nonlinear corrections were applied in 2017 is comparable to that obtained at flat-orbit in 2016. Figure 10 compares the β-beat obtained for Beam 1 in the 2017 operational configuration, to flat-orbit in 2016. An excellent quality for the predicted luminosity imbalance contribution from optics was also obtained:

$$\frac{L_{\mathrm{CMS}}}{L_{\mathrm{ATLAS}}} = 1.003 \pm 0.004 \qquad (1)$$

OPTICS TOOL DEVELOPMENT

In preparation for 2017 commissioning and operation significant effort was invested into the development of existing and new optics correction tools. Table 5 provides some details of the scope of the ongoing optics tool development.

Of particular relevance to 2017 commissioning, considerable work was invested to automate several of the more

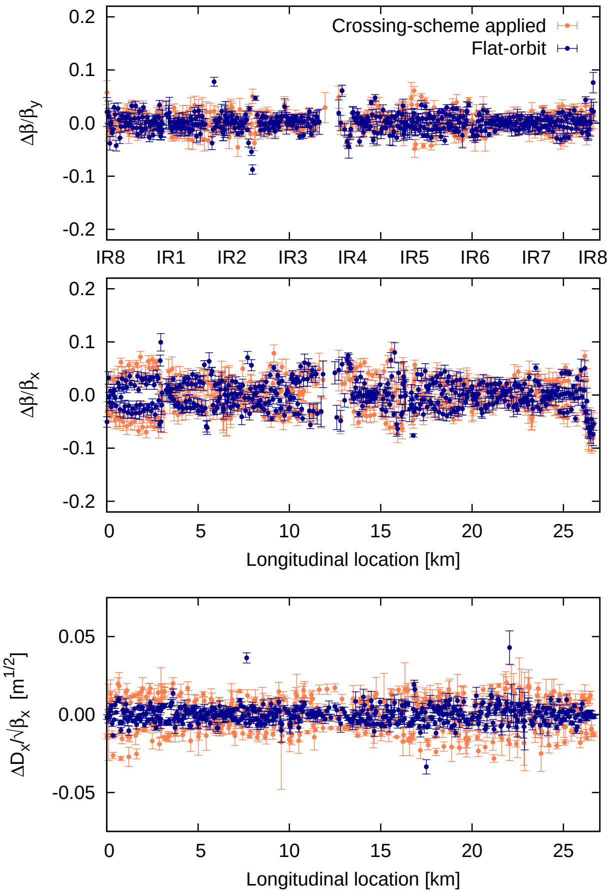

Figure 9: β-beat (top, center) and normalized dispersion (bottom) of LHC Beam 2, measured at flat-orbit after application of global linear optics corrections, and at the operational crossing scheme after application of all nonlinear corrections in 2017.

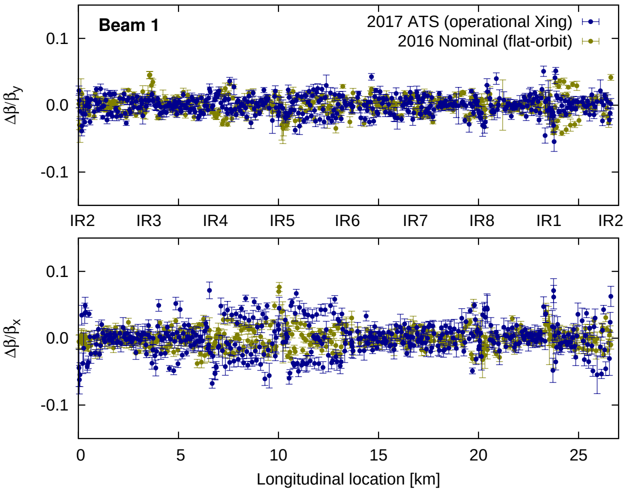

Figure 10: β-beat in LHC Beam 1 measured for nominal optics in 2016 at flat-orbit and in 2017 for the operational configuration of ATS optics at $\beta^* = 0.4\,\mathrm{m}$.

Table 4: Comparison of linear optics quality obtained with flat-orbit for the 2017 ATS optics at $0.4\,\mathrm{m}$, to that obtained with flat-orbit in 2016 for the nominal $0.4\,\mathrm{m}$ optics. Values for 2016 were taken from [4].

	2017 Flat-orbit (linear corrs)	2017 OP-crossing (after NL corrs)	2017 OP-crossing (after linear reoptimization)	2016 Flat-orbit (linear corrs)
Beam 1 $\beta_x\|_{\mathrm{RMS}}$ $[\%]$	2.3	2.7	2.5	1.4
Beam 1 $\beta_y\|_{\mathrm{RMS}}$ $[\%]$	1.5	2.8	1.3	1.8
Beam 2 $\beta_x\|_{\mathrm{RMS}}$ $[\%]$	2.6	3.2	2.5	1.4
Beam 2 $\beta_y\|_{\mathrm{RMS}}$ $[\%]$	1.5	1.8	1.8	1.4
Beam 1 $\frac{\Delta D_x}{\sqrt{\beta_x}}\|_{\mathrm{RMS}}$ $[10^{-2}\mathrm{m}^{-\frac{1}{2}}]$	0.45	0.96	0.73	0.52
Beam 2 $\frac{\Delta D_x}{\sqrt{\beta_x}}\|_{\mathrm{RMS}}$ $[10^{-2}\mathrm{m}^{-\frac{1}{2}}]$	0.58	1.11	0.61	0.62

Table 5: OMC tool development in 2017.

Project	**Main Branch Commits in 2017**	**Lines of code**
Python codes	455	127230
Java GUIs	178	38843

trivial tasks which need to be performed during LHC optics studies. Notable developments were the introduction of automatic logging of all AC-dipole/MKA/MKQ kicks and the relevant parameters to the OMC elog, and automation of the immediate post-processing of the recorded turn-by-turn data via SVD cleaning and spectral analysis with SUSSIX [14]. Automation of these tasks, in conjunction with an ongoing program to improve the speed of OMC codes, improved the efficiency of optics measurements in the control room helping facilitate the incorporation of additional nonlinear commissioning activities in 2017.

Of particular interest, the development of the optics tools allowed a basic global coupling correction to be calculated online following excitation of the beam [15]. This is also of relevance to coupling measurement and correction during LHC operation for luminosity production, since existing tools featured significant limitations. Continuous online measurement of the coupling via the BBQ is prone to errors due to large local variations of the coupling resonances around the ring (meaning the value of the coupling RDT measured at the BBQ location does not reflect the global $|C^-|$). With strong octupole sources present the BBQ may also be unable to measure coupling at all, and give misleading results based upon measurements of noise [16, 17, 18]. By contrast measurement of the coupling with AC-dipole provides the best possible measurement, but can only be performed with a single pilot. This limits the possibility to reliably monitor and correct the linear coupling during regular operation.

In 2017 however, developments to the transverse damper allowed it to drive forced oscillations of single bunches, essentially functioning as an AC-dipole [19, 20]. Combining with the newly automated OMC tools, this enabled coupling corrections to be calculated online during regular operation. Figure 11 shows an example of correction of coupling using the new ADT AC-dipole tools.

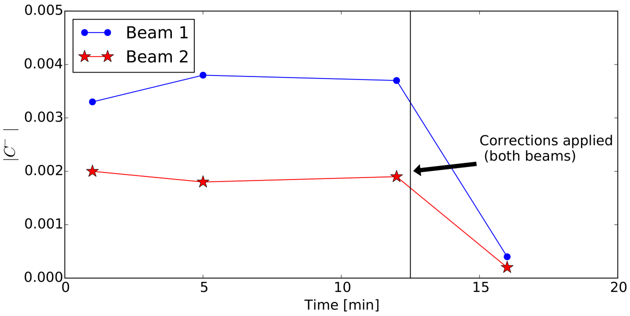

Figure 11: Correction of linear coupling using the LHC transverse damper functioning as an AC-dipole.

CONCLUSIONS

Optics commissioning strategy for low-β^* operation underwent a significant revision in 2017, moving away from the exclusively linear approach utilized in previous years, and towards a combined linear and nonlinear optics commissioning. For the first time corrections for normal and skew sextupole errors, and for normal and skew octupole errors, were applied in the ATLAS and CMS insertions. Expansion of the commissioning strategy into the nonlinear regime yielded a number of significant benefits. Correction of normal octupole errors helped to provide a stable tune-footprint upon which to implement Landau damping during the squeeze, and also significantly improved the performance of online tune measurement with the LHC BBQ. The later result allowed high-quality K-modulation measurements to be taken, even at very low β^*, demonstrating the benefits of nonlinear optics commissioning not only to direct nonlinear machine parameters, but also to control of the linear optics. Corrections for further multipole species also significantly improved the stability of the linear optics, linear coupling and tune separation as a function of crossing angle. The latter two are particularly relevant to maintenance of Landau damping in 2017, since prior to correction the introduction of crossing angle levelling into regular operation had the potential to generate significant fluctuations of coupling and tune separation due to feed-down.

To provide the best possible optics quality and luminosity imbalance, optics corrections were performed for the first time in the operational configuration of the crossing scheme. This final iteration of the optics commissioning allowed a comparable quality of optics control to be obtained in the operational configuration to that previously obtained only at flat-orbit in previous years.

2017 represents a considerable expansion of OMC activities during the commissioning period. Such an expansion would not have been possible without the continual development and refinement of OMC codes and tools. A particularly significant development is the introduction of automatic calculation of coupling corrections following every kicker excitation, which significantly reduces time spent on basic coupling corrections during optics measurements and helped facilitate the inclusion of additional nonlinear measurements into optics studies and commissioning. Additionally these automatic coupling correction methods have been incorporated for use with the newly developed ADT AC-dipole which allows reliable online measurement of the linear coupling during regular LHC operation with bunch trains.

The advances in LHC optics commissioning strategy presented in this paper benefited operation in 2017. Beyond this however, they represent a significant step towards overcoming some of the challanges which will be associated with successful commissioning and operation of the HL-LHC in coming years [21].

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