OPERATING THE LHC OFF-MOMENTUM FOR p-Pb COLLISIONS

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Abstract

The first high-luminosity p-Pb run at the LHC took place in January-February 2013 at 4 Z TeV energy per beam. The RF frequency difference of proton and Pb is about 60 Hz for equal magnetic rigidities at that energy, which means that beams move to slightly off-momentum, non-central, orbits during physics when frequencies are locked together. The resulting optical perturbations ("beta-beating") restrict the available aperture and required a special correction. This was also the first operation of the LHC with low beta function in all four experiments and it required a specific collimation set up. Predictions from offline calculations of beta-beating correction are compared with measurements during the optics commissioning and collimator set-up.

INTRODUCTION

In early 2013, the Large Hadron Collider (LHC) provided p-Pb collisions at high luminosity for the first time [1]. The maximum beam energy was $4\,Z$ TeV, implying that a significant RF frequency difference of about 60 Hz remained between the beams on central orbits at top energy. Consequently, in addition to many challenges related to the injection and energy ramp with unlocked RF frequencies [2], at least one beam had to be brought off-momentum to ensure that collisions took place in the experiments. In order to reduce the resulting central trajectory offset, it was distributed between the two beams. For an ideal machine, this corresponded to a relative momentum deviation $\delta = \pm 2.3\times10^{-4}$ for p and Pb respectively, generating a maximum horizontal offset of the central trajectory of 0.5 mm in the machine arcs. Optical errors arising from the non-centred orbit (intrinsic beat-beating) were calculated and a correction scheme was computed [3] and superimposed on the usual beta-beating correction on-momentum [4]. This was implemented for the commissioning of the new squeeze procedure prepared especially for the p-Pb run. This strategy was adopted to reduce the commissioning time with off-momentum beams as much as possible. The first section of this paper presents the correction scheme for intrinsic beta-beating. Then we will focus on the squeeze optics commissioning. Off-momentum beams affected the collimation set up, as reported in the third section.

INTRINSIC BETA-BEATING

Considering the nominal lattice without errors, the beta-beating at a given position s_0 resulting from a momentum offset δ can be calculated as follows (in either horizontal or vertical plane):

$$\frac{\Delta\beta}{\beta}(s_0) = -\frac{\delta}{2\sin(2\pi Q)}\sum_{\text{quad, sext}}\beta(K_1 - K_2 D_x)L\cos(2|\varphi-\varphi(s_0)|-2\pi Q) \quad (1)$$

with quad and sext standing for quadrupole and sextupole, K_1, K_2, are the quadrupole and sextupole strengths, β the nominal optical function, L the magnetic element's length, D_x, the dispersion function, and ϕ the phase advance. Q is the nominal tune of the machine. Increments to compensate the intrinsic beta-beating are introduced by writing $K_1 = K_{10} + \Delta K_1$. The compensating strengths ΔK_1 are optimised taking care to limit the effect on the tune and dispersion. Similarly to (1), the normalized dispersion error and tune shift can be written as:

$$\frac{\Delta D_x}{\sqrt{\beta}}(s_0) = \frac{\delta}{2\sin(\pi Q)}\sum_{\text{quad}}\sqrt{\beta}\,\Delta K_1 D_x L\cos(|\varphi-\varphi(s_0)|-\pi Q) \quad (2)$$

$$\Delta Q = \frac{1}{4\pi}\sum_{\text{quad}}\beta\,\Delta K_1 L \quad (3)$$

Consequently a set of $\Delta K_{1,i}$ minimizing the following vector has to be found:

$$\begin{bmatrix} a_{11} & \cdots & a_{1N_q} \\ \vdots & \ddots & \vdots \\ a_{N_M 1} & \cdots & a_{N_M N_q} \\ b_{11} & \cdots & b_{1N_q} \\ \vdots & \ddots & \vdots \\ b_{N_M 1} & \cdots & b_{N_M N_q} \\ c_1 & \cdots & c_{N_q} \end{bmatrix} \cdot \begin{bmatrix} \Delta K_{1,1} \\ \vdots \\ \Delta K_{1,N_q} \end{bmatrix} + \begin{bmatrix} (\Delta\beta/\beta)_1 \\ \vdots \\ (\Delta\beta/\beta)_{N_M} \\ 0 \\ \vdots \\ 0 \\ 0 \end{bmatrix} \quad (4)$$

where a_{ij} are the correcting factors calculated according to (1), b_{ij} to (2) and c_i to (3). N_q is the number of correctors, N_M the number of reference points for optics measurements.

Corrector strengths were calculated using the SVD method in Mathematica [5] and compared to an optimisation obtained using tracking data as input to the software available for online beta-beating measurements and correction in the control room. Only quadrupole correctors with unshared power supplies for the two beams were used, so that the corrections were fully independent. As an example, Figure 1 shows the results for Beam 1 in the horizontal plane with $\beta^* = (0.6, 0.6, 0.6, 2.0)$ m at the experimental Interaction

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Points, IP1(ATLAS), 2(ALICE), 5(CMS) and 8(LHCb). Intrinsic beta-beating could have exceeded 10% for this set of β^*, but it was a bit less during the run as 0.8 m was adopted as minimum β^* for machine protection reasons. The analytic calculation gives very similar results compared to the optimisation based on tracking data.

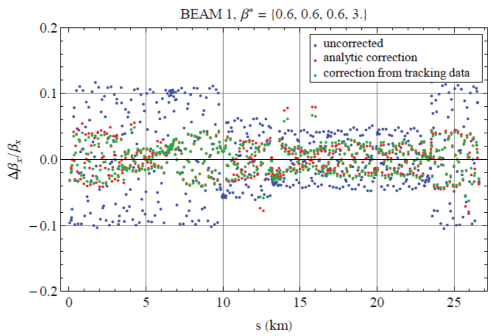

Figure 1: Theoretical horizontal intrinsic beta-beating in Beam 1 due to off-momentum operation for the smallest envisaged β^* (0.6 m). Here $s = 0$ corresponds to IP6.

OPTICS COMMISSIONING

A new squeeze process, taking the LHC from its injection optics with $\beta^* = (11.0, 10.0, 11.0, 10.0)$ m to the collision values of $\beta^* = (0.8, 0.8, 0.8, 2)$ m was created and commissioned for the p-Pb run; the first configuration with a low β^* value at all four experimental IPs. The final β^* at the high luminosity IPs was uncertain until the last moment: until the results of aperture measurements around ALICE were available to ensure appropriate margins for triplet magnets protection [6, 7].

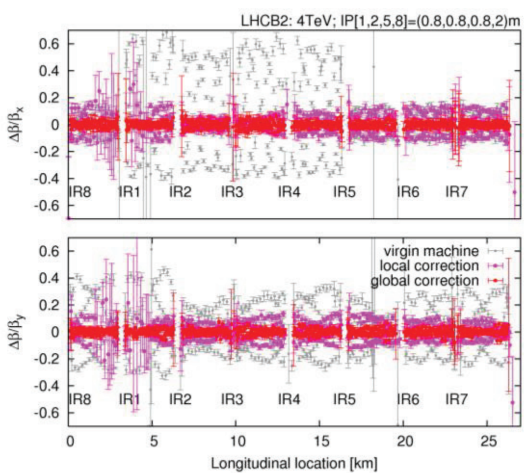

Figure 2: Beam 2 beta-beating for on-momentum proton beam, before and after corrections.

The squeeze optics commissioning was done with protons in both beams on 11–15 January, in four steps:

- On-momentum squeeze in steps, to measure the beta-beating arising from magnetic and alignment errors.
- On-momentum squeeze in steps, with same stops to measure the beta-beating after applying corrections. Figure 2 shows the results for Beam 2. Errors exceeded 60% before correction (in grey), and were brought down to less than 20% after local correction (only in the Interaction Regions (IRs), in pink), and to about 5% after global correction (fine tuning in the arcs, in red). Similar results were obtained for Beam 1.
- On-momentum squeeze with separation bumps switched on around the experiments, measurements at the end of the squeeze only.
- Off-momentum measurements in physics conditions for $\delta = \pm 2.3 \times 10^{-4}$ with correction for intrinsic beta-beating applied.

Once on-momentum correction was computed and applied, the additional correction knob for off-momentum intrinsic beta-beating was tested successfully. Both signs of momentum offset were treated to anticipate the beam reversal, foreseen half way through the run. The correction described in the first section was calculated for each intermediate set of beta functions during the squeeze but was applied only for $\beta^* < 2$ m at IP1, 2, 5, as the errors were negligible for higher values. Figure 3 shows the off-momentum beta-beating measurements for Beam 2 in red ($\delta < 0$) and in blue ($\delta > 0$), compared to $\delta = 0$ in grey. Thanks to the correction knob, the beta-beating is not increased when the beam is off-centred.

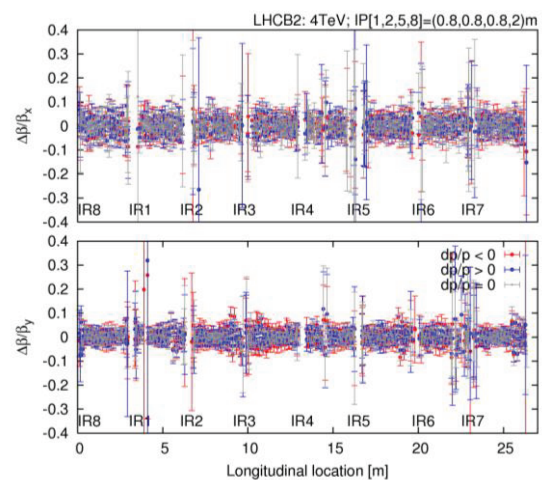

Figure 3: Horizontal (top) and vertical (bottom) beta-beating on- and off-momentum in Beam 2 for $\beta^* = 0.8$ m, with intrinsic beta-beating correction knob switched on.

Similar results were obtained for Beam 1 with $\delta > 0$. However an increase of beta-beating for $\delta < 0$ remains unexplained.

COLLIMATION SET UP

As the time allocated for physics is very short, the LHC heavy-ion runs usually capitalise on the well-established machine settings of the preceding p-p run to commission as quickly as possible. Since it was not yet excluded to operate with $\beta^* = 0.6$ m in 3 of the 4 IPs (as done in 2 IPs for p-p in 2012), the main cleaning insertions, IR3 for momentum cleaning and IR7 for betatron cleaning, were set up with the same "tight" collimator settings as for p-p [8]. This allowed a proper collimation hierarchy within the available aperture. In the end, it was decided to operate at $\beta^* = 0.8$ m, and the tertiary collimator (TCT) settings, needed to protect the quadrupole triplets in the four colliding IRs, had to be adapted (Table 1).

Table 1: β^* and TCT settings used during the p-Pb run in early 2013 compared with the p-p run in 2012. The σ unit refers to a normalised proton emittance of 3.5 μm.

	IP1, IP5		IP2		IP8	
	β*	setting	β*	setting	β*	setting
p-p	0.6m	9σ	3.0m	12σ	3.0m	12σ
p-Pb	0.8m	10σ	0.8m	10σ	2.0m	12σ

Since the primary collimators in IR7 are just a few mm from the beam centre, and to ensure the collimation hierarchy, the collimation system must be precisely aligned around the correct beam orbit, which was off-centred due to the momentum offset. For the p-Pb run the bunch charges were an order of magnitude smaller than in p-p operation. In order to provide correct orbit measurements in this range of intensities, filters on the beam position monitors had to be changed. This implied re-establishing the beam orbit and correcting it to the nominal orbit before putting the beams off-momentum.

From offline calculations of the orbit as well as from the first validation of IR7 hierarchy during the pilot run in Sept. 2012 [9], the effect of δ was expected to be small thanks to the small dispersion at the primary and secondary collimators. Indeed no significant difference was found in the IR7 alignment with respect to the alignment performed in March 2012. Therefore the beam centres and collimation jaw positions from 2012 were taken over for the p-Pb run. After this alignment check, only the 16 TCTs in the colliding IRs had to be re-aligned for every new physics configuration (approximately 1h procedure at five occasions in the whole run).

The leakage of betatron and off-momentum losses to the cold magnets was measured by performing loss maps at injection, flat top, during the squeeze and in collision (provoking losses and measuring the loss distribution around the ring).

Figure 4 shows the loss maps in the final configuration for physics in the first half of the run (p in Beam 1, Pb in Beam 2). As expected, cleaning for Pb in IR7 is worse than for protons due to nuclear reactions [10]. This, in addition to the tight collimator settings, required to increase the beam loss monitor thresholds up to a factor 4.5 (ending up above the assumed magnet quench limit) in order to avoid a systematic trigger of the beam dump. Higher losses were observed in IR2 and IR8 compared to the p-p run, because of the smaller β^*. Unexpected losses appeared in IR3 for p in Beam 1 during the qualification loss maps but were explained as cross-talk with Pb during the beam excitation with the transverse damper.

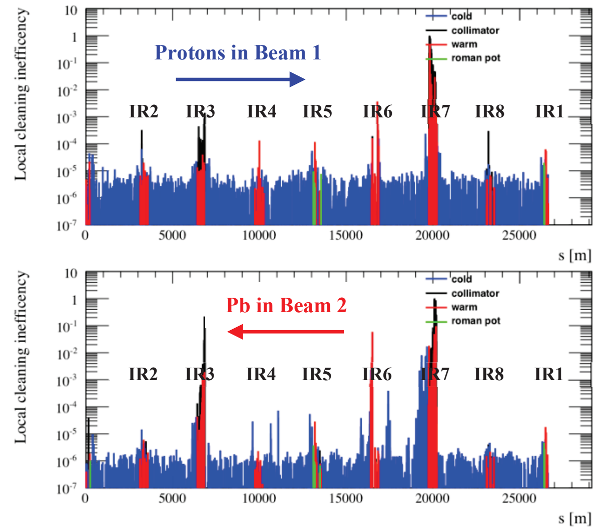

Figure 4: Horizontal betatron loss maps during collisions with Roman pots in, p in Beam 1 ($\delta > 0$) and Pb in Beam 2 ($\delta < 0$). Arrows indicate direction of propagation.

CONCLUSION

Commissioning the LHC for the p-Pb run in 2013 gave rise to new challenges compared to previous heavy ion runs. The machine had to restart after a technical stop. A new squeeze had to be commissioned and performed off-momentum, and a substantial collimation set up was required to validate the off-momentum operation. A new correction knob was calculated analytically and successfully implemented in operation to compensate for the beta-beating arising from the off-centred horizontal orbit of the beams. Thanks to this approach, several iterations on optics measurements and corrections could be avoided. Loss maps showed the expected cleaning efficiency for both proton and ion beams.

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REFERENCES

[1] J.M. Jowett *et al.*, these proceedings.
[2] J.M. Jowett *et al.*, Proc. Workshop on LHC performance, Chamonix, CERN-2011-005 (2011).
[3] R. Versteegen, CERN-ATS-Note-2012-102-PERF.
[4] R. Tomás *et al.*, Phys. Rev. ST Accel. Beams **13**, 121004 (2010).
[5] Wolfram Research, Inc., Mathematica 8.0 (2010).
[6] R. Versteegen, J.M. Jowett, CERN-ATS-Note-2012-051-PERF.
[7] P. Hermes *et al.*, to be published.
[8] R. Bruce *et al.*, Proc. Workshop on LHC performance, Chamonix, CERN-2012-006 (2012).
[9] R. Versteegen *et al.*, CERN-ATS-Note-2012-094 MD.
[10] G. Bellodi *et al.*, Proc. IPAC2011, San Sebastián (2011).

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