Operating the LHC Off-momentum for p-Pb Collisions

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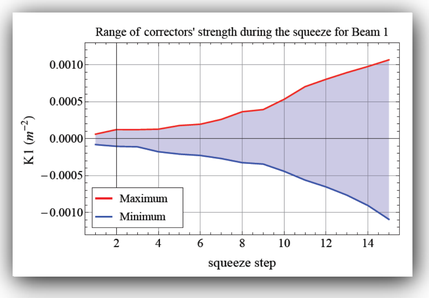
Introduction

In early 2013, the Large Hadron Collider (LHC) provided p-Pb collisions at high luminosity for the first time. 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, the beams had to be brought off-momentum to ensure that collisions took place in the experiments. For an ideal machine, this corresponded to a relative momentum deviation $\delta_p = \Delta p/p = \pm 2.3\text{x}10^{-4}$ for p and Pb respectively, generating a maximum horizontal offset of the central trajectory of 0.5 mm in the machine arcs which affected the collimation set up. Intrinsic beat-beating was calculated and a correction scheme was computed and superimposed on the usual beta-beating correction on-momentum. This strategy was adopted to reduce the commissioning time of the squeeze procedure with off-momentum beams as much as possible.

Correction scheme for intrinsic beta-beating



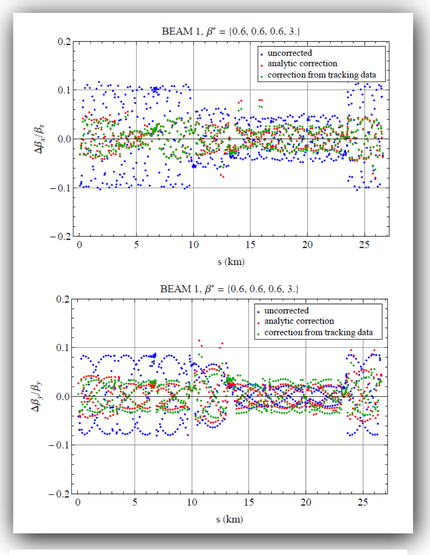


Figure: Analytic calculation of the correction compared to the optimisation on tracking data.

Optical functions errors due to off-momentum orbit:

$$\frac{\Delta\boldsymbol{\beta}}{\boldsymbol{\beta}}(s_0) = -\frac{\boldsymbol{\delta_p}}{2\sin(2\pi\boldsymbol{Q})}\sum_{\substack{\boldsymbol{quad},\\ \boldsymbol{sextu}}} \boldsymbol{\beta}(\boldsymbol{K_1} - \boldsymbol{K_2 D_x})\boldsymbol{L}\cos(2|\boldsymbol{\varphi} - \boldsymbol{\varphi}(s_0)| - 2\pi\boldsymbol{Q})$$

Introducing increments in the quadrupole strength, $K_1 = K_{1,0} + \Delta K_1$, we can write:

$$\Delta\left(\frac{\Delta\beta}{\beta}(s_0)\right) = \frac{\Delta\beta}{\beta}(s_0) + \sum_{i=1}^{N_q} a_i \Delta K_{1,i}$$

Normalized dispersion and tune shift:

$$\frac{\Delta D_x}{\sqrt{\beta}}(s_0) = \frac{\delta_p}{2\sin(\pi Q)}\sum_{quad}\sqrt{\beta}\Delta K_1 L\, D_x \cos(|\varphi - \varphi(s_0)| - \pi Q) = \sum_{i=1}^{N_q} b_i \Delta K_{1,i}$$

$$\Delta Q = \frac{1}{4\pi}\sum_{quad}\beta\Delta K_1 L = \sum_{i=1}^{N_q} c_i \Delta K_{1,i}$$

A set of $\Delta K_{1,i}$ is calculated to **minimize this vector** through the whole squeeze:

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

Results were compared to the optimisation based on tracking data. And implemented in the operation system as **a knob**.

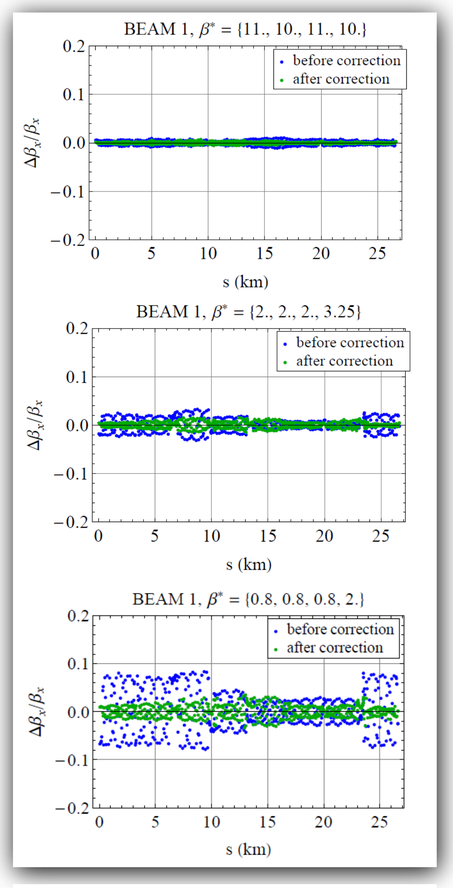
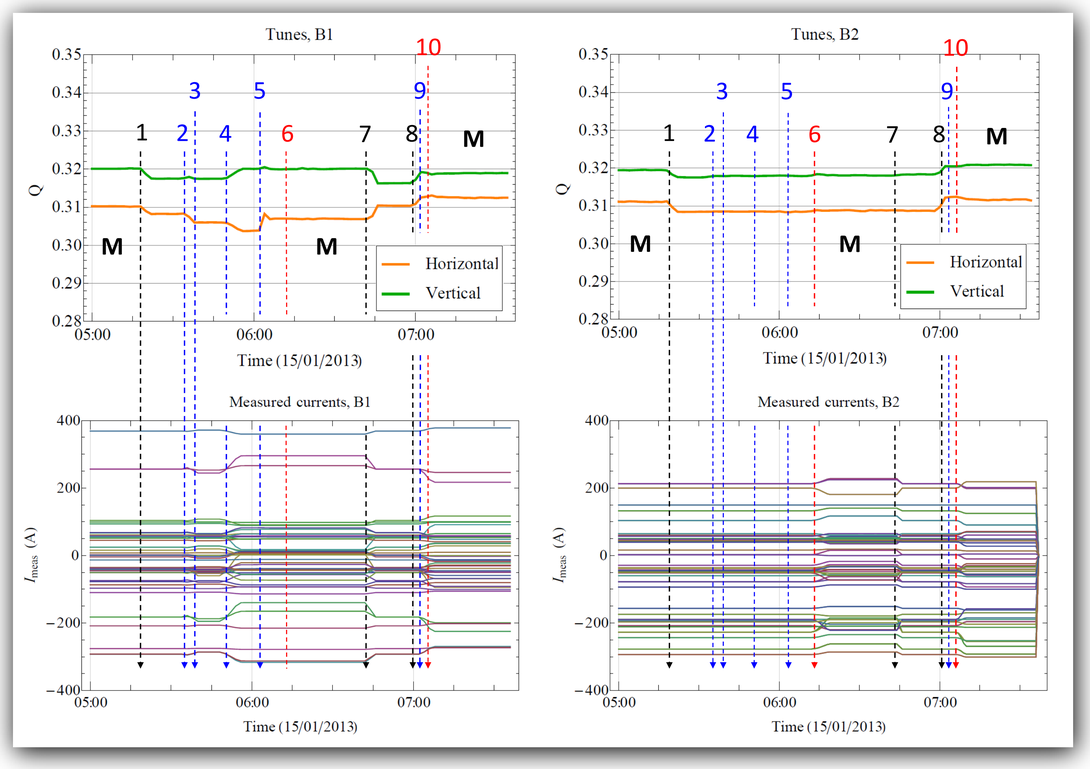
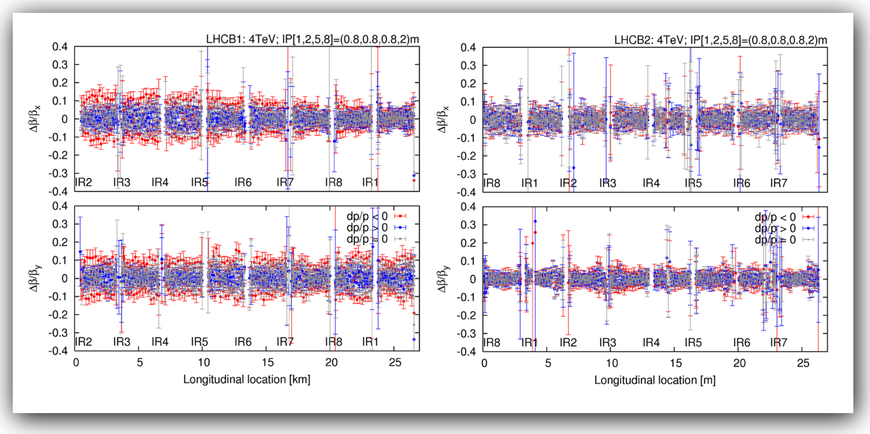


Figure: Calculated correction through the new squeeze process.

Off-momentum measurements with protons at β^* = (0.8, 0.8, 0.8, 2.0) m

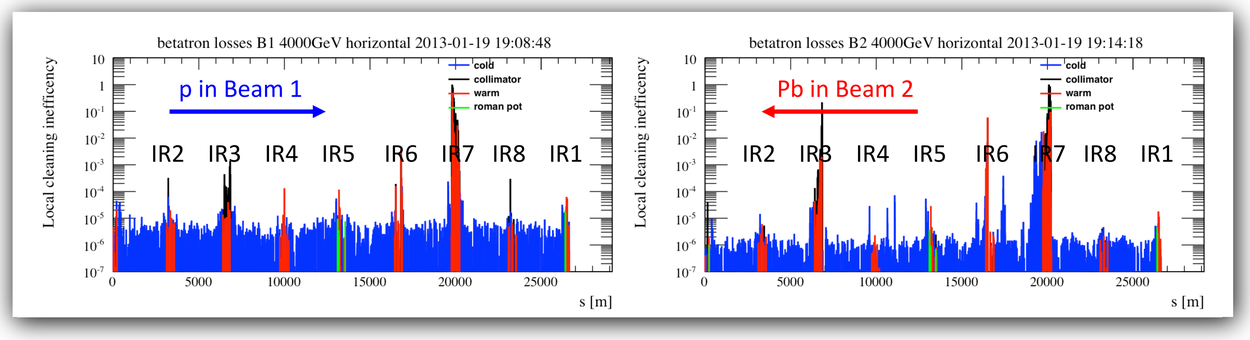


1	Δf_{RF} = +33 Hz
2	ΔK_i(BEAM 1, δ < 0) = +20%
3	ΔK_i(BEAM 1, δ < 0) = -30%
4	ΔK_i(BEAM 1, δ < 0) = +100%
5	ΔQ(BEAM 1) = +0.003
6	ΔK_i(BEAM 2, δ < 0) = +100%
7	ΔK_i(BEAM 1, BEAM 2) = 0
8	Δf_{RF} = -33 Hz
9	ΔK_i(BEAM 1, δ > 0) = +100%
10	ΔK_i(BEAM 2, δ > 0) = +100%
M	Optics measurement



- Correction knobs for intrinsic beta-beating were applied in steps for **both signs** of momentum offset **with p** in both beams,
- An unexpected tune shift was observed in the first case (B1, δ < 0), not canceled after stepping backwards; hysteresis effect is suspected,
- In all cases but B1 and δ < 0, the correction knob showed to be efficient **not to increase the beta-beating**,
- The knob was **used routinely** for each squeeze, from β^* = 2 m.

Collimation set up with off-momentum beams



- IR3 and IR7 settings were **kept identical** to 2012 to reduce the commissioning time,
- **Central orbit** had to be carefully corrected on-momentum before off-momentum operation,
- Offsets due to off-momentum beams were **small** enough **not to have to realign** IR3 and IR7,
- **TCT settings had to be adapted** depending on β^* for each IP, TCTs were **re-aligned for each physics configuration**,
- Loss maps showed the expected **degradation of cleaning for Pb** compared to protons due to nuclear reactions on the collimators.

	Hor. central orbit in **IR3**		Hor. central orbit in **IR7**	
	BEAM 1	BEAM 2	BEAM 1	BEAM 2
TCP	0.53	0.56	0.15	0.06
TCSG	0.35	0.35	0.12	0.08

Table 1: Calculated maximum horizontal orbit shifts at the primary and secondary collimators.

	IP1 and IP5		**IP2**		**IP8**	
	β^* (m)	Setting	β^* (m)	Setting	β^* (m)	Setting
p-p	0.6	9 σ	3.0	12 σ	3.0	12 σ
p-Pb	0.8	10 σ	0.8	10 σ	2.0	12 σ

Table 2: Tertiary collimators settings during p-Pb run compared to 2012 settings at the colliding IPs.

Conclusion

Commissioning the LHC for the p-Pb run in 2013 gave rise to new challenges compared to previous heavy ion runs. 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.

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