BEAM OFFSET STABILIZATION TECHNIQUES FOR THE LHC COLLISION POINTS

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Abstract

Maintaining head–on collisions over many hours is an important aspect of optimizing the performance of a collider. For the current LHC operation where the beam optics is fixed during periods of colliding beam, mainly ground motion induced perturbations have to be compensated. The situation will become significantly more complex when luminosity leveling will be applied following the LHC luminosity upgrades. During β* leveling the optics in the interaction region changes significantly, feed–downs from quadrupole misalignment may induce significant orbit changes that may lead to beam offsets at the collision points. Such beam offsets induce a loss of luminosity and reduce the stability margins for collective effects that is provided by head–on beam–beam. It is therefore essential that the beam offsets at the collision points are minimized during the leveling process. This paper will review sources and mitigation techniques for the orbit perturbation at the collision points during β* leveling, and present results of experiments performed at the LHC to mitigate and compensate such offsets.

BEAM POSITION AT THE INTERACTION POINT

The stability of the beam position at the LHC interaction points (IPs) must be at the level of one rms beam size or better in the most critical phases within the operation cycle. The most critical dynamic phases concern future modes of operation that imply a mixture of dynamic optics changes and colliding beams. Luminosity leveling by β*, where the betatron function at the IP is adjusted with colliding beams during experiments data taking, is one of those modes. Colliding the beams during the betatron squeeze (collide–and–squeeze) to profit from the Landau damping from head-on beam-beam collision is another mode. In both cases the beams must remain colliding head-on within roughly one rms beam size.

The main disturbances of the beam positions are ground motion, noise sources that generate orbit drifts as well as feed-down from the changing quadrupole gradients during the optics changes that take place during β* leveling or collide–and–squeeze. The disturbances are compensated by the LHC orbit feedback. Some residual perturbations of the IP position can however not be excluded, for example when some beam position monitors malfunction and due to the limited accuracy of the beam position monitors.

Table 1 presents simulated IP beam separations that can build up during the full optics change associated with β* leveling or collide–and–squeeze. For quadrupole rms misalignments of δ_Q of 100 µm, the separation reaches tens of rms beam sizes.

Table 1: Impact of the initial misalignment and BPM errors on the beam separation d_{IP} when the LHC optics is changed from injection to physics β* (squeeze). Different assumptions are presented for the perturbation and the correction (with or without the common orbit correctors near the IP – MCBX).

r.m.s. δ_Q	BPM errors	Used MCBX	Max d_{IP}
100 µm	20 µm	no	11 σ
100 µm	20 µm	yes	6 σ
100 µm	100 µm	yes	20 σ

Although the values presented in Tab. 1 indicate huge beam separations at the IPs, the real shifts from ground motion are much smaller. An analysis of the orbit drifts and orbit corrector strengths in LHC Run 1 (2011–2012) [1] indicates that the beam separation due to ground motion does not exceed 0.1 σ on the time scale of 12 hours, a typical inter-fill time. Ground motion is therefore not expected to be an issue, but the beam position monitor reproducibility of around 50 µm and possible larger reading outli ers can have a more important impact.

During LHC operation in 2015 large and unexpected orbit drifts were observed. The origin was rather quickly localized in one of the LHC low-beta quadruples in IP8 (LHCb experiment) whose radial position was oscillating by around 30 µm] with a period of 8 hours [2]. The root cause of the movement was eventually tracked down to the regulation of the thermal shield of the quadrupole (mal-functioning valve). This effect caused some luminosity oscillations until an orbit feedback was introduced during physics data taking.

FEEDBACK ON LUMINOSITY

The principle of the method presented here to measure and correct possible orbit shifts is based on a small modulation of the luminosity that is superposed to the beam orbit. The modulation consists of a circular beam position scan, a *rotation scan*: a circular rotation of one beam around the other (with a small separation – scan radius) will cause a modulation of the luminosity. In case the beam position is stable the luminosity is constant. If an offset is present between the two beams the luminosity will be modulated, the offset and its evolution is encoded in the modulation amplitude and phase. The scan concept is illustrated in Fig. 1: the direction α, initial value and average speed v_Δ of the drift $\Delta(t)$ may be extract from the time evolution of the luminosity.

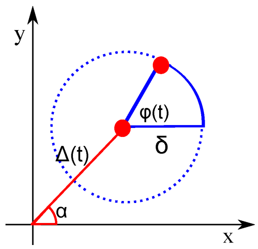

Figure 1: Transverse position of the beams at the IP. One beam is considered fixed at point (0,0), the red • represents the second (moving) beam. The beam has a varying offset $\Delta(t)$ due to external perturbations. The rotation is superposed onto the movement, the dotted circle represents one full scan of the beam.

For a beam rotation at frequency f and initial phase ϕ_0, the angle $\phi(t)$ is given by $2\pi f t+\phi_0$. The transverse positions $(x(t), y(t))$ of one beam relative to the other is:

$$\begin{aligned} x(t) &= \Delta(t)\cos(\alpha) + \delta\cos(\phi(t)) \\ y(t) &= \Delta(t)\sin(\alpha) + \delta\sin(\phi(t)) \end{aligned} \tag{1}$$

We assume the offset evolution $\Delta(t)$ is described by a linear drift[1] with speed v_Δ and initial separation Δ_0 such as $\Delta(t) = \Delta_0 + v_\Delta t$. The luminosity may be parameterized, factoring out terms depending on the beam separation $d(t)^2 = x(t)^2 + y(t)^2$, as:

$$\mathcal{L}(t) = \mathcal{L}_0 \frac{\beta_0}{\beta(t)} \exp\Big[-\frac{d(t)^2}{4\varepsilon\beta(t)}\Big] \tag{2}$$

where $\mathcal{L}_0$ is the unperturbed peak luminosity, β is the betatron function at the IP (round beams) and ε the beam emittance. We define $\overline{\mathcal{L}_\phi(t)} \equiv \log\big[\frac{\mathcal{L}(t)}{\mathcal{L}_0}\big] - \log\big[\frac{\beta_0}{\beta(t)}\big]$ as normalized luminosity over the scan and obtain:

$$\overline{\mathcal{L}_\phi(t)} = \Big[-\frac{x(t)^2 + y(t)^2}{4\varepsilon\beta(t)}\Big] \tag{3}$$

To identify the direction (α) and average speed (v_Δ) the scan duration must be as short as possible and the luminosity rate must be high and match the scan period. Taking into account the hardware constraints (like power converter ramp rates and acceptable total scan time driven by the optics change) the optimal luminosity rate must be at least 3 Hz [3] for scan periods around 15 seconds. Substitution of Eq. 1 into Eq. 3 leads to the following equation that can be used as a base for a fit:

$$\begin{aligned} f_{\text{fit}}(t) = &\left(-a_{2_{\text{fit}}}t^2 - a_{1_{\text{fit}}}t + a_{0_{\text{fit}}}\right)\cos(c + 2\pi f t) \\ &+ \left(-b_{2_{\text{fit}}}t^2 - b_{1_{\text{fit}}}t + b_{0_{\text{fit}}}\right) \end{aligned} \tag{4}$$

Where parameters $a_{2_{\text{fit}}}$ and $b_{2_{\text{fit}}}$ encodes the information for the drift as direction and the speed.

[1] assuming short scan duration

FIRST EXPERIMENTAL RESULTS

A series of experiments were carried throughout the 2015 LHC machine development program [4,5]. The experiments were done with a scanning radius of $0.5\,\sigma$. In all cases a deliberate change of beam separation was pre-programmed (up to $1\,\sigma$ per 60 s) to take place in parallel to the rotation scans.

At LHC IP1 (ATLAS experiment) measurements were performed for the collision optics (β*=0.8 m, σ^* =18 µm) with 3 Hz luminosity data. Figure 2 illustrates the recorded luminosity with the fitted luminosity evolution. The pre-

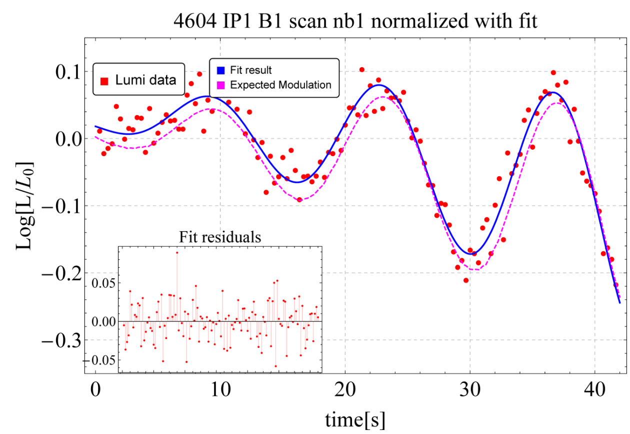

Figure 2: Scan test with 3 Hz luminosity data in IP1: the expected and fitted luminosity modulation have been superposed to the data and agree well.

programmed separation drift was reconstructed accurately from the fit as illustrated in Fig. 3.

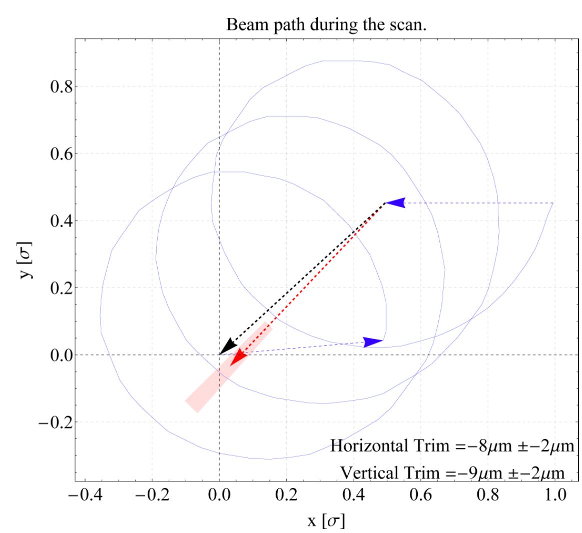

Figure 3: Reconstructed beam separation drift (red arrow) together with the pre-programmed value (black arrow). The blue line illustrates the path of the rotating beam.

Similar tests were performed at IP8 (LHCb experiment) at a larger β* of 3 m (beam size σ^* =30 µm). Luminosity data was collected in real-time at 10 Hz from LHCb. Fig-

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ures 4 and 5 illustrate the results of a test with one beam moving around the other.

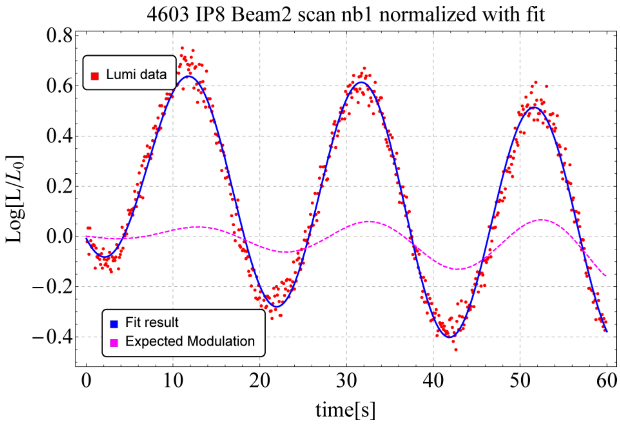

Figure 4: Example of a rotation scan in IP8. The shape of the luminosity evolution indicates some initial separation and constant drift, compensated with a pre-programmed scan drift.

Figure 4 illustrates the luminosity recorded in the period of scan length as well as the fit and reconstructed beam scan. The discrepancy between the expected modulation and the recorded one in Fig. 4 is due to a superposed real drift and an initial offset between the beams. The same reason applies to the result in the final correction trim estimation seen in Fig. 5. Both cases, with initial HO collisions like in Fig. 2

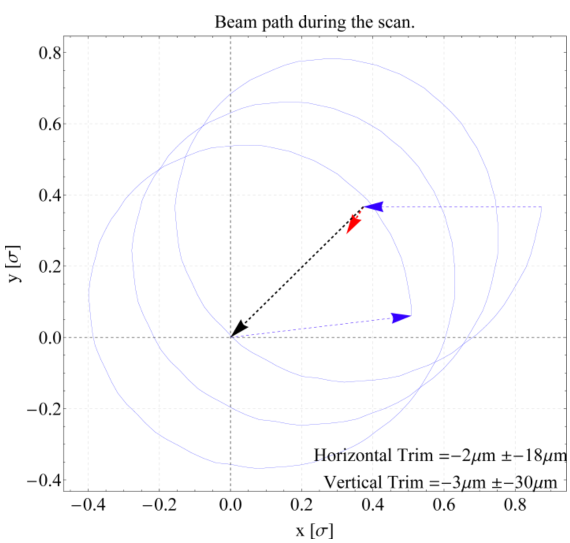

Figure 5: The beam scan path and the result on of the post processing.

or with a small initial separation (Fig. 4) can be handled by the resolving algorithm.

Beam Position Reconstruction

At the time of the measurements the beam position monitors around IP1 were already equipped with a new high sensitivity DOROS [6] electronics. The readings may be interpolated in a straight line to the IP to measure the beam position at the collision point. Figure 6 shows the expected and recorded positions of the beam at the IP for one scan. The agreement for the rotating beam is very good, but expected coupling occured on beam 2. This may be due to the beam effect.

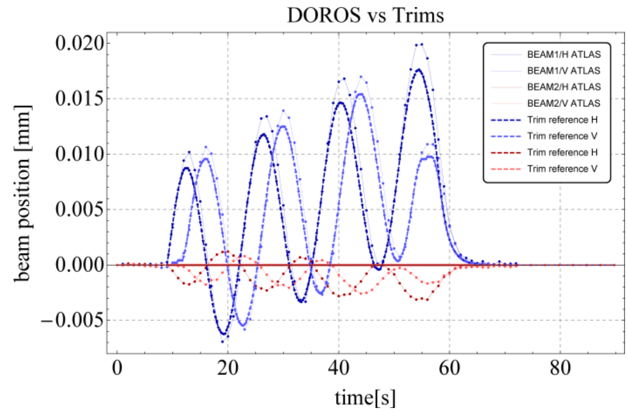

Figure 6: Beam positions at IP1 during one of the scans: the reconstructed beam position is compared to the expected change (labelled as trim). The agreement is very good for the moving beam 1, but the coupling to beam 2 is not fully explained.

CONCLUSIONS AND OUTLOOK

A novel method to determine the offsets of colliding beams by rotating the beams around each other was experimentally tested at the LHC. The technique is able to reconstruct collision offsets on the time scale of tens of seconds to one minute. It provides a good method to stabilize the beams at the IP for luminosity leveling at the LHC. It however requires a real-time exchange of luminosity information between experiments and machine at a rate of at least 3-10 Hz that is not yet operationally available. Some controls aspects must also be solved to apply such scans in realtime during beam manipulations. The impact of beam-beam on the accuracy still needs to be assessed.

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