EXPERIMENTAL DEMONSTRATION OF β^* LEVELING AT THE LHC

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Abstract

The HL–LHC project foresees to boost the LHC peak luminosity beyond the capabilities of the LHC experimental detectors. Leveling the luminosity down to a constant value that is sustainable for the experiments is therefore the operational baseline of HL–LHC. Various luminosity leveling techniques are available at the LHC. Leveling by adjusting β^*, the betatron function at the interaction point, to maintain a constant luminosity is favorable because the beams remain head-on which provides optimal stability from the point of view of collective effects. Smooth leveling by β^* requires however excellent control of the beam orbits and beam losses in the interaction regions since the beam offsets should not vary by more than around one r.m.s. beam size during the process. This leveling scheme has been successfully tested and experimentally demonstrated during the LHC machine development program in 2015. This paper presents results on luminosity leveling over a β^* range from 10 m to 0.8 m and provides an outlook on future developments and use of this technique at the LHC.

LUMINOSITY, PILE–UP AND BEAM STABILITY

An important parameter affecting the quality of the recorded integrated luminosity is the *event pile–up* – the number of simultaneous particle interactions during one bunch crossing. A large event pile–up complicates the physics analysis and degrade the quality of the data for certain types of physics channels. The relation between event pile-up and the performance of the collider is given by [1]: $\mu = \mathcal{L}_{bb} \times \sigma_p$ where $\mathcal{L}_{bb}$ is the collider luminosity for one bunch crossing and σ_p is the cross section for given physical process. The total luminosity of the collider $\mathcal{L}_p$ is given by $\mathcal{L}_p = k\ \mathcal{L}_{bb}$ where k is the number of bunch crossings per turn. For the LHC the design average pile-up if 27 while for the HL–LHC it is around 140. For the coming LHC runs until the HL–LHC the maximum pile-up should remain below a soft limit of 40 to 50. Certain operation scenarios [2] will exceed the acceptable pile–up and will require luminosity leveling.

The peak luminosity for round beams (same emittance and β^* for both beams and planes) at the interaction point (IP) can be written as

$$\mathcal{L}_p = \frac{N_1 N_2 k f \gamma}{4\pi\varepsilon_N \beta^*} \times R(\beta^*, d, \phi, \sigma_z) \qquad (1)$$

where N stands for number of particles in the bunch, k for the number of the bunches and ε_N is the normalized emittance. The factor $R()$ is smaller than 1 and represents reduction factors that depend on the crossing angle ϕ, the transverse separation of the colliding beam d, the bunch length σ_z and the betatron function at the IP β^*. Those variables may be used to level luminosity.

β^* *Leveling & Collide–And–Squeeze*

One of the luminosity leveling methods consists in a change of the beam size (via β^*) at the concerned IP. β^* is lowered stepwise to maintain a constant luminosity as the intensity decays. In the period when β^* is adjusted, the beam orbit must be stabilized to high precision to avoid unwanted beam separation at the IP that could lead to beam instabilities due to the loss of Landau damping provided by the head-on collisions [3].

To counteract instabilities arising during operation with very bright beams during the betatron squeeze at high energy, it has been proposed to collide the beams during the betatron squeeze phase, a so-called *Collide–and–squeeze* mitigation scheme. This option allows to profit from enhanced Landau damping coming from the HO beam–beam interactions [3].

Collide–and–squeeze and β^* luminosity leveling both imply a change of β^* with colliding beams. For a collide–and–squeeze the process should be as fast as possible, while for β^* leveling the time frame is defined by the luminosity and intensity decay. From the beam controls point of view the two processes are similar.

Whereas for the LHC only operation with the brightest beams ($N > 1.3e11$ protons per bunch and $\varepsilon_N < 3\,\mu$m) would require luminosity leveling, there was no indication in 2015 run that collide and squeeze is needed before 2017. For the HL–LHC β^* leveling is an operational base line scenario. The peak luminosity of $\mathcal{L}_p = 20 \times 10^{34}$ cm^{-2}s^{-1} must be leveled down to $\mathcal{L} = 5 \times 10^{34}$ cm^{-2}s^{-1} [4].

MACHINE EXPERIMENTS

While the first successful attempts of a collide–and–squeeze scheme were performed in 2012 [5], a more robust beam control scheme was demonstrated during the LHC machine development (MD) periods of the 2015 run. Two dedicated experiments took place on 30th August [6] and 8th November 2015 [7].

β^* *And Luminosity*

The first fills of August MD were used to setup the orbit references and establish collisions all along the betatron squeeze, from β^* of 11 m down to 80 cm in the high luminosity experiments. The first fill of the November MD was used to re-establish the reference orbits and validate the long term reproducibility of the settings [8].

The last fill of the November MD, fill 4604, was used to demonstrate a complete collide–and–squeeze in a single step. As shown in Fig. 1 the luminosity increased steadily along the squeeze in all points. This is clearly visible from the ATLAS and LHCb data. The CMS data was spoiled by a luminometer calibration that started at the time of the scheduled end the MD. Only off–line data allowed to reconstruct the luminosity evolution.

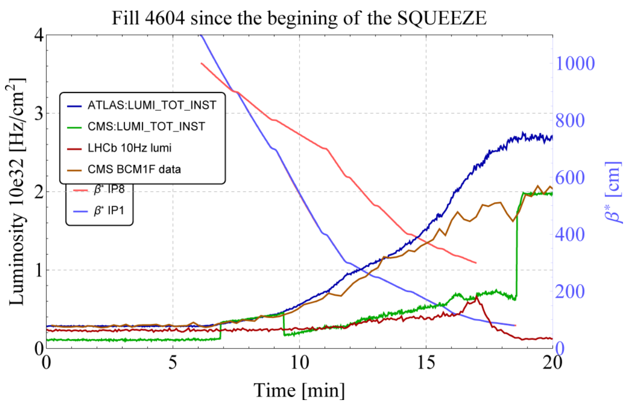

Figure 1: The evolution of luminosity and β^* for the three IPs with collisions (ATLAS, CMS and LHCb) in the last MD. The 'jumps' of the CMS luminosity were caused by the calibration of the luminometer.

Collimators And Beam Loss

The tertiary collimators (TCTs) of the LHC are protecting the superconducting low-beta quadrupoles located around the IPs from beam induced quenches and damage. Uncontrolled losses at those collimators during β^* leveling or collide–and–squeeze could be a serious issue. Thanks to the very good orbit control, no losses were recorded on TCTs in any of the fills. Figure 2 shows the relative orbit movement with respect to the center of the TCTs during one of the experiments. The relative movements correspond to less than 0.25 r.m.s. beam sizes at the TCTs.

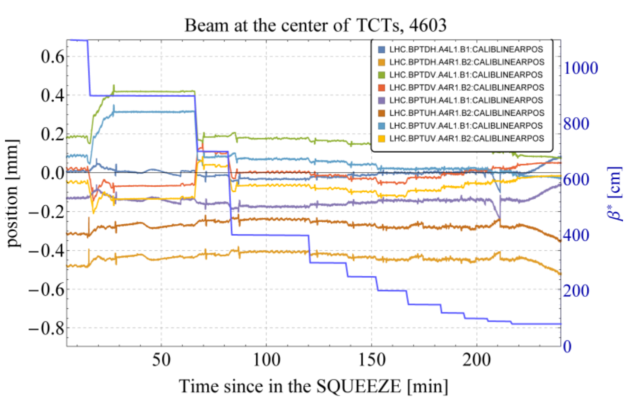

Figure 2: Example of orbit evolution at the TCTs in IP1 (ATLAS) during one of the squeeze tests with colliding beams. The position is recorded by beam position monitors embedded into the collimator jaws.

Orbit Drifts At IPs

The difficulty of controlling the orbit was one of the important difficulties of the β^* leveling tests performed during LHC Run 1 [5]. With an improved control system for the LHC orbit feedback system, conditions improved significantly for the 2015 MDs.

Since the time interval between the two MDs was over two months, the long term reproducibility could be cross–checked with predictions [8]. The expected quadrupole r.m.s. alignment change over such a time interval (70 days) is $\delta_Q \simeq$ 21 µm. For such a modest change the beam separation (at the end of squeeze) should not exceed 1 σ. Figure 3 shows the relative change in the corrections that had to be applied along the squeeze to maintain beams in collision for the November MD with respect to the August MD. For IP1 and IP5 the results agree well with the expectations. Some larger excursions for IP8 were related to issues with the settings.

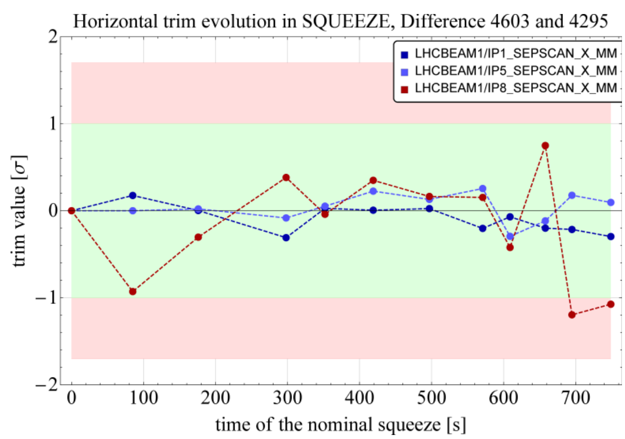

Figure 3: Horizontal luminosity corrections applied in November 2015 in unit of beam size as a function of the time along the squeeze w.r.t. to the settings established in August 2015.

In 2105 a high resolution beam position measurements electronics (DOROS [9]) was installed on the quadrupoles surrounding the IPs. The recorded positions may be used to detect beam position drifts during β^* leveling or collide–and–squeeze. If the measurements are reliable, a direct feedback on the beam position is possible to maintain the beams colliding head-on, thus increasing the robustness of the schemes. Figures 4 and 5 illustrate the evolution of beam position at the IPs as measured by DOROS. The first results are extremely promising, a stability of better than one beam sigma seems well within reach.

CROSSING ANGLE MEASUREMENTS

The continuous luminosity data from the collide and squeeze can be used to determine the crossing angle at the IP through the form factor. Such a measurement is independent of the beam position monitors and provides an indirect measurement of that observable. No emittance growth was measurement over the time interval of the squeeze, the average emittance recorded from the synchrotron light monitor was used for normalization of the beam size [7].

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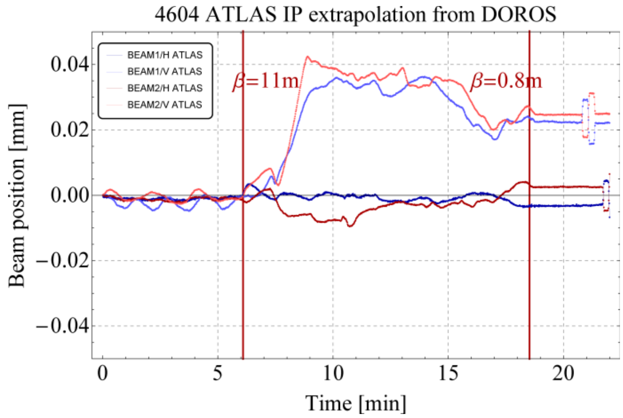

Figure 4: Evolution of the beam positions in ATLAS obtained by extrapolation of the DOROS data in fill 4604.

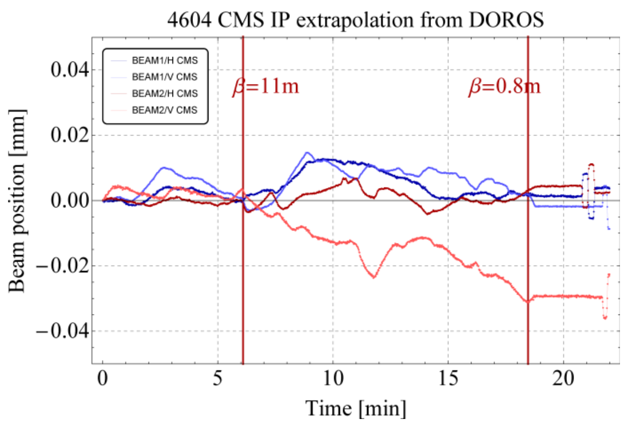

Figure 5: Evolution of the beam positions in CMS obtained by extrapolation of the DOROS data in fill 4604. A separation (of about 1.5σ) developed close to the beginning of the squeeze, mainly driven by a beam 2 vertical drift.

The dependence of the geometry form factor F on β^* and on the crossing angle ϕ is given by:

$$F(\beta^*, \phi) = \frac{1}{\sqrt{1 + \left(\frac{\sigma_z^2 \gamma}{\beta^* \sqrt{\varepsilon_1 \varepsilon_2}}\right)\left(\frac{\phi}{2}\right)^2}} \quad (2)$$

where $\varepsilon_1, \varepsilon_2$ are the beam 1 and beam 2 emittances. The actual beam intensities were included into the analysis as well as a shift of 20 cm of the betatron function waist away from the IP [10, 11]. These corrections were included in this analysis for all values of β^*. The half–crossing angle estimate obtained from the collide and squeeze MD for IP1 was $\phi/2 = 164 \pm 5$ µrad for a nominal setting of $\phi/2 = 145$ µrad. The crossing seems therefore to be 10% larger than expected, in agreement with independent K–Modulation measurements [12].

OUTLOOK AND CONCLUSIONS

A continuous squeeze with beams remaining in head-on collision within better than one beam sigma was demonstrated for the first time at the LHC. All necessary controls

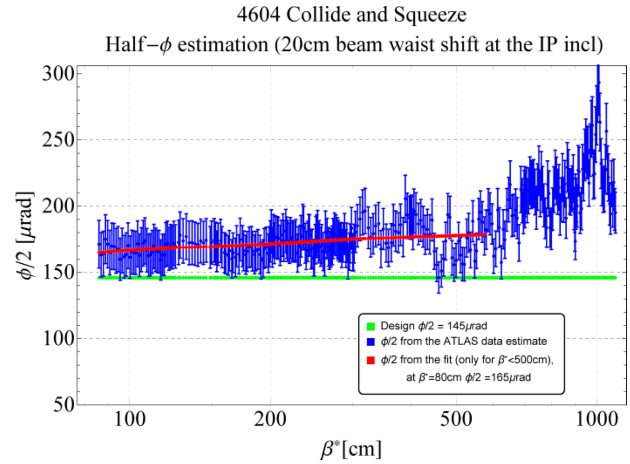

Figure 6: The estimate of the crossing angle ($\phi/2$) versus β^* for IP1 during the LHC fill 4604.

tools are available and will be streamlined in the near future. High resolution position measurements around the IP could be included in the future to perform a direct position feedback on the beams at the IPs. The long term stability and the orbit reproducibility for such a scheme was measured to be in agreement with predictions.

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