LEVELING OPTIONS AND STRATEGY

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Abstract

This paper gives an overview of possibilities for luminosity leveling in the LHC Run 2. Different scenarios together with detailed proposals will be presented. Since luminosity leveling by transverse offset was operationally proven part of this paper will describe in detail how leveling of luminosity will be done using β^* adjustment on the example of LHCb.

EXPECTED PEAK PERFORMANCE

After the long shutdown the LHC will restart beam operation in 2015 at an energy of 6.5 TeV. The LHC's two high luminosity experiments, ATLAS and CMS can cope with a maximum average pile–up of 50 and a time-averaged pile-up(μ) of 30 to 40. The LHCb experiment on the other hand will operate at a maximum pile-up of $\mu = 1.6$. Assuming two restart scenarios [1], the relaxed parameter set ($\beta^* = 0.65$m and $\varphi = 170\mu$rad) does not require of the luminosity leveling in ATLAS and CMS. However, LHCb, due to it's nature, will always require leveling. With the pushed parameter set ($\beta^* = 0.4$m and $\phi = 155\mu$rad, assumed to be used as from 2016 and onwards) both ATLAS and CMS will require leveling for up to 2.5h at the beginning of each high intensity fill.

A step back to 50ns operation will require the leveling for ATLAS and CMS as from beginning of the high intensity operation due to pile–up values reaching 146. The time needed to level this excess will reach 4h in the most pessimistic case.

For the LHC luminosity upgrade HL-LHC (from 2023) [2] luminosity leveling by β^* is part of the operational baseline. Therefore, an extended learning period is required to master the process.

LUMINOSITY LEVELING METHODS

Two main luminosity leveling methods are considered for Run 2, namely leveling by beam offset d and leveling by β^*. The range of both methods is limited by practical aspects or by beam dynamics effects. Beam stability is an issue with too large offset while beam control is an issue for β^* leveling [3].

Offset Leveling

Offsetting the beams is easily implemented with local orbit bumps around a collision point. This technique was used routinely during LHC Run 1 for the LHCb experiment [4]. The main drawback of the method is related to transverse beam stability. The LHC high intensity beams must be stabilized by a transverse feedback and by Landau damping from octupoles and from head-on (HO) beam-beam collisions. Bunches colliding with offsets have less Landau damping and may suffer from instabilities. Leveling by offset is also a potential source of emittance growth. For these reasons, offset leveling cannot be applied at all LHC collision points at the same time [5].

β^* Leveling

Another way for controlling the pile–up is to change the beam size of the colliding beam through β^*. This technique does not affect the beam–beam parameter since the beams remain head-on. Landau damping from HO collisions is therefore preserved [6]. During a change of β^* the optics of the entire interaction region and long straight section is affected. The gradient changes in the quadrupoles require adjustments of the crossing angle shapes and lead to orbit changes due to feed-down from the beam offsets in the quadrupoles (due to misalignments). Leveling by β^* requires therefore excellent control of the beam orbit in the straight section and at the collision point whenever the optics (β^*) is changed to maintain the luminosity. The beam separation d should ideally not exceed 0.5σ during the process. Furthermore the interlocked collimators, located close to the low-beta quadrupoles, must follow the optics changes smoothly.

STRATEGY FOR LEVELING DURING LHC RUN 2

LHCb – Proposal

A base line for the LHC β^* leveling implementation consist of directly implementing it in LHCb, using all possible optic points plus 4 additional new points to satisfy luminosity excursion constraint ($\frac{\Delta L}{L} < \pm 0.05 \Rightarrow \frac{\Delta\beta^*}{\beta^*} < 0.10$).

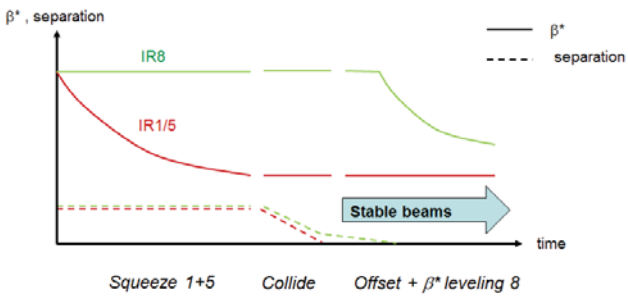

Figure 1: Operation scenario of LHC for 2015 at 6.5 TeV. In a first step the optics is squeezed (β^* reduction) in IR1 and IR5 with non-colliding beams. The beams are then brought into collision. At that stage the experiments start data taking ('Stable beams'). The luminosity if IR8 is first leveled by offset before β^* leveling takes over after some time.

Due to the large pile up (up to μ=12) and the injection constrains of initial $\beta^* = 10m$ (process of un–squeeze every fill would extend turnaround time of the machine) it is not sufficient to use only β^* leveling. Therefore, a mixture with the offset leveling may be considered. It was simulated that offset leveling time will last up to 6h for each fill (if bright BCMS beams are used). To limit the influence and the possible operation complications of the leveling by $\beta*$ it is considered to squeeze LHCb to 8m before going into collisions. That extends the period of the offset luminosity leveling to maximum of 8h. As the most probable is to restart with is the 25ns beam (n=1.2e11 and ε_N = 2.6μm) a respective times are a maximum of 3h (10m) and 5h (8m). Furthermore comparison of these values with an average fill length [9] and the number of the fills that actually were longer that this time, leads to the conclusion that 240 (10m) and respectively 200 (8m) for an average year of the fills would potentially give an experience with $\beta*$ leveling. Performing $\beta*$ leveling in LHCb operation may not remain transparent for the ATLAS and CMS performance. Due to global $\beta*$ change a variation of recorded luminosity is expected to happened. Therefore, the ratio between the recorded luminosity in both experiments may not be constant. All necessary corrections to compensate this effect will be included in the commissioning phase but it is possible that residual errors will remain.

The commissioning implies careful optics and orbit corrections to keep the beams head-on during each step. The optics must be corrected such that it minimizes the perturbation of $\beta*$ in IR1 and IR5. A total of 20 optics points are required to cover the $\beta*$ range of 10 m to 3 m. The time needed for this was estimated to 4 shifts [7].

ATLAS / CMS: Collide and Squeeze

An implementation of a combined *Collide and Squeeze* beam process gives the same experience as $\beta*$ leveling and may be needed in case of increased beam-beam instability observations [8]. However, it doesn't solve the need of leveling in LHCb. Therefore, two sub options are proposed: Direct $\beta*$ leveling implementation or full offset leveling. The *Collide and Squeeze* option requires the heaviest work for beam process preparation (Fig.2). But it also gives the most flexible and the most adaptive configuration including readiness for the 50ns fallback scenario and the ultimate 2016 performance requirements (need of leveling in ATLAS and CMS with pushed scenario reaches max. 3h of each fill).

MDs

Testing $\beta*$leveling during the cyclic Machine Development period (MD) gives the possibility to use any of the LHC IPs. However, this requires a certain time to prepare beam processes in advance. Moreover, this approach does not give a regular experience in the view of possible need of usage: collide and squeeze and/or leveling. Additionally, long time intervals between two MDs will lead to extended time of preparation since quality of the service depends on global reference orbit stability which over so long period of the time, is not given and has to be re–establish. The number of possible experience possibilities is a factor of 50 less then in case of direct implementation in LHCb and almost a factor 100 less if *collide and squeeze* is implemented in ATLAS

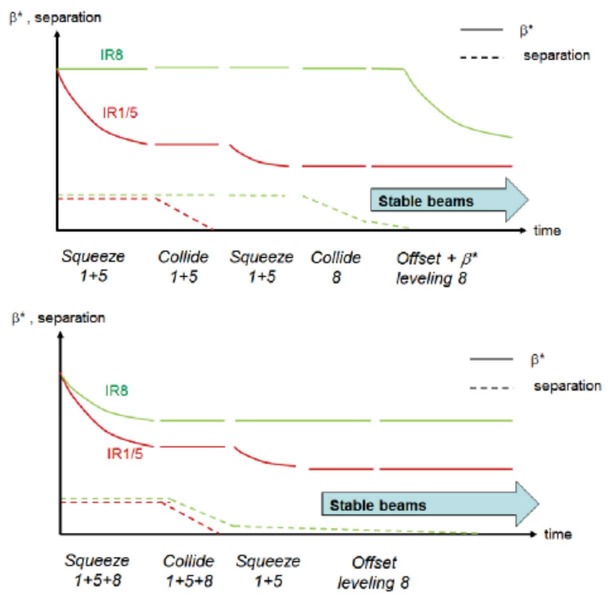

Figure 2: Operation scenario of LHC if Collide and Squeeze will be implemented. In the first step the optics is pre squeezed (β* reduction) in IR1 and IR5 with non-colliding beams, followed by bringing them into collision. After this stage, a continuous reduction of β* is performed down to the minimal value without declaring stable beams (top Fig.). The same but with SB declaration would give a β* leveling when required. The luminosity of IR8 is either leveled via offset (top Fig.) or like on 1 scenario as a mixture of offset and β* leveling (bottom Fig.).

and CMS: it is estimated that in MDs there will be a total of 4 attempts per year.

ALICE

The fourth possible testing solution is a leveling while producing luminosity with heavy ions. It has the same requirements and advantages as $\beta*$ leveling in LHCb but unlike for the protons (leveling in ALICE that would need a range starting form $\beta*$=1km) for heavy ions would be required to start around $\beta*$=4m. The number of the fills that would give the exercise experience is only limited by the length of the heavy ion run.

SELECTED SCENARIO AND DETAILS

A closer look at the process (Fig.3) example of LHCb start-ing from $\beta*$=10m highlights the operation details. The sim-ulation was performed for a standard beam: 25ns, n=1.2e11 and ε_N =2.6μm. To overcome the luminosity peak at the beginning a transverse offset leveling is applied in the first 3h of the fill followed for another 10h by $\beta*$ leveling. This gives a 3h of $\beta*$ leveling, assuming on average fill length of 6h.

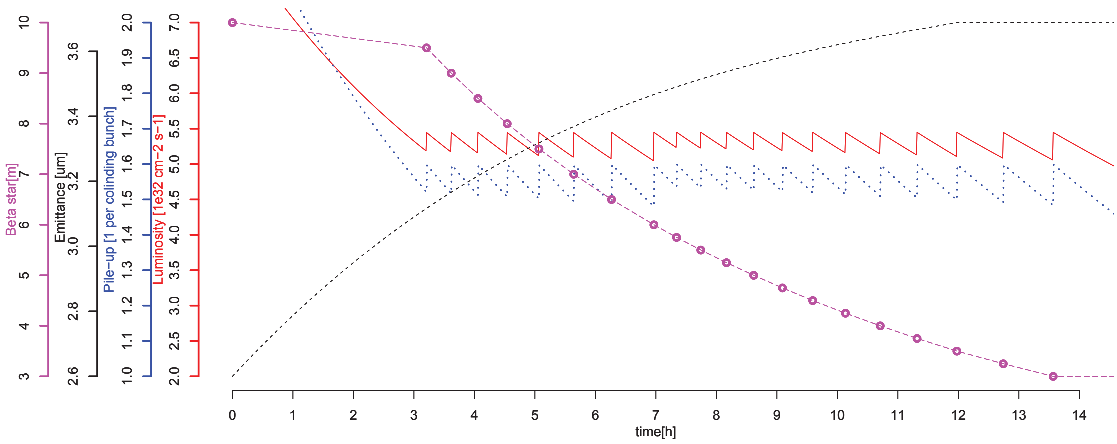

Figure 3: Evolution of several parameters during β^* Leveling at LHCb. The luminosity (red) is leveled to match an average event pile-up (blue) of 1.6. The beam emittance (black) increases during a fill and is based the observed evolution during Run 1. The β^* (magenta) change is made in steps corresponding to predefined matched optics. In the first part of the fill the luminosity is leveled by offset.

β^* implementation in details

A closer look at the β^* change step (one of the peaks in Fig.4 , [10]) leads to the definition of the sequence of the actions.

- A luminosity decay phase due to the intensity decrease and emittance blow up.
- The preparation of the next the step (**A**) when all the currents functions are loaded into the power converter controllers. Position functions are loaded into the control of the collimators. The orbit feedback receives a function to track the reference orbit.
- The step execution (**A** $\mapsto$ **B**) when power converters and collimator execute their pre-defined functions.
- The end of the step (at **B**) when the collimator position thresholds are updated. At that point the luminosity is re-optimized in case the orbit was not corrected perfectly leaving a non-zero residual offset d.

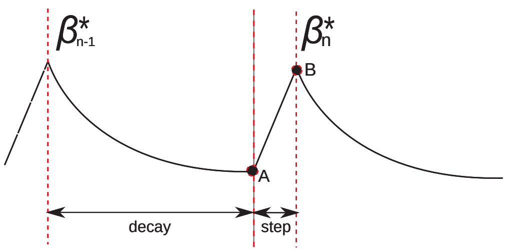

Figure 4: One step in the β^* leveling sequence. Three main phases can be seen on the picture: the luminosity decay phase at constant β^*, the step start, execution and end.

During the leveling step (**A** $\mapsto$ **B**) the beam orbit feedback system must ensure that the beams remain in collision. Since the shape of the crossing angle bumps used to provide long-rang beam-beam separation changes with β^*, the reference orbit must be dynamically adapted during the step. It is crucial to ensure the traceability of the corrections that are applied at each step, a complete history of the correction applied during all steps must be maintained, including adjustments by the orbit feedback system.

Software challenge

A simple JAVA application is currently controlling luminosity leveling by offset as it was used during LHC Run 1. The application listens to messages from the experiments (leveling requests) and informs the experiments of the leveling status [4]. Due to concurrency problems in case multiple instances of the application run in parallel, a dedicated server will be developed to handle all request related to luminosity optimization and leveling. It will consist of two leveling modules, each dedicated to one method: offset leveling and β^* leveling, business logic of the existing application will be moved into a dedicated module whereas a β^* control module will be developed from scratch.

CONCLUSIONS

Luminosity leveling will be required during the entire life cycle of the LHC. Depending on the machine and beam parameters, it may be already required for all experiments during Run 2. For the HL-LHC upgrade, luminosity leveling is mandatory and must be done by the use of with β^* leveling. Therefore an experience that can be achieved the during upcoming run is crucial.

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