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IMPLEMENTATION OF LUMINOSITY LEVELING BY BETATRON FUNCTION ADJUSTMENT AT THE LHC INTERACTION POINTS

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Abstract

Growing expectations for integrated luminosity during upcoming LHC runs introduce new challenges for LHC beam operation in the scope of online luminosity control. Because some LHC experiments are limited in the maximum event rates, their luminosity is leveled to a constant value. Various techniques may be used for luminosity leveling, changing the betatron function at the interaction point is one of them. This paper explains the main operational requirements of a betatron function leveling scheme for the upcoming LHC run. Issues concerning the beam optics, orbits and collimator settings are discussed. The proposed architecture for control system integration will be discussed. A few operational scenarios with different beam configurations foreseen for the next LHC run will be presented.

LUMINOSITY

An important parameter that affects the quality of the recorded luminosity at the LHC is the *event pile–up*, the number of simultaneous particle interactions during one bunch crossing. A high event pile–up complicates the physics analysis and degrades the data quality for certain types of physics channels. The event pile–up μ is directly proportional to the luminosity per bunch crossing L_{bb}, $\mu = L_{bb} \times \sigma_P$, where σ_P is the total cross section for pp interactions at the LHC, $\sigma_P = 70 - 85$ mbarn. The total luminosity L_p is given by $L_p = k\ L_{bb}$ where k is the number of bunch crossings per turn.

The bunch pair luminosity for round beams at an interaction point can be written as

$$L_{bb} = \frac{N^2 f\gamma}{4\pi\varepsilon_N \beta^*} \times F \times \exp\left[-\frac{d^2}{4\beta^*\varepsilon_N}\right] \qquad (1)$$

where N stands for number of particles in the bunch, ε_N for the normalized emittance and β^* for the betatron function at the interaction point. f is the revolution frequency and γ the relativistic factor. F is a correction factor for the crossing angle. For round beams ε_N and β^* are identical for both transverse planes. d is the transverse offset (separation) between the colliding beams. The transverse separation d and the betatron function β^* can be seen as a way for control luminosity.

LHC RUN 2 BEAM PROJECTIONS

After the long shutdown the LHC will restart beam operation in 2015 at an energy of 6.5 TeV. The LHC has two high luminosity experiments ATLAS and CMS that are installed at interaction points 1 and 5 (IR1 and IR5). Those experiments can cope with a maximum average pile–up of 50 and a time-averaged pile-up of 30 to 40. The LHCb experiment in IR8 on the other hand will operate at a maximum pile-up of $\mu = 1.6$. Table 1 gives possible operation scenarios for Run 2 with bunch spacings of 25 ns and 50 ns. The 50 ns spacing yields very high maximum pile–up and is only considered as a backup scenario if electron cloud effects cannot be overcome with 25 ns beams.

Luminosity leveling is required for the LHCb experiment for all scenarios, while for the high luminosity experiments only the 50 ns scenario definitely requires leveling. With 25 ns some leveling is required in IR1 and IR5 only for the brightest beams.

For the LHC luminosity upgrade HL-LHC (from 2023) [1] luminosity leveling by β^* is part of the operational baseline.

Table 1: Selected Operating Scenarios for LHC During Run 2

spacing (ns)	N [10^{11}]	ε_N [μrad]	L [10^{32} Hz/cm^2] IR1/5	IR8	Max. μ IR1/5	IR8
25	1.15	1.9	164	36	55	12
25	1.2	2.6	164	31	37	8
50	1.7	1.1	275	65	146	34

LUMINOSITY LEVELING METHODS

Two main luminosity leveling methods [2] can be used at LHC 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, for this reasons offset leveling cannot be applied at all LHC collision points at the same time [5,6]. Leveling by offset is also a potential source of emittance growth.

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Figure 1 shows the luminosity leveling of LHCb during a typical LHC fill in 2012. The average pile–up was around $\mu \simeq 1.6$ which corresponds to a luminosity of 4×10^{32} cm^{-2}s^{-1}.

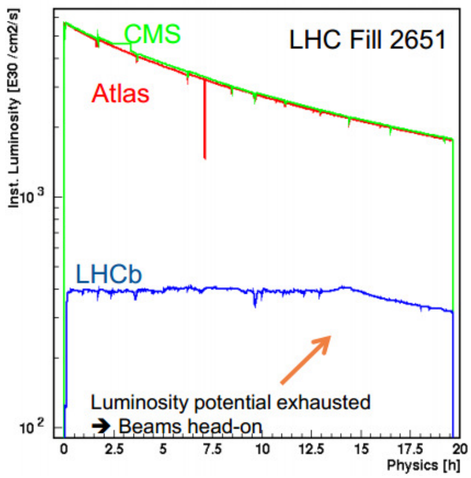

Figure 1: Luminosity evolution for the 3 main LHC experiments during a fill in LHC Run 1. The luminosity at the LHCb experiment is leveled by offset.

β Leveling*

Another way for controlling the pile–up is to change the beam size of the colliding beam through $\beta*$. This technique does not affect the beam–beam parameter since the beams remain head-on. Landau damping from HO collisions is therefore preserved [7].

During a change of $\beta*$ 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 $\beta*$ requires therefore excellent control of the beam orbit in the straight section and at the collision point whenever the optics ($\beta*$) is changed to maintain the luminosity. The beam separation d should ideally not exceed 0.5σ during the process: this corresponds to $d = 10-50$ μm depending on beam and optics parameters. Furthermore the interlocked collimators located close to the low-beta quadrupoles must follow the optics changes smoothly.

β* LEVELING AT LHCB

One of the operation scenarios for Run 2 involving luminosity leveling is shown in Fig. 2. This scenario is based on the implementation of $\beta*$ leveling at the LHCb experiment as a preparation to leveling in the high luminosity IRs in case of high beam brightness.

Due a limitation of the maximum β^* at injection in LHCb, offset and $\beta*$ leveling must be combined: in the first part of a fill, the initial β^* of 10 m is too small and offset leveling must be used. Once the beams are head-on $\beta*$ leveling takes over.

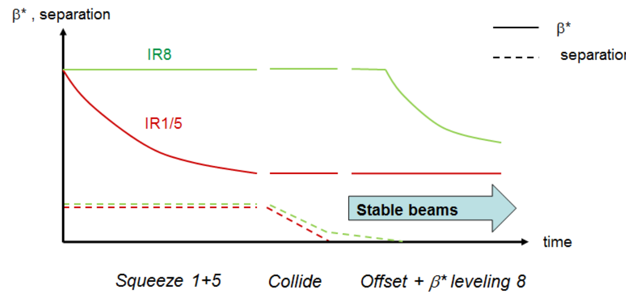

Figure 2: Operation scenario of LHC for 2015 at 6.5 TeV. In a first step the optics is squeezed ($\beta*$ reduction) in IR1 and IR5 with non-colliding beams. The beams are then brought into collision. At that stage the experiments start data taking ('Stable beams'). The luminosity if IR8 is first leveled by offset before $\beta*$ leveling takes over after some time.

The evolution of some parameters during LHCb leveling is presented in Fig. 3. During the first few hours leveling by offset is used until the beams are head-on ($d = 0$). Once the beams are head-on, the luminosity is adjusted by step-wise $\beta*$ reduction. $\beta*$ leveling requires ideally a continuous set of well matched optics for every possible value of $\beta*$. In practice the required number of points may be defined by the maximum luminosity excursion that can be tolerated, $\frac{\Delta L}{L} < \pm 0.05 \Rightarrow \frac{\Delta\beta^*}{\beta^*} < 0.10$. Each pre-defined $\beta*$ point is prepared and commissioned before it is used in regular operation. The commissioning implies careful optics and orbit corrections to maintain the beams head-on during each step. The optics must be corrected such as to minimize 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. Initially it will only be possible to move from a larger to a smaller $\beta*$ value, not step back will be possible.

DESIGN OVERVIEW

Figure 4 shows in detail one $\beta*$ leveling step. The main phases are:

- 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 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.

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

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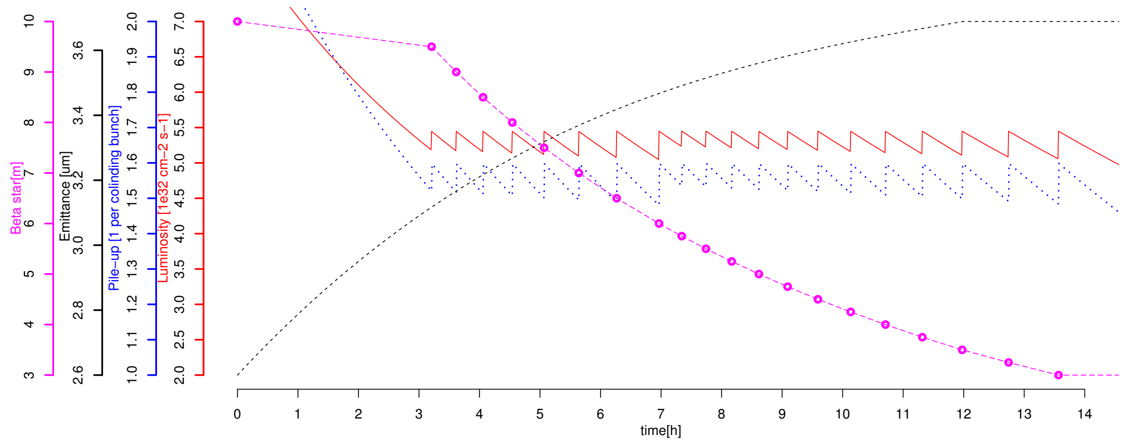

Figure 3: Evolution of several parameters during β* Leveling at LHCb. The luminosity (red) is leveled to match an average event pile-up (blue) of 1.6. The beam emittance (black) increases during a fill and is based the observed evolution during Run 1. The β* (magenta) change is made in steps corresponding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

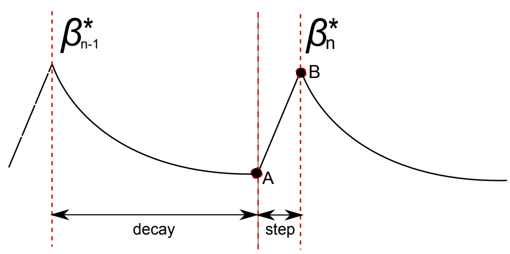

Figure 4: One step in the β* leveling sequence. Three main phases can be seen on the picture: the luminosity decay phase at constant β*, the step start, execution and end.

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.

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.

SQUEEZE WITH COLLIDING BEAMS

In case of severe beam instabilities during the intensity and luminosity ramp up in Run 2, it may be required to collide the beams while the betatron squeeze is performed in IR1 and IR5, see Fig. 2. In that situation colliding the beams with the smallest possible offset in 2 experiments will be particularly critical. Experience gained with β* leveling in LHCb will be essential in order to develop such a complex operation scheme.

CONCLUSIONS

Luminosity leveling will be required during the entire life cycle of the LHC, depending on 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 made with β* leveling. It is proposed to operate with β* leveling in the LHCb experiment at the start of Run 2. It will provide important input on the operation of this method with limited risk. The decision to level by β* in LHCb will be made at the latest by the end of 2014.

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