MEASUREMENT AND SIMULATION OF LUMINOSITY LEVELING IN LHC VIA BEAM SEPARATION*

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Abstract

Leveling of the luminosity in LHC by means of separating the beams colliding at an interaction point is examined. An experiment in which the separation of the beams was stepwise increased to up to 2.5 times the beam width is presented. The luminosity at all IPs and emittance of the beams were measured to detect possible side effects of the collision with an offset. Strong-strong simulations that closely follow the experimental setup are discussed and compared with the measurements. Finally, potential alternatives for luminosity leveling are briefly described.

LUMINOSITY

The high-luminosity upgrade of the LHC aims at increasing the *integrated luminosity* $\int L\mathrm{d}t$ significantly beyond the nominal value [1]. Here L is the *instantaneous luminosity*. For two equal circular beams with Gaussian density profiles colliding head-on, the luminosity (per collision) is given by

$$L_0 = \frac{N^2 f_0}{4\pi\epsilon\beta^*}, \qquad (1)$$

where N is the number of particles per bunch, f_0 is the revolution frequency, ϵ is the emittance and β^* is the beta function at the interaction point (IP).

The gain in luminosity relies on an increase of the beam intensity and brightness, as well a decrease of the beta function at the IPs. Maximizing the instantaneous luminosity with these parameters is not the target, though. There are several reasons to limit the peak luminosity. One reason is the limited pile-up capacity of the experiments, i. e. the limited number of simultaneous reactions that can be distinguished in the analysis. Another reason is that the luminosity decays the faster the larger the initial luminosity is, due to emittance growth and particle loss.

In order to maximize the integrated luminosity without driving the peak luminosity to extremes, *luminosity leveling* will be employed. Luminosity leveling is a measure to keep the luminosity at a constant value, which is significantly smaller than the potential peak luminosity without leveling, as long as possible. As Fig. 1 reveals, leveling avoids high pile-ups and slows down the beam degradation thus permitting longer storage times [1]. The leveling ends when the beam deterioration can no longer be compensated (t_{lev} in Fig. 1). Collisions still go on until the luminosity drops below a threshold which triggers a beam dump (t_{dec}). The time gap for injection and preparation of new beams until collisions can be resumed ($_{\mathrm{ta}}$) is independent of this procedure.

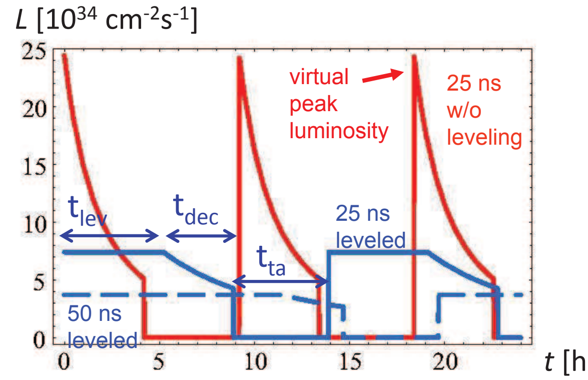

Figure 1: Projected luminosity in the high luminosity LHC as a function of the time. The red line indicates the luminosity that would be yielded without leveling. The solid blue line shows the target course with leveling. The dashed blue line refers to an alternative set of beam parameters also with leveling.

Courtesy O. Brüning [1]

The suppression of the luminosity decay overcompensates the reduction of the peak luminosity. In addition, the increased storage time improves the ratio of the usable time $t_{\mathrm{lev}}+t_{\mathrm{dec}}$ to the restoration time t_{ta}. Consequently, the long term integrated luminosity is increased by leveling.

Luminosity leveling requires a reversible reduction of the instantaneous luminosity. Reversibility is essential to compensate the natural luminosity decay. In addition, at LHC the leveling has to be strictly local to match the individual needs of all 4 experiments. Thus only beam optical parameters can be varied for leveling. Another prerequisite for a useful method is a weak to negligible impact on the beam quality.

One lever for luminosity leveling is β^*, according to Eq. 1. Two other options are a based on a reduction of the

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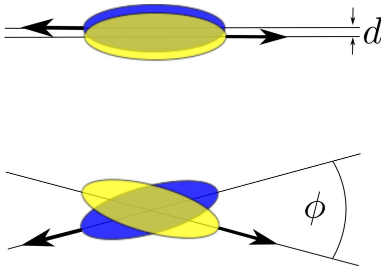

Figure 2: Sketch of the reduced luminous region due to a beam separation d and crossing angle ϕ.

luminous region by preventing the bunches from fully overlapping during the collision. The first option is based on a separation of the beams at the IP, or, in other words, adding an offset to one beam with respect to the other beam. The other option is a crossing angle of the trajectories. Figure 2 illustrates the reduction of the luminous region for an offset and a crossing angle. In this report we focus on luminosity leveling via beam separation.

The luminosity of two beams colliding with an offset d_x in the horizontal plane and a small crossing angle ϕ_y in the vertical plane is given by [2]

$$L(L_0, d_x, \phi_y, \sigma_x, \sigma_y, \sigma_s) = L_0 \frac{e^{-\frac{d_x^2}{4\sigma_x^2}}}{\sqrt{1+\zeta^2}}, \quad (2)$$

where σ_x, σ_y and σ_s are the rms sizes of the bunch in the horizontal, vertical and longitudinal direction, respectively, and $\zeta = \frac{\phi_y}{2}\frac{\sigma_s}{\sigma_y}$. In operation with many bunches the beams in LHC have to collide with a finite crossing angle to avoid parasitic collisions.

The reduction of the effective luminosity by an offset is obvious. However, care has to be taken to ensure that the off-centered collision has local effects only. When colliding with an offset, the symmetry of the beam-beam force is broken. Therefore a dipolar kick is applied to the other beam. Due to non-linearities in the LHC, the most notable being the beam-beam force, a coherent excitation is expected to cause an emittance growth. Earlier investigations indicated that collisions with an offset might lead to an increase of the emittance [3]. Other side effects might be reduced life time, losses, orbit perturbations and luminosity loss at the other experiments.

In order to recognize or rule out any beam perturbations, an experiment was performed in LHC to investigate collisions with separated beams [4, 5]. The experiment is described in the next section. The section thereafter presents simulations performed to search for beam dynamical effects numerically. A short section is dedicated to another leveling schemes. The report closes with conclusions.

OFFSET COLLISIONS IN LHC

A fill of LHC was dedicated to an experiment to test luminosity leveling with an offset. The first subsection depicts the setup of the experiment. The second subsection presents some results. More information about this experiment can be found in Refs. [4, 5].

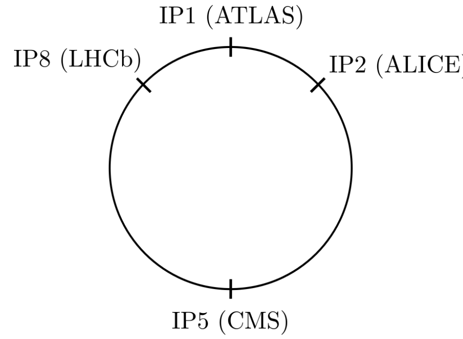

Figure 3: Scheme of the LHC with its 4 interaction points and experiments. For the experiment, the beams were separated at IP8.

Table 1: Beam Parameters in the Experiment. The numbers in the subscripts of σ refer to the corresponding beam. The beam sizes refer to IP8.

Parameter / Unit	Value
Q_x	64.31
Q_y	59.32
N	1.1×10^{11}
σ_{x1} / μm	45
σ_{x2} / μm	35
σ_{y1} / μm	49
σ_{y2} / μm	45
σ_s / cm	7.55
$\delta p/p$	1.1×10^{-4}
ϕ / μrad	120
bunch spacing / ns	75

Setup

During the experiment two proton beams were put into collision all 4 IPs. β^* varied from IP to IP as in regular operation. A sketch of the LHC with its IPs and associated experiments is shown in Fig. 3. The beam parameters mostly correspond to those of a regular fill in LHC. An overview is given in Tab. 1.

After the optimization of the luminosity, the beam separation at IP8 was incremented from 0 to 2.5 σ_x in steps of 0.5 σ_x. Each separation was maintained for 20 minutes. The luminosity in all IPs was monitored as well as the emittance of the beams.

Results

The luminosity at IP8 is shown in Fig. 4. After about 1 hour, the luminosity was optimized before the separation begun. The figure clearly reveals the stepwise increase of the beam separation that followed the optimization. The steady decay of the luminosity is well visible before and

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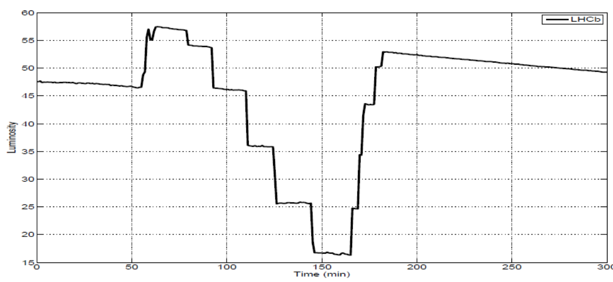

Figure 4: Measured luminosity at IP8 versus time. The steps indicate the change of the beam separation.

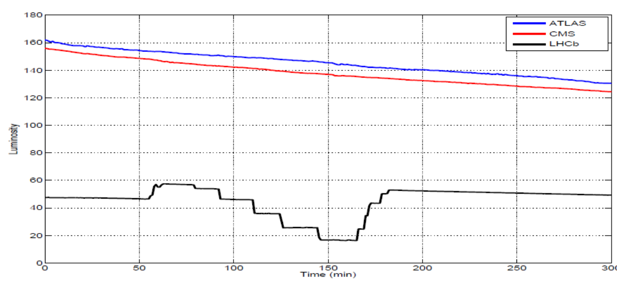

Figure 5: Measured luminosity at IP1, IP5 and IP8 versus time. The beam separation at IP8 affects only the luminosity at IP8.

after that procedure.

Figure 5 shows the luminosity in IP1 and IP5 in addition to IP8. It demonstrates that the luminosity at the other IPs was not affected by the changes of the offset at IP8. The decay of the luminosity is not visibly altered at IP1 and IP5.

Also the emittance proved insensitive to the offset at IP8. In Fig. 6, the horizontal and vertical emittance of beam 1 are shown together with the luminosity at IP8. The emittance growth does not change while the offset is varied. The same observation was made for beam 2 [5].

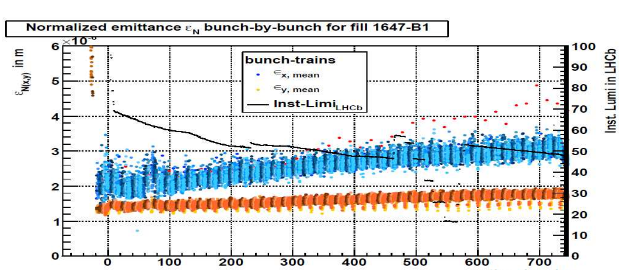

Figure 6: Emittance of beam 1 versus time (horizontal in blue, vertical in orange). Black dots represent the luminosity at IP8. The beams were separated from about 450 minutes to 600 minutes on the plotted time scale. The emittance grows constantly all the time.

SIMULATION OF THE EXPERIMENT

Computer simulations were accomplished to study the beam dynamics under experimental conditions. The code *BeamBeam3D* [6] was employed to simulate beam-beam effects using the strong-strong collision model. First the setup is described, than the results.

Setup

In strong-strong simulations both beam are represented as a set of macro particles which mutually interact, as opposed to weak-strong simulations where only one beam is perturbed by a non-linear lens representing the other beam. The disadvantage of the strong-strong approach is its numerical cost. The advantage is that it is physically more realistic, in particular if both beams are (almost) equal—like in LHC.

In our simulations the beam-beam force was computed either self-consistently or assuming a Gaussian particle density, the width of which was adjusted to the spread of the actual particle distribution. The latter approach is called soft Gaussian method. This method is faster than the self-consistent one (but still slow compared to the weak-strong method). For the simulations shown here, there was no visible difference between self-consistent and soft Gaussian calculations.

The beam parameters were adapted from the experiment (Tab 1). The transfer maps between the IPs were generated using MADX and the beam optics of the LHC. Only first order maps were used. A feedback system similar to the real one in LHC was active to damp coherent betatron oscillations. Long-range beam-beam effects effects were considered negligible in the experiment [5] and were not included in the simulations.

Compared to the real machine, a major simplification had to be made with regard to the collision scheme. For the sake of the computing time, the smallest number of bunches allowing collisions in all IPs was simulated. The symmetry between IP1 and IP5 allows one pair of bunches to collide twice per turn. In IP2 and IP8 collisions are possible only with different bunches. Hence one bunch in beam 1 and 3 bunches in beam 2 were required to achieve 4 collisions per turn (in one of the beams). Figure 7 illustrates this reduced collision scheme.

Like in the experiment, beams with a separation ranging from 0 to 2.5 σ_x, incremented in 0.5 σ_x, were considered. Instead of changing the offset during a single run, several simulations with different static offsets were launched, though. This is a valid approach as long as the beams remain stable and maintain their original parameters. According to the experiment this should be the case in good approximation. Due to the slowness of strong-strong simulations, only 25,000 turns, corresponding to slightly more than 2 s, were simulated.

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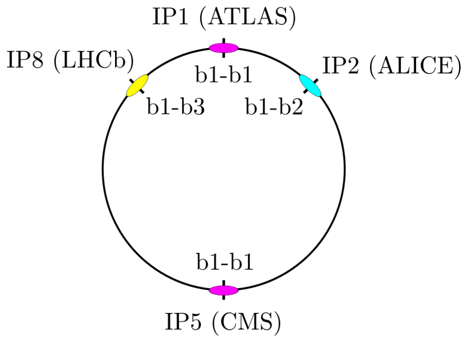

Figure 7: Reduced collision scheme in the simulations. There is only one bunch in beam 1. The pairs colliding in each IP are written b1-bX, where X corresponds to the number of the bunch in beam 2. The colors visualize different pairs.

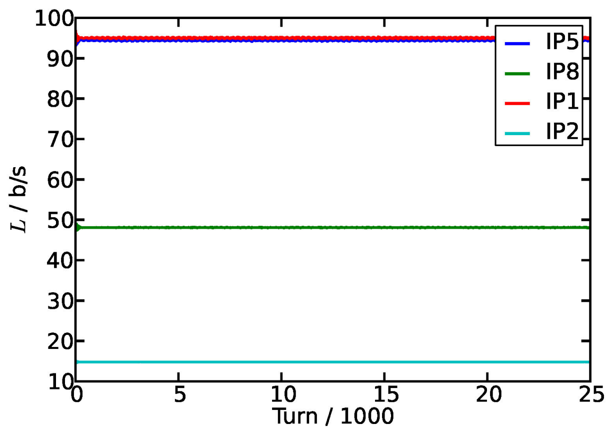

Figure 8: Simulated luminosity versus time without offset. In all IPs the luminosity is stable on the time scale of the simulation.

Results

The luminosities as a function of the time are shown without offset in Fig. 8 and with a $2.5\,\sigma_x$ offset at IP8 in Fig. 9. The luminosity is stable at all IPs in both cases. As expected, the luminosity at IP8 is significantly lower when the beams are separated.

Using Eq. 2 and the parameters given in Table 1, the luminosity can be calculated as function of the offset. The inequality of the horizontal and vertical sizes of the beams is then neglected. The comparison of the relative luminosities, that is normalized to the value without offset, are presented in Fig. 10. The simulated luminosity is in excellent agreement with measurements. The analytical calculation agrees well with measurement and simulation. The very small deviations are attributed to the uncertainty of the measured d and a not perfectly Gaussian particle distribution in the experiment. The analytic calculation represents the case with equal, circular beams, which is an approximation for the actual beams.

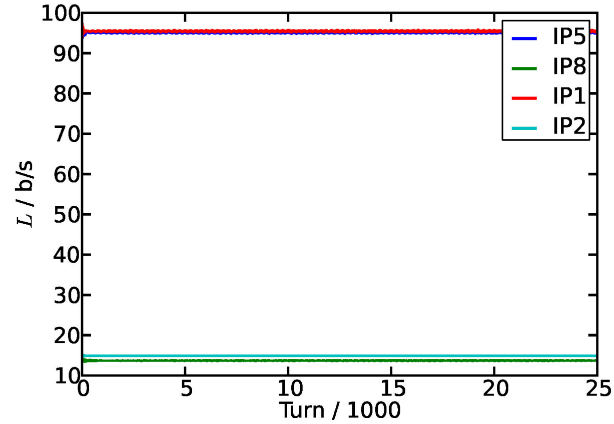

Figure 9: Simulated luminosity versus time with a beam separation of $2.5\,\sigma_x$ at IP8. Compared to Fig. 8 the luminosity at IP8 dropped while all others remained unchanged.

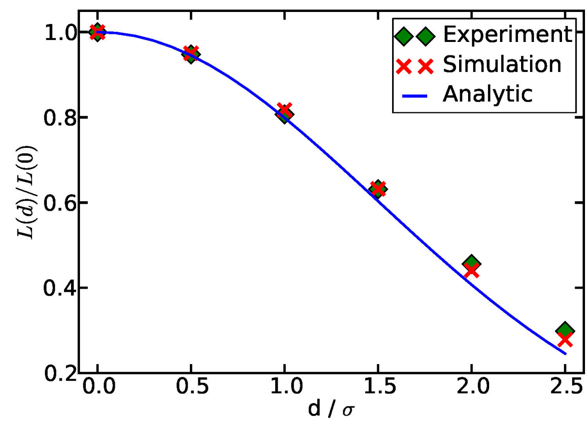

Figure 10: Normalized luminosity as a function of the beam separation. Experiment and simulation agree very well with each other and well with the analytic calculation.

ALTERNATIVE LEVELING METHODS

As mentioned in the introduction, β^* and ϕ could in principal be employed for luminosity leveling, as well. However, in practice, the usability of ϕ is limited because long-range beam-beam effects impose restrictions on ϕ [7]. β^* on the other hand, is considered a good candidate. Leveling experiments with variable β^* in LHC have been started recently.

Another means for leveling may become available in future: crab cavities. With the high-luminosity LHC parameters, the beams have to cross with angles of several $100\,\mu$rad to reduce the impact long-range beam-beam effects. Without counter measures, an intolerable luminosity loss would arise from these angles. Crab cavities are meant to avoid the geometric luminosity loss due to the crossing angle. Therefore crab cavities are an important element of

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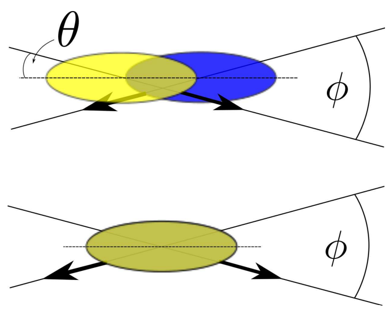

Figure 11: Scheme of two bunches that collide without geometric luminosity loss because they have been tilted by θ by virtue of a crab cavity.

the high-luminosity LHC [8].

Crab cavities tilt the colliding bunches to align their z-axes despite their non-parallel motion. The principle of a collision with crabbed bunches is depicted in Fig. 11. With crab cavities, the tilting angle θ can be varied from 0 to $\phi/2$ to level luminosity. However, crab cavities will not be available for tests in LHC shortly. In near future, only numerical simulation can be employed to study this method.

CONCLUSION

The concept of luminosity leveling by virtue of a separation of the beams at the collision point has been investigated in an experiment and simulations. Increasing the beam separation, the luminosity at one IP could be reduced in a well controlled manner. Neither the emittance nor the luminosity at the other IPs experienced side effects.

Strong-strong simulations of the experimental conditions delivered results in very good agreement with the experiment. The good agreement with the analytic calculation indicates a high predictability of the luminosity as a function of the beam separation. Hence, the principle of leveling via beam separation has been tested successfully.

Investigations of more complicated cases, e. g. offsets in many IPs and including long-range effects, have to be done to prove the feasibility of this method in practice. Other candidates for luminosity leveling, like β^* or crab cavities, are of interest as well, but have yet to be studied.

REFERENCES

[1] O. Brüning, F. Zimmermann, “Parameter space for the LHC luminosity upgrade”, MOPOPC005, IPAC2012

[2] W. Herr, “Concept of luminosity”, CERN Accelerator School 2003, CERN-2006-002, 2006

[3] T. Pieloni, W. Herr, J. Qiang, “Emittance growth due to beam-beam effects with a static offset in collision inthe LHC”, WE6PFP039, PAC 2009

[4] G. Papotti, R. Alemany, F. Follin, R. Giachino, W. Herr, T. Pieloni, M. Schaumann, R. Calaga, R. Miyamoto, “Experience with offset collisions in the LHC”, TUPZ025, IPAC 2011

[5] R. Alemany-Fernandez, R. Calaga, R. Giachino, W. Herr, D. Jacquet, R. Miyamoto, G. Papotti, T. Pieloni, L. Ponce, M. Schaumann, “Test of luminosity levelling with separated collisions”, CERN-ATS-Note-2011-028 MD, CERN, 2011

[6] J. Qiang, M. A. Furman, R. D. Ryne, “A parallel particle-in-cell model for beam-beam interaction in high energy ring colliders”, J. Comp. Phys., vol. 198, 2004

[7] W. Herr, R. Alemany, R. Giachino, G. Papotti, T. Pieloni, R. Calaga, E. Laface, M. Schaumann, “Observations of beam-beam effects at high intensities in the LHC”, WEODA01, IPAC 2011

[8] R. Calaga, R. Tomás, F. Zimmermann, “LHC crab-cavity aspects and strategy”, TUOAMH02, IPAC’10

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