LUMINOSITY OPTIMISATION AND OPERATION SCHEMES DURING LHC RUN 2

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Abstract

This contribution summarizes the significant evolution of the LHC and its injector complex during its second Run, dating from 2015 to 2018. We present the diverse set of different beam production schemes and machine configurations used throughout the Run to optimize the luminosity production. Eventually, these improvements allowed to surpass the LHC design instantaneous luminosity by a factor of two, setting a luminosity world record at $2.2 \cdot 10^{34}\,\mathrm{cm^{-2}s^{-1}}$ in 2017.

In a second part, we present the improvements to the LHC luminosity control system during Run 2. Replacing the existing LHC luminosity control application was by a new client-server system allowed for novel luminosity levelling mechanisms (by crossing angle and β^*), and provided fully automatic luminosity scans, e.g. for calibrating the luminosity monitors using the Van der Meer method.

OVERVIEW OF LHC RUN 2

In figures 1 and 2, the peak instantaneous and integrated luminosities in LHC Run 1 and 2 are shown. Apart from 2015, which was dedicated to recommissioning the LHC after Long Shutdown 1, the luminosity yield in Run 2 (2015-2018) greatly exceeded the one of Run 1, eventually surpassing the LHC design peak luminosity of $10^{34}\,\mathrm{cm^{-2}s^{-1}}$ [1] in 2016, and setting a new luminosity world record of $2.2 \cdot 10^{34}\,\mathrm{cm^{-2}s^{-1}}$ in 2017.

This improvement can be attributed to three main contributions. First, the flat-top energy was increased from 4 TeV per beam to 6.5 TeV per beam ($\sqrt{s}$ = 8 TeV and $\sqrt{s}$ = 13 TeV at the center of mass, respectively). This, apart from enabling new physics cases, decreased the beam size due to adiabatic damping. Second, the bunch spacing was halved from 50 ns to 25 ns, allowing to circulate almost twice the number of bunches per ring. Third, starting from 2016, the machine configuration (β^*, crossing angle) was gradually tightened, in particular by the introduction of the Achromatic Telescopic Squeeze (ATS, [2]) which allowed for β^* in IP 1 and 5 beyond the LHC design value.

Improvements in the injector chain, most notably the introduction of the Batch Compression Merging and Splitting (BCMS) beam production scheme [3], allowed increasing the beam brightness by decreasing the injected beam emittance from $\sim$3 μm to $\sim$1.7 μm. The beam intensity was however limited to $\sim 1.15 \cdot 10^{11}$ ppb throughout the Run due to the heating of the injection kicker (MKI) in 2016 [4], and the contamination of cell 16L2 as of 2017 [5].

The different machine configurations and beam types used in Run 2 are compiled in table 1; the history of their usage is shown in figure 3. In the second half of 2017, "8b4e" (4 empty bunch slots every 8 bunches) type beams were used to minimize the electron cloud build-up, mitigating the impact of the contamination of cell 16L2 [5]. After a thermal cycle during the year end technical stop 2017-2018 which partially cleaned the contamination in cell 16L2, using "BCMS" type beams was possible again in 2018.

It is worth noting that the "8b4e-BCS" configuration of 2017 and the "BCMS" configuration of 2018 yield a similar peak luminosity. However, due to the lower number of bunches in the "8b4e-BCS" scheme, the pile-up exceeded the acceptable range of the ATLAS and CMS experiments, requiring luminosity levelling at $1.5 \cdot 10^{34}\,\mathrm{cm^{-2}s^{-1}}$.

Starting from 2017, new luminosity levelling techniques allowed reducing the crossing angle and β^* in IP 1 and 5 during collisions, allowing to exploit the margins resulting from the beam intensity decay over the course of a fill.

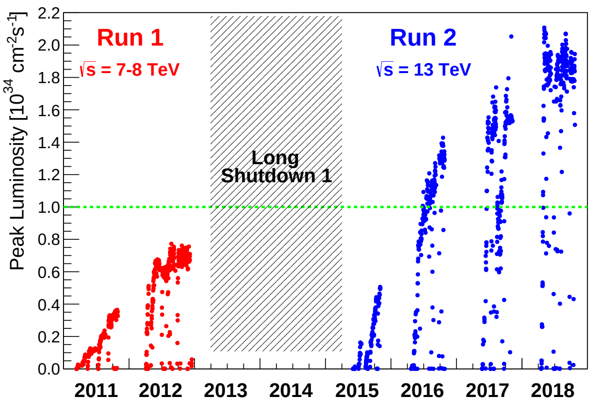

Figure 1: The LHC peak luminosity evolution over Runs 1 and 2. The green line denotes the LHC design luminosity.

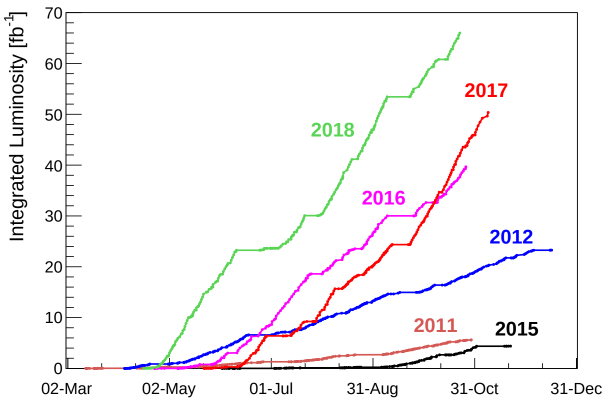

Figure 2: The LHC integrated luminosity production per year of operation.

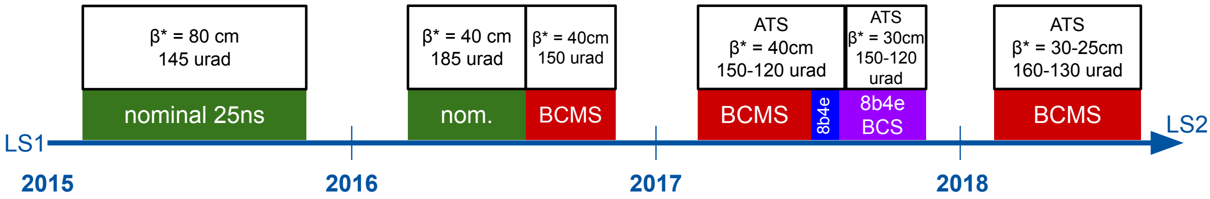

Figure 3: Timeline of LHC Run 2 with the proton beam types and machine configurations (crossing angles and β^* in IP 1 and 5). For 2017 and 2018, when crossing angle and β^* were reduced during collisions, the range of the respective parameter is given.

Table 1: Proton beam types and typical beam parameters used in LHC Run 2 [6, 7].

	nominal 25ns	**BCMS 25ns**	**nominal 8b4e**	**8b4e-BCS**
PS Bunch Splitting	$6 \to 18 \to 72$	$8 \to 4 \to 12 \to 48$	$7 \to 14 \to 56$	$8 \to 32$
Max. Bunches in LHC	2880	2556	1916	1868
Injected Emittance	$\sim 3\ \mu m$	$\sim 1.7\ \mu m$	$\sim 1.9\ \mu m$	$\sim 1.2\ \mu m$
Emittance in Collisions	$\sim 3.5\ \mu m$	$\sim 2\ \mu m$	$\sim 2.3\ \mu m$	$\sim 1.8\ \mu m$
Max. Bunch Intensity	$\sim 1.15 \cdot 10^{11}$ ppb *(limited by external conditions in the LHC)*			

LUMINOSITY LEVELLING

Separation Levelling

Levelling by separation uses local 4-corrector closed orbit bumps to introduce a beam separation around the IPs [8]. The separation is introduced perpendicular to the crossing angle. To minimize the displacement of the beams with respect to the physical aperture, the separation is applied to both beams symmetrically with opposite sign. Due to the local and relatively small orbit bumps involved, separation levelling is the simplest approach to control the instantaneous luminosity in all 4 IPs individually.

To level the luminosity by separation, the LHC Luminosity Server implements a feedback loop on the measured luminosity of the experiment concerned [9]. The target luminosity and the control loop parameters (step size, integration time) can either be given by the experiment over the LHC-Experiment Data Interchange Protocol (DIP), or by the LHC operators in the control room.

Levelling by separation has been used since LHC Run 1 for the low-luminosity experiments ALICE (IP 2) and LHCb (IP 8). When the pile-up in IP 1 and 5 exceeded the maximum acceptable values during the second half of 2017 with "8b4e-BCS" type beams, the concept was generalized to allow levelling all LHC IPs. In the following, the instantaneous luminosity in IP 1 and 5 was levelled to $1.5 \cdot 10^{34}\ \mathrm{cm^{-2}s^{-1}}$ in the first hours of each fill (figure 4).

To study the impact of the levelling on the integrated luminosity in IP 1 and 5, a test fill was done where the beams were left head-on. The luminosity of this test fill is compared to a levelled fill with the same peak luminosity in figure 7.5. As expected, the instantaneous luminosity after the end of the levelling is slightly higher in the levelled fill. In terms of integrated luminosity, ~4 % are lost to the levelling for fills with a typical length of 12-14h (figure 5).

With the return to "BCMS" type beams in 2018 after the partial cleaning of the contamination in cell 16L2, separation levelling was no longer needed in IP 1 and 5.

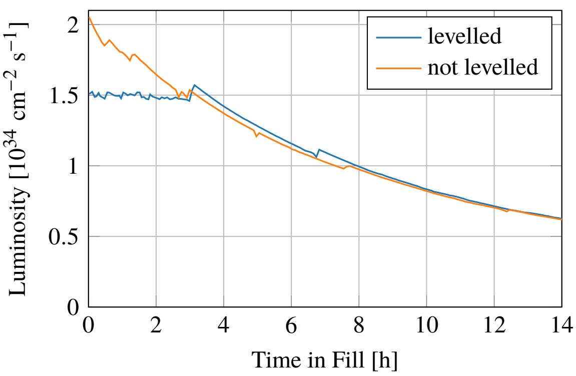

Figure 4: Instantaneous luminosity recorded by the ATLAS experiment in fills 6358 (non-levelled) and 6360 (levelled).

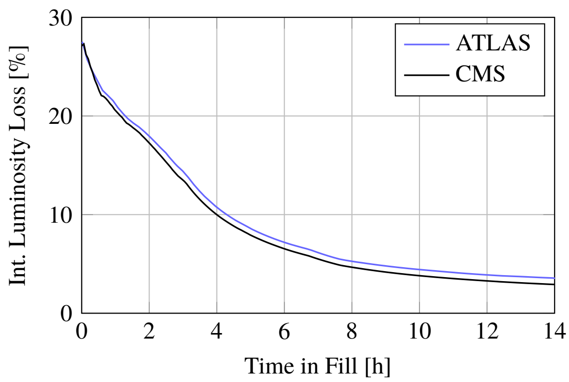

Figure 5: Loss in integrated luminosity due to luminosity levelling, derived from fills 6358 and 6360.

Crossing Angle "Anti"-Levelling

Since the two LHC beams share a common vacuum chamber around the IPs and the bunch spacing is shorter than this common chamber, a crossing angle is needed to avoid parasitic collisions. The minimum value of this crossing angle is given by the detrimental effect of the long-range beam-beam encounters in the common regions on the Dynamic Aperture (DA) [10]. Since the crossing angle decreases the luminosity through the geometric factor [8] and it limits the β^* reach through the physical aperture limit of the focusing triplets, the crossing angle should be kept as small as possible.

As the beam-beam long-range effects weaken with the decreasing beam intensity over the course of the fill, the crossing angle can be reduced. This increases the instantaneous luminosity and possibly allows for a later reduction of β^*. Since this type of "levelling" is based on machine limits rather than on experiment's requests, and since it effectively increases the maximum instantaneous luminosity, it is also referred to as "anti-levelling".

Unlike levelling by separation, changing the crossing angle implies a significant orbit change. Therefore, it cannot be treated as a small perturbation by the orbit feedback system (OFB) and tertiary collimators (TCTs) anymore. Instead, the steering magnets, the reference for the OFB and the positions of TCTs need to move in a synchronized, self-consistent manner. This "orchestration" was first introduced in the LHC control system in 2017.

Over the course of 2017 operation, the half crossing angle at IP 1 and 5 was then reduced in steps of 10 μrad from 150 μrad to 120 μrad over the course of each fill. The steps were done manually, roughly following a DA target of 5σ, gaining ~3% of integrated luminosity [10].

The concept was improved for 2018 operation to allow a quasi-continuous reduction of the half crossing angle in steps of 1 μrad from 160 μrad to 130 μrad, while automatically following a pre-programmed iso-DA reference contour. A screenshot of the control room application at the end of a typical fill is shown in figure 6. This technique mitigated a part of the losses observed during the crossing angle reduction steps in 2017, and increased the integrated luminosity by ~5%.

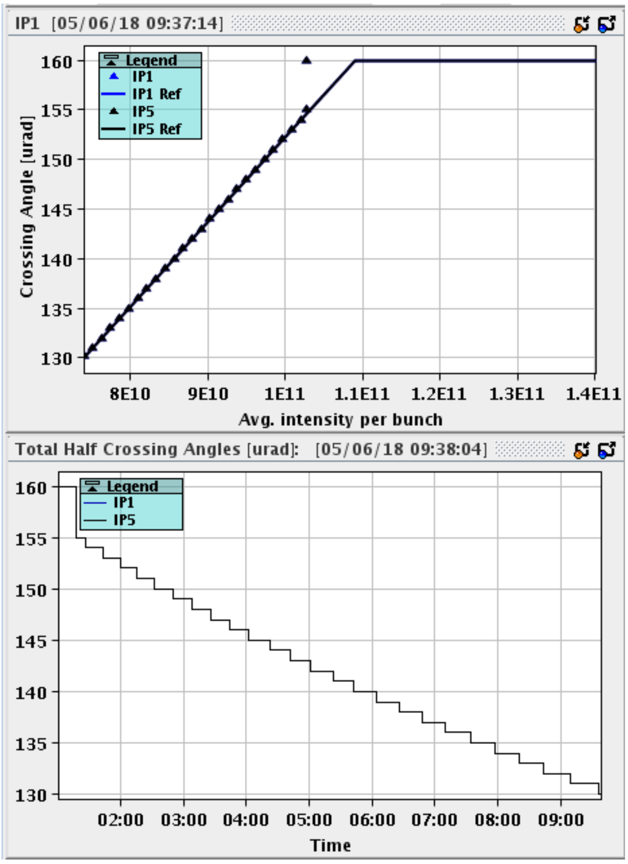

Figure 6: Screenshot of the control room application for quasi-continuous crossing angle anti-levelling. The top panel shows the pre-programmed iso-DA contour which is being followed. The bottom panel shows the half crossing angle in IP 1 and 5.

β^* Levelling

The most advanced technique of controlling the luminosity is through the focusing at the IPs, β^*, effectively changing the beam size. Unlike a separation or the crossing angle, this implies a change of the machine optics which is in general a non-local process, and therefore operationally most challenging. Compared to levelling by separation, β^* levelling has the advantage of providing the full stabilizing effect of the head-on beam-beam tune spread independently of the luminosity. Furthermore, offset collisions which lead to a coherent beam-beam kick and could drive resonances are avoided.

When changing the optics for β^* levelling, closed orbit bumps in the affected machine regions (e.g. crossing angles) change their shape. Also, additional orbit perturbations might be introduced due to misalignments. The reference for the OFB must hence be updated to follow the expected change of orbit, and the feedback loop must be operated with more aggressive settings suitable to correct the unwanted perturbations over the course of the change. Also, the TCTs around the IPs may need to follow both the change of orbit (displacing their center), as well as the change of beam size (changing the opening of the jaws), if either of these effects is significant.

After proving the physical feasibility of β^* levelling in Machine Development (MD) sessions [11], the necessary changes to use it in operation were implemented over the course of 2017 in the LHC Luminosity Server. The technique extends the "orchestration" approach used for crossing angle transitions in collisions, adding support to coherently change TCT gaps and the reference for the Power Converter Interlock (PcInterlock) system along with the optics transition and running the OFB in high-gain mode in addition to orchestrating power converters, the OFB reference, and TCT positions. The settings for the optics change source from a reference squeeze beam-process; the new mechanics allow

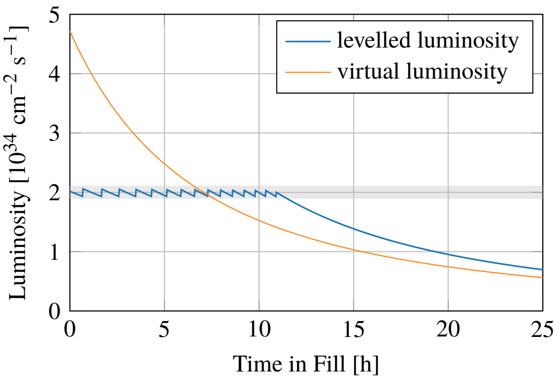

Figure 7: A possible β^* levelling scenario for LHC Run 3. Starting from $\beta^* = 1$ m in IP 1 and 5, the beams are squeezed to $\beta^* = 30$ cm while keeping the luminosity within 5 % around $2 \cdot 10^{34}$ cm^{-2}s^{-1} (grey band).

driving the LHC to any matched optics point within a given reference, both squeezing and un-squeezing the beams [12].

Using this novel mechanics, β^* levelling was introduced operationally at the LHC in 2018 in "anti-levelling" mode: 8-10h into a fill, after the crossing angle anti-levelling had finished at 130 μrad, the β^* was reduced in two steps from 30 cm to 27 cm and finally to 25 cm in IP 1 and 5. Each step increased the instantaneous luminosity by ~7%. The gain in integrated luminosity was at the level of ~2% in addition to the gain from the crossing angle anti-levelling. More importantly, the long-term feasibility of β^* levelling in day-to-day operation was proven. In further MD sessions, the use of β^* levelling starting from $\beta^* = 1$ m was demonstrated, effectively replacing the regular LHC squeeze.

For LHC Run 3, due to the increase of beam brightness following the LHC Injector Upgrade (LIU, [13]), controlling the luminosity in IP 1 and 5 through β^* levelling is considered a baseline scenario [14]. During the levelling process, the crossing angle should be kept as small as possible to reduce the radiation to the focusing triplets. Assuming an emittance of 2.5 μm and a bunch intensity of $1.8 \cdot 10^{11}$ ppb, a β^* levelling sequence in 14 steps between $\beta^* = 1$ m and $\beta^* = 30$ cm in IP 1 and 5 could level the luminosity in the desired band around $2 \cdot 10^{34}$ cm^{-2}s^{-1} $\pm$ 5 % as shown in figure 7.

Combined Levelling Schemes

To provide maximum flexibility in luminosity levelling, the various levelling techniques can be combined. For example, in 2017 and 2018 operation, crossing angle and β^* anti-levelling were used in IP 1 and 5, while IP 2 and 8 were levelled by separation in parallel. For Run 3, it is foreseen to change the crossing angle along with the β^* levelling steps in IP 1 and 5 (while still levelling IP 2 and 8 by separation).

It can be considered to combine levelling by β^* and separation in IP 1 and 5 to allow for different targets for the two IPs, and to regulate the luminosity within tighter tolerance bands. In such a scenario, the β^* levelling mechanics would be used to reach a luminosity slightly higher than the request by the experiments; then, a separation (local to each IP) would be introduced to reach the exact target. While physically feasible, such a scheme is not currently foreseen for LHC Run 3, as the $\pm$5 % tolerance band achievable by pure β^* levelling is considered acceptable by the experiments.

LUMINOSITY SCAN IMPROVEMENTS

Van-der-Meer Scans

Van-der-Meer (VdM) scans [15] have been used in LHC for absolute calibration of the luminosity measurements of the experiments since Run 1 [16]. At the end of 2015, the scan protocol between the LHC and the experiments was extended to allow scanning arbitrary beam position patterns in a fully automated manner. The sequence of beam displacements during a particular scan is provided by the experiment in question in a text file using a Domain Specific Language (DSL) [17]. While running the scan, the LHC Luminosity Server publishes the scan progress and actual beam separation to the experiments via DIP. This automation significantly simplified the luminosity calibration scan sessions in 2016 and 2017, in particular for the experiment specific length-scale calibration scan sequences (an example is given in figure 8). It saved ~20% of beam time per calibration session [18] with respect to the manual procedure applied in Run 1, and eliminated the risk of operational mistakes.

For Run 3, the system will be further improved to manage the scan sequence files under Git version control in CERN GitLab [19]. Furthermore, a web application has been developed to allow the VdM scan coordinators of the experiments to view, edit and upload the scan sequence files [20].

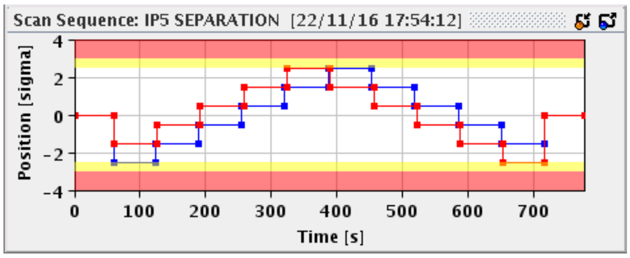

Figure 8: A typical VdM Length Scale Calibration scan sequence for the CMS experiment (IP5).

Emittance Scans

A new type of fast luminosity separation scans, called Emittance Scans, was introduced in LHC Run 2 [21]. The scans were performed systematically at the start and at the end of almost every proton physics fill in IP 5, and, at a lower frequency, in IP 1. Unlike full Van-der-Meer calibration scans, which typically take ~45 minutes per scan pair for the two transverse planes, a pair emittance scans can be carried out in ~5 minutes. This is achieved by reducing the number of scan points (typically 7 or 9 per plane) and the integration time per point. While not providing a precision measurement like VdM calibration scans, emittance scans provide a handle both on transverse emittance and the closed orbit separations at the interaction points at a bunch-by-bunch level. The scans were run in an automated manner (upon start by the operators) by the Luminosity Server.

The emittance measurements derived from these scans were used as a fully independent benchmark of the measurements obtained from beam instrumentation, most notably, the LHC Beam Synchrotron Radiation Telescope (BSRT, [22]). In multiple occasions throughout the Run, this allowed to spot the deterioration of the BSRT measurements and clearly attribute it to an instrumental cause, e.g. due to damage to the BSRT intensifier [23].

The measured beam-beam closed orbit separations allowed a direct, quantitative observation of long-range beam-beam PACMAN effects [24]. They were compared to, and agreed to agree well with, numerical simulations from an improved version of the TRAIN code [21, 25].

Also, these scans were used by the experiments to derive a calibration estimate for their luminosity monitors in each fill. This allowed to track the long-term stability of the individual sub-detectors [26, 27]. This approach will be further pursued in Run 3.

CONCLUSIONS

Over the course of LHC Run 2, the machine configurations and beam parameters were gradually pushed to best exploit the luminosity production potential. A new beam production scheme, BCMS, was introduced in the injector complex to provide beams of higher brightness to the LHC. This allowed to reach peak instantaneous luminosities of more than $2 \cdot 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ in 2017 and 2018 operation. The contamination of cell 16L2 in 2017 made it necessary to temporarily use different, electron cloud suppressing "8b4e" beam types (along with other complementary measures) for mitigation.

The LHC luminosity control application was replaced by a new client-server based system. This new system allowed to introduce novel luminosity levelling methods by smoothly changing the crossing angle and β^* in collisions. In Run 2, these functionalities were used to improve the integrated luminosity yield by reducing the crossing angle and β^* in IP 1 and 5 as the intensity decayed over the course of a fill, gaining $\sim$5 % in integrated luminosity. For Run 3, controlling the luminosity in IP 1 and 5 through β^* levelling is considered a baseline scenario.

Furthermore, with the new luminosity control system a new protocol for performing luminosity calibration scans was introduced. This allows the LHC experiments to program arbitrary scanning patterns in a Domain Specific Language, which can be played by the LHC luminosity control system in a fully automated manner. During these scans, the LHC control system communicates to the experiments the actual beam separations and the status of the scan. With respect to the manual execution of scan sequences by the operators, this new system significantly improved the efficiency of the luminosity calibration sessions.

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