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LHC OPERATIONAL EXPERIENCE OF THE 6.5 TEV PROTON RUN WITH ATS OPTICS

M. Pojer†, M. Albert, R. Alemany-Fernandez, T. Argyropoulos, E. Bravin, A. Calia, G. Crockford, S. D. Fartoukh, K. Fuchsberger, R. Giachino, M. Giovannozzi, G.-H. Hemelsoet, W. Höfle, M. Hostettler, Y. Le Borgne, D. Nisbet, L. Ponce, S. Redaelli, B. Salvachua, M. Solfaroli, R. Suykerbuyk, D. J. Walsh, J. Wenninger, M. Zerlauth, CERN, Geneva, Switzerland

Abstract

In May 2017, the CERN Large Hadron Collider (LHC) restarted operations at 6.5 TeV using the Achromatic Telescopic Squeeze (ATS) scheme with a target beta-star of 40 cm in ATLAS and CMS. The number of bunches was progressively increased to a maximum of 2556 with emittances of 2.5 µm. In August, several machine parameters had to be re-tuned to mitigate beam loss induced instabilities and maintain a steady increase of the instantaneous luminosity. The use of a novel beam type and filling pattern produced in the injectors, allowed filling the machine with very low emittance beam (1.5 µm) achieving an equivalent luminosity with 1868 bunches. In September, the beta-star was further lowered to 30 cm (using, for the first time, the telescopic technique of the ATS) and the bunch intensity pushed to 1.25×10^{11} protons. In the last 3 months of 2017, the LHC produced more than 500 pb^{-1} of integrated luminosity per day, delivering to each of the high luminosity experiments 50.6 fb^{-1}, 10% above the 2017 target. A general overview of the operational aspects of the 2017 proton run will be presented.

PHYSICS RESTART IN 2017

2017 has been, so far, the most remarkable year for the LHC in terms of integrated luminosity production and peak luminosity achieved. The objectives fixed before the restart were reached and even exceeded; the investigations on new optics and levelling methods to be used in the High Luminosity (HL) LHC era [1] were successful. All this was achieved despite a technical issue discovered during the year, which limited the performance reach.

The 2016-2017 year-end technical stop (YETS) was extended by one month to allow for the replacement of a cryo-dipole in one of the octants of the machine, following the identification of a possible inter-turn short. An entire 3 km-long sector had to be warmed to room temperature and cooled-down again. The re-commissioning of the almost 1600 superconducting circuits was then performed, with a particularly long list of tests performed in the sector which underwent the thermal cycle. The machine check-out completion at the end of the month of April signed the restart of beam operation at the LHC.

The following three weeks were marked by a thorough commissioning of the operational cycle, with multiple iterations on orbit, tune, chromaticity and coupling, the validation of all beam instrumentations and operational tools, the collimator alignment and the validation of their hierarchical protection, the optics measurements and corrections, the aperture measurement, the setup of collisions and all the necessary machine protection qualifications. Soon afterwards, the first collisions and a partial intensity ramp-up (progressive increase of the number of bunches injected and collided) were performed. The detailed breakdown of the whole operation period is shown in Table 1 and also on Figure 1.

Table 1: Duration of Different Operational Phases in 2017

Phase	Days
Commissioning and Intensity ramp-up	35
Scrubbing	7
25ns Proton Physics	**127**
Special Physics Runs	18
Machine Development (MD)	18
Technical Stops (TS1+TS2)	8
TS Recovery	4
Total	217

After a successful week dedicated to *beam scrubbing* [2], aimed at reducing the impact of e-cloud, the number of bunches could be progressively increased to 2556 per beam, also thanks to the tuning of all machine parameters and stabilization knobs, i.e. high chromaticity and octupole current, optimization of the tune working point, longitudinal blow-up, transverse damper, etc. A peak luminosity of 1.5×10^{34} $cm^{-2}s^{-1}$ was routinely obtained in this phase.

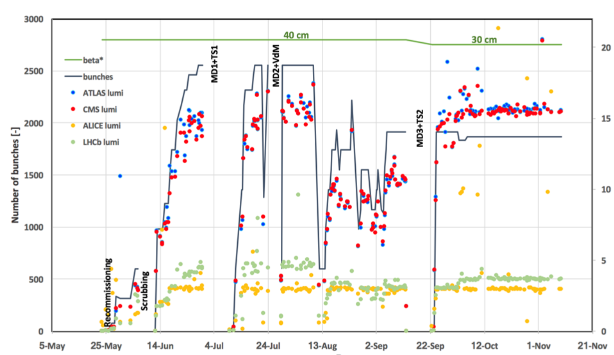

Figure 1: Different operation periods in 2017, with number of bunches and luminosities reached.

Managing the Unforeseen

During the quick ramp-up and the first period of physics, multiple events were observed, which lead to beam

† Mirko.pojer@cern.ch

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dumps on fast losses in the betatronic cleaning region (IR7), with a typical rise-time of 10-20 ms and an instability signature matching UFO-like [3] events. Losses were systematically observed in cell 16L2, correlated to the IR7 losses. Several attempts were made to try and identify the origin of these losses (discussed in details in [4]), and after lengthy and detailed investigations, it was concluded that the 16L2 issue was likely due to air trapped in the beam screen, which produced a flow of gas under the effect of e-cloud.

To mitigate the instabilities, a new filling scheme was then tested, the so-called 8b4e, already used during the scrubbing runs. Its production is illustrated in Figure 2. This is a variant of the standard 25 ns beams and is composed of 8 nominal, 25ns-spaced bunches followed by 4 empty slots [5]: this scheme has a much lower e-cloud stimulation (the e-cloud production is largely suppressed due to the gaps in the 25ns bunch trains), and was effective in reducing the losses in 16L2. In addition, a solenoid with a static field in the order of a few mT was installed around the location to partially mitigate the e-cloud build-up; this decreased steady state losses by 60-70 %.

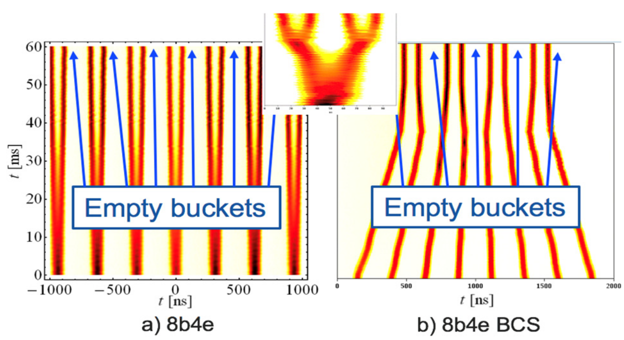

Figure 2: Beam production in the injectors: PS filled buckets alternated by empty ones, are split in 8 for the normal 8b4e; 4 double bunches separated by empty buckets are compressed before splitting in 4 for the BCS.

With these mitigation measures, stable physics with 1916 bunches of up to 1.25×10^{11} p/b could be achieved.

PERFORMANCE REACH

A valuable resource for the LHC, which helped in overcoming the difficulties, was the flexibility of its injector chain, with the possibility of producing and transferring beams of different types across the whole accelerator complex. In addition, shortly after the 8b4e, another beam was put in operation, which was a variant of this one, i.e. the so-called 8b4e Bunch Compression and Splitting (BCS), shown in Figure 2, capable of providing higher brightness beams with the same e-cloud suppression capability. The lower emittance of this beam is shown in Figure 3 and compared (in the different moments of the operational cycle) with the other beams used in 2017 [6].

Thanks to this new beam and to the excellent optics and collimation performance that allowed a β* of 30 cm, machine performance was additionally pushed, reaching a maximum instantaneous luminosity of 2.2×10^{34} cm^{-2}s^{-1} (2.05×10^{34} cm^{-2}s^{-1} in Stable Beams) in ATLAS and CMS. The performance reached and the parameters used with the different beams are listed in Table 2. The large pile-up value made this luminosity not fully exploitable by the experiments and it had to be levelled down to 1.5×10^{34} cm^{-2}s^{-1}, applying a levelling by separation, as the one used since years for ALICE and LHCb.

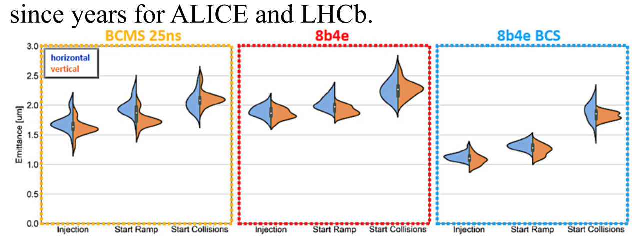

Figure 3: Emittance for the three beam types in different cycle phases: injection, ramp start and collision start.

The last physics period (see Figure 1) was characterized by operation at this levelled luminosity and allowed integrating more than what was targeted at the beginning of 2017: 50.6 fb^{-1} (vs 45 fb^{-1} initially foreseen) were cumulated in ATLAS/CMS (1.76 fb^{-1} in LHCb and 16.6 pb^{-1} in ALICE), with 0.77 fb^{-1} produced in a single record fill and about 0.5 fb^{-1}/day on average after Technical Stop (TS) 2. This was also due to a very good machine availability, which resulted (despite the 16L2 problem) in an average value of 49% of time in Stable Beams along the year [7].

Table 2: Parameters for the Three Beams Used in Physics

	Nominal	8b4e	8b4e BCS
No. injected bunches	2556	1916	1868
Proton/bunch [10^{11}]	1.35	1.2	1.25
Emittance in SB [μm]	2.1	2.3	1.8
β* [cm]	40	40/30	30
Half crossing angle [μrad]	150	150	150/110[1]
Peak lumi [10^{34}cm^{-2}s^{-1}]	1.74	1.90	2.06/1.5[2]
Peak pile-up	n.a.	n.a.	80/~60[2]

[1] Minimum crossing angle during anti-levelling
[2] Value after luminosity-levelling by separation

ATS OPTICS AND MACHINE SETUP

In a process of optimization of the time to go to physics, in the last two years a new ramp, combining ramp to high energy and squeeze, has been developed, the so called Combined Ramp & Squeeze (CRS) [8]: 1m β* is reached at flat top in ATLAS and CMS, 3 m in LHCb (final value for physics), while in ALICE the injection value of 10 m is left unchanged; following this first reduction, a further squeeze is done in ATLAS and CMS. This additional squeeze step was initially set to 40 cm as in 2016, upon confirming the available space in dynamic aperture and setting the collimators to the configuration shown in Table 3. An additional step to 30 cm was done in 2017 after TS2, which increased the integrated luminosity by about 8%.

The most important innovation in 2017 was however the use of a new optics, the Achromatic Telescopic Squeeze (ATS), after its successful validation in several machine development studies in 2016. ATS optics is the

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baseline for HL-LHC and it was important to set it in operation already during Run 2, as a proof of principle and to gain operational experience with it.

Table 3: Collimator Settings, in σ, at Injection and Physics for 30 cm β*

Collimator family	Inj. set.	Phy. set.
Primary, secondary and absorbers in IP7	5.7/6.7/10	5/6.5/10
Primary in IP3	8/9.3/12	15/18/20
Tertiary (IR1, 2, 5, 8)	13	8.5/37/8.5/15

The ATS consists in dedicated optics manipulation which allows to build up collision optics with extremely small beta* without hitting any practical matching limits (i.e. with quadrupoles running out of strength with too high or too low current requested otherwise), which represents its main motivations, while controlling in addition the chromatic aberrations induced (off-momentum β beating, non-linear chromaticities, spurious dispersion deriving from the large crossing angle which is required at small β*) [9,10]. It is divided in two parts: a so-called pre-squeeze segment, which acts on the matching quadrupoles of the interaction regions (IRs) in a traditional way and which relies on additional phase matching conditions to be met on several sections of the ring; a telescopic squeeze, which acts in a more global way, making use of the insertion arcs located at either side of the IR, creating β-beating waves in the arcs which are directly adjacent to the low-β insertions, with their maximum at the sextupoles of a same electrical circuit. Consequently, the chromatic correction effectiveness of these sextupoles will increase at constant magnetic strength, which offers a cure for the chromatic aberrations.

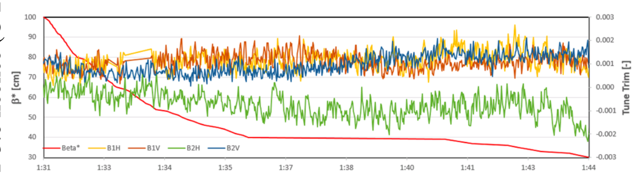

Figure 4: Tune trims during the β* reduction in squeeze.

In the first period of operation in 2017, only the pre-squeeze was used to push β* down to 40 cm; the following step to 30 cm was instead relying on the new telescopic squeeze. As a confirmation of the stability and reproducibility of the optics corrections done during the ATS squeeze, in Figure 4 the tune corrections applied all along the squeeze are shown for a specific fill and the min, max and average values for 50 fills are listed in Table 4.

Table 4: Tune Trims for the 2 Beams/Planes During Squeeze

	Min	Max	Avg	St_dev
Qtrim-B1H [10^{-3}]	-2.2	3.4	1.1	0.5
Qtrim-B1V [10^{-3}]	-0.3	2.9	1.0	0.6
Qtrim-B2H [10^{-3}]	-3.5	2.4	-0.8	0.6
Qtrim-B2V [10^{-3}]	-0.8	3.3	1.2	0.5

The trims appear to be very small, in the order of a few 10^{-3}, and, above all, their reproducibility is very good.

Crossing Angle Levelling

Another relevant implementation in 2017 was the setting up of the crossing angle (anti-)levelling, with functions sent synchronously to the power converters, orbit feedback and tertiary collimators [11]. Qualified in MD in 2016, this levelling process allows reducing the crossing angle progressively while the beam intensity decays (allowing closer long-range beam-beam separation); the gain in dynamic aperture allows to reduce the crossing angle without losing beam stability (keeping the beam lifetime under control).

Starting from a half crossing angle of 150 µrad, the angle was reduced in steps of 10 µrad down to a minimum value of 90 µrad, at the beginning of the year, and to 120 µrad for most of the fills at β* = 30 cm. An average gain of integrated luminosity in the order of 3-4% per fill could be obtained thanks to this optimization.

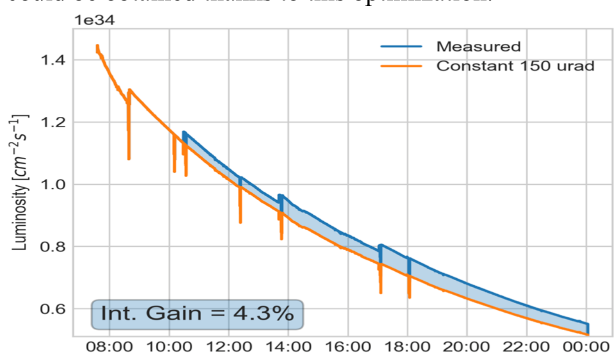

Figure 5: Example of crossing angle anti-levelling during physics.

Other important improvements were also introduced, among them the full detuning of the superconducting RF (which allows reducing the klystron forward power thus allowing for larger bunch intensity) and a new beam coupling measurement approach using the transverse damper to excite a selected bunch (measurements all along cycle, with high octupoles current) [12].

CONCLUSION

All main initial goals of 2017 were achieved. First of all, the increase in performance, by using BCS beams (lower transverse emittance) and applying the ATS optics (starting with β* 40 cm at IPs 1&5, further reduced later in the run), marking an important milestone towards the HL-LHC era (also with the RF full detuning). This, combined with a very good machine availability, allowed maximizing the integrated luminosity.

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