ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-MOPMF051

LHC OPERATIONAL SCENARIOS DURING 2017 RUN

B. Salvachua, M. Albert, R. Alemany-Fernandez, T. Argyropoulos, E. Bravin, H. Burkhardt, G. Crockford, J.C. Dumont, S. Fartoukh, K. Fuchsberger, R. Giachino, M. Giovanozzi, G.H. Hemelsoet, W. Hofle, J.M. Jowett, Y. Borgne, D. Nisbet, M. Pojer, L. Ponce, S. Redaelli, M. Solfaroli, R. Suykerbuyk, D.J. Walsh, J. Wenninger, M. Zerlauth, CERN, Geneva

Abstract

During 2017, the CERN Large Hadron Collider (LHC) delivered luminosity for different physics configuration in addition to the nominal 6.5 TeV proton-proton run. About 18.5 days were dedicated to commissioning and delivering special physics configurations to the experiments. VdM runs at 6.5 TeV with high beta-star of 19 m and 24 m for luminosity calibration took place. A dedicated p–p run at 2.5 TeV that provides reference collision data to the experiments for heavy ion (Pb–Pb, p–Pb) collisions at the same energy also took place during the last weeks of November. A very short (0.5 days) but effective ion run was scheduled where the LHC had the first Xe beams colliding and delivering about 3 μb^{-1} to ATLAS and CMS. The run finished with a low pile-up run at 6.5 TeV. This contribution summarises the operational aspects and delivered targets for the different configurations.

INTRODUCTION

The Large Hadron Collider (LHC) at CERN is the accelerator providing the world highest center-of-mass energy ($\sqrt{s}$) collisions [1]. The main LHC programme is therefore to provide high energy *pp* collisions at the maximum possible energy of $\sqrt{s}$ = 13 TeV. However, dedicated time periods are scheduled every year to provide special physics configurations. Fig. 1 shows the relative distribution of running time for the 2017 LHC schedule. A total of 18.5 days were dedicated to the special physics programme, corresponding to 6 % of the LHC available time. The following sections will summarize each of these special runs.

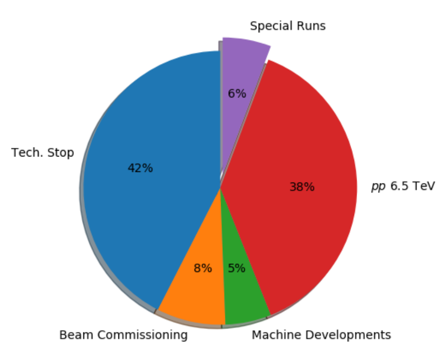

Figure 1: Pie chart of the time distribution of the 2017 LHC schedule.

P-P RUN AT 6.5 TeV

The major part of the run was dedicated to provide p–p collisions at 6.5 TeV beam energy. The main goal was to maximise the delivered integrated luminosity while implementing some of the future High Luminosity LHC baselines [2]. Three main novel features were implemented:

- Combined energy ramp-squeeze [3–5]. The energy ramp to 6.5 TeV is performed in parallel to an intermediate β^* squeeze. The final point are β^* = 1 m in IP1 and IP5, β^* = 3 m in IP8 and β^* = 10 m in IP2.
- Achromatic Telescopic Squeezing (ATS) scheme [6]. This new optics scheme enables for a very low β^* in the high-luminosity IRs, ATLAS and CMS. In 2017, with a pre-squeeze down to β^* = 40 cm and a later squeeze down to β^* = 30 cm was used.
- Radio-frequency (RF) full detuning [7–9]: the bunches are now located within the constraints of the RF system in a configuration that minimises the required RF power.

Despite a vacuum issue that was limiting the maximum intensity injected in the machine for a certain period the run was very successful. A dedicated note covers in more detail the LHC p–p run [10]. The initial luminosity target of 45 fb^{-1} was overpassed. ATLAS and CMS received more than 50 fb^{-1} with the peak luminosity exceeding 2.0×10^{34} $cm^{-2}s^{-1}$ reached on 2 November, 2017. These peak luminosities were achieved thanks to an excellent optimisation of the cycle and by exploring new beam with higher brightness (8b4e scheme [11]), with beam transverse emittances below 2 μm rad.

Because of the high peak luminosities, luminosity levelling was necessary in order to maintain the number of pile-up events below a limit of 60 average interactions per bunch crossing, corresponding to about 1.5×10^{34} $cm^{-2}s^{-1}$ of peak luminosity was requested by the experiments. Pending the deployment of luminosity levelling with β^*, the option of levelling by acting on the parallel separation at the IP was used instead. When the levelling was exhausted and the peak luminosity started to decay naturally, a change of cross angle was implemented to push up the peak luminosity again. The explored crossing angles during 2017 range from the starting point of 150 μrad to 120 μrad. Below these values parasitic collisions with long range bunches were already observed by the experiments. Table 1 shows a summary of the final machine parameters.

ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-MOPMF051

Table 1: Run at 6.5 TeV proton-proton collisions

Beam energy	6.5 TeV
Maximum peak luminosity	2.0×10^{34} cm^{-2}s^{-1}
Total delivered luminosity	50 fb^{-1}
Max. No. of bunches (25 ns)	2556
Max. No. of bunches (8b4e)	1500
Half crossing angles	150 μrad – 110 μrad
Intensity per bunch	$1.5 - 1.0 \times 10^{11}$ p/b

XE ION RUN

No regular one-month heavy-ion run was initially foreseen in 2017. However, in October 2017 the SPS was preparing to provide xenon beams to the NA61/SHINE [12] experiment and there was a unique opportunity to try a short cycle with collisions of Xe–Xe collision run at the LHC at a beam energy of 6.5 Z TeV [13]. Only 16 hours of preparation and physics data-taking were scheduled. The machine setup was very similar to the p–p run during injection, ramp to 6.5 TeV and squeeze to $\beta^* = 30$ cm with the only changes of:

- Reduction of external half-crossing angle in ALICE (IP2) from 200 μrad to 135 μrad. Re-alignment of tertiary collimators in IP2, for the new crossing angle.
- RF settings adjusted for the speed of the ions.

The total beam charge was kept below 3×10^{11} charges. The intensity was distributed among 20 bunches in the first fill (6294) and 16 bunches in the second fill (6295). The run successfully took place on 12 October delivering about 3 μb^{-1} to the experiments. Table 2 shows a summary of the final parameters.

Table 2: Run at 6.5 Z TeV xenon-xenon collisions.

Beam energy	6.5 Z TeV
Total delivered luminosity	about 3μb^{-1}
No. of bunches	16 – 20
Bunch intensity [10^8 ions]	2.87 ± 0.14

P-P RUN AT 2.51 TeV

A proton-proton run at an intermediate energy of 2.51 TeV was requested by the experiments as a reference for the ion run Pb–Pb collisions at the same collision energy per nucleon [14]. The run took place between the 11-20 November. The full squeeze was implemented in parallel with a faster energy ramp making the cycle shorter. ATLAS, CMS and LHCb were squeezed to the same value of $\beta^* = 3.1$ m and ALICE remained at $\beta^* = 10$ m. The half crossing angles were set to 170 μrad as in the previous reference run in 2015.

The collimator settings were defined by the interpolation of 2.51 TeV from the operational ramp at 6.5 TeV. The final choice of collimators settings is shown in Table 3.

The machine was setup in a very short time with only 3 intermediate intensity fills (50 bunches, 500 bunches and 1300 bunches) before reaching the final configuration of 1836

Table 3: Collimator settings in nominal σ at 2.51 TeV proton-proton run (assuming 3.5 μm of normalised transverse emittance)

Collimator Family	Setting [σ]
TCP / TCSG / TCLA in IP7	5.5/6.6/10
TCP / TCSG / TCLA in IP3	10.4/12.3/14.7
TCDQ / TCSP in IP6	7.8/7.4
TCTs in IP1, IP5 and IP8	13
TCTs in IP2	20

bunches was reached. The peak luminosities in ATLAS and CMS are shown in Fig. 2, the maximum achieved was around 1.3×10^{34} cm^{-2}s^{-1} for ATLAS and 1.4×10^{34} cm^{-2}s^{-1} for CMS. The total delivered luminosity is shown in Fig. 3. About 3 fb^{-1} were delivered to ATLAS and CMS.

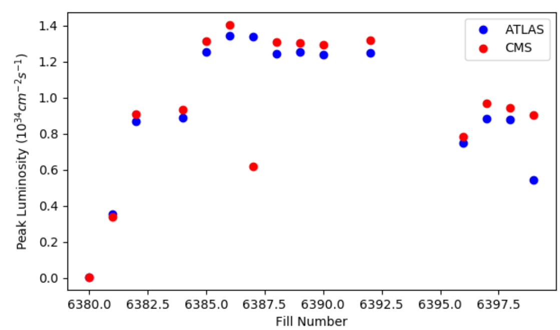

Figure 2: Peak luminosity for each fill during the proton-proton reference run at 2.51 TeV.

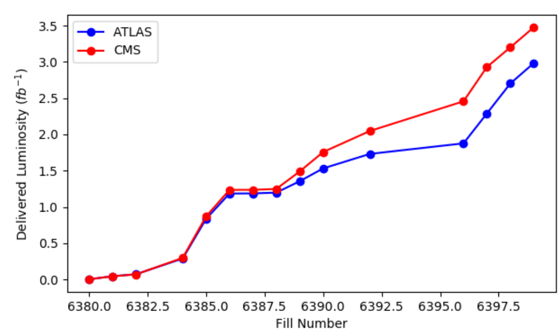

Figure 3: Delivered luminosity for each fill during the proton-proton reference run at 2.51 TeV.

VAN DER MEER SCANS

Special runs at medium beta-star are requested by the experiments every year in order to perform precise luminosity calibrations, these are the so called Van der Meer scans. Data taking in collisions is provided with different machine configuration. Optics with large beta-star (close to 19 m for ATLAS, CMS and ALICE and 24 m for LHCb) and zero crossing angle for ATLAS and CMS, see Table 4 for more details on the machine configuration. The advantage of using larger beta-star is that it gives larger beam sizes at the colliding IRs which improves the vertex resolution in the colliding experiments [15].

ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-MOPMF051

Collimator settings in the main cleaning regions (IP3 and IP7) are the same as for the 6.5 TeV run, while in the colliding IRs the tertiary collimators have more relaxed settings, see Table 5 for detail collimator settings in beam sigma.

Table 4: Beta-star and half crossing angle configuration during Van der Meer run.

Experiment	Beta-star	Half Crossing-angle
ATLAS/CMS	19 m	0 μrad
ALICE	19 m	160 μrad
LHCb	24 m	−170 μrad

Table 5: Collimator settings in nominal σ at 6.5 TeV during van der Meer proton-proton run (assuming 3.5 μm of normalised transverse emittance).

Collimator Family	Setting [σ]
TCP / TCSG / TCLA in IP7	5/6/10
TCP / TCSG / TCLA in IP3	15/18/20
TCDQ / TCSP in IP6	8.3/7.3
TCTs in IP1, IP5 and IP2	37
TCTs in IP8	25

The goal of the Van der Meer fills is to scan the crossing and beam separation while monitoring the luminosity. An example of a scan performed for ATLAS is shown in Fig. 4. Three fills were dedicated to this scans (fill number 6012, 6015 and 6016). Most of the luminosity calibration tests were achieved then in the third fill, number 6016, on the 28 July 2017. The delivered luminosity was about 240 nb^{-1} for ATLAS and CMS together. Fig. 5 shows the evolution of the delivered luminosity as a function of time.

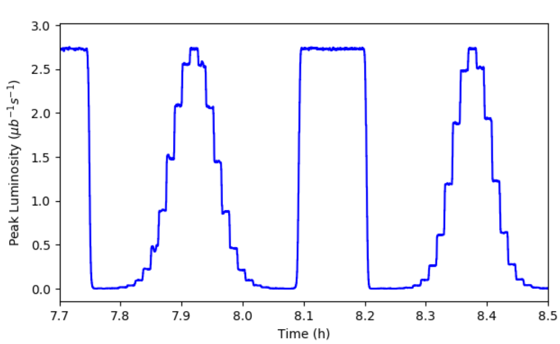

Figure 4: Peak luminosity during a van der Meer scan in ATLAS.

HIGH-BETA RUN AT 450 GeV

A special run to measure the total cross section using elastic scattering at injection energy of 450 GeVwas requested [16–18] . The optics and collimator settings were validated, however the background observed need to be further understood. The run will be repeated again in 2018.

LOW PILE-UP P-P RUN AT 6.5 TeV

Since the low energy high beta run was postponed for 2018 its slot was replaced by a few days of running at low pile-up. ATLAS and CMS requested pile-up values of 1 to 3 events per bunch crossing. The machine was configured the same as for the nominal 2017 operation only colliding with a large separation in order to decrease the pile-up contribution.

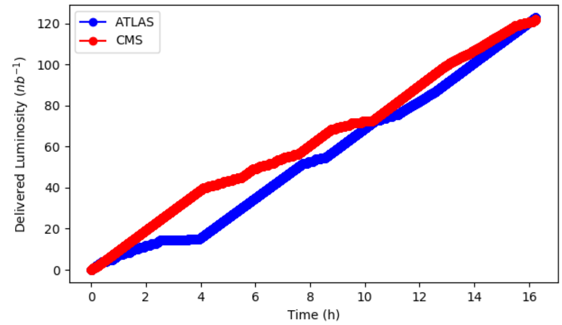

Figure 5: Delivered luminosity for the main fill on the proton-proton van der Meer run at 6.5 TeV for ATLAS and CMS.

The run took place between the 21-26 November, about 82 h of collisions in stable beams conditions were delivered, distributed in 6 fills. About 0.25 fb^{-1} of integrated luminosity was delivered to CMS and 0.15 fb^{-1} to ATLAS. The difference comes from their request of peak luminosity that for CMS was 0.8 nb^{-1}s^{-1} and for ATLAS 0.5 nb^{-1}s^{-1}. The peak luminosity evolution is shown in Fig. 6. The figure shows an initial high peak luminosity that corresponds to head-on collisions, then collisions were levelled with an offset in the separation plane to the requested luminosity.

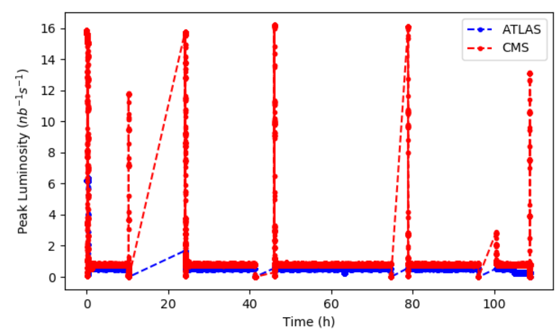

Figure 6: Peak luminosity to ATLAS and CMS as function of time during the low pile-up proton-proton run at 6.5 TeV.

ACKNOWLEDGEMENT

The authors would like to acknowledge all the teams involved on the preparation of the 2017 LHC run, in particular the CERN injector complex, equipments groups and controls team for the excellent support all along the year.

REFERENCES

[1] O. Bruning *et al.*, "LHC Design Report", CERN, Geneva, CERN Yellow Reports: Monographs, 2004.

[2] G. Apollinari *et al.*,"High-Luminosity Large Hadron Collider (HL-LHC), Preliminary Design Report", CERN, Geneva, CERN Yellow Reports: Monographs, 2015.

ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-MOPMF051

[3] N. Ryckx,“Combined energy ramp and betatron squeeze at the large hadron collider”, CERN-THESIS-2012-004.

[4] J. Wenninger *et al.*,“First beam test of a combined ramp and squeeze at LHC”, CERN-ACC-NOTE-2015-0023.

[5] M.Solfaroli, “LHC Nominal Cycle”, Proceedings of the 6th Evian workshop, pp. 45-48.

[6] S. Fartoukh, “An Achromatic Telescopic Squeezing (ATS) Scheme for the LHC Upgrade”, in Proc. IPAC ’11, San Sebastián, Spain, paper WEPC037, pp. 2088-2090.

[7] D. Boussard, “RF Power Requirements for a High Intensity Proton Collide - Part I”, in Proc. PAC ’91, San Francisco, May 1991, p. 2447.

[8] T. Mastoridis, P. Baudrenghien and J. Molendijk, “Cavity voltage phase modulation to reduce the high-luminosity Large Hadron Collider RF power requirements”, PRAB 20,101003 (2017).

[9] P. Baudrenghien and T. Mastoridis,“Proposal for an RF roadmap towards ultimate intensity in the LHC”, in Proceedings of the 3rd International Particle Accelerator Conference, New Orleans, LA, 2012 (IEEE, Piscataway, NJ, 2012).

[10] M. Pojer *et al.*, “LHC Operational experience of the 6.5 TeV proton run with ATS optics”, presented at IPAC ’18, Vancouver, Canada, Apr-May 2018, paper MOPMF050, this conference.

[11] H. Damerau *et al.*, “LIU: exploring alternative ideas”. https://cds.cern.ch/record/1977365/files/127-137-Damerau.pdf

[12] N. Abgrall *et al.*, [NA61/SHINE Collaboration] JINST 9 (2014) P06005.

[13] M. Schaumann *et al.* , “First Xenon-Xenon Collisions in the LHC’, presented at IPAC ’18, Vancouver, Canada, Apr-May 2018, paper MOPMF039, this conference.

[14] M.Solfaroli and J.Wenninger,“2.51 TeV ramp configuration”, LBOC meeting 24 Oct2017.

[15] S.White, “Determination of the Absolute Luminosity at the LHC”, CERN-THESIS-2010-139, 2010.

[16] LHC Background Studies number 89, https://indico.cern.ch/event/693454/

[17] H. Burkhardt, “LHC perspective, review and outlook”, Workshop on LHC forward physics programme, https://indico.cern.ch/event/575250/

[18] A Garcia-Tabares Valdivieso *et al.*, “Optics measurements and corrections at β^{*}= 2.5 km", CERN-ATS-Note in preparation.