LESSONS LEARNT IN LHC OPERATION IN 2015

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Abstract

In 2015 the LHC entered the first year of its second long Run, and the first collisions at 13 TeV CoM energy were delivered to the experiments on 3 June, after two months of beam commissioning. The rest of the year was characterized by a stepwise increase in the number of bunches that allowed reaching 2244 bunches per ring and a peak luminosity of $\sim 5 \times 10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}$, for a total of just above 4 fb^{-1} delivered to the high luminosity experiments. While the machine efficiency was hampered by many different issues related to the high intensity and high energy, the luminosity performance was excellent, thanks to little losses and good emittance preservation through the cycle, in combination with excellent luminosity lifetimes in physics. This paper reviews the 2015 proton-proton physics performance and the parameters that allowed reaching it. It also collects relevant input presented at the Evian workshop that is not collected elsewhere in this workshop.

INTRODUCTION

The year 2015 marked the restart of LHC operation with beam after its first Long Shutdown (LS1). Operation with beam started relatively late in the year, as the first three months were still devoted to hardware commissioning. It is in particular worth recalling that the Copper Stabilizer Continuity Measurement required the extension of the LS1 by one month, that the dipole training campaign to 6.5 TeV took longer than expected, and that a worrisome earth fault appeared in the dipole circuit in sector 34 [1]. The machine checkout interwove with the end of the hardware commissioning, and finally the first probe beams were circulated on Easter Day (5 April).

Beam commissioning, including also recommissioning all machine protection systems, lasted 8 weeks and culminated with the first “Stable Beams” declared in the morning of 3 June. During this period, and despite the low intensity beams, issues were found at the location 15R8: first fast losses, with signature similar to the Unidentified Falling Objects (UFOs), then, after a thermal cycle of the beam screen to $\sim$ 80 K, an aperture restriction, now dubbed the ULO (Unidentified Lying Object, [2]).

The summer was devoted to a step-wise scrubbing run and intensity ramp-up: first with 50 ns, then with 25 ns beams. A total of $\approx$ 3 weeks were dedicated to electron-cloud scrubbing at 450 GeV [3]. In September and October, the intensity ramp-up with 25 ns continued, mostly limited by the heat load induced on the cryogenic system [4]. Note that the month of August was particularly difficult as the machine availability was impaired by Single Event Effects on the Quench Protection Systems [5] and by high UFO rates [6], so much that most of the luminosity production happened only in the months of September and October.

The last month of beam operation was dedicated to physics with lead ion beams [7, 8]. It is also worth recalling that proton-proton physics operation was interrupted throughout the year to accommodate special physics runs (e.g. the low pile-up LHCf run, the 90 m run for TOTEM and ALFA, the proton-proton reference run at 2.51 TeV/beam), 3 scheduled stops for hardware maintenance (Technical Stops, TS), and three 5-day long Machine Developments (MDs).

This paper first reviews the luminosity performance achieved in 2015, but then also draws attention to some of the lessons learnt with operation at high energy with 25 ns beams that are not covered elsewhere (mostly recalling highlights of the Evian workshop held in December 2015).

LUMINOSITY PERFORMANCE

At the end of the proton physics running period, the instantaneous luminosity reached $\sim$ $0.5 \times 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$, achieved when the number of bunches per ring was maximum for the year (i.e. 2244, see Fig. 1). The main beam and machine parameters that allowed reaching such luminosity

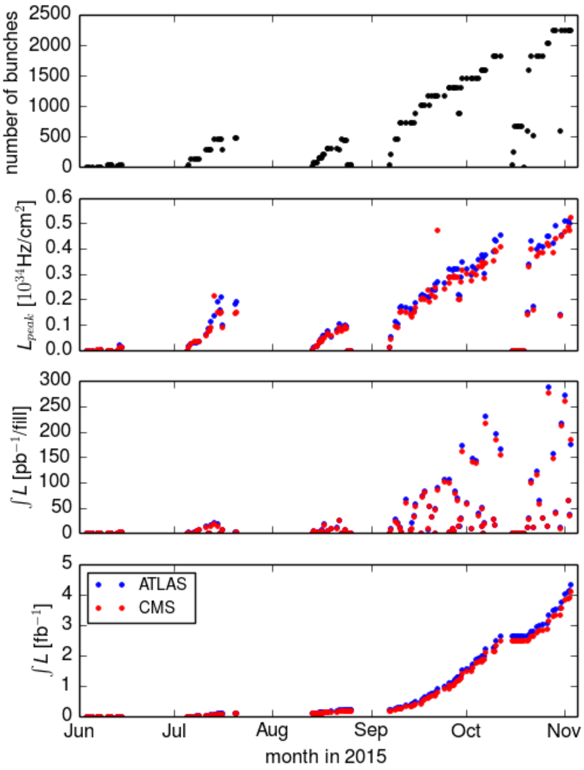

Figure 1: Performance plots for the year 2015. From the top: number of bunches per fill, peak luminosity per fill, integrated luminosity per fill, and luminosity integrated since the start of the year.

are shown in Table 1, where also the 2012 values are shown for comparison. In particular, the beam energy and number of bunches were higher in 2015, but the beams were brighter in 2012.

Table 1: Beam and machine parameters in 2012 and 2015, typical best achieved.

Parameter	**2012**	**2015**
energy [TeV]	4	6.5
bunch spacing [ns]	50	25
β^* [m]	0.60	0.80
half crossing angle [μrad]	145	145
N_b [10^{11} ppb]	1.6	1.15
transverse emittance [μm]	2.5	3.5
colliding pairs in IP1 and 5	1368	2232
total number of bunches per ring	1374	2244
L [10^{34} cm^{-2}s^{-1}]	>0.7	~ 0.5
pile-up μ	~ 35	~ 15
stored energy [MJ]	140	270

The luminosity integrated by ATLAS and CMS over the course of the 2015 proton physics run is just above 4 fb^{-1}, while LHCb and ALICE integrated 360 pb^{-1} and 9 pb^{-1} respectively. The integrated luminosity ran short of the initial projection due to the delayed start (~ 1 month) and the difficulties encountered in August, in addition to the time allocated for the special physics runs and for scrubbing. The production rates in the end of the run though reached 200-250 pb^{-1}/day and ~ 1 fb^{-1}/week, which make good foundations for the 2016 physics production (see Fig. 1).

The luminosity lifetime was notably healthy, ~ 30 – 60 h, thanks to the high energy and thus synchrotron radiation damping, and the lower brightness compared to 2012. In fact, the better luminosity lifetime in 2015 made up for the lower peak luminosity, so that the integrated luminosity for long fills (e.g. 12 hours) was very similar.

A LHC luminosity model is being developed [9], taking into account IntraBeam Scattering (IBS), synchrotron radiation, and luminosity burn-off in IP1 and IP5. It is based on a single fully parametrised function, and it can be run bunch-by-bunch. The transverse emittance growth predicted by the model is less than the actual measured growth, indicating that there are missing components that contribute to the growth. In fact, the use of the measured emittance for the evolution results in a better match to the intensity and longitudinal behaviours. Preliminary results of studies on non-colliding bunches [10] and their evolution during a fill indicate strong differences between fills, and confirm the very good vacuum conditions (i.e. very small scattering on the residual gas).

The losses per beam mode were calculated [11] and are reported in Table 2, together with a comparison with 2011 and 2012 [12]. In 2015 the losses through the cycle added up to ≈ 2%, despite the high chromaticity (Q') and octupole strength. For comparison, in 2011 the losses were negligible and in 2012 up to 4 – 5% of the beam was lost before collisions.

Table 2: Losses for the beam modes ramp, squeeze and adjust, for beam 1 and beam 2, for 2011, 2012, and 2015. The total losses are from start of acceleration to end of adjust for fills that lasted until Stable Beams.

	2011		**2012**		**2015**	
	b1	**b2**	**b1**	**b2**	**b1**	**b2**
Ramp	0.8%	0.2%	1.7%	1.6%	1.1%	0.8%
Sque.	0.1%	0.1%	1.2%	2.0%	0.2%	0.3%
Adj.	0.5%	0.3%	1.8%	1.7%	0.9%	0.8%
Total	0.8%	0.7%	3.8%	4.7%	2.2%	1.9%

Emittance Evolution

From studies with Wire Scanners (WS) on low intensity fills [13], IBS is the main source for horizontal emittance growth. In the vertical plane, a typical growth of ~ 5% in 10 minutes was measured, indicating an additional source of emittance growth which is not known, but seemingly independent of brightness, Q', octupole strength, transverse damper settings. The comparison between the WS at injection on the first train and the emittance at the start of collisions derived from the ATLAS luminosity indicated an average growth of ~ 0.5 μm (25%) over the course of the cycle, resulting in ~ 3 μm emittances at the start of fill.

The emittance evolution in physics from OP scans [14] shows an average horizontal growth of ~ 0.03 μm/h and a vertical shrinkage of ~ 0.02 μm/h, so that the convoluted emittance is constant within the measurement error. Longitudinal shrinkage is also observed, and it is consistent with the expectation from synchrotron radiation damping [15]. The bunches are ~ 1.3 ns long after the controlled longitudinal blow-up applied during the ramp, and over the course of a long fill they decrease to below 0.8 – 0.9 ns. When bunches become that short they lose Landau damping and become unstable (mostly dipolar oscillations were seen). A technique for bunch flattening with the purpose of restoring Landau damping was developed as a mitigation measure, first tested in MD time and then also tried in a few physics fills.

The only physics fill that brought BCMS beams (Batch Compression, Merging and Splitting) into collisions had an average emittance of ~ 2.5 μm, with some bunches as low as 1.9 μm. The fill used ~ 600 bunches and was only 2 hours long. An horizontal emittance increase of ~ 0.1 μm/h was measured with OP scans, while the vertical emittance was constant within the measurement error.

IP1/5 Luminosity Difference

During 2015 the online luminosities of ATLAS and CMS were consistently different. The ratio between the two favoured ATLAS by ≈ 9% at the start of the fill, and then decreased towards 4% towards the end of long fills [14]. An improved calibration derived from the vdM scans became available only after the run was finished: the ATLAS luminosity was too high (∼ 3%), and the CMS luminosity too low (∼ 4%). With the new calibration factors the difference between the two luminosities decreased to ≈1%.

The worry about the possible difference triggered additional studies in the second part of the year, e.g.:

- the measured β at the Interaction Point (IP) were larger than expected (i.e. ≈ 84 cm [16]);
- the waist position was shifted by 20 cm with respect to the IP [16];
- the crossing angles were ∼ 10 – 20% larger than expected [17].

The results and lessons learnt will be brought forward into the 2016 commissioning, and beyond, modifying the optics correction strategy, e.g. to include online k-modulations, and the use of the ballistic optics.

MISCELLANEA

While the execution of ramp, squeeze, and adjust are very reproducible, injection is the phase in which the biggest improvement is possible. The shift crews often spend over twice the theoretical minimum time in this phase. While a detailed discussion took place elsewhere [18], here some important points are recalled:

- the transfer of two trains of 12 bunches helped getting rid of fills dedicated to transfer line steering (as opposed to “steering while filling”). This helped the machine efficiency, resulting in very little time dedicated to injection tuning (∼ 20 h). It should be pointed out that the trajectory references were better than in 2012 and that the transfer line stability has also improved sensibly.
- in 2015 the problem of injection losses was much mitigated, partly due to the 144-bunch limitation per transfer. Still, at times, the losses were close to the dump threshold, especially on the TDI BLMs. The use of the diamond BLMs as additional diagnostics should be pursued [19], and the warning thresholds on the IQC should be followed up [18].
- automation of manual measurements also helps the efficiency: the tune and Q’ tools improved in 2015; the WS application improved, and further improvements are still possible; tools for measuring the coupling will become available in 2016.

The tune feedback (QFB) was used for ramp and squeeze throughout the year [20]. This was possible thanks to the improved tune signals, and thanks to the use of gating on both the BBQ and the transverse damper. The co-existence with the abort gap cleaning is still a problem in the squeeze.

The orbit feedback could be used in Stable Beams [20], thanks to the improved software stability and configurability, and thanks to the improved BPM signal quality profiting from the temperature controlled racks. This was decisive for the tolerance of the IR8 triplet movement which would have otherwise caused orbit drifts up to ∼ 0.2 mm rms. The origin of the triplet movement is not understood yet.

Tune and chromaticity drift and snapback were well controlled, thanks to the cooperation between FiDeL and the QFB [21]. The tune dependence on intensity at injection was studied and a dependence on intensity was quantified. Ideally it will be automatically corrected in 2016.

Fifteen days were invested in MDs in 2015, organized and reviewed by the LHC Studies Working Group (LSWG). Highlights of the results are: the preparation of $\beta^* = 40$ cm for operation in 2016, the commissioning of a combined ramp and squeeze (already used for operation in 2015 in the 2.51 TeV run), the demonstration of the feasibility of keeping the beams in collisions while squeezing, and many others [22].

CONCLUSIONS

2015 was successful for LHC operation: 25 ns beams were collided routinely at 6.5 TeV, with up to 2244 bunches per ring, laying a stable foundation for the 2016 physics production. Despite the intensity ramp up not being fully finished due to limitations on the cryogenic system, at the end of the year the production rates reached 200-250 pb^{-1}/day and 1 fb^{-1}/week. ATLAS and CMS integrated ∼ 4 fb^{-1} each, this performance being impaired by a late start with beam, issues with QPS SEUs, abundant UFO rates, the ULO, etc. The e-cloud and the consequent abundant heat-load for the cryogenic system remain a challenge for 2016. The good peak luminosities and the excellent luminosity lifetimes were enabled by an excellent transmission through the cycle, low losses during physics (excluding luminosity burn-off), and an acceptable emittance growth (for which some causes have yet to be pinned down).

Additionally, during the year much improvement was gained in the understanding of the machine and how to operate it, both during regular operation, during scrubbing and during machine developments.

Yet and again, successful operation was made possible by an excellent system performance and experts’ motivation.

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