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LHC Performance in Run 2 and Beyond

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An overview of the performance of the LHC in 2015 is given. The year saw the recovery and recommissioning following Long Shutdown 1, somewhat of struggle to address issues arising, and the eventual establishment of reasonable performance at 6.5 TeV with 25 ns beam. The time-line of the year is presented, the challenges encountered are outlined, and the achieved performance quantified. The outlook for the rest of Run 2 is discussed.

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1. Introduction

The principle aims of 2015 were to re-commission the machine without beam following the major consolidation and upgrades that took place during LS1, and from a beam perspective to safely establish operations at 6.5 TeV with 25 ns bunch spacing and deliver a significant data sample to the LHC experiments.

The beam configuration targeted was close to nominal i.e. 25 ns bunch spacing with around 2800 bunches of near nominal bunch intensity (1.15×10^{11} protons per bunch). Lower β^* implies larger beams in the triplet magnets on the either side of the high luminosity experiments and here aperture concerns dictated caution. A relatively relaxed β^* of 80 cm in ATLAS and CMS was chosen to provide some aperture margin in inner triplets and thereby less rigorous demands on the collimator settings required to protect said aperture. The ultimate β^* for Run 2 is envisaged to be around $\beta^* = 40$ cm and this value was tested in machine development during the year.

Recommissioning at 6.5 TeV with a bunch spacing of 25 ns was anticipated to be more of a challenge than previous operations at 4 TeV with 50 ns beams. The increased energy implies lower quench margins and thus lower tolerance to beam loss. The hardware (beam dumps, power converters, magnets) is pushed closer to maximum with potential knock-on effects to availability. 25 ns was anticipated to have significantly higher electron-cloud than that experienced with 50 ns. UFOs rates had been shown to to be higher with smaller bunch spacing. 25 ns has more long range collisions with a larger crossing angle as a result. It also implies higher total beam current and also higher intensity per injection than previously. All of these factors came into play in 2015 making for a challenging year.

The outline plan for the year was:

- initial beam commissioning for about 8 weeks exiting with first Stable Beams with low beam intensity;
- a 10 days scrubbing run with 50 and 25 ns beams;
- 2 to 3 weeks of operations with 50 ns;
- a second 2 week scrubbing run with 25 ns beam preparing the way for 25 ns operations;
- 25 ns operations progressing via a phased increase in the number of bunches.

The schedule also included the usual mix of technical stops, machine development periods, and special physics runs.

Lepton Photon 2015 took place towards the end of August. For completeness an account of the full LHC year is presented here.

2. Initial commissioning

At the end of 2014 and start of the 2015 the LHC was cooled down sector by sector and all magnet circuits put through a powering test campaign to fully re-qualify everything. The 6 month long programme of rigorous tests involved the quench protection system, power converters, energy extraction, UPS, interlocks, electrical quality assurance, and magnet quench behaviour. The powering test phase eventually left all magnetic circuits fully qualified for 6.5 TeV.

Some understandable delay was incurred during this period and three things may be highlighted. First was the decision to perform in situ tests of the consolidated splices – the so called Copper Stabilizer Continuity measurement (CSCM) campaign. These were a success and provided confirmation of the quality work done during the shutdown. Secondly dipole quench re-training took some time. In particular the sector 45 dipoles proved a little recalcitrant and reached the target 11,080 A after some 51 training quenches. Thirdly, after an impressive team effort coordinated by the machine protection team to conceive, prototype, test and deploy the system, a small piece of metallic debris that was causing an earth fault in a dipole in sector 34 was successfully burnt away on the afternoon of Tuesday 31st March.

First beam 2015 went around the LHC on Easter Sunday 5th April. Initial commissioning delivered first beam at 6.5 TeV after 5 days and first Stable Beams after 2 months of careful set-up and validation. The magnetic behaviour, optical properties, and aperture of the machine were confirmed to be in good shape, and all the key beam-related systems were re-commissioned, again after a lot of work in LS1. There was excellent and improved system performance of all key systems, namely: Beam Instrumentation; Transverse feedback ; RF; Collimation; Injection and beam dump systems; Vacuum; Machine protection; Software & analysis tools. A lot of hard won experience was brought to bear.

Of note:

- the LHC is magnetically reproducible as ever;
- the optics is good and corrected to excellent;
- the aperture is fine and compatible with the collimation hierarchy;
- the magnets behave well at 6.5 TeV (operation in 2015 saw 4 additional training quenches at 6.5 TeV);
- operationally things are well under control (injection, ramp, squeeze...).

3. Scrubbing

When an accelerator is operated with small bunch spacing an electron cloud can develop in the beam chamber due to secondary emission from the chamber wall. The electron cloud can have a strong impact on beam quality (electron cloud induced instabilities, particle losses, emittance growth). It can cause dynamic vacuum pressure increase and, importantly for the LHC, heat load in the cold sectors of the machine. Electron bombardment of vacuum surfaces has been proven to reduce drastically the secondary electron yield (SEY) of a material. This technique, known as scrubbing, provides a mean to suppress electron cloud build-up. Scrubbing has been used already in the LHC and there is a wealth of experience from other machines [1].

Electron cloud gets worse with reduced bunch spacing and it was anticipated to be an issue with 25 ns beam, and dedicated scrubbing periods were foreseen. A scrubbing beam produced in the SPS consisting of bunchlets spaced by 5 ns was prepared and its use in the LHC tested. This beam has the potential to generate significant electron cloud and accelerate the scrubbing process.

A two stage scrubbing strategy was pursued: a first scrubbing period (50 ns and 25 ns) to allow for operation with 50 ns beams at 6.5 TeV; followed by scrubbing with 25 ns and the doublet beam to allow for operation with 25 ns beams at 6.5 TeV. The use of doublet beam proved difficult. It was concluded that the SEY was still too high for its effective use and that more 25 ns scrubbing will be required before it can be used effectively.

Preparation for the runs was excellent (tools, monitoring, simulations, understanding, preparation of beams) with significant anticipatory effort from the vacuum, cryogenics, RF, injectors, accelerator physicists, and operations teams. The execution of the scrubbing periods was efficient and the two scrubbing runs delivered good beam conditions for around 1500 bunches per beam after a concerted campaign to re-condition the beam vacuum. However, electron cloud was still significant at the end of the scrubbing campaign.

4. Phase 1 of the intensity ramp-up

The initial 50 ns and 25 ns intensity ramp-up phase was tough going and had to contend with a number of issues, including earth faults, so-called unidentified falling objects (UFOs), an unidentified aperture restriction in a main dipole, and radiation affecting specific electronic components in the tunnel. Combined these problems made operations difficult but nonetheless the LHC was able to operate with up to 460 bunches and to deliver some luminosity to the experiments albeit with poor efficiency. The intensity ramp-up phase is designed to flush out intensity related issues, particularly those potentially relating to machine protection, and this period may be considered as successful in this regard.

4.1 Quench Protection System (QPS)

1268 modified QPS boards (mDQQBS) were used for the Copper Stabilizer Continuity measurement (CSCM) campaign during circuit re-commissioning. Time pressure led to the boards being left in the machine following the end of the CSCM campaign [2]. Non radiation hard components were present on these board. Their susceptibility was exposed during the intensity ramp-up phase. The boards were replaced during the second technical stop (31$^{\text{st}}$ August to 4$^{\text{th}}$ September) and there has been no re-occurrence of the problem since.

4.2 Unidentified Falling Objects (UFOs)

UFOs in the LHC became apparent during Run 1 and a lot of effort was made to understand and simulate the process [3]. The accepted scenario is as follows.

- A macroparticle (dust) falls from the top of the beam screen.
- The macroparticle is subsequently ionized due to elastic collisions with the beam.
- The now positively charged macroparticle is subsequently repelled away from the beam.
- For the duration of the UFO-to-beam interactions, there may be significant losses due to inelastic collisions, resulting in a beam dump and or magnet quench.

UFOs are distributed around the ring. The number of UFO events have been seen to exceed 10 per hour with notable increases after long shutdowns and or with a decrease in bunch spacing. In 2015 beam loss monitor thresholds were set judiciously to strike a balance between unwanted dumps and the possibility of UFO induced quenches. Conditioning - the reduction in UFO rates - had been observed in Run 1 and the essential hope was that the same would be observed in 2015. After worrying high rates during the initial ramp-up phase this conditioning was indeed observed with a very acceptable reduction seen towards the end of the operational year.

4.3 Unidentified Lying Object (ULO)

A localized aperture restriction in a dipole in sector 81 (15R8) was measured at injection and 6.5 TeV [4]. Local orbit bumps were deployed to move the beam away from the restriction and thus optimize the available aperture. UFOs, double UFOs and quench inducing UFOs were also observed at the same location. The UFOs died away as the year progressed but the presence of the restriction was confirmed by measurements at the end of the year. An intervention during the Christmas break is precluded because of the time required to warm-up and cool-down the affected area.

4.4 Injection absorbers (TDI)

The TDI are movable vertical absorbers – 4.2 m in length – downstream of injection kickers. The main blocks are made of hexagonal boron nitride (hBN). High temperature bake-out tests revealed that the hBN blocks cannot withstand temperatures higher than 450 °C (B_2O_3 reactant melting temperature). Because of this, a limitation on number of injection was imposed to avoid potential damage (maximum allowed temperature = 400 °C). This limited injection to 2 PS batches per injection (144 bunches) and reduced the maximum number of bunches to around 2400 in 2015. The hBN blocks will be replaced with graphite during the 2015 end-of-year stop so this issue poses a temporary limitation.

In addition, during scrubbing and subsequent high intensity injection, heating and out-gassing of from the TDI right of point 8 was observed with vacuum spikes up to and above interlock limits.

These TDI problems were painful in 2015 but they should not be long term issues for Run 2.

5. Phase 2 of the intensity ramp-up

The second phase of the ramp-up following the technical stop at the start of September was dominated by the electron cloud generated heat load and the subsequent challenge for cryogenics which had to wrestle with transients and operation close to their cooling power limits [6]. The ramp-up in number of bunches was consequently slow but steady culminating in the final figure for the year of 2244 bunches per beam. Importantly, electron cloud generated during physics at 6.5 TeV served to slowly condition the surface of the beam screens in the cold sectors and so reduce the heat load at a given intensity. As time passed, this effect opened a margin for the use of more bunches. Operations of the cryogenics was thus kept close to the acceptable maximum heat-load and at the same time in the most effective scrubbing regime. The number of bunches was maximized given the limits from heat-load by exploiting the possibility of introducing gaps into the bunch configuration.

6. Proton physics at 6.5 TeV - performance

By the end of the 2015 proton run, 2244 bunches per beam were giving peak luminosities of approximately 5.0×10^{33} cm^{-2}s^{-1} in ATLAS and CMS with a total delivered integrated luminosity of around 4 fb^{-1} delivered to both experiments (see figure 1). Levelled luminosity of 3×10^{32} cm^{-2}s^{-1} in LHCb and 5×10^{30} cm^{-2}s^{-1} in ALICE was provided throughout the run. Also of note were dedicated runs at a high β^* for TOTEM and ALFA. These provided important data on elastic and diffractive scattering at 6.5 TeV, and interestingly a first test of CT-PPS which aims to probe double pomeron exchange.

The overall machine availability is a critical factor in integrated luminosity delivery and remained respectable with around 32% of the scheduled time spent in Stable Beams during the final period of proton-proton physics from September to November. Also of note was excellent luminosity lifetime which was generally in the order of 40 hours. This is a marked improvement on 50 ns operation with high bunch population and allowed the beams to be usefully kept in Stable Beams for up to 24 hours. A comparison of key parameters for Run 1 and 2015 is shown in table 1.

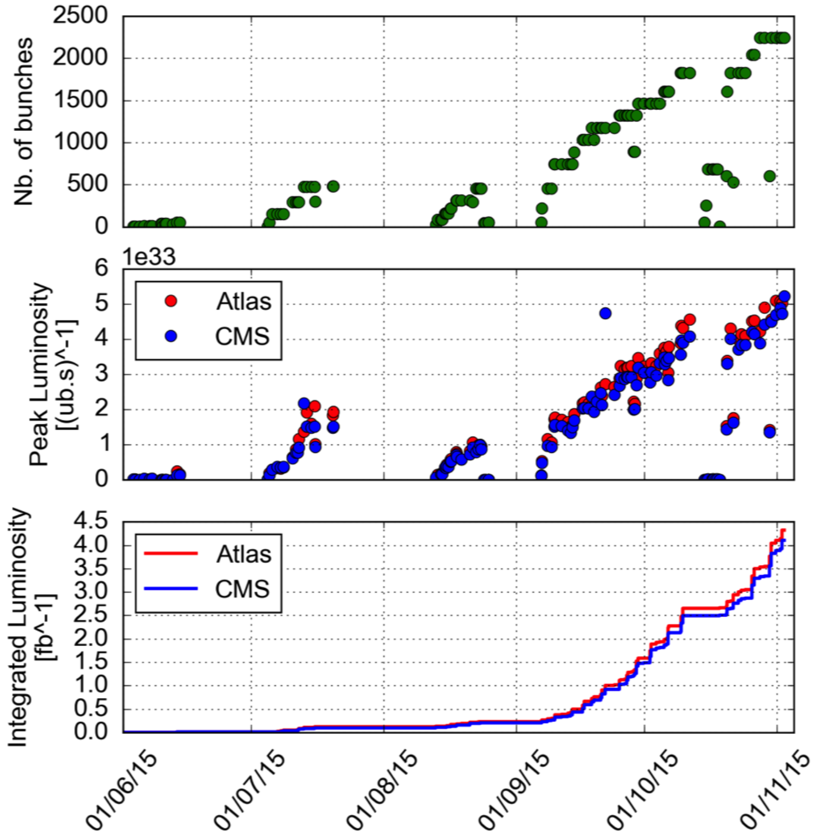

Figure 1: Summary of 2015 performance showing evolution of total number of bunches, peak and integrated luminosity. Image courtesy of Giovanni Iadarola.

Table 1: Evolution of key LHC performance parameters during Run 1 and the start of Run 2

Parameter	**2010**	**2011**	**2012**	**2015**	**Design**
Beam energy [TeV]	3.5	3.5	4	6.5	7
β^* in IP 1 and 5 [m]	2.0/3.5	1.5/1.0	0.6	80	0.55
Bunch spacing [ns]	150	75/50	50	25	25
Number of bunches	368	1380	1380	2244	2808
Protons per bunch	1.2×10^{11}	1.45×10^{11}	1.7×10^{11}	1.2×10^{11}	1.15×10^{11}
Normalized emittance [μm]	$\approx$2.0	$\approx$2.4	$\approx$2.5	$\approx$3.5	3.75
Peak luminosity [$cm^{-2}s^{-1}$]	2.1×10^{32}	3.7×10^{33}	7.7×10^{33}	5.0×10^{33}	1×10^{34}
Max. mean number of events per bunch crossing	4	17	37	16	19
Stored beam energy [MJ]	$\approx$28	$\approx$110	$\approx$140	$\approx$270	362

7. Ion run

As is now traditional, the final four weeks of operations in 2015 were devoted to the heavy ion program. To make things more challenging it was decided to include a 5 day proton-proton reference run in this period. The proton-proton run was performed at a centre-of-mass energy of 5.02 TeV giving the same nucleon-nucleon collision energy as that of both the following lead-lead run and the proton-lead run which took place at the start of 2013. Both the proton reference run and ion run demand re-setup and validation at new energies. Despite the time pressure both runs went well and were counted a success. Performance with ions is strongly dependent on the beam from the injectors (source, Linac3, LEIR, PS and SPS) and extensive preparation allowed the delivery of good intensities which open the way for the delivery of the levelled design luminosity of 1×10^{27} $cm^{-2}s^{-1}$ to ALICE and over 3×10^{27} $cm^{-2}s^{-1}$ to ATLAS and CMS. For the first time in an ion-ion run LHCb also took data following their participation in the proton-lead run. Dedicated ion machine development included crystal collimation and quench level tests, the latter providing important input to future ion operation in the HL-LHC era.

8. Conclusions

The efforts of 2015 have opened the way for a full production run in 2016. Following initial commissioning, a short scrubbing run should re-establish the electron cloud conditions of 2015 allowing operation with 2000 plus bunches. This figure can then be incrementally increased to the nominal 2700 as conditioning progresses. Following extensive machine development in 2015, the β^* will be reduced to around 40 cm for the 2016 run. Nominal bunch intensity and emittance will bring the design peak luminosity of 1×10^{34} $cm^{-2}s^{-1}$ within reach. Reasonable machine availability and around 150 days of 13 TeV proton-proton physics should allow of the order of 30 fb^{-1} to be delivered to ATLAS and CMS.

The Run 2 schedule foresees a similar total number of 13 TeV proton-proton physics days in both 2017 and 2018. Some options are available to continue pushing the performance of the machine, given these and, as always, good availability the integrated target of 100 fb^{-1} for Run 2 should be within reach.

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References

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