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LHC: Status, Prospects and Future Challenges

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This paper discusses the status of the CERN LHC collider as of June 2016, the prospects and the future challenges for the next weeks, months, years and decades.

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1. Introduction

The goals for the LHC Run 2 (i.e. from 2015 to 2018) are the following [1]: (i) operation with 25 ns bunch spacing; (ii) peak luminosity of 1.3 10^{34} cm^{-2} s^{-1}; (iii) integrated luminosity of ~ 100 fb^{-1}; (iv) prepare for (or go to) 14 TeV operation. The year 2015 was a commissioning / exploratory year to establish proton-proton collision at 13 TeV with 25 ns and low betatron function β* at the Interaction Point (IP) 1&5 to prepare the production runs in 2016, 2017 and 2018. The aims for 2015 were to optimise the machine availability for physics and to perform a Pb-Pb run at the end of the year. As first year of production, the goal for 2016 is to reach ~ 25 fb^{-1} at 13 TeV, performing also a p-Pb run at the end of the year.

Section 2 reviews the status of the LHC, discussing first the main results and lessons from 2015 and then the results already achieved in 2016. The prospects for the coming weeks and months are then discussed in Section 3, while Section 4 is devoted to the possibilities and challenges for the next years and decades.

2. Status

Figure 1 shows the evolution of the integrated luminosity since 2011. As can be seen, the most productive year so far was 2012, when the Higgs-like Boson was discovered and when the machine was operated with 50 ns bunch spacing at 8 TeV collision energy. Since 2015 the machine is operated with 25 ns bunch spacing and at 13 TeV collision energy, which significantly changed the picture, as will be discussed below. This is why until the LHCP conference in August 2015 only a very small amount of luminosity was integrated and this is also why since LHCP2015 only a modest amount of luminosity has been collected. However, it can be observed that the slope of the integrated luminosity over the last few weeks is impressive and very promising for the future.

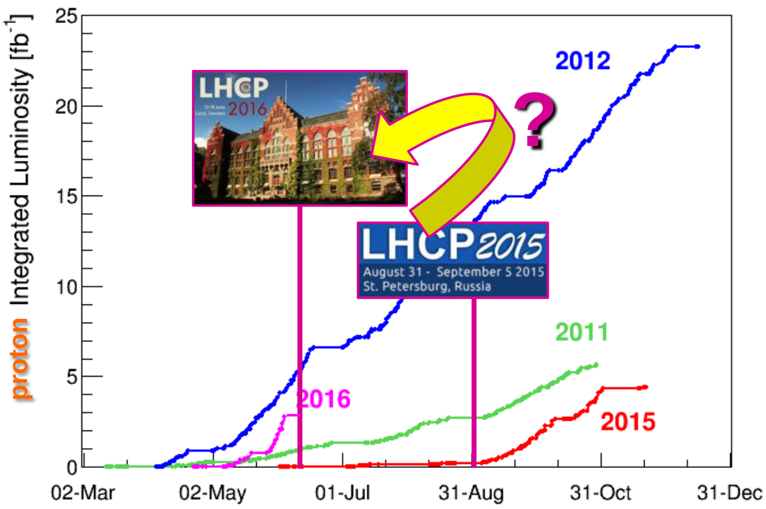

Figure 1: Evolution of the integrated luminosity over the last years and since the last LHCP2015 conference. Courtesy of J. Wenninger.

2.1. 2015

The main LHC and beam parameters used in 2015 are collected in Table 1, where they are compared to the nominal values [2] and to the values used in 2012. The value of 6.5 TeV for the maximum beam energy was first chosen (instead of the nominal 7 TeV) due to the required important number of additional training quenches to reach the nominal energy. The value of 80 cm for the β* at IP1&5 (instead of the nominal 55 cm) was chosen to try and reduce as much as possible the beam-beam long-range effects (as, in particular, instabilities were observed in 2012 at the end of the betatron squeeze, which could not be mitigated), to start smoothly and concentrate first on the main expected limiting effect, which should be electron cloud (e-cloud). This was a good choice as, as will be seen below, 2015 was a challenging year due to the operation with 25 ns bunch spacing and the limitations imposed by e-cloud on the available cooling capacity and some hardware issues. The bunch intensity and transverse emittances were almost nominal, i.e. the beam brightness was also almost nominal and therefore about two times smaller than in 2012. However, the number of bunches per LHC injection was limited to 144 (with 4 batches of 36 bunches from the SPS) due to a hardware issue with the LHC injection protection target dump (see Fig. 2), called TDI (Target Dump Injection) [3]. The hardware issue was due to nonconformities observed on the individual blocks of hBN (hexagonal Boron Nitride) composing the TDI (see Fig. 2(lower left)). Furthermore, during the year larger impedances (both longitudinal and transverse) and vacuum spikes were observed on the TDI at the injection point 8 (TDI8), where an issue with the Titanium coating was revealed at the end of the year, when the equipment was removed, checked and measured (see Fig. 2(lower right)) [3]. The reason for which we injected the 144 bunches in the LHC in 4 batches of 36 bunches from the SPS (instead of 2 batches of 72 bunches) was to reduce the e-cloud induced heat load as we were running at the limit of the cryogenics cooling capacity, as can be seen in Fig. 3(middle), which perturbed the intensity ramp-up during the full year: the head-load limit is ~ 3 W/m or ~ 160 W for a half cell (whose length is ~ 53 m). The progress during 2015 was therefore limited by the e-cloud heat load and the available cooling capacity on the arc beam screens but also by the transient heat loads (this will be solved for the 2016 run). As can be seen from Fig. 3, a huge difference exists between the different sectors (with a factor ~ 2-3), the sector S12 being the worst, which has not been understood yet. If all the sectors would behave like the less critical ones, the situation would therefore be much easier. The 2015 scrubbing run was perturbed by the fact that we could not scrub with 288 bunches due the TDI issues, and we could not then use the special "doublet beam" to scrub even more, as we should not run at the cryogenics limit to have sufficient margin [4]. The results of the scrubbing run are summarized in Fig. 4, where it can be seen that the Secondary Emission Yield (SEY) was reduced from ~ 2.4 down to ~ 1.4. It was then decided to continue the scrubbing using the more efficient beam in physics. In two months of physics (with the 25 ns beam) the accumulated electron dose was 94 mC/mm^2 whereas only 6 mC/mm^2 was accumulated during the scrubbing run. This dose should have been more than enough to remove the electrons from the arcs, but this was not the case and an important e-cloud remained during all the year.

Many lessons have been learned during this first year of operation with the 25 ns beam. First, due to the presence of the important e-cloud and the high values of chromaticities and Landau octupoles current necessary to stabilize the beam, the working point at injection needed to be optimized to accommodate the large tune spread which was hitting the third order resonance and which was generating beam losses at the end of the batches [5]. The working point was moved (see Fig. 5(left)) from (0.28,0.31) to (0.275,0.295). The improvement in the beam lifetime by lowering the vertical tune can be clearly seen in Fig. 5(right). A second observation was that the Laslett tune shifts [6] needed to be well compensated as the transverse tunes were now closer to each other and in the presence of uncorrected linear coupling (described by the closest tune approach, denoted $|C^-|$) some instabilities could be observed (see Fig. 6). A third important observation was that a train of 72 bunches required about 5 times more Landau octupoles current at 6.5 TeV to reach beam stability than predicted from impedance and related beam instability only on 28/08/2015, whereas on 05/11/2015 (i.e. after some scrubbing [5]) the required Landau octupoles current was compatible with impedance predictions, as can be observed in Fig. 7. Furthermore, the first instability observed on 28/08/2015 was clearly different from the one on 05/11/2015 as the synchronous phase shift was ~ 0.8 deg (revealing the presence of an important e-cloud) compared to ~ 0.3 deg for the second instability, the instability rise-time was ~ 0.5-1 s compared to ~ 15-20 s in the second case and finally the first instability revealed one node (when several consecutive traces of the headtail monitor were superimposed), whereas two nodes were revealed later (in agreement with the predictions from the impedance-induced instabilities) [9].

It is worth mentioning that in 2015 the rms bunch length was ~ 10 cm (compared to the nominal value of ~ 7.5 cm, corresponding to a full, 4σ, bunch length of ~ 1 ns) due to e-cloud heat load reasons whereas it was also increased in 2012 to ~ 10 cm but at that time the main reason was the beam-induced RF heating [10]. In the end only a modest peak luminosity of ~ 0.5 10^{34} cm^{-2}s^{-1} could be reached in 2015. In 2015, we also saw for the first time the clear effect of synchrotron radiation with a proton machine, as the excellent luminosity lifetime allowed for long fills [11]. In the longitudinal plane, the full bunch length reduced from ~ 1.3 ns down to ~ 0.85 ns when the bunch became unstable (depending on the bunch intensity) due to the loss of longitudinal Landau damping (see Fig. 8) [12]. The means to avoid this kind of instability is to increase the RF voltage (the maximum nominal value is 16 MV) or perform some controlled blow-up or profile flattening [13]. In the transverse plane, as can be seen from Fig. 9, an horizontal growth of ~ 0.03 μm / h and a vertical shrinkage of ~ 0.02 μm / h were observed. Compared to predictions from Synchrotron Radiation (SR) and Intra-Beam Scattering (IBS), it can be seen that some sources of emittance growth (mainly in the horizontal plane) still need to be identified and quantified. The worry about the possible luminosity difference between ATLAS and CMS (which lasted during the full year and finally the ATLAS luminosity was found to be too high by ~ 3% whereas the CMS luminosity was found to be too low by ~ 4%) triggered additional optics studies, which revealed that i) the measured β at the IP was larger than expected (~ 84 cm instead of the foreseen 80 cm), ii) the waist position was shifted by 20 cm with respect to the IP and iii) the crossing angles were ~ 10−20% larger than expected (see Fig. 10) [14]. As concerns the UFOs (Unidentified Falling Objects) [15], it was realized during the year that most of the events that caused dumps would not have caused quenches (see Fig. 11). The policy then changed and the BLM thresholds were increased to avoid dumping on UFOs as a strategy to maximize the availability. In addition to the UFOs, a ULO (Unidentified Lying Object) was also revealed as an aperture restriction in MB.C15R8 (see Fig. 12): the BLM thresholds around 15R8 were lowered to avoid quenches and a bump was introduced to avoid the aperture restriction, which allowed operation without any problem [16]. To conclude the

2015 review, it is worth reminding also that the radiation failures on the quench protection tunnel electronics was solved during the Technical Stop 2 and that several operations have been improved / automated: (i) co-existence between tune feedback and transverse damper (gating); (ii) tune and chromaticity drift and snapback well controlled thanks to the cooperation between FiDeL and tune feedback; (iii) tune dependence on intensity at injection studied and quantified (which will be automatically corrected in 2016). Finally, some Inner Triplet (IT) movements were observed and were being followed up as will be reported later.

The Pb-Pb ion run took place as foreseen, with a number of new features, and it was very successful (see Fig. 13) [17]: more than the expected number of bunches could be used, the BFPP quench test confirm past predictions and the design luminosity was finally exceeded by a factor 3.6. The evolution of the integrated nucleon-pair luminosity over all the ion runs is shown in Fig. 14, where it can be seen in particular that an integrated nucleon-pair luminosity of slightly more than 30 pb^{-1} has been already accumulated in ATLAS in 2015, to be compared to the goal of 43 pb^{-1} to be accumulated in the first decade of operation.

Parameter	Nominal	2012	2015
Energy [TeV]	7	4	6.5
Bunch spacing [ns]	25	50	25
Bunch population [10^{11}]	1.15	1.6	1.15
Bunches / LHC injection	288 (4×72)	144	144 (4×36)
Total number of bunches	2748 (2808 in DR)	1374	2244
Collisions in IP1&5	2736 (2808 in DR)	1368	2232
Transv. emittance [μm]	3.75	2.2	3.5
Brightness [10^{11} / μm]	0.31	0.73	0.33
β* in IP1&5 [cm]	55	60	80
X-angle in IP1&5 [μrad]	142.5	145	145
Rms bunch length [cm]	7.55	10	10
Peak lumi [10^{34} $cm^{-2}s^{-1}$]	**~ 0.99** (1)	**~ 0.77**	**~ 0.5**

Table 1: Comparison between the main LHC and beam parameters: i) from the Design Report (DR), ii) used in 2012 and iii) used in 2015.

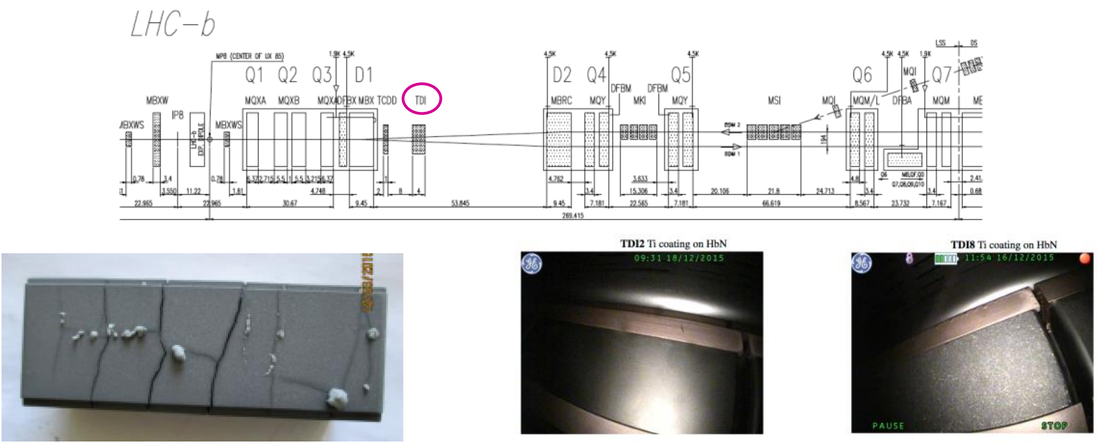

Figure 2: (Upper) position of the TDI at the injection point 8 (TDI8). (Lower left) nonconformities observed on the individual blocks of hBN (hexagonal Boron Nitride) composing the TDI. (Lower right) TDI8 Ti coating issue, which was not observed on the TDI at the injection point 2 (TDI2). Courtesy of N. Biancacci.

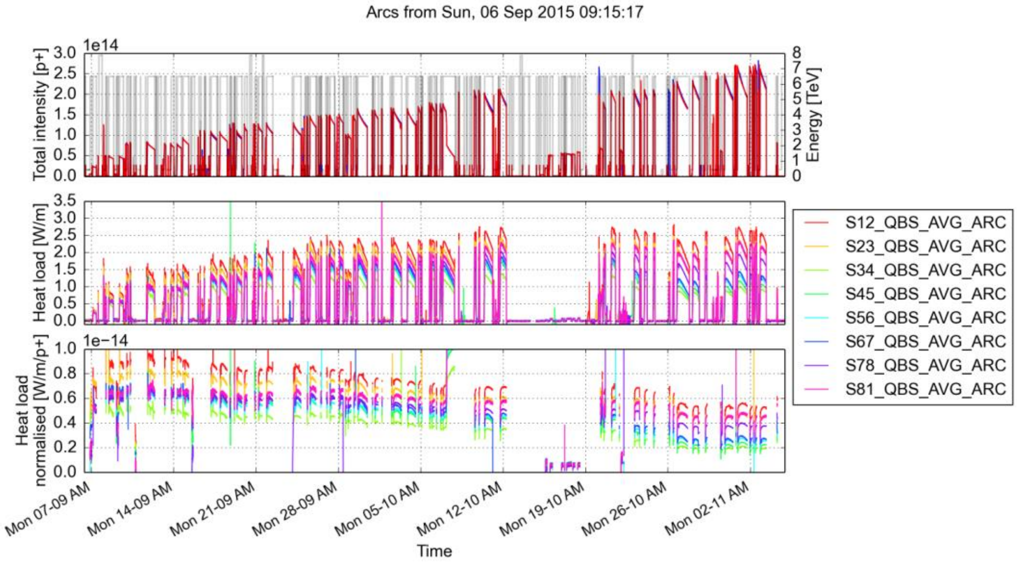

Figure 3: Evolution of the (e-cloud induced) heat load in the 8 LHC sectors during 2015. Courtesy of G. Iadarola.

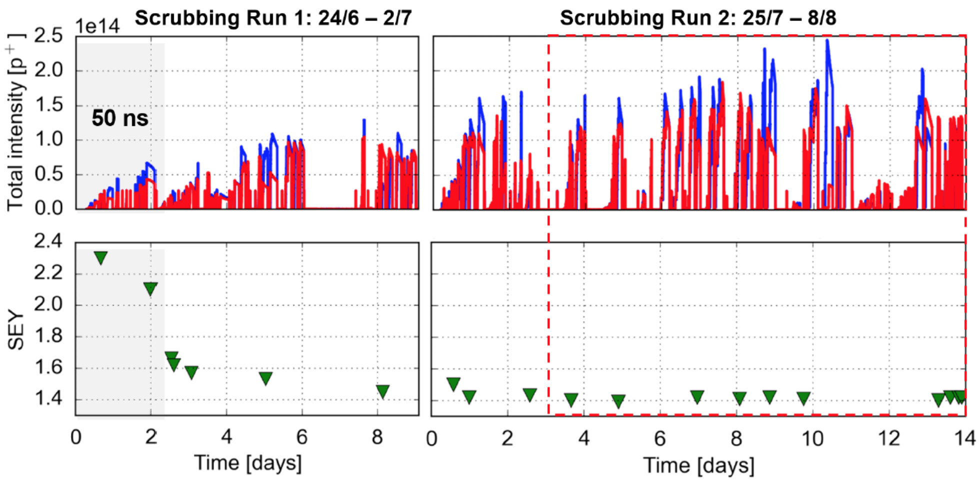

Figure 4: Evolution of the Secondary Emission Yield (SEY) during the two periods of the 2015 scrubbing run. Courtesy of G. Iadarola.

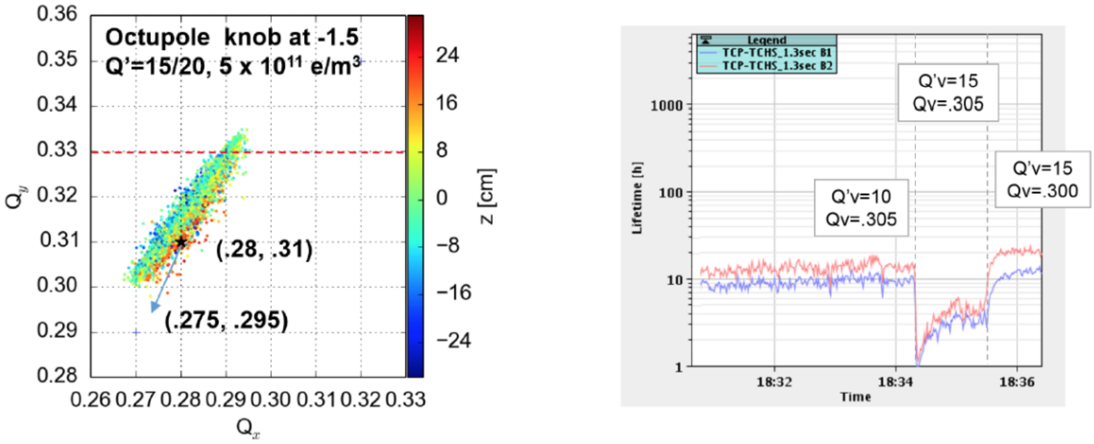

Figure 5: Optimization of the working point at injection. Courtesy of A. Romano.

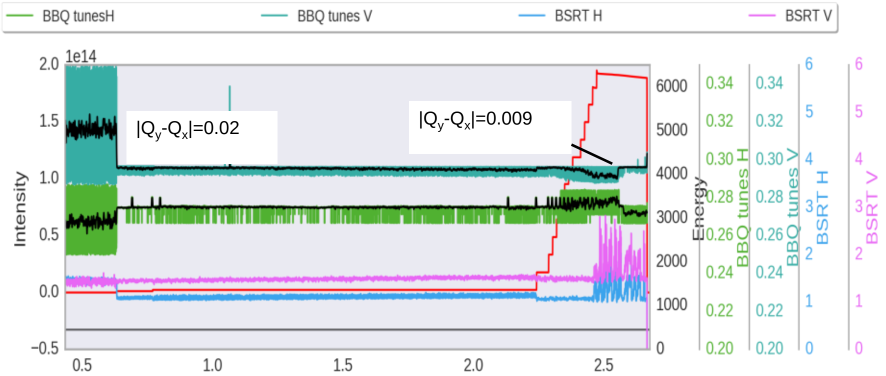

Figure 6: Observation of transverse beam instabilities during the injection process when the Laslett tune shifts were not corrected. Courtesy of L.R. Carver.

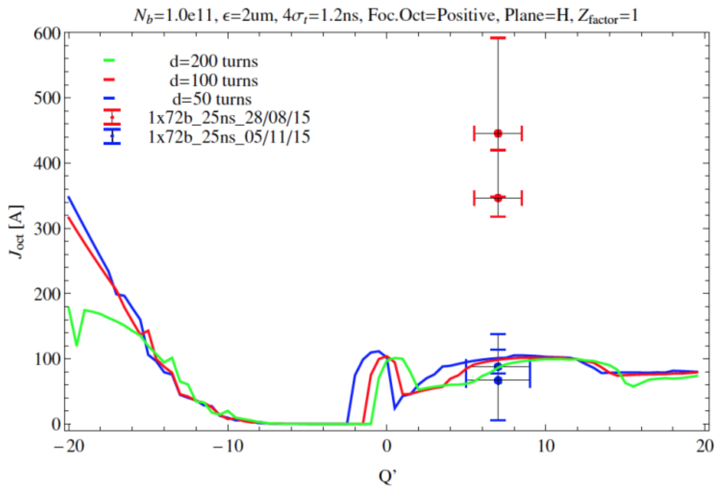

Figure 7: Instabilities observed at 6.5 TeV with a train of 72 bunches, which required about 5 times more Landau octupoles current to reach beam stability than predicted from impedance and related beam instability only. These instabilities disappeared after slightly more than one month of scrubbing. The predictions were made with DELPHI [7,8], assuming a perfect transverse damper. Courtesy of L.R. Carver.

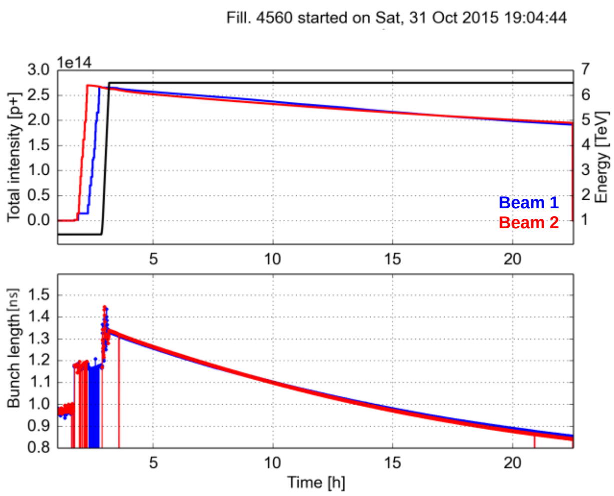

Figure 8: Evolution of the bunch length during a long fill. Courtesy of G. Iadarola.

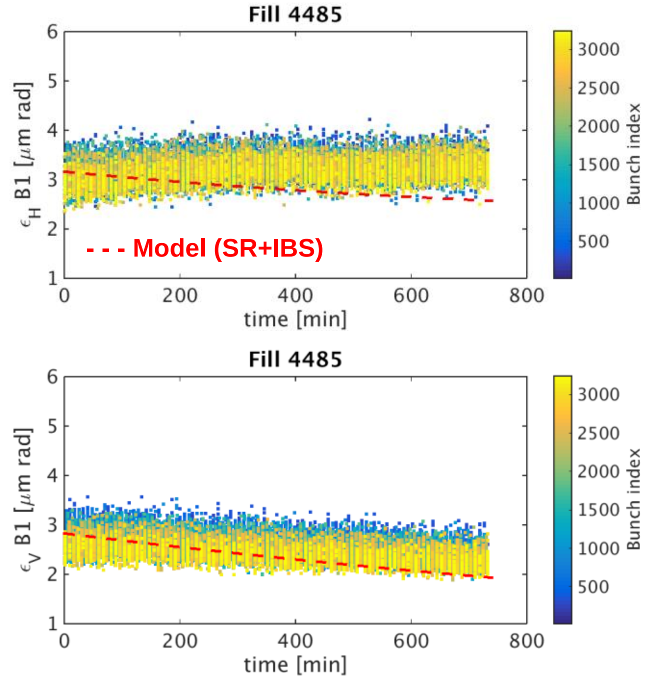

Figure 9: Evolution of the transverse emittances in stable beams. Courtesy of F. Antoniou.

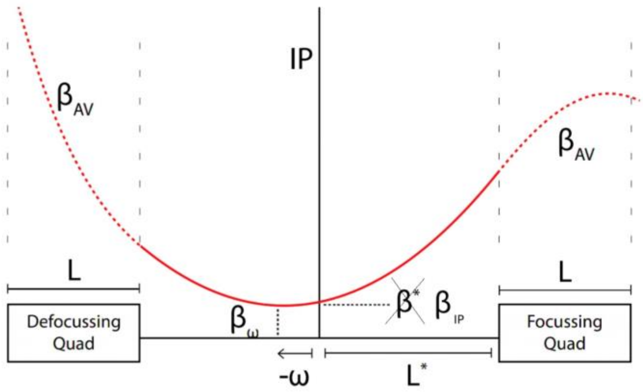

Figure 10: Optics measurements at the IP revealing a larger β*, a shift of the waist position and larger crossing angles than foreseen. Courtesy of T. Persson.

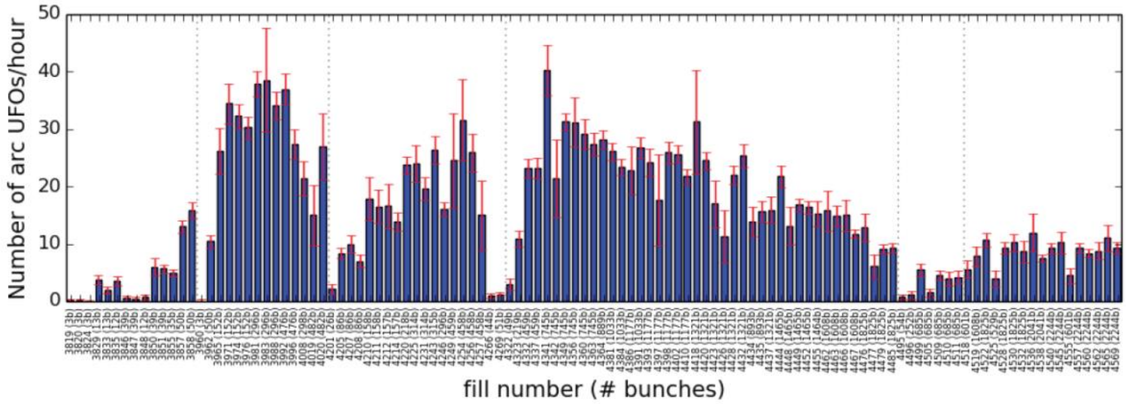

Figure 11: Evolution of the number of arc UFOs per hour vs. time. Courtesy of G. Papotti.

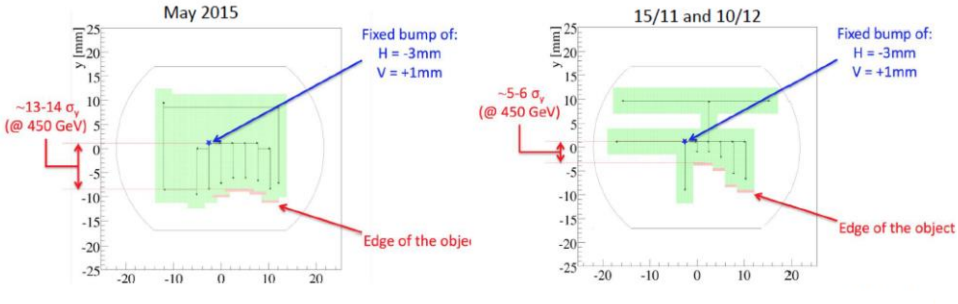

Figure 12: ULO leading to an aperture restriction in MB.C15R8. Courtesy of D. Mirarchi.

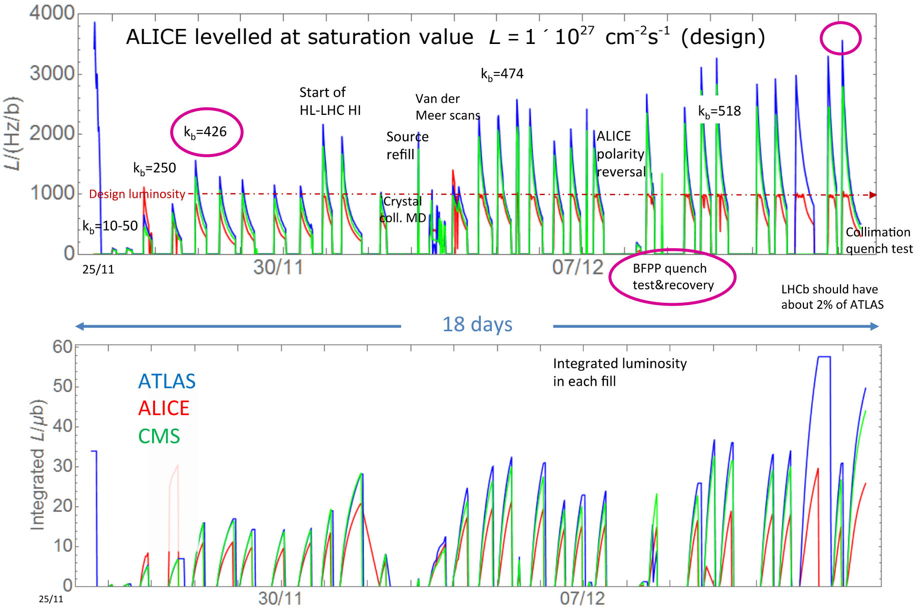

Figure 13: Summary of the 2015 Pb-Pb ion run vs. time. Courtesy of J. Jowett.

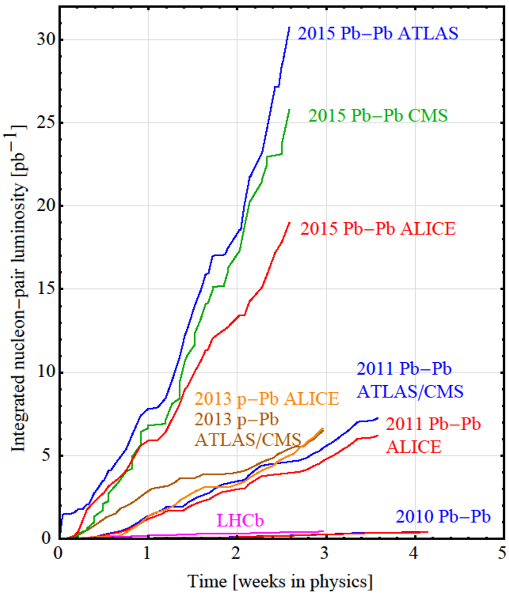

Figure 14: Evolution of the integrated nucleon-pair luminosity over all the ion runs. NB: the 2012 pilot p-Pb run is not shown. It was only one fill but with major physics output. Courtesy of J. Jowett.

2.2. 2016 (already done)

The main LHC and beam parameters used so far in 2016 are collected in Table 2, where they are compared to the nominal values, the values used in 2012 and the values used in 2015. The main improvement so far in 2016 was to reduce the β* from 80 cm down to 40 cm, which worked very well [18]. The measured peak β-beating at 40 cm was ~ 5% (see Fig. 15), which is an excellent result as it gives then more available aperture. Furthermore, a phase knob has been introduced to protect the TCTs (Tertiary Collimators) from asynchronous dumps and to push the β* (see Fig. 16) [19]. In summary, the optics was extremely well controlled [20]. The long-term stability still needs to be checked in the future. As concerns the collimation system, after several years of studies and hardware modifications to reduce the margins while ensuring adequate protections in case of fast beam failures, the stored energy reached 270 MJ at 6.5 TeV (to be compared to the 360 MJ from the design) and no quench of a magnet due to cleaning losses has been observed yet. Some new collimators with integrated BPMs (Beam Position Monitors) have been installed, which considerably reduced the collimator alignment time (see Fig. 17) [21]. The cleaning efficiency is excellent: the highest cold losses are at the level of ~ 10^{-4}. The crossing angle has been set to 185 μrad knowing that some margin should exist and that a possible reduction could happen later in the run after detailed beam-beam long-range and dynamics aperture studies. An almost nominal bunch intensity, transverse emittance and therefore bunch brightness were used so far, similarly to 2015. The number of bunches from the SPS had to be reduced even further compared to 2015 due to another hardware issue, a vacuum leak this time of the SPS beam dump (called TIDVG). Therefore, only batches of 72 bunches could be injected into the LHC at a time, which limited the number of bunches in the LHC so far to 2040 bunches. The bunch length was still kept longer than nominal, but slightly lower than before, i.e. ~ 9.4 cm instead of ~ 10 cm before. With all these parameters, the record peak luminosity of 2012 (i.e. ~ 77% of the design luminosity) could be reached again but now with 25 ns bunch spacing (instead of 50 ns) and at 6.5 TeV (instead of 4 TeV). The evolution of the heat load vs. time is depicted in Fig. 18. It is worth mentioning that due to several hardware issues, only ~ 12 h of dedicated scrubbing run could take place in 2016, which was sufficient to recover the 2015 performance but no sign of further reduction has been observed so far (it can be seen from Fig. 18 that the heat load is still high and close to the limit of ~ 160 W). The cryogenics feed-forward, which has been introduced for the 2016 run, works very well and there is no limitation anymore in the transients, which eased a lot the intensity ramp-up.

E-cloud is still very important in the LHC, which requires to use high values of chromaticities and Landau octupoles current. However, despite the high value of chromaticities (~ + 15 units), a new type of transverse instability, called "popcorn instability" has been observed after few hours in stable beams (see Fig. 19) [22]. This instability happened on both beams, only in vertical plane, at the end of trains of 72 bunches with an emittance blow-up of a factor ~ 2 and no beam loss. It was cured by increasing the chromaticity even more, to ~ + 22 units. Some instabilities were also predicted when linear coupling between the transverse planes is not well corrected and such an instability was observed at ~ 2 m during betatron squeeze (see Fig. 20) [22]. This measurement confirmed (for the first time) that a factor ~ 4-5 times more Landau cotupoles current can be required if linear coupling is not well corrected. As a consequence, careful measurements and corrections of linear coupling all along the LHC cycle are needed.

As concerns the IT movements and beam separation, we know, since 2015, that we are sensitive to the temperature of the IT thermal shields (50K-80K). In 2015 mostly the triplet in IR8 was affected, whereas in 2016 the amplitude of the effect is smaller by a factor of 2-3, and predominantly affects the triplet in IR1 (see Fig. 21). The aim is to operate IR1 and IR5 at ~ 70K ± 10K after the Technical Stop 1 [23]. To conclude the review of the 2016 operation so far, the UFOs rates are similar to those at the end of 2015, no beam-induced RF heating issues have been observed (thanks to a lot of work with the equipment groups since 2012), the situations with the TDIs is much better in 2016 compared to 2015 (with the Ti coated HbN replaced by Cu coated graphite). Some issues are still observed with the TDI8, which need to be full understood. Some time could be gained in the cycle using a combined ramp and squeeze (down to 3 m in IP1&5) and using a 3.5 TeV pre-cycle instead of 6.5 TeV, which should come into operation soon. The lessons learned from 2015 were implemented and automatic corrections continued, such as the Laslett tune shifts correction at injection (see Fig. 22) [24].

Parameter	Nominal	2012	2015	2016 (done)
Energy [TeV]	7	4	6.5	6.5
Bunch spacing [ns]	25	50	25	25
Bunch population [10^{11}]	1.15	1.6	1.15	1.15
Bunches / LHC injection	288 (4×72)	144	144 (4×36)	72 (1×72)
Total number of bunches	2748 (2808 in DR)	1374	2244	2040
Collisions in IP1&5	2736 (2808 in DR)	1368	2232	2028
Transv. emittance [μm]	3.75	2.2	3.5	3.4
Brightness [10^{11} / μm]	0.31	0.73	0.33	0.34
β* in IP1&5 [cm]	55	60	80	40
X-angle in IP1&5 [μrad]	142.5	145	145	185
Rms bunch length [cm]	7.55	10	10	9.4
Peak lumi [10^{34} cm^{-2}s^{-1}]	**~ 0.99** (1)	**~ 0.77**	**~ 0.5**	**~ 0.77**

Table 2: Comparison between the main LHC and beam parameters: i) from the Design Report (DR), ii) used in 2012, iii) used in 2015 and iv) used so far in 2016.

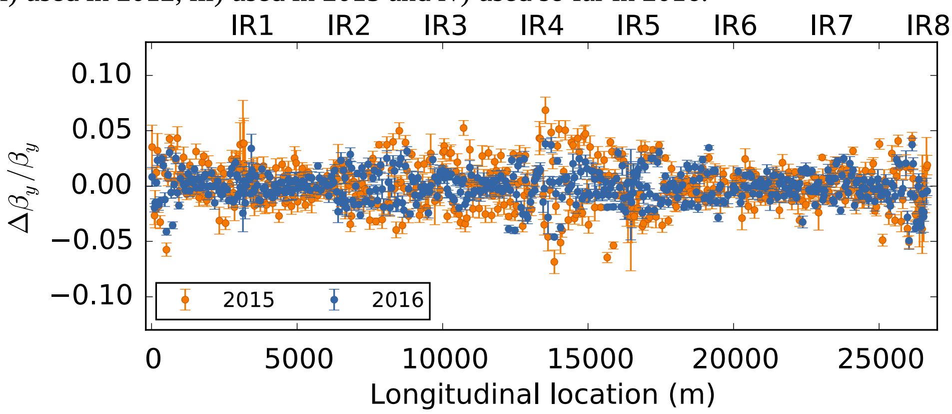

Figure 15: Measured peak β-beating at 40 cm of ~ 5%. Courtesy of R. Tomas.

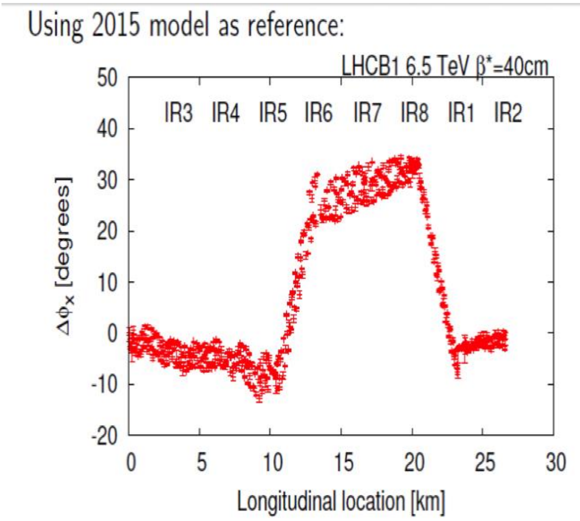

Figure 16: Phase knob to protect the TCTs from asynchronous dumps and to push the β*. Courtesy of R. De Maria.

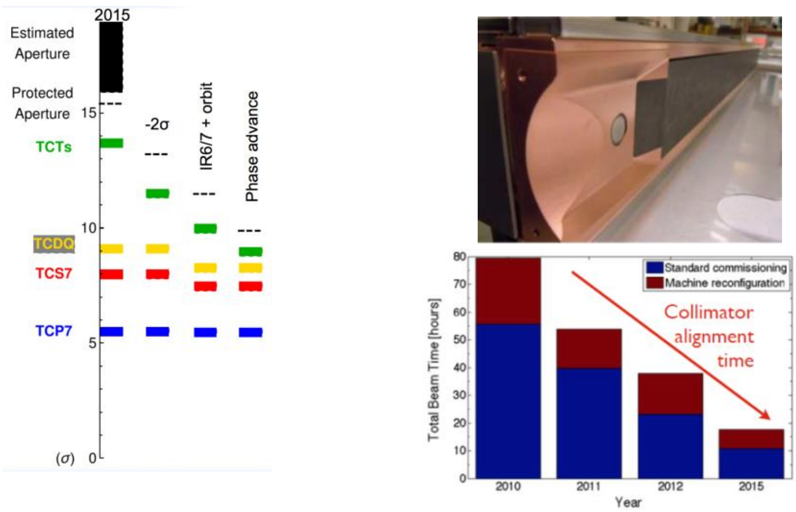

Figure 17: Reduction of the collimator alignment time over the years. Courtesy of S. Redaelli.

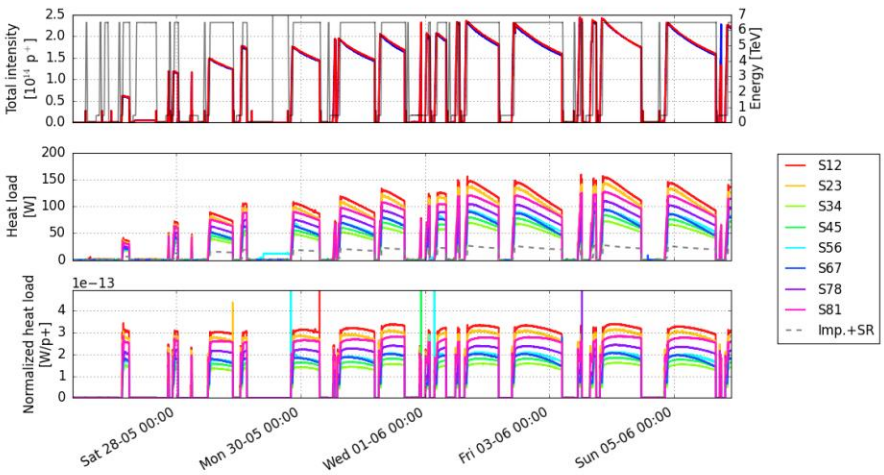

Figure 18: Evolution of the heat load in the 8 LHC sectors since the beginning of the 2016 run. Courtesy of G. Iadarola.

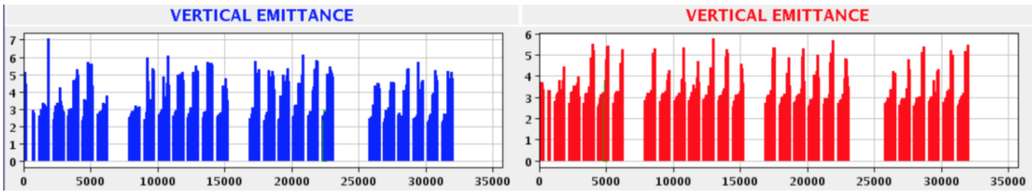

Figure 19: Transverse instability observed for the first time in the LHC after few hours of stable beams, called "popcorn instability".

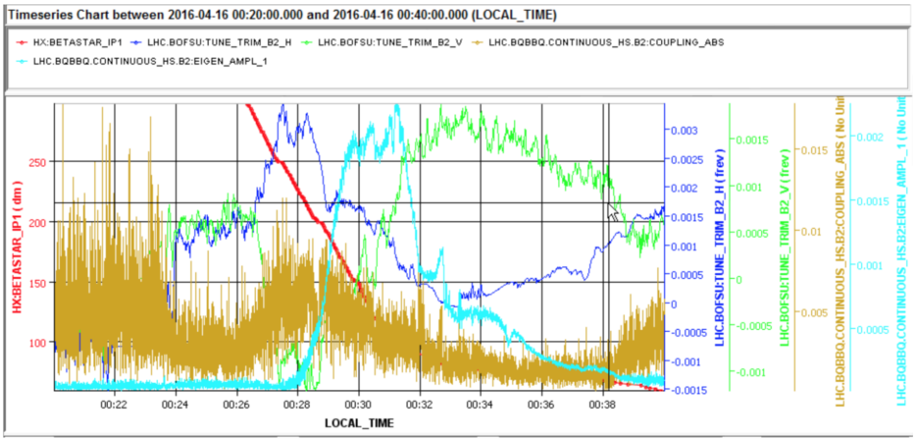

Figure 20: Transverse instability (in the horizontal plane of the Beam 2) due to linear coupling between the transverse planes at ~ 2 m during betatron squeeze.

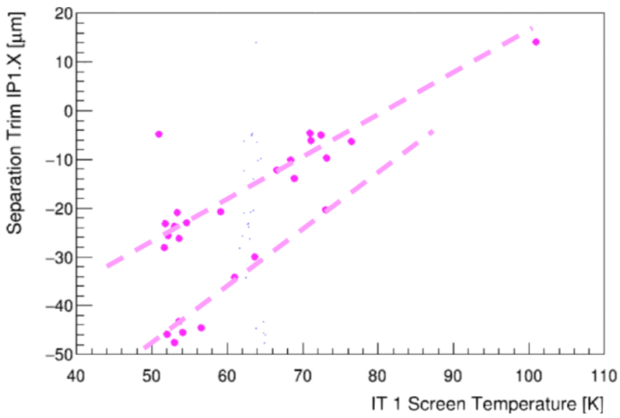

Figure 21: Inner Triplet (IT) movements and beam separation vs. the temperature of the IT thermal shield. Courtesy of J. Wenninger.

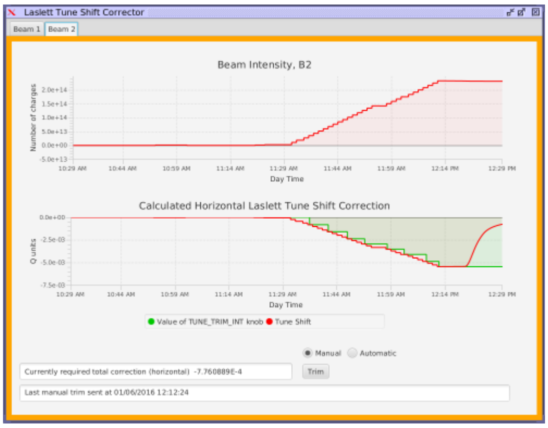

Figure 22: Automatic correction of the Laslett tune shifts at injection. Courtesy of J. Wenninger.

3. Prospects

The goals for 2016 are shown in Fig. 23: more than ~ 5 fb^{-1} should be accumulated for mid-July and ~ 25 fb^{-1} by the end of the run. The recently updated LHC schedule for 2016 is shown in Fig. 24, and the activities breakdown is depicted in Fig. 25 [25]. As can be seen from Fig. 23, the slope of integrated luminosity reached so far is very promising for the 2016 run and it should be possible soon to reach more than that design peak luminosity (see Table 3). Increasing a bit the intensity per bunch and using the nominal bunch length should be enough to reach the design peak luminosity. Then, even higher peak luminosities could be reached by i) decreasing the transverse emittances using the BCMS beam, ii) reducing the crossing angle as some margin exists and iii) increasing the number of bunches from the SPS depending on the state of its beam dump (TIDVG). Overcoming the design peak luminosity by few tenths of percent seems therefore within reach. For completeness, the plan for the p-Pb run at the end of the year is mentioned in Fig. 26 [26].

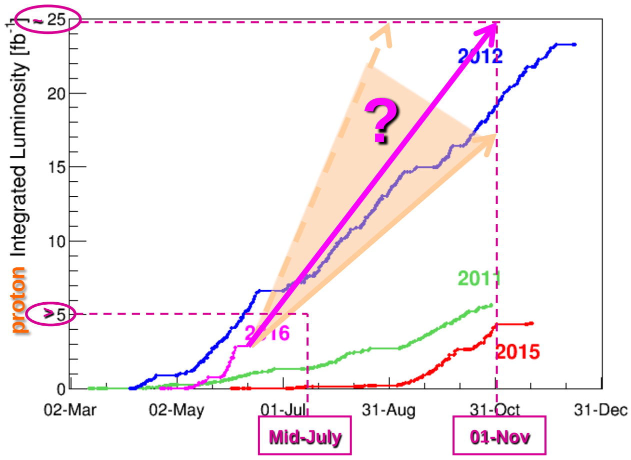

Figure 23: Goals for 2016.

Figure 24: Recently updated LHC schedule for 2016. Courtesy of M. Lamont.

Phase	Cham	April 23	June 1
Initial Commissioning	28	28	28
Scrubbing: 4 days + ad hoc	7	7	2
Technical issues	-	-	12+2
Proton physics 25 ns	**152**	**145**	**141**
Special physics runs	8	8	8
Machine development	22	22	20
Technical stops	15	15	12
Technical stop recovery	6	6	6
Ion setup/proton-lead run	4 + 24	4 + 24	4 + 24
Total	266 days (38 weeks)	259 days (37 weeks)	259 days (37 weeks)

Figure 25: Activities breakdown after the recently updated LHC schedule for 2016. Courtesy of M. Lamont.

Parameter	Nominal	2016 (done)	2016 (possible?)
Energy [TeV]	7	6.5	
Bunch spacing [ns]	25	25	
Bunch population [10^{11}]	1.15	1.15	1.25 (?)
Bunches / LHC injection	288	72	SPS dump limit?
Total number of bunches	2748 (2808 in DR)	2040	
Collisions in IP1&5	2736 (2808 in DR)	2028	↗ (?)
Transv. emittance [μm]	3.75	3.4	3.5 (?) ↘ (BCMS?)
Brightness [10^{11} / μm]	0.31	0.34	
β* in IP1&5 [cm]	55	40	
X-angle in IP1&5 [μrad]	142.5	185	↘ (?)
Rms bunch length [cm]	7.55	9.4	7.55 (?)
Peak lumi [10^{34} cm^{-2}s^{-1}]	**~ 0.99** (1)	**~ 0.77**	**1 => 1+**

Table 3: Comparison between the main LHC and beam parameters: i) from the Design Report (DR), ii) used in 2016 so far and iii) which should be possible later during the run.

	M	T	W	T	F	S	S
week1	set up 5	set up 5	set up 5	5 TeV	5 TeV	5 TeV	5 TeV
week2	5 TeV	5 TeV*	set up 8	set up 8	set up 8	set up 8	8 TeV
week3	8 TeV	8 TeV	8 TeV	8 TeV	8 TeV / LHCf run*	LHCf run* / reversal	reversal
week4	reversal / 8 TeV	8 TeV	8 TeV	8 TeV	8 TeV	8 TeV	MD

operation	days
5 TeV setup	3
8 TeV setup (both directions)	4
direction reversal	2
MD	1
LHCf run	1 (hopefully less than 12hrs)
5 TeV data taking	6
8 TeV data taking	11 days (5.5 for each direction)
Total	28 days (= 4 weeks)

*-source re-fill

Provide luminosity with collisions at 2 different c.m energies

Shorthand:
5 TeV = $\sqrt{s_{NN}}$ = 5.02 TeV
8 TeV = $\sqrt{s_{NN}}$ = 8.16 TeV

3

Figure 26: Plan for the p-Pb run at the end of 2016. Courtesy of J. Jowett.

4. Future challenges

The plan for the next years and decades is shown in Fig. 27 [1], while Fig. 28 reviews the full heavy-ion programme [17]. It is worth noting that the next p-Pb run, after the one of this year, is planned for 2028, i.e. in more than 10 years. As concerns the proton programme, ~ 100 fb^{-1} should be collected by the end of the Run 2, ~ 300 fb^{-1} by the end of the Run 3 and ~ 3000 fb^{-1} by 2035. The key ingredient for the success will be the machine availability, towards which all the efforts should converge. Some answers to important questions still need to be found: how will the LHC conditioning evolve? Will we be able to remove the e- from the dipoles? Why is there such a huge difference between the different sectors? One still need to fully demonstrate the nominal performance of the LHC and possibly exceed it (looking closely to the scrubbing, beam stability, beam-beam limits, dynamic aperture and luminosity models, non-linear models and corrections, collimation performance, etc.) and envisage all the scenarios for its full exploitation (such as the ultimate energy, etc.). One should also explore the modes of operation in preparation for HL-LHC (with the new ATS optics, β* leveling, etc.) and validate key choices for the HL-LHC nominal and alternative scenarios and further optimize the cost and performance (with the crab cavities, the beam-beam long-range compensation, etc.) [27].

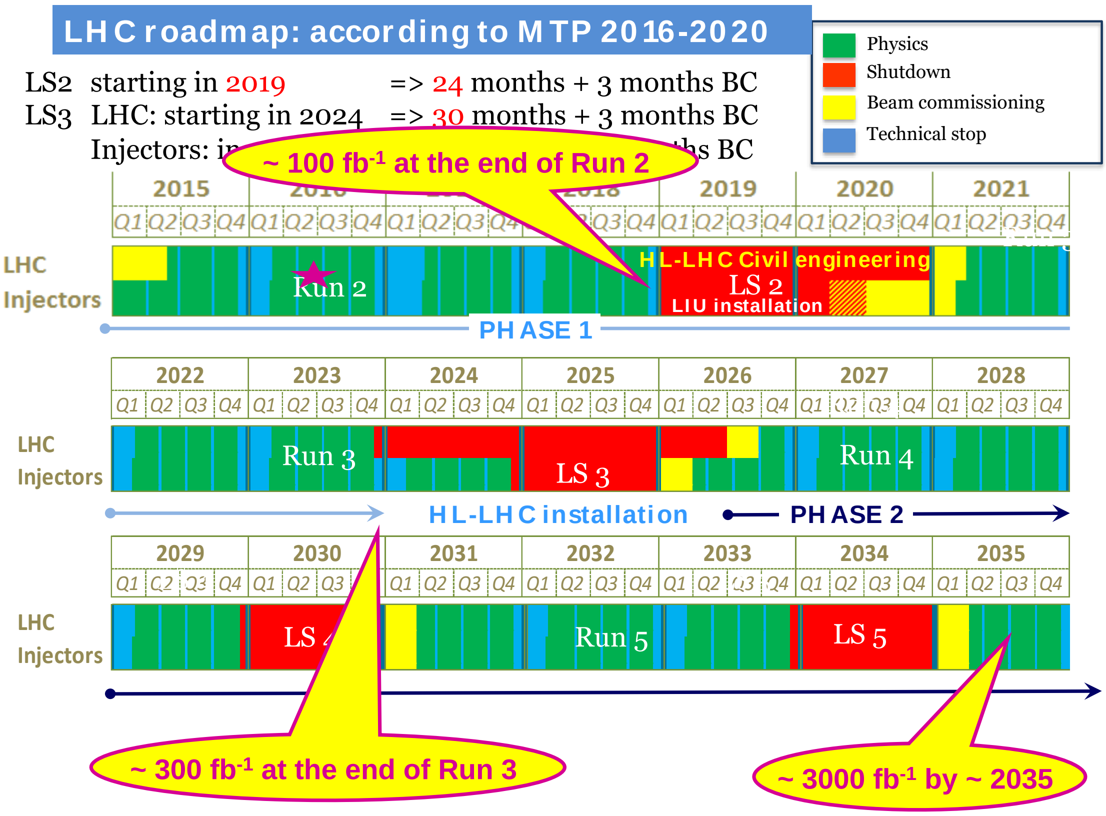

Figure 27: LHC roadmap for the coming two decades. Courtesy of F. Bordry.

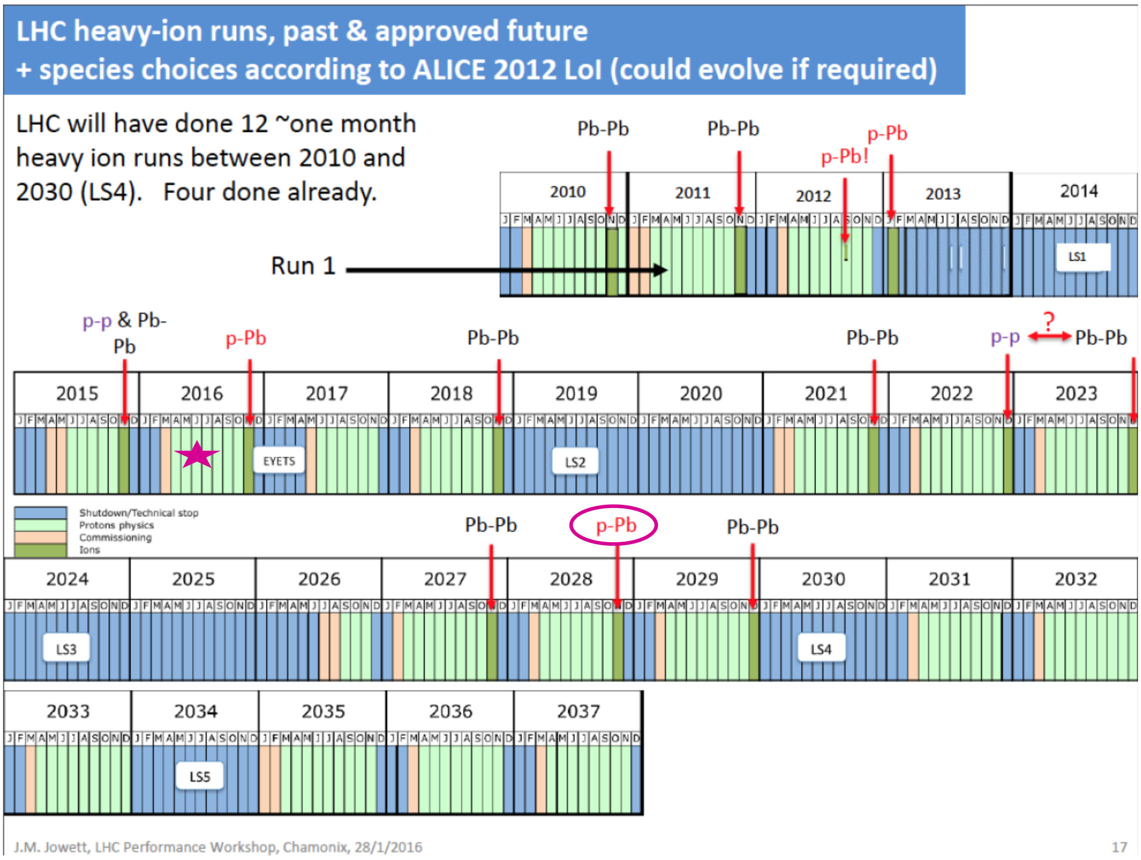

Figure 28: Plan for the LHC heavy-ions runs. Caveat: some discussions are still ongoing. Courtesy of J. Jowett.

5. Conclusions

The 2016 luminosity production has been hindered so far by (many) hardware faults in the injectors (and the weasel in the LHC): i) Linac2 vacuum leak, ii) proton source vacuum leak, iii) SPS beam dump (TIDVG) vacuum leak, iv) PS main power converter (POPS) and v) PS rotating machine.

However, everything is in place for a great 2016 year at 6.5 TeV and 25 ns bunch spacing, to reach all the goals, i.e. more than ~ 5 fb^{-1} by mid-July (~ 3 fb^{-1} were already collected by the Technical Stop 1), ~ 25 fb^{-1} by November and a p-Pb run during 4 weeks (mid November – mid December).

The slope of the integrated luminosity reached recently is very promising for the 2016 run and the record peak luminosity of 2012 (i.e. ~ 77% of the design luminosity) has been already reached again but now with 25 ns bunch spacing (instead of 50 ns) and at 6.5 TeV (instead of 4 TeV). Furthermore, a new record peak luminosity was reached yesterday (see Fig. 29) and the design peak luminosity should be reached and exceeded soon. The exploration of the new energy frontier can really begin!

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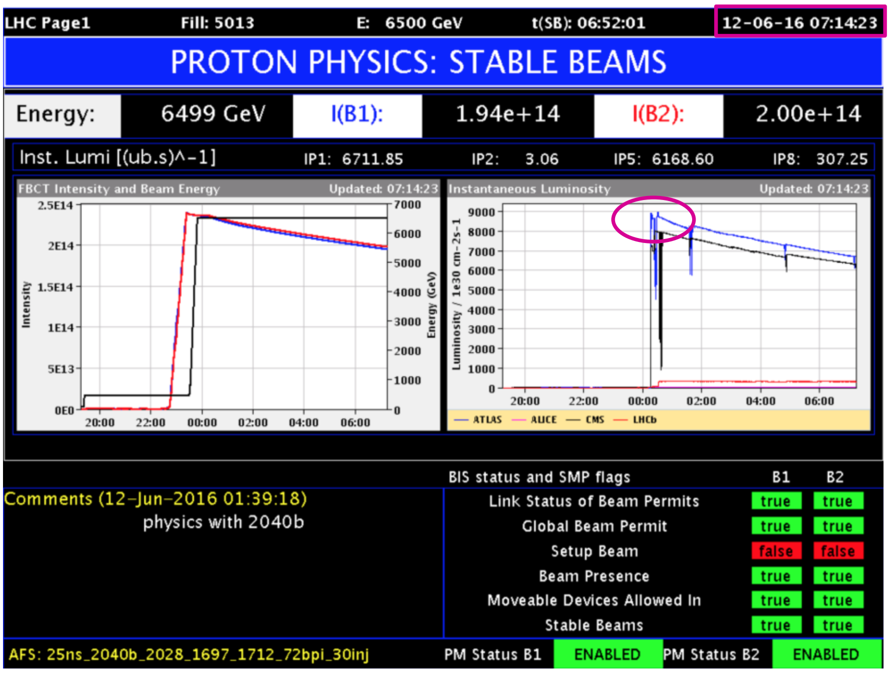

Figure 29: New record peak luminosity reached yesterday.

Acknowledgements

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References

[1] F. Bordry, *Recommendations and general discussion*, Summary session of the LHC Performance Workshop - Chamonix 2016, CERN, 03/03/2016 (https://indico.cern.ch/event/486336/contributions/2006462/attachments/1238124/1824002/Fk_Bordry_Chamonix_2016_Conclusions_final.pdf).

[1] (Ed.) O. Brüning et al., *LHC Design Report*, CERN-2004-003 (Vol. I), 4 June 2004.

[2] N. Biancacci et al., *Impedance measurements and simulations on the TCT and TDI LHC collimators*, Proceedings of IPAC2016, May 2016, Busan, Korea.

[3] G. Iadarola et al., *Scrubbing: expectations and strategy, long range perspective*, Proceedings of the LHC Performance workshop (Chamonix 2014), September 2014, Chamonix, France.

[4] K. Li et al., *Electron cloud observations during LHC operation with 25 ns beams*, Proceedings of IPAC2016, May 2016, Busan, Korea.

[5] F. Ruggiero, Single-beam collective effects in the LHC, Proceedings of the Workshop on Large Hadron Colliders, October 1994, Montreux, Switzerland.

[6] N. Mounet, *DELPHI: an analytic Vlasov solver for impedance-driven modes*, CERN HSC meeting, 07/05/2014.

[7] E. Métral et al., *Beam Instabilities in Hadron Synchrotrons*, IEEE Trans. on Nucl. Sci., Vol. 63, NO. 2, April 2016 (invited contribution for the 50th anniversary of the PAC conference).

[8] L.R. Carver et al., *Current status of instability threshold measurements in the LHC at 6.5 TeV*, Proceedings of IPAC2016, May 2016, Busan, Korea.

[9] B. Salvant et al., *Expected impact of hardware changes on impedance and beam-induced heating during Run 2*, Proceedings of the LHC Performance workshop (Chamonix 2014), September 2014, Chamonix, France.

[10] G. Iadarola, *First time observed radiation effects for protons in LHC*, TWIICE2 workshop, February 2016, Oxford, England.

[11] J.F. Esteban Müller et al., *Beam measurements of the LHC impedance and validation of the impedance model*, Proceedings of IPAC2014, June 2014, Dresden, Germany.

[12] P. Baudrenghien et al., *Longitudinal emittance blow-up in the LHC*, Proceedings of IPAC2011, September 2011, San Sebastian, Spain.

[13] T. Persson et al., *β* corrections strategies*, CERN LBOC meeting, 24/11/2015.

[14] G. Papotti et al., *Macroparticle-induced losses during 6.5 TeV LHC operation*, Proceedings of IPAC2016, May 2016, Busan, Korea.

[15] D. Mirarchi, Investigation of the Unidentified Lying Object in C15R8, CERN LBOC meeting, 19/05/2016.

[16] J. Jowett, *Accelerator (collider) conditions in the near future*, 3rd International Conference on the Initial Stages in High-Energy Nuclear Collisions (InitialStages2016), Lisbon, Portugal, 27/05/2016.

[17] A. Langner et al., *LHC optics commissioning at β* = 40 cm and 60 cm*, CERN-ACC-NOTE-2015-0035, October 2015.

[18] R. De Maria, *Squeeze to 40 cm with phase constraints*, CERN LBOC meeting, 08/03/2016.

[19] T. Persson, *2016 optics measurements and corrections*, CERN LBOC meeting, 05/04/2016.

[20] G. Valentino et al., *First operational experience with embedded collimator BPMs in the LHC*, Proceedings of IPAC2016, May 2016, Busan, Korea.

[21] E. Métral et al., *Measurement and interpretation of transverse beam instabilities in the CERN Large Hadron Collider (LHC) and extrapolations to HL-LHC*, Proceedings of HB2016, July 2016, Malmö, Sweden.

[22] J. Wenninger, *Triplet movements and beam separation*, CERN LBOC meeting, 07/06/2016.

[23] J. Wenninger, *Machine status and plans for restart after TS1*, CERN LMC meeting, 08/06/2016.

[24] M. Lamont, *LHC schedule update*, CERN LMC meeting, 01/06/2016.

[25] J. Jowett, *Update on plan for the 2016 p-Pb run of LHC*, CERN LMC meeting, 08/06/2016.

[26] (Ed.) O. Brüning and L. Rossi, *The High Luminosity Large Hadron Collider*, World Scientific, 398 p, 2015.