SETTING THE SCENE

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OVERVIEW OF 2016

After four full years of LHC operations, sophisticated tools and experience mean that preparatory phases are executed without too much fuss. Hardware commissioning for 6.5 TeV operation, although intense in terms of a testing schedule, proceeded calmly. There was the usual high level of interest for first circulating beam on 25th March. This was followed by 4 weeks of relatively smooth commissioning with beam with the machine fully validated for β^* = 40 cm in this period. This led to first Stable Beams being declared on the 19 th April.

The effect of improved tools, experience, diagnostics and well-developed understanding of the key hardware systems was clearly apparent during commissioning. Two points of note: the reduced availability of key personnel for critical commissioning steps; and the need for iteration and the passage of time to resolve issues, particularly those relating to machine protection. The time freed up as a result during this period allowed the team to push forward operational development, preparation for special physics runs, and more exotic system development.

The first part of the operating period was hit by a number of serious problems in both the LHC and the injectors.

- 26th April: The development of a vacuum leak on the high energy internal dump (TIDVG) of the SPS. Caution subsequently limited the beam intensity injected from the SPS for the rest of the year.
- 27th April: Severe damage to a capacitor container of the PS POPS system. The rotating machine subsequently failed bringing the PS down for around 6 days.
- 29th April: Damage to the bushings of a 66 to 18 kV transformer initiated by curious beech marten.

After the POPS recovery, however, things progressed very well. The number of bunches was ramped up to 2040 per beam – the maximum with 72 bunches per injection. A bunch population of 1.1×10^{11} gave a peak luminosity of $\approx 8 \times 10^{33}$ cm^{-2}s^{-1}. Already at this stage this was coupled with excellent availability and the week Mon 30th May — Sunday 5th June saw:

- Record luminosity in a fill: 380 pb^{-1}
- Record luminosity per day: 390 pb^{-1}
- Record luminosity per week: 1.98 fb^{-1}

Design luminosity was reached on the 26th June thanks to the reduced β^* and lower transverse beam sizes from the injectors compensating the lower number of bunches. The excellent job in injectors to optimize beam brightness via continuous optimization, the change of PSB working point, and the deployment of BCMS should be acknowledged. Indeed in July, the PS started to deliver BCMS beam to LHC. A peak luminosity of around +20% and a new record of $\approx 1.2 \times 10^{34}$ cm^{-2}s^{-1} was obtained as a result.

The smaller emittances allow the reduction of the crossing angle from 370 μrad to 280 μrad and a concomitant increase in the geometrical reduction factor from around 0.59 to 0.7. This measure was deployed following the autumn technical stop. Performance was also helped by the use of a reduced bunch length in Stable Beams.

Thus, despite the limit in number of bunches and limit in bunch intensity from injection kicker vacuum issues the peak performance of 40 - 50 % over nominal was obtained – see table 1.

Parameter	Value
Protons per bunch	$\approx 1.1 \times 10^{11}$
Number of bunches	2220
Normalized emittance	≈2.0 mm.mrad
β^*	40 cm
Crossing angle	280 μrad
Bunch length	≈1.05 ns
Peak luminosity (CMS)	$\approx 1.5 \times 10^{34}$ cm^{-2}s^{-1}
Peak mean pile-up	≈45

Table 1: 2016 peak performance parameters

2016 was also blessed by unprecedented machine availability: The machine was available for operation 72% of the time scheduled for physics. Overall Stable Beam efficiency of 49% (to be compared to 36% in 2012, and 30% for the short production period in 2015).

CONCLUSIONS

In a full operational year at 6.5 TeV the LHC has enjoyed the following.

- Good peak luminosity via full exploitation of all available parameters (β^*, bunch length, crossing angle, emittance from injectors). Bunch number and bunch intensity were limited in 2016 but the full range remains to be exploited in 2017.
- Excellent luminosity lifetime in general with only moderate emittance blow-up in Stable Beams and minimal non-luminosity beam loss after the first hour or so.

- Stunning availability following sustained effort from hardware groups accompanied by effective fault tracking.
- Few premature dumps allowing long fills: the UFO rate is down and radiation to electronics effects have been largely mitigated, again after a sustained and successful campaigns.
- Excellent and improved system performance across the board, for example, the new developments of the transverse damper system(OBSbox etc.); collimator alignment software, injection kicker performance.
- The magnets, circuits and associated systems are behaving well at 6.5 TeV.
- Good beam lifetime through the cycle
- Operationally things are very well under control
- Magnetically reproducible as ever
- Optically good, corrected to excellent by the OMC team
- Aperture is fine and compatible with the collimation hierarchy.
- Collimation system is demonstrating excellent performance and impressive robustness
- Machine protection regime assuring safe exploitation

After the trials of 2015, 2016 was really the first year when it all came together: injectors; operational efficiency; system performance; understanding and control; and availability. Remarkable operational flexibility was demonstrated, in particular, during the exceptional proton-lead run during the last running period. Flexibility also allow the team to handle the slower than expected electron cloud conditioning, the implications of which remain a worry for the HL-LHC era to be understood fully. It should also be noted that it was fortunate that UFO rates have conditioned down, accompanied, as elsewhere, by excellent diagnostics, well thought through mitigation actions and understanding through simulation.

The LHC has moved from commissioning to exploitation, and is enjoying the benefits of the decades long international design, construction, installation effort – it's clear that the foundations are good. It's present performance is worthy reflection of this effort and the huge amount of experience and understanding gained and fed-forward over the last years. Progress represents a phenomenal ongoing effort by all the teams involved.