LESSONS LEARNT FROM THE 2016 LHC RUN AND PROSPECTS FOR HL-LHC AVAILABILITY

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Abstract

The LHC exhibited unprecedented availability during the 2016 proton run, producing about 40 fb^{-1} of integrated luminosity, surpassing the sum of production during the 4 previous years. This was achieved while running steadily with a peak luminosity above the design target of $10^{34} cm^{-2}s^{-1}$. Individual system performance and an increased experience operating the LHC were fundamental for these achievements, following the consolidations and improvements deployed during the Long Shutdown 1 and the Year End Technical Stop in 2015. The implications of this excellent performance in the context of the High Luminosity LHC are discussed in this paper, with the goal of defining the possible integrated luminosity reach of HL-LHC when considering the different operating conditions and the newly developed systems and technologies.

OVERVIEW: 2016 LHC AVAILABILITY

The 2016 LHC proton run began on March 25th and ended on October 31st. A total of 146 days was devoted to luminosity production, plus 7 days dedicated to a 'special physics' run with 2.5 km β*. During the reference period, 779 faults were registered and analysed in the Accelerator Fault Tracker (AFT) [1, 2, 3, 4, 5], with 65 relevant parent/child relationships. In such cases, the occurrence of a primary failure/event (parent) affects the performance of a number of secondary systems (children).

Figs. 1,2,3 show the evolution of the LHC performance in three reference periods, corresponding to stable operation between technical stops for scheduled maintenance. In the figures, 'Operations' refers to the nominal LHC cycle, plus measurements, injection tuning and planned machine interventions. 'Stable Beams' is the term indicating the period of experiments' data-taking. 'Pre-cycle' accounts for the time required for magnet cycling after failures or machine accesses.

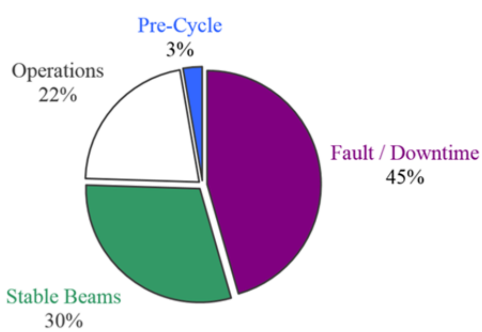

Figure 1: LHC Mode breakdown during the 2016 proton run (Restart-TS1).

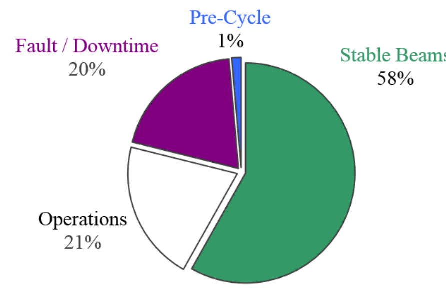

Figure 2: LHC Mode breakdown during the 2016 proton run (TS1-TS2).

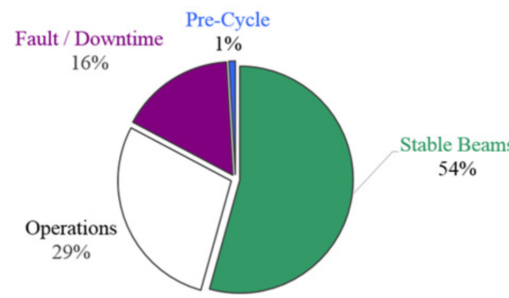

Figure 3: LHC Mode breakdown during the 2016 proton run (TS2-TS3).

In the period between the restart of operation with beam to the first Technical Stop (TS1), the LHC experienced 45 % fault / downtime. Two long periods of unavailability within this period were due to the failure of a 66 kV transformer in LHC Point 8 (about 6 days) and the main power supply of the Proton Synchrotron (about 5 days). The availability increased significantly in the period from TS1 to TS2, reaching the record of physics efficiency for the LHC (58 % of time in stable beams). This was achieved despite another long stop (about 3 days) due to flooding in LHC Point 3, which affected in particular the control system of the collimators in this section. In the last period of the proton run from TS 2 to TS3, the performance was still remarkable (achieving 54 % of time in stable beams).

Combining these figures for the whole proton run yields 49 % average stable beams over the year, for a total of more than 1800 h in stable beams. For comparison, the 25 ns proton run in 2015 yielded 33 % physics efficiency, which implies an absolute gain in 2016 of more than 15 %.

Figure 4 shows the evolution of the availability by week and relates it to the physics production. 'Incomplete weeks' indicate that the corresponding week was not entirely devoted to luminosity production (e.g. for technical stops or Machine Developments). Several weeks exhibited more than 90 % availability with more than 3

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fb^{-1} produced. Weeks 17 and 21 are characterised by a low availability (about 30 %) and correspond to the occurrence of the aforementioned 66 kV transformer failure in Point 8 and the failure of the PS main power supply, respectively.

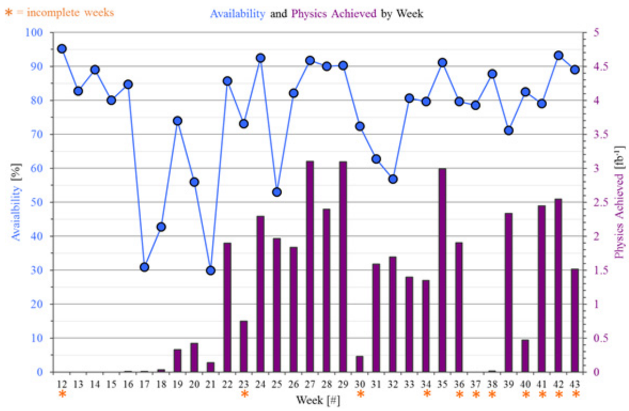

Figure 4: Availability (blue) and luminosity production (purple) per week in 2016.

The increased machine availability in 2016 is related also to the significant reduction of the number of premature dumps with respect to previous runs. Figure 5 shows the ratio of fills reaching stable beams which are prematurely dumped due to failures or intentionally by LHC operators. In total, 53 % of the fills were dumped due to failures (5 % due to radiation effects) and 47 % by operators. In 2015 about 70 % of the fills were dumped by failures, highlighting an improvement also in this respect of 15-20 %. Many factors contribute to this achievement, the main ones being:

- The optimization of Beam Loss Monitor (BLM) thresholds in the LHC arcs, which allowed limiting the number of unnecessary dumps due to Unidentified Falling Objects [6]
- The low number of radiation-induced failures, thanks to lower radiation levels in the arcs than predicted and the mitigation measures deployed in the first Long Shutdown (LS1) and the winter TS in 2015-16

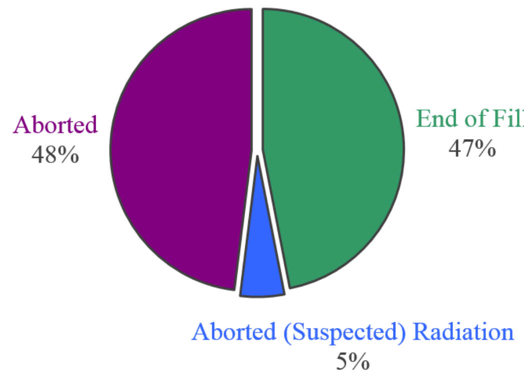

Figure 5: Physics beam aborts in 2016: due to failures (purple), due to radiation effects (blue) or triggered intentionally by operators (green).

The average duration of fills which were dumped due to failures (8 h) was remarkably stable during the year, indicating a very reproducible operation and a well-established machine reliability. These factors suggest that the LHC is reaching its maturity and is now ready to operate above its design peak luminosity with high efficiency.

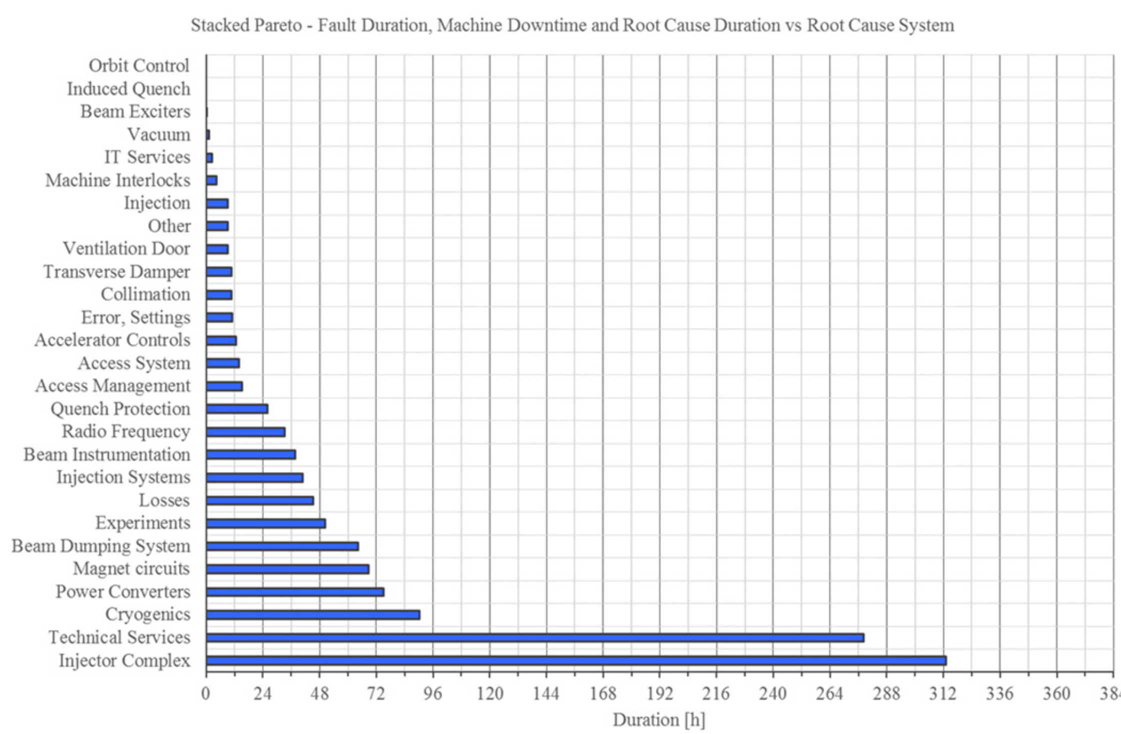

Figure 6: 2016 LHC system downtime.

LHC DOWNTIME ANALYSIS

A total of 779 faults was registered in the AFT for the 2016 proton run. Figure 6 shows the system contributions to LHC downtime, accounting for possible parallelism of faults and parent/child relationships.

The top contributors to downtime are the injector complex and technical services, both having caused over ten days of downtime. The downtime is in both cases dominated by isolated, high-impact faults. The technical services suffered from the occurrence of the 66 kV transformer failure in Point 8 and the flooding in Point 3, with a combined downtime of about ten days. In addition, 22 premature dumps were triggered by perturbations in the electrical network. The downtime of the injector complex was dominated in 2016 by the Proton Synchrotron, which experienced several problems including main power supply issues and a vacuum leak.

The cryogenic system is still amongst the top contributors to downtime, but has significantly improved its availability in 2016. This is due to the optimization of the cryogenic configuration (only four cold-compressor units supply the eight arcs), which led to a reduced failure rate, and the implementation of a feed-forward system for the dynamic compensation of transient heat-loads on the beam screens. These are primarily related to the effects of electron cloud [7] during injection of high-intensity beams, which exhibited a continued conditioning trend from 2015. These factors resulted in a major reduction of the number of premature beam dumps and hence machine downtime.

The Quench Protection System, which in previous runs has been responsible for a significant fraction of the LHC downtime, operated very reliably throughout 2016, with an average availability above 99 % during the proton run. This is a result of the efforts invested in the improvements of the system over the past years. In particular, the deployment of a radiation tolerant 600 A quench detection system in the winter TS in 2015-16 has proven to be very effective against radiation induced failures.

IMPLICATIONS FOR HL-LHC

The integrated luminosity production target for the nominal HL-LHC is set to 250 fb^{-1} per year. Considering 160 days allocated for luminosity production, reaching the target requires an average production of 1.56 fb^{-1} per day. Based on current HL-LHC beam parameters, a HL-LHC fill colliding for 12 h produces about 1.5 fb^{-1}. In first approximation one can conclude that the target physics efficiency of HL-LHC is therefore 50 %. The 2016 LHC run demonstrates that this target is within reach for a mature machine. Nevertheless, HL-LHC will feature the introduction of new systems and technologies (new cryogenic plants, crab cavities, etc.), that might have an impact on the achieved availability. It must be verified that the performance of these systems will not significantly affect the machine availability. The impact of crab cavity failures on availability and luminosity production is discussed in detail in [8].

The effect of the change of beam parameters should also be evaluated for its implications on availability. The shorter luminosity lifetime associated to higher brightness beams implies shorter optimal fill lengths. This results in more frequent filling of the LHC and, thus, requires an even more reliable injector chain. In the HL-LHC era, ageing effects in the injector complex might become sizeable, therefore consolidation actions should be prioritized accordingly. In addition, radiation levels will increase as a consequence of the higher total intensity and luminosity production, potentially leading to an increase of radiation induced failures of electronic systems. Significant efforts have been devoted to qualify components used within particularly exposed systems in order to limit such effects. The target is to have a maximum of 0.1 dumps/fb^{-1} due to radiation induced failures.

The uncertainty related to the introduction of new systems and technologies calls for a sensitivity analysis of expected failure rates and recovery times, to define appropriate availability targets for individual systems. The outcome of such analysis, based on the Monte Carlo model presented in [9], is shown in Fig. 7. The goal of 250 fb^{-1} per year is within reach for 2016-like availability, but the introduction of new systems might lead to an increase of the number of premature dumps (e.g. due to crab cavity failures) or an increase of the average recovery time (e.g. due to failures of the additional cryogenic plants). The resulting impact on integrated luminosity can be easily derived based on Fig. 6.

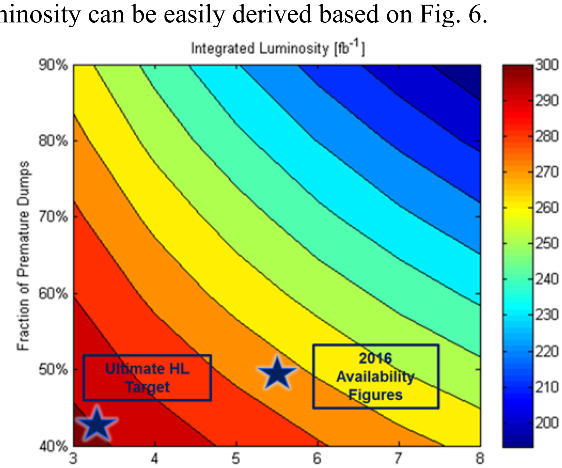

Figure 7: HL-LHC integrated luminosity production evolution as a function of machine availability.

CONCLUSIONS

The LHC exhibited unprecedented availability in 2016, which resulted in the production of 40 fb^{-1} of integrated luminosity, well beyond the target set at the beginning of the year. Several factors contributed to this success, above all the profound understanding of the machine and the improved system reliability. Based on such results, the HL-LHC integrated luminosity target of 250 fb^{-1} is

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achievable, nevertheless the impact of new systems and technologies and of equipment ageing should be carefully taken into account for related performance predictions.

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