2015 AVAILABILITY SUMMARY

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Abstract

This paper presents an overview on LHC availability in 2015, covering the period from 6th April to 13th December. The reference data-set for the presented results is coming from the Accelerator Fault Tracker (AFT), which was used in 2015 by members of the Availability Working Group for availability tracking.

The main contributors to LHC downtime (Cryogenic system, Power Converters, Quench Protection System) are analysed in detail in the paper, highlighting relevant dependencies on other systems and operational modes. The concept of the availability matrix is introduced to describe the performance of hardware systems.

The presented availability studies focus on the 25 ns and Ion Run in 2015, to derive reference figures for the upcoming 2016 Run.

FAULT REVIEW IN 2015

The AFT was released at the beginning of the 2015 LHC Run, allowing for systematic and consistent LHC fault tracking throughout the year. Results presented in this paper are based on data stored in the AFT.

In 2015, a weekly fault review was carried out (about 5 h per week, for two people) by the core members of the Availability Working Group (AWG) to ensure high-quality data for availability studies for both hardware systems and operational performance [1]. The aim of availability studies is to identify weaknesses related to LHC operation, possible mitigations and the related cost/benefit, while assessing the possible impact on luminosity production. The scope of the fault review process therefore extends to all possible causes of LHC downtime, not only considering hardware faults.

The analysis presented in this paper focuses on the period from 6th April to 13th December 2015 (Week 15 to Week 50), i.e. starting from the beam commissioning phase up to the end of the ion run. In the reference period, 1375 downtime causes were recorded and analysed. Where applicable, specific attributes were assigned to each downtime cause, to account for the effective LHC downtime and the resulting operational overheads. These attributes are: 1) Access needed 2) Blocking operations 3) Precycle needed 3) Radio protection needed.

In addition, the AFT allows defining relevant dependencies among different downtime causes. The most commonly observed dependency is the so-called 'parent/child relationship'. A primary downtime cause ('parent') is responsible for the occurrence of additional downtime ('child'). As an example, beam losses (parent) can lead to a magnet quench (child), which implies a quench recovery time for the cryogenic system (2nd-level child). In 2015, 90 relevant parent/child dependencies were identified and recorded.

The review process also involved the analysis of LHC operational modes, which were consistently tracked in 2015. The following operational modes allow describing the status of LHC operation: 1) Stable Beams 2) Beam In (LHC cycle, not including Stable Beams and Ramp-down) 3) No Beam (planned shutdowns) 4) Fault 5) Measurements (e.g. floating MDs) 5) Injection Tuning 6) Loss maps 7) Pre-cycle 8) Setup (mainly ramp-down).

The so-called "Cardiogram of LHC Operation" (Fig. 1), produced by the AFT, provides an overview of LHC Availability over a given time period. The cardiogram provides information related to beam energy and intensity, the accelerator mode, time in stable beams and system availability over time and allows easily correlating faults with operating conditions. Downtime associated to a given cause is indicated in red in the chart. This view was consistently used in 2015 to monitor LHC performance evolution throughout the year.

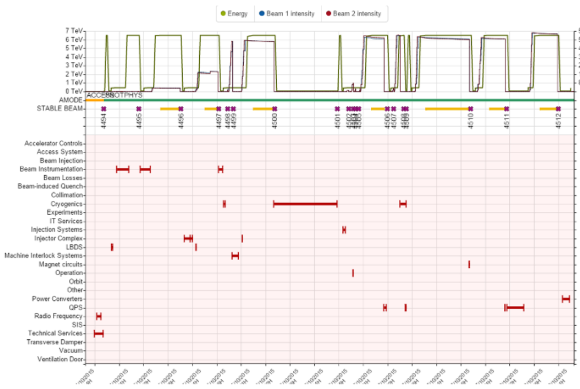

Figure 1: An example of the so-called "cardiogram" of LHC operation

OVERVIEW: 2015 AVAILABILITY

Data stored in the AFT database was used to produce a summary of the statistics on availability in 2015. Fig. 2 shows the recorded Number of Faults (blue) and Downtime (red) by week. The number of faults ranged from about 20 to 60 faults per week, with an associated downtime of 20 to 100 h. As a result, LHC availability in 2015 was on average 69 %. In the period between Technical Stop 1 (TS1, week 25) and Technical Stop 2 (TS2, week 36), the availability dropped to 64 % (see explanation below). A 69 % availability was then recovered after TS2 and culminated in 79 % availability during the ion run (Fig. 3).

A detailed overview of the system downtime distributions between TSs is shown in Fig. 4.a, b, c, d. The downtime shown in these figures accounts for all systems faults, even those occurring in the shadow of others, and will be therefore referred to as 'integrated' system downtime. As explained in the following, the period extending up to TS2 was used to address teething problems related to hardware interventions and changes to the machine performed during the Long-Shutdown.

In the period leading up to TS1, the biggest contributors to the downtime were the cryogenic system, the injector complex and the QPS. In particular two long stops associated to the injectors had a direct impact on LHC operation: the replacement of a Linac2 HV cable and a SPS magnet replacement.

The period extending from TS1 to TS2 was dominated 1) by the downtime associated to the occurrence of an earth-fault on circuit RCS.A78.B2 and 2) by the sensitivity to radiation effects (Single Event Upsets, SEUs) of the QPS mBS boards [2], which appeared while ramping-up the beam intensity, and 3) by the downtime of the cryogenic system. The QPS mBS boards were replaced during TS2, which solved the problem with SEUs completely. The RCS circuit was instead condemned and has not been in use for the rest of the run. The cryogenic system was still responsible for the longest downtime in this time period, as performing machine scrubbing (50 ns and 25 ns) had a direct impact on the produced heat loads to be managed by the cryogenic system [3].

After TS2 all major hardware teething problems were solved, therefore the period between TS2 and TS3 (25 ns proton Run) is considered the reference period for the evaluation of LHC performance in view of future runs. Fig. 4.c highlights that the main limitation of operation was in this period coming from the performance of the cryogenic system, which is highly affected by the increasing heat loads when ramping-up the beam intensity [4].

The system downtime distribution after TS3 (the period including the ion preparation run and the ion run), is shown in Fig. 4.d. Excellent availability was achieved in this period (almost 80 %, see Fig. 3). In fact, thanks to the reduced heat loads during ion operation, the performance of the cryogenic system was comparable with that of the other systems leading to very high overall availability.

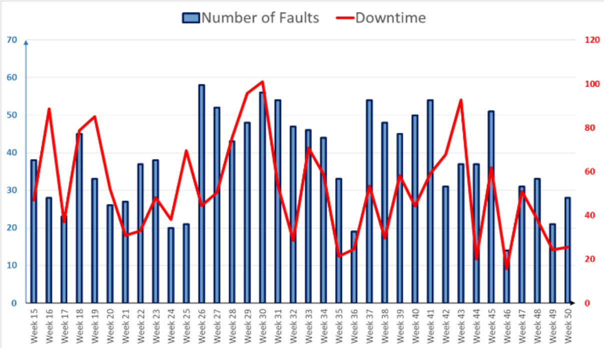

Figure 2: Number of Faults (blue) and Downtime (red) by week in 2015

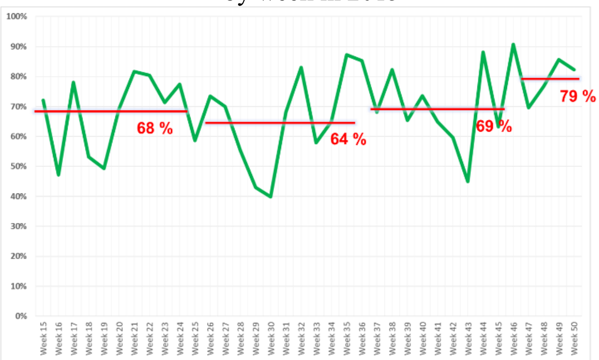

Figure 3: LHC Availability by week in 2015

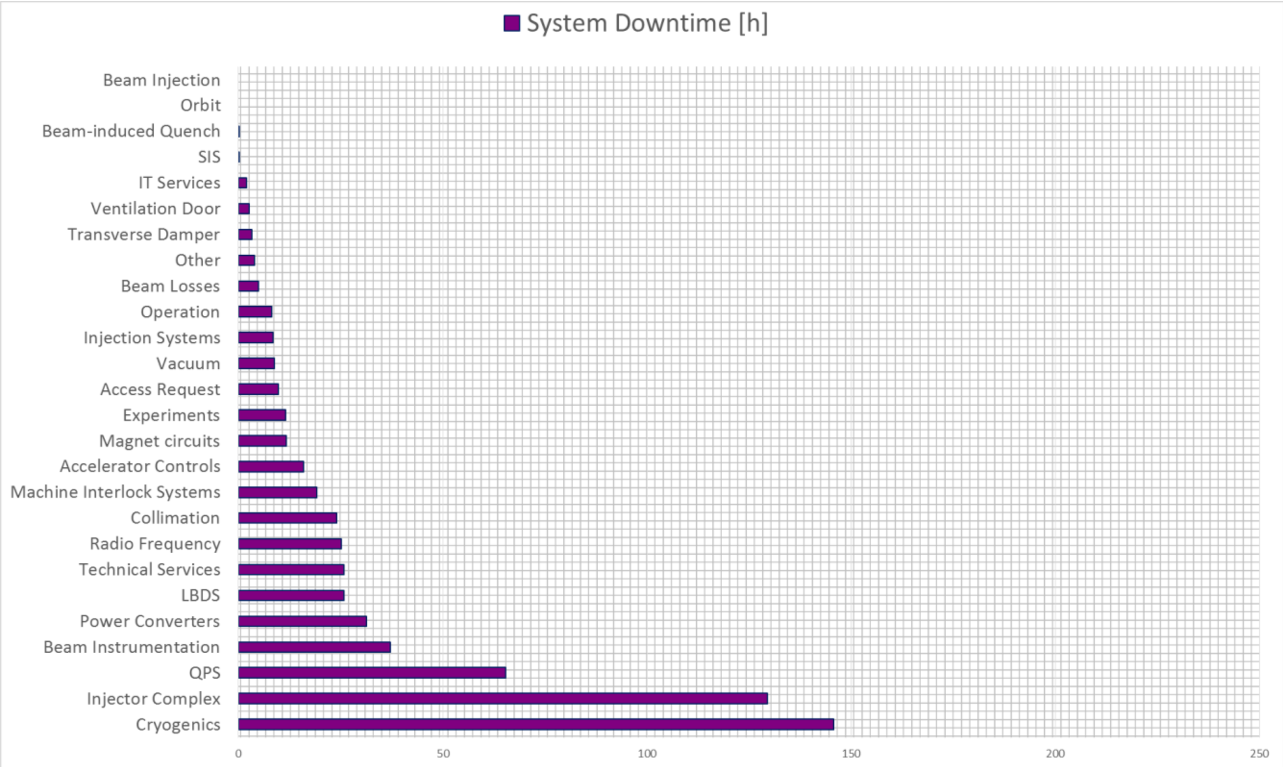

Figure 4.a: Integrated system downtime before TS1.

Figure 4.b: Integrated system downtime between TS1 and TS2.

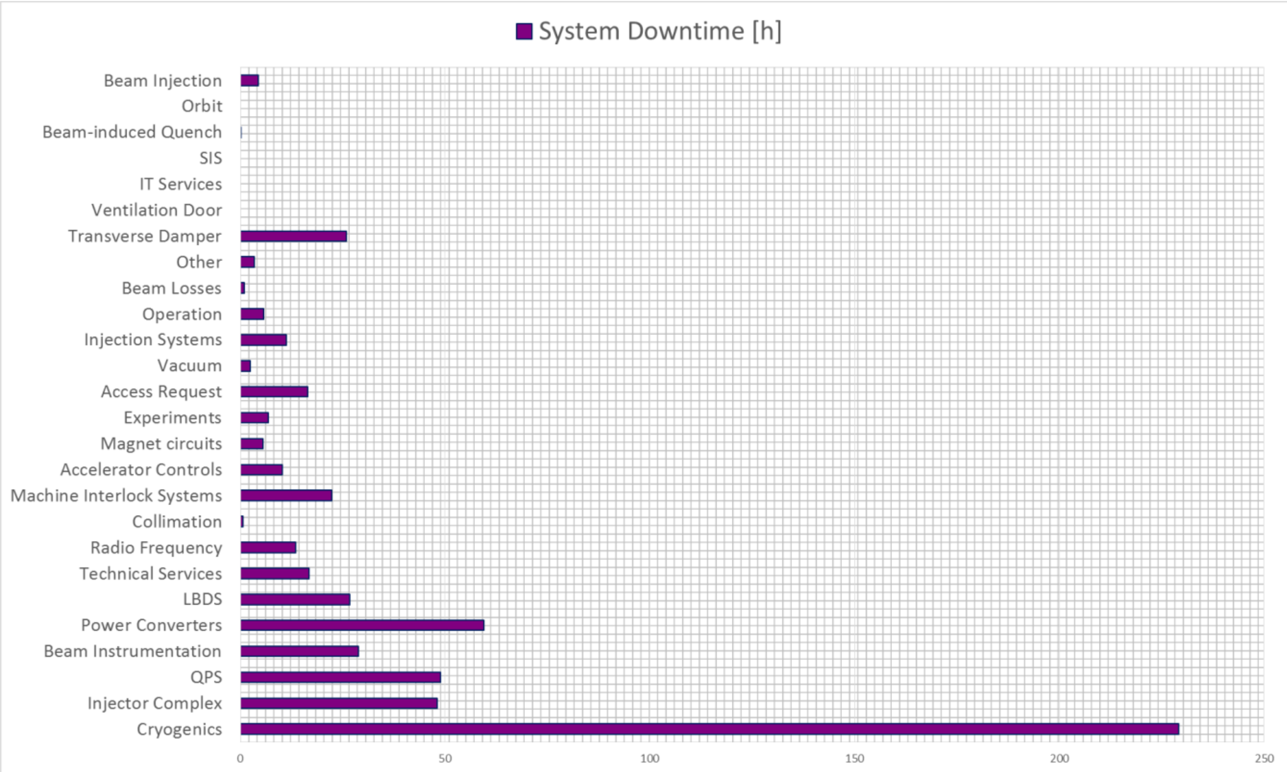

Figure 4.c: Integrated system downtime between TS2 and TS3.

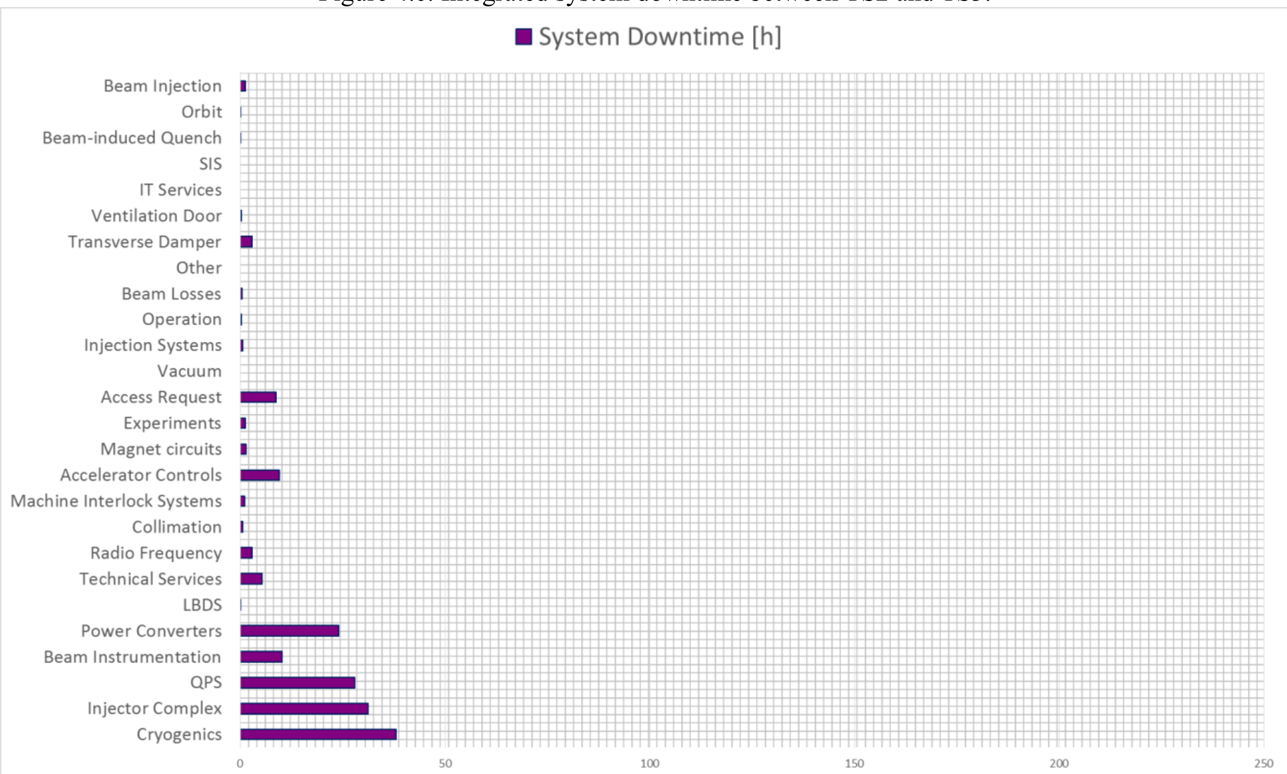

Figure 4.d: Integrated system downtime after TS3.

FOCUS: 25 NS RUN

A detailed analysis of the availability during the 25 ns run has been carried out, as this is considered the most reproducible period of operation and is taken as a reference for extrapolation to future runs.

During the 25 ns run (Fig. 5), a total of 455 h was spent in stable beams, amounting to 32.7 % of the total time. The downtime amounted instead to 426 h (30.6 %).

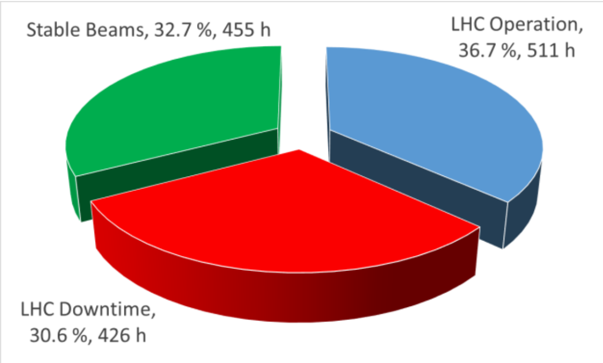

Figure 5: Breakdown of LHC Operation during the 25 ns Run.

A total of 70 fills reached stable beams, out of which 22 were dumped by operators (End-Of-Fill, EOF) and 48 (68.6 %) were prematurely dumped due to failures. The average turnaround time deduced from these figures is 7.3 h and the average downtime per fill to stable beams was 6 h.

The distribution of the time spent in stable beams is illustrated in Fig. 6. The average duration of stable beams (both EOF and terminated by failures) was 6.3 h. Many fills were dumped prematurely (average 5 h), but some very long fills, lasting up to 20 h, are also present (average for EOF 9.5 h). Long fills were justified by the remarkably long luminosity lifetimes (~30 h, see [5]).

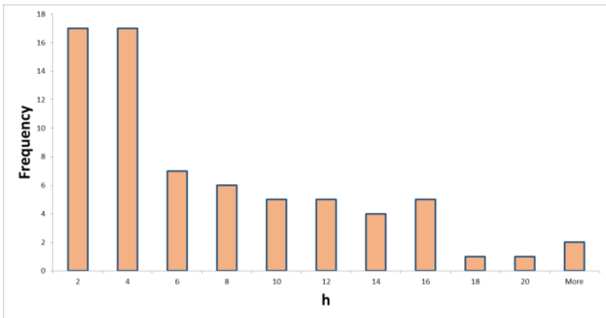

Figure 6: Distribution of stable beams duration during the 25 ns Run.

The system downtime distribution for the 25 ns Run is shown in Fig. 7. The purple bar indicates the integrated system downtime, whereas the blue bar represents the effective downtime of the LHC caused by the given system. The figure allows identifying the cryogenic system as the main LHC downtime cause. Nevertheless, this view still considers child faults as part of the system directly affected by the fault occurrence (e.g. downtime due to quench recoveries is still attributed to the cryogenic system, even if a quench is not a primary cryogenic system fault). Taking the blue bars in Fig. 6 as a reference, a re-assignment of downtime due to child faults to the respective parents was carried out. The time lost due to a pre-cycle was also added (in orange). Furthermore, an additional quantity, the so-called 'lost-physics' time, is assigned to all systems responsible for dumps while in stable beams. In each of such cases, additional 3 h (i.e. the difference between the average duration of a fill terminated by EOF and the average fill duration) are added to the system causing the dump. The result of this analysis is presented in Fig. 8.

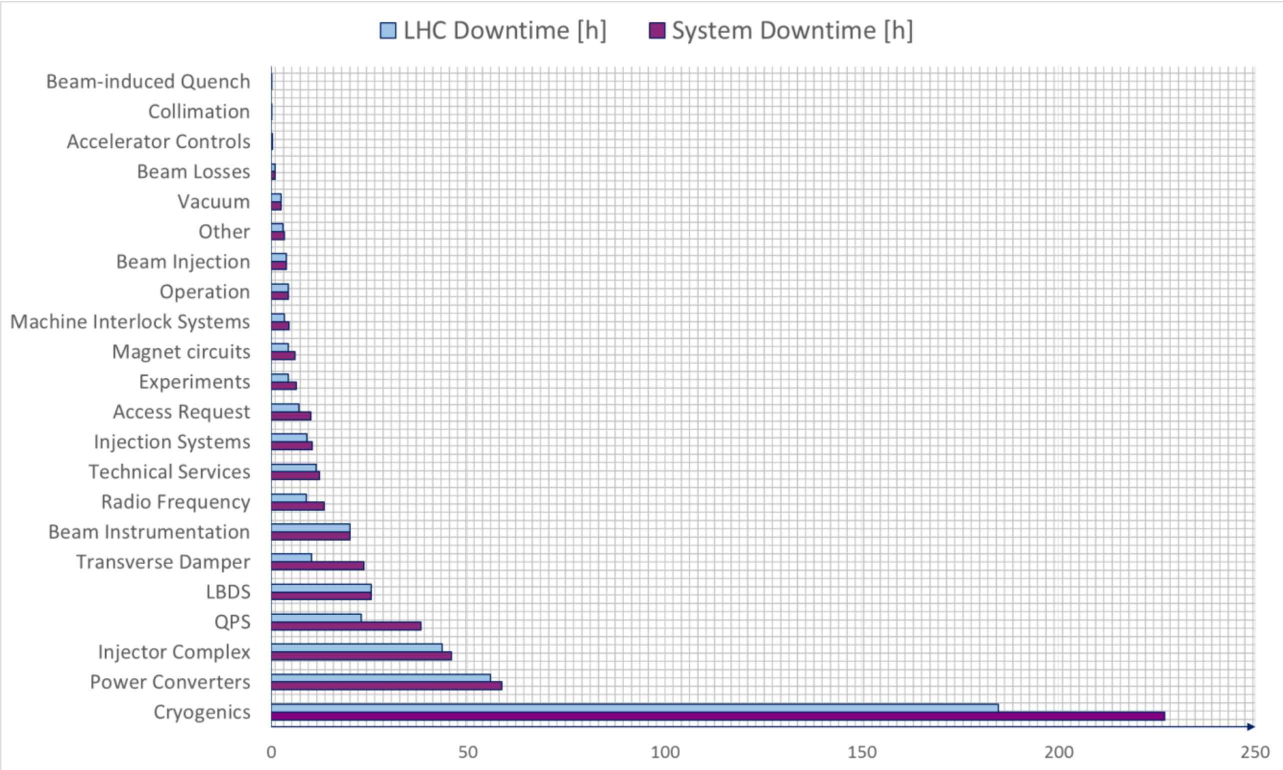

Figure 7: System downtime distribution during the 25 ns Run. The integrated systems downtime is shown in purple and the corresponding LHC downtime in blue.

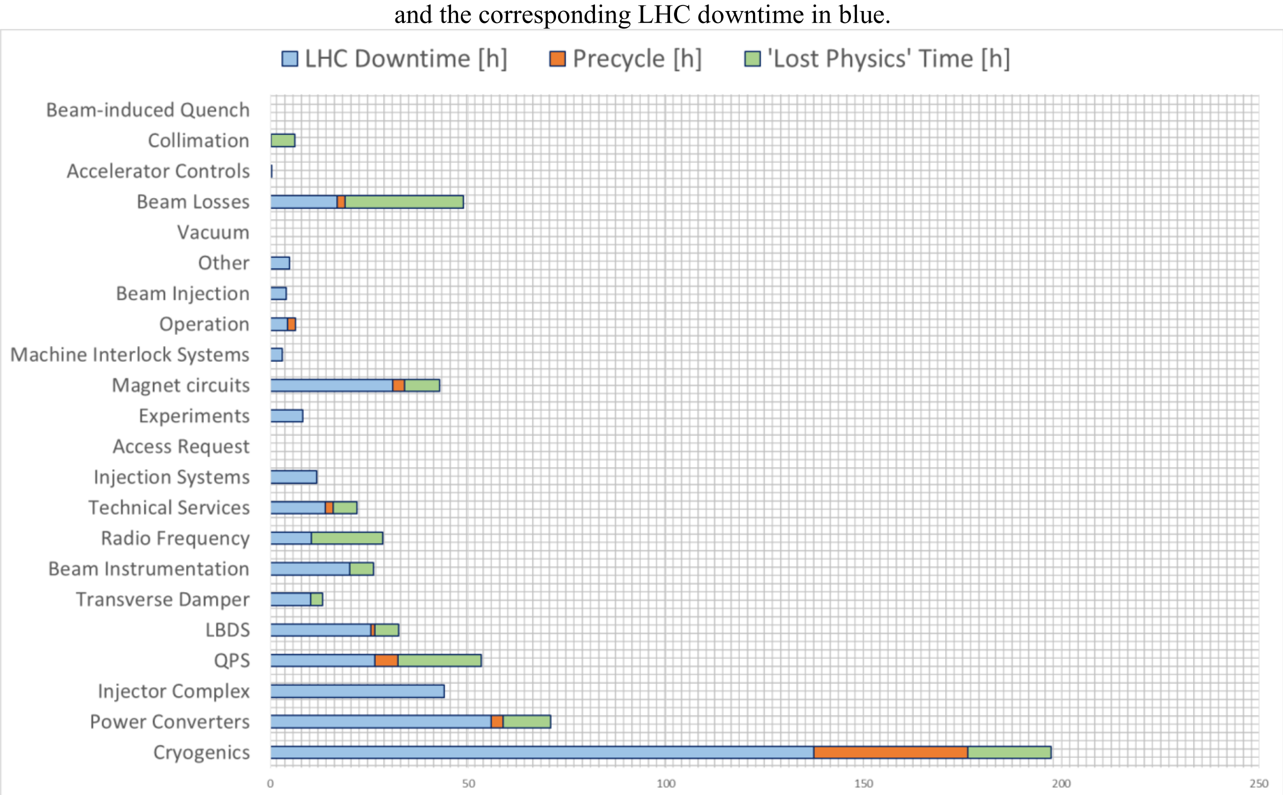

Figure 8: System impact on LHC availability, accounting for system downtime (light blue), required precycles (orange) and 'lost physics' (green)

The figure allows to directly compare the effect of different failure causes (beam-related or hardware-related) on LHC operation and luminosity production. The chart shows that the cryogenic system is still the leading contributor to downtime, but that after it power converters, QPS, beam losses (= UFOs, see below) and magnet circuits (training quenches + earth faults) have a comparable impact on LHC operation.

For the identified 'top five' contributors to LHC downtime, a more detailed analysis is presented below. The analysis is based on the concept of an 'availability matrix' [1]. The matrix describes the impact of system failure modes by the related downtime and frequency of occurrence. Failure modes foreseen to be mitigated in 2016 are shown in green, those which are not going to be mitigated or for which a mitigation is not justified are shown in red, those partially mitigated in purple.

Cryogenic System

The total cryogenic system downtime amounted to 227 h, out of which 185 directly translated into LHC downtime. A breakdown of such downtime is shown in Fig. 9. The main contribution is related to the time from the loss of "Cryo-Maintain" (CM) to its recovery (green). Further details on this category are presented in [6]. From the operations point of view, an additional downtime must be considered for the recovery of the "Cryo-Start" (CS) signal (orange), since LHC operation is inhibited until the latter is available. A separate category is considered for delays in operations due to stabilization of cryogenic conditions (blue). Finally, an additional category accounting for the integrated time lost due to short glitches of CM is considered. Operation is effectively inhibited between such glitches, despite their short duration.

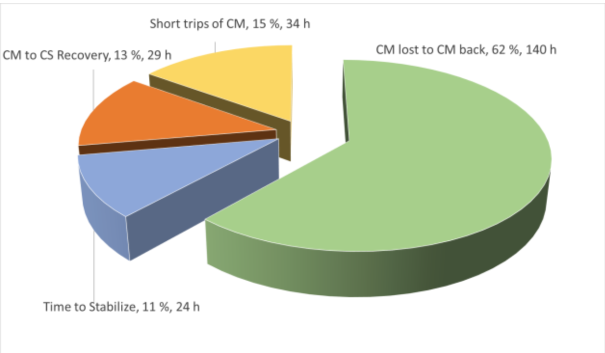

Figure 9: Breakdown of cryogenic systems downtime

A total of 52 h was due to parent faults (mainly quenches). The cryogenic system was also responsible for 7 dumps while in stable beams and required 39 precycles to recover from faults.

The main system failure modes are shown in Fig. 10 and detailed in [4].

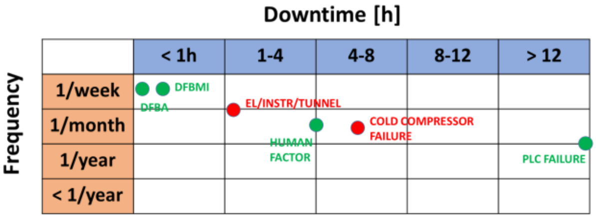

Figure 10: Cryogenic system availability matrix.

Power Converters

The total downtime due to power converters amounted to 53.5 h, out of which 50.5 h directly translated into LHC downtime. No parent/child dependencies were observed in the case of power converters. Power converters caused 4 dumps in stable beams and required 3 precycles for recovery of operating conditions.

The classification based on different converter types is shown in Fig. 11 and more details on the mitigation strategies can be found in [7].

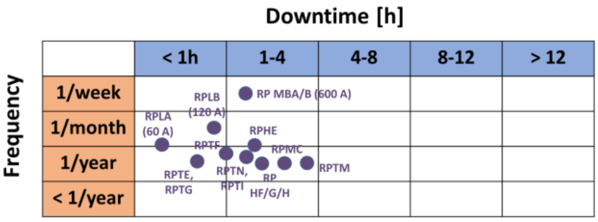

Figure 11: Power converters availability matrix.

Quench Protection System and Energy Extraction

The total system downtime amounted to 38 h, out of which only 23 h directly translated into LHC downtime. The QPS was responsible for additional child faults, specifically of the cryogenic system (e.g. spurious firing of quench heaters leading to a magnet quench). The QPS caused 7 dumps in stable beams and required 6 precycles for recovery of operating conditions.

The main sub-system failure modes are shown in Fig. 12. More details can be found in [2, 8].

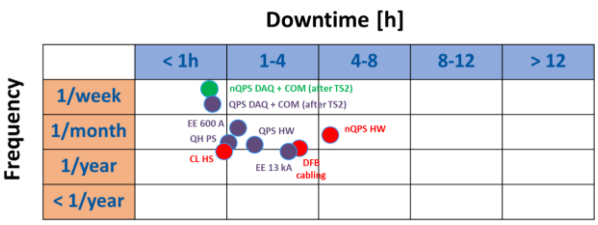

Figure 12: QPS + Energy Extraction availability matrix.

Magnet Circuits

The category 'magnet circuits' includes both earth faults and downtime due to training quenches. The availability matrix for such failure modes can be seen in Fig. 13. More details can be found in [8].

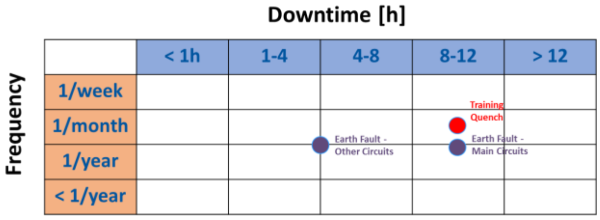

Figure 13: Magnet circuits availability matrix.

Beam Losses

A statistical analysis of the observed beam losses during the LHC cycle was carried out to identify possible limitations in view of the 2016 run. The analysis focused on different phases of the LHC cycle: injection, stable beams and 'rest of the cycle'. The resulting classification and statistics can be seen in Fig's 14.a, b, c.

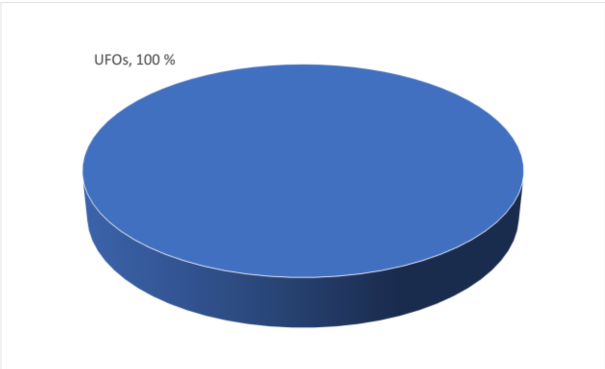

Figure 14.a: Dump due to beam losses – stable beams.

All dumps due to beam losses in stable beams were caused by UFOs (10 dumps, 1 leading to a quench). The impact of UFOs is particularly relevant when trying to extrapolate for future operation [9]. Experience from 2015 confirmed that many factors play a role in this respect. It has been shown that a strong conditioning effect can be observed while running the machine, but that the effect of long machine stops on the observed UFO rate and more statistics from stable operation should be gathered before a final assessment of the potential limitations. Given the observations in 2015, an optimized BLM threshold strategy for the machine in 2016 has been studied and presented in [10].

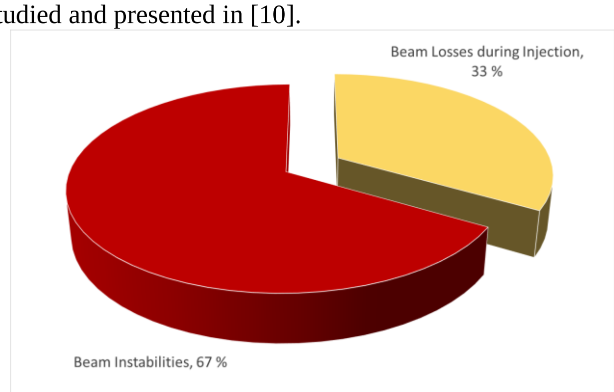

Figure 14.b: Dump due to beam losses – injection.

At injection, 3 dumps due to beam losses were registered. Six dumps due to beam instabilities were also observed, out of which 5 were triggered by BLMs and 1 by the interlocked BPMs in IR6.

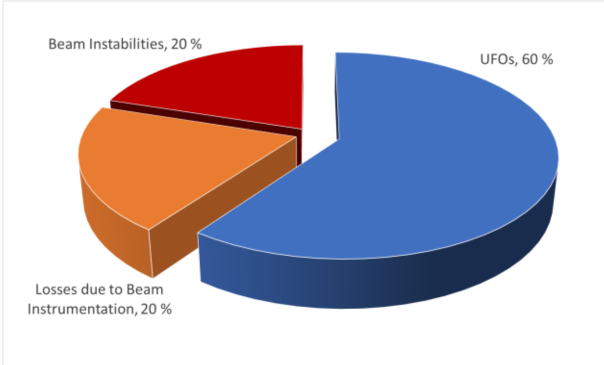

Figure 14.c: Dump due to beam losses – 'rest of the cycle'.

During the rest of the cycle, only one dump was triggered due to beam instabilities. Three dumps were triggered by UFOs and 1 due to losses caused by a misbehaviour of the tune feedback (Beam Instrumentation).

Extrapolating for future runs based only on a limited amount of data and with limited performance in terms of beam intensity is difficult, but no major limitations are expected in the future runs, provided that a suitable strategy to cope with UFOs will be available.

LHC Operation

Optimization of LHC operations is one of the many factors potentially having a direct impact on the achieved luminosity production. In [11] a detailed analysis of the LHC cycle is presented, highlighting the main areas for possible improvements. Available margins to reduce the time spent at injection should be exploited, as currently injection takes on average about 1h30, compared to the potential minimum of 37 min [12]. Significant time could be gained by a redefinition of the precycle strategy, as presented in [11].

FOCUS: ION RUN

The ion run took place from 23/11/2015 to 13/12/2015. Similarly to what has been presented for the 25 ns proton run, a breakdown of LHC operation with ions is shown in Fig. 15. A total of 203 h was spent in stable beams, amounting to 40.4 % of the total time. The downtime amounted instead to 88 h (17.5 %).

A total of 35 fills reached stable beams, out of which 30 were dumped by operators (EOF) and 5 (14.3 %) were prematurely dumped due to failures. The average turnaround deduced from these figures is 5.8 h and the average downtime amounts to 2.5 h for each fill to stable beams.

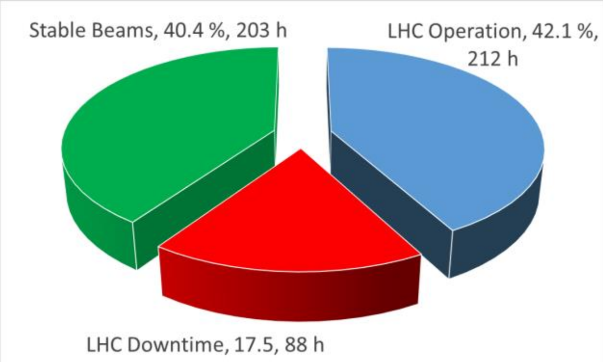

Figure 15: Breakdown of LHC Operation during the Ion Run.

Overall, a very significant improvement in terms of availability was observed during the ion run. Thanks to the reduced heat loads due to the lower beam intensity, the cryogenic system was not as impacted by operating conditions as during the proton run (Fig. 16). The performance of the cryogenic system was therefore in line with that of the other hardware systems, yielding a global availability of about 80 % (Fig. 3).

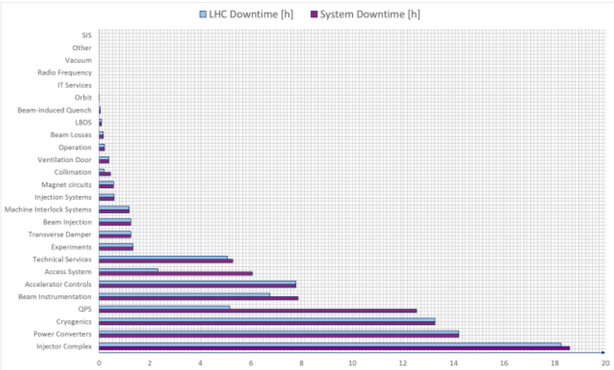

Figure 16: System downtime distribution during the Ion Run. The integrated systems downtime is shown in purple and the corresponding LHC downtime in light blue.

The distribution of the time spent in stable beams can be seen in Fig. 17 and compared with Fig. 6 (for protons). The distribution shows a peak around 6-8 h, which is the range of the ideal fill lengths for ions. The distribution is approximately symmetric, which confirms that most fills were dumped by operators for luminosity optimization and only a very small fraction was dumped prematurely due to failures.

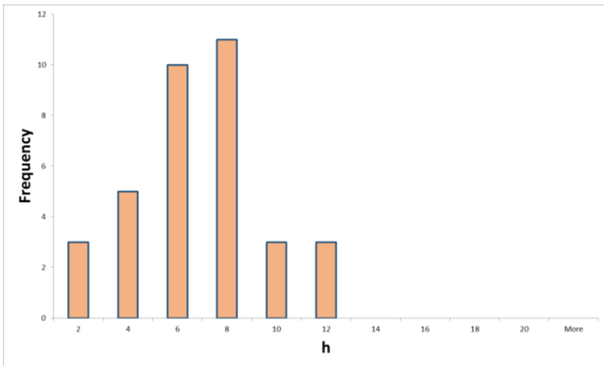

Figure 17: Distribution of stable beams duration during the Ion Run.

CONCLUSIONS

In this paper a summary of the achieved availability in 2015 was given, with a particular focus on the 25 ns proton run and the ion run. The period extending up to TS2 served as a necessary machine conditioning phase, for re-establishing optimal operating conditions and addressing teething problems following the Long Shutdown (LS1). After this period, the 25 ns proton run showed similar performance in terms of availability as for LHC in 2012 [12], i.e. about 70 % availability. This was achieved despite the numerous hardware interventions and consolidations in the machine shutdown, the increased operating energy and consistent use of a 25 ns bunch spacing (as compared to 50 ns, for most of 2012). The availability during the ion run increased up to about 80 %, thanks to the reduced heat loads, which allowed optimal operation of the cryogenic system. Thus, the ion run sets a reference for comparison of future performance of hardware systems.

In view of the 2016 proton run, the biggest concerns remain related to the performance of the cryogenic system with increasing heat loads when further increasing beam intensity and to the observation of UFOs. The adopted BLM threshold strategy [10] should allow minimizing the number of unnecessary dumps due to UFOs, provided that the achieved conditioning in 2015 will be kept after the year-end technical stop.

ACKNOWLEDGMENTS

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