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RELIABILITY AND AVAILABILITY OF PARTICLE ACCELERATORS: CONCEPTS, LESSONS, STRATEGY

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Abstract

This paper will present the results and latest status of an extensive effort to analyse and improve the reliability and availability of the LHC. After the introduction of basic concepts and definitions, the paper reviews the performance of the LHC in 2015-2017. A direct comparison of the luminosity production years 2016 and 2017 is presented, with a focus on the main differences in the observed failure modes. Based on the lessons learnt in this time window, expectations for the performance during future LHC runs are discussed. In particular, the thought process for the evaluation of the possible full energy exploitation of the LHC is described, considering relevant factors such as the expected availability loss and the risk associated to magnet training.

INTRODUCTION AND BASIC CONCEPTS

Availability is one of the Key Performance Indicators (KPI) of particle accelerator performance, being a measure of the time spent delivering the expected accelerator output. This quantity can widely differ for different applications of particle accelerators, i.e. particle colliders, synchrotron light sources, neutron spallation sources or medical accelerators. A very general definition of availability, applicable to all machines, is: "*Availability is the probability that a particle accelerator is not in a faulty state at a given time t*" (i.e. it is ready to operate with beam). In this paper, the focus is on circular colliders, with the Large Hadron Collider (LHC) taken as an example.

The goal of the LHC is the production of integrated luminosity, achieved by colliding particles in the LHC experiments. Before reaching collisions, the LHC performs a so-called cycle composed of several phases (e.g. *injection*, *ramp*, *squeeze*, *adjust*) to reach the required energy and beam parameters for optimized luminosity production. The phase of actual physics data taking in the LHC cycle is called *stable beams* and the time between two consecutive stable beams periods is referred to as *turnaround*. The turnaround comprises the nominal cycle outlined above, plus all necessary actions to set-up the machine for operation with beam, such as clearing faults and performing magnet pre-cycles, injection tuning and measurements of relevant beam parameters. The ideal duration (t_{opt}) of the stable beams phase is typically 10-15 h, depending on several factors, including luminosity lifetime, average turnaround duration, observed failure frequency and availability of beam from the injectors. The fraction of time with colliding beams over the total time is defined as *physics efficiency* and represents the ultimate measure of the particle collider performance. This directly correlates to integrated luminosity production, given certain beam parameters.

The definition of reliability for particle accelerators is more difficult to generalize, as reliability closely depends on the operating conditions of the machine. For a collider such as the LHC, it is frequent that even consecutive cycles adopt slightly different beam parameters, making the measure of reliability more difficult to interpret and compare. Here the following definition of reliability is proposed for the LHC, once the stable beams phase is reached: "*Reliability is the probability that the stable beams phase extends up to the optimal duration t_{opt}, with given beam parameters*". A direct measure of the LHC reliability is therefore the time spent in stable beams for each LHC fill.

In the following section, based on the proposed definitions, the performance in terms of availability and reliability of the LHC will be reviewed for the current LHC Run 2.

LESSONS LEARNT DURING LHC RUN 2

LHC operation restarted in 2015 after the Long-Shutdown 1 (LS1) and is scheduled to last until the end of 2018, before entering the Long-Shutdown 2 (LS2). This period is referred to as "LHC Run 2". In this section, a summary of the lessons learnt so far during LHC Run 2 is given, by comparing the achieved availability and reliability of the LHC over this period. These statistics are based on data recorded via the LHC Accelerator Fault Tracker (AFT) [1], in use since 2015.

Figure 1 summarizes the achieved availability and physics efficiency during the years 2015-2017 [2, 3]. The year 2015 was devoted to the recommissioning of the machine following the major consolidations of LS1 and setting-up of beam operation with 25 ns bunch spacing.

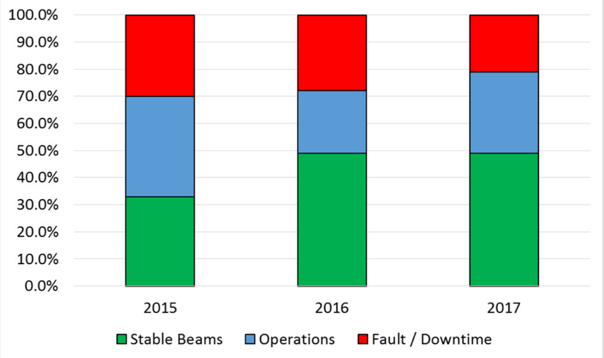

Figure 1: LHC Mode breakdown for the proton run during the period 2015-2017.

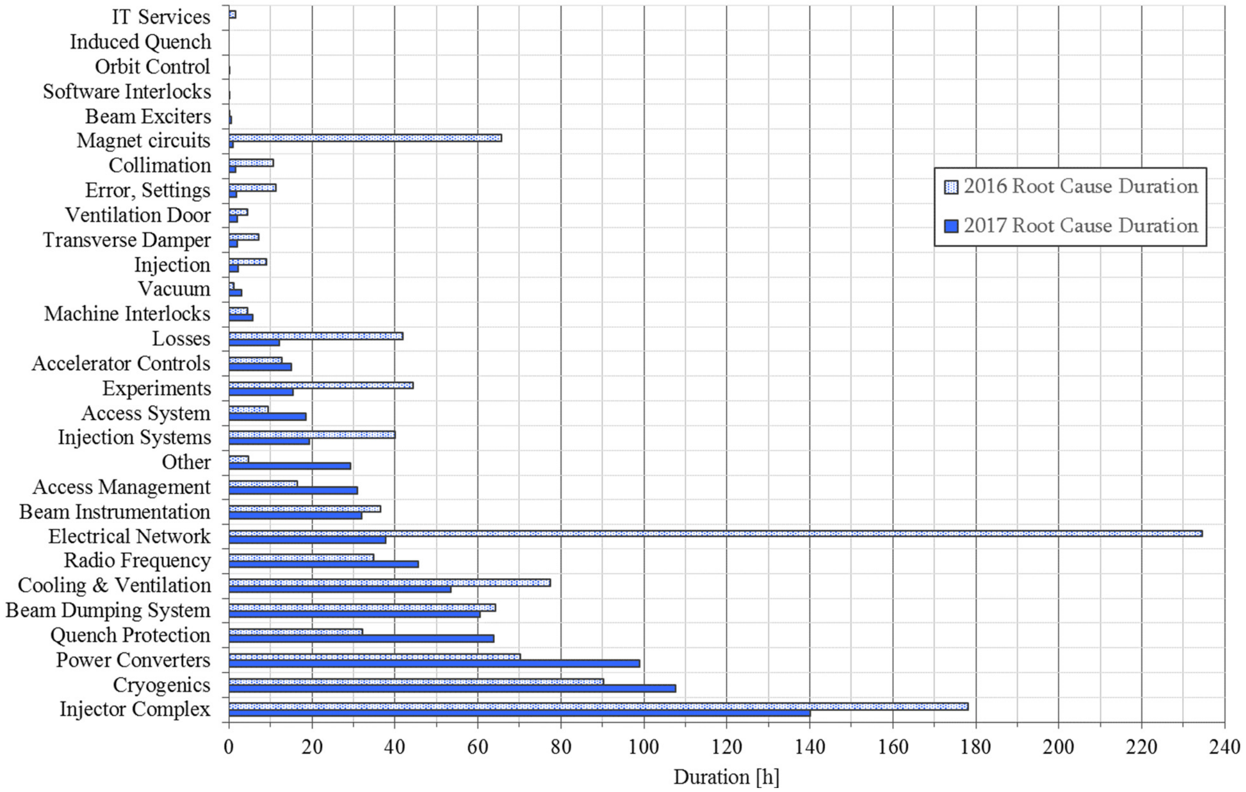

Figure 2: System downtime distribution in 2016 and 2017.

Operating the machine in the first year of run 2 was particularly challenging considering the impact of electron cloud and high UFO (Unidentified-Falling-Objects [4]) rates. The length of the luminosity production run was only 58 days.

Both 2016 and 2017 were instead intended as 'production years', devoting a total of 156 and 140 days to luminosity production, respectively. It can be seen that the LHC performance steadily improved with time, yielding an availability of 70% in 2015, 72% in 2016 and of 79% in 2017. It is interesting to compare the physics efficiency achieved in the two production years (2016-2017). In both years, 49% physics efficiency was achieved, despite the higher availability in 2017. In order to explain this observation, a more detailed analysis of failure causes in the different years is required.

Excellent equipment availability is at the core of the success of LHC performance. The downtime distributions for LHC systems in 2016 and 2017 is reported in Fig. 2. In 2016, the impact of technical infrastructures (electrical network, cooling and ventilation) on operation was significant due to the occurrence of isolated, high impact faults: a major fault in an 18 kV transformer and water flooding in one of the LHC underground areas. In this operating regime and considering the exceptional luminosity lifetime (about 30 hours), it was decided to have long fills in the machine for a significant part of the year. The downtime in 2017 was instead driven by recurring beam aborts (66 in total) due to localized beam losses in cell 16L2 of the LHC, possibly caused by contamination due to an un-detected air leak present during the Year-End Technical Stop (YETS) 2016-2017 [4, 5]. Even if these were failures with a very short duration, the stable beams phase was frequently prematurely interrupted, reducing the physics efficiency. Extensive investigations were required to understand the source of the problem. Beam intensities had to be limited to reduce the number of premature beam aborts. The adoption of a filling scheme "8b4e" [5] mitigated the e-cloud and consequently the overall loss of integrated luminosity. 50 fb^{-1} were delivered to the experiments, 10 fb^{-1} more than 2016.

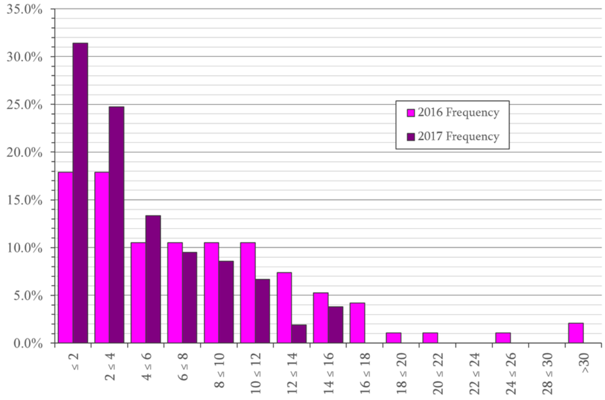

Figure 3: Stable beams time distribution for fills dumped by failures in 2016 and 2017.

The higher frequency of recurring failures implies that to achieve the same integrated time in stable beams more cycles were needed. This can be seen in Fig. 1 by looking at the larger contribution of 'operations' in 2017 as opposed to 2016. Another way to look at this requires a comparison

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of the distribution of the time in stable beams for fills dumped by failures. Figure 3 shows the higher number of short fills in 2017 than 2016 due to the 16L2 beam losses. Given the reliability definition proposed above, one can conclude that 2016 operation was more reliable than 2017 operation, despite achieving a better availability in 2017 and an overall equal physics efficiency.

An additional aspect needs to be considered when dealing with reliability issues of the LHC. Considering the higher number of cycles and, thus, injections to be performed, the availability of the injector chain becomes of utmost importance. A key to the successful integrated luminosity production campaign of 2017 was the excellent availability and flexibility of the injector complex, delivering different beam types to the LHC in a timely fashion, and therefore allowing to cope with the recurring beam losses in 16L2.

Experience gathered so far in LHC run 2 yields the following conclusions:

1. Availability during the first year after a long-shutdown is expected to be lower than in an average production year, given the significant hardware changes deployed in the machine and anticipating deconditioning effects (for example e-cloud and UFOs)
2. Operating with short turnaround times is a key aspect to achieve a high physics efficiency. Optimum fill lengths have to be determined as a trade-off between luminosity lifetime and average turnaround time. Considering the higher beam brightness foreseen following the LHC Injectors Upgrade (LIU) during LS2, the optimal fill length is expected to become shorter, making the availability requirements for the injector complex more demanding. Detailed fault tracking in the injector complex was identified as a key activity for present and future operation, leading to the extension of the AFT to the CERN injectors in 2017.
3. Mitigation measures deployed during LS1 (radiation tolerant electronics designs, remote reset capabilities) were very effective in reducing fault times, yielding a significant improvement in terms of availability as compared to LHC Run 1.
4. For machine protection, Beam Loss Monitors (BLMs) measure beam losses around the LHC ring. If the loss measured by one BLM exceeds a threshold, the beams are preventively aborted. The adopted strategy in terms of thresholds setting [6] minimised the number of spurious beam dumps due to UFOs, with only very few magnet quenches (3 in 2015, 3 in 2016 and none in 2017).
5. The cryogenic configuration adopted in 2016 and 2017, operating with only 4 out of the available 8 cold compressor units [7] allowed optimisation of machine availability. Faults of cold compressor units lead to a downtime of up to 24 h. Operating fewer units limits the number of failures and therefore reduces the overall downtime, without having an impact on the cooling capacity.
6. Management of transient heat loads due to high intensity beams are a challenge for LHC operation, having a potential impact on the turnaround time and, thus, on the physics efficiency [8].
7. The performance of the technical infrastructures can affect LHC and its injectors. It is important to maintain a high availability of the infrastructure through monitoring and preventive maintenance. The Technical Infrastructure Operations Committee (TIOC) at CERN is in charge of following up all issues related to technical infrastructures.
8. The reliability of the kicker generators of the beam dumping system, for both extraction kickers (MKDs) and dilution kickers (MKBs), is highly correlated with their operating voltage and, hence, beam energy. Mitigation measures are foreseen for LS2 to reduce the voltage over a single switching element of the generators and reduce their failure rate [9].
9. Systematic follow-up of observed failures is a key aspect of improving the performance of the CERN complex and to drive future consolidation initiatives. Since 2017, the AFT tracks faults in all CERN accelerators, allowing consistent logging of data for reliability analyses.
10. Optimizing accelerator schedules and technical stops for maintenance could lead to a significant gain in terms of available time for luminosity production [10]. The optimum trade-off between the observed number of failures and number of technical stops for preventive maintenance should be found.
11. Any potential change to consolidated machine settings or hardware should be extensively tested in an environment as close as possible to the operating one before deployment.

RISK ASSESSMENT AND STRATEGY FOR FUTURE LHC RUNS

Experience gained with the first two LHC runs allows an informed risk assessment when dealing with decisions regarding the future exploitation of the LHC. As an example, we report below the thought process that guides the evaluation of the possibility of running the LHC at its nominal energy. The LHC is presently running at 6.5 TeV, i.e. 0.5 TeV below its nominal energy. The decision on whether to operate or not at 7 TeV and eventually to the ultimate energy of 7.5 TeV depends on several factors.

The first aspect to be considered is the time and risk associated to training LHC superconducting magnets to the nominal energy and beyond. Present observations highlight a probability of 1 % (although based on only two events) of developing a short-to-ground during magnet quenches [11, 12]. In both cases the short-to-ground was caused by metallic residue from the magnet manufacturing process accumulating in the half-moon connections of the magnet cold diode box [11]. The probability of occurrence of these events is deemed unacceptable in view of future runs at nominal energy and a campaign to insulate the cold diode boxes of LHC dipoles is foreseen in LS2 to mitigate this failure mode. On the other hand, operation at 7 TeV implies higher magnetic forces, which could potentially lead to an increased probability of observing an inter-turn short in the magnet coils. Only one event of this type was observed so far in the machine in 2016 and the magnet was replaced in the YETS 2016-2017 [12].

The second aspect to consider is the expected loss of availability and physics efficiency related to operating the machine at higher energy. A systematic study of the impact of 7 TeV operation on availability was carried out [13], analysing all systems potentially being affected by the energy increase. Based on what was described in the previous paragraph, the systems affected by the higher energy are mainly the cryogenic system and the LHC Beam Dumping System (LBDS). In addition, the increased probability of beam-induced quenches due to UFOs and (spontaneous) magnet flat-top quenches has to be considered.

Two scenarios were considered (‘conservative’ and ‘optimistic’) to assess the potential impact of operation at 7 TeV on the physics efficiency. The ‘conservative’ scenario assumes fault distributions in line with the one of 2016, while the ‘optimistic’ scenario assumes as a reference 2017-like distributions. The impact of operation at 7 TeV is quantified via the additional failures to be expected, which are summarized in Table 1. A detailed explanation of the numbers reported in Table 1 can be found in [11].

Table 1: Expected LHC Failures Due to the Potential Energy increase to 7 TeV, for the ‘Conservative’ and ‘Optimistic’ Scenarios

	Conservative		Optimistic	
	Rate (1/y)	Downtime (days)	Rate (1/y)	Downtime (days)
MKD erratic	2	4	1	2
MKB erratic	2	2	2	2
Flat-top quench	10	4	3	1.5
UFO-induced quench	10	3	3	1.5
Cold-compressor failure	8	6	2	1.5

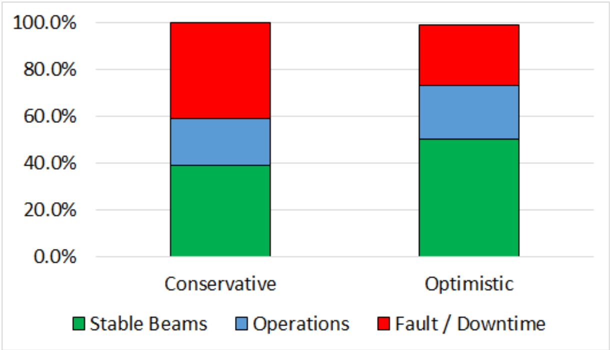

Figure 4: Comparison of expected availability and physics efficiency for 7 TeV LHC operation for the ‘conservative’ and ‘optimistic’ scenarios.

The final results of the assessment are shown in Fig. 4, in which a comparison of the expected availability and physics efficiency is provided. In the ‘conservative’ scenario the availability and physics efficiency would be 59 % and 39 %, respectively. In the ‘optimistic’ scenario the impact on the performance would be reduced, with an availability of 74 % and a physics efficiency 50 %, in line with 2016 and 2017.

The third factor to be taken into account for the decision is the acceptable integrated luminosity loss related to operating at 7 TeV as opposed to 6.5 TeV. This should be provided by the particle physics community, also considering the outcomes of the data analysis during the entire LHC Run 2.

Finally, the duration of the magnet training campaign is an important parameter to decide on the optimum time to go to 7 TeV and has to be evaluated against the consequent loss of integrated luminosity as compared to operation at 6.5 TeV. Today, there are rather big uncertainties concerning the possible duration of the training campaign [14, 15], as no LHC sector was so far trained to 7 TeV in the machine. An educated estimate will be available following the foreseen training of two LHC sectors to 7 TeV at the end of 2018, which will allow for a final decision on the operating energy of the LHC for future runs.

CONCLUSIONS

This paper summarized the lessons learnt during the LHC Run 2 concerning the machine reliability and availability. As was shown in the last section, the considerations made in this paper are planned to be the basis for future strategic decisions and to optimize the integrated luminosity production in the coming years. The advent of the LIU era, after LS2, and the HL-LHC era, after LS3, will further increase the focus on enhanced availability of the whole CERN accelerator complex and its related infrastructure. Studies are currently ongoing to model the reliability of new systems for LHC upgrades and future machines (such as CLIC and FCC) to assess their expected impact and maximize the future physics performance.

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