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ROADMAP TOWARDS HIGH ACCELERATOR AVAILABILITY FOR THE CERN HL-LHC ERA

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Abstract

High Luminosity-LHC is the future upgrade of the LHC that aims at delivering an integrated luminosity of 3000 fb-1 over about 10 years of operation, starting from 2025. Significant modifications [1] will be implemented to accelerator systems, including new superconducting magnets, crab cavities, superconducting links, new collimators and absorbers based on advanced materials and design and additional cryo-plants. Due to the limit imposed by the number of simultaneous events at the experiments (pile-up) on peak luminosity, the latter will be levelled to $5*10^{34}$ $cm^{-2}s^{-1}$. The target integrated luminosity can only be achieved with a significant increase of the total available time for beam collisions compared to the 2012 LHC run, despite a beam current that is planned to double the nominal 0.58 A. Therefore one of the key figures of merit to take into account for system upgrades and new designs is their impact on the accelerator availability. In this paper the main factors affecting LHC availability will be discussed and predictions on the impact of future system upgrades on integrated luminosity presented. Requirements in terms of the maximum allowed number of dumps for the main contributing systems to LHC unavailability will be derived.

INTRODUCTION

High availability is becoming one of the key requirements for many accelerator facilities in the world. In the past only few categories of accelerators were considered as availability-critical. These are typically user-oriented facilities like synchrotron light sources and medical accelerators. Nowadays the challenging objectives on new projects around the world impose to consider availability as a fundamental requirement from early project and design stages. HL-LHC is the first particle collider with a defined integrated luminosity target [1]. HL-LHC aims at producing 250-300 fb^{-1} per year, for a total of 3000 fb^{-1} over about 10 years of operation. For ultimate parameters, the project is aiming at 400 fb^{-1} per year.

The considered baseline for the yearly LHC run time for physics production is 160 days. This implies an average integrated luminosity production of 1.9 fb^{-1} per day. For comparison, the total integrated luminosity produced by the LHC in 2011 was 5 fb^{-1}. Such increase of luminosity production has strong implications on availability requirements. Figure 1 shows that considering 2012 LHC availability and nominal HL-LHC parameters, a yearly production of 200 fb^{-1} could be achieved [2, 3]. Availability is expressed in the chart as a function of two quantities, the so-called *machine failure rate* and the *average fault time*. The *machine failure rate* indicates the fraction of premature beam aborts (i.e. beam dumps) which are initiated by machine protection systems upon the detection of any system failure. In 2012 the machine failure rate amounted to 70 %. Every time the beams were dumped, an average of 5.5 h – the so-called turnaround time - was required before colliding beams could be re-established. The *average fault time* measures the time spent to recover operating conditions after a fault occurs. In [3] it was shown that the fault time ranges from few minutes to many hours, depending on the fault and system root cause.

Improving these figures is mandatory to achieve the challenging goals of integrated luminosity of the HL-LHC project. The plot shows that an improvement of about 50 % of the average fault time, combined with a reduction of about 20 % of the machine failure rate will be required. This has strong implications on the system designs.

In this paper the main limitations to LHC availability will be discussed, based on the experience with the first LHC run (2010-2012). A strategy to identify individual system requirements in view of the HL-LHC era will be presented.

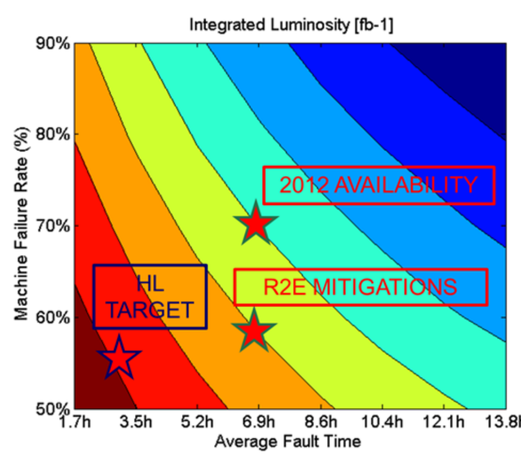

Figure 1: Fault time classification from 2012 observations.

LIMITING FACTORS FOR HL-LHC AVAILABILITY

The first LHC run allowed identifying possible availability bottlenecks for future LHC runs. Several system failure modes and effects were identified as critical for operation. Considering HL-LHC operation requires extrapolating the current knowledge to new operating conditions, i.e. increased energy and beam intensity and reduced operational margins for all systems. LHC run 2 (2015-2018) will represent an important

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period to validate and extend the achieved machine understanding and improve the developed availability models [2] towards the HL era.

Among the main limiting factors for availability identified during LHC run 1, Radiation To Electronics (R2E) has been proven to be responsible for a significant fraction of premature dumps. In 2012, 56 dumps out of 585 have been attributed to R2E by system experts, i.e. about 10 % of the total. The systems which were mostly impacted by R2E effects were the Quench Protection System (QPS, 31 dumps, about 50% of the QPS total) and the power converters (14 dumps, about 25 % of the total for power converters). The consequences of a R2E-induced stop ranged from about 30 min of fault time, to several hours in case of a failure involving the cryogenic system [4]. It is therefore mandatory to consider R2E as a possible availability bottleneck for HL-LHC, when radiation levels will be unprecedented compared to previous LHC runs.

Concerning beam-related effects affecting availability, finding the right balance between tolerable beam losses and beam-induced quenches will be crucial for efficient operation. Beam Loss Monitors (BLMs) are the backbone of the LHC Machine Protection System (MPS). If a BLM detects beam losses above a predefined threshold, the circulating beams are preventively dumped to avoid damage to accelerator equipment. A total of about 3600 BLMs are used to have a full coverage of the LHC ring. Setting BLM thresholds has a direct impact on availability. Tight thresholds allow intercepting even small beam losses, i.e. increasing equipment protection, but may generate unnecessary beam dumps, thus, affecting availability. On the other hand, adopting less stringent thresholds may lead to a number of beam-induced quenches, requiring long recovery times from the cryogenic system (6-8 h at 6.5 TeV) before being able to resume nominal operation. The optimal balance between these two aspects should be found by improving the understanding of magnet quench levels and beam loss mechanisms [5]. Dedicated studies are ongoing and the beginning of LHC run 2 provides an important chance to validate the developed models.

A particular concern for protection and availability is linked to the detection of the so-called Unidentified Falling Objects (UFOs). These are dust particles that interact with the beam and are able to generate fast beam losses, possibly leading to magnet quenches. As shown in [6], it is fundamental to investigate the impact of increased energy and reduced bunch spacing (25 ns as compared to 50 ns) on the UFO rate and quantify the potential reduction of availability due to these effects. UFOs are expected to be one of the possible availability bottlenecks for future LHC runs and HL-LHC.

The introduction of many new systems for HL-LHC will certainly have a significant impact on protection requirements and availability. The so-called crab cavities will allow performing more efficient collisions by ensuring a full overlap of colliding bunches at the interaction points [7]. Failures of crab cavities can lead to fast beam deflections – i.e. within one LHC turn (89 μs) - and severe damage of accelerator equipment [8]. New MPS will have to be designed to avoid any damage-induced downtime. Nevertheless the additional complexity of MPS can increase the probability of having false failure detections, leading to unnecessary preventive dumps. Managing new systems and the related protection is the main concern in view of HL-LHC also in terms of availability.

In the HL-LHC era all systems will run close to their design limits, leading to unprecedented operational loads for components. It is known that reducing operating margins has an impact on component failure rates and accelerates the onset of wear-out. During the first LHC run, the energy was limited to 4 TeV, operating well below design specifications. Already during LHC run 2, systems will work close to design limits to reach 6.5 TeV. The impact of this aspect on system reliability will be carefully assessed to identify a suitable maintenance strategy.

STRATEGY TOWARDS HIGH ACCELERATOR AVAILABILITY

The LHC underwent an extensive period of maintenance from 2013 to 2015 (Long-Shutdown 1, LS1) to address most of the outstanding issues discovered in the first LHC run. Two additional long shutdown periods are foreseen before 2025.

R2E consolidations represented a big investment of resources during LS1 and the deployed solutions already accounted for HL-LHC requirements. In particular the Quench Protection System (QPS) and the power converters significantly improved their radiation tolerance by adopting new designs including radiation tolerant components and passive measures such as shielding and relocation of equipment from exposed areas [9]. The upgrade of the converter controls (FGClite [10]) will likely be deployed at the end of the 2015 run. The enhancement of remote reset capabilities for equipment in the tunnel will allow a reduction of the fault time. In the HL-LHC era, radiation levels will be greatly enhanced due to the increased luminosity at the beam interaction points and by higher collimation losses [11]. LHC equipment and experimental particle detectors will profit in the future from the respective experience achieved in the first LHC run. A new facility called CHARM is operational at CERN and allows for component characterization and tests in a radiation environment [12].

To preserve system reliability and availability, a series of measures are already foreseen to be deployed for the HL-LHC era. The increased luminosity production will have a significant impact on the thermal load on superconducting magnets at the interaction points. New cryo-plants will therefore be installed to decouple such magnets from the rest of the sector. Similarly, the superconducting cavities in the LHC point 4 will also be decoupled from the sector cryogenic system. A detailed

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quantification of the availability gain deriving from such measures is ongoing.

Many of the current LHC systems will be running for more than 20 years when entering the HL-LHC era. It is already known that several systems will reach the end of their lifetime by then. As an example, superconducting triplets close to the main experiments will be replaced by Nb_3Sn triplets. The triplets currently in use in the LHC were designed for a total integrated dose equivalent to 300 fb^{-1}, which will be reached by 2025. Similarly, electronic systems belonging to the MPS are expected to be redesigned in view of HL-LHC. This process will both ensure the implementation of new system requirements and an upgrade to up-to-date technologies. Obsolescence of components may become an issue in 10 years from now, as some may not be commercially available for purchase. Management of spare parts is a crucial aspect to be taken into account while designing a new system that should operate for at least 20 years.

As a general remark, aiming at a reduction of the fault frequency implies the design of even more reliable systems. Considering again R2E failures as an example, effective measures as relocation of equipment, shielding and use of radiation tolerant components have been already applied during LS1 and will have to be enforced in the future. For MPS, detailed studies on architectures for the next generation of interlock systems would allow significant improvements in terms of availability [13].

Availability studies require dedicated means for efficient tracking of faults occurring during operation. All developed models and extrapolations are based on the recorded data from the past LHC runs. High-quality data allows for accurate modelling and identification of critical areas for future improvements. The Accelerator Fault Tracking (AFT) project was launched at CERN to ensure consistent fault tracking from the beginning of LHC run 2 onwards [14]. The project goal is to provide the tools for both machine operators and system experts to share relevant information on follow-up of equipment faults, pending issues to be addressed and quantification of the efficiency of operational practices and equipment maintenance strategies.

AVAILABILITY MODELLING AND LUMINOSITY PREDICTIONS

For the HL-LHC project it is foreseen to evaluate the relative impact of different design options and system upgrade scenarios by estimating, amongst others, their impact on availability and, thus, on integrated luminosity. The Monte-Carlo model used to produce Fig. 1 allows making predictions based on the estimated fault frequency and fault time distributions for each accelerator system.

As an example, the maximum tolerable number of R2E-induced dumps in the different phases of the LHC run has been calculated. All R2E failures that appeared in 2012 were therefore considered and their impact extrapolated up to HL-LHC, considering in first approximation the deployed mitigations during LS1 and the different operational and environmental conditions, which determine the radiation levels in the LHC tunnel, and assuming no additional failure sources. Table 1 shows an extrapolation of the predicted number of dumps per year and of the respective fault time.

Table 1: Extrapolation of R2E-Induced Dumps and of the Respective Fault Time Per Year. The 2012 Run Is Taken as a Reference

LHC phase	# dumps per year	Total downtime	Average downtime
2012 (ref)	56	250-300	4.3-5.2
Run 2 (>2015)	9-12	35	3.9
HL-LHC	25-40	84	3.4

Assuming that a reduction of 5 % of the machine failure rate should be gained through the mitigation of R2E effects to reach the HL-LHC luminosity goals (see Fig. 1), the calculation shows that a theoretical maximum of 16 R2E-induced dumps could be accepted per year. Assuming to have the same distribution of R2E dumps among systems observed in 2012 and an average fault time of 3.5 h, the resulting number of dumps per system and the corresponding downtime are shown in Table 2. Aiming for a low total number of failures, only a few individual failures can be accepted for each possibly affected equipment group, thus highlighting the challenge to: (a) monitor and analyse such failures during LHC Run 2 and Run 3 and (b) linked to the high number of exposed systems and components, imply very strong radiation qualification criteria for all electronic developments.

Table 2: Maximum Acceptable Number of Dumps (target, TG) and Relative Fault Time Due to R2E-Induced Failures in the HL-LHC Era

System	R2E dumps (2012)	R2E downtime (2012)	R2E dumps (HL TG)	R2E downtime (HL TG)
QPS	31	80 h	9	32 h
PC	14	60 h	4	14 h
Cryo	4	70 h	1	3.5 h
Vacuum	4	20 h	1	3.5 h
Others	3	30 h	1	3.5 h

CONCLUSIONS

In this paper the expected main limitations to availability in the HL-LHC era have been discussed. The strategy on how to address availability requirements for different systems has been presented. New projects (e.g. the AFT) and facilities (e.g. CHARM) were developed at CERN and witness the importance of availability for the future LHC. An example of the calculation of availability

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requirements for individual systems has been shown regarding R2E-induced failures.

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