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UPDATE ON PREDICTIONS FOR YEARLY INTEGRATED LUMINOSITY FOR HL-LHC BASED ON EXPECTED MACHINE AVAILABILITY

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Abstract

Machine availability is one of the key performance indicators to reach the ambitious goals for integrated luminosity in the post Long Shutdown 1 (LS1) era. Machine availability is even more important for the future High Luminosity LHC (HL-LHC) [1]. In this paper a Monte Carlo approach has been used to predict integrated luminosity as a function of LHC machine availability. The baseline model assumptions such as fault-time distributions and machine failure rate (number of fills with stable beams dumped after a failure / total number of fills with stable beams) were deduced from the observations during LHC operation in 2012. The predictions focus on operation after LS1 and its evolution towards HL-LHC. The extrapolation of relevant parameters impacting on machine availability is outlined and their corresponding impact on fault time distributions is discussed. Results for possible future operational scenarios are presented. Finally, a sensitivity analysis with relevant model parameters like fault time and machine failure rate is discussed.

INTRODUCTION

After three years of successful running from 2010 to 2012, the operational experience gained has given an in depth understanding of the LHC systems. The goal of future LHC runs is to enlarge the discovery reach for new physics. To achieve this, the energy will be increased towards the initial design energy, and the machine performance will be pushed to the maximum. A major campaign is currently being carried out during the LS1 for splice consolidation to allow nominal energy of 7 TeV per beam to be reached. Mitigation strategies and measures have been adopted in order to reduce the impact of faults that were observed during run 1 and that have a high impact on machine availability, in particular measures to reduce radiation-induced Single Event Upsets (SEU) in electronics. Reaching nominal performance will require every system to operate closer to its design limits, causing higher stress levels on components. Given the complexity of the systems involved and the many interdependencies, it is not straightforward to quantify the effect of such changes on LHC availability.

A Monte Carlo model was developed to predict the impact of future operational scenarios on machine availability and integrated luminosity. Basic definitions of quantities adopted in the model can be found in [2]. The model is able to reproduce a realistic timeline of LHC operation based on the observed distributions of turnaround time, fault time and stable beams time (i.e. time for physics data taking) in 2012. By properly shaping such distributions the impact of future operational scenarios can be studied. It is inherently difficult to model and account for all aspects of LHC operation; nevertheless the model allows performing sensitivity analyses with respect to different relevant parameters (e.g. fault times, turnaround time, etc.) and extrapolate possible future scenarios from such analyses.

Figure 1 shows the LHC integrated downtime caused by each system in 2012. Extrapolating what would be the future evolution of such distribution is a key factor for luminosity predictions.

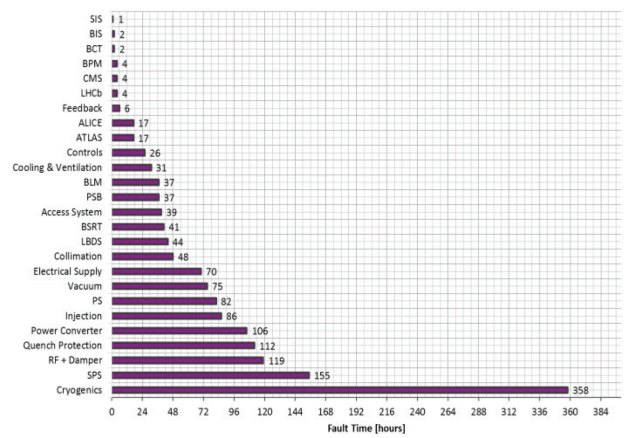

Figure 1: Fault time classification from 2012 observations.

LHC AVAILABILITY FOR POST-LS1 OPERATION

The efforts to mitigate consequences of failures that limited LHC availability between 2010 and 2012 are reviewed in [3]. Here the systems with the largest contributions to LHC downtime in 2012 will be discussed, as well as the most significant changes to the LHC systems.

As shown in Fig. 1, the cryogenic system had the largest contribution to LHC downtime, though the absolute number of failure events has been lower than that for other systems. Cryogenic stops have long recovery times, ranging from some hours to few days with an average of 9.6 h. After LS1, the higher energy of 6.5 TeV will increase the resistive heat load by a factor 4, resulting in an operating point closer to design values. Failures of rotating machinery will have a higher impact on availability; it will take longer time to recover operating conditions after magnet quenches. Mitigation strategies for the cryogenic system consist in major overhauls of rotating machinery, reinforcement of magnetic bearing controllers in the cold compressors against electro-magnetic coupling and implementation of mitigations

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against single event upsets in point 2, 4 and 6 of the LHC [3].

A significant contribution to LHC downtime is caused by failures of the power converter systems. Recovery times are shorter than for cryogenics (the average fault time amounts to 1.6 h), but failures are more frequent. Known failure modes are being addressed during LS1 with dedicated solutions: in particular voltage sources are being consolidated to be more reliable than during run 1. A project for the replacement of the current power converter controllers (FGC2) was launched with the scope of having a radiation-tolerant system in the future (FGClite). This system will not be in place for the restart of the LHC in 2015. When first deployed, care must be given to reduce failures caused by 'infant mortalities' of the new system, such that the machine availability will not be affected significantly [3].

Similarly as for the power converters, the Quench Protection System (QPS) caused in 2012 a high number of relatively short stops (with an average fault time of 2.2 h). These were mainly due to sensitivity of electronic components to radiation in exposed areas and to bad connections leading to spurious triggers of the quench detection electronics and the energy extraction system. A campaign was launched to mitigate such effects: the relocation of electronics, in combination with the use of radiation-tolerant electronics, will mitigate 30% of radiation-induced faults; cabling will be carefully checked before the restart. In addition a remote-reset functionality has been implemented to mitigation lost communication with quench detection electronics. These measures will improve the recovery time from QPS faults [3].

For all other LHC systems, consolidation of failure modes identified during run 1 is currently being carried out. In this respect, the philosophy being followed is to first improve safety and then availability. Some of the consolidation measures could potentially reduce availability in order to ensure higher safety. An example is the LHC Beam Dumping System (LBDS) retriggering line via the BIS, which will provide an independent means of triggering a beam dump in case of a complete failure of the LBDS redundant triggering [4]. A dedicated study was performed to quantify the impact of such implementation on reliability and availability, showing that the overall impact on availability will be negligible. Another example is the implementation of additional interlocking channels in the Software Interlock Systems (SIS), which were not present during run 1, as e.g. the interlock linked to the monitoring of the abort gap population. This interlock will ensure a clean abort gap avoiding large particle losses during the rise time of the LBDS kicker pulse.

Considering beam-related events, the extrapolation of observed Unidentified Falling Objects (UFOs) to 6.5-7 TeV forecasts up to 100 dumps per year after LS1 [5]. UFOs have shown a clear conditioning trend during LHC run 1, however, deconditioning is expected following the consolidations in the machine vacuum segments. Relocation of BLMs to catch UFO events will ensure maintaining the high level of protection while allowing to increase BLM thresholds at the quadrupole locations. The redefinition of BLM thresholds, according to recent studies on quench limits [6], should allow the right balance between detection of dangerous events versus unnecessary LHC stops to be found.

INTEGRATED LUMINOSITY PREDICTIONS

The basic assumption for all luminosity predictions in this paper is to have 160 days of luminosity operation per year. For HL-LHC, considering the exploitation of luminosity levelling at $5*10^{34}$ [$cm^{-2}s^{-1}$] from a virtual peak luminosity of $2.1*10^{35}$ [$cm^{-2}s^{-1}$] at 7 TeV, a maximum luminosity levelling time of 6.5 h can be achieved with a luminosity lifetime of 4.5 h. This implies that fills longer than 6.5 h will experience the typical luminosity exponential decay observed without levelling. A Monte Carlo model was used to make predictions of integrated luminosity based on the definition of the following possible operational scenarios:

1. Extension of 2012 fault distributions to Post-LS1 operation (machine failure rate = 70%, turnaround time = 6.2 h, fault time = 7 h)
2. Impact of UFOs at 6.5/7 TeV
3. Impact of increased BLM thresholds and Beam-Induced Quenches (BIQ)
4. Impact of LS1 mitigations regarding SEUs
5. Combination of scenarios 3 and 4

The simulation results are summarized in Table 1.

Table 1: Simulated Scenarios in the Availability Model

Scenario	Assumption	Integrated luminosity/yr
1	2012 distributions	213 [fb^{-1}]
2	100 UFO dumps	179.5 [fb^{-1}]
3	3 times higher BLM thresholds + scenario 2	203 [fb^{-1}]
4	20 SEU-induced dumps	220.5 [fb^{-1}]
5	Scenarios: 3 + 4	208.5 [fb^{-1}]

The results show that the goal of 250-300 fb^{-1} is very ambitious based on the currently achieved LHC availability. It has to be noted that these scenarios are based on the current understanding of the machine and related faults. HL-LHC will require the introduction of new systems (e.g. crab cavities) bringing possibly new failure modes which require time and experience to be efficiently managed.

In order to further address these questions, a sensitivity analysis to the average fault time and machine failure rate was carried out (Fig. 2). It can be seen that, assuming current stable beams distributions, a major reduction of average fault time and machine failure rate is necessary to reach 250-300 fb^{-1} per year.

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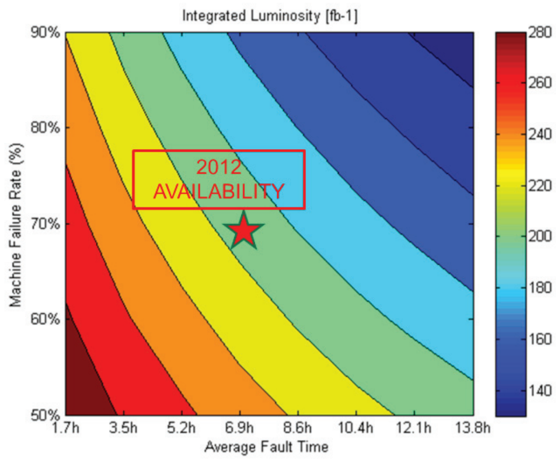

Figure 2: Achievable integrated luminosity per year for HL-LHC depending on Machine failure rate and average fault time.

INTEGRATED LUMINOSITY TARGETS AND ASSUMPTIONS

Given the assumptions introduced above and to set availability targets for HL-LHC, the expected integrated luminosity per year has been calculated as a function of fill length and number of fills, adding constraints in terms of turnaround time, machine failure rate and average fault time.

Five scenarios were defined:

1. Optimized luminosity without machine faults, i.e. maximum achievable luminosity; (machine failure rate = 0%, turnaround time =4 h)
2. Optimized luminosity including external faults, i.e. faults out of CERN's control (machine failure rate = 0.08%, turnaround time =4 h, fault time = 2.7 h)
3. Optimized luminosity with figures from 2012 (machine failure rate = 70%, turnaround time = 6.2 h, fault time = 7 h)
4. Optimized luminosity in case all machine faults would require no access in the tunnel to be solved (machine failure rate = 70%, turnaround time = 6.2 h, fault time = 1 h)
5. Optimized luminosity in case all machine faults would require one access (machine failure rate = 70%, turnaround time =6.2 h, fault time = 4 h)

The results for the five scenarios described above are summarized in Table 2 and show the maximum achievable integrated luminosity for optimized fill lengths (levelling time / luminosity exponential decay, only for fills not terminated by failures) and number of fills.

These results exhibit purely theoretical values, as such optimization (e.g. for scenario 3) can be performed only after measuring fault distributions that occurred during the run. Every time a fault occurs during operation, the optimum working point in terms of ideal fill length would change. The fill length becomes longer with increasing fault times, as could be assumed intuitively. It is also worth noting that ideal fill lengths range from ~8.5 (scenario 1) to ~ 11 hours (scenario 3), not far from what was done in 2012 (the average fill length for fills dumped by operators was 9.64 h).

This approach can be useful in defining the goals in terms of availability which have to be met in order to reach 250-300 fb^{-1} per year. For example, considering a machine failure rate of 50% and an average fault time of 5 h would lead to 290 fb^{-1} assuming optimized fill lengths.

Table 2: Optimized Luminosity and Operational Parameters for Different Availability Scenarios

Scenario	Fill length [h]	Number of fills	Integrated luminosity
1	6.5 / 1.9	309	448.7 [fb^{-1}]
2	6.5 / 2.1	308	435.3 [fb^{-1}]
3	6.5 / 4.8	217	236.3 [fb^{-1}]
4	6.5 / 3.6	291	310.8 [fb^{-1}]
5	6.5 / 4.3	249	268.3 [fb^{-1}]

CONCLUSIONS

In this paper the main factors driving LHC availability in the post-LS1 era have been discussed and the impact on the yearly integrated luminosity has been quantified for HL-LHC, for different operational scenarios. A sensitivity analysis to the average fault time was carried out to identify the recovery times and acceptable number of machine faults to be achieved. Luminosity targets have been presented, as a function of optimum fill length and number of fills, according to various assumptions on fault times and turnaround times.

In order to meet the challenging luminosity goals of HL-LHC, significant efforts will be needed to define strategies to increase LHC availability.

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