AVAILABILITY FOR POST-LS1 OPERATION

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Abstract

Availability is one of the key factors to be taken into account to improve the LHC performance after LS1 and for future LHC upgrades. A comprehensive view of LHC availability in 2012 is given in this paper, based on the analyses of the Availability Working Group. The main contributions to LHC un-availability for Post-LS1 operation are highlighted following the outcomes of the Dependability Workshop, held in November 2013. Goals and foreseen project stages of the Accelerator Fault Tracking (AFT) are presented. Integrated luminosity predictions and sensitivity analyses to relevant operational parameters are shown, as a function of possible future availability scenarios.

2012 LHC AVAILABILITY

A summary of the studies [1] carried out by the Availability Working Group (AWG, [2]) in 2012 is presented in this paragraph and is the base for the extrapolation of future availability scenarios.

The distribution of beam aborts in 2012 is shown in Fig. 1, according to the dump cause classification in the post-mortem database. A classification of beam aborts is proposed, differentiating between aborts caused by experiments, beam-related effects, equipment failures, causes outside CERN's control (external) or initiated by operators. Dumps classified as 'end of fill' (EOF) are generally those executed by operators for luminosity optimization and amount to 30% of the total.

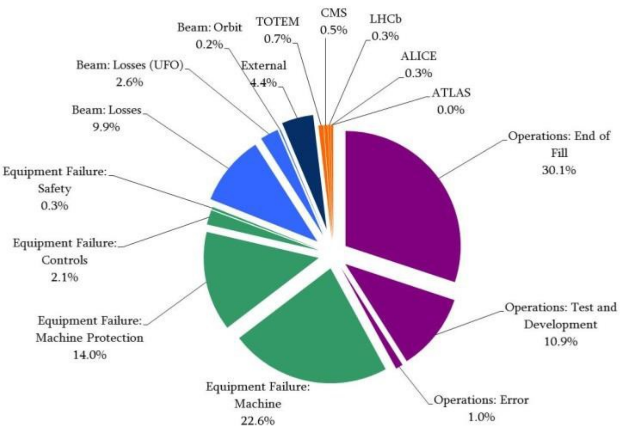

Figure 1: Distribution of beam aborts in 2012.

Figure 2 shows the LHC integrated downtime caused by each system in 2012, based on the data taken from the operational eLogbook (manual entries). The largest contributions to LHC unavailability for beam operation are the cryogenic system, the lack of beam from the SPS and the RF and damper systems.

Following a beam dump, a minimum time of about 3h is necessary again before reaching stable beams with a new fill, when no faults occur (so-called 'turnaround time'). The average time in stable beams for fills terminated by EOF amounts to ~9h and the corresponding time for fills terminated for failures amounts to ~ 4.5h. Luminosity production is then significantly limited by faults occurring after only few hours of stable beams. In this case the unavailability for physics production should not only take into account the fault time associated to the system causing the beam dump, but also the necessary time to go back to stable beams ('lost physics' time). In Fig. 3 a penalty of up to 3h (i.e. the turnaround time) is assigned to systems causing a premature beam dump (<9 h in stable beams), on top of the integrated fault time shown in Fig. 2. Considering this additional factor, which gives an indirect estimate of the failure frequency, the biggest contributions to LHC unavailability come from the cryogenic system, the power converter system and the Quench Protection System (QPS).

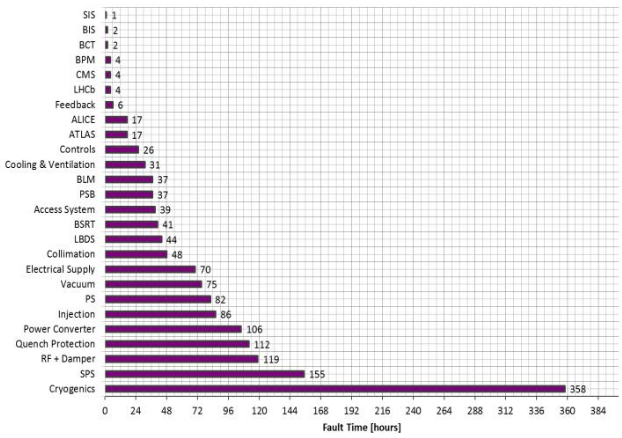

Figure 2: Fault time classification from 2012 observations.

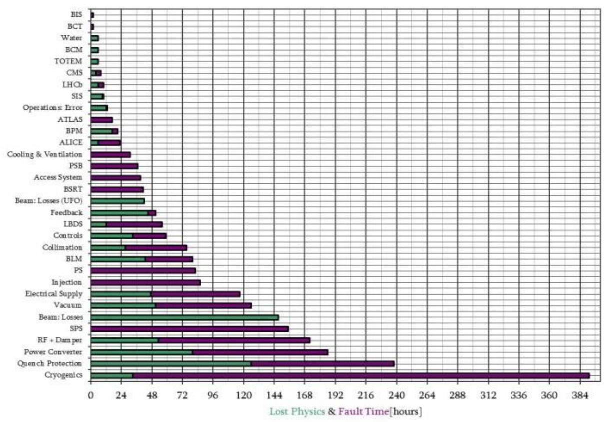

Figure 3: Fault time classification, including 'lost physics' time.

Figure 4: 'Cardiogram' of LHC operation. Few days of the LHC run in August 2012 are reported here as an example.

Figure 4 shows a visual representation of the relevant quantities for availability tracking, besides the fault times, in the so-called 'cardiogram' of LHC operation. The horizontal axis is the LHC run time. The accelerator mode (green: proton physics, orange: access, blue: beam setup), the BIS input indicating machine access (orange: taken from the CCC BIC "Access System" input), energy (black) and intensities (blue and red lines) are shown in the top part of the picture. The green lines indicate stable beams and purple crosses post-mortem events. Red lines indicate equipment faults by system, according to the classification shown in Fig. 2. This representation is based on data coming from different sources (eLogbook, post- mortem database, TIMBER, etc.) and is very useful to spot data inconsistencies for proper availability tracking.

Figures 2, 3 and 4 only give a partial view of the LHC failures, i.e. the ones directly impacting on availability. There are many other faults that are transparent for LHC operation (e.g. due to internal system redundancies), but still need to be taken into account for reliability analyses of individual systems. Tracking failures and failure modes of individual systems is therefore an important element to be considered.

LHC AVAILABILITY FOR POST-LS1 OPERATION

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 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 hence 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 against single event upsets in points 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 and auxiliary power supplies 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 deploying a more radiation-tolerant system in the future (FGClite). This system will not be in place for the restart of the LHC in 2015 but will be progressively deployed in exposed areas during Run 2. 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 systems. A campaign was launched to mitigate such effects: the relocation of electronics, in combination with the use of radiation-tolerant electronics, is expected to 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 without requiring machine access. These measures will improve the recovery time from QPS faults [3].

For all other LHC systems, consolidation measures of failure modes identified during Run 1 are 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] if the BLM thresholds used for the 4TeV run are maintained. UFOs have shown a clear conditioning trend during LHC run 1, however deconditioning is expected following the consolidations in many of the machine vacuum segments. Relocation of BLMs to better protect against UFO events will ensure maintaining the high level of protection while allowing increasing 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.

ACCELERATOR FAULT TRACKING PROJECT

Following the conclusions of the Workshop on Machine protection [7], the Availability Workshop held in November 2013 [3] and previous Evian Workshops, an Accelerator Fault Tracking project (AFT) for the LHC was launched in February 2014 [8]. The main goals of this project are:

- Know when machines are not in use when they should be.
- Know what are the causes of unplanned downtime.
- Look for patterns, relations between systems, operational modes, etc.

The initial focus of the project will be on the LHC, but the infrastructure should be able to handle data from any CERN accelerator. The project timeline currently foresees three project stages:

1. Fault tracking infrastructure to capture LHC fault data from an operational perspective (to be ready for the restart of LHC in 2015)
2. Focus on equipment group fault data capture
3. Integration with other CERN data management systems.

INTEGRATED LUMINOSITY: ASSUMPTIONS AND TARGETS

The basic assumption for all luminosity predictions in this paper is to have 160 days of physics operation per year. The BCMS option is considered as a baseline for the luminosity predictions [9]. Considering the exploitation of luminosity levelling at $1.54*10^{34}$ [$cm^{-2}s^{-1}$] from a virtual peak luminosity of $2.2*10^{34}$ [$cm^{-2}s^{-1}$] at 6.5 TeV, a maximum luminosity levelling time of 2.1 h can be achieved. This implies that fills longer than 2.1 h will experience the typical luminosity exponential decay observed without levelling. These calculations refer to stable and reproducible BCMS operation (nominal parameters) and are therefore not to be intended for 2015, when a transition period to recover 2012-like operating conditions is expected.

Given the assumptions introduced above and to set availability targets for the new LHC run, 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. The machine failure rate is defined as the number of fills with failures over the total number of physics fills.

Six 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)

6. Optimized luminosity in case all machine faults would require major interventions (machine failurerate = 70%, turnaround time =6.2 h, fault time = 12 h)

The results for the six scenarios described above are summarized in Table 1 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.

Table 1: Optimized Luminosity and operational parameters for different availability scenarios.

Scenario	Stable Beams [h]	Number of fills	Integrated luminosity
1	2.1 / 3.4	405	100.5 [fb^{-1}]
2	2.1 / 3.5	396	98.3 [fb^{-1}]
3	2.1 / 5.9	229	56.4 [fb^{-1}]
4	2.1 / 4.7	316	75.9 [fb^{-1}]
5	2.1 / 5.4	266	64.5 [fb^{-1}]
6	2.1 / 6.3	211	52.3 [fb^{-1}]

INTEGRATED LUMINOSITY PREDICTIONS

A Monte Carlo model [10] for LHC Availability was used to make predictions of integrated luminosity based on statistics and distributions from 2012 for fault time, turnaround time, machine failure rate and intensity ramp- up. A sensitivity analysis to the average fault time and machine failure rate was carried out and results are presented in Fig. 5.

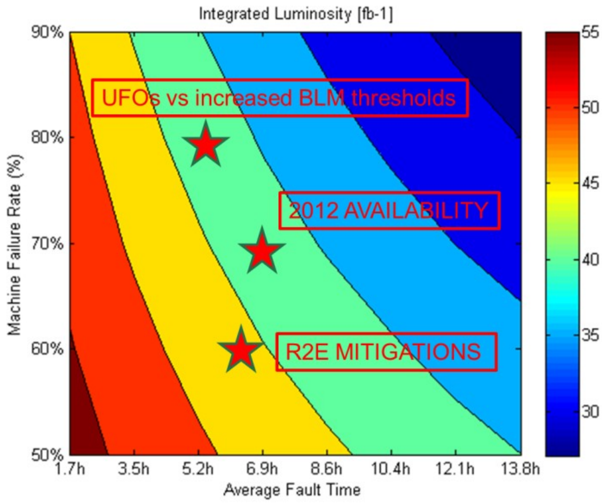

Figure 5: Sensitivity analysis to the average fault time and machine failure rate for BCMS operation.

This analysis shows that for 2012 like operation ~ 40 fb^{-1} could be reached. As mentioned in the previous paragraphs, UFOs could significantly worsen the machine failure rate, even with increased BLM thresholds. In the picture a preliminary estimate of the impact of UFOs at 6.5 TeV in case of a factor 3 higher BLM thresholds is presented. This shows that a less conservative choice of the thresholds, even tolerating few beam-induced quenches per year, would allow keeping the same integrated luminosity target which was obtained with the 2012 distributions. By keeping the BLM thresholds used in 2012, a reduction of ~ 15% integrated luminosity would be expected instead.

Mitigations of radiation-induced effects will have a positive impact on the machine failure rate, which will be reduced by ~10%, allowing up to ~45 fb^{-1} to be produced.

CONCLUSIONS

In this paper the main factors driving LHC availability in 2012 were reviewed based on the studies carried out by the Availability Working Group. The expected availability in the LHC Run 2 has been discussed, taking into account the major consolidation works carried out during LS1 and the impact of future operational scenarios.

The Accelerator Fault Tracking project, allowing for more consistent availability tracking was presented, as well as the foreseen project stages.

Yearly luminosity targets for Run 2 have been calculated, assuming BCMS as a baseline, as a function of optimum fill length and number of fills and depending on various assumptions on fault times and turnaround times.

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 during future operation.

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