# HOW TO REACH THE REQUIRED AVAILABILITY IN THE HL-LHC ERA

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*Abstract*

The HL-LHC has ambitious integrated luminosity goals in the region of 250 $fb^{-1}$ per year. This level of performance will required excellent machine availability. After a definition of terms and assumptions, the availability to date is reviewed while noting the importance of accurate and reliable tracking. Other possible areas of improvement and future challenges which could impact the overall availability are then discussed. Estimates based on extrapolation from present experience are given. Injector availability will also be important for the overall LHC performance and the need for sustained, well-planned consolidation is recalled.

## INTRODUCTION

### *Definition of terms*

**Scheduled proton physics time (SPT)** is the time scheduled in a given year for high luminosity proton physics. It does not include initial re-commissioning, special physics runs, ions, MD, and technical stops. It does include the intensity ramp-up following re-commissioning at the start of the year. One could include special physics runs, operation with ions, and MD in the scheduled time but we single out proton physics because we eventually want to make luminosity predictions. Note that high luminosity running involves a number of challenges not present in other modes of operation and different availability can be expected.

**Availability** is the scheduled proton physics time minus the time assigned to faults and fault recovery expressed as a percentage of the SPT. Edge effects (recovery from access, the precycle) tend not, at present, to be fully included in the assigned fault time.

The **turnaround time** is defined as time taken to go from Stable Beam mode back to Stable Beam mode in the absence of significant interruptions due to fault diagnosis and resolution.

**Physics efficiency** is the fraction of the scheduled physics time spent in Stable Beams.

### *Recall 2012*

The overall faults statistics for 2012 [1] are shown in figure 1. Subsequent re-analysis of 2012's SPT gave a total of 1411 hours or 58.8 days of fault time or approximately 71% availability for a 201 day physics run [2]. Even given the caveat of incomplete assignment of fault recovery time noted above, this is an excellent result given the complexity and relative youth of the LHC.

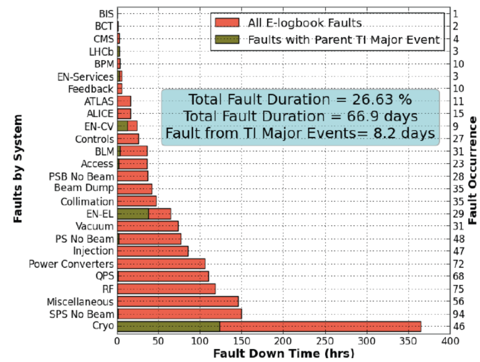


Figure 1: 2012 LHC fault analsysis taking into account all scheduled operation. Figure courtesy Alick Macpherson.

Technical infrastructure major events generated 8.2 days of fault time with some major knock-on effects to cryogenics. Recovery from major events has been helped by experience, procedures, and buy-in from the concerned equipment groups. The importance of injector complex availability can be clearly seen. Miscellaneous comes in third suggesting the need for more refined tracking.

### *Overhead of a fault*

Faults cover an enormous range from a simple front-end reboot to the loss of a cold compressor with corresponding loss of time to operations ranging from 10 minutes to potentially days.

The impact of a typical fault requiring tunnel access was considered. It showed the following sequence of steps from the occurrence of the original fault through to full recovery.

- Premature beam dump in Stable Beams.
- Original diagnosis of fault by control room operator. Contact expert.
- Remote diagnosis by expert.
- Access required and prepared. Travel of expert to site. Travel of radiation protection piquet to site.
- Intervention, on-site diagnosis and repair by expert.
- Recovery from access.
- Recovery from the impact of the fault (for example, cool-down following quench).
- Re-establish machine state: precycle, injection etc.

It can be seen that besides the cost to fix a fault, there is also significant overhead.

- Faults often dump the beam. For those with long recovery times this is almost incidental, but for the rest the cost is a premature dump of a fill.

- There is need for diagnosis of the problem both by the control room and the expert.
- Preparation for the intervention can require magnet switch off, radiation survey, and access.
- There is travel time for the expert and, if required the radiation protection piquet.
- Recovery from the intervention can be problematic. Things do not like being switched off and there can be knock-on faults.

The clear message is that fixing the fault is only part of the cost. Fault resolution and recovery should be accounted for as such. This is not at present the case.

The cost in time of turnaround and its fault recovery component is now examined in a little more detail.

## TURNAROUND

The turnaround time is defined above as time taken to go from Stable Beam mode back to Stable Beam mode. Before examining potential issues, the ideal case is presented.

### *7 TeV turnaround*

A breakdown of the foreseen HL-LHC turnaround time is shown in table 1.

Table 1: Breakdown of turnaround with estimated minimum times shown

| Phase | Time [minutes] |
|---|---|
| Ramp down/pre-cycle | 60 |
| Pre-injection checks and preparation | 15 |
| Checks with set-up beam | 15 |
| Nominal injection sequence | 20 |
| Ramp preparation | 5 |
| Ramp | 25 |
| Squeeze | 30 |
| Adjust/collisions | 10 |
| Total | 180 |

From table 1, one can see that realistically a three hour minimum turn around time may be assumed. The main components are the ramp-down from top energy; the injection of beam from the SPS; the ramp to high energy; and the squeeze. The ramp-down, the ramp, and the squeeze duration are given by the current rate limitations of the power converters. Of note is the 10 A/s limit up and down for the main bends; and the need to respect the natural decay constants of the main quadrupoles, the individually powered quadrupoles and the triplets during the ramp-down and the squeeze. These quadrupoles are powered by single quadrant power converters and take a considerable time to come down. A faster precycle via upgrades to the power converters might be anticipated. Two quadrant power converters for the inner triplets for example would remove them as a ramp-down bottle neck.

In practice, the turnaround has to contend with a number of issues which could involve lengthy beam based set-up and optimization. Typical beam based optimization might include: the need to re-steer the transfer lines; occasional energy matching between the SPS and LHC; the need for the SPS to adjust scraping during the injection process. Injector and LHC tuning and optimization are accounted for in the average turn around time.

### *Turnaround time 2012*

The fastest turnaround in 2012 was 2 hours 8 minutes. This was close to the theoretical minimum for 4 TeV operation. The average for the year was around 5 hours 30 minutes. What is going on?

- Clearly the main component of the turnaround is the nominal cycle outlined in the previous section: injection, ramp, squeeze, ramp-down/precycle.
- Also included are test ramps and squeezes which do not result in Stable Beams. These have to be counted as justifiable (at this stage) allowing as they do clean set-up of parameters and understanding of beam based issues.
- Transfer and injection optimization and general wrestling with the injection process (respecting tight demands on beam quality etc.).
- Unrecorded faults and problem resolution which are fixed on the fly possibly even with beam in the machine. Typically these could include: controls and data acquisition problems; kicker overheating; problems in the injectors; etc. etc.
- As mentioned above fault recovery such as access recovery, precycle and so on are not costed to the originating fault.
- Fills lost in the ramp and squeeze to beam induced problems (instabilities) or, for example, feedback system faults are not separated out. The machine in principle effectively stays “available”.

There is definitely a case for a more detailed break-down of the turnaround time which could include appropriate allocation of time to: test fills; lost fills; recovery time; etc.

## LOST FILLS

One also must consider overheads and the pain of losing a fill (in ramp, in squeeze, in physics...). The list of premature dumps above 450 GeV in 2012 [3] are shown in figure 2. 70% of all fills are terminated by a fault. It is worth considering the table in some detail and asking what will still be an issue in the HL-LHC era.

The number one cause of lost fills, beam loss, was in fact not fault related and could be regarded as somewhat self-inflicted courtesy the choice of pushing instantaneous performance via tight collimator settings, low $\beta^*$, and high bunch intensity. Does it matter? 58 fills were lost to beam losses in 2012. If we simply assigned a 3 hour turnaround

| Dump Cause | # | Dump Cause | # |
|---|---|---|---|
| Beam: Losses | 58 | BPM | 8 |
| Quench Protection | 56 | Operations: Error | 6 |
| Power Converter | 35 | SIS | 4 |
| Electrical Supply | 26 | LBDS | 4 |
| RF + Damper | 23 | TOTEM | 4 |
| Feedback | 19 | CMS | 3 |
| BLM | 18 | BCM | 2 |
| Vacuum | 17 | Water | 2 |
| Beam: Losses (UFO) | 15 | Access System | 2 |
| Cryogenics | 14 | LHCb | 2 |
| Collimation | 12 | ALICE | 2 |
| Controls | 12 | Beam: Orbit | 1 |

Figure 2: Premature dumps above 450 GeV in 2012. Table courtesy Ben Todd et al [3]

to each we have around 180 hours or 7.5 days lost. In 2012 this would have equated to a loss of around 1.3 $fb^{-1}$ maximum. This is insignificant on the grand scale of things and probably worth it for the instruction. However it would be clearly unacceptable in HL-LHC era and operationally robust choices of parameters will be required.

Number 2 and 3 on the list are the QPS and power converters respectively. These are, of course, huge distributed systems with direct exposure to the radiation field of the beam. Correspondingly there is a significant fraction of beam dumps attributed to Single Event Effects (10% of total dumps). This issue is being addressed by the Radiation to Electronics (R2E) effort and is discussed in more detail below.

Besides the usual mix of equipment faults operations is exposed to some other problems before Stable Beams is established. Noticeably in 2012:

- orbit feedback problems - the resolution time is usually short but if the problem provokes a dump the cost is a full turnaround (around 13 dumps);
- instabilities and beam loss in squeeze and adjust caused 32 dumps (addressed above).

## FILL LENGTH

Both the average fill length and fill length distribution will play an important role in the overall exploitation of the LHC. They will also be key factors in any estimates of future performance.

Some simple arithmetic:

- Reduced the schedule physics time SPT by the availability factor.
- Assume an average turn around and average fill length in the time thats left and reduce available time by number of fills times turn around to get the time spent in Stable Beams - previously defined as Physics Efficiency (PE).

The physics efficiency may thus be expressed as:

$$PE = (A \times SPT - N_f \times T_{\text{around}}) \qquad (1)$$

where A is the availability, SPT is the scheduled physics time, $T_{\text{around}}$ the average turn-around time, and $N_f$ the number of fills which may be expressed as:

$$N_f = \frac{A \times SPT}{T_{\text{fill}} + T_{\text{around}}} \qquad (2)$$

$$PE = A \times SPT \times \left(1 - \frac{T_{\text{around}}}{T_{\text{fill}} + T_{\text{around}}}\right) \qquad (3)$$

The 2012 data shown in table 2 can be used as an illustration.

Table 2: Overall operational performance 2012

| | |
|---|---|
| Scheduled physics time | 201 days |
| Availability | 71% |
| Average fill length | 6.0 hours |
| Average turn around | 5.5 hours |
| Mean luminosity delivery rate | 12.97 $pb^{-1}$/hour |
| Peak luminosity delivery rate | $\approx$ 25 $pb^{-1}$/hour |

Given a time in Stable Beams the obvious question is how much luminosity might one hope to produce in said time. It is not luminosity as a function of time in a fill integrated over the average fill length multiplied by the number of fills because of the impact of the fill length distribution. An average fill length of 6 hours sounds pretty good but theres a difference between the distribution shown in figure 3 and the 2012 distribution shown in figure 4.

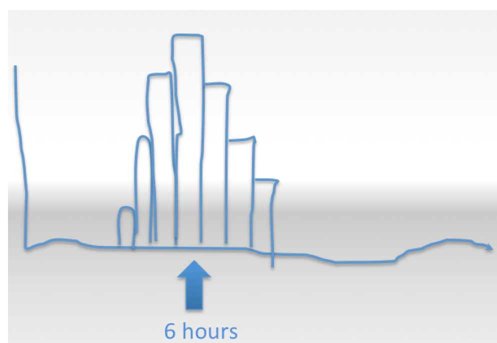


Figure 3: Hypothetical and far from realistic fill length distribution.

Inspection of figure 4 reveals a lot of short unproductive fills and some not so productive long fills. The cost of the short fills is a corresponding number of extra turnarounds which fold directly into lost time for physics.

A brief analysis of the causes for lost fills during the first two hours of stable beams is shown in table 3. It can be seen that the large distributed systems again play an important role and are clear candidates for careful, considered consolidation with a view to high availability in what will be tough conditions. The higher loss fill rate in the first two hours is at least in part due to challenging beam conditions. These will include: peak losses in collimator regions; peak losses in the interaction regions coming from luminosity

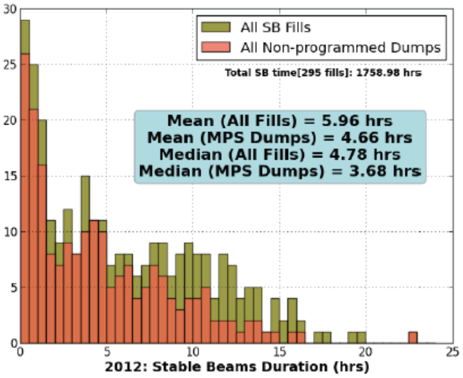


Figure 4: Fill length distribution in 2012. Figure courtesy Alick Macpherson.

debris; peak beam loading for the RF; peak beam induced heating. Given that the HL-LHC plans, with levelling, to maintain these conditions for as long as possible, all possible efforts should be made to address the causes of the premature beam dumps.

Table 3: Systems responsible for most of the fills lost in first two hours of Stable Beams 2012. * includes SEUs

| System | No. fills lost |
|---|---|
| Power converters* | 17 |
| Tests | 10 |
| QPS* | 8 |
| Vacuum | 8 |
| UFO | 6 |

## REQUIRED AVAILABILITY

The fill length distribution can be visualized in a different way. Figure 5 shows the integrated time for fills terminating between 0 and 1, 1 and 2 hours etc. As might be expected the short fills contribute a low amount of integrated time.

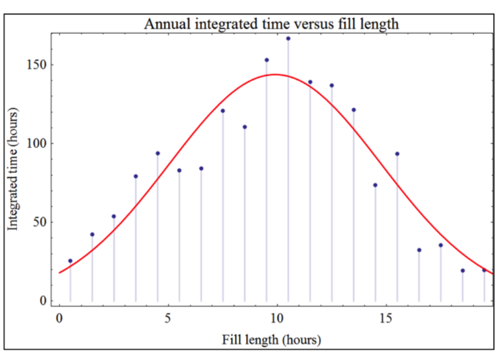


Figure 5: Integrated time per given hour in fill in 2012

Integrating across the hours to get the total time in the year delivered per given hour of a fill we get the result shown in figure 6.

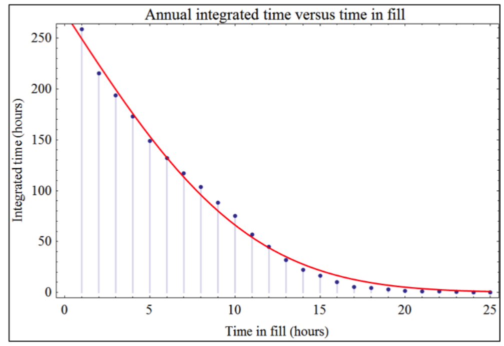


Figure 6: Integrated time per given hour in fill in 2012

An appropriate fit motivated by the Gaussian fit of figure 5 is the complementary error function. Given this fit it is then trivial to calculate the integrated luminosity per year assuming any (average) luminosity profile through a fill.

For example, assume:

- 2012 fill time distribution and naively scaled it to 160 days (this implies the same availability and average turnaround time);
- 5 hours levelling at $5\times10^{34}$ cm$^{-2}$s$^{-1}$;
- 5 hour luminosity lifetime after the levelling period;
- dump any fill that survives that long after 13 hours.

The result of this particular set of assumptions is shown in figure 7. Integrating over fill length, the total luminosity for a HL-LHC year given 2012's availability and turnaround time is around 210 fb$^{-1}$.

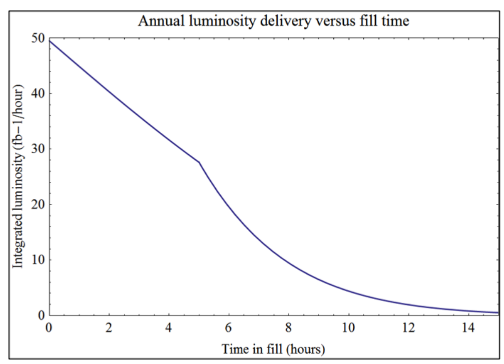


Figure 7: Integrated yearly luminosity versus time in fill given assumptions above.

A Monte Carlo approach which also extends the 2012 figures to the full HL-LHC (and assumes the average turnaround time is increased from 5.5 to 6.2 hours) gets a figure of 213 fb$^{-1}$ [4]. The team also simulates the impact on the integrated luminosity of SEUs, UFOs, quenches and gives a range of 180 to 220 fb$^{-1}$ in simulations that attempt to take these factors into account.

The details of the calculations are unimportant but what is clear is that given 2012's availability and turnaround

around 85% of the HL-LHC annual target would be achieved. This is encouraging but clearly the already good availability must be maintained and improved if the ambitious goals of the HL-LHC are to be reached.

## WHAT CAN BE DONE?

In the above discussion some main areas that might be targeted in the interest of improved availability and operational efficiency have been identified.

- Reduce number of faults (hardware and software) - this would be the standard target of improved availability.
- Reduce time to fix faults, reduce intervention times, reduce number of interventions (for example by universal remote reset functionality or improved remote diagnostics or increase redundancy).
- Reduce number of beam induced faults (R2E, beam induced heating, vacuum issues).
- Reduce the mean turn around time (besides reducing number of unwanted dumps before stable beams). Here one could imagine targeting optimization, test runs, the nominal cycle.

### *What has been done*

It is clear that the groups involved have been working hard to target areas of improved availability with some success. The groups implicated include: cryogenics; QPS; power converters; vacuum; BLMs; RF; collimation; injection; beam dump system; feedbacks; controls; technical infrastructure.

One notable thrust has been the major combined effort to alleviate the serious problem of single event effects coordinated by the R2E team. R2E has done a vitally important job so far including the development of test facilities, links with external companies and so on. It is extremely important for the HL-LHC era that this effort continues.

The long term strategy is wide reaching and includes: superconducting links with feed-boxes and main power converters on the surface. 120 A, 60 A converters will remain exposed in tunnel and there is power converter R&D ongoing for radiation tolerant design. Given the results the decision about what else to bring up will be made. Radiation tolerant solutions are being developed for QPS and cryogenics that remains in tunnel and RRs with some 10,000 units that will remain in the tunnel. A robust solution is required for equipment in both radiation and no radiation areas with stringent demands on MTBF. Beam instrumentation is also targeting radiation-tolerant design and upgrades.

Having built up considerable knowledge and expertise in the area of testing and radiation-tolerant design the R2E team worry about knowledge continuity through LS3.

### *What will have been done*

2012 is, of course, only partially representative of the foreseen HL-LHC operational regime and extrapolation must be tempered with caution. However, on the positive side the next runs through to 2023 will see:

- 10 years or so of debugging, consolidation, understanding and flushing out of system problems.
- 10 years of beam dynamics, understanding, control, instrumentation, diagnostics, combat tools at 6.5 to 7 TeV with 25 ns beam.
- Certainly to be quantified in the next 8 years or so
  - Higher energy operation: power converters, cryogenics nearer limits, beam induced quenches
  - Training de-training after thermal cycling
  - E-cloud, scrubbing, conditioning,de-conditioning after LS
  - UFOs: Conditioning, thresholds adjustment, clean MKI

### *Cryogenics [5]*

As regards availability the cryogenics team achieved: 90% for the 5 weeks in 2009, 90% in 2010, 89% in 2011 (impacted by SEUs), 95% in 2012-13. This includes MDs and physics, with typical operational period of 260 days/year. The teams forecasts would be for post-LS1: 90% in 2015, 92% in 2016, 95% in 2017 considering: correct understanding of cryo process and equipment (now well tuned and with procedures), experienced staff and shift organisation; that “quick” fixes will be required, but not often and with pre-defined protocols, therefore with minor impacts on integrated availability. Considerations for post-LS1 beam operation parameters with respect to the “reduced parameter set” pre-LS1 will include: for sure increased heat loads, in particular higher “dynamic””(resistive-RI2 and beam related) with respect to static conditions. However operation should still in the range of “nominal mode with respect to design” and below the “installed capacity”.

The baseline target is 95% for HL-LHC era while noting the addition of 3 additional cryogenics facilities.

### *Less faults*

An ongoing, committed effort from the equipment groups concerned will be required. Some potential target areas are:

- more rigorous preventive maintenance and appropriate technical stops to allow said;
- sustained, well-planned consolidation of injectors;
- installation of plant redundancy e.g. back-up cooling pumps, fully reliable UPS;
- updated system design for reliability, targeted radiation-tolerance, robust, redundant system upgrades given experience and testing.

### *Reduced fault overhead*

There is certainly scope for reducing the overhead of fixing a fault. Possible measures include:

- better diagnostics;
- less tunnel interventions via remote resets, redundancy, remote inspection;
- relocation of hardware to the surface;
- the use of 21st century technology;
- faster interventions, for example by using TIM for radiation surveys, visual inspections and the like.

### *Operational efficiency*

One would anticipate fully and robustly establishing all necessary procedures required in HL era. Possible examples would include:

- BLM thresholds completely optimized across all time scales;
- compress the cycle e.g. combined ramp and squeeze, reduced injection time (dedicated  singe batch injection);
- more efficient and fully optimized set-up in place: injectors; transfer and injection; collimators, squeeze, optics;
- less test ramps and squeezes;
- use of optimum fill length strategy;
- precycle:, optimized pre-cycles/dynamic use of model
- upgraded system performance: e.g. 2Q triplet power supplies.

### *Concerns*

It will be a mature system but with major upgrades operating with unprecedented bunch and beam intensities.

Potential concerns include:

- ageing, long-term radiation damage;
- robustness of systems such as QPS, power converters (that remain in tunnel);
- increased intervention overheads because of higher radiation levels (cool-down requirements and remote handling requirements); radiation protection in the HL era should be fully study across the full intervention space;
- the cost in time of recovering from de-conditioning (UFOs, electron-cloud) following long shutdowns.

### *Fault tracking*

In order to fully track availability and to be able to be target weaknesses it is vital that an adequate fault tracking tool be developed and implemented for the LHC restart after LS1. This tool should provide:

- a new LHC fault tracking tool and fault database;
- means of fully assigning the downtime due to a fault including the fault recovery time;
- metric to reflect lost integrated luminosity due to a fault;
- a defined and agreed reference metrics to consolidate views on definitions used in availability calculations;
- reliability tracking of the critical elements of the machine protection systems to ensure that LHC machine protection integrity is acceptable.

## CONCLUSIONS

The HL-LHC will place challenging demands on availability and operational efficiency if the ambitious integrated luminosity goals are to be met. The machine availability in 2012 was encouraging but there are still a number of known unknowns to be evaluated e.g. electron-cloud, UFOs, 7 TeV operations. 10 years more years of operations will surely see a concerted effort to address these issues. Unknown unknowns wait to be discovered, among these will be the operability of the LHC with very high bunch populations, very high total beam current, with a novel optics providing a challenging final $\beta^*$.

R2E will continue to be very important and continued system improvements across the board will be necessary to get close to the required level of availability. Radiation protection and associated issues will be critical and must be anticipated.

A more formal approach to availability and the proposed developments for coherent tracking and accounting should be fully supported.

There would appear to some room for improved operational and fault fixing efficiency. Certainly the HL-LHC will have to take full advantage and work hard on all possible fronts.

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