LHC AVAILABILITY 2017: PROTON PHYSICS – SETTING THE SCENE

B. Todd[*], A. Apollonio, L. Ponce, D. Walsh, C. Roderick, CERN, Geneva, Switzerland.

Abstract

This paper summarises the LHC machine availability for the standard proton physics period in 2017. This paper first considers operational aspects, such as beam mode ratios, beam dump causes, fill length and turn-around. Following this, a detailed breakdown of all faults and their impact upon LHC is given, with notable faults and new root causes identified. This paper compares the LHC's 2017 and 2016 availability performance, giving principle changes observed.

This work has been produced and ratified by the Availability Working Group [1], which has compiled fault information for the period in question using the Accelerator Fault Tracker [2].

INTRODUCTION

The data presented herein is based on information captured by the Availability Working Group (AWG), using the Accelerator Fault Tracker (AFT). The AWG processes and the use of the AFT have evolved over the last five years. LHC data captured in both 2016 and 2017 is robust, and gives a good insight into the real availability performance of the LHC. The data from 2017 includes ratified faults for the LHC injectors, giving the availability picture for the whole accelerator complex.

Fault Tracking Process

The management of faults at the machine level is a straightforward flow, with only a two basic steps required for the machine to be successfully exploited. The initial trigger is a machine moving from an operational into a faulty state, due to a failure occurring. At this point:

1. The operations team observe the failure and identify the *faulty system* that is preventing the machine from operating.
2. The operations team call the relevant on-call service to correct the failure and return the machine to the operational state – this may also require a *pre-cycle*.
    - There may be iterations in order to correctly diagnose the exact system and fault to address.

At the end of step 2, the accelerator is returned to an operational state and can be used. Fault tracking consists of four additional steps:

3. The *fault* is logged by operations in the eLogbook.
4. The AFT is triggered by the creation of the *fault*, creating a *blocking-op* fault record, and emailing the *fault-tracking expert* from the *faulty system*, and the *AWG core members*.
5. At some point later one or more of the following occurs:
    - *AWG core-members* update fault information, such as; *duration*, *states* and *dependencies*.
    - The *fault-tracking expert* acknowledges the fault, optionally adding the *faulty sub-system*, and flags the fault as **expert reviewed**.
    - The *fault-tracking expert* indicates the *faulty system* has a dependency with another *fault*, or *system*, and raises a concern to the AWG.
    - Labels may be added to the fault to assist analytics, (e.g. Technical Infrastructure failures are labelled "TIOC" and are studied by a dedicated committee)
6. The Availability Working Group periodically assess all dependencies and conflicts raised; once per month in LHC, once per week in the injector complex. When all disputes are fully resolved, *faults* are marked as **AWG reviewed.**

Failure is defined as "being unable to operate with beam", with the fault being given a state "*blocking-op*". This is a Boolean value, operation in degraded mode is not considered. It is possible to have a fault that does <u>not</u> block operations having a "*non-blocking-op*" state. Such faults are worked around, or are mitigated by redundancy.

AWG LHC Reports

The AWG use the recorded fault information and operational data to create LHC availability reports, in 2017 there were four such reports:

- Restart → Technical Stop 1
  CERN-ACC-NOTE-2017-0046 [3]
- Technical Stop 1 → Technical Stop 2
  CERN-ACC-NOTE-2017-0053 [4]
- Technical Stop 1 → End of Standard Proton Physics
  CERN-ACC-NOTE-2017-0062 [5]
- Proton Physics
  CERN-ACC-NOTE-2017-0063 [6]

This paper and the availability reports strictly consider faults with the state "*blocking-op*".

MACHINE EXPLOITATION

The period studied covers 2017's proton physics production, note that the final month of operation deviated quite substantially from the baseline plan [7], due to changes to the LHC schedule [8].

The period studied is from 28th April until 10th November, a total of 188 days used for "standard physics", giving duration of each machine mode as follows:

---

[*] benjamin.todd@cern.ch

Table 1: Machine Mode Breakdown

Machine Mode	Days
Beam Commissioning	39 ½
Ion Cycle Setup	1
Special Physics Commissioning	1
Scrubbing	7
Machine Development	10
Special Physics	**3 ½**
Physics	**126**
Σ	188

Some 129 ½ days were dedicated to physics or special physics. Some physics was also carried out during the intensity ramp up following the restart, giving a total **140 ½ days physics** production in 2017.

In 2017, there were **13 ½ fewer days dedicated to physics** than in 2016 (having 153 days), this difference of is largely due to the Extended End of Year Shutdown (EYETS) at the start of 2017.

Availability & Physics Delivered

Availability was tracked from week 17 to week 45; fill number 5577 to 6373. The mean availability was 82.9%, and total physics delivered reported by ATLAS was around 51.8 fb^{-1} [9]. Figures 3 and 4 give a comparison of 2016 and 2017. The main differences are:

- The *mean availability* increased from 75.8 to 82.9% (+7.1%)
- The *peak weekly integrated luminosity* increased from around 3.2 to 5.0fb^{-1} in 2017 (+1.8 fb^{-1})
- The *total physics* delivered increased from 38.7 to 51.8 (+13.1 fb^{-1}).

Operation Mode

The 140 ½ days of physics was 3362.1 hours of machine operation. The operation mode during this time interval was as follows:

Table 2: 2017 Operation Mode Breakdown

Operation Mode	Hours	
Stable Beams	1633.9	*49%*
Operations	1018.1	*30%*
Fault / Downtime	652.9	*19%*
Pre-Cycle	57.2	*2%*
Σ	3362.1	

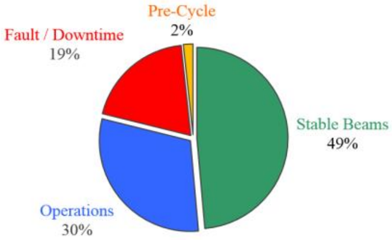

Figure 1: 2017 Operational Mode Breakdown

Figures 5 and 6 show the breakdown of operational mode on a weekly basis. Comparing 2016 and 2017:

Table 3: 2016-17 Operation Mode Breakdown

Operation Mode	2016 [%]	2017 [%]	
Stable Beams	49	49	
Operations	23	30	*+7%*
Fault / Downtime	26	19	*-7%*
Pre-Cycle	2	2	
Σ	100	100	

Operations is the time when the machine has no fault, is not pre-cycling, and is not in stable beams. It mostly consists of the time taken to ramp down, re-fill and ramp-up, as well as special measurement campaigns.

In 2017, the LHC spent **7% less time in *fault* and 7% more time in *operations*** than in 2016. This observation can be attributed to such effects as the 16L2 contamination, which led to numerous aborted ramps, leading to more time between periods of stable beams.

Beam Aborts

In 2017 there were 762 fills considered, of which 211 had a period of stable beams. The root causes of the end of stable beams in each case is broken down as follows:

Table 4: 2016-17 Beam Abort Root Cause Breakdown

Root Cause	2016	2017
End of Fill	84 (47%)	106 (50%)
Aborted	86 (48%)	95 (45%)
Aborted by Radiation Event	9 (5%)	10 (5%)
Σ	179	211

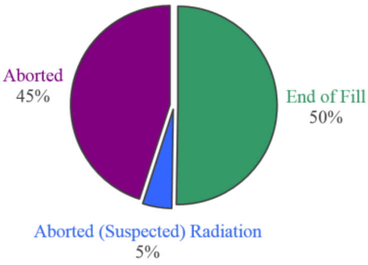

Figure 2: 2017 Beam Abort Root Cause Breakdown

Comparing 2017 to 2016. In 2017;

- Around 3**% more** fills reached End of Fill.
- There were **32 more fills** with stable beams despite having 13 ½ fewer days of physics. This can be attributed to the luminosity lifetime giving a shorter optimum fill length.
- The number of fills aborted by radiation effects remained **roughly constant** at 5%, despite the increased luminosity production. This may be attributed to improvement in the machine radiation fields [11] and improvements made during EYETS regarding radiation tolerant systems, such as the installation of the radiation tolerant function generator controller (FGClite) [12].

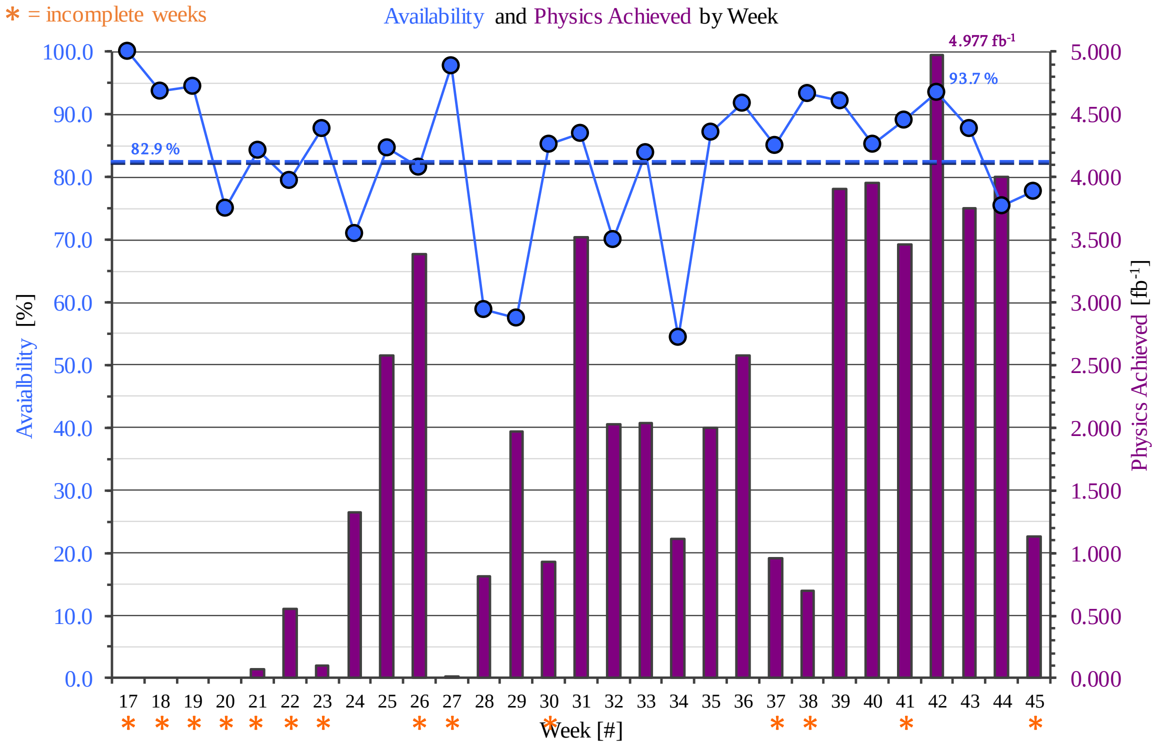

Figure 3: 2017 Availability and Physics Achieved by Week

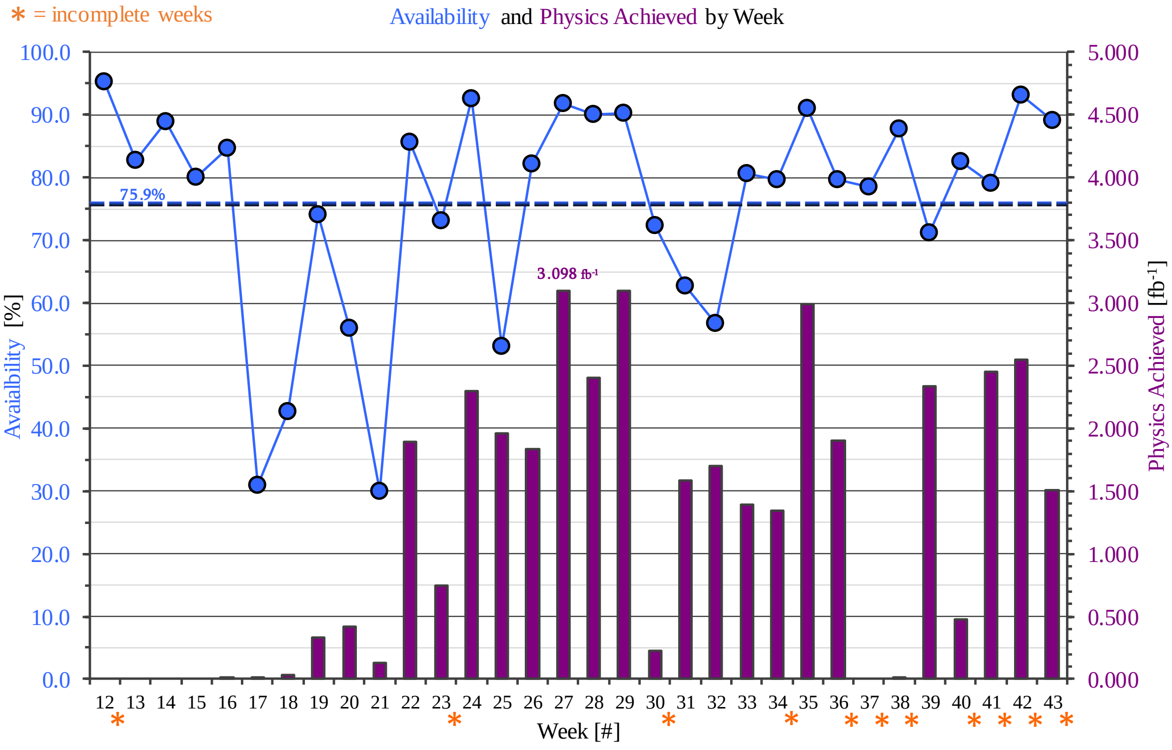

Figure 4: 2016 Availability and Physics Achieved by Week

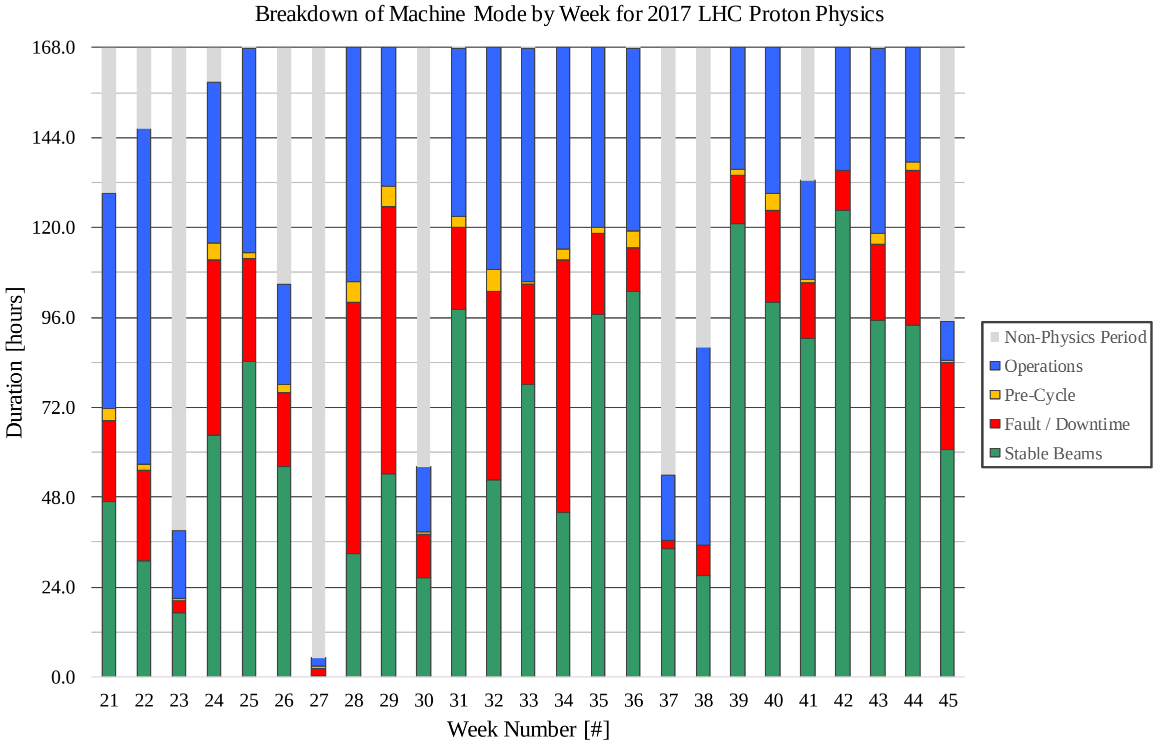

Figure 5: 2017 Operational Mode by Week

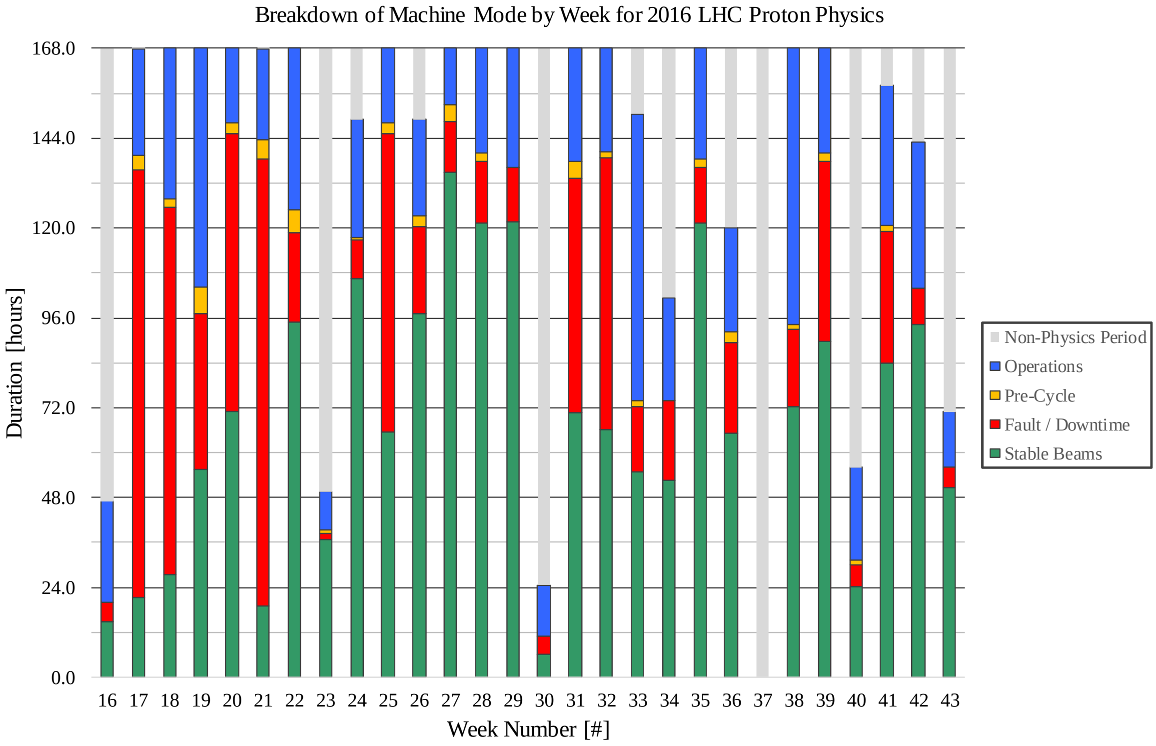

Figure 6: 2016 Operational Mode by Week

Stable Beams Duration

Of the 211 fills, 106 reached End of Fill, 105 were aborted, 10 of which were suspected radiation induced events. The time distribution for each of these in 2017 is shown in Figs 9, 10 and 11.

Distributions from 2017 and 2016 are compared in Figs 12 and 13. Observations are:

- The average duration of End of Fill reduced from 13.1 to 10.7h, this is due to the optimum fill length being around 12 hours due to luminosity lifetime.
- The average duration of aborted fills reduced from 7.8 to 4.6h. This means that faults are appearing earlier, no root cause to explain this is immediately evident.

Turnaround

Turnaround is the duration of time that it takes to get from stable beams of one fill from the end of stable beams of the pervious fill. In 2017 there were 211 fills with stable beams, ignoring those fills that have a mode change associated, and ignoring the fills that have long faults leads to 194 turnarounds being considered. These are shown in Figs 14 and 15.

A comparison of 2016 and 2017 distributions of turnaround times is shown in Fig. 16:

- The shortest turnaround time reduced to 2.2h from 2.5h.
- The average turnaround was reduced to 6.2 from 7.1h.
- ~24% of turnarounds were 2-3h in duration, compared ~18% previously.

FAULTS

Considering the faults with the state *blocking-op* for the period concerned, there were 631 faults, with 76 pre-cycles due to faults. For each fault there are two values recorded:

- *Fault Duration* – the integrated fault time assigned to each system, not including the pre-cycle. This does not account for parallelism of faults, or fault dependencies. This does not reflect the real impact on operation, reflecting faults as seen from the equipment viewpoint.
- *Root Cause Duration* – the value of Fault Duration with correction for parallelism of faults, and dependencies. This reflects faults as seen from the operations viewpoint.

There are three categories used for the classification;

- Equipment (E). This is a system required for the operation of the machine; this is generally a physical system, although in cases it can be software.
- Beam (B). This fault is induced by the beam or by beam processes. Typically, these are root causes of other faults, such as a beam impact causing a quench.
- Operation (O). This fault is related to manner in which the machine is being exploited.

A pareto of this information is shown in Fig. 17

Table 5: 2017 Faults

System	Faults [#]	Fault Duration [h]	Root Cause Duration [h]
E – Injector Complex	96	145.2	140.2
E – Cryogenics	31	207.0	107.7
E – Power Converters	84	113.7	98.9
E – Quench Protection	55	61.8	63.8
E – Beam Dumping System	22	63.7	60.6
E – Cooling & Ventilation	7	14.9	53.4
E – Radio Frequency	32	47.3	45.5
E – Electrical Network	15	36.3	37.8
E – Beam Instrumentation	22	32.6	32.0
E – Other	22	20.7	29.2
E – Injection Systems	18	20.6	19.4
E – Access System	10	16.5	18.5
E – Experiments	28	16.1	15.4
E – Accelerator Controls	24	15.4	15.0
E – Machine Interlocks	5	4.3	5.7
E – Vacuum	2	3.4	3.0
E – Transverse Damper	4	3.8	2.1
E – Ventilation Door	2	0.7	2.0
E – Collimation	10	2.5	1.7
E – Magnet circuits	17	13.7	1.1
E – Beam Exciters	1	0.5	0.5
E – Orbit Control	1	0.0	0.0
E – Software Interlocks	1	0.0	0.0
E – IT Services	1	0.0	0.0
B – Losses	66	3.3	12.1
B – Injection	8	2.3	2.3
B – Induced Quench	0	0.0	0.0
O – Access Management	24	42.5	31.0
O – Error, Settings	23	3.9	1.9
Σ	**631**	**892.7**	**800.7**

Around 19% of fault occurrences were Beam or Operations related, without an equipment fault:

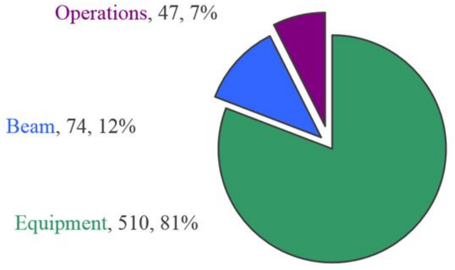

Figure 7: Fault Occurrence Ratio

However, around 94% of root cause downtime was due to equipment;

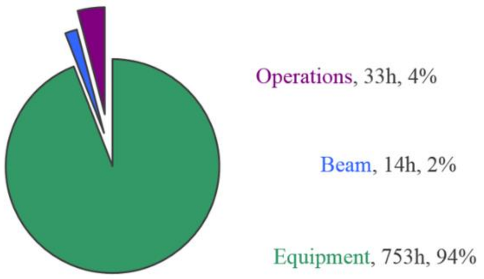

Figure 8: Root Cause Ratio

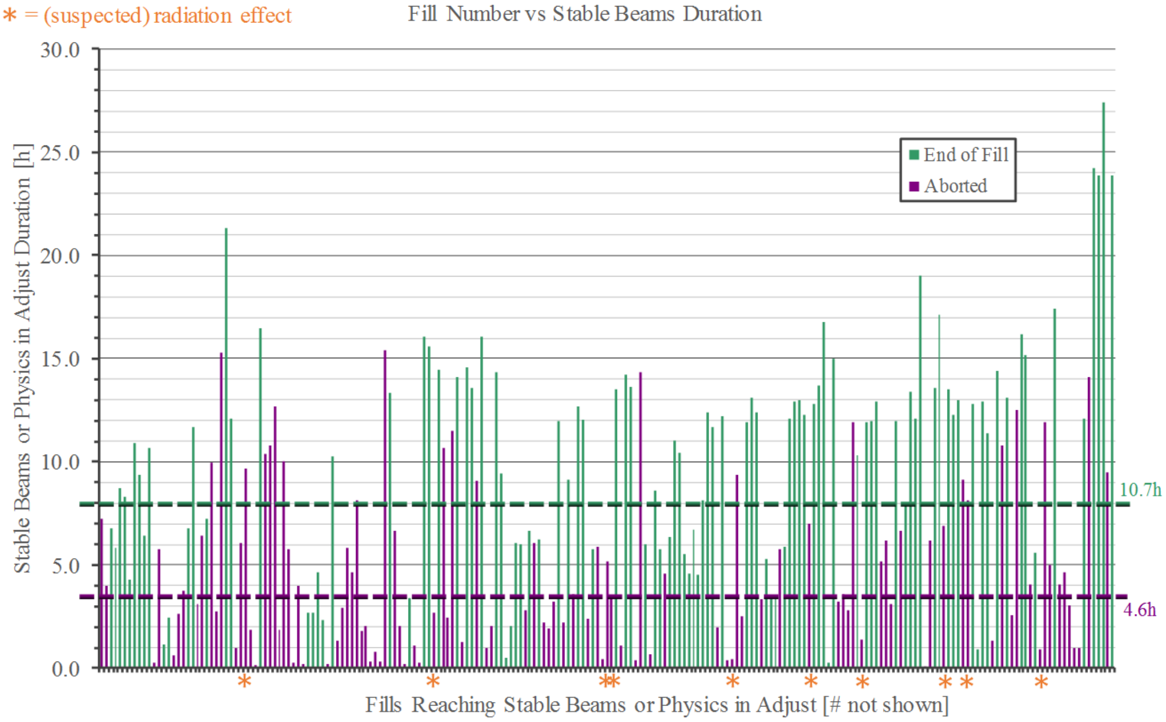

Figure 9: Stable Beams Duration

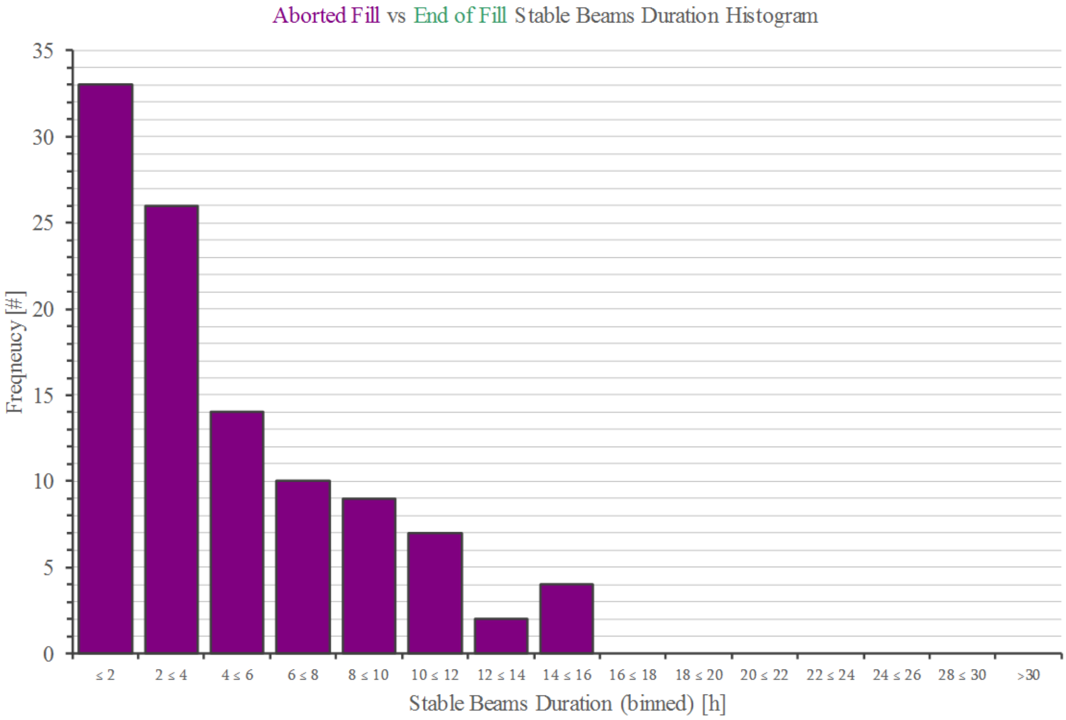

Figure 10: Stable Beams Duration – Aborted

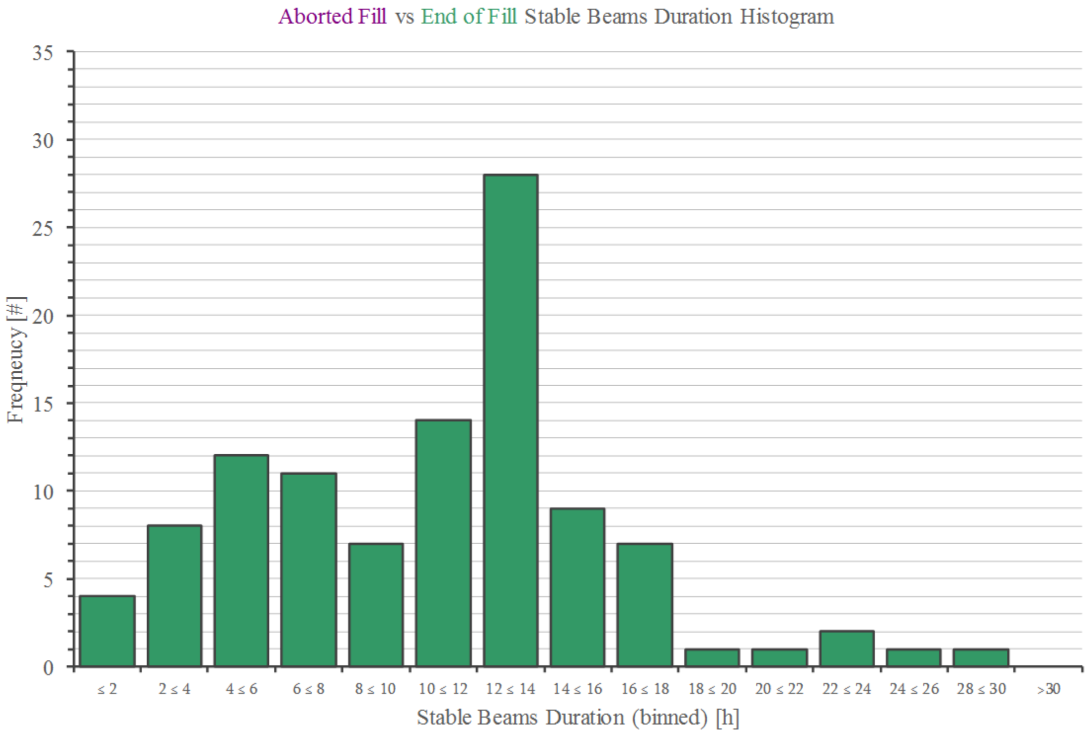

Figure 11: Stable Beams Duration – End of Fill

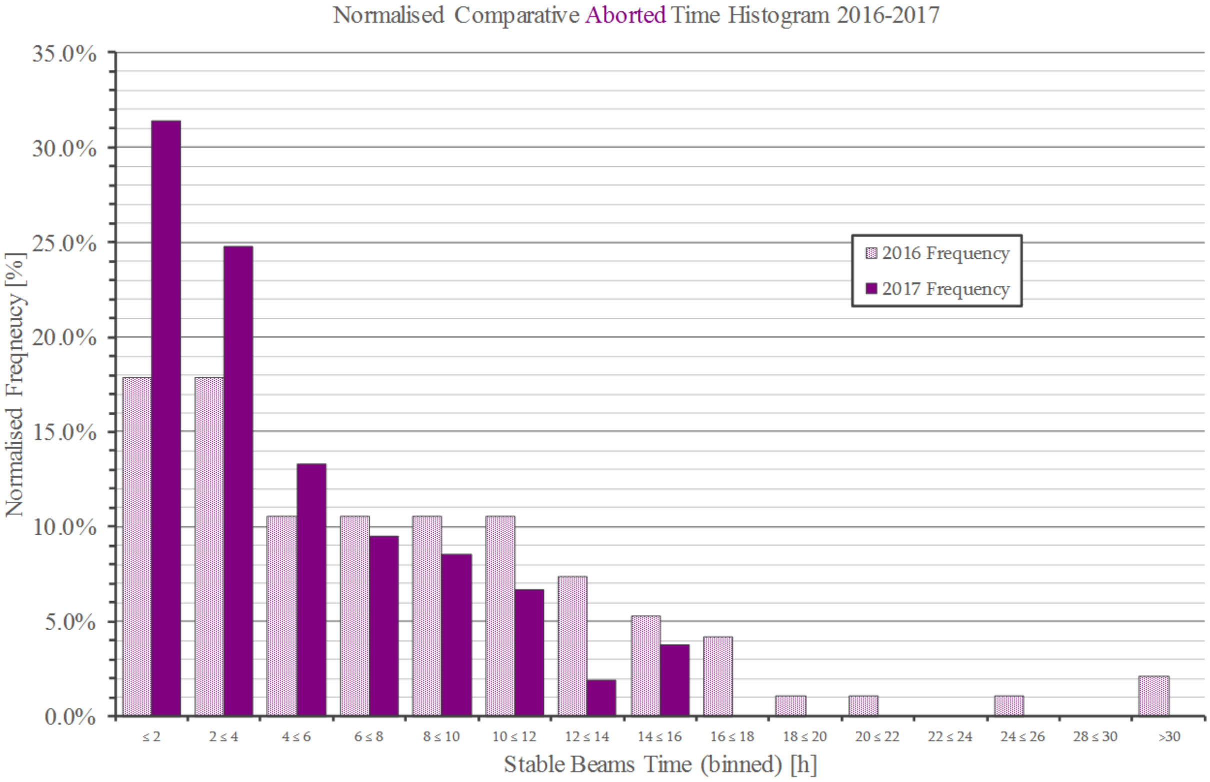

Figure 12: Stable Beams Duration – Aborted – 2016 vs 2017

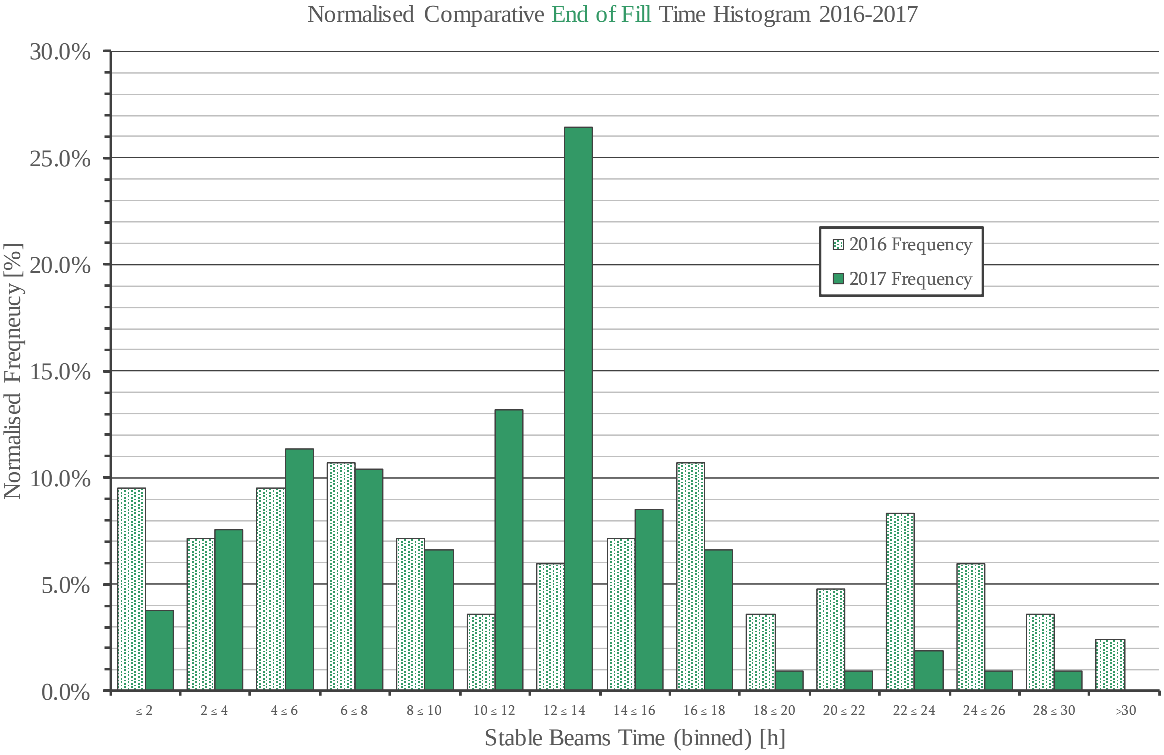

Figure 13: Stable Beams Duration – End of Fill – 2016 vs 2017

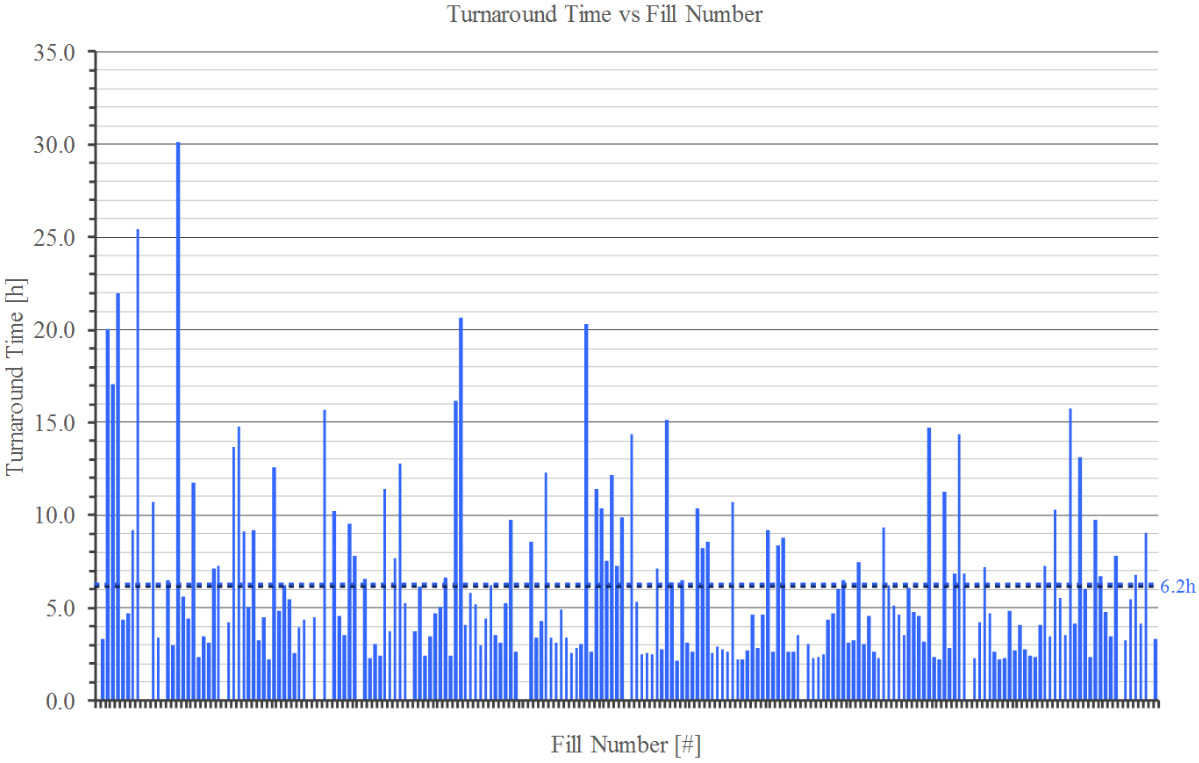

Figure 14: Turnaround

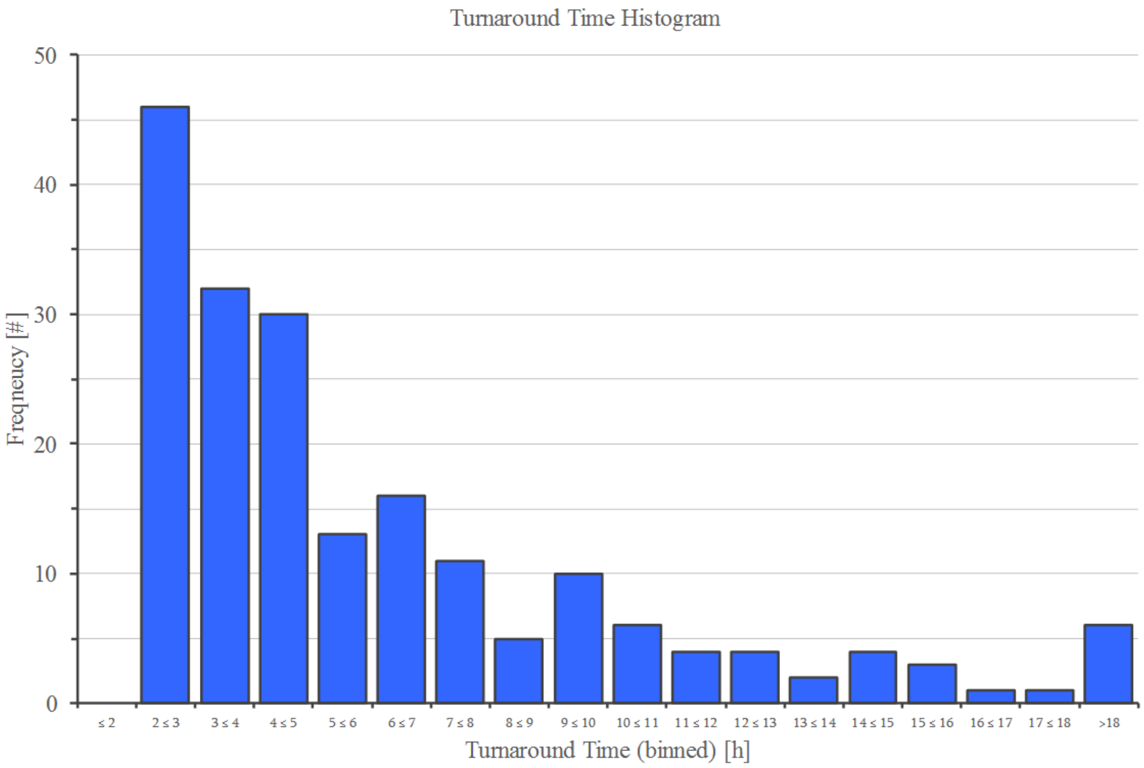

Figure 15: Turnaround Time Duration

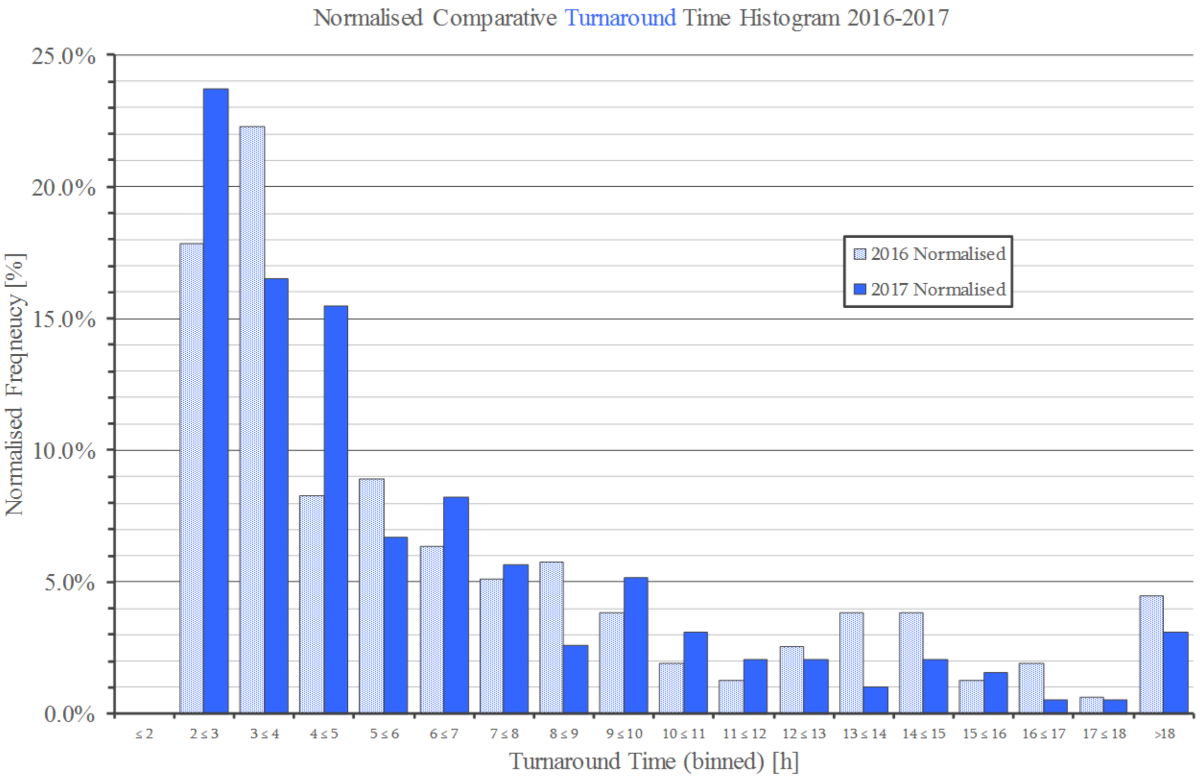

Figure 16: Turnaround Time Duration – 2016 vs 2017

Top Faulty Systems

The total root cause duration for the period in question was **800.7 hours**. The top five root causes account for **over half** of this duration (471.2 of 800.7 hours):

Table 6: 2017 Top Five Systems

System	Fault Duration [h]	Root Cause Duration [%]
Injector Complex	140.2	17.5
Cryogenics	107.7	13.5
Power Converters	98.9	12.3
Quench Protection	63.8	8.0
Beam Dumping System	60.6	7.6
Σ	**471.2**	**58.8**

Concerning the top systems, several points emerge:

The power converter category had faults related with radiation effects to electronics, this concerns converters that are scheduled for renovation and will be retrofitted with radiation tolerant control systems during LS2.

70% of Injector Complex downtime was due to the SPS, 16% due to the PS, 9% due to the PSB and 12% due to LINAC2. Of these faults, 10% were "beam in setup", 90% were "no beam" faults [13].

2016 vs 2017

Figure 18 compares the two years. Notably;

Injector Complex, despite being the largest impact on the LHC availability, is markedly improved from 2016, when it was almost 25% of LHC un-availability.

Cryogenics, Power Converters and Quench Protection all take a larger share of accelerator un-availability, this could be due to generally higher unreliability, or due to improvements in the injector complex giving a larger time during which others systems must be operational.

Efforts from EPC to consolidate fast magnet sensitivity and to improve radiation tolerance of the closed orbit dipole converters has proven to be successful.

Recurring Faults

16L2 contamination led to beam aborts throughout the accelerator cycle, only a small percentage of which occurred in "Stable Beams". In total around 60 aborts occurred due to this issue during the period.

- Turnaround was impacted, as several ramps were needed, in cases, due to spurious beam losses.
- Accesses were made to install diagnostics, in each case these were followed by pre-cycles

The TDE beam-2 has a pressure issue, which required refilling of nitrogen bottles at a regular interval

- This has been classified within "Access Management" and "Beam Dumping System" categories, depending on the exact nature of the intervention.
- Each access to re-fill required a pre-cycle

Energy extraction systems on RQD.A12 led to beam aborts, and required accesses to correct the issue.

Several dumps occurred due to communication timeouts with middleware (CMW):

- Two aborts were "power converter interlock".
- One dump was "β* interlock".

These faults manifested as issues with the software interlock system, but were gateway-computer issues. These are being investigated by the controls group

High-Impact Faults

A water leak in US45 required a preventive electrical distribution stop, affecting the cryogenic system in point 4 (1 day downtime)

The cryogenics system had several issues;

- Failure of a compressed air pressure transmitter, which triggered the temporary stop of the cold box of LHCB-4, 4.5 K refrigerator. (11 ½ hours downtime)
- Loss of cryogenic conditions in following detection of oil at the 3rd coalescer of compressor station QSCB-4 (13 ½ hours downtime)

The RB.A12 power converter had faults due to water leaks of water-cooled heatsinks (≈19 hours downtime)

The dilution kicker system (MKD) had four beam aborts during stable beams, the MKD generator was replaced, and the system was then revalidated (1 day downtime).

A grounding cable was not correctly removed following an intervention on a magnet circuit during a technical stop, this had a long diagnosis time (½ day downtime).

Cooling and Ventilation systems had a brief interruption in the supply of demineralised water, this was quickly corrected, however, this interrupted the cryogenic system, which required significantly longer to recover.

System-Level Interfaces

Two dumps during the ramp were due to trip of 60A orbit corrector power converters, which are trimmed in real-time by the orbit control system using information from Beam Position monitors: A noisy BPM signal results in poor regulation of the real-time trims on the converter, ultimately leading to a converter trip.

The same root cause occurred seven times on the the connection between Power Converter, Quench Protection and Powering Interlocks, on RQ10.L8. A spurious interlock appears with no system indicated as the triggering source. Whist this has had a low impact, it has not yet been possible to identify the true root cause of this fault

Magnet Circuits have been assigned faults due to zero voltage crossing issues. Certain 600A circuits tripped during ramp-down or pre-cycle, this root cause is mitigated by modifying converter ramp rates.

Servers used for the External Post-operational Checks for the LHC Beam Dumping System (XPOC) and Post Mortem (PM) have been observed to have slow data collection and transfer, which leads to data analysis time-out. When this occurs, an expert must manually check data before re-injection is permitted. These issues have a higher impact during the re-start phase due machine protection validation tests, which make extensive use of the automated testing infrastructure. These faults have been assigned to Accelerator Controls, but are still being investigated.

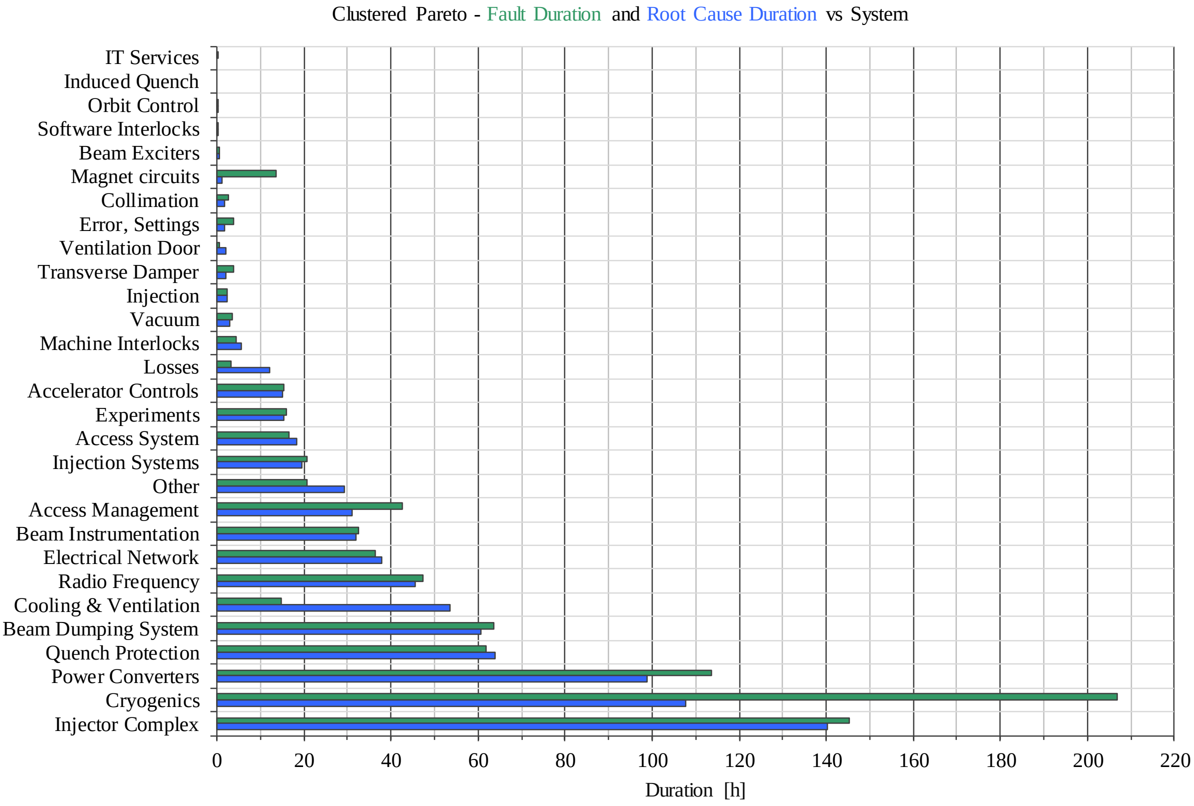

Figure 17: Turnaround Time Duration – 2016 vs 2017

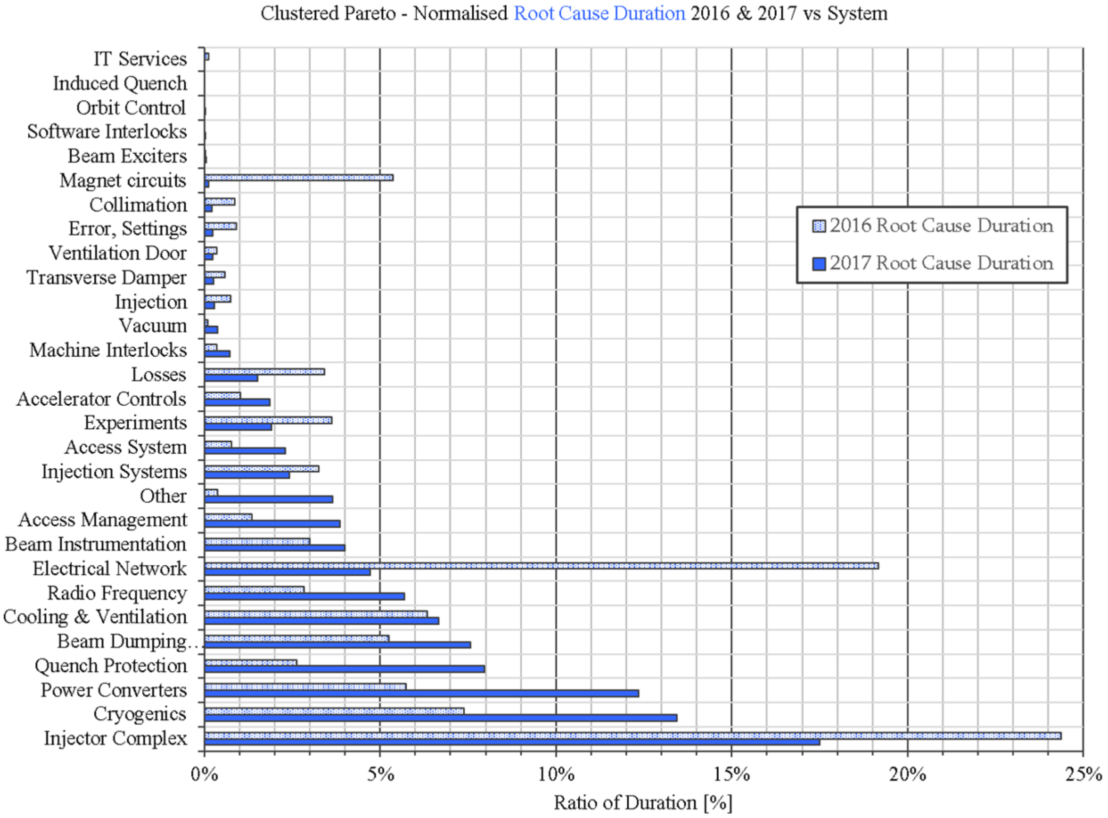

Figure 18: Turnaround Time Duration – 2016 vs 2017

CONCLUSIONS

2017 has been a year with unprecedented availability, and has set a new baseline for the achievable performance of the LHC machine. Week 42 was a milestone, with **over 93%** availability, giving a maximum physics production of almost **5fb^{-1}** per week, this week serves as a reference for the operation of LHC.

This improvement in 2017 is largely due to the absence of the long, rare, events of 2016. 2017 is likely to be a more representative year of operation for the future studies in CERN accelerator availability.

Future Work

Four points emerge concerning availability studies, following 2017:

1. New metrics are needed to address the real "lost-physics" due to faults. These are to be investigated by the AWG, in collaboration with BE/BI and TE/ABT during 2018.
2. The metric of turnaround is complex, and requires further study. This was started in 2017, but should be improved, in parallel with point #1 above.
3. The application of the AFT to the injectors has resulted in a data set around six times larger than is used to being dealt with, in addition, post LS2, the injector availability will be a key area to assess – this requires a strategic commitment of resources.
4. The presentation of work and the compilation of reports for the injectors has been requested at the IEFC. For this to be achievable, the tools involved must be optimised to create reports and figures automatically in order to be presented.

ACKNOWLEDGMENTS

The authors would like to acknowledge the work of the entire AWG and AFT teams for their significant efforts in the creation of this paper.

REFERENCES

[1] https://espace.cern.ch/LHC-Availability-Working-Group/SitePages/Home.aspx

[2] https://aft.cern.ch/

[3] "LHC Availability 2016: Restart to Technical Stop 1", B. Todd, L. Ponce, A. Apollonio, CERN-ACC-NOTE-2016-0047, 2016.

[4] "LHC Availability 2016: Technical Stop 1 to Technical Stop 2", B. Todd, L. Ponce, A. Apollonio, CERN-ACC-NOTE-2016-0066, 2016.

[5] "LHC Availability 2016: Technical Stop 2 to Technical Stop 3", B. Todd, L. Ponce, A. Apollonio, CERN-ACC-NOTE-2016-0065, 2016.

[6] "LHC Availability 2016: Proton Physics", B. Todd, L. Ponce, A. Apollonio, CERN-ACC-NOTE-2016-0067, 2016.

[7] M. Lamont et al., "LHC Schedule 2017", version 1.0, March 8th 2017.

[8] M. Lamont et al., "LHC Schedule 2017", version 1.7, November 3rd 2017.

[9] L. Ponce, A. Apollonio, extracted from the Operations Super-Table, for the period concerned. https://acc-stats.web.cern.ch/acc-stats/#lhc/super-table

[10] M. Pojer, et al. "LHC Operation", these proceedings.

[11] R. Garcia, et al. discussions in "Session 1", Radiation to Electronics Project Cost and Schedule Review, https://indico.cern.ch/event/666689/ October 12th-13th 2017.

[12] S. Uznanski, et al. "FGClite Deployment – Phase 1 – Arc", January 2017, LHC-RF-EC-0001.

[13] B. Mikulec et al. "Availability 2017 – Injectors", these proceedings.