

## LHC AND INJECTOR AVAILABILITY: RUN 2

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### Abstract

This paper summarises machine availability of the LHC and injector complex, starting with an evaluation of the machine performance in 2018, working backwards to then appraise the whole of Run 2.

The first section of this paper considers LHC; identifying operational aspects, beam mode ratios, beam dump causes, fill length, turn-around, a detailed breakdown of all faults and impacts, with notable faults and new root causes identified.

The second section covers the injector complex.

The final section introduces new concepts and approaches which are currently being considered for practical application in availability studies.

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 throughout Run 2 is robust, giving an objective good insight into the observed availability performance of the LHC. From 2017 onwards, data has included ratified faults for the LHC injectors, giving an availability overview for the whole accelerator complex.

### AWG LHC Reports

The AWG use the recorded fault information and operational data to create LHC availability reports, during Run 2 twelve such reports were produced for the LHC:

- 2016: Restart → Technical Stop 1 [3]
- 2016: Technical Stop 1 → Technical Stop 2 [4]
- 2016: Technical Stop 2 → Technical Stop 3 [5]
- 2016: Proton Physics [6]
- 2017: Restart → Technical Stop 1 [7]
- 2017: Technical Stop 1 → Technical Stop 2 [8]
- 2017: Technical Stop 2 → Technical Stop 3 [9]
- 2017: Proton Physics [10]
- 2018: Restart → Technical Stop 1 [11]
- 2018: Technical Stop 1 → Technical Stop 2 [12]
- 2018: Technical Stop 2 → Technical Stop 3 [13]
- 2018: Proton Physics [14]
- LHC injector Availability 2018 [15]

For more information concerning a specific interval of time, the documents listed above give a detailed overview of observations during the periods in question. This paper and the availability reports consider *blocking-faults*, which have the state filter "*blocking-op*" applied.

### AWG Injector Reports

Since 2017 faults have been tracked in the injector complex, culminating in the first publication of injector fault at the the end of 2018.

### LHC AVAILABILITY

The period being studied covers the proton physics operation of the LHC during the whole of Run 2, from the start of 2016, to the end of 2018. The information in this section begins with a summary of machine performance in 2018, before looking back at to how this has evolved over the course of Run 2. The machine mode during 2018 breaks down as follows:

Table 1: 2018 Machine Mode Breakdown

Machine Mode	Days
Beam Commissioning	21½
Physics / Commissioning	17
Scrubbing	1
Machine Development	23
Physics	128
Special Physics	16
$\Sigma$	<b>206½</b>

In total, around **161 days** were dedicated to **physics or special physics**. This figure is approximated as intervals are rounded to nearest half-days. Using the same metrics, in 2016 there were **153** days dedicated to physics and in 2017 there were **140½**.

### Availability & Physics Delivered

The LHC availability in 2018 was tracked from week 13 to week 44; fill number 6488 to 7395. The mean availability in this period was 78.7%, the total physics reported by ATLAS was around 65.176fb<sup>-1</sup>. Figs. 1, 2 and 3 compare the three periods of Run 2.

The mean availability 2016, 2017 and 2018 was 75.8, 82.9 and 78.7% respectively. The maximum weekly luminosity in the same interval was 3.1, 4.9 and 5.3 fb<sup>-1</sup> respectively.

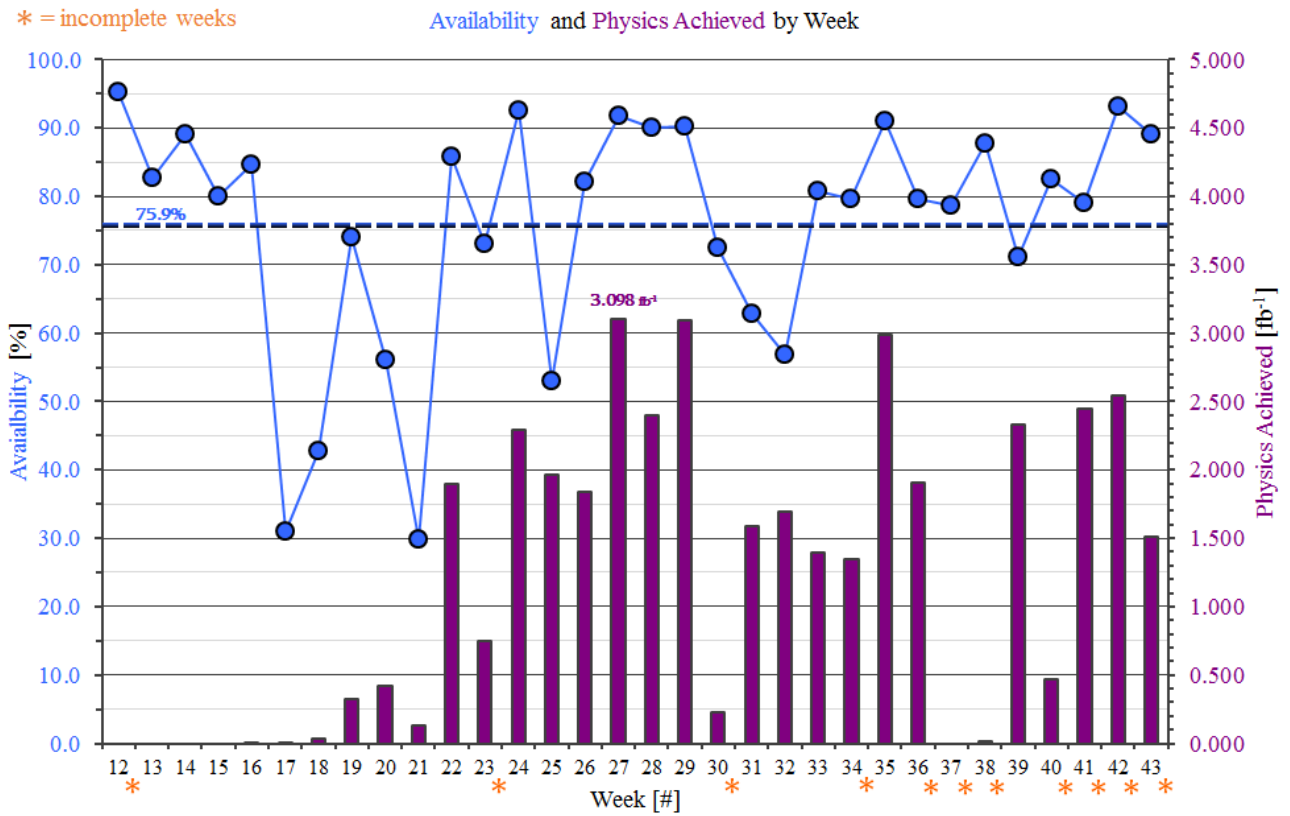


Figure 1: Availability 2016

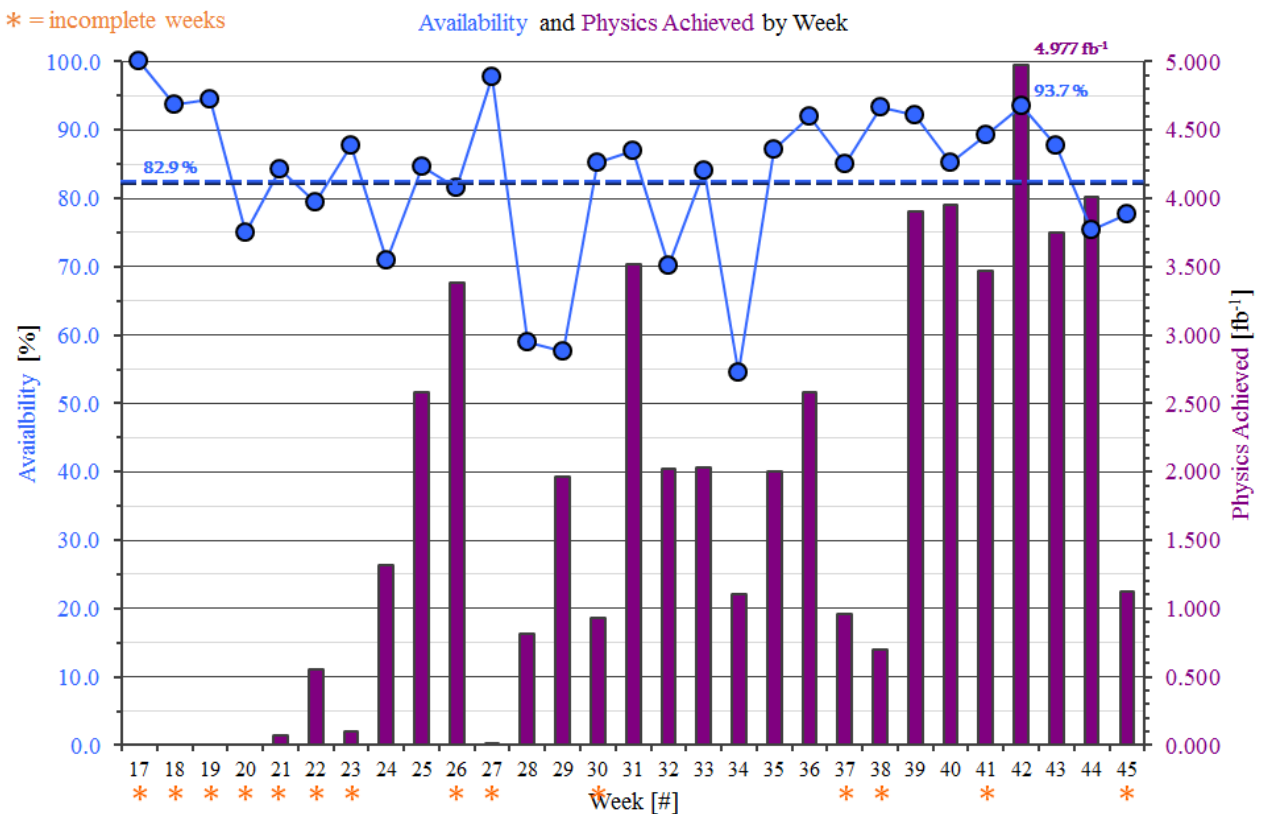


Figure 2: Availability 2017

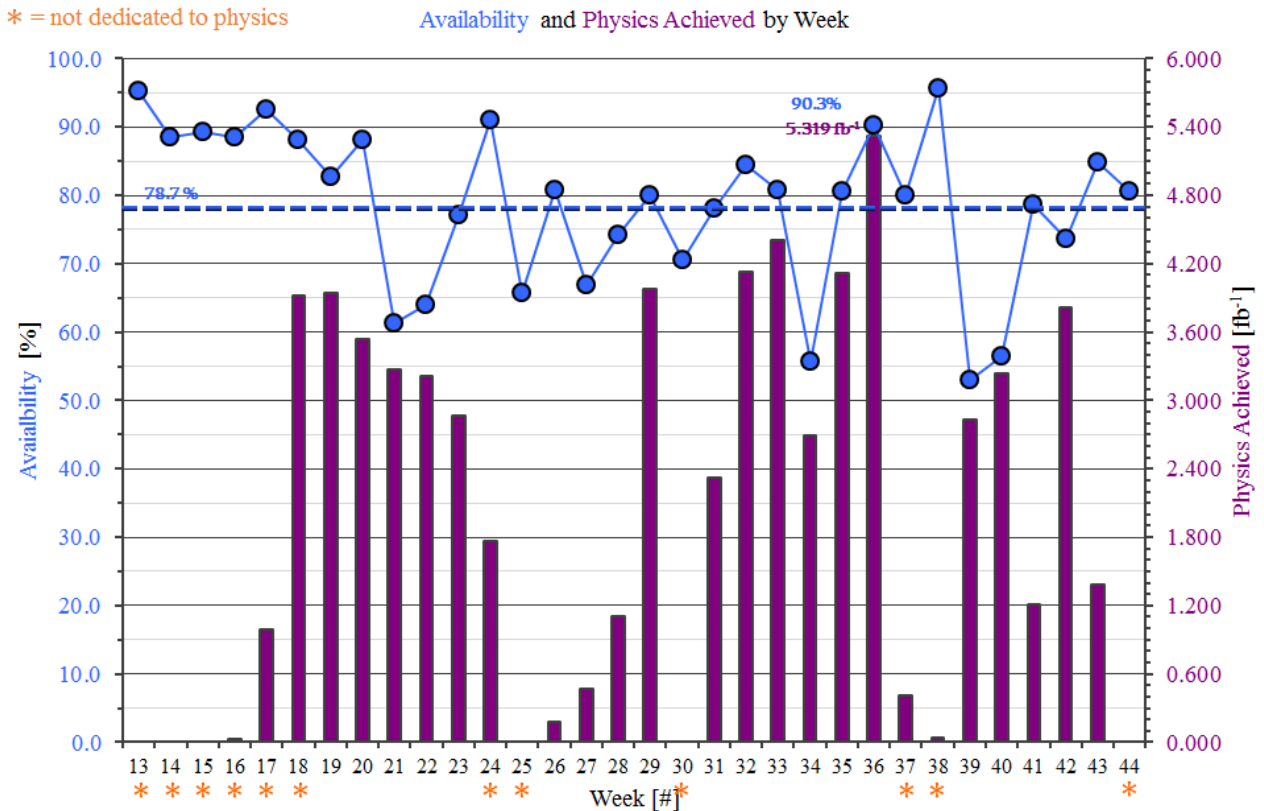


Figure 3: Availability 2018

Operational Mode

3943.9 hours account for the approximate 161 days duration of physics. The operation mode during this period was as follows:

Table 2: 2018 Mode Breakdown

Operation Mode	Hours	
Stable Beams	1931.8	49%
Operations	992.0	25%
Fault/Downtime	942.8	24%
Pre-Cycle	77.3	2%
<b>3943.9</b>		

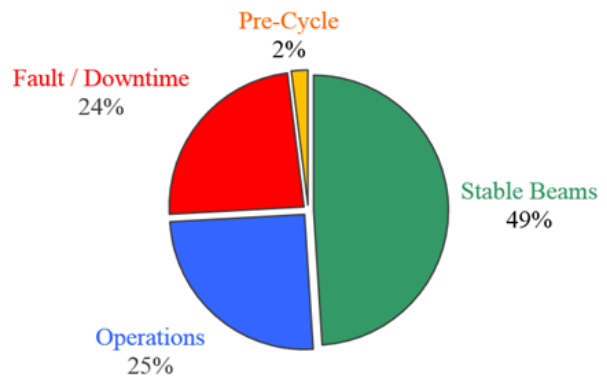


Figure 4: 2018 Operational Mode Breakdown

As a pie chart, in Fig. 4, this shows almost 50% of the physics period was spent in stable beams.

Figs. 5, 6 and 7 compare the three periods of Run 2. Comparing 2016, 2017 and 2018 directly gives;

Table 3: 2016-17-18 Mode Breakdown

Operation Mode	2016	2017	2018
Stable Beams	49%	49%	49%
Operations	23%	30%	25%
Fault/Downtime	26%	19%	24%
Pre-Cycle	2%	2%	2%

The Stable Beams ratio is **steady around 49%**, the pre-cycle around 2%. On the other hand, the remaining 49% of time is shared between operations and fault, with a slightly varying split.

Beam Aborts

In 2018 there were 908 fills considered by the availability studies, of which 252 had stable beams. The root causes of the beam aborts can be broken down into;

- *End of Fill* - where the operations team decided to end the current mission, and refill the machine.

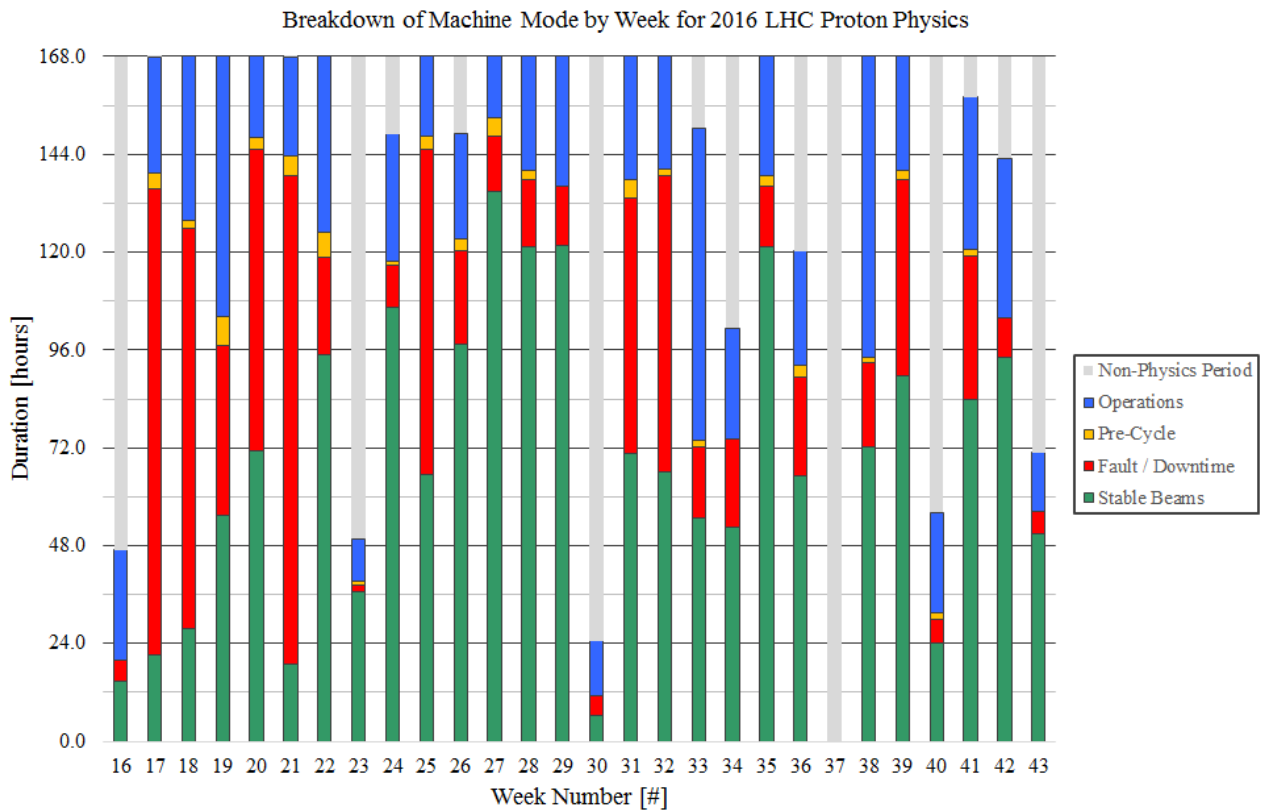


Figure 5: Beam Mode Breakdown by Week 2016

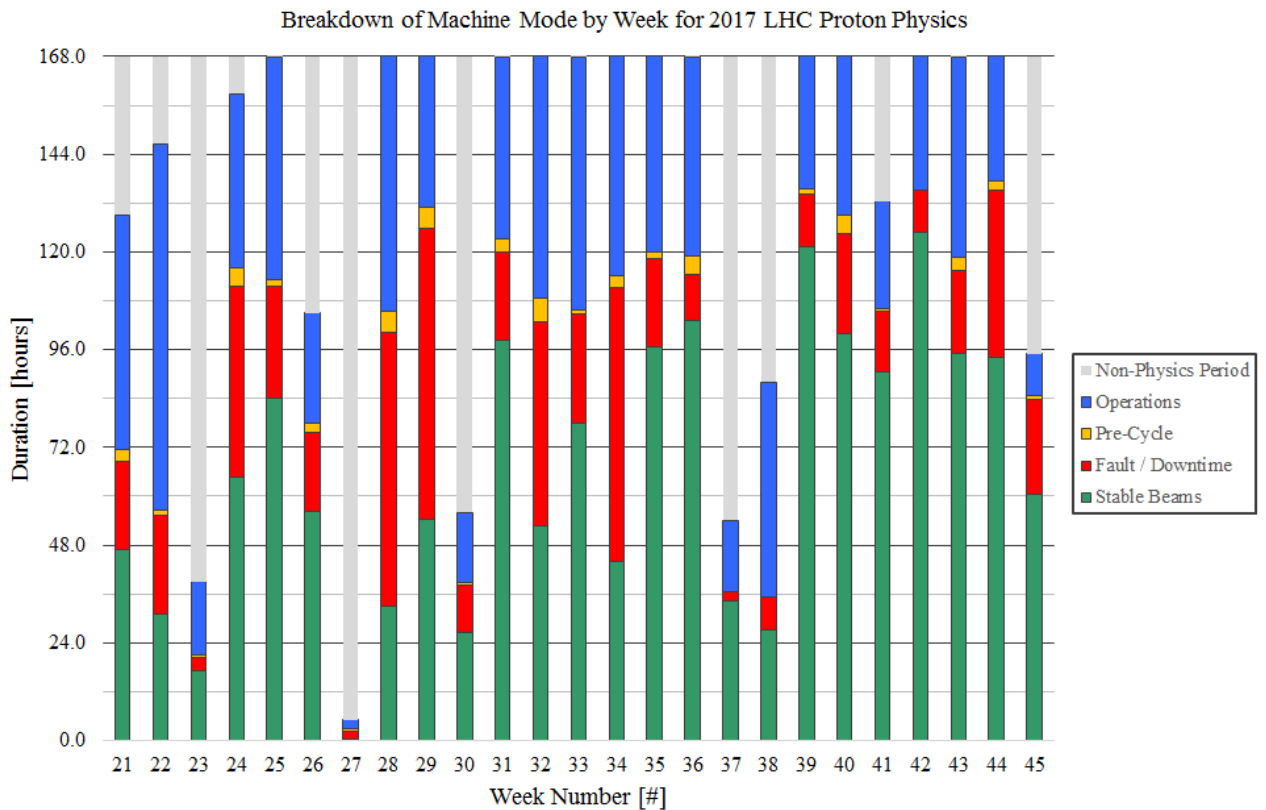


Figure 6: Beam Mode Breakdown by Week 2017

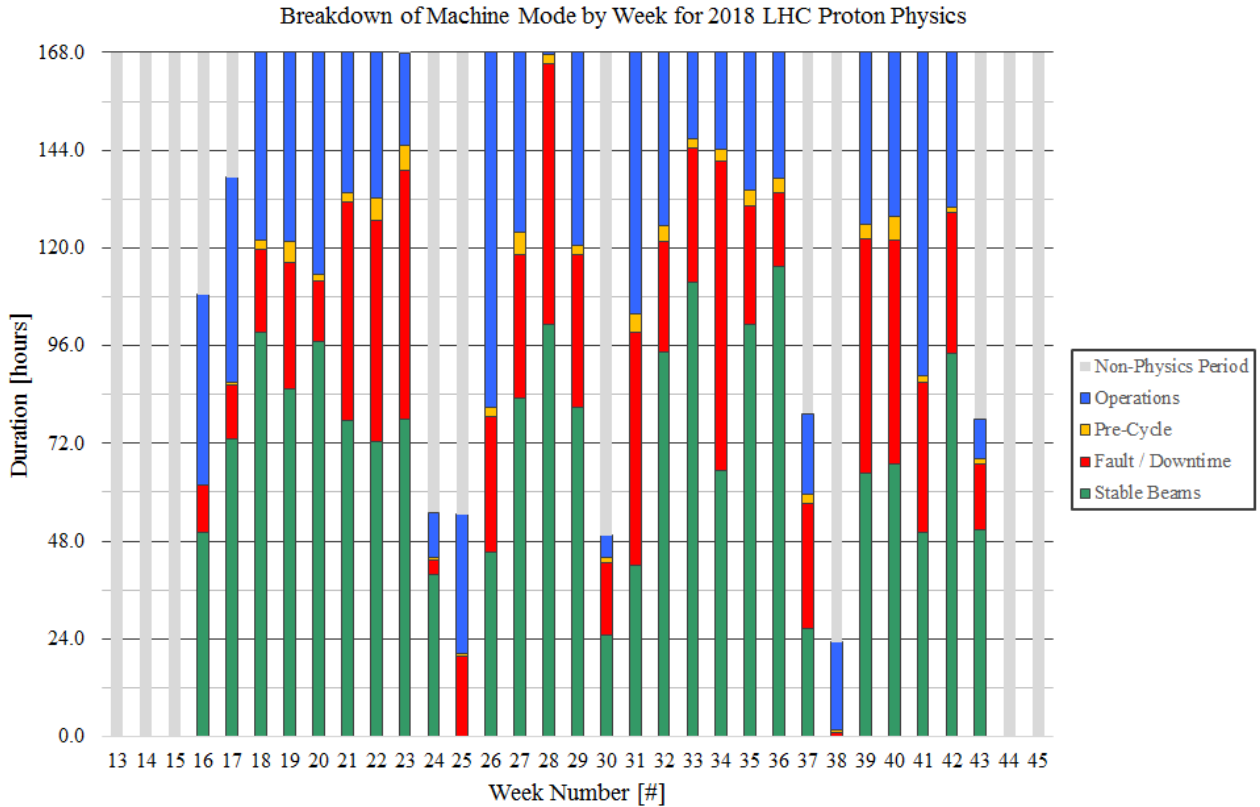


Figure 7: Beam Mode Breakdown by Week 2018

- *Aborted* - where a fault or failure leads to a premature abort of the fill.
- *Aborted Suspected Radiation (R2E)* - where a fault who’s root causes are suspected to be radiation related lead to a premature abort of the fill.

Comparing this information over the whole of Run 2 gives the following table:

Table 4: 2016-17-18 Beam Abort Root Cause Breakdown

Root Cause	2016	2017	2018
End of Fill	84 (47%)	106 (50%)	150 (59%)
Aborted	86 (48%)	95 (45%)	82 (33%)
Aborted R2E	9 (5%)	10 (5%)	20 (8%)
$\Sigma$	<b>179</b>	<b>211</b>	<b>252</b>

Showing these ratios for 2018:

from 2016 to 2017, the major changes were 3% more fills reaching *end of fill*, from 2017 to 2018 the major changes have been 9% more *end of fill* and 3% more suspected radiation induced aborts.

In 2018, the ratio of fills that reached *end of fill* increase is largely due to a campaign of physics at injection, where numerous fills having a stable beams indicator took place over a short period of time, all being marked as end of fill.

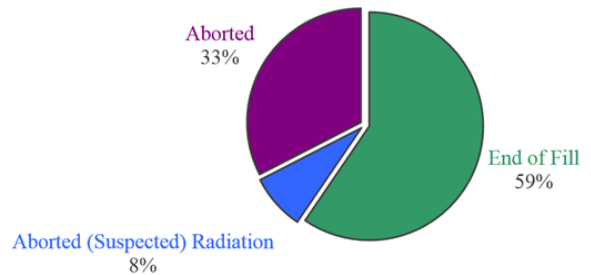


Figure 8: 2018 Beam Abort Root Cause Breakdown

### Stable Beams Duration

In 2018, of the 252 fills considered, 150 reached end of fill, 102 were aborted, 20 of which were due to radiation induced events. The time distribution for these events are shown in Figs. 9, 10 and 11. Also labelled are the fills which have been aborted due to events related to contamination of the LHC vacuum chamber, labelled as suspected 16L2 events.

### Turnaround

Turnaround is the duration of time that it takes to get to stable beams of one fill from the end of stable beams of the previous fill. In 2018 there were 252 fills with stable beams, ignoring those fills that have a mode change associ-

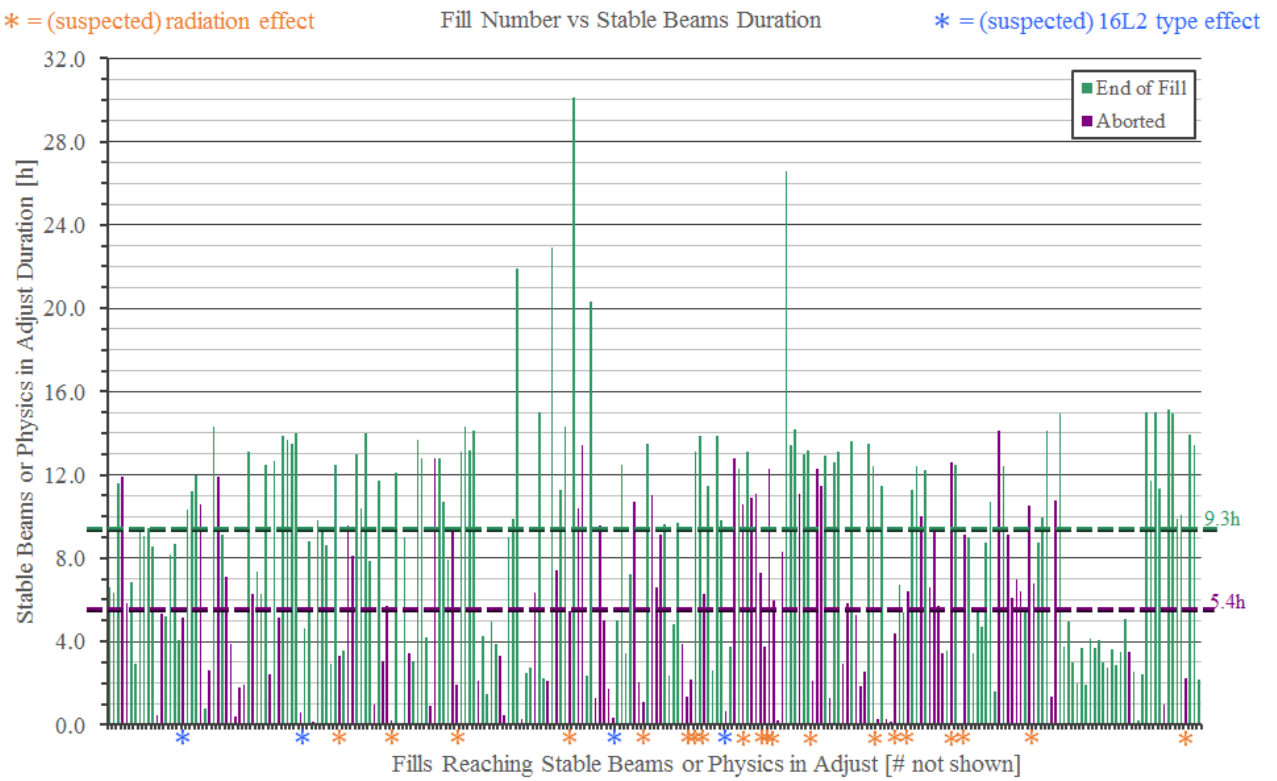


Figure 9: Fill Duration by Fill Number for Both Root Causes 2018

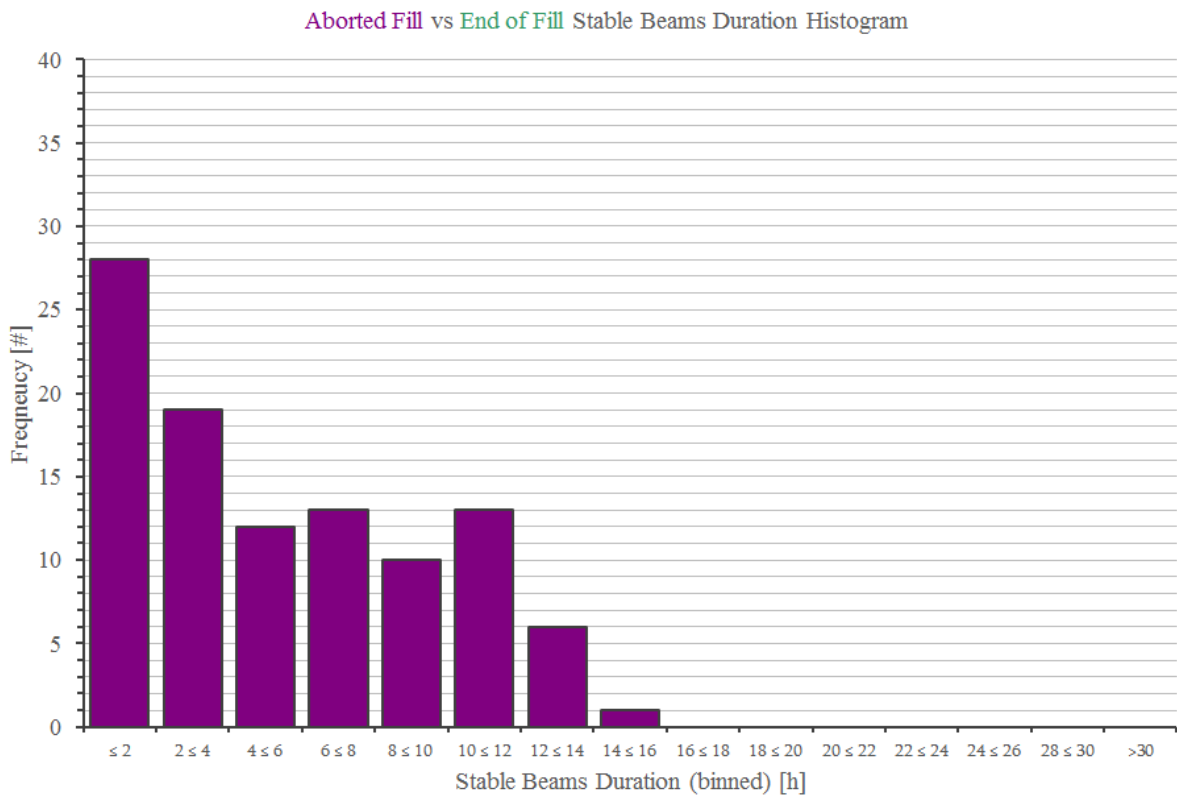


Figure 10: Fill Duration Distribution for Aborted Root Cause 2018

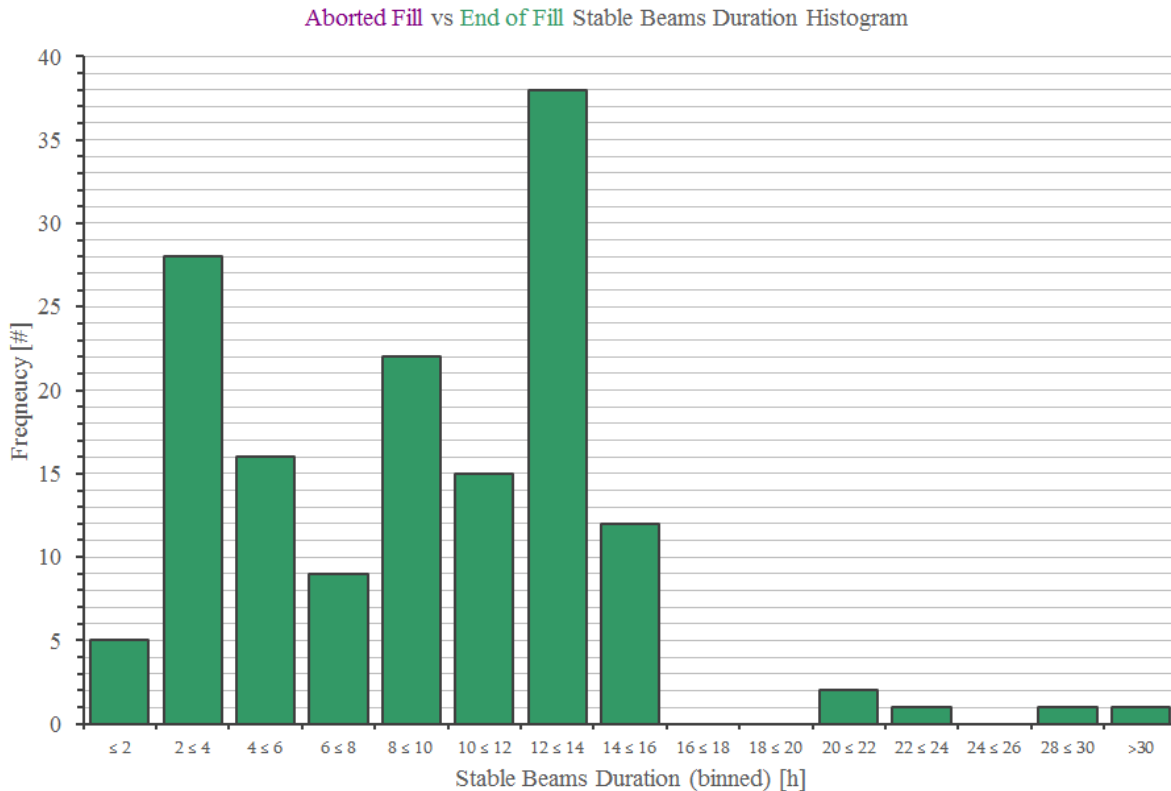


Figure 11: Fill Duration Distribution for End of Fill 2018

ated, and ignoring the fills that have long faults leads to 218 turnarounds being considered.

A comparison of 2016, 2017 and 2018 is shown in Fig. 13. The key changes to note are:

- an **increase** in shorter turnarounds, specifically in 2018 the first turnarounds of **<2 hours** were recorded.
- an **increase** in the frequency of turnarounds having a duration of **10-12 hours**.
- a general **decrease** in long turnarounds, which have a duration over **>13 hours**.

In 2016, 2017 and 2018, the average length of a turnaround when faults were present was 7.1, 6.2 and 6.0h respectively. Similarly the average turnaround duration with no fault present was 4.3, 3.5 and 3.5h respectively. This indicates that the turnaround process has been improved over the course of Run 2.

### Faults

Considering the faults with the state blocking-op for 2018, there were 915 faults, with 107 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

The Table 5 shows the durations of the faults in each of these categories in 2018.

A pareto of this information is shown in Fig. 14, as is a comparison of the root cause duration in Fig. 15.

In 2018, around 22% of all faults were related to Beam or Operational reasons:

Where as 90% of downtime was due to Equipment failure.

### Top Faulty Systems

Throughout Run 2, the top five faulty systems generally account for almost two-thirds of downtime. The systems

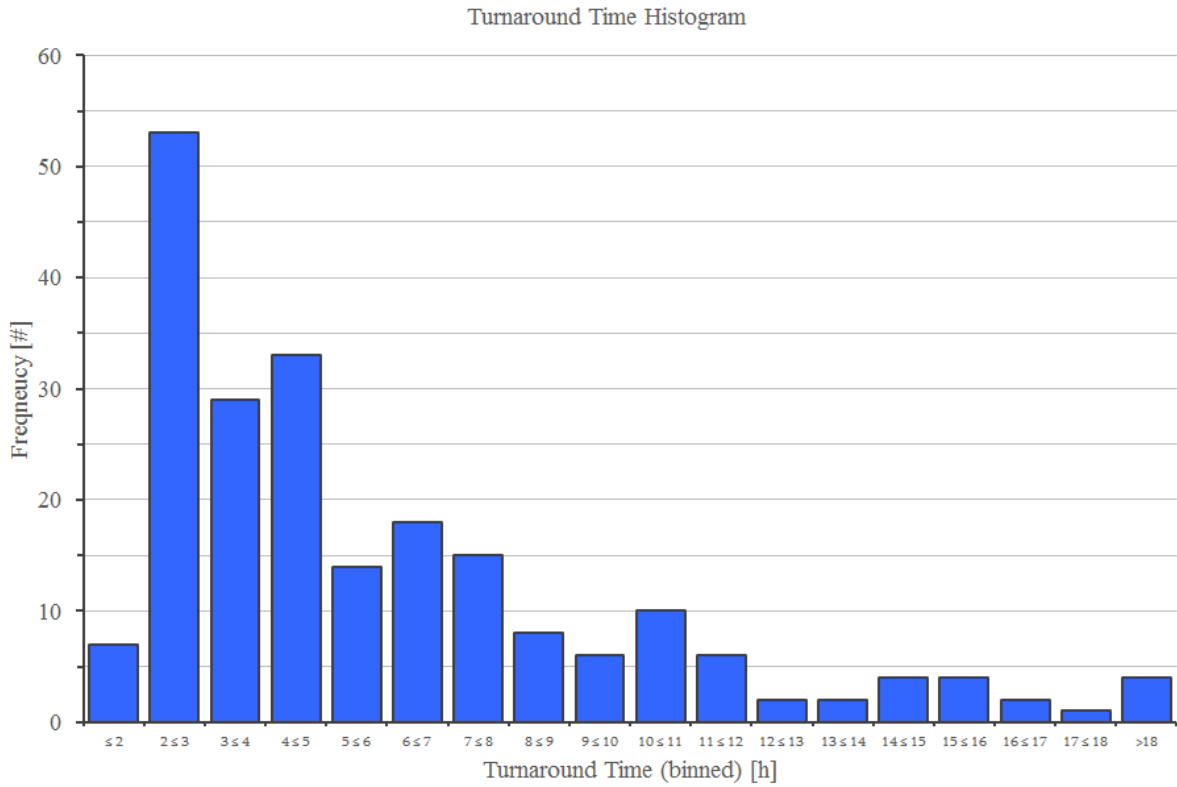


Figure 12: Turnaround Duration Binned for 2018

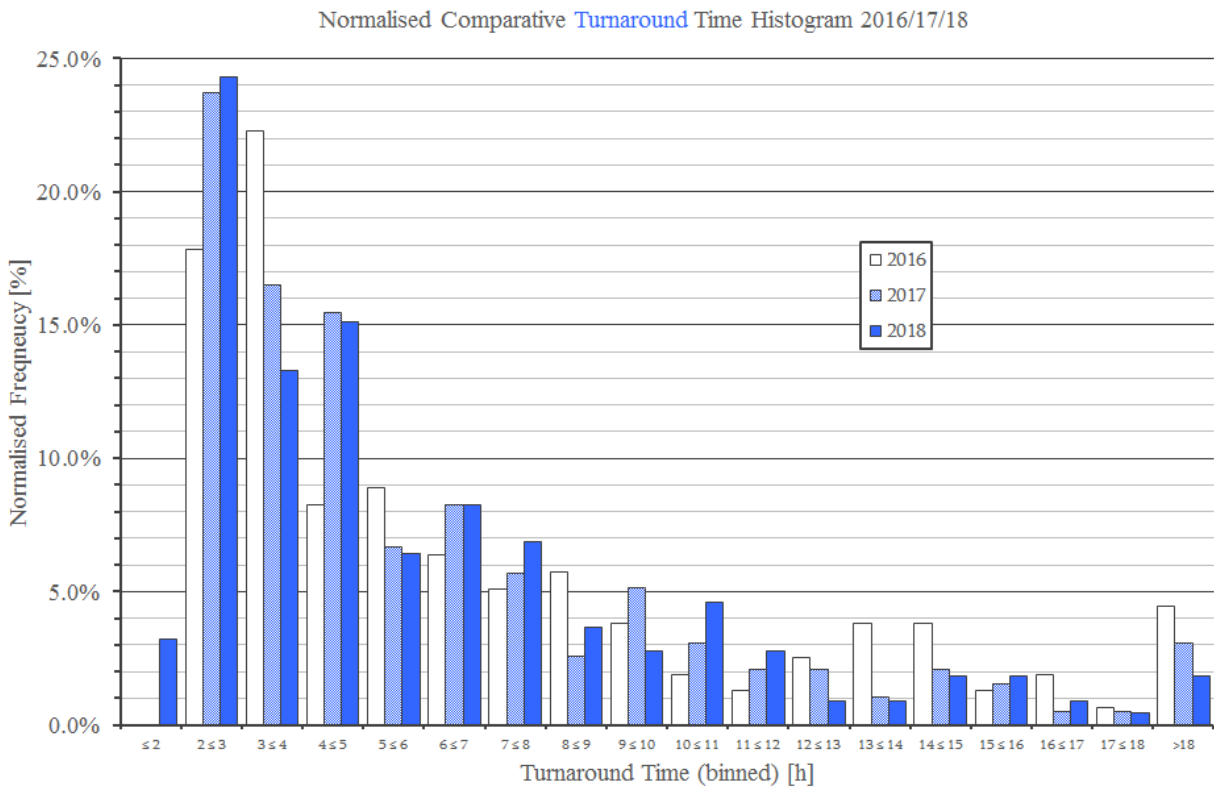


Figure 13: Turnaround Duration Binned for Run 2



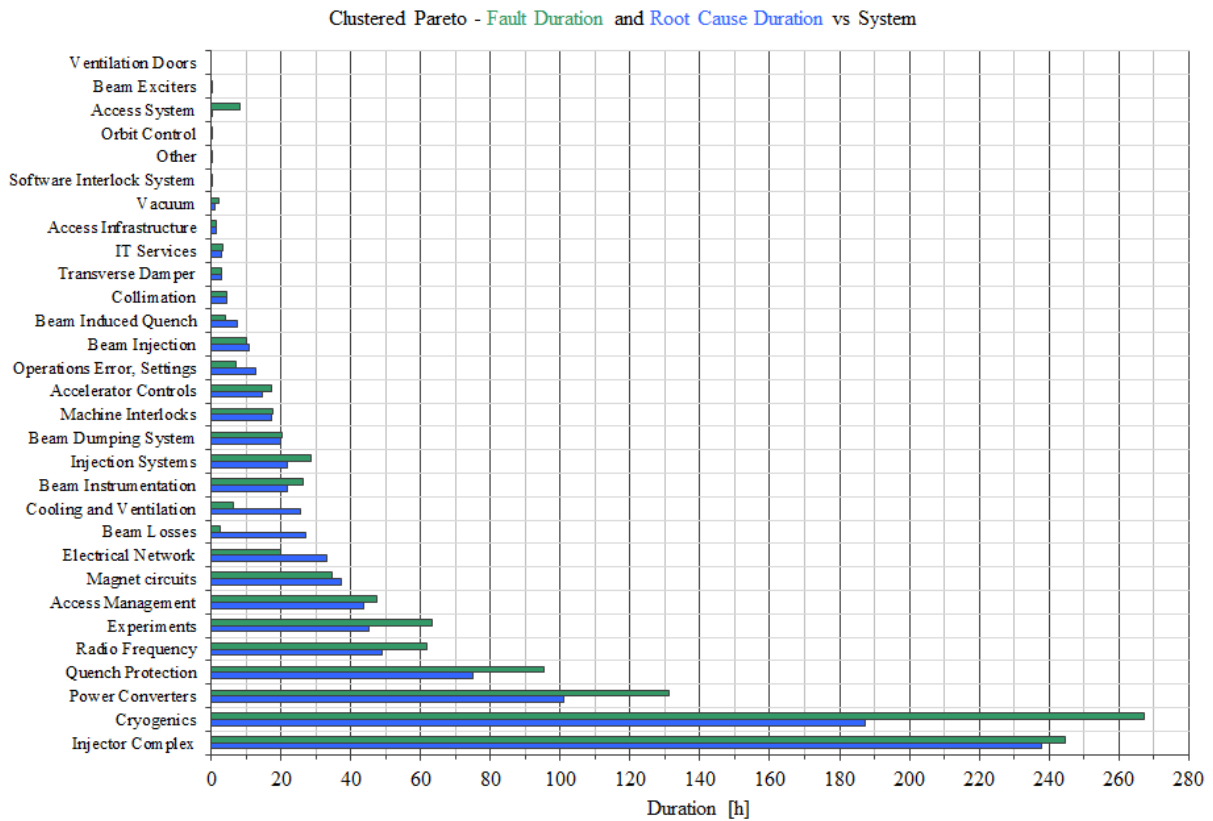


Figure 14: Fault Duration Pareto 2018

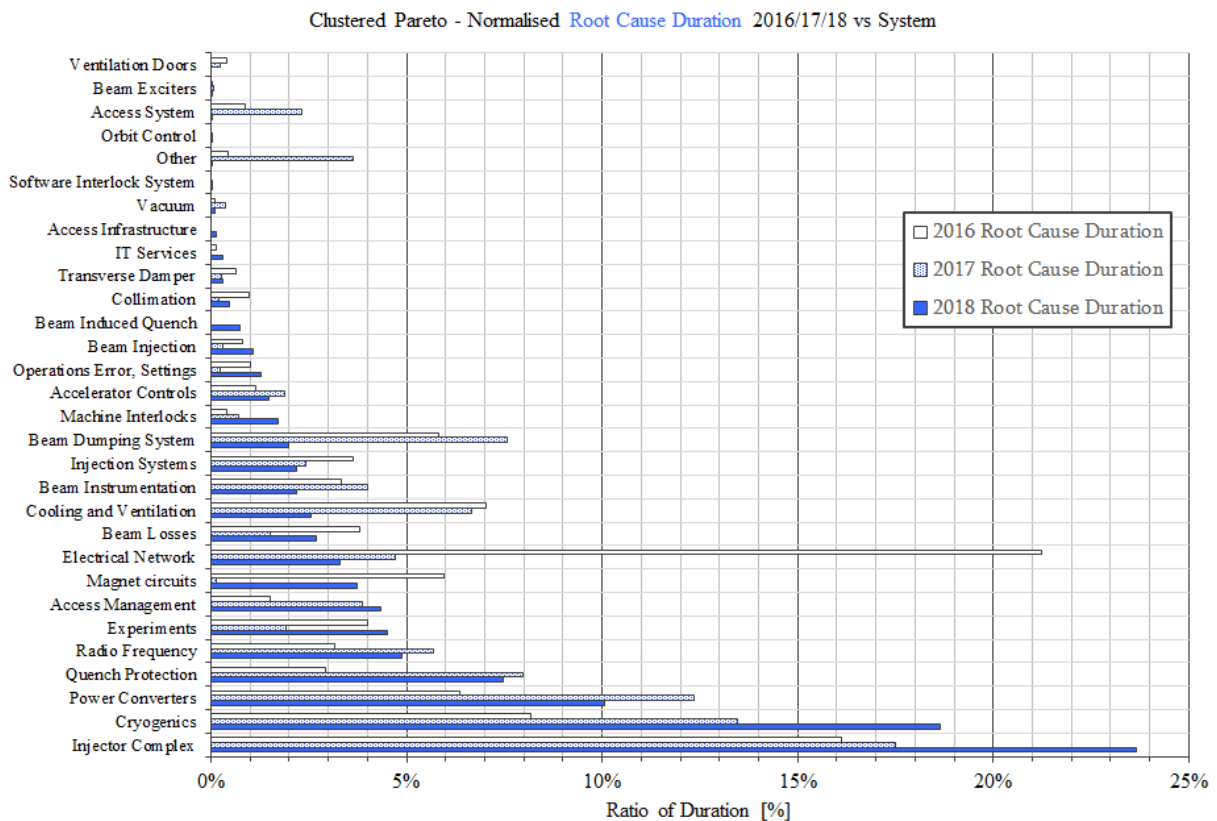


Figure 15: Fault Root Cause Duration Pareto Run 2

Table 5: 2018 Faults

System	Faults [#]	Fault Duration [h]	Root Cause Duration [h]
E - Injector Complex	141	244.7	237.9
E - Cryogenics	38	267.2	187.3
E - Power Converters	159	131.1	101.0
E - Quench Protection	75	95.5	75.2
E - Radio Frequency	59	61.9	49.2
E - Experiments	45	63.4	45.3
E - Magnet Circuits	32	34.6	37.5
E - Electrical Network	27	20.1	33.1
E - Cooling & Ventilation	5	6.5	25.7
E - Beam Instrumentation	26	26.3	22.0
E - Injection Systems	18	28.5	22.0
E - Beam Dump System	22	20.5	20.1
E - Machine Interlocks	13	17.5	17.2
E - Accelerator Controls	13	17.2	14.7
E - Collimation	11	4.6	4.6
E - Transverse Damper	4	3.1	3.1
E - IT Services	3	3.3	3.0
E - Access Infrastructure	1	1.5	1.5
E - Vacuum	5	2.3	1.0
E - Software Interlocks	3	0.4	0.4
E - Other	4	0.3	0.3
E - Orbit Control	3	0.3	0.3
E - Access System	5	8.2	0.1
E - Beam Exciters	1	0.1	0.1
E - Ventilation Doors	0	0.0	0.0
B - Losses	33	2.6	27.2
B - Injection	98	10.3	10.9
B - Induced Quench	5	4.2	7.6
O - Access Management	17	47.4	43.8
O - Error, Settings	49	7.2	12.9
$\Sigma$	<b>915</b>	<b>1130.6</b>	<b>1004.9</b>

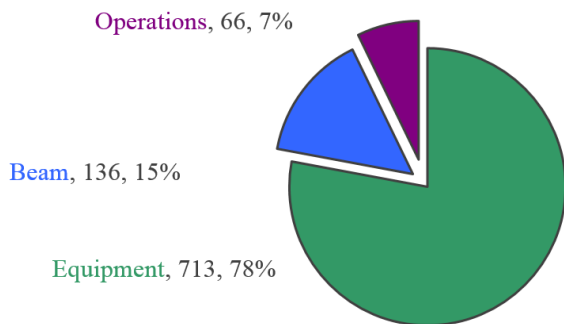


Figure 16: Fault Occurrence Ratio 2018

consistently seen as large contributors to faults in Run 2 have been the Injector Complex, Cryogenics, Power Converters and Quench Protection. Both the Beam Dumping and Radio Frequency systems have been significant contributors to the overall fault duration throughout Run 2.

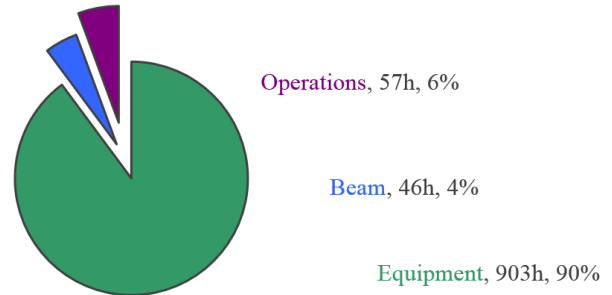


Figure 17: Fault Root Cause Ratio 2018

### Recurring Faults

There are four categories of recurring faults which have been of significant throughout Run 2.

- 16L2-type Losses, with events in 2017 and 2018.
- UFO-type Losses, with events throughout Run 2. Three magnet quenches in 2016, and two in 2018 were due to such losses
- Radiation induced events, with events throughout Run 2. An increase in the rate of these events has been observed in 2018. This could be related to collimator settings.
- Electrical glitches, also with events throughout Run 2.

### High-Impact Faults

Each year of Run 2 has seen a set of rare faults, which lead to long down-times.

In 2016, the key events were the weasel ingress onto electrical equipment, which created around six days of downtime. Flooding in point 3 of the LHC, which led to three days of downtime. In addition there were several issues in the injectors, leading to around seven days of downtime.

In 2017 the high impact faults consisted of an 18kV electrical transformer issue, and three events on the cryogenic production systems. Each event last around one day, leading to four days lost for high-impact faults in total.

In 2018 there was a damaged magnet in the SPS, taking two days to repair, and three events on the cryogenic system, leading to an additional three days of downtime.

## INJECTOR AVAILABILITY

This section presents a summary of injector availability statistics for 2017 and 2018. Detailed analyses for these years are available in references [15, 16]. Dedicated availability data collection in the injectors started in 2017. Thus, the first years of the Run 2 are omitted from this analysis. In both years, the injector complex was the leading cause of the LHC unavailability. This downtime was caused both by hardware failures in the injectors and by beam set-up. The latter consist of set-up time that occurs when the beam for the LHC is not ready when needed. This set-up time does not include the delays caused by failed injection attempts [17].

The injector unavailability for individual machines is shown in Fig. 18. It is based on data collected by injector operators and it shows lower availability than the LHC statistics. This is caused by two factors: i) the LHC requires injectors only during fills, and ii) injectors provide beam for multiple destinations. While a fault can stop the beam for a single location, an injector may still be able to provide the beam for the LHC. The leading causes for individual injector unavailability are shown in Fig. 19. It is notable that the majority of the SPS power converter downtime in 2018 was caused by a single failure that only affected the North Area. The long downtime was a result of a decision to defer the corrective maintenance for several days.

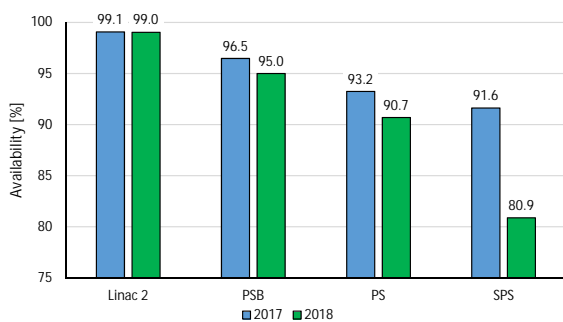


Figure 18: Injector availabilities in 2017 and 2018.

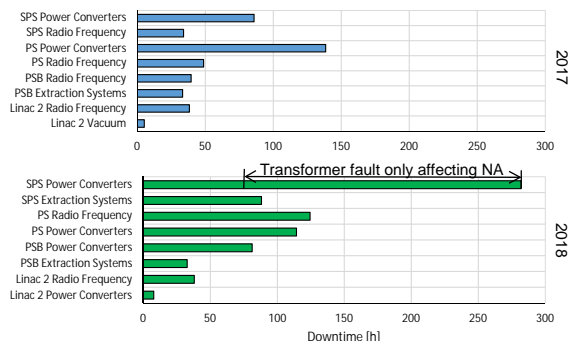


Figure 19: Leading causes for injector unavailabilities with impacts. Long transformer failure in the SPS that only affected North Area stands out.

There were also some individual high impact failures with significant downtime. For example, a short circuit in an 18 kV breaker on 28<sup>th</sup> of July 2018 led to 4 days of downtime including 2.5 days of degraded operations when bunch trains were not available for the LHC due to RF problem in the PS. Also, on the 20<sup>th</sup> of August 2018, beam induced damage in the SPS led to two days of downtime.

## ONGOING STUDIES

Several concepts have been studied in parallel to the core availability studies.

### Lost Physics

The concept of lost physics provides the means to compare the impact of faults occurring at LHC top energy with faults

occurring during the rest of the cycle. Even a short fault occurring in stable beams (e.g. a UFO, few ms, assuming no magnet quench) represents for LHC a big operational overhead, as the average turnaround is, depending on the year, >3 hours long. Faults occurring at top energy should therefore be ‘penalized’ for this additional impact on operations. This allows taking into account fault frequency when presenting downtime statistics and homogeneously comparing the impact of hardware systems and physics processes (e.g. beam losses due to UFOs). The amount of the penalty is in the worst case equal to the average turnaround, as that is the time it would take to recover the same conditions than when the fault occurred. Nevertheless it might be that the fault occurs close (i.e. within less than the average turnaround duration) to the optimal fill length, set a priori for luminosity optimization. In this case the penalty should only amount to the difference between the optimal fill length and the fill length which was reached at the time of the dump. Fig. 20 shows the principle of the lost physics metric with a simple example.

Based on the presented metric, the downtime distributions in the years 2016-2018 have been updated including the lost physics (see Fig.s 21, 22, 23).

Fig. 21 shows that in 2016, the biggest contributions to lost physics came from the electrical network and beam losses [18]. In the first case, most of the failures at top energy were caused by mains disturbances caught by the Fast Magnet Current Change Monitor (FMCM), with 22 events. In 13 of these 22 cases only 4 magnet circuits (RD1.LR1, RD1.LR5, RD34.LR3 and RD34.LR7) were affected, i.e. the involved power converters showed a particular sensitivity to electrical glitches due to the adopted network topology. This was mitigated in the EYETS 2016-17 by the introduction of SATURN power converters. Beam losses were mainly determined by UFOs, whose conditioning after the restart in 2015 was still ongoing in 2016, with 13 observed events.

In 2017 the largest contributions to lost physics came from power converters and QPS for hardware systems (Fig. 22). Adding lost physics, power converters became the first contributor to LHC unavailability, surpassing the injector complex. In addition, recurring beam losses in 16L2 had a major impact on operations in 2017. Considering lost physics, 16L2 events were responsible for the same performance loss of the Beam Dumping System in 2017, i.e. in the range of 80 h. This can be considered an underestimation, as many 16L2 events occurred in the rest of the LHC cycle (before reaching stable beams) and are therefore not accounted in the lost physics metric.

In 2018 again the largest contributions to lost physics came from power converters and QPS for hardware systems (Fig. 23). This can be mostly explained by the increased number of radiation induced failures with respect to previous years (8% in 2018 vs 5% in 2016 and 2017). It can be noted that the impact of 16L2, thanks to the mitigation measures deployed in 2017, was very limited in 2018 compared to 2017.

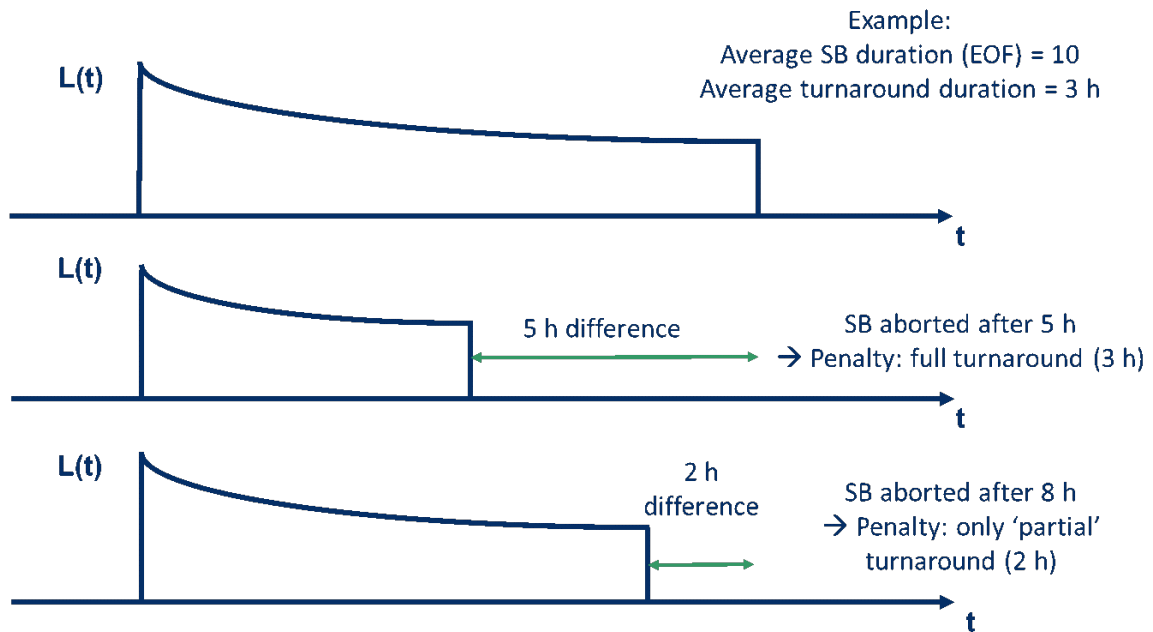


Figure 20: Definition of LHC lost physics metric.

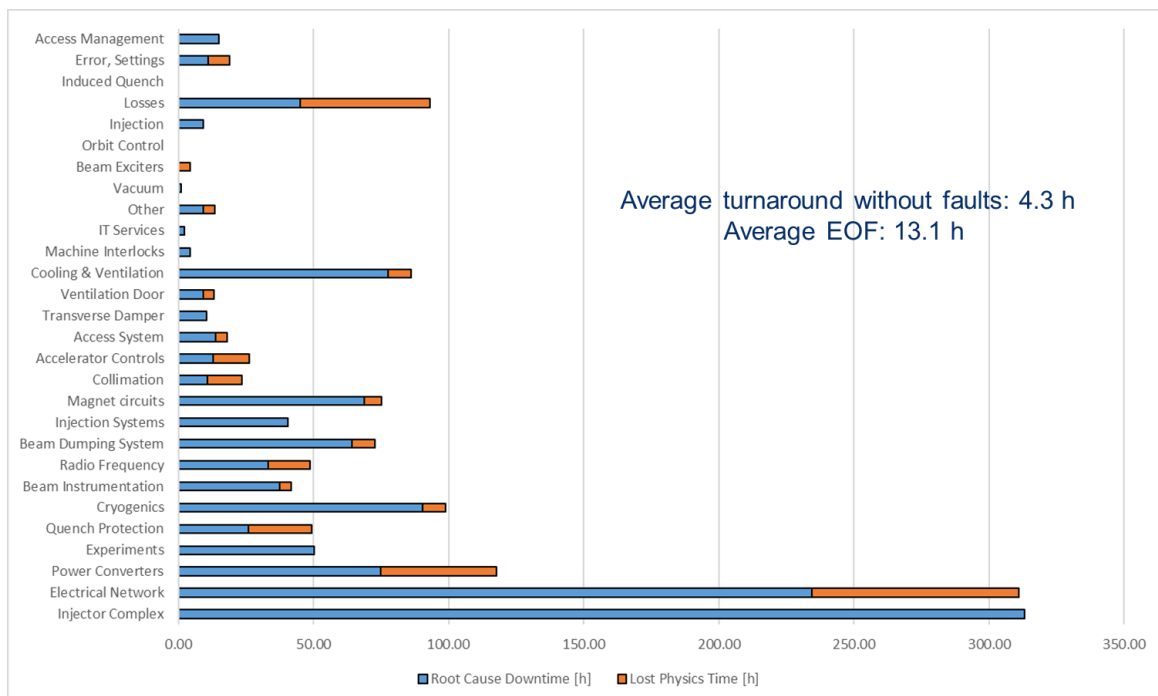


Figure 21: LHC lost physics in 2016.

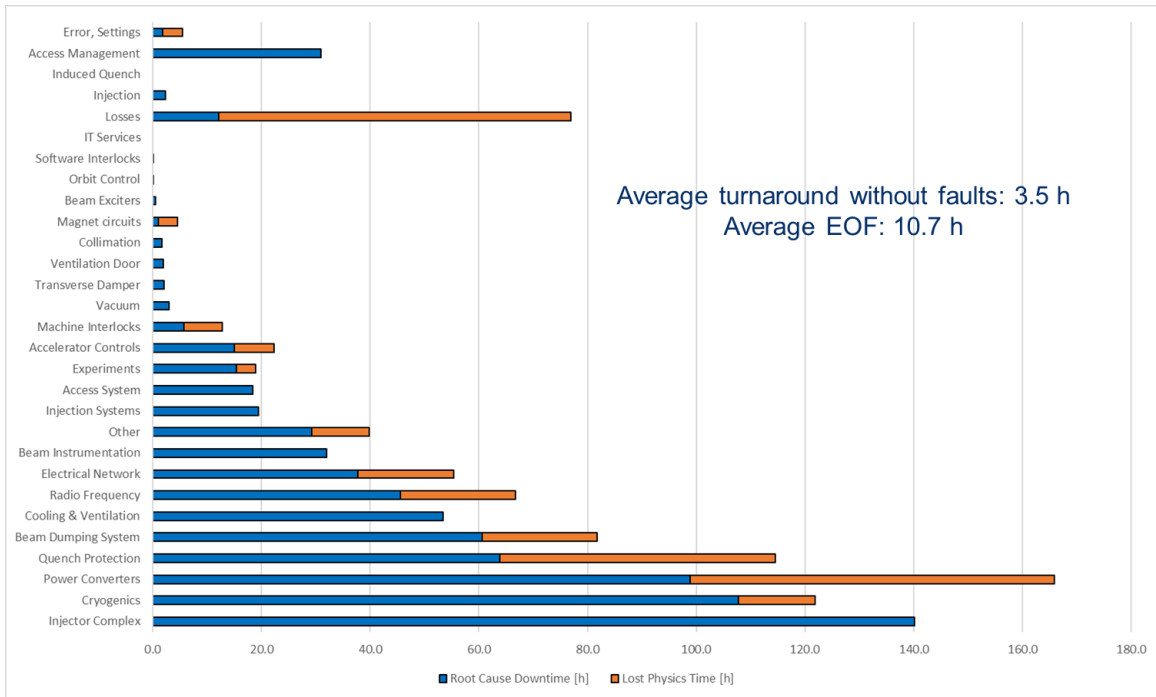


Figure 22: LHC lost physics in 2017.

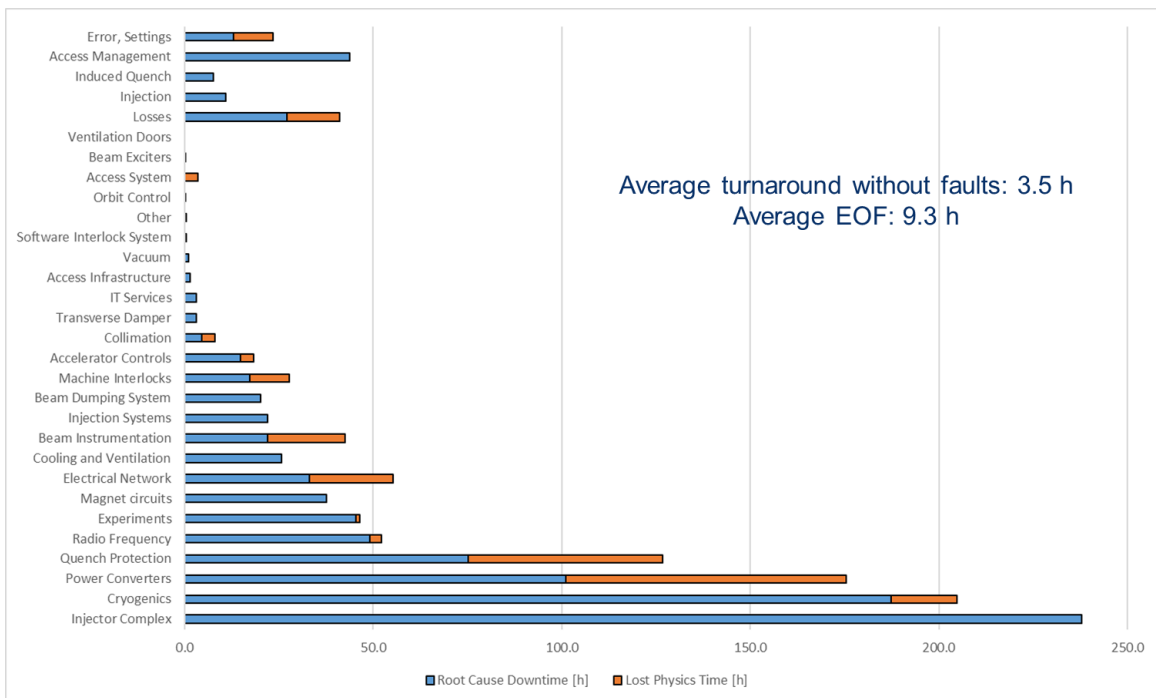


Figure 23: LHC lost physics in 2018.

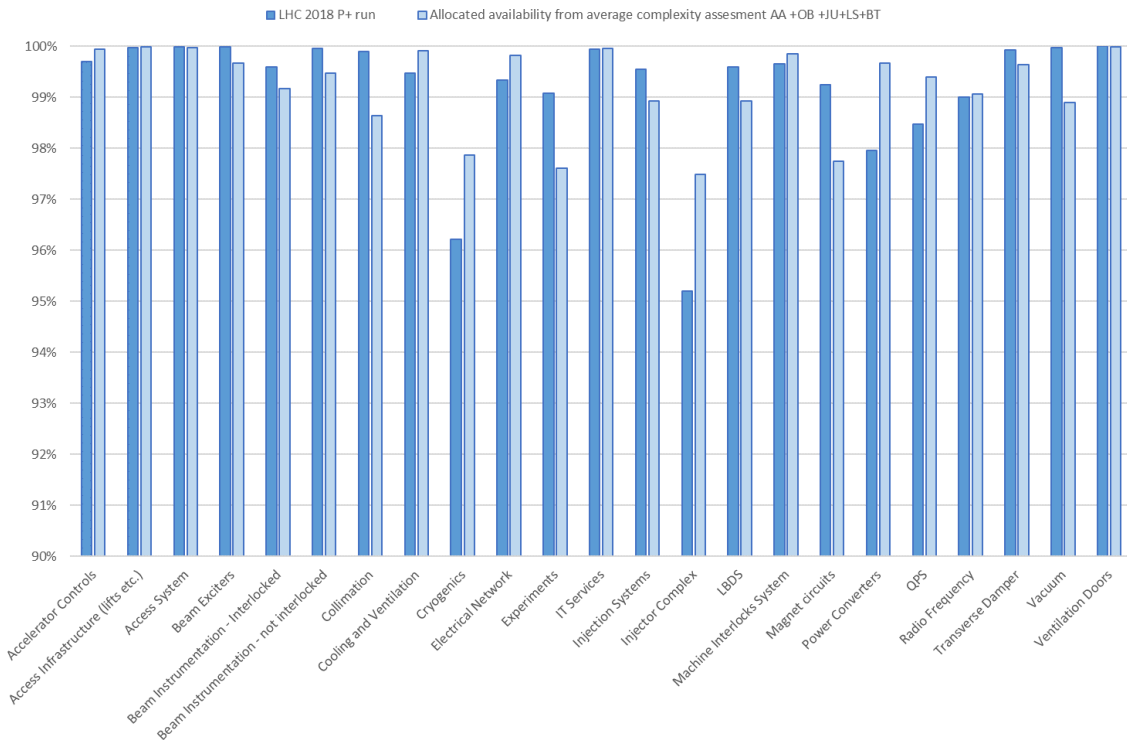


Figure 24: A comparison between observed LHC systems availability (dark blue) and the complexity-based estimate of systems availability (light blue).

### Complexity Scaling

Downtime distributions presented in this paper reflect top-level categories displayed in the AFT. These categories were established and consolidated over the years in collaboration with system experts by the members of the Availability Working Group, trying to provide a representative functional decomposition of the LHC. Each of the categories is actively reviewed by one or more system experts, so the adopted decomposition also serves the purpose of defining independent review units. As a result, the abstraction level reached by each of the categories is not necessarily uniform, i.e. systems belonging to different categories often have a different complexity. In this paper we evaluate for the first time the possibility of defining a metric for system complexity with the scope of providing a more objective interpretation of fault data for evaluating system performances. Given the impossibility of providing a quantitative definition of complexity in the context of particle accelerator (how to compare magnets, electronic systems, passive absorbers,...?), the proposed approach is based on a qualitative assessment and is inspired by well-established industrial methods. The assessment is based on the estimate on a scale from 1 to 10 of the following parameters (rated by members of the MARP):

- Recovery time: systems with intrinsically longer recovery times should be allowed to be less available (e.g. cryogenics)
- Criticality: systems which are necessary for LHC operation (e.g. machine protection systems) will certainly

prevent operation if failed, with direct impact on availability. In other cases (e.g. injection systems, beam instrumentation), faults are only relevant during particular modes or states of the LHC, so in some cases their failures can be resolved before affecting availability.

- Intricacy: a system which is per se very complex (i.e. large and distributed) is expected to fail more.
- State of the art: a system based on innovative technologies (as opposed to well-established ones) is expected to fail more.
- Environment: Systems exposed to harsh environmental conditions (mainly radiation) are expected to fail more.
- Ageing: Older systems (possibly inherited from previous accelerators or projects) are expected to fail more.
- Designed for reliability: Systems that underwent a thorough reliability-driven design (e.g. interlocks, LBDS) are expected to fail less.

Given the observed LHC availability in the different years, individual system availabilities can be allocated to the different systems based on the rated complexity, with the constraint the total allocated availability should be the same as the observed LHC availability. An example of such procedure can be seen in Fig. 24 for 2018.

A comparison of the allocated availability according to complexity and the observed system availability allows identifying systems that performed better or worse than expectations (Fig. 25) over the years. Furthermore, trends in the system availability can be identified, highlighting the dependence on the operating conditions of the machine. Most

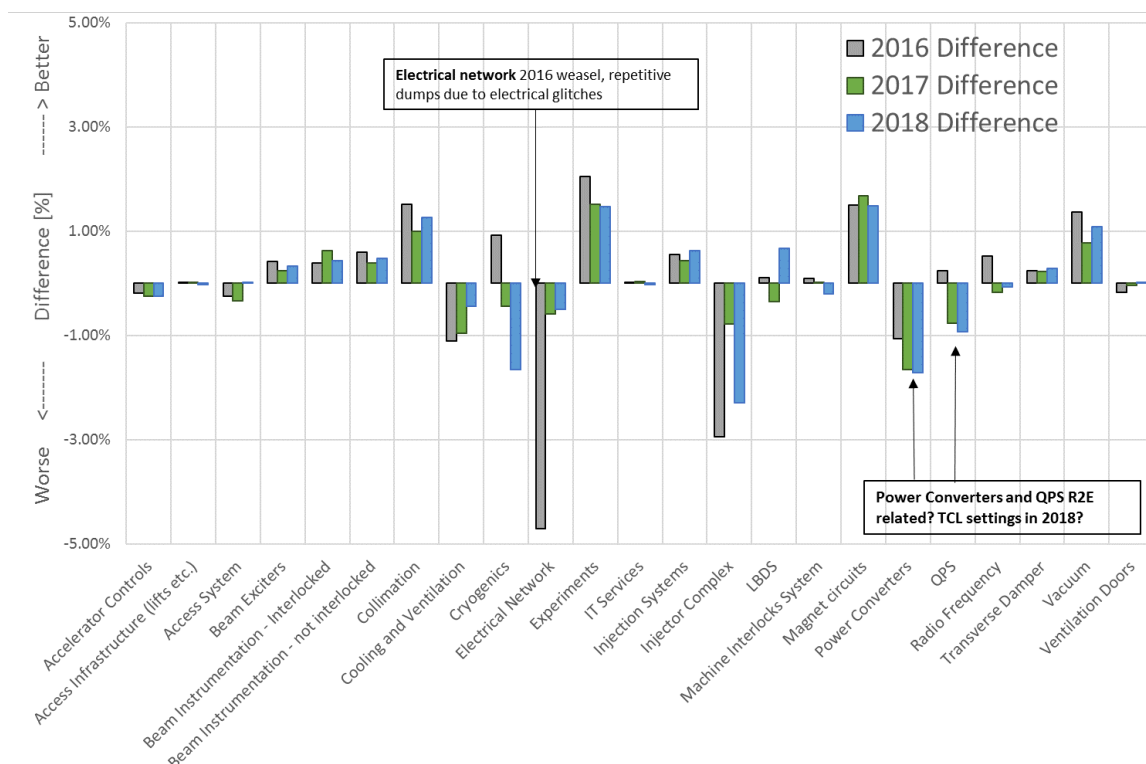


Figure 25: LHC systems performance evaluated over the years 2016-2017-2018 according to the defined complexity criteria.

systems appear to be in line with expectations (or even performing better), with an agreement of better than 0.5% with the allocated availability. Some exceptions can be observed. The electrical network was severely impacted in 2016 by long faults (e.g. weasel), while its performance was close to the target in 2017 and 2018. The cryogenic system performed exceptionally well in 2016, but then its performance degraded in 2017 and 2018. A similar pattern can be observed for power converters and QPS, whose performance also got worse over the years. This can be related to the increased number of radiation induced failures for these systems.

## CONCLUSION

2018 represented the culmination of three years of physics production at the LHC. Several new records were established, including a weekly production of  $5.3\text{fb}^{-1}$ , and new minimums in turnaround.

At the same time, several records from 2017 remain unbroken, including the highest weekly availability of 82.9%.

## ACKNOWLEDGEMENTS

This work is the result of significant effort from everyone involved in accelerator fault tracking, the authors would like to express their gratitude to all involved, in their continuing work on fault tracking and availability improvements.

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