2016 AVAILABILITY SUMMARY

A. Apollonio, L. Ponce, C. Roderick, R. Schmidt, B. Todd, M. Zerlauth, CERN, Geneva, Switzerland.

Abstract

The LHC exhibited unprecedented availability during the 2016 proton run, producing more than 40 fb^{-1} of integrated luminosity, significantly above the original target of 25 fb^{-1}. This was achieved while running steadily with a peak luminosity above the design target of $1*10^{34}$ cm^{-2}s^{-1}. Individual system performance and an increased experience with the machine were fundamental to achieve these goals, following the consolidations and improvements deployed during the Long Shutdown 1 and the Year End Technical Stop in 2015 (YETS 15-16). In this presentation, the 2016 LHC availability statistics for the proton run are presented and discussed, with a focus on the main contributors to downtime.

INTRODUCTION

The Accelerator Fault Tracker (AFT) was released at the beginning of the 2015 LHC Run, allowing systematic and consistent LHC fault tracking in 2015 and 2016. The fault review procedure was further streamlined in 2016 to allow for a direct interface of system experts with the AFT. As a result, system experts actively participated in the fault review throughout the year, validating entries created by the LHC operations team and the core members of the availability working group. Before each of the three technical stops, the data collected was validated in a meeting of the Availability Working Group and the results published in dedicated technical notes [1][2][3][4]. Results presented in this paper summarize the results of these analyses for the proton run.

Table 1: 2016 LHC exploitation [days].

	Restart - TS1 [d]	**TS1 – TS2 [d]**	**TS2 – TS3 [d]**	**Total [d]**
Beam Commissioning	29	1.5	2.5	33
Ion Cycle Setup	0	0	2	2
Special Physics Commissioning	0	3	0	3
Scrubbing	2	0	0	2
MDs	0	11	9	20
Special Physics	3	0	4	7
Physics	40	79	27	146

OVERVIEW: 2016 AVAILABILITY

The 2016 proton run began on the 25th March and ended on the 31st October. Table 1 shows the breakdown of the time allocated for different machine activities during this period. Out of the 213 days, 146 were devoted to integrated luminosity production, plus 7 dedicated to the 'special physics' run with 2.5 km β*. Beam commissioning and scrubbing took 33 and two days respectively. Machine Developments (MDs) were carried out in five blocks, for a total of 20 days. Twenty-five hours were dedicated to ion cycle commissioning, over two days.

In the reference period, 779 faults were registered and analysed in the fault tracker, with 65 relevant parent/child relationships. In such cases, the occurrence of a primary failure/event (parent) affects the performance of a number of secondary systems (children). It is important to account for these dependencies to correctly prioritize consolidation actions and identify the most effective failure mitigation strategies.

Two new fault/downtime categories were introduced in 2016: 'ventilation doors' and 'access management'.

Fig.s 1-2-3 show the evolution of the LHC performance in the three reference periods introduced in Table 1.

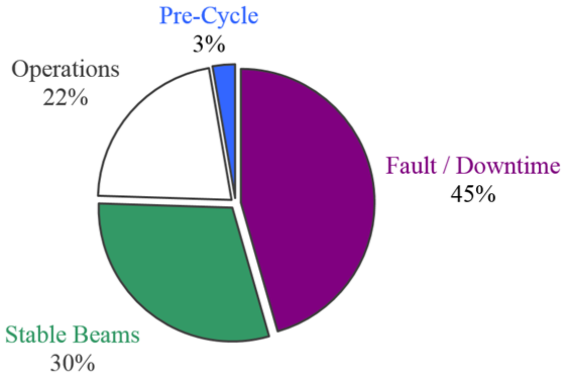

Figure 1: LHC Mode breakdown during the 2016 proton run (Restart-TS1).

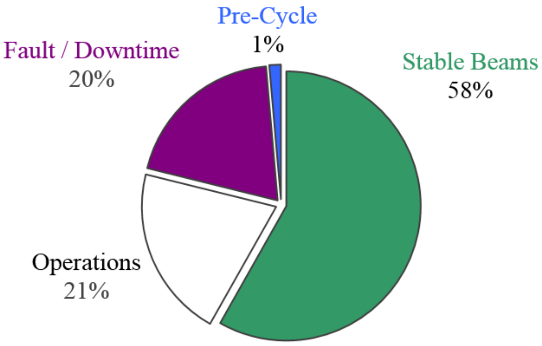

Figure 2: LHC Mode breakdown during the 2016 proton run (TS1-TS2).

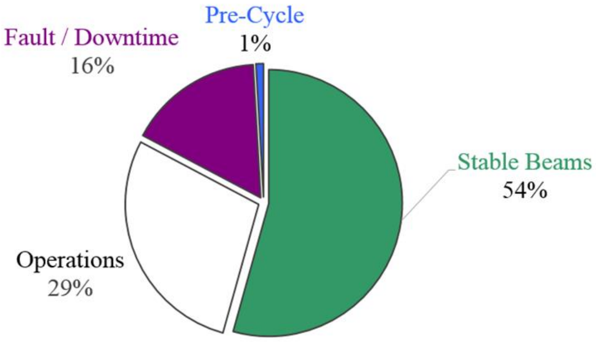

Figure 3: LHC Mode breakdown during the 2016 proton run (TS2-TS3).

'Operations' includes the nominal cycle, measurements, injection tuning and planned accesses for machine interventions.

In the period between the restart of operation with beam to the first Technical stop (TS1), the LHC experienced 45 % fault / downtime – two long periods of unavailability within this were due to the failure of a 66 kV transformer in Point 8 (about 6 days) and the mains power supply of the PS (about 5 days). The availability increased significantly in the period from TS1 to TS2, reaching the record of physics efficiency for the LHC (58 % of time in stable beams). This was achieved despite another long stop (about 3 days) due to a flood in Point 3, which affected in particular the control systems of the collimators. In the last period of the proton run from Technical Stop 2 to 3, the performance was still excellent (achieving 54 % physics efficiency).

Combining these figures for the whole proton run yields the results shown in Fig. 4 (49 % average physics efficiency over the year), for a total of more than 1800 h in stable beams. For comparison, the 25 ns proton run in 2015 yielded 33 % physics efficiency, which implies a gain in 2016 of more than 15 %. Also of note was the fraction of time dedicated to pre-cycles; this was reduced by 50 %, thanks to the reduced number of failures requiring pre-cycles and to the shorter pre-cycle duration [5].

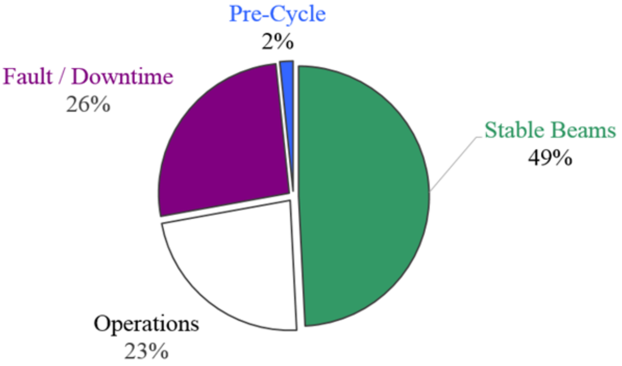

Figure 4: LHC Mode breakdown during the 2016 proton run (all).

Fig. 5 shows the evolution of the availability by week and relates it to the physics production. 'Incomplete weeks' indicate that the corresponding week was not entirely devoted to luminosity production (e.g. for technical stops or MDs). Several weeks exhibited more than 90 % availability with more than 3 fb^{-1} produced. Weeks 17 and 21 are characterised by a low availability (about 30 %) and correspond to the occurrence of the aforementioned 66 kV transformer failure in Point 8 and the failure of the PS main power supply, respectively.

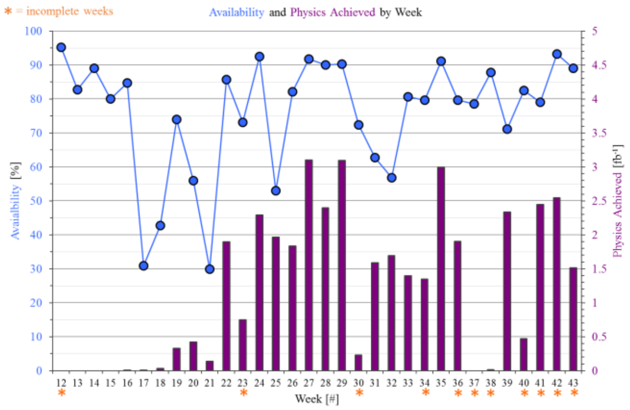

Figure 5: Availability (blue) and luminosity production (purple) by week in 2016.

The increased machine availability in 2016 is related also to the significant reduction of the number of premature dumps with respect to previous runs. Fig. 6 shows the ratio of fills reaching stable beams which are prematurely dumped due to failures or intentionally by LHC operators. In total, 53 % of the fills were dumped due to failures (5 % due to radiation effects) and 47 % by operators. In 2015 about 70 % of the fills were dumped by failures, highlighting an improvement also in this respect of 15-20 %. Many factors contribute to this achievement, the main ones being:

- The optimization of BLM thresholds in the LHC arcs, which allowed limiting the number of unnecessary dumps due to UFOs
- The low number of radiation-induced failures, thanks to lower radiation levels in the arcs than expected and the mitigation measures deployed in LS1 and the YETS 15-16

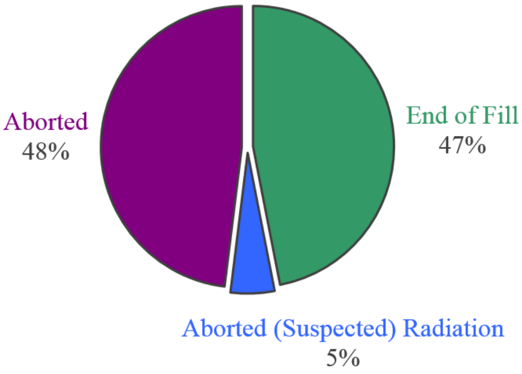

Figure 6: Physics beam aborts in 2016: due to failures (purple), due to radiation effects (blue) or triggered intentionally operators (green).

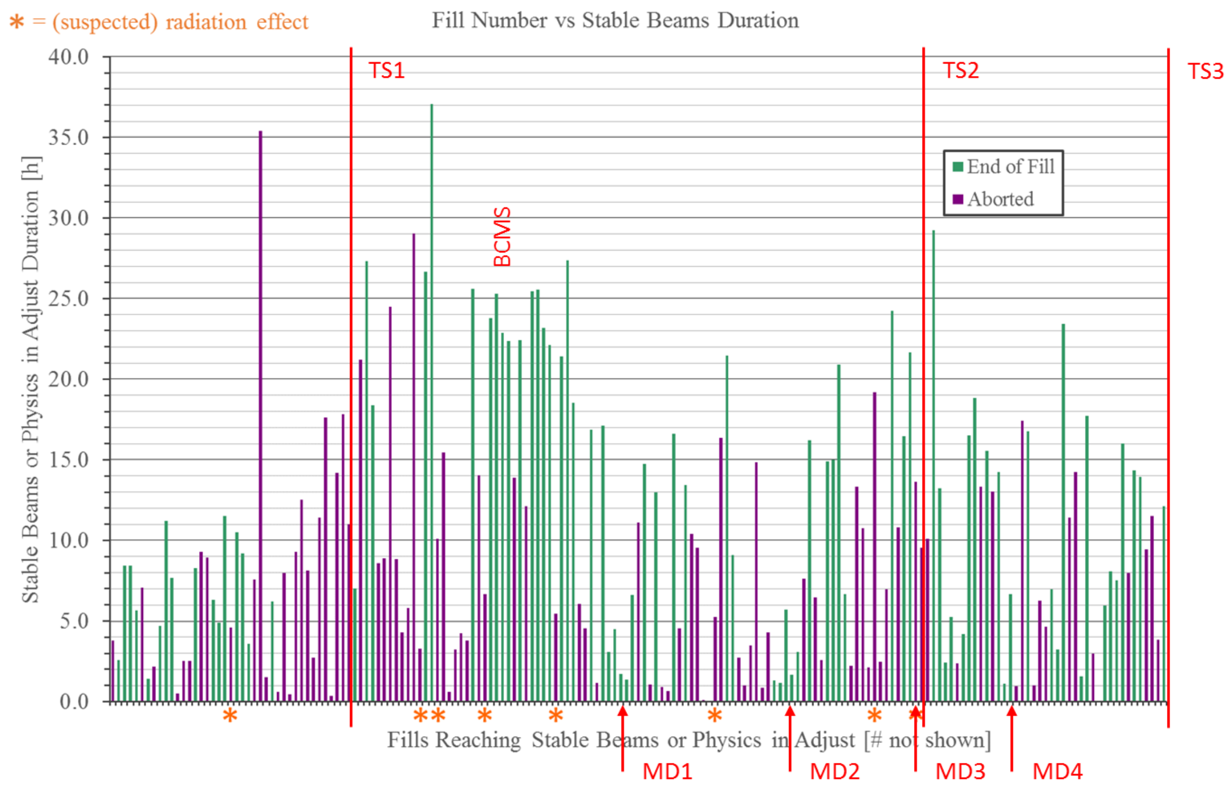

Figure 7: Duration of fills to stable beams in 2016 (green: dumped by operators, purple: dumped due to failures).

ANALYSIS OF FILLS TO STABLE BEAMS

A detailed analysis of the 179 fills that reached stable beams was carried out (4 during the special physics run, where collisions were performed in ‘adjust’). In the period up to TS1 the intensity ramp-up was carried out, requiring relatively short fills to stable beams (20 h integrated time for each intensity step). In this period a record fill was kept in the machine for 35 h. In the period from TS1 to TS2, the best period in terms of physics efficiency (58 %), many fills lasted up to 24 h. After the introduction of BCMS beams, which imply a higher peak luminosity and a shorter luminosity lifetime, the optimal fill length was set to 15 h. In the last part of the year, the physics efficiency was reduced to 54 %. This is the result of the shorter optimal fill length, which requires performing more cycles for the same total time in stable beams. Furthermore, in this period additional time was dedicated to measurements and tests even outside MDs (e.g. end-of-fill studies). Table 2 summarizes the average fill durations in the three reference periods.

Table 2: Average stable beams duration in 2016.

	Restart - TS1	**TS1 – TS2**	**TS2 – TS3**
Aborted	8.0 h	7.7 h	7.8 h
End of Fill	6.9 h	16.2 h	11.5 h

The average duration of fills dumped due to failures was remarkably stable during the year, indicating a very reproducible operation and a well-established machine reliability. Short fills (few hours) dumped by operators are either relative to the intensity ramp-up (e.g. following TSs or MDs) or were triggered to anticipate the loss of cryogenic conditions.

DOWNTIME ANALYSIS

A total of 779 faults were registered in the AFT for the proton run, with 77 pre-cycles due to faults. Table 3 shows the statistics related to faults in terms of occurrence and downtime. Three different classes of downtime are presented:

1. ‘Fault duration’: integrated downtime logged for the faults
2. ‘Machine downtime’: real impact on machine operation, accounting for possible parallelism of faults
3. ‘Root cause duration’: real impact on machine operation, accounting for possible parallelism of faults and parent/child relationships

Fig.s 8-9-10 visually show the contributions of the different systems to LHC downtime. Fig. 10 is used as a basis for the assessment of the top contributors to the unavailability in 2016.

Table 3: 2016 LHC downtime.

Root Cause Class	Root Cause System	Faults [#]	Fault Duration [h]	Machine Downtime Duration [h]	Root Cause Duration [h]
Equipment	Injector Complex	138	360.38	317.82	313.21
	Technical Services	67	221.68	210.73	278.35
	Power Converters	66	106.62	87.84	75.05
	Experiments	52	59.86	50.27	50.27
	Quench Protection	45	36.97	31.02	25.93
	Cryogenics	42	361.08	133.15	90.32
	Beam Instrumentation	40	47.08	37.91	37.56
	Radio Frequency	40	40.20	33.68	33.37
	Beam Dumping System	30	70.20	64.78	64.15
	Injection Systems	30	46.27	42.19	40.70
	Magnet circuits	27	74.50	73.36	68.75
	Collimation	23	73.42	61.73	10.72
	Accelerator Controls	19	9.63	9.61	12.77
	Access System	12	24.50	9.99	13.88
	Transverse Damper	10	13.84	10.60	10.60
	Ventilation Door	10	21.12	9.30	9.16
	Machine Interlocks	8	5.96	4.39	4.39
	IT Services	2	2.52	1.51	2.40
	Other	2	0.13	0.13	9.15
	Vacuum	2	1.37	1.20	1.20
	Beam Exciters	1	0.04	0.04	0.04
	Orbit Control	0	0.00	0.00	0.00
Beam	Injection	29	9.18	9.12	9.12
	Losses	27	0.75	0.72	45.21
	Induced Quench	5	0.34	0.00	0.00
Operations	Error, Settings	44	11.36	11.31	11.05
	Access Management	8	21.48	19.00	15.11
	Σ	**779**	**1620.5**	**1231.4**	**1232.4**

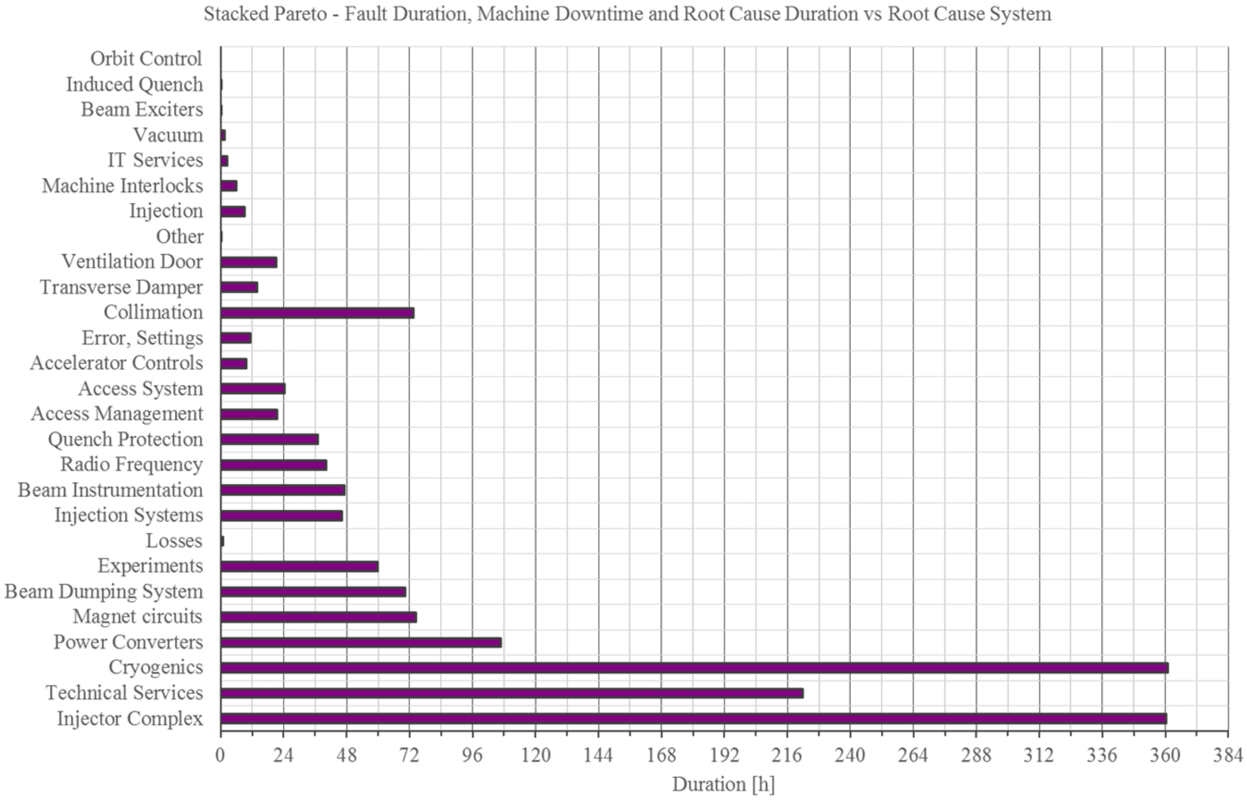

Figure 8: 2016 LHC fault duration

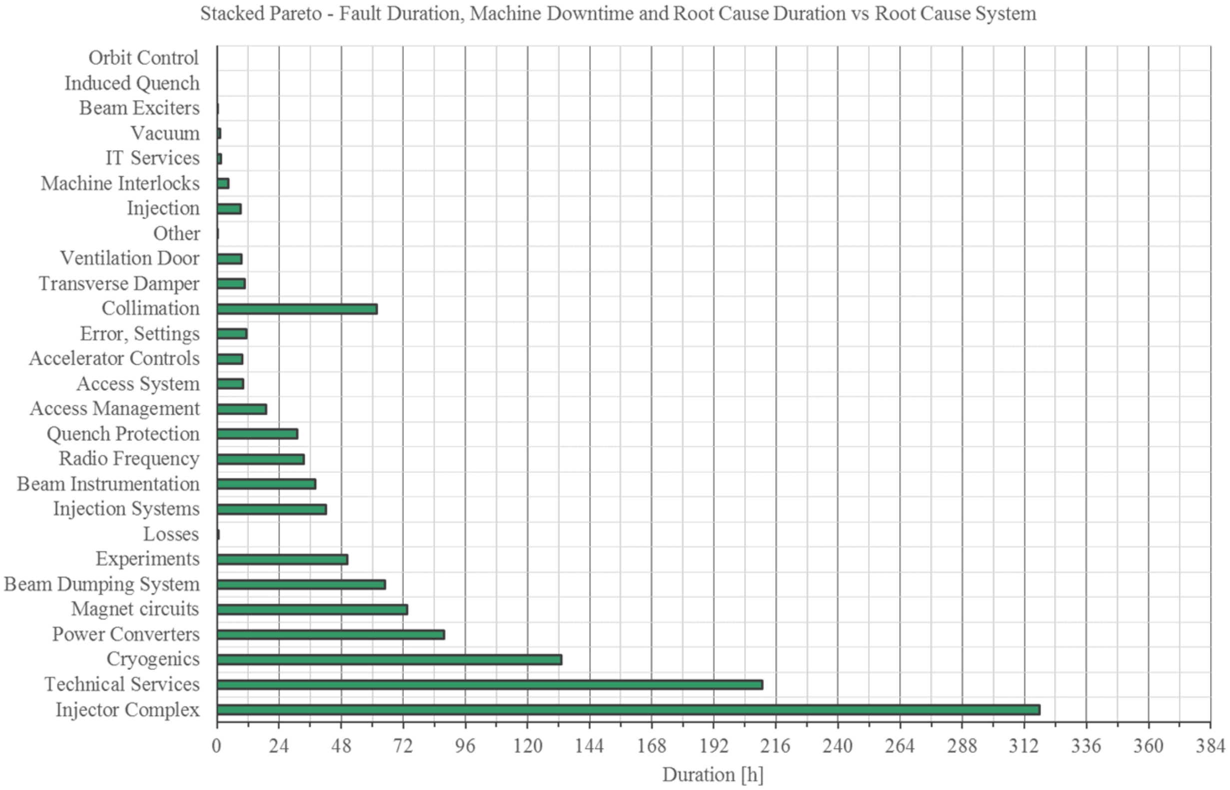

Figure 9: 2016 LHC machine downtime.

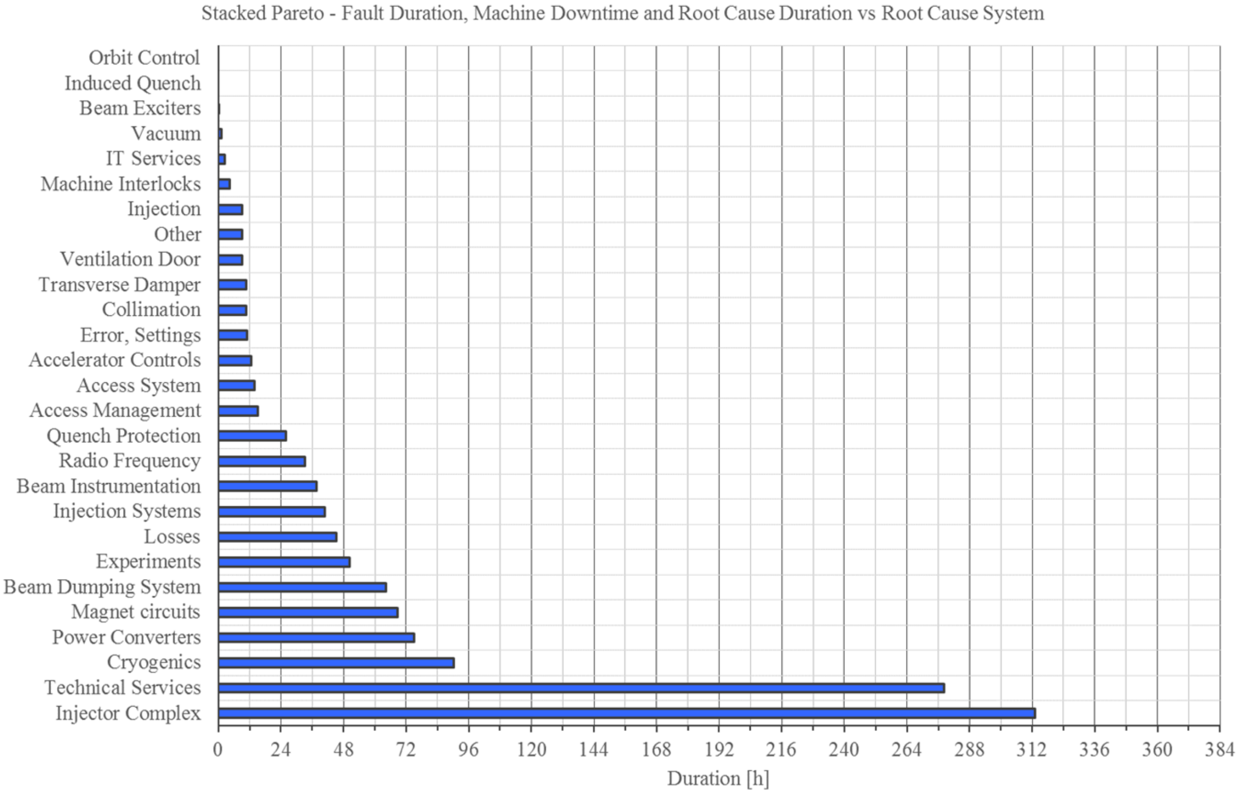

Figure 10: 2016 LHC root cause duration.

The top contributors to downtime are the injector complex and technical services, both having caused over ten days of downtime. The downtime is in both cases dominated by isolated, high-impact faults. The technical services suffered from the occurrence of the 66 kV transformer failure in Point 8 and the flood in Point 3, with a combined downtime of about ten days. In addition, 22 premature dumps were triggered by perturbations in the electrical network (see [6], [7]). The downtime of the injector complex was dominated in 2016 by the PS, which experienced several problems including main power supply issues and a vacuum leak [8].

The cryogenic system is still among the top contributors to downtime, but has significantly improved its availability in 2016 [9]. This is due to the optimization of the cryogenic configuration (only four cold-compressor units supply the eight arcs) which led to a reduced failure rate and the implementation of the feed-forward system for the dynamic of compensation of transient heat-loads on the beam screen. Also, the issues observed for DFB level adjustments in 2015 were solved. These factors resulted in major reduction of the losses of cryo-maintain and therefore reduced the number of premature beam dumps.

The QPS operated very reliably throughout the year, with an average availability above 99 % [10]. This is a result of the efforts invested in the improvements of the system over the past years. In particular, mitigations deployed in the YETS 15-16 on 600 A quench detection systems have proven to be very effective against radiation induced failures.

A few more events are of note; for magnet circuits, a long stop (about 40 h) was required for the investigation of the suspected inter-turn short in RB.A12. Concerning the Beam Dumping System [11], two MKB erratics occurred in 2016, leading to synchronous beam dumps. These required the replacement of two generators and a system revalidation (10 + 5 h for each of the two events). In addition, one more generator was preventively replaced (10 h).

CONCLUSIONS

The LHC exhibited unprecedented availability in 2016, which resulted in the production of 40 fb^{-1} of integrated luminosity, well beyond the target set at the beginning of the year. Several factors contributed to this success, certainly the profound understanding of the machine and the improved system reliability. In this respect, all mitigation measures deployed in LS1 and the YETS 15-16 have proven to be very effective in operation. Furthermore, the changes of critical settings/configurations (BLM thresholds, cryogenic feed-forward, etc.) were a key factor for the improved performance.

In 2017 the machine should profit from the lessons learned in 2016 and from the continued machine conditioning. Similar equipment availability should be observed in 2017, as that which was experienced in 2017. Nevertheless, it is important to consistently monitor the performance of the different systems to identify recurring effects and the first signs of component ageing and end of life. Changes in accelerator operating conditions could impact on the availability; for example, time might be required to optimize the injection of trains of 288 bunches. In addition, the possible deconditioning of sector 1-2 following the dipole magnet replacement will have to be assessed in terms of e-cloud and UFO rate.

ACKNOWLEDGMENTS

The author would like to acknowledge the work of the AWG-core team for the preparation of the material for this paper. The author would also like to thank the AWG members, the AFT team and the co-authors for the precious discussions and valuable inputs.

REFERENCES

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

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

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

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

[5] “Turnaround and pre-cycles: analysis and improvements”. K. Fuchsberger, 7th Evian Workshop, 2016.

[6] “Technical services: unavailability by machine, root causes, strategy and limitations”, J. Nielsen, 7th Evian Workshop, 2016.

[7] “Recurring sources of premature dumps”, M. Zerlauth, 7th Evian Workshop, 2016.

[8] “Injectors: unavailability by machine, root causes, strategy and limitations”, B. Mikulec, 7th Evian Workshop, 2016.

[9] “Cryogenics: unavailability by machine, root causes, strategy and limitations”, K. Brodzinski, 7th Evian Workshop, 2016.

[10] “QPS”, J. Steckert, 7th Evian Workshop, 2016.

[11] “LBDS”, E. Carlier, 7th Evian Workshop, 2016.