AVAILABILITY 2017: INJECTORS

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Abstract

For the first year the Accelerator Fault Tracker (AFT) was implemented and employed by the Large Hadron Collider (LHC) injectors. In this paper, the LHC downtime due to the injector chain will be analysed with data from AFT and compared to last year [1]. The main root faults from the injectors will be explained. In addition, future AFT improvements and potential new applications will be outlined.

INTRODUCTION

One outcome of the last LHC Performance Workshop [2] was the recommendation to introduce the Accelerator Fault Tracker (AFT) tool developed within the Controls Group at CERN originally for the LHC also to the LHC injectors (and in general to CERN accelerators). Work started immediately to evaluate the differing needs with respect to the LHC that lie mainly in the fact that the injectors deliver beam constantly to many different destinations, of which the LHC is only one. Moreover, specificities like the four rings of the Proton Synchrotron Booster or the notion of 'degraded' operation had to be treated as well. Fault category names for the injectors were harmonised with the LHC convention.

Despite the complexity of the task, the first AFT version for the LHC injectors was available in time for the 2017 beam start-up, which included not all features yet, but allowed correct data capture. Throughout the year, the tool was steadily developed further, in parallel with the required changes to the machine elogbooks, where the machine faults are entered. To assure as far as possible correctness of the entered faults, their details and dependencies between machines, machine supervisors of the injectors met weekly to discuss the list of faults with members from the Availability Working Group (AWG); this was also very beneficial to get everybody acquainted with the new tool, to report bugs and submit additional requests for improvements. The end result is that the 2017 analysis of the injector faults/availability presented here is fully based on AFT.

2017 INJECTOR DOWNTIME FOR LHC OPERATION

As has been shown [3], the availability of the LHC has greatly improved in 2017 compared to the 2016 run. This is also the case for the reduction of the total blocking root cause fault duration for the LHC originating from the LHC injectors, which has decreased from 295.1 h and 131 faults in 2016 [3] to **140.2 h** and **96 faults** in 2017 (see Fig. 1). Normalised to the LHC proton run periods taken into account for the analysis (2016: 25/03 9:00 – 31/10 06:00 and for 2017: 28/04 18:00 – 10/11 15:00) this means an **improvement by a factor 1.88**.

The 140.2 h of LHC downtime due to the injectors correspond to **17.5% of the total LHC downtime**, of which 15.9 h (11.3%) and 30 faults were because the LHC had to wait due to 'Beam in Setup' in the injectors, whereas the remaining 124.3 h and 66 faults were due to equipment faults and therefore 'No Beam' from the injectors.

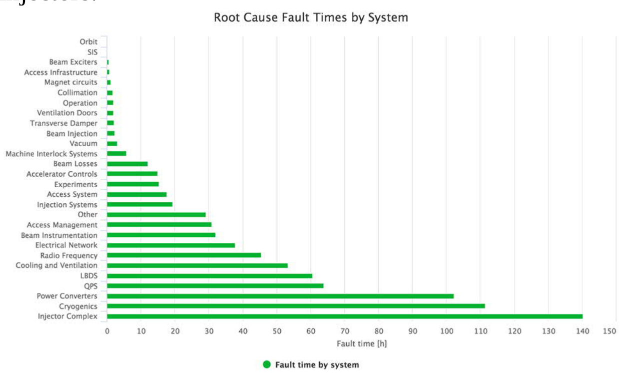

Figure 1: LHC root cause fault times [h] by system for the 2017 LHC proton run (only blocking faults).

Table 1 shows the 2017 LHC injector faults split up into the four injectors Linac2, Proton Synchrotron Booster (PSB), Proton Synchrotron (PS) and Super Proton Synchrotron (SPS). It has to be pointed out that for the LHC injectors these numbers are not representative for the availability of each individual machine, as injector faults that happen once the LHC is filled are usually not registered by LHC operators, as they are not affecting LHC operation.

Table 1: LHC root cause fault times/percentages of Linac2, PSB, PS and SPS for the LHC 2017 proton run.

	Linac2	**PSB**	**PS**	**SPS**
Root cause fault duration	17.27 h	12.78 h	23.28 h	86.86 h
Percentage of LHC injector complex faults	12.3%	9.1%	16.6%	62.0%

Linac2 Faults for the LHC Run

For Linac2 7 faults were registered during the 2017 proton run that prevented beam injection into the LHC, all of them due to radio-frequency (RF) problems. The longest fault for the LHC of 9h 24m occurred on the 20th of August, followed by 3 consecutive faults of ~5h 13m total downtime on the 26th/27th of July. These faults concerned the debuncher cavity in the Linac2 transfer line as well as the tank 2 Frank James amplifier; the recovery time can be explained through complex debugging and consecutively appearing faults.

PSB Faults for the LHC Run

The LHC noted 13 faults for the PSB, of which the longest fault for the LHC amounted to 2h 52m total (issues with the PSB main power supply on 22nd of June), followed closely by a fault of 2h 23m duration (access to replace the amplifier tube of the ring 3 C16 cavity on 26th of June).

PS Faults for the LHC Run

The PS had a total count of 27 faults for LHC proton operation. The longest fault on 9th of June of 5h was due to an amplifier repair of the 40 MHz cavity, followed by 2h 36m downtime when an 80 MHz cavity had to be swapped with its spare in the night of 9th of August, and an access for septum 16 on 26th of June leading to 2h 25m waiting time for the LHC.

SPS Faults for the LHC Run

This year, the longest single injector fault noted for LHC proton operation was due to an electrical fault in the SPS on the 18 kV network that started on 12th of June and affected LHC operation during 22h 46m. A second long-lasting fault occurred on the 22nd of July, where the main bending magnets and the main focusing quadrupoles suffered from ripples and current glitches and prevented LHC beam injection during 21h 47m. The last downtime exceeding 5h for LHC operation concerned issues with the dump kicker and spurious beam dumps (5h 19m on 3rd of August; after investigations, the exchange of a controls card solved the problem). Only 10 more faults from the total registered number of 49 faults were then blocking for longer than 1h.

2017 INJECTOR AVAILABILITY

As pointed out before, it is impossible to see trends or draw conclusions on the injector availability from the injector downtime numbers registered by the LHC, as the average LHC fill duration is of the order of 10 h [3], during which injector faults are not relevant. This is the reason why the availability and faults per LHC injector during the entire 2017 LHC proton running period is as well shortly analysed in this paper.

Linac2 Faults during the 2017 LHC Proton Run

During the entire LHC proton run period Linac2 had an excellent **availability of 99.1%**. The fault distribution (see Fig. 2) shows that the largest fraction of downtime is due to radio-frequency problems (32.25h in total).

From the total number of 44 faults the three longest-lasting faults were:

1. Issue with the debuncher cavity (9h 52m): Several faults/repairs and double tube replacement (first tube broken)
2. Buncher1 issue (4h 40m): replacement of directional coupler and amplifier output coupler
3. RFQ (3h 44m): Double replacement of auxiliary power supply (first one not working).

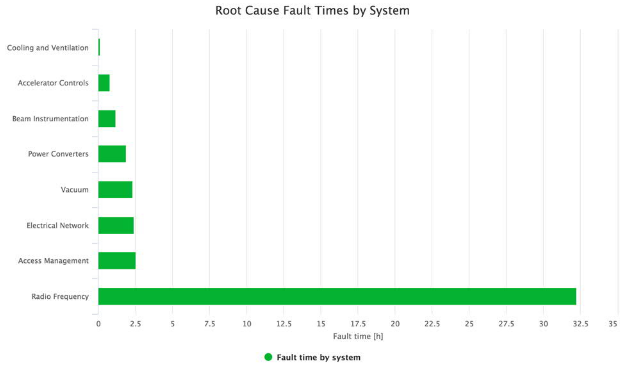

Figure 2: Root cause fault times [h] by system for Linac2 during the 2017 LHC proton run.

An observation that can be made is that there was not a single fault during 2017 related to the Linac2 source, contrary to 2016 where the source was the number 1 fault category [1]. This indicates that the preventive maintenance program during the EYETS2016/17 (Extended Year-End Technical Stop) and during technical stops was effective.

There were no recurrent faults during 2017. It should nevertheless be mentioned that the Linac2 vacuum situation remains worrisome for the last year of Linac2 operation to come before replacement by Linac4 (there were for example issues with corrosion on the intersection of tank 1 before the start of the LHC run).

PSB Faults during the 2017 LHC Proton Run

The PSB had also an excellent year with an overall availability of 96.9%, exceeding once more the value for the previous year. The total number of registered faults was 251, distributed as shown in Fig. 3.

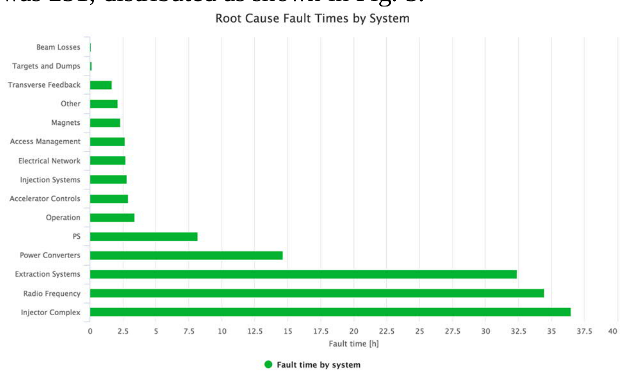

Figure 3: Root cause fault times [h] by system for the PSB during the 2017 LHC proton run.

25.5% of the faults were due to Linac2 unavailability, followed by radio-frequency issues (24.1%) and problems with the beam extraction systems (22.6%). When excluding the Linac2 faults and downtime due to PS accesses in the Switchyard, the PSB availability was **97.9%** during the period of the LHC proton run.

The three top faults were:

1. Burnt strip line of recombination septum BT1.SMV10 (total of 16h 10m): Difficult

repair due to space restrictions in area of high radiation (long radiation cool-down)

2. Repair of ring 3 C16 cavity (6h 27m): Several subsequent issues inside and outside tunnel
3. Ring 3 C02 cavity (3h 28m): Replacement of final blower.

During 2016 the extraction system was the most important fault category for the PSB [1]; excluding the longest downtime due to BT1.SMV10 this year a clear improvement can be noted thanks to the exchange of most electro-valves with a more robust type. Concerning the mentioned septum strip line fault all strip lines including the ones that are very difficult to access will be thoroughly inspected during the YETS2017/18.

No recurrent faults were observed. The importance of sufficient maintenance time in particular for the RF systems could be pointed out; it is expected that this fault category will drastically decrease after the Long Shutdown 2 (LS2), when the conventional ferrite-loaded cavities will be replaced by Finemet modules [4].

PS Faults during the 2017 LHC Proton Run

As the LHC injectors are connected in series, the further one moves downstream the chain, the more important the 'Injector Complex' fault category becomes (applies alike to the LHC). It is therefore also the top fault category for the PS (35.9%), followed by the category 'Power Converters' (31.1%) and 'Radio Frequency' (12.5%), as can be seen in Fig. 4. The total number of faults for the PS during this period was 474. Conforming to the general 2017 trend, the availability of the PS was excellent as well with 93.1% during the LHC proton run, and corrected for the injector faults it reached even **95.6%**.

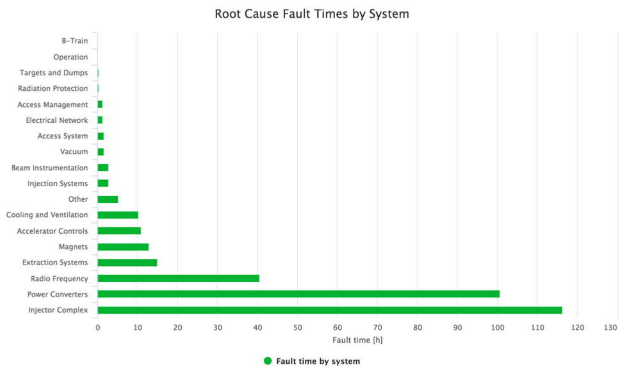

Figure 4: Root cause fault times [h] by system for the PS during the 2017 LHC proton run.

With the PS example, it is obvious that in the future statistics should be separated by beam destination; in fact, all 4 longest-lasting faults for the PS during the 2017 LHC proton run did not affect LHC operation. These faults stopped beam production for the AD machine, nToF or the East Area, but had no effect for the SPS or the LHC. These 4 faults alone amounted already to ~48h and therefore almost 50% of the total downtime attributed to 'Power Converters'. Excluding faults not relevant for LHC operation, the 3 longest-lasting faults in the PS were the following:

1. RF (5h 23m): Repair of 40 MHz amplifier (tunnel access)
2. RF (3h 40m): Replacement of a broken pulse repeater (special old electronics card version changed subsequently to a standard version)
3. Accelerator controls (3h 25m): Replacement of a broken (standard) pulse repeater for the 200 MHz cavity.

In terms of recurrent faults there have been issues with the pole face winding power supplies towards the start of the year and repeated trips of the PS main power supply (POPS) rather towards the end of the run, but both problems are by now understood and solved. Due to the high complexity of the RF system in the PS the third place of the RF category in terms of downtime can be understood; again, the need for sufficient maintenance time every year has been underlined by the specialists to retain low system downtime.

SPS Faults during the 2017 LHC Proton Run

The SPS is also no exception in the 2017 trend with a particularly good availability of 90.7% (1019 faults). The downtime distribution by system is shown in Fig. 5.

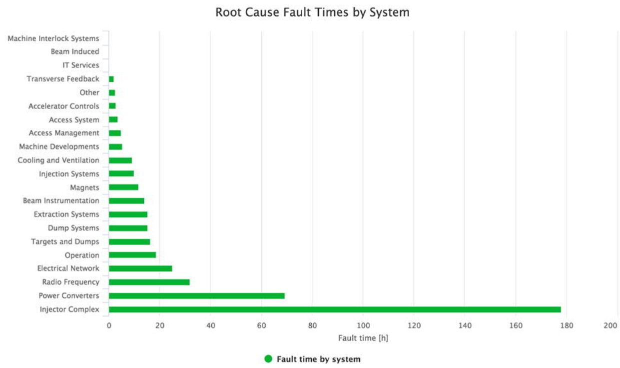

Figure 5: Root cause fault times [h] by system for the SPS during the 2017 LHC proton run.

The 'Injector Complex' category leads the root cause fault time distribution due to the reason explained before with 40.7% of the SPS downtime, followed by 'Power Converters' (15.9%) and 'Radio Frequency' (7.3%). Removing again the downtime due to the SPS injectors the SPS availability rises to **94.5%**.

Below the 3 faults with the longest SPS downtime are noted:

1. Power converters (1d 4h 30m): Glitches of the main bending and main focusing quadrupole power supplies due to Profibus communication error
2. Electrical Network (23h 05m): Fault of the 18 kV network
3. Electrical Network (14h 15m): Fault of the BEQ3 compensator.

The power converter problems have all been followed up. For RF, there were several, but not very long-lasting faults.

ACCELERATOR FAULT TRACKING IMPROVEMENTS FOR 2018

Before the start of the 2017 run AFT has been upgraded to also be useful for the LHC injectors. After a detailed evaluation of the different use-cases in particular the following points were implemented: Faults attributed to 'impacted destinations' (different for each machine) instead of timing users, fault duration per destination, 'degraded mode' in addition to 'blocking faults' or the ability to select individual PSB rings being in fault. Throughout the year the team worked on bug fixes and other improvements related for example to visualisation of statistics or individually configurable dashboards.

Now that the data capture is working nicely, the following improvements are planned for 2018:

- **Link faults between accelerators**; it will be possible to link a fault to a parent fault in another machine
    - Allows implementation of reporting of potentially missing faults from upstream machines for improved data consistency
- **More detailed availability statistics**:
    - Availability per impacted destination
    - Availability per impacted cycle or cycle family
- Propose during fault review **selection of faulty element names from layout database** → potentially useful for operations and equipment specialists for failure statistics by equipment or equipment type
- Introduce notion of '**suspended faults**'; this is essential to produce sensible availability statistics for machines with periods without support for immediate response to faults (examples: Linac4, ISOLDE).

These improvements will enable new possibilities of data analysis for operations, experiments, equipment experts or even higher-level planning for example for decisions on equipment consolidation or intervention support.

SUMMARY

During the 2017 LHC proton run the injector complex comprising the accelerators Linac2, PSB, PS and SPS accounted for 17.5% of the total LHC root cause downtime, which corresponds to an improvement of a factor of ~1.9 compared to 2016.

Availability of the individual LHC injectors has also improved with respect to last year, mainly thanks to the lack of particularly long-lasting faults.

Accelerator fault tracking has been developed and used for the first year for the injectors, a considerable progress to provide better statistics. During 2018 AFT will be further improved and will in particular allow statistics in the injectors to be based on beam destination. This will finally lead to consistent statistics for the LHC injectors and open up possibilities to use the data for new applications.

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