INJECTORS: UNAVAILABILITY BY MACHINE, ROOT CAUSES, STRATEGY AND LIMITATIONS

B. Mikulec, V. Kain.

CERN, Geneva, Switzerland

Abstract

During the 2016 LHC proton run the main contributor to LHC downtime turns out to be the LHC injector chain. In this paper the corresponding LHC downtime will be assigned to either Linac2, the Proton Synchrotron Booster (PSB), the Proton Synchrotron (PS) or the Super Proton Synchrotron (SPS). The main root causes for the injector faults will be explained and a strategy outlined for the future to increase the injector availability. Ideas how to improve the injector fault tracking will also be given.

2016 INJECTOR FAULT ANALYSIS

As presented by the LHC Availability Working Group (AWG) and based on the LHC Accelerator Fault Tracking (AFT), the injector complex accounted for >25% of the total LHC root cause duration (corrected for parent/children faults and fault parallelism) during the 2016 LHC proton run [1]; see Fig. 1.

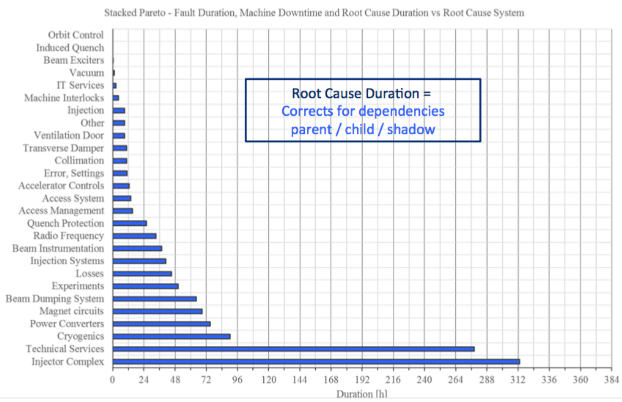

Figure 1: Root cause duration for the various LHC fault categories [1]. The injector complex is the main root cause for LHC downtime during the 2016 proton run, followed by the Technical Services and Cryogenics.

During the last years, a lot of effort has been made by the various equipment groups to minimise downtime for the LHC with visible success. The injector complex has not yet been in the focus, but this has changed this year, also due to a few long-lasting incidents. The next paragraphs will analyse the 2016 injector faults and propose a few improvements and strategies to reduce the fault duration for the next years.

It should nevertheless be mentioned that the LHC proton chain consists of four individual accelerators (Linac2, PSB, PS and SPS) that have to work in series to produce the LHC beam, while they are all serving in parallel various other physics facilities at CERN. Each of these four accelerators has their own equipment fault catalogue and should perhaps be treated as separate fault category entry for the LHC fault analysis.

For the 2016 LHC proton run, 138 faults were recorded in the LHC elogbook for the injectors; their total (uncorrected) downtime amounted to 360.38h (15d 23m), of which 9.8% happened during 'beam in set-up'. These faults were extracted with their occurrence in time from AFT, but a big fraction of the faults was not yet attributed to a specific machine of the injectors[1]. Therefore the description of each single injector complex fault had to first be checked in the LHC elogbook, then identified in one of the four injector elogbooks and the root cause of the fault understood from there to be able to obtain its final categorisation of accelerator plus fault class.

Two observations could be made in this context: Firstly the fault duration is of course different between the LHC and injector elogbooks (the LHC only notes the time of the fault when it was affected, i.e. during injection preparation and execution, but the fault in the injectors could have lasted much longer), and secondly quite often no fault was noted in the injector elogbooks (in particular for beam quality issues, seen as beam setup and not as fault and in case of the SPS also because there is no more automatic fault insertion when it runs under LHC mastership).

2016 INJECTOR DOWNTIME FOR LHC OPERATION

After manual analysis of all the 138 injector faults registered by the LHC operations team, only less than 6 minutes of downtime could not be assigned to any of the injectors (not traceable anymore). The remainder was attributed to the different accelerators and fault categories.

As a remark, these statistics do not reflect 'degraded' beam operation, where there might be limits to the total intensity in the ring or extracted, in the maximum number of bunches, in beam quality or setting up efficiency. Examples for this might be that certain RF cavities are not working, one PSB ring is out of operation, beam dump issues, kicker limitations, noise problems with certain equipment, issues with the proton source current/stability or electron cloud limitations. It might be interesting to define for the future a way to account for degraded operational modes as well.

[1] 2016 was the first year members of the injector complex were nominated to join the AWG; they started since ~mid of the year to attribute LHC Injector Complex faults to their specific machines.

Linac2 Faults for LHC Run

Linac2 had an unusually bad year in 2016, accumulating a few longer-lasting interventions around the source and radio frequency (RF) issues. Nevertheless it appears with only three faults in the LHC fault statistics, amounting to a total of **6h 20m downtime for the LHC** (see Fig. 2). The main fault concerned the replacement of the ignitron for RFQ and tank 1 (RF) of >3h duration on 29/10, followed by Linac2 source parameter tuning after intensity fluctuations and a problem with a PLC of the cooling station.

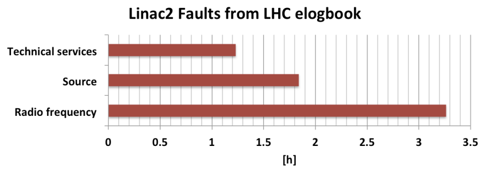

Figure 2: 2016 Linac2 faults for LHC running. Total registered downtime: 6h 20m.

This low fault duration despite a few additional serious Linac2 problems during 2016 can be explained by the fact that either the Linac2 interventions could be scheduled to happen in the period when the LHC was in 'Stable Beams' or the LHC stopped requesting the beam (and noting the faults), adapting their program and waiting for the fault to be resolved.

PSB Faults for LHC Run

The PSB accumulated **11h 45m of downtime** during the period when the LHC prepared for beam injection (see Fig. 3). The top fault category was Beam Transfer due to an issue with septa electrovalves throughout the year, which required access into the machine (plus radiation cool-down time) for repair. The longest individual PSB fault for the LHC (>4h) was due to a problem with a controller of a power supply in the PSB recombination line.

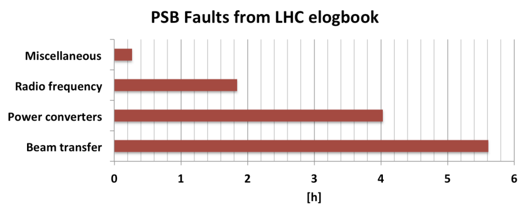

Figure 3: 2016 PSB faults for LHC running. Total registered downtime: 11h 45m.

PS Faults for LHC Run

The total fault duration noted by the LHC operations team during the 2016 proton run that was attributed later to the PS was **9d 10h 34m** (see Fig. 4). The PS suffered during the 2016 run from faults related to their main power supply ('new' POPS and 'old' MPS). This is reflected in the downtime of 6d 10h 17m under the category 'Power Converters' with POPS faults (short circuit of DC1 capacitor bank in April and replacement of the motor of a POPS cooling pump in October) and the longest fault of 5d 19m concerning the MPS (start of fire of the 6 kV high-power switch in May). The second-largest contributor to the downtime was vacuum with a single fault of 1d 5h 5m when a leak on a vacuum flange downstream of the dump nearby the PS injection septum had to be repaired (long radiation cool-down time involved). Contributor number three was Radio Frequency with several un-correlated faults (mainly cavity trips); there it has to be taken into account that the PS uses a large number of cavities tuned at different frequencies and complex control loops to allow the required complex longitudinal beam manipulations (splittings, bunch merging, bunch rotations etc.).

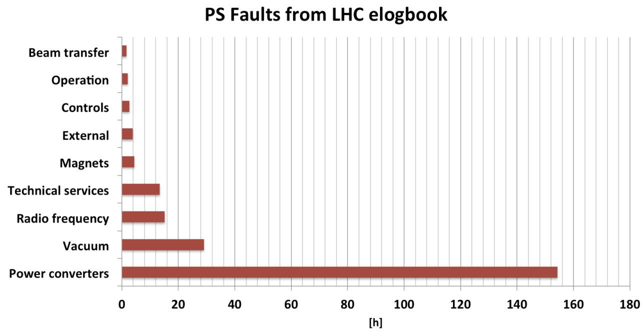

Figure 4: 2016 PS faults for LHC running. Total registered downtime: 9d 10h 34m.

SPS Faults for LHC Run

2016 was also a difficult year for the SPS. Intensity limitations were imposed throughout the year after a vacuum leak had developed on the SPS internal dump (TIDVG). After analysis, the **SPS downtime for LHC operation amounted to ~4d 19h 38m**. The longest integrated fault duration per category was attributed to Power Converters (1d 8h 47m) with the following main interventions: 18 kV cable head fault on MBE2103 (8h 33m), a fault with the current measurement for the Beam Energy Tracking System (7h 36m) and the removal of a busbar for the septum MSE2183 after a water leak. Power Converter downtime was followed by the one for Targets and Dumps (several TIDVG issues with the longest individual fault duration of 16h 52m) and Radio Frequency (uncorrelated high and low level RF faults).

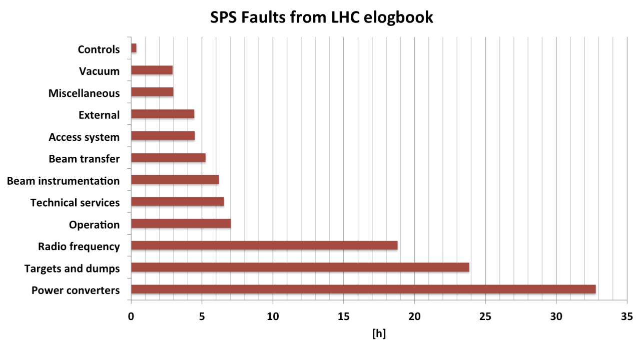

Figure 5: 2016 SPS faults for LHC running. Total registered downtime: 4d 19h 38m.

Although not in the top three most important SPS fault categories, it is interesting that Operation is in fourth place with >7h of downtime. The main reason for this is that the LHC beam was still being set up in the SPS or checked while the LHC was preparing or was ready to inject. The LHC beams are not constantly played in all injectors; parameters are drifting and require re-adjustments before LHC injection.

2016 INJECTOR UNAVAILABLITY

As mentioned before, the injector complex faults 'seen' by the LHC represent only a subset of all the faults that actually occurred in the injector chain. In order to draw some valid conclusions on the most important faults or to identify recurring faults for each of the injectors during 2016 and to evaluate appropriate mitigations and predictions for the 2017 run, the comprehensive injector fault overview should be used instead.

Linac2 Total Faults during 2016 Proton Run

Figure 6 summarises the total registered downtime in hours for Linac2 during the 2016 proton run, split into the different fault categories. Data was extracted from the Linac2 elogbook for the period from 02/03/2016 – 14/11/2016. The **total downtime** amounted to **6d 22h 22m**, which has to be put into contrast with the 6h 20m of Linac2 faults registered for LHC running.

The source had many problems throughout the year and was responsible for >44% of all the Linac2 faults. There were two vacuum leaks at the source, whose detection was quite time-consuming. The source cathode had to be exchanged twice, and in addition quite some time was spent during the run to investigate problems with decreased source current or current fluctuations along the Linac2 pulse. The degraded Linac2 source performance had some repercussions on high-intensity users like the ISOLDE experiments, but for LHC beams there was no important brightness reduction, also because the LHC was running for the major part of the year with BCMS[2] beams that require only low intensities injected into the PSB.

The second-most important fault category concerned Radio Frequency (34.6% of all faults). The following main faults occurred: Problems with the high voltage (HV) system (ignitron, RF amplitude jitter due to a broken HV cable connector), a broken RFQ tuner1 (worn out thread) and issues with the reference amplifier.

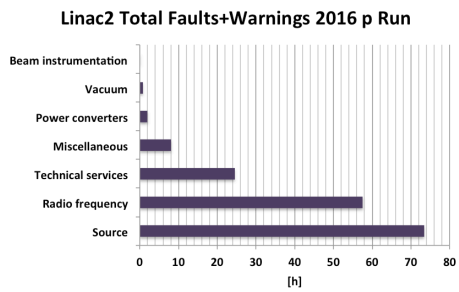

Figure 6: Linac2 total faults (and warnings) during the 2016 proton run. Total downtime: 6d 22h 22m.

In summary, the total uptime of Linac2 was 97.3%, which is slightly less than the 98.3% average over the last 15 years [2].

The following actions will be taken to improve the Linac2 availability and performance for the 2017 run:

- **Spare Linac2 source**: During the extended year-end technical stop (EYETS) 2016/17 a spare source with a ~10% larger anode aperture will be extensively tested; this source will be put into operation for the 2017 run if successful. In parallel the source used during the 2016 run will undergo its annual maintenance.
- BE-ABP and BE-RF will make a full **inventory of the Linac2 RF equipment and its state** during the EYETS; they will also investigate the spare situation and produce new parts if necessary.

PSB Total Faults during 2016 Proton Run

The 2016 PSB proton run (from 08/03/2016 – 14/11/2016) did not contain any serious long-lasting faults. The **total downtime was 16d 24m**, of which 6d 22h 22m were Linac2 downtime. The availability reached 93.9%, which is an improvement compared to the 2015 run (92.5% uptime).

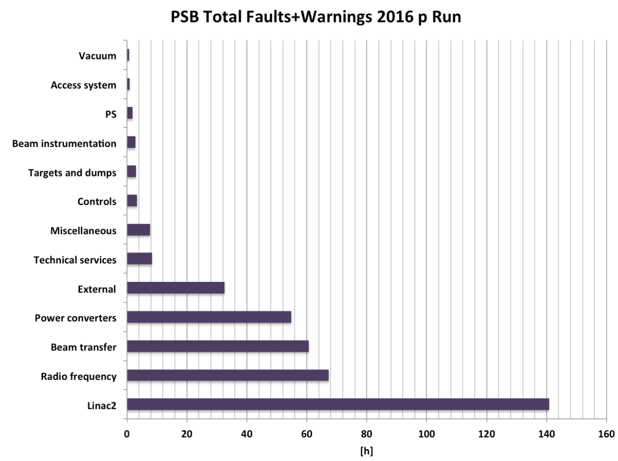

Figure 7: PSB total faults (and warnings) during the 2016 proton run. Total downtime: 16d 24m.

After the contribution of Linac2 faults (36.6% of PSB downtime - see previous section), radio frequency is next (17.5%), followed by beam transfer (15.8%) and power converters (14.3%). The total list of faults (and warnings) during the 2016 proton run is illustrated in Fig. 7.

Taking the PSB as example, one can illustrate the problem this year that **warnings could not be separated from faults in the 2016 statistics**. There were two periods of >1d in October during which the C16 cavities of the PSB (used for longitudinal blow-up and also intensity control through longitudinal shaving for certain beams) were not working due to a water leak of the

[2] BCMS: Batch Compression, Merging and Splitting scheme.

prototype Finemet cavity that sprayed water on the cavities. Nevertheless, most of the beams could still be provided to the users after some operational adjustments (except during the required machine accesses); therefore the machine was operating in degraded mode (no real fault). Correcting for these particular two periods, the PSB statistics look different (see Figure 8). The radio frequency fault category has moved to the forth place (10.3% of total faults), and after Linac2 (39.8%) we now find beam transfer (17.2%) and power converters (15.5%).

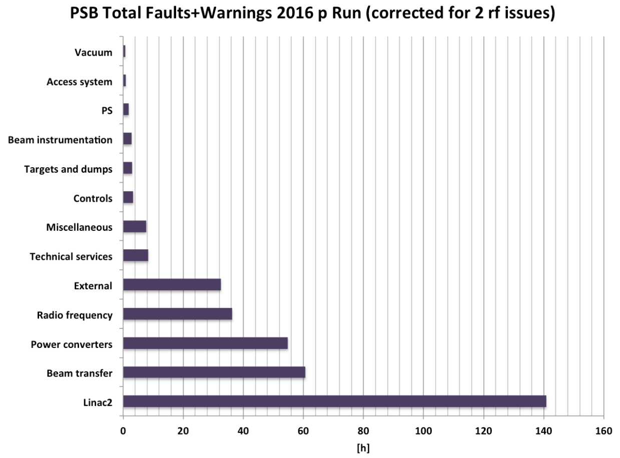

Figure 8: PSB total faults (and warnings) during the 2016 proton run, corrected for the degraded operation after two Finemet water leaks in October. Total downtime corrected to 14d 17h 26m.

As previously mentioned, the main reason for the beam transfer downtime were **electrovalve failures of the septa**; for their repair machine access was needed, and because of the relatively high dose rate around the septa corresponding radiation cool-down times. The electrovalve failures were unexpected, as this equipment had been renewed before 2016. Unfortunately, the new type of valve deployed seems to be less radiation tolerant. During the 2016/17 stop these valves will be exchanged with yet another type for the septa that showed the highest failure occurrence and if successful, all valves will be replaced. It is therefore hoped that the downtime for the PSB Beam Transfer category will decrease for the 2017 run.

PS Total Faults during 2016 Proton Run

Concerning the faults, the year 2016 for the PS was characterised by several long-lasting issues with the PS main power converters – the 'new' POwer supply for the PS (POPS) system and the previous Main Power Supply (MPS), still used as backup during longer POPS breakdowns.

The considered period for the PS fault statistics was from 14/03/2016 – 14/11/2016. During this period **30d 07h of downtime** were registered, which includes 8d 01h of downtime from the PS injectors.

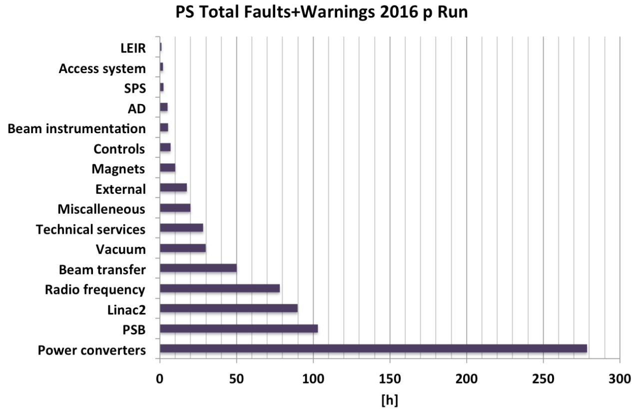

Figure 9: PS total faults (and warnings) during the 2016 proton run.

As mentioned, the main fault contributor were the power converters (38.3% of total downtime); towards the beginning of 2016 the DC1 converter of POPS developed a short circuit that forced major reparation of the system. Shortly before the start of the 2016 run, the system was repaired and ready to restart, when an additional short circuit developed on one of the capacitors in the DSP1 container of POPS. This short circuit led to the explosion and collateral damage of the container and of all the 126 capacitors installed there. During the repair time the rotating machine (MPS) was brought back into operation, but on 20th of May one of the two MPS generator output switches broke due to an incorrect closing position and developed an arc with important smoke generation. This fault led to the longest fault registered for the PS in 2016 of >150h.

Not taking into account the downtime from the PS injectors already covered earlier (26.6%), radio frequency systems follow (10.7%) and beam transfer (6.9%). For RF, no systematic faults were observed.

Like for the other machines, **corrective actions** have already been taken in particular for the most important fault category to improve the situation for the 2017 run [3]. Concerning **POPS**, two newly designed containers are under construction, one to replace the damaged DSP1 plus a spare. The capacitor banks in these containers were re-arranged to divide the total capacitance into four groups, each group protected by an individual fusing element. This will reduce the amount of energy and peak discharge current in the event of an internal fault. A new capacitor design has been deployed and tested at CERN to mitigate the weaknesses of the older version. Non-negligible downtime for POPS was also due to failures of non-reliable cooling water pump motors; a new model was purchased and tested during more than three years. All old **water pump motors** will be replaced with the new ones during the EYETS 2016/17. For the MPS, the damaged high-power switch has been repaired; the MPS has been successfully tested at the end of the run and can continue to serve as POPS backup.

The PS is a good example to illustrate that the **availability can vary significantly from user to user**.

For the various PS proton beam users, this number has a span between ~79% and ~94%. This is due to several reasons:

1. Different start dates per user
2. Users can switch on and off their beam request depending on the situation of their experiment
3. Certain users are not permanently programmed in the supercycle
4. Some equipment is beam-specific (e.g. certain cavity combinations or extraction elements), leading to different availabilities in case of faults of this equipment.

For a future machine availability analysis of the injectors it will therefore be necessary to separate the data for different users/beams, contrary to the LHC situation.

SPS Total Faults during 2016 Proton Run

The SPS fault analysis is based on the period from 18/04/2016 until 14/11/2016. For the Fixed Target (FT) physics the 2016 uptime was 74.8% (compared to 85.5% in 2015). The **total time the SPS was unavailable to deliver the FT beams was 56d 22h**, including 20d 11h from the injectors.

Like Linac2 and PS, the SPS was also suffering in 2016 from major breakdowns; in the SPS case the main problem concerned the vacuum leak of the internal dump (TIDVG), leading to long downtimes and a serious operational limitations throughout the year to avoid dumping too much beam on the TIDVG, as no operational spare was available for replacement.

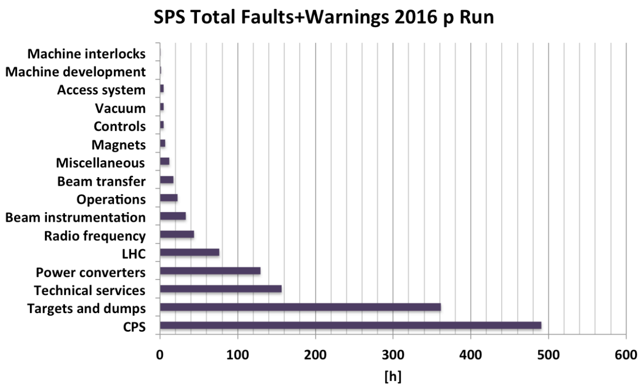

Figure 10: SPS total faults (and warnings) during the 2016 proton run.

Fig. 10 shows the distribution of the 2016 faults for the SPS. Neglecting the number one fault contributor, the PS Complex (35.9%; see previous subsections), targets and dumps follow with 26.5%, technical services and power converters amount to 9.8% and 9.5%, respectively. The main contributor to the downtime for the technical services was the BA3 overheating incident; for the power converters the principal fault lasted 49h 14m and was due to an insulation fault of an 18 kV cable head in the auto-transformer of MBE2103.

Concerning the TIDVG fault, a newly designed dump is under construction and will hopefully replace the damaged TIDVG before the 2017 restart. This would allow lifting the operational limitations that affected LHC operation, but even more North Area physics delivery. It should be pointed out that this **degraded operation is not visible from the fault statistics** (apart from the investigation time).

INJECTOR AVAILABILITY

It is not at all straightforward to provide availability data for the injectors. There are several issues with the injector availability statistics that are summarised here:

1. **Manual insertion of faults in the injector elogbooks** → not everything is captured. In the SPS a system called 'Big Sister' is used that automatically inserts an elogbook entry if there are three consecutive cycles without beam for a user, for which 'Big Sister' is enabled. It could be discussed whether a modified implementation for Linac2, PS and PSB would make sense, but the faster the machines cycle, the more care has to be taken that the elogbook will not be submerged with entries.
2. **Availability for a given destination** (e.g. LHC):
   a. Statistics are reliable if a user is permanently played in the supercycle, but breaks down for beams on request (e.g. LHC, AWAKE, ISOLDE, nTOF…). For those users the request is often removed when beam production is not possible due to a fault, thus the faults are not any longer accounted for in the specific user availability statistics. There is no obvious solution for this issue, and at the same time it has to be mentioned that this leads to the high flexibility and optimum beam usage for the physics experiments served by the injector chain.
   b. The SPS does not automatically note any fault when the LHC beam is in the supercycle and under LHC mastership; it cannot distinguish between 'no request' and 'request, but fault'.
   c. Currently faults are attributed to 'timing users' (slots that can be used for various types of beams); this will be modified for 2017, when faults will be assigned to LSA contexts (non-ambiguous cycles).
   d. There exists no automatic link between LHC faults for the injectors and the injector elogbook entries. Since June 2016 selected persons from each injector are at least

attributing the faults noted by the LHC to the correct injector.

   e. Beam setup: Sometimes the LHC is waiting for beam from the injectors, when the beam is still being set up or checked/optimised. This leads to a fault entry in the LHC elogbook, but not for the injectors. This time should of course be minimised by in-time announcement of the LHC intention to inject, and the current situation is judged acceptable for the moment.

3. The root fault cause is sometimes not correctly identified → we propose to assign this task on a weekly basis to the team of the weekly machine supervisors.
4. Degraded mode – how should it be accounted for?
   a. Degraded machine operation (warnings) will be separated in 2017 from the machine faults.
   b. A solution should be identified to mark also long-term degraded operation (like in the SPS after the TIDVG fault).

Plans for 2017 Injector Statistics - AFT

A working group has been put in place in 2016 to evaluate the possibility of extending the LHC Accelerator Fault Tracking (AFT) to the injectors. The outcome of this work is that a modified version will be implemented to allow at least the correct data capture from the start of the 2017 run, followed by the full functionality including visualisation throughout the year. This will address several of the above-mentioned problems through the following points:

- Harmonisation of the injector fault categories with the LHC categories; these categories have already been defined per injector and will be implemented in the 2017 injector elogbook version
- Use LSA contexts instead of timing users: Statistics will be produced by LSA context or groups of LSA contexts (e.g. all LHC cycles)
- Implementation of the interface elogbook/AFT similar to the LHC, but context-dependent
- Separation of warnings and faults in the statistics
- Weekly review of root causes in the injectors.

Still there are outstanding issues that will not yet be solved by the 2017 injector AFT version, and it is proposed that discussions should continue on these subjects.

SUMMARY

The injector complex accounted for >25% of the total LHC root cause duration (corrected for parent/children faults and fault parallelism) during the 2016 LHC proton run. LHC and injector elogbook data has been analysed for the 2016 proton run, and the resulting downtimes per injector are summarised in table 1.

Table 1: Summary of injector downtimes during the 2016 proton run. The percentage values in the downtime for the LHC have been rounded. In the last row the downtimes of the upstream machines have been subtracted to provide the individual machine downtime durations.

	Linac2	**PSB**	**PS**	**SPS**
Downtime for LHC	6h 20m **(1.8%)**	11h 45m **(3.3%)**	9d 10h 34m **(62.9%)**	4d 19h 38m **(32.1%)**
Total downtime per machine	6d 22h	16d	30d 7h	56d 22h (FT)
Total individual machine downtime	6d 22h	9d 2h	22d 6h	36d 11h (FT)

The injector downtime in 2016 has been marked by a few uncorrelated major faults, and mitigation measures have been laid out that should allow increased injector availability for the 2017 run.

A first version of the injector AFT will be put in place for the 2017 run, and efforts should continue to improve the fault and availability statistics for the injectors.

Despite a quite bad year 2016 for the injectors, their flexibility has been a big contributor to the success of the 2016 LHC run and the physics runs of the many experiments served by the different injectors.

REFERENCES

[1] A. Apollonio *et al.*, “LHC Availability 2016 Proton Run”, 7th Evian workshop, these proceedings.

[2] Information D. Küchler.

[3] Personal communication F. Boattini.