Turnaround - Analysis and possible Improvements

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Abstract

This paper will present data of turnaround times during the previous run, give some insights in the distribution and try to spot different bottlenecks. The impact of the turnaround time on the optimal fill length will be shown and different contributing factors to the turnaround itself will be discussed. The final goal is to identify areas of improvements and give concrete proposals, based on data presented.

INTRODUCTION

When talking about the turnaround in the Large Hadron Collider (LHC), then we usually define this as the period between the end of stable beams of one fill until the start of stable beams of the subsequent fill. This is illustrated in Fig. 1.

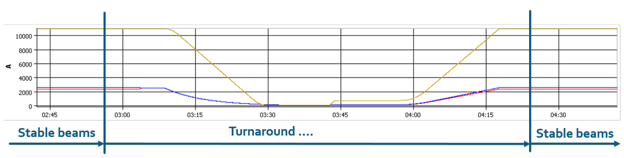

Figure 1: Definition of the turnaround during an LHC Cycle: Time between end of stable beams of one fill and start of stable beams of the subsequent fill.

Since the turnaround is the only time (during standard operational periods) which is lost for physics production, there is a high motivation to keep it as short as possible. Unfortunately, at the same time, the turnaround is the least reproducible period of operation, because of many manual steps to be done by the operators and the strong dependence on external systems (injector chain).

In the attempt to gain more detailed insights, the following sources of information were used for this paper:

- Full dataset of faults, extracted from the Accelerator Fault Tracking System (AFT),
- Excel sheet, compiled and manually filtered and compiled from the full AFT dataset by A. Apollonio,
- Timing events extracted from the CERN Accelerator Logging Service (CALS),
- All Shift data extracted from the LHC Logbook.

After having these datasets available, the temptation was high to combine all of it. It turned out to be a challenge to get speaking results out of it, as described in the following sections.

A FIRST GLANCE

As a starting point, Fig. 2 shows the turnaround durations throughout the year 2016. Already from this it is visible that some of the turnarounds show very high numbers. This comes from different special periods with no stable beams (e.g. technical stops, MDs, etc). In the plot these periods are shown with a white background, while the physics periods are marked with a green background.

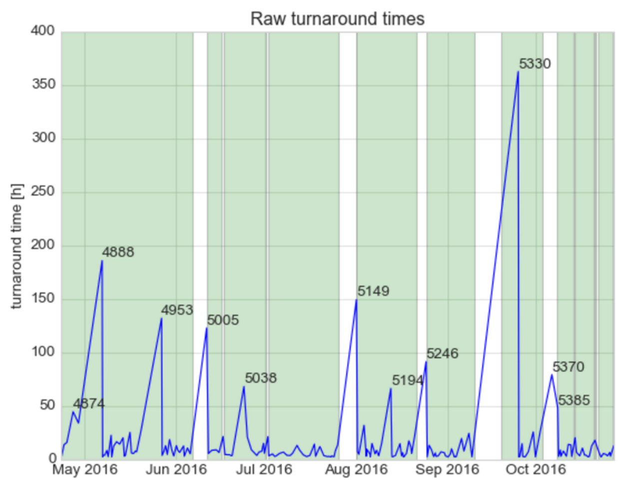

Figure 2: A first glance on the turnaround durations throughout the year 2016. The numbers indicate the fill numbers of notably long turnaround durations. Green background indicates physics production periods, white background indicates other periods.

To make more sense out of this data, we apply the same strategy as applied in [1, 2] and exclude the following datasets:

- Faults longer than 24 hours.
- Fills following accelerator mode changes, which therefore have no associated turnaround:
  - Following the Restart (#4851, #4874)
  - Following Technical Stops (#5005, #5330)
  - Following Special Physics Commissioning (#5024, #5068, #5251, #5287)
  - Following Ion Cycle Commissioning (#5437)

– Following Machine Development (#5149, #5246, #5385)

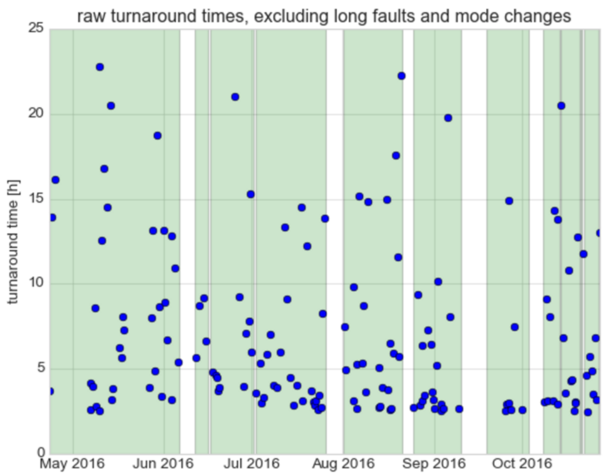

Figure 3: Turnaround durations after filtering out faults longer than 24 hours and turnaround after accelerator mode changes.

The resulting turnaround durations throughout the year are shown in Fig. 3. The distribution of these times is shown in Fig. 4 and the relevant statistical results are listed in Table 1.

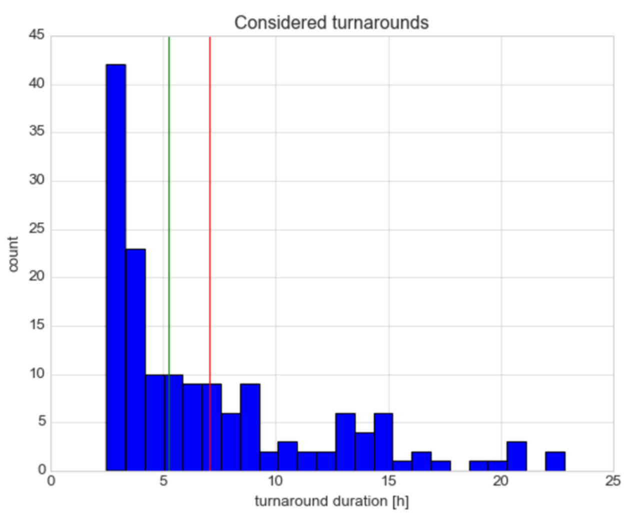

Figure 4: Histogram of turnaround times after filtering. The green line indicates the median, the red line shows the mean.

Min	Median	Mean
2.5 h	5.2 h	7.1 h

Table 1: Statistic results of the filtered turnaround times.

TURNAROUND PHASES

This section summarizes some more detailed analysis of individual phases of the turnaround, highlighting potential problems.

Dump vs. End of Stable Beams

As the turnaround is defined as the time from end of stable beams to start of the next stable beams and some of the following analysis is based on beam mode changes, the first aspect to look at is the relation between the actual dump time and the first beam mode change in the turnaround (STABLE BEAMS → BEAM DUMP). Since this time in some sense (at least in the case of protection dumps) corresponds to a reaction time of the operations crew to the dump event, we will in the following denote it as such.

Figure 5 shows the distribution of these reaction times in the case of protection dumps and Table 2 shows the corresponding statistics results.

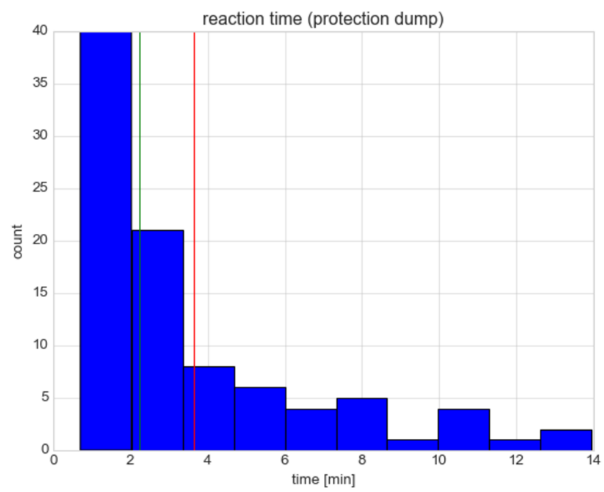

Figure 5: Reaction times (times between dump and beam mode change) for protection dumps.

Min	Median	Mean
0.7 min	2.2 min	3.6 min

Table 2: Statistic results of the reaction times for protection dumps.

In an attempt to identify potential impacts of daytime on such reaction times, those times are plotted against the time of the day in Fig. 6. However no evident trend could be deduced from this analysis. The same analysis was done for the reaction times for dumps which were not protection dumps, but programmed dumps. Despite there is no strong technical reason to have delays in this case, there can be some observed. These delays are due to the current operational practice which is used in this situation, were some sequences have to be run after the actual dump event to

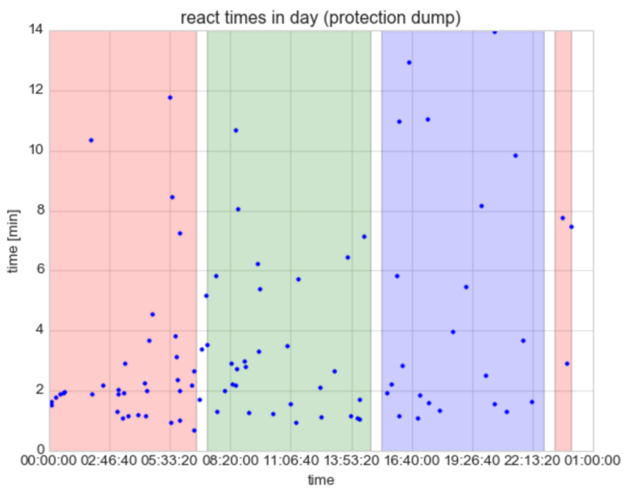

Figure 6: Reaction times (times between dump and beam mode change) for protection dumps.

switch the beam mode from Stable Beams to Beam Dump. Nevertheless, the delays are clearly smaller than in the protection case, as expected. This is illustrated in Fig. 7 and Fig. 8 and summarized in Table 3.

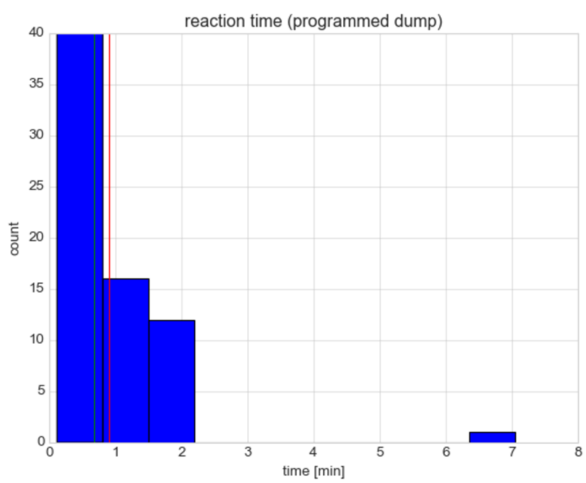

Figure 7: Reaction times (times between dump and beam mode change) for programmed dumps.

Min	Median	Mean
0.1 min	0.7 min	0.9 min

Table 3: Reaction times for programmed dumps.

Dump to Start of Rampdown

The next phase to consider is the time between the actual dump and the start of the rampdown. The main factor of this delay is again that some sequences have to be executed in between. Amongst others, the currents of the power converters are driven to the start of the rampdown cycle. This process also dominates the minimal time required. The corresponding distribution is shown in Fig. 9 and the statistical results are shown in Table 4.

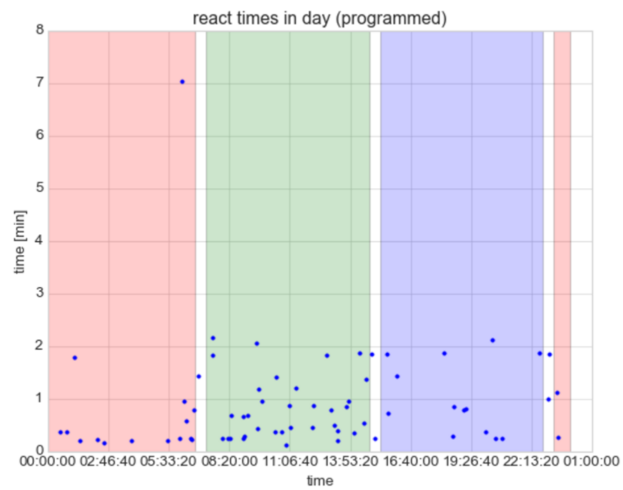

Figure 8: Reaction times (times between dump and beam mode change) for programmed dumps.

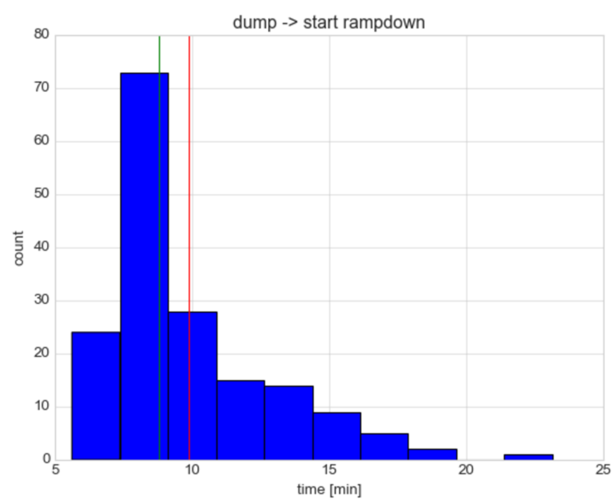

Figure 9: Distribution of delays between actual dump time and the start of the rampdown.

Min	Median	Mean
5.6 min	8.8 min	10 min

Table 4: Statistical Results for times between dump time and start of rampdown.

Start of Rampdown to End of Rampdown

This phase has always the same length: Exactly 21 minutes. This is simply due to the fact that there is no manual action to done in between. The rampdown is started with a timing event and then executed by the power converters.

Pre-Injection phase

As this phase, we consider the time between the end of the rampdown and the time of the first injection. The first part of it is taken up by several individual magnets, (e.g. the triplet magnets) which do not do a function-driven rampdown like e.g. the main magnets, but are switched to openloop at the start of the rampdown and take longer to reach their standby current. This is illustrated in Fig. 10: The first vertical marker indicates the time when the main bends reach their standby current and the second one the time when the triplets reach it. The amount of time the slowest magnet takes longer than the main bends, is about 11 min.

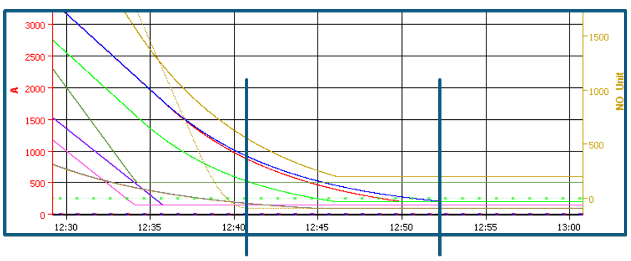

Figure 10: The triplets reach their standby current slower than the main magnets.

The rest of the preinjection phase is completely fault dominated (which is natural, because this is the phase at which the operations crew usually waits until all problems (e.g. in the injectors) are sorted out. This way the risk of required precycles is minimized).

Clean Turnarounds

Despite several tries to subtract recorded fault times from the preinjection phase and deduce meaningful statistics, none of them proved to provide reliable results. Therefore, the only means to determine potential operational margins for time reduction, was to fall back to restricting the following analysis to ”clean turnarounds”. By ”clean turnarounds” we denote turnarounds with the following properties:

- No gap in fill-numbers
- No faults during the full turnaround
- No precycle between the fills
- No end of fill MDs

Applying these criteria, 14 turnarounds fall into this category. All of them intrinsically follow a programmed dump, because any protection dump is considered automatically as fault by the fault tracking tool. The distribution of the length of such turnarounds is shown in Fig. 11 and the statistical results are given in Table 5.

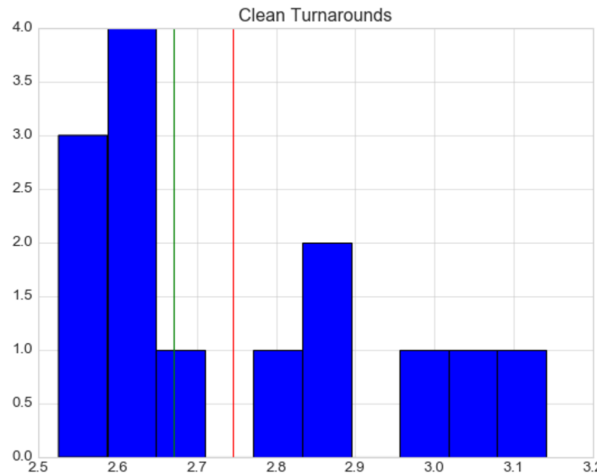

Figure 11: Distribution of durations of clean turnarounds.

Min	Median	Mean
2.5 h	2.67 h	2.74 h

Table 5: Statistical Results for durations of clean turnarounds.

Taking into account only these clean turnarounds, then a more representative figure for the pre-injection durations can be given, as illustrated in Fig. 12 and Table 6. So the currently minimal achievable duration for this phase is about 15 minutes, out of which about 11 minutes can be accounted to the abovementioned end of the rampdown of some power converters.

Min	Median	Mean
15 min	19 min	21 min

Table 6: Statistical Results for preinjection durations, taking into account only clean turnarounds.

Injection

Also the injection phase is very fault dominated. Therefore it also makes sense in this case to look only at clean turnarounds. Since more details and durations of phases with beam are covered in [3], we will focus here only on a simple estimation of the efficiency of the filling phase of the LHC. Each time before filling, pilot beams are injected into the LHC. To keep the following simple, we consider

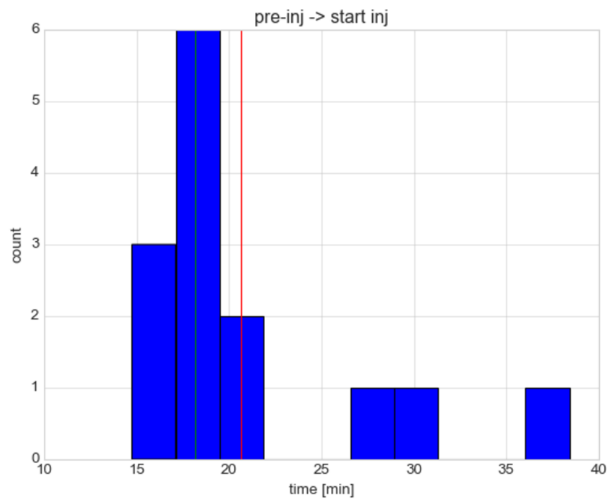

Figure 12: Distribution of times from pre-injection to start of injection (mode INJECTION PROBE).

the filling phase as the time between the third injection and the last injection, which is mostly correct, especially in the considered cases (of clean turnarounds).

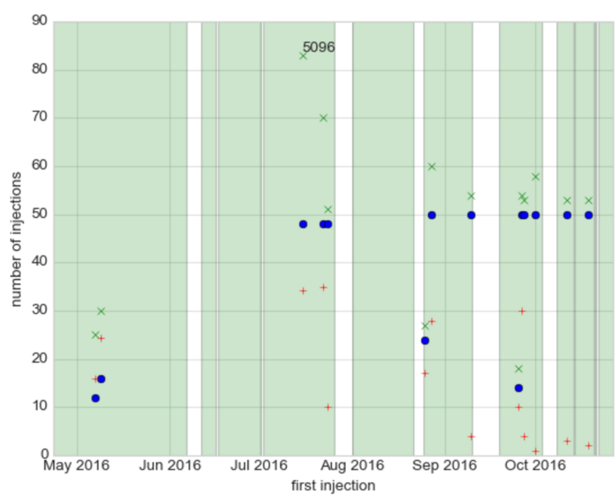

Figure 13: Required injections (blue), number of possible injections from time spent at injection (green dots) and number of missed injections (red crosses). Only clean turnarounds considered.

Figure 13 shows a comparison (for clean turnarounds) of the required number of injections (blue dots), the received injection events (green crosses) and the number of injections which could have been done more in the time spent (red crosses) - denoted as ”missed injections” in the following. The statistical values for those missed injectinos, are summarized in Table 7.

Comparing these numbers to the 50 injections required for a standard physics fill in 2016, it turns out that about every 3rd injection was missed. In other words, we spent about 50 % more time while filling than necessary.

Min	Median	Mean
5	17	25

Table 7: Statistical Results for ”Number of missed injections”.

The reasons why injections are missed can vary a lot. Examples are:

- The injection request is rejected by the CBCM,
- an interlock appeared,
- or the injection was blocked by the SPS BQM (Beam Quality Monitor).

Unfortunately, the root causes are currently not tracked in enough detail. Therefore, more detailed conclusions are practically impossible for the moment.

To improve this situation, a new diagnostics tool [4] is under development and is hoped to record more detailed information, starting after the coming EYETS (End of Year Technical Stop). It is based on a simple Domain Specific Language to describe different conditions. Both, the input values of these conditions and their result will be logged, so that it can be postprocessed for analysis in detail. Figure 14 shows a screenshot of the online GUI of this new filling diagnostics tool. Each line presents one assertion (condition).

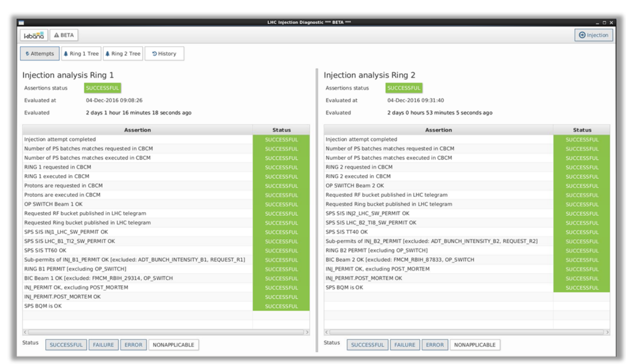

Figure 14: Screenshot of the newly developed system for filling diagnostics, which is supposed to provide more detailed insights in 2017.

PRECYCLE

Another relevant part of the turnaround is the magnetic precycle. It is executed each time something goes wrong in a cycle which would have a relevant impact on the quality of the magnetic field. The precycle guarantees reproducible initial condition at the start of a cycle.

The precycling strategy was changed in June 2016 (fill 5000 onwards) from cycling the whole machine to a current in the main bends equivalent of 6.5 TeV to a current equivalent to 3.5 TeV only. This way, the duration could be reduced from 1 h down to 35 min.

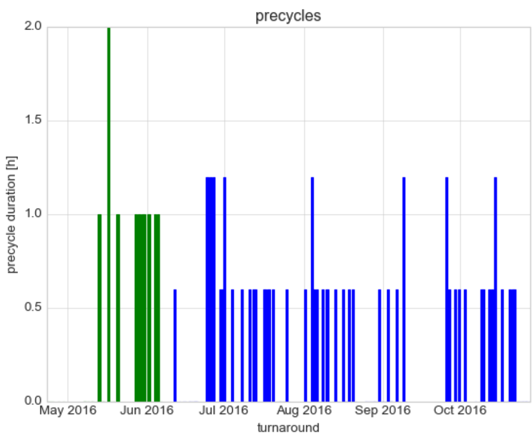

Figure 15: Time spent for precycling, grouped by fill.

Figure 15 shows all the executed precycles in 2016 and their length. In total 64 precycles were executed, 53 of them being short ones. This corresponds to a gain of 21 hours compared to a situation if the original strategy would have been kept. The cost of the change was estimated to about 8 hours of commissioning.

Can we do better?

The main constraining components which prevent the precycle from being shortened more, are several independently powered quadrupoles (IPQs). Currently, the slowest one (RQ4.R2) takes about 5 minutes longer to reach its standby current than the main bends, as illustrated in Fig. 16. If this could be shortened, about 5 hours of cycling time could be gained for the next run (assuming a similar number of precycles than in 2016). Such a change could be implemented without significant commissioning time, as the tune decay could be measured parasitically.

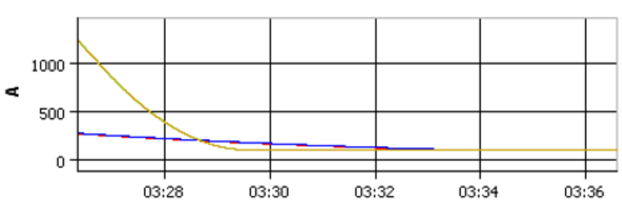

Figure 16: End of precycle. The plot shows the current for the main bends (yellow) and the current for the currently slowest magnet in the precycle, RQ4.R2 (blue), which takes about 5 min more to reach standby than the main bends.

Shortening the precycle even further, would require changes in the cycle of the main bending magnets (RBs). From the field quality point of view, the lowest meaningful flat-top value would be a current equivalent to 2 TeV of beam energy. This would safe about 8.5 min per cycle, which corresponds to about 9 h over the full year. However, this option would require further discussions before being implemented, because it comes with a significant commissioning cost to requalify the field quality and e.g. re-measure chromaticity along the cycle. The required time is estimated to about 2 shifts (16 h).

SUMMARY

Summing up the mean values of the phases discussed in the previous sections and taken from [3], results in 3.0 h, while the sum of the minimal values gives 2.2 h. The fastest turnaround in 2016 (2.5 h) is quite close to this number, which basically represents the absolute minimal operationally achievable time at the moment (without significant changes in the process). The average values of the individual phases of the turnaround, together with the corresponding minimal values (in brackets) are summarized in Fig. 17 (with some numbers quoted from [3]).

From this, the biggest potential gains and possible improvements can be identified as:

- Injection Probe (potential gain of 15 min): During this phase, the parameters of the machine are corrected. Common principles could help here to correct just enough but not more: E.g. Which coupling to correct and which better to leave?
- Injection Physics (potential gain of 11 min): Faster diagnostic tools could help to identify problems quicker when the beam does not come; Also common principles could help again: E.g. When to correct the Transferlines, when not?
- Adjust (potential gain of 8 min): Do we need to optimize before stable beams?

Using the numbers derived in the previous sections (Median 5.2 h; Average 7.1 h) and relating them to the optimal fill-length, using the same approach as in [5], then an optimal fill length of about 13 to 17 hours can be expected. This is illustrated in Fig. 18.

For the precycle, two potential options are available, both with a moderate gain which have to be weighted against the required commissioning times.

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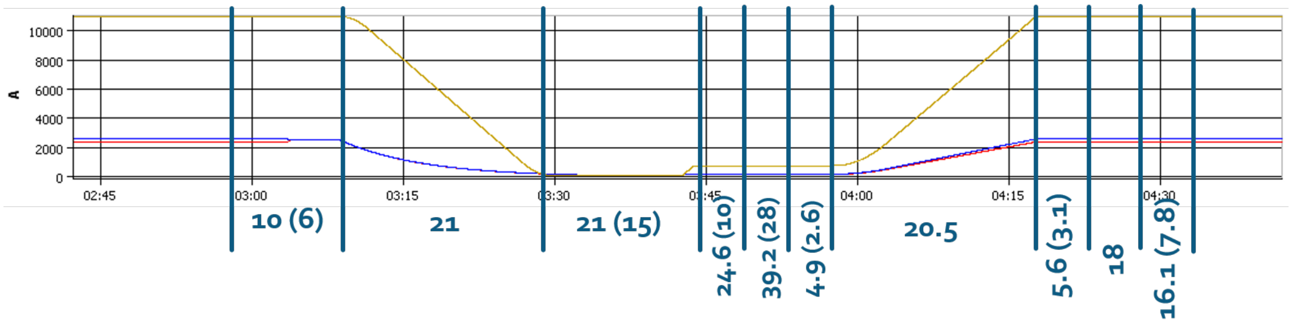

Figure 17: Average lengths of the individual phases of the turnarounds and the corresponding minimal values (in brackets) for 2016. Numbers for phases with beam taken from [3].

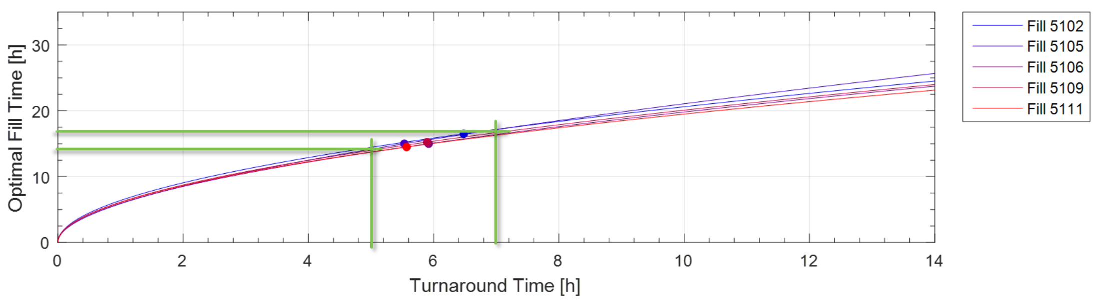

Figure 18: Turnaround times between 5 and 7 hours result in an optimal fill length between 13 and 17 hours.

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