INJECTION

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Abstract

The time spent at injection takes a big share the LHC global turnaround time. This paper will explain the elements of the injection process and how they contribute to the injection duration, with an attempt to analyse where improvement could be made to increase the injection efficiency.

INTRODUCTION

By “time at injection” we mean time spent in the following beam modes: “INJECTION PROBE BEAM”, “INJECTION PHYSICS BEAM” and PREPARE RAMP”.

During the 2015 proton run, considering only the protons fills that ended up in stable beam (all the special runs, MDs and major problems excluded), the average time spent at injection was 90 mins. The maximum supercycle length in the injectors was 59 seconds, and the average number of injections per fills was 22. So in a perfect world, the time spent should have been: 22 mins for injection + 10 mins for measurements with pilots + 5 mins for prepare ramp = 37mins. That leaves a potential of 50 mins improvement.

If we do the same exercise for the ion run, the average number of injections being 36 with 65s long supercylce in SPS, the ideal injection duration would be 54 mins, whereas we get an average of 110 mins from the statistics.

In both cases we spend twice the time that is strictly necessary to fill the LHC and get ready for ramp.

What is done at injection, where is the time lost, what are the issues and what can be improved? Those are the questions this paper will try to answer.

INJECTORS

Supercycle length

The length of the SPS supercycle has a direct impact on the injection process duration. Whereas the LHC filling cycle in SPS is only 21.6 seconds, most of the time the supercycle used for LHC filling is 59s long. With our average of 22 injections per fill, if we reduce the supercycle to only contain the LHC cycle we would gain in average 14 mins per filling. So…Why not?

Firstly, in order to request beam at every SPS cycle, the injection request has to be sent a few seconds before the start of the SPS cycle as the decision to produce the beam for LHC is taken at the booster.

- In case of interleaved injection in LHC (beam1 and beam2 requested one after the other), the injection sequencer sends the request for the other beam as soon as the injection event is received. In this configuration 4 seconds between 2 consecutive LHC cycles are enough to ensure that the beam is requested every cycle.
- If we inject first one beam then the other (as it was often the case in 2015), the injection sequencer send the next request only after the Injection Quality check has confirmed if the beam was injected or not. In this configuration, around 10s is needed between 2 consecutive LHC cycles in SPS.

Secondly, the cryogenic system needs to stabilize the beam screen temperature. Therefore the injection process requires to inject slowly with frequent pauses of several minutes. In this condition, a dedicated supercycle would have penalized too much the north area physics, for no significant gain of time for the LHC.

Nevertheless, for the next run, a dedicated supercycle should be reconsidered if this conditions are met:

- The cryogenic system is more stable
- Setting up is quite fast in the SPS
- Nothing prevent the LHC from interleaved injections.

This could even be an advantage for the SPS users. When the LHC cycle is present in the supercycle, the quality of the north area is very poor because of the magnetic history being different in the supercycle. In addition they have much less duty cycle during the filling. So it is also in north area user’s interest to shorten the LHC filling time, as they could gain in beam quality and availability the rest of the time.

Beam setting-up time

Looking at the statistics for protons and ions in 2015, 152h of downtime were assigned to “No beam from injectors”, and 28h assigned to “injector setting-up”. The first number is out of scope and won’t be explained. The second one represent the time when LHC is waiting for the beam while injectors still need time for setting-up.

To explain this downtime, first thing to note is that in 2015 many different beams have been requested and prepared in the injectors:

- 50ns proton beam at the beginning of the run

- 25ns proton beam with different number of bunches per batch and different batch spacing (attempts to mitigate e-cloud in LHC).
- Doublets and 8b4e
- 100ns proton beam
- Ions beam with 3 different gaps between batches (to increase the maximum number of bunches in LHC)
- Many combinations of pilots and indiv (intensity, batch spacing, bigger emittances)

It was common that filling schemes contained 3 types of beam. In this case the setting-up for filling takes more time.

The requested beam characteristics changed quite frequently, and sometime injectors were given too short notice to prepare new beam parameters. This leads to downtime that could be avoided by a better communication and anticipation of the requests.

The TIDV dump intensity interlock slowed down the setting up, and this will get worse when setting up 288 bunches beam. (This interlock prevents from dumping too much intensity on the TIDV).

The SPS has many clients for MDs or Hiradmat operation that are not always compatible with LHC beam preparation. If these conflicts cannot be avoided, in some cases a better synchronisation of LHC and SPS planning could have improved the situation. (i.e. don't plan an LHC injection study while SPS is running on coast for UA9).

SPS beam quality

Before the LHC beam is extracted from the SPS, several parameters are checked by the SPS beam quality monitor (SPS BQM). It checks that the LHC gets the requested number of bunches, in the right buckets with correct intensity and that the rephasing worked well. The BQM dumps the beam if one of the monitored parameter is out of limits. For 25ns proton beams:

- 15% of the requested beams are dumped for 12 bunches and single bunch beams.
- 20% of nominal beam requests are rejected.

With 22 injections per fill, the average time lost per fill is around 4 mins.

To be noted that a lot of the BQM thresholds can be modified by the SPS operator, who has to find the best compromise between quality and efficiency in agreement with the LHC operations team.

FILLING SCHEME

Almost 200 filling schemes have been used in 2015. 48 were used for proton physics, for which almost as many were created as alternatives and not used. Besides the schemes used for intensity ramp-up, many configurations of injection spacing, number of bunches per injection and SPS batch spacing were tried to mitigate e-cloud. Seven schemes were used for ion physics, for intensity ramp-up and with reduced SPS batch spacing to maximise the number of bunches in the LHC. 44 schemes were used for scrubbing run. The others were used for setting-up and MDs.

Obviously the filling scheme have a big impact on the injection duration, not only because of the number of injections, but also for the following reasons:

First, the limitation of 144 bunches/injection (nominal is 288 bunches/injection) from the TDI jaw problem, doubled the number of injection requests for a given number of bunches.

In addition, a lot of filling schemes with even less bunches per injection were used to mitigate e-cloud effects by injecting shorter trains, therefore more injection requests. In the example of the 2 schemes named *25ns_1176b_1176_1080_111-_144bpi10inj* and *25ns_1176b_1176_1096_72bpi18inj*, for the same number of bunches and collisions in every IP, the second scheme takes at least 16 mins more to inject.

The filling schemes have to be optimized as well to reduce the number of SPS supercycle changes during the filling, as it takes several minutes each time.

A filling scheme that contains 3 injections of intermediate intensity (nominal bunch intensity, from 1 to 12 bunches) at the beginning of the filling will allow for steering online. The first injection can be a single nominal or a 12 bunches, it will allow to correct the orbit with the right BPM sensitivity. With the second injection the correction will be calculated and applied, with the 3rd injection, the correction will be checked before the nominal beam can be injected. Therefore the 2nd and 3rd injection have to be on the same SPS cycle than the nominal to ensure the corrected trajectory is representative of the nominal beam trajectory.

TRANSFER LINES

Commissioning and references establishment

During the transfer line commissioning, a trajectory reference has to be established for both injection lines. In the commissioning phase, a pilot is used for the trajectory measurement and collimators alignment, but the reference will be used for the correction of a nominal beam. In 2015 the procedure has been improved to make the probe's trajectory more representative of the nominal beam trajectory.

- The kicker delays were changed during the commissioning so that the pilot is positioned at the middle of the kicker waveform.
- In the SPS the pilot beam was played on the nominal cycle in order to get comparable magnetic history.

Thanks to this improved procedure, the references we had in 2015 were much better.

Transfer line Steering

During the proton run, only 14 hours were spent for dedicated steering. It was much smoother and easier than in run 1:

- 50% of the steering was done while filling thanks to the appropriate schemes: several hours gained!
- The shot by shot instabilities of the trajectory were cured during LS1 thanks to hardware change on the SPS extraction septa to supress the current ripple.

Almost no beam dump at injection was triggered by injection losses in 2015, this is partially explained by the optimization of the BLM thresholds and the replacement of some BLMs by LICs (ionization chambers) that are less sensitive and give more margin.

Still, it has to be kept in mind that this was with a limited number of injected bunches, injection of 288 bunches may be more challenging![1]

INJECTION QUALITY CHECK

The Injection Quality Check application, IQC, compiles and analyses the injection post mortem data from beam position monitors, beam loss monitors, injection kickers, ring and transfer line BCTs and LHC Beam Quality Monitor (BQM).
From this data the IQC determines if the beam was injected or not, and indicates the quality of the injection. The 4 possible results of the IQC are:

- REPEAT if beam was not injected
- Ok when all measured parameters are within thresholds
- WARNING when only the ring BLMs are above thresholds
- ERROR for any other value out of thresholds.

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The injection sequencer relies on the IQC to know if the beam was injected or not and to decide how to proceed with the next injection. In case of an ERROR result from the final analysis, the IQC applies a software interlock that prevents the next beam injection until a manual reset is perform by the operator.

Since LS1 (where modification on the BQM triggering was done), the BQM frequently published data taken before beam was injected instead of measurements of the last injected beam. The IQC analysis was then confused because it received indication of beam injected from the BCTs whereas the BQM pretended no beam was injected, it then published UNKNOWN and raised the software interlock. As a consequence, the injection sequencer paused to ask the operator to check manually if beam was injected or not. The software interlock had to be cleared before next injection can be requested.

Time is then lost because the opareration crew has to manually verify if beam was injected, the next request is sent too late for the next supercycle, and this can also lead to mistakes and risk of unwanted over-injection.

A second problem with the IQC is the misleading thresholds for BLM warnings. In 2015, the IQC analysis result was systematically WARNING, even when very low losses were observed. Most of the time it came from losses on the TDI. The reason is that when injecting less than the maximum 288 bunches, the analysis does a scaling of the losses with the number of bunches. If it estimates that with the given injection losses, a 288 bunches injection would be closed to the dump limit, the IQC gives a warning. This direct scaling with the number of bunch is not applicable for the TDI where most of the beam losses come from unbunched beam, so the losses are systematically over-estimated. With systematic unjustified warnings, there is a big risk for operation team to disregard also a warning that would make sense and require an action.

In 2015, because of the described problems, the IQC has lost a part of its credit and didn’t completely fulfil its role. This can be improved for the next run, with a review of the BLM warning limits and an appropriate scaling applied for each of them. The operation team should have more control on some of the thresholds and set them to a value in phase with the real situation. The most important is to modify the BQM triggering system to get back reliable injection post-mortem data.

The IQC analysis could also be pushed further to help the operation team to understand when a steering is really needed by correlating the beam position at the collimators with the beam losses and spot critical beam positions.

MEASURMENT AT INJECTION

Tune and chromaticity

Since LS1 the damper gain system is more flexible: the so called “Witness Gain” applies on the first 400 buckets whereas the nominal gain apply on all the others. The witness gain is set very low so that the damper doesn’t affect the tune measurement. As long as there is at least one bunch in the first 400 buckets, the chromaticity and tune measurements are much improved.
This is an important improvement for the feedback that gets much more reliable during the ramp, but also at injection it reduced considerably the setting-up time and measurement accuracy.

Wire scanners

In the operational procedure, systematic wirescanner measurement of the first 144 injected bunches are performed for each beam and each plane.
This measurement takes too much time: the high voltage takes several minutes to be ready the first time we fly the wires, the application also takes several minutes to retrieve the filled buckets after beam is injected. It is not

possible to measure B1 and B2 at the same time, and the acquisition settings are not persisted.
The new operational application for the wirescanners that was developed during LS1 is already a big improvement compared to what was available before, but it can still be improved to reduce this measurement time.

On the other hand, the necessity to do this measurements systematically every fill can be questioned, as we have a well calibrated and performant BSRT that gives the same information.

LIMITATIONS AT INJECTION

Cryogenics

The temperature of the beam screen is directly linked to the number of bunches in the machine and the e-cloud. [2] The injection process creates temperature transients that are difficult to compensate by the cryogenic system. Therefore the cryogenics operator frequently asked to stop the injection process in order to wait for the stabilization of the temperature. 24 hours of downtime was assigned to this waiting time, but at the end of the proton run, after a fine tuning of the parameters and thanks to the reduction of the e-cloud by scrubbing, the waiting time was less dominant.

TDI.B2

Due to a deformation of its jaw, the TDI in beam 2 was outgazing during the filling [3]. At a certain level of vacuum, the injection process had to be stopped before the interlock level is reached and the beam dumped. In 2015, 3 hours of downtime was assigned to this waiting time, and the interlock dumped 5 times at injection. To mitigate this problem, the procedure was to inject beam 2 first, then retract the TDI before completing beam 1 injection.

MKI.B2 vacuum

In the MKIs (mainly in the interconnection tubes next to the kickers), there is a pressure rise when running with 25 ns beams. In some places the vacuum can reach the interlock level and blocks the injection. At the end of the run it was possible to run with 2244 bunches in trains of 36 bunches. At the end of the run the attempt to fill the machine with trains of 72 bunches failed as the interlock level was reached for beam 2 when there was only 1800 bunches in the machine. It does not seem that the vacuum improved with the scrubbing, so the solution for next run will be to increase the vacuum interlock level for MKI.b2.

Instability and blow-up

During the intensity ramp up, instabilities and blow-up started to appear when more than 1100 bunches were injected. It was not systematically every fill, sometime on Beam 1 and sometime on Beam 2. Several time the beam couldn’t be used for physics and had to be dumped. 16 of such dumps were recorded for protons, with sometime the necessity to wait for the cryogenic system to stabilize the beam screen temperature before the beam could be injected again.

The instabilities were not fully understood [4], but one problem on the ADT was finally identified and solved. The ADT gains were optimized. Better diagnostic on the damper would be very useful to help on instability diagnostic.

CONCLUSIONS

Whereas the time spent in ramp, squeeze or rampdown is determined by the function settings where only small optimization can be done, injection is the part of the LHC cycle where a significant time can be gained by:

- Optimization of the SPS supercycle length.
- Filling schemes that minimize the supercycle changes in SPS and the number of requested injections, and allow for steering while filling.
- Reduction of the time spent for beam measurement
- Better diagnostics
- Optimum coordination between the LHC needs and the SPS daily operations, allowing more time for beam set-up before LHC is ready for injection.

Limitations started to appear when the number of bunches increased and will need to be addressed:

- Beam instabilities that still need to be better understood
- The cryogenic system has difficulties to stabilize the beam screen temperature; do we still have a lot of margin?
- The heat load getting closer to the limit for some hardware.

It has to be kept in mind that next run we will have 288 bunches injection. This will be more challenging.

REFERENCES

[1] Florian Burkart “How to obtain clean injection?” these proceedings
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[4] Lee Robert CARVER “Instabilities and beam induced RF heating in 2015”, these proceedings