# INJECTION – ISSUES AND POTENTIAL SOLUTIONS

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## *Abstract*

Due to the sensitivity of the LHC beam loss monitor systems combined with low thresholds, losses at injection became a limiting factor during the filling of the LHC. All parameters, longitudinal and transverse had to be well controlled not to trigger the beam dump at injection. The cause of these losses will be summarized and typical loss patterns and other diagnostics described. Mitigation measures together with promising first results will be presented together with the plans for 2011. Finally the weak points of the current injection procedure will be discussed in terms of efficiency and protection, improvements for the 2011 run will be proposed.

## INTRODUCTION

Towards the end of the first year of LHC operation in 2010, optimisation of the overall turn-around times started to become important. A critical analysis of the achieved turn-around times during the 150 ns proton run from September to October was presented at the Evian LHC operation workshop. Most time was lost at injection corresponding to the LHC beam modes “injection probe beam” and “injection physics beam”. On average 3 h were spent in these modes [1]. Injection is one of the phases were LHC parameters are still extensively corrected by the operations crew, in the other phases LHC operation depends heavily on functions and feedbacks. Thus some of the lost time can be attributed to this fact. Part of the inefficiency is however due the injection process itself. Issues with over-injection, intermediate intensity injection, preparation of LHC beams in the injectors, the LHC filling tools and losses at injection all contributed to sometimes lengthy filling periods. This paper will summarise the observed problems and propose solutions for 2011.

## OVER-INJECTION

Injection of high intensity into the LHC is only permitted by the interlocking system if beam is already circulating. Only probe intensity (currently $< 10^{10}$ charges) can be injected into an empty machine. This is the concept of “beam presence”. A number of so-called “safe machine parameters” (different flags derived from beam current measurements in the SPS and LHC and other quantities distributed across the machine) are combined in the permit equation in the master beam interlock controllers for the SPS extraction to guarantee this condition.

In 2010 the probe bunch required for beam presence was injected into RF bucket 1 and then over-injected onto the TDI with the first high intensity injection. If however no beam was extracted from the SPS during an over-injection attempt, the probe beam was kicked out, the beam presence condition was lost and therefore the possibility to resume the filling was lost as well. Cycles in the injectors had to be changed to switch back to probe beam production and time was lost.

For 2011 it is therefore planned to place the probe bunch at a better location around the LHC circumference such that over-injection does not occur during the first injection but later. The injection scheme editor will calculate the appropriate position.

Keeping the probe bunch as part of the filling scheme as a witness bunch is another possibility. Both options will be used in 2011.

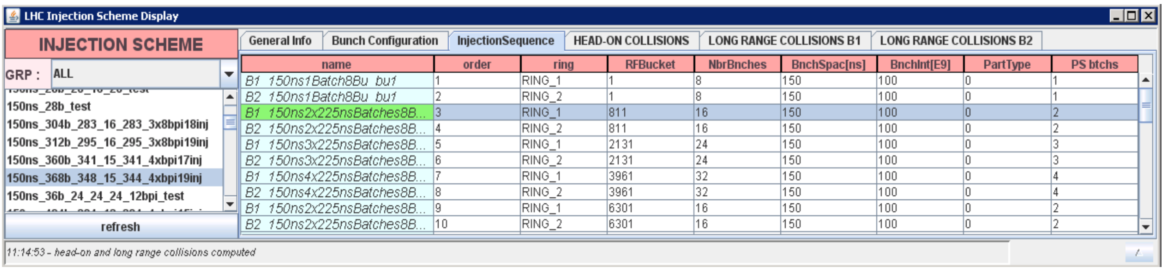
## INTERMEDIATE INTENSITY INJECTION

The LHC does not change settings when switching from probe beam to nominal beam (except sensitivity settings for some BI equipment). The injectors however are running at different settings and hence different cycles for the different beams. As consistency of settings between the different cycles is not guaranteed, intermediate intensity beam is extracted from the SPS first before high intensity. The typical filling scenario therefore consists of a pilot bunch, an intermediate batch followed by full batches. The intermediate batches are the final validation of the injection process.

In 2010 the LHC was filled with single batch injections from the booster into the PS, with the booster RF running on harmonic 2 (+1). The intermediate intensity batch was generated by injecting a single booster ring into the PS instead of three. The other two were disabled manually followed by adjusting the splitting in the PS. Intermediate intensity batches could not be generated in an automated way.

For 75 ns the intermediated intensity corresponded to 8 bunches, for 50 ns to 12 bunches and for 25 ns taking a single booster ring with one injection from the booster would correspond to 24 bunches.

The required manual intervention of the operations crew and the tuning of the splitting then in the PS



150ns_28b_test
150ns_304b_283_16_283_3x8bpi18inj
150ns_312b_295_16_295_3x8bpi19inj
150ns_360b_341_15_341_4xbpi17inj
150ns_368b_348_15_344_4xbpi19inj
150ns_36b_24_24_24_12bpi_test

| name | order | ring | RFBucket | NbrBnches | BnchSpac[ns] | BnchInt[E9] | PartType | PS btchs |
|---|---|---|---|---|---|---|---|---|
| B1 150ns1Batch8Bu bu1 | 1 | RING_1 | 1 | 8 | 150 | 100 | 0 | 1 |
| B2 150ns1Batch8Bu bu1 | 2 | RING_2 | 1 | 8 | 150 | 100 | 0 | 1 |
| B1 150ns2x225nsBatches8B... | 3 | RING_1 | 811 | 16 | 150 | 100 | 0 | 2 |
| B2 150ns2x225nsBatches8B... | 4 | RING_2 | 811 | 16 | 150 | 100 | 0 | 2 |
| B1 150ns3x225nsBatches8B... | 5 | RING_1 | 2131 | 24 | 150 | 100 | 0 | 3 |
| B2 150ns3x225nsBatches8B... | 6 | RING_2 | 2131 | 24 | 150 | 100 | 0 | 3 |
| B1 150ns4x225nsBatches8B... | 7 | RING_1 | 3961 | 32 | 150 | 100 | 0 | 4 |
| B2 150ns4x225nsBatches8B... | 8 | RING_2 | 3961 | 32 | 150 | 100 | 0 | 4 |
| B1 150ns2x225nsBatches8B... | 9 | RING_1 | 6301 | 16 | 150 | 100 | 0 | 2 |
| B2 150ns2x225nsBatches8B... | 10 | RING_2 | 6301 | 16 | 150 | 100 | 0 | 2 |

11:14:53 - head-on and long range collisions computed

Figure 1: Current injection schemes: The current injection schemes consist of a number of injection requests. An injection request tells the injectors into which LHC ring and into which RF bucket the next injection should occur and how many PS batches should be injected into the SPS. The number of injections into SPS can be controlled on the fly. The same is not possible for the number of booster injections into the PS.

before and after the intermediate batch injections caused some considerable holdup during the LHC filling. Improvements of the mechanism to switch to intermediate intensities should be investigated for 2011.

### *Possibilities to speed up switching in and out intermediate batch injections*

Two possibilities to make the switching to intermediate intensities more efficient are discussed:

1. Separate user for intermediate intensities
2. New type of LHC injection requests.

Separate user: this approach would not require any modifications of the existing way of controlling the LHC beams in the injectors. Nominal and intermediate intensity would be run on different cycles in the injectors. As the intermediate intensity cycle is also used to steer the SPS to LHC transfer lines and to avoid the complication of having to copy the steering settings to the nominal cycle which risks to be forgotten, the same user in the SPS should be used for intermediate and nominal. Only the PS and the booster would run with different users. The drawbacks of the "separate user" solution are the larger number of users locked for the LHC beams, the potential issue of the copy of the transfer line steering in case of different SPS users and that the switching from intermediate to nominal and vice versa cannot be done through LHC injection requests. The timing system would have to be re-configured to play the other user. In this way intermediate intensities could only be used as first injection. Mixed filling schemes using nominal and intermediate intensity injections throughout the filling to optimise the luminosities at the different interaction points would not be possible.

New LHC injection requests: the drawbacks of the first possible solution could all be elegantly avoided by the introduction of more flexible LHC injection requests. An example of a filling scheme with the current type of injection requests is shown in Fig. 1. Note that the number of PS injections into the SPS can be piloted on the fly by the LHC injection request with today's Central Timing. This is not the case with the number of booster rings. However, the concept of different destinations for different booster rings exists. And different PS equipment settings can be associated with these different destinations. The idea behind the "new LHC injection requests" is to use a possibility for different settings for different booster ring destinations or different number of booster rings and upgrade the "LHC injection request" to also pilot the number of booster rings between 1 and 6 (2 x 3 rings for 2 batch injection from the booster).

Despite the obvious advantages for injection protection and overall flexibility of building injection schemes of this proposal, there are some drawbacks. The 2010/11 shutdown is short and this proposal would require a major, but technically feasible, modification of the LHC and Central Timing System and settings management in the PS. Possibilities to exploit the "separate users" proposal or speeding up the tuning of the PS splitting will be investigated for 2011. In addition we will study and prepare a new type of LHC injection requests to be ready for implementation during the shutdown 2011/12.

## PREPARATION OF BEAMS IN THE INJECTORS

The LHC physics beams have strict quality requirements. A set of parameters in the transverse and the longitudinal plane has to be verified and frequently tuned before the beams can be declared ready for filling. Regularly preparation in the injectors only started when pilot beam was already circulating in the LHC with the LHC crew waiting for physics beam.

A list of issues has been compiled by the injector teams in connection with LHC beam preparation:

- "The LHC does not get rid of the mastership": the LHC mastership is a concept in the Central Timing under which the LHC is the master of the execution of the LHC beams in the injectors. Under LHC mastership there is no LHC beam in the injectors without request. And without beam no checks can be performed.
  In 2011 it will be possible to have the beam up to the PS if the LHC keeps the mastership and does not request any beam.
- Not everything is testable without mastership: the RF re-phasing at SPS flattop for example can

only be tested under real conditions with an LHC injection request under mastership.

- Not enough diagnostics: there is no continuous emittance measurement in the injectors, no satisfying diagnostics for the 800 MHz cavities in the SPS, no summary status of the complex interlocking condition for SPS extraction to the LHC, etc.
- No well defined procedure for required parameters in the injectors: transverse blow-up on/off,...

For 2011 a series of improvements are planned including more discipline of the LHC crew concerning the handling of the LHC mastership, more tools like the example in Fig. 2 and more communication with the injectors and long term planning of requirements.


SPS to LHC Extraction Display - SPS.USER.LHCFAST1
02 Mar 2011 17:08:40 SPS - LHCFAST1, 06
☑ Auto Select TO LHC Cyc
Mastership: SPS
SPS
Time: 2011.03.02 17:08:33
User: LHCFAST1
MMI Traget: LHCPILOT
Total Intensity: 0.00E0
Mean Bunch Intensity:
Number of Bunches:
MKP: 1 INJECTION ENABLED
BQM: DUMP
Scraper: RETRACTED
SPS RF Timings
To LHC Clock: ENABLED
Rephasing: ENABLED
Playback: ENABLED
Playback Record: DISABLED
Blowup Longitudinal: DISABLED from LSA
Blowup Transv. H: DISABLED
Blowup Transv. V: DISABLED
Beam 1 Transfer Line
FBCT TT60: 0.00E0
FBCT TI2: 0.00E0
Beam Mode: LHC-RING1
BIS: NOT OK
MKE 6: FAULTY
TED TT60: DUMP
TBSE TI2: DUMP
TED TI2: DUMP
Interlocked PC: Cannot start... | Cannot start... | Cannot start...
BIS LHC: Cannot start monito... | Cannot start monito...
Beam 2 Transfer Line
FBCT TT40: 0.00E0
FBCT TI8: 0.00E0
Beam Mode: LHC-RING2
BIS: NOT OK
MKE 4: STANDBY
TED TT40: BEAM
TBSE TI8: DUMP
TED TI8: DUMP
Interlocked PC: Cannot ... | Cannot ... | Cannot ... | Cannot ...
BIS LHC: Cannot start monito... | Cannot start monito...
LTIMs FEI816: DISABLED | DISABLED | DISABLED
LHC Beam 1
FBCT: 0.00E0
Number of Bunches: 0
LHC Beam 2
FBCT: 0.00E0
Number of Bunches: 0

Figure 2: "SPS to LHC extraction monitoring": an application to summarising the conditions for beam extraction to the LHC.

## FILLING SCHEMES AND TOOLS NOT OPTIMISED

In 2010 no dedicated LHC filling cycles were used. The LHC was filled in parallel to the fixed target program in the injectors. A typical supercycle constellation in the SPS can be seen in Fig. 3 with the LHC filling cycle at the end of the supercycle. The length of such a supercycle was about 40 s. In addition to the long supercycles, the LHC filling schemes consisted of many injections. The number of injections per beam for the different schemes during the 150 ns run are summarised in Table 1.

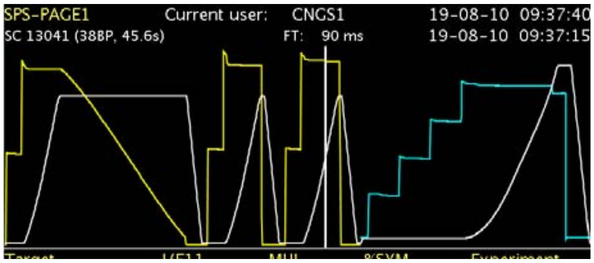


Figure 3: Typical supercycle in the SPS used for LHC filling.

Table 1: Number of injections for filling schemes during 150 ns proton run 2010.

| **Total number of bunches** | **# Injections** |
|---|---|
| 56 | 7 |
| 104 | 13 |
| 152 | 17 |
| 248 | 15 |
| 256 | 17 |
| 306 | 18 |
| 312 | 19 |
| 360 | 17 |
| 368 | 19 |

The LHC filling tools in 2010 were also not optimised yet for dedicated filling. The so-called "injection sequencer" was programmed such that it would wait for the response of the automatic "LHC Injection Quality Check" (IQC) taking place after each injection in the LHC. This did not leave enough time for the LHC beam to be prepared in the injectors for the next LHC cycle with a single cycle in the SPS supercycle. This constraint will be lifted for 2011 for interleaved injection schemes. As soon as the production of the first beam starts, the request of the other beam will be sent to the Central Timing depending on the result of this beam's last injection.

Another issue associated with the filling tools consisted of the dependence of the injection logic on the BCTs. The logic of repeating the last injection, continuing with the next one or stopping all together depends on the result of the LHC IQC. This analysis used two BCTs per transfer line to compute the result in 2010. Unfortunately the transfer line BCTs turned out not to be fully reliable especially with ions. The applied logic of the injection sequencer broke down with wrong BCT results and manual intervention for the normally fully automated injection process was required. In 2011 the IQC will derive whether beam has been injected or not using three devices, two transfer line BCTs and the longitudinal LHC beam quality monitor (BQM), with more weight on the BQM than on the BCTs.

## INJECTION LOSSES

The experience of 2010 showed that the regular losses at injection are close to the LHC injection region BLM thresholds on the short running sums. Frequently the losses even exceeded the thresholds. The reasons for these losses are:

1. Transfer line collimators (TCDIs) cutting transverse beam tails: losses on Q6, Q7 and Q8, see Fig. 4.
2. Uncaptured beam in the LHC: losses on TDI lower jaw and equipment downstream (triplets, TCTVb)
3. Satellites, uncaptured beam from the SPS: losses on the TDI upper jaw and equipment downstream (triplets, TCTVb)

In the following solutions for the different loss mechanisms are treated. Point 3 will not be further discussed as this can be fully avoided with sufficient diagnostics.

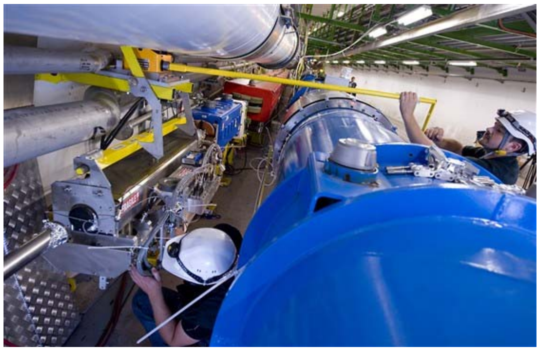


Figure 4: The transfer line collimators are located at the end of the lines where the transfer line is close to the LHC superconducting magnets. Showers created by the collimators are seen by the LHC beam loss monitors on the superconducting magnets.

## Loss Evolution

The loss maxima for the injections during the 150 ns run period with higher and higher injected intensities are summarised in Table 2. The losses due the showers from the TCDIs grow almost linearly with intensity. The losses due to uncaptured beam depended on the parameter adjustments in the LHC (synchro error). It will however definitely be worse for nominal beams with the larger bunch length spread across the injected batch. 1 % of capture loss is expected for 25 ns bunch spacing, where it is used to be 0.3 % for 150 ns with the BLMs frequently triggering.

Table 2: Loss maxima per injected intensity in 2010.

| **Loss Type** | **Losses in % of dump threshold B1/B2** | | | |
|---|---|---|---|---|
| | **8 b** | **16 b** | **24 b** | **32 b** |
| TCDI shower | 1/2 | 3/5 | 4/6 | 5/8 |
| Uncaptured beam | 4/2 | 12/3 | 12/5 | 16/8 |

The results of 2010 were scaled to the expected maximum injected intensities required in 2011. The period with the highest intensity injected will be the scrubbing test at the beginning of the year. For these predictions, the 2010 injections with 48 bunches during the scrubbing test in November were used. The 48 bunch injections had not been optimised. Table 3 is summarising the estimates in terms of expected losses.

Table 3: Loss maxima per injected intensity: projection to 2011 using the non-optimised 48 bunch injection from 2010

| **Loss Type** | **Losses in % of dump threshold B1/B2** | | |
|---|---|---|---|
| | **48 b** | **96 b** | **144 b** |
| TCDI shower | 23/24 | <50 | <75 |
| Uncaptured beam | 20/8 | <40 | <60 |

From Table 3 it can be concluded that for 2011 no mitigation is required to live with the injection losses. An uncertainty however comes from the losses on the transfer line collimators. The data of 2010 is based on small emittance beams, with emittances smaller than 2.5 μm. In 2011 partly nominal emittances will be used.

## Mitigation: Transfer Line Collimators

Different possibilities of mitigation for the LHC BLMs triggering on transfer line collimator showers are being investigated. Placing shielding between the TCDIs and the LHC BLMs and opening up the TCDIs from 4.5 $\sigma$ to 5 $\sigma$ are possibilities which could be put in place without having an impact on the machine protection functionality of collimators or BLMs. If this is not sufficient so-called "BLM sunglasses" could be the solution. "BLM sunglasses" would ensure that the BLMs in the injection region do not take the losses during injection into account for interlocking, as under these conditions the losses come from the outside of the vacuum chambers and do not correspond to a loss scenario the LHC BLM thresholds have been designed for. "BLM sunglasses" would mean a modification of the machine protection functionality and have to be carefully designed if needed. More on the different mitigation possibilities for losses due to TCDI showers can be found in [2].

## Mitigation: Uncaptured Beam

Like for the losses from the TCDI showers, shielding could be envisaged downstream of the TDI. Studies are ongoing. A reduction of the capture losses during capture itself is probably not realistic, especially not for nominal bunch spacing. A promising active method to reduce the amount of unbunched beam around the circumference is cleaning.

Abort gap cleaning switched on during injection reduces the maximum losses towards the end of the filling by a factor 3. The results of a test filling with and without abort gap cleaning is shown in Fig. 5. Abort gap cleaning is fully operational at injection and was extensively used during the scrubbing test, where injections took place over many hours.

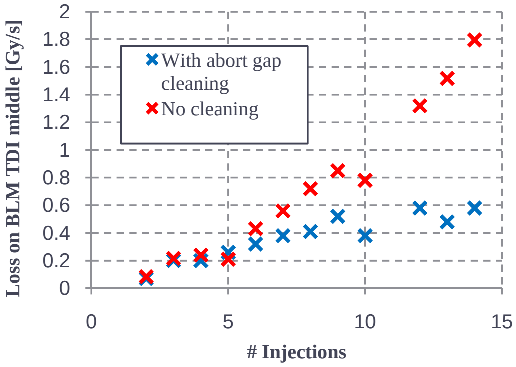


Figure 5: Abort gap cleaning on during injection reduces the losses towards the end of filling by a factor 3.

Even better results can be achieved by introducing injection gap cleaning in addition to abort gap cleaning. Injection cleaning cleans the location of the next injected batch before the new beam is injected using the same technique as abort gap cleaning [3]. Fig. 6 illustrates the optimum cleaning situation during filling with abort gap cleaning and injection cleaning. The results obtained with injection cleaning and abort gap cleaning during a test filling are shown in Fig. 7. The losses due to unbunched beam on the TDI are reduced by a factor 10.

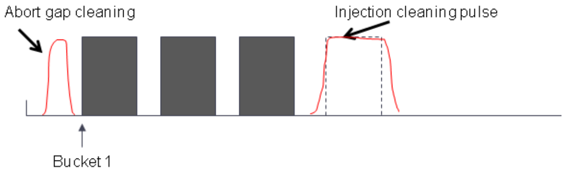


Figure 6: Illustration of injection cleaning: before the next batch is injected the longitudinal space for the next injection is cleaned using the same technique as abort gap cleaning. In grey the already injected batches are shown.

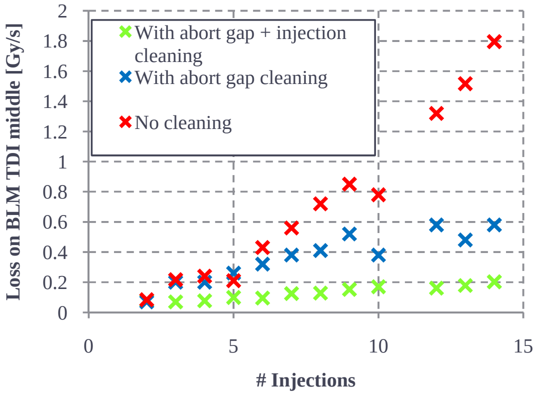


Figure 7: Abort gap cleaning and injection gap cleaning on during injection reduce the losses towards the end of filling by a factor 10.

## SUMMARY

The LHC injection phase has been identified as the most inefficient period. On average 3 h had been spent at injection during the high proton luminosity phase in 2010. Improvements have been proposed for certain areas. The injection procedure will be adapted concerning over-injection, intermediate intensities and communication with the injectors. More diagnostics and improved tools are being prepared. Losses at injection might become a limiting factor for higher intensity injections. The expected maximum injected intensities in 2011 however do not require any mitigation yet. Mitigation is being studied and prepared. Abort gap cleaning and injection gap cleaning gave promising results in significantly reducing the losses due to unbunched beam during the injection pulse.

## REFERENCES

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