THE LHC INJECTION SEQUENCER

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Abstract

The LHC injection process is controlled by the injection sequencer. Predefined filling schemes stored in the LHC control database are used to indicate the number of injections, the type of beam and the longitudinal place of each. The injection sequencer sends the corresponding beam requests to the CBCM, the central timing manager which in turn synchronizes the beam production in the injectors. The injection sequencer is also in charge of giving information on the next injected beam to other LHC systems, e.g. instrumentation that need to be configured accordingly.

This paper will describe how the injection sequencer is implemented and its interaction with the other systems involved in the injection process.

INTRODUCTION

The LHC is the largest accelerator at CERN. The 2 beams of the LHC are colliding in four experiments. Each beam can be composed up to 2808 high intensity bunches. The LHC beam is generated at the source of the LINAC, and then accelerated in the Booster, PS and SPS accelerators to 450 GeV, before being injected to the LHC through the 3km long transfer lines called TI8 and TI2. The injected beam contains up to 288 high intensity bunches, corresponding to a stored energy of 2 MJ. This powerful beam could easily create damage, and many protections at different level are in place to prevent from any incident. To build for each LHC ring the complete bunch scheme that ensures a desired number of collision for each experiment, several injections are needed from the SPS to the LHC. The type of beam that is needed and the longitudinal place of each injection have to be defined with care.

The LHC injection sequencer is the user interface that allows the LHC operator to request the beam to be injected into the LHC, following predefined schemes created for the purpose of different type of operation like physics production, beam studies or injection tests for example. The request is transmitted to the central timing manager that will ensure the beam production in the injectors and synchronize the whole accelerator complex. In parallel other pieces of software have been implemented to check the beam at different stages and ensure that the injected beam has the requested characteristics (bunch spacing, bunch number, longitudinal position in the LHC…).

LHC INJECTION SCHEMES

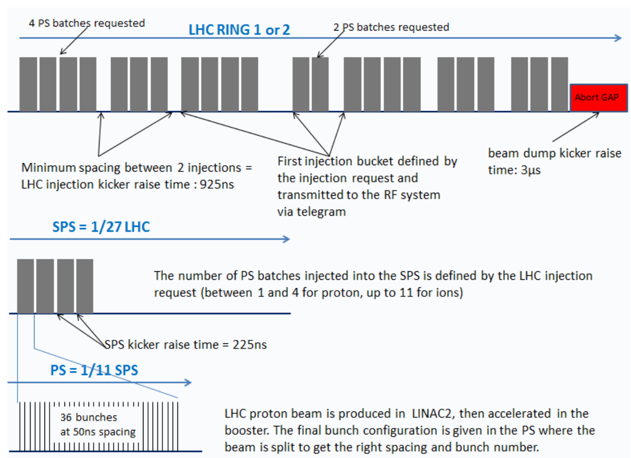

Figure 1: LHC injection scheme.

The LHC beam is constructed and shaped in the different injectors as showed in Figure 1. An example with 50ns bunch separation is presented, this is the beam that was used during the first 3 years of operation, but the nominal LHC beam has 25ns bunches separation.

The SPS beam for LHC is composed of a variable number of PS injections. Larger spaces appear in the bunch structure of the SPS batch due to the injection kicker raise time. Similarly in the LHC, 2 consecutive injections have to be separated by at least 925ns (LHC injection kicker raise time). In the LHC, SPS batches are injected at longitudinal positions defined by the first injection bucket. A gap of 3µs has to be left empty for the beam dump kicker raise time. The longitudinal distribution of beam 1 and beam 2 determine the number of collision in each interaction points.

An injection scheme is made-up of injection requests for beam 1 and beam 2. An injection requests specifies the number and distribution of bunches and the longitudinal position and ring of the beam. Many injections schemes are stored in the control database for diverse operational needs. In 2012 for luminosity production, beams of 1374 bunches were used, with a bunch spacing of 50ns. Full scheme was built with 12 injections per beam, the number of injected bunches varying from 6 to 144. The number of collisions was 1368 for Atlas and CMS, 1262 for LHCb and none for Alice.

ISBN 978-3-95450-139-7

INJECTION PROCESS MAIN ACTORS

The injection process involves a lot of equipment and systems that have a direct role in the injection process. Here are briefly presented the main actors:

Injection sequencer: the application that is responsible for the sequential requests of beam injection in the LHC to the CBCM.

CBCM [1]: the central timing manager that is responsible to orchestrate the LHC beam production in the injectors, and ensure the accelerator complex synchronisation by sending timing events and publishing information via telegrams.

Interlock system [2][3]: to ensure the safety of accelerator's equipment, interlock system are in place in every accelerator. In particular for LHC injection, there is a hardware and software interlock system per beam that will prevent any injection to happen if the status of the LHC equipment is not compatible with a safe injection. In SPS, there is also one extraction interlock system per extraction line. This system is independent from the injection sequencer, the requests can be sent even if an interlock is present. Depending on the interlock nature, the request will either be directly rejected by the CBCM, or SPS extraction kicker/LHC injection kickers won't pulse and the beam will be lost on a dump.

Injection Quality Check (IQC) [4]: after each injection, this software analysis the injection, then publishes the status of the injection (beam has been injected or not, with the right trajectory, demanded longitudinal position and acceptable beam losses). The injection sequencer relies on these analysis results to decide if the injection has been successful and if the next request can be sent. When the IQC analysis concludes that the injection quality was not good enough, it raises an injection software interlock to prevent the next injection to arrive. This interlock has to be manually reset by the operator if, after checking diverse parameters, he estimates that it is safe to inject again. For convenience, this reset can be done from the injection sequencer application.

LHC BQM: Beam quality monitor has a role in the injection process as a monitor of the beam presence in each LHC buckets

SPS BQM: beam quality check for the SPS, it will block the beam extraction from SPS if the beam characteristic doesn't meet predefined criteria. For example, the injection sequencer sends the expected bunch pattern before each injection to the SPS BQM. The beam is interlocked in case the measured pattern doesn't match the expected one.

SPS extraction kickers / LHC injection kickers: are informed by the CBCM of the next injection ring so that only the desired kickers are fired by the LHC injection events.

LHC RF synchronisation system [5]: it ensures the fine synchronisation of LHC equipment with beam by generating the revolution frequency and the kicker's prepulses. At the moment of the injection, the SPS frequency is rephased to the LHC injection frequency. The LHC injection frequency is delayed by the RF synchro system so that bucket 1 of the SPS is aligned with the first bucket of next coming injection.

LHC controls database: During the injection process, the injection sequencer updates the database with the active injection scheme, active injection request and circulating bunch configuration (list of buckets filled with beam). A database process publishes this information on change to LHC equipment and to the experiments.

Injection cleaning system [6]: when sitting at injection, the circulating beam can be slightly debunched and some beam can be found in the area of the next injection, implying unwelcome beam losses. Thanks to the transverse damper system of the LHC, the next injection area can be cleaned just before injecting. When a new injection scheme is created, the default status of the cleaning is set for this particular scheme as it is not needed for every kind of operation. In any case, in the injection sequencer application the operator can choose to enable or not the injection cleaning.

INJECTION PROCESS

Physics Beam Injection Pre-requisite

Once the LHC has been prepared for injection, i.e. all the magnet currents are at injection level, all collimators are at injection position, the operator has to request the mastership over the LHC cycles in the injectors. Getting mastership means that LHC sequencer has the control of the LHC beam production in the injectors. Once the mastership has been granted to the injection sequencer by the CBCM, LHC beam is produced only on LHC sequencer request.

The operator selects from the list of available injection schemes the scheme that is needed for the next LHC operation. The injection sequencer displays one list of injections per beam. Injection processes for beam 1 and beam 2 can be launched independently, the sequencer will ensure the synchronisation between the 2 processes.

Before starting the injection of the beam that will be used for physics, a pilot beam has to be injected. A pilot beam is a beam of only one bunch with a low intensity (<1E10 protons). It is used to make sure that there is no obvious injection problem, and to correct the main beam parameters like trajectory, tune and chromaticity. The interlock system enforces the use of a pilot before the physics beam is injected by preventing to inject a beam with a total intensity larger than 1.5E10 into the LHC when no beam is already circulating.

Injection of Physics Beams

Once pilot beams for beam 1 and beam 2 are there and all beam parameters corrected, the operator can launch the

ISBN 978-3-95450-139-7

injection process. He can choose to send request one by one manually, or start the complete sequence for both beams. The 2 injection processes are synchronised, the first process locks the request possibility while the other process is waiting. After the injection event has been received, the first process unlocks the request and the second process is notified that it can proceed with its injection request, and locks the injection process for itself until next injection event.

Figure 2 represents the simplified flow chart of an injection process:

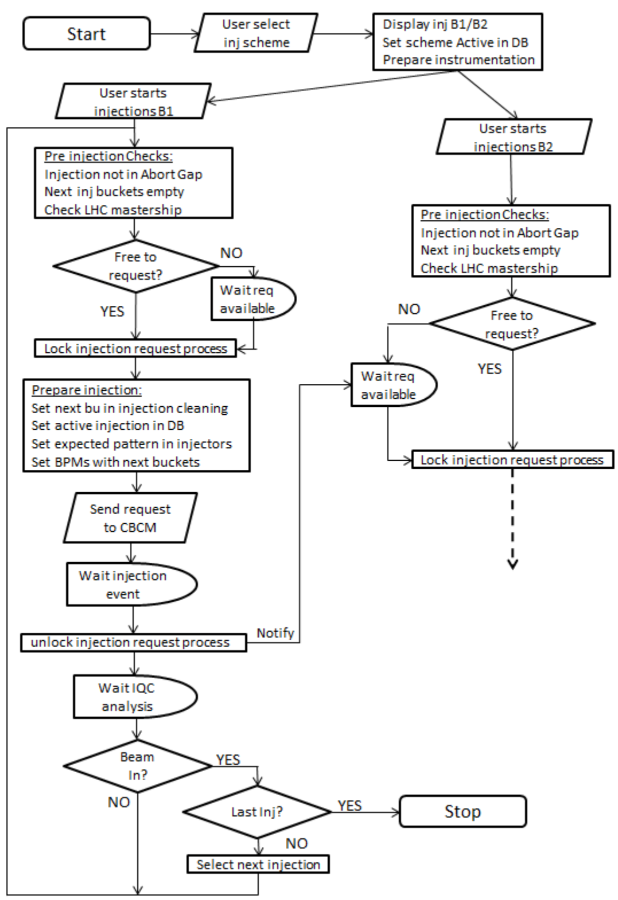

Figure 2: Simplified flow chart of the injection process.

The injection process starts with sanity checks before sending a request to the CBCM:

- Check that the LHC still has the mastership.
- Check that the first injection bucket is not in the abort gap keeper zone: to avoid injecting beam in the abort gap, the kicker doesn't pulse if the first injection bucket is closer than 8µs from the start of the abort gap, 8µs corresponding to the maximum beam longitudinal size (nominal 25ns beam with 4 PS batches).
- Check that the database circulating bunch configuration (list of filled bucket) agrees with the LHC BQM measurement, request the user to sort out the situation in case of incoherency.
- Check that there is no beam in the buckets that will be filled by the next injection by comparing next injected buckets and circulating bunch configuration in the control database.

Before sending the request to the CBCM, equipment needs to be prepared for the next injection

- The injection is set as active in the control database.
- If enabled, the injection cleaning system is set with the next area to be cleaned.
- The beam position monitors are set with the next injected buckets.
- Next expected pattern is set in the SPS BQM, this latter will prevent the beam to be extracted if measured pattern is not the requested one.

In case of problems during the injection preparation, the process is stopped and the system released for the other injection thread. Otherwise the injection sequencer sends the request to the CBCM.

Once the request has been accepted by the CBCM, meaning the configuration of the injectors allows for LHC beam production, the sequencer triggers the injection cleaning by the transverse damper. The cleaning will last the time needed for the injectors to produce the beam (around 30s) and be automatically stopped by the injection forewarning event a few milliseconds before injection.

The beam production in the injectors takes up to several minutes during which the sequencer is waiting for the injection event.

Receiving an injection event doesn't mean that the beam has really been injected; it may have been lost in the injectors, or extraction interlock may have prevented the beam to come out of the SPS. The injection sequencer relies on the IQC analysis results to know if beam is injected or not.

The IQC analysis is triggered by the injection event, after a few seconds of analysis it publishes the status of the injection, beam injected or not. The injection sequencer waits to be notified of a new IQC publication. If the beam has been injected, the next injection of the scheme is selected and the injection process continues. If it was the last injection of the scheme, the process is stopped. If the beam has not been injected, the same request is processed again. At any time, the user can stop the loop and the process will be stop at the end of the current injection.

The IQC also publishes the result of a more complete analysis that estimates the quality of the last injection according to predefined criteria like the beam position in the transfer lines, the beam losses level, check of the filled buckets… A process in the injection sequencer listens to the published result. A colour code has been defined for the injection quality: red=bad quality, orange= warning, green= good quality and blue=IQC is unable to analyse the beam properly. When a new IQC result is published, this process displays the last result and colours the corresponding injection line with the quality result

ISBN 978-3-95450-139-7

colour code (at the end of the injection process operators easily have a global view of the quality of all injections)

CBCM (Central Timing Manager)

The CBCM is orchestrating the cycles that are played in each accelerators by sending telegram information and timing events to all accelerator equipment for them to know which settings to play and when to start actions. The accelerator operators program manually in the CBCM the sequence of cycles to be played at a given time in every accelerator. When cycles in Booster, PS and SPS are linked as part of the same operation they are called "*beam*". Every *beam* is associated to a *beam destination*, for example SPS_DUMP, FIXED_TARGET, PS DUMP or EASTE_AREA according to the final destination of the beam. Figure 3 is an example of the beams and sequences configuration in LHC injectors.

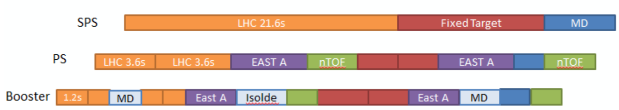

Figure 3: Example of sequences definition in the CBCM.

When the LHC is not requesting beam, injectors are running different cycles to serve their other clients. Once the LHC beam is dumped and LHC accelerator is being prepared for the next injection, the cycles for next LHC operation are prepared in the injectors. The LHC beam is not automatically included in the injectors on LHC's request, but need to be manually programmed in the sequence by the operators.

The CBCM needs to recognize the LHC cycles because they don't behave like the other injectors cycles, the operator has to make sure to tag them as "TO_LHC" cycles. The behaviour of "TO_LHC" cycles depends on the LHC mastership:

- When LHC does not have mastership, the LHC cycles behaves like normal cycles and are produced in the injectors with destination SPS_DUMP destination (meaning that the beam is dumped at the end of SPS cycle). This allows SPS operator to have control on the beam while they are tuning the parameters.
- Once LHC gets the mastership :
  - Beam is produced only on LHC sequencer request. In the absence of request, the cycles are played but the beam is cut at the linac by the tail-clipper.
  - The Beam destination becomes dynamic, meaning that it changes according to the LHC ring requested.

When the LHC sequencer requests an LHC injection, the request is sent to the CBCM with the number of PS batches to be injected, the destination ring and the first RF bucket. The CBCM will allow only the production of the requested number of PS batches by triggering the LINAC tail-clipper on unnecessary cycles. The dynamic destination will be set to LHC ring1 or LHC ring2. This information is published by the telegram. The kickers will fire or not accordingly. The RF first bucket information is received by the RF synchronization system that ensures that the SPS bucket 1 is aligned with the requested first injection bucket in the LHC.

This is a simplified view of the CBCM that doesn't reflect the complete complexity of the system that has for example to take into account a lot of external conditions for each accelerator. Complete information on the CBCM system for LHC injection can be found at the following web page:
http://wikis/display/CBCM/LHC+filling+2012

CONCLUSION

The LHC injection process requires the intervention of many equipment and systems in the entire accelerator complex from which the injection sequencer application is one of the main actors. Its role is to synchronise the beam request sent to the CBCM, but during 3 years of operation many functionalities have been incorporated to improve the injection process efficiency, distribute information on next injection request to different systems, guarantee coherency between database information and beam measurement and help the LHC operator to keep track of the injection quality along the process.

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ISBN 978-3-95450-139-7