

INJECTION BEAM LOSS AND BEAM QUALITY CHECKS FOR THE LHC

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Abstract

The quality of the injection into the LHC is monitored by a dedicated software system which acquires and analyses the pulse waveforms from the injection kickers, and measures key beam parameters and compares them with the nominal ones. The beam losses at injection are monitored on many critical devices in the injection regions, together with the longitudinal filling pattern and maximum trajectory offset on the first 100 turns. The paper describes the injection quality check system and the results from LHC beam commissioning, in particular the beam losses measured during injection at the various aperture limits. The results are extrapolated to full intensity and the consequences are discussed.

INTRODUCTION

Injection of the 2 MJ 450 GeV p+ beam into the LHC [1] is challenging given the high injected beam energy, the very small apertures and the tight tolerances on the delivery precision [2]. To fill the LHC with nominal intensity 12 injections per beam are required. In addition to the hardware and software interlock systems that ensure machine safety, parameters of several key systems are monitored automatically after each injection in order to rapidly verify injection quality and stop the injection process if needed. The Injection Quality Check (IQC) is designed to improve operational efficiency, by catching abnormal beam configurations and hardware problems.

To date the IQC system monitors the injection kicker pulse waveforms, the RF injection buckets and the beam losses in the injection region and at key locations around the ring. Additional checks are planned for the future, e.g. injection efficiency and injection oscillations.

In the following the main functionality of the IQC system is briefly described, including the currently used data sources and acquisition architecture. The analysis algorithms are explained. Finally, observations and issues seen with beam losses for overinjection and for injection of higher intensity bunches are discussed.

INJECTION QUALITY CHECKS

The IQC software is based on the LHC post-mortem framework [3] and composed of three layers: data collection, analysis server and GUI (Fig. 1), all written in Java. The data acquisition and the analysis are triggered by the INJECTION timing event. The analysis result is sent to the IQC GUI, to the Injection Sequencer, and the Software Interlock System (SIS). The Injection Sequencer orchestrates the whole injection process, and checks the

injection quality after each injection. The SIS inhibits the next injection in case of a bad IQC result. The operators need to analyze bad IQC results in the IQC GUI before they can reset the SIS and enable injection again.

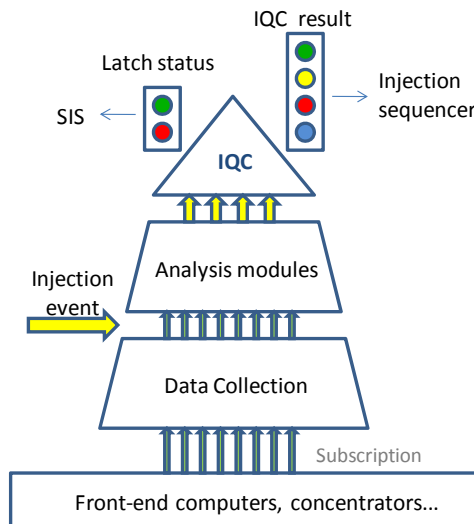


Figure 1. IQC architecture overview.

IQC Analysis

The analysis is carried out in two steps, and implemented as interconnected analysis modules. This is shown in Fig. 2 where the data flows from left to right. The boxes on the left represent the raw data acquired from the equipment, those in the middle represent the analysis modules, and the one on the right is a module that calculates the overall IQC result. Lines between modules represent the flow of data.

The IQC-Intensity module takes as input the beam current transformers from the injection lines and defines the intensity extracted from the SPS. The injection kicker (MKI), BLM and RF Bucket modules are discussed in more detail below. The different modules can be masked for testing purposes and setting-up.

At the end of this first level analysis the analysis results are combined in the overall IQC result. There are four possible IQC outcomes (and colour codes): good (green), repeat (yellow), bad (red), unknown (blue). The result of the IQC-Intensity module conditions the combined result. If no beam has been extracted (IQC-Intensity = false), the results of the other modules are not taken into account and the overall result is “repeat” for the injection sequencer. In case there has been beam extracted (IQC-intensity = true), the results of the other modules have to be true for an overall outcome of “good”

and to make the sequencer continue, otherwise it is “bad” and the sequencer stops requesting injections. If the data is missing the overall result is also “bad”. Missing BCT data results in the outcome to be “unknown”. In this case the injection sequencer stops requesting injections and also informs the operations crew to clarify the situation with the control room tools before continuing.

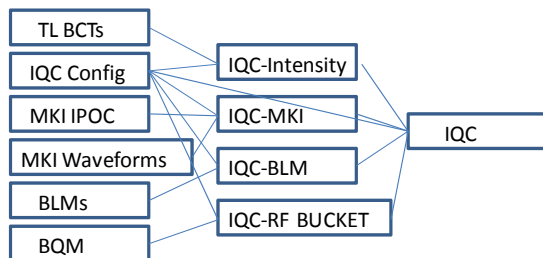


Figure 2. The IQC analysis is made at several levels.

INJECTION KICKER CHECKS

The IQC-MKI module ensures adequate quality of the kicker waveforms to keep emittance growth within specification and to survey the kicker hardware for possible degradations. It uses data from the waveform measurement and the Internal Post Operational Check (IPOC) software running on a front-end computer. The IPOC calculates characteristic parameters of the waveforms such as fall time, rise time, flat top length, etc. The IQC compares IPOC values to tight thresholds defined via the Management of Critical Settings (MCS) in the LHC operational database (LSA) [4]. MCS ensures that only authorised personnel can modify these thresholds on the IQC application.

RF BUCKET CHECKS

To collide the correct pattern of bunches or to collide at all for runs with very few bunches it has to be guaranteed that the RF synchronisation between the injectors and the LHC is working correctly and the bunches are in the correct buckets in the LHC. The IQC RF bucket check module compares the measured longitudinal positions of the bunches with the requested bunch configuration after each injection. Any discrepancy returns false and stops the injection process. The measured positions of the filled buckets are obtained by the LHC Beam Quality Monitor system using the RF wall current monitor.

BEAM LOSS CHECKS

The result of the comparison of losses with thresholds of the LHC beam loss monitor system is connected to the LHC beam interlock system. Going beyond these thresholds triggers the LHC beam dump. The IQC uses a special buffer of the BLM system, the capture data buffer, which is triggered synchronously with injection. The BLM concentrator concentrates data from several relevant crates (injection regions and LHC collimators) and downsizes it to 512 loss readings every 40 μ s around injection per BLM. The IQC BLM thresholds are even

tighter than those connected to the hardware interlocks to control the quality of the injected beam. Individual BLMs can be masked on the IQC without masking the entire module. This feature is used during commissioning and defining the threshold values through measurements. The thresholds (sum of the 512 samples and maximum over the data samples) are managed by MCS.

OPERATIONAL EXPERIENCE

Kicker Waveform

The IQC-MKI module proved already useful at the start of the 2010 LHC run. A bad contact developed on the measurement circuit of one Pulse Forming Network of the beam 2 MKI system. As the contact degraded the measured rise times and fall times became shorter until they hit the tight IQC thresholds. Experts then intervened and found a hardware problem which was repaired.

Beam Losses at Injection

Two separate issues concern the beam losses at injection. The first is overinjection. Because of the high injected beam energy, injection of a high intensity ($>10^{10}$ p+) beam into the LHC is only allowed if there is a low intensity bunch circulating, to avoid settings errors [5].

To allow the machine to be filled with the nominal bunch pattern, the circulating low-intensity probe bunch must be overinjected with a higher intensity bunch or batch, which occupies the same RF bucket. The injection kicker then also deflects the circulating probe bunch onto the injection stopper TDI (Target Dump Injection), conceived partly for this purpose. The resulting beam losses must not trigger any beam dump from the BLM system; during initial commissioning it was found that several monitors on the TDI were saturated from this beam loss, and that the signals were always above threshold. The issue was solved by removing the fully saturated TDI BLM from the interlock chain, and by integrating a RC delay with a time constant of 7 ms into the hardware of the corresponding BLMs. This allows extension of the upper end of the dynamic range of the ionisation chambers of the BLMs by a factor of 175.

The loss pattern for an overinjection of 5×10^9 p+ is shown in Figure 1. The losses are measured in Gy/s, but for a 40 μ s time window, such that the peak loss recorded is of the order of 10^{-3} Gy. The blue monitors are maskable channels (which means that they can be removed from the interlock chain for very low intensity only), and the green ones are on superconducting elements (and as well maskable). The dump thresholds are shown in red. The monitor on the TDI which is removed from the interlock chain is in grey, and the monitor near threshold on the TDI is in yellow. Several interesting features are visible. The large loss spike on the TDI is a factor of 10^5 above the background level. The loss pattern decays steeply after the DI, with alternate monitors recording higher losses, which is a signature of the beam losses being higher to the inside of the ring (injection is from outside).

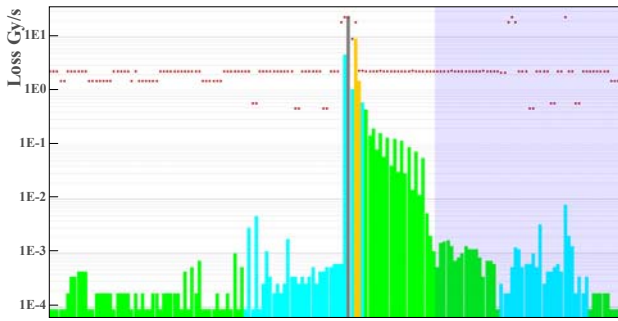


Figure 3. Beam1 losses in the LHC injection region IR2 for overinjection onto 5×10^9 p+.

The second issue is the cross-talk from losses on the transfer line collimators TCDI (Target Collimator Dump Injection). These are set at $\pm 4.5 \sigma$ to protect the LHC aperture, and any beam tails will be cut. At the end of the transfer line the TCDI collimators are right next to the LHC superconducting dipoles, and large signals are seen on the BLMs on magnets over about 100 m, Figure 4.

The losses shown were recorded after the addition of RC filters to some monitors giving a factor 175 extension in the dynamic range. The losses are about $\times 10$ below the dump thresholds, so a factor of 30 improvement is still needed for full intensity injection of 288 bunches. The thresholds can be further adjusted by maybe a factor 3-5, and a further factor 6-10 will need to be found, possibly by scraping the beam tails in the SPS [6] or by opening slightly the TCDI collimators if the extra margin given by the better-than-specified LHC orbit allows.

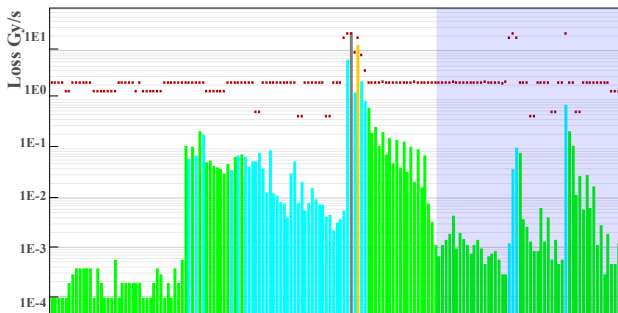


Figure 4. Beam1 losses in the LHC injection region IR2 for the overinjection of 1.1×10^{11} p+ onto 5×10^9 p+.

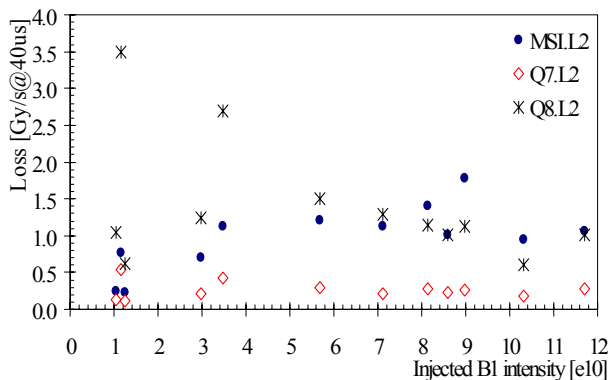


Figure 5. Beam1 losses from TCDI cross-talk in the LHC injection region IR2 for the injection of 1 to 11×10^{10} p+.

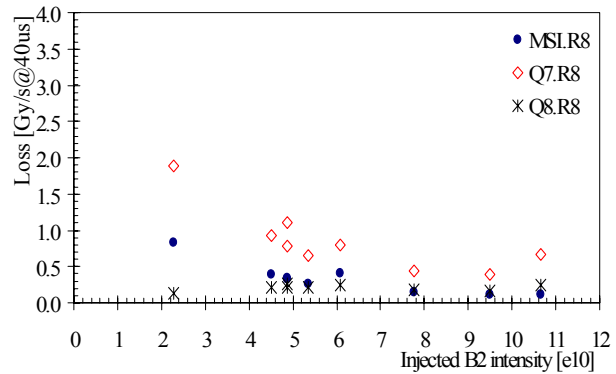


Figure 6. Beam2 losses from TCDI cross-talk in the LHC injection region IR8 for the injection of 1 to 11×10^{10} p+.

Concerning the evolution of these losses it was found during the intensity increase that the losses were actually worse for the lower intensity injected beam, Figures 5 and 6. This is almost certainly due to the method of producing the single-bunch beam in the LHC injectors.

SUMMARY

The Injection Quality Check (IQC) software has been put in place to monitor hardware and guarantee adequate injection quality for the LHC. It analyses key injection systems and beam parameters at each injection and notifies the injection sequencer with the result before the next injection. The different analysis modules of the IQC have already proved to be useful to maintain clean injections and prevent hardware problems. Beam losses on the transfer line collimators and from the operationally required overinjection are an issue with the tight thresholds and limited dynamic range of the monitors on superconducting elements, and must be addressed before injection of a nominal full LHC batch.

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