AUTOMATIC INJECTION QUALITY CHECKS FOR THE LHC

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Abstract

Twelve injections per beam are required to fill the LHC with the nominal filling scheme. The injected beam needs to fulfill a number of requirements to provide useful physics for the experiments when they take data at collisions later on in the LHC cycle. These requirements are checked by a dedicated software system, called the LHC injection quality check. At each injection, this system receives data about beam characteristics from key equipment in the LHC and analyzes it online to determine the quality of the injected beam after each injection. If the quality is insufficient, the automatic injection process is stopped, and the operator has to take corrective measures. This paper will describe the software architecture of the LHC injection quality check and the interplay with other systems. Results obtained during the LHC run 2011 will finally be presented.

INTRODUCTION

The LHC is filled through two transfer lines (TI2 and TI8) from the last pre-injector, the SPS. Currently the LHC runs with 1380 bunches per beam, which require 12 injections (plus one low intensity bunch) per ring. The maximum number of bunches per injection is 144 corresponding to 1 MJ stored energy.

Injection is a complicated process. The correct number of PS batches has to be injected in the correct RF bucket in the LHC. The injector timing system [1] and the LHC RF system ensure LHC dynamic injection requests and synchronisation. The extraction event from the SPS is forwarded to the LHC timing system as LHC injection event to trigger beam instrumentation.

The series of required injections is pre-programmed as an injection sequence driven by the injection sequencer. According to the filling scheme requests are sent to the injector timing system. At each injection the injection quality check (IQC) analyses data from key equipment in the LHC and the transfer lines and provides a result instructing the injection sequencer how to proceed: continue, stop or repeat the same request.

The IQC also provides software interlocks which are picked up by the software interlock system (SIS) and inhibit injections. A GUI for visual display of the detailed result is provided for monitoring and operator interaction, see Fig 1. The interplay of the IQC with other systems is shown in Fig. 2. There is also a playback tool for reviewing events. This paper presents the IQC architecture and results from the LHC run 2011.

Figure 1: IQC GUI for monitoring and operator interaction. BLM panel showing loss distribution over the injection region.

LHC INJECTION QUALITY CHECKS

The injection quality check analysis is triggered automatically at each LHC injection event. Only data which has a time stamp within a certain time window around the injection time stamp are accepted. This window is set individually for each system and ranges from 1 s before the injection to 6 s after.

The analysis is composed of separate analysis modules which are launched as soon as the required data is ready. The different modules are combined to an overall result at the final stage.

Data collection takes on average 4.5 s and analysis about 0.5 s. In case of missing data the analysis automatically times out after 10 s. The injection sequencer and IQC analysis are independent for beam 1 and beam 2. In this way the next injection can already be requested while the analysis on the other beam is still ongoing.

IQC Architecture

The IQC uses the LHC post mortem framework for data storage and analysis [2]. Data collection as well as analysis are written in JAVA and are running on JAVA servers. The results are published through Java Messaging System (JMS) and are picked up by the by the injection sequencer, the SIS and the IQC GUI.

For threshold management the IQC analysis uses the LSA Management of critical settings [3]. The thresholds can be modified by experts in the IQC GUI.

Event data stored on the post mortem server can be replayed offline on a separate, but identical application. This feature can be used for diagnostics of previous events, for testing and to make statistics.
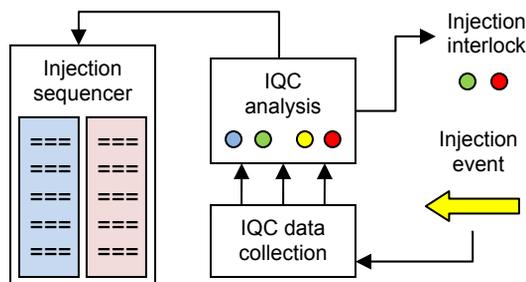
Figure 2: Figure showing the interplay of the IQC with injection sequencer, the SIS (Injection Interlock) and timing system. The analysis is triggered by the injection event. The overall result is published to the injection sequencer, and flags are produced for the SIS.

ANALYSIS MODULES

Correctly Filled Bunch Pattern

Not every injection request is successful. Due to bad beam quality beam might not even be extracted from the SPS. To determine whether the beam was injected into the LHC, the results of the upstream and downstream BCTs in the transfer lines are combined with the BQM result. Three devices are used for the analysis due to reliability issues of the BCTs in the transfer lines. If the devices disagree the overall outcome of the IQC is UNKNOWN.

The LHC BQM uses the wall current monitors to find the longitudinal positions of the injected bunches [4]. In the module RF bucket check, the IQC compares this information with the requested filling pattern. In case of inconsistency the IQC stops the injection sequencer.

Injection Kicker Checks

The LHC injection kicker system (MKI), consisting of four vertical kicker magnets per beam, needs to have a short kicker rise time of less than 1 μs, little ripple on about 8 μs long flattop and fall times not longer than 3 μs, [5]. The characteristics of the injection kicker waveforms generated by oscilloscopes in the tunnel are analysed by the IQC after each injection. With the tight IQC thresholds deterioration of the kicker characteristics are noticed immediately.

Beam Losses

The module which is used mostly and provides very useful information for injection tuning is the beam loss module. At each injection the beam loss monitor crates of interest are triggered to produce a special buffer for the IQC, consisting of 512 beam loss samples per monitor around the injection event with 40 μs integration times.

The transfer line collimators (TCDIs) are at the end of the lines and losses on these are seen on the BLMs of the LHC superconducting magnets. The BLMs have low dump thresholds and small losses on the transfer line collimators can already lead to a beam dump while filling the LHC. The loss profile from the transfer line

collimators is a valuable diagnostic for beam quality problems in the transverse plane.

Also the losses around the protection devices (TDI, TCLIa, TCLIb) protecting against injection kicker failures are shown. Losses from uncaptured circulating beam, satellites or uncaptured beam from the injectors as well as nominal beam in case of kicker problems ends up on these. The loss signature for the different cases is typical and is used for problem identification. Fig. 3 shows the loss distribution plot from the IQC BLM panel.

In addition to the LHC ring data the beam loss monitors in the transfer lines are also recorded.
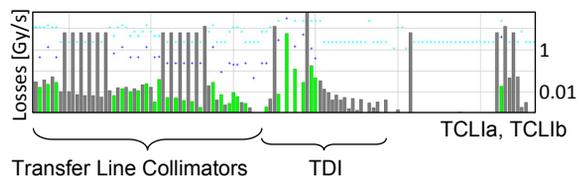

Figure 3: Distribution of beam losses as seen in the IQC GUI. The beam loss pattern is used to indicate the source of losses.

Injection Oscillations and Transfer Line Trajectory

The setting of all the protection devices in the LHC is valid for a given aperture in the machine. The settings have to include tolerances for orbit distortions, energy errors, beta beat and injection oscillations. If the injection oscillations are larger than the tolerance, protection against beam impacting the aperture during e.g. injection kicker errors cannot be guaranteed.

Orbit information as well as turn-by-turn data from BPMs triggered at injection is acquired by the IQC in the LHC injection regions. The injection oscillation amplitudes have to be below the IQC limit of 1.5 mm (1.75 mm for TI 2 H).

If the limit is exceeded, the SIS inhibits injection of high intensity for that particular beam. A special flag is provided by the IQC for the SIS for that purpose. Low intensity (about 10^{12} protons) can be injected to correct. The flag is automatically reset as soon as the injection oscillations are within limit again.

The reading of the BPMs in the transfer lines are also recorded in the IQC. The trajectory offsets in the transfer line collimators have to be minimised to reduce losses.

2011 EXPERIENCE

Since the first running period in 2010 the IQC analysis has become an integral tool of understanding injection problems and optimising injection efficiency. The beam loss monitor results are used routinely.

Statistics From Mid July to Mid August 2011

60 LHC fills from mid July to mid August 2011 were analysed. Within this period 1483 IQC analyses were triggered. The IQC latched 7.9% of the time indicating quality issues. For 11.7% of the events the expert warning result was given due to beam losses. The full distribution

of results is given in Fig. 4. For a detailed distribution of failures see Fig. 5.

During the period of these 60 fills the injections were very clean. The beam scraping in the SPS was used at maximum to cut beam tails. No other injection issues occurred. The less than 1 % of IQC result "UNKOWN", associated with missing data, indicate the good performance of the overall system.
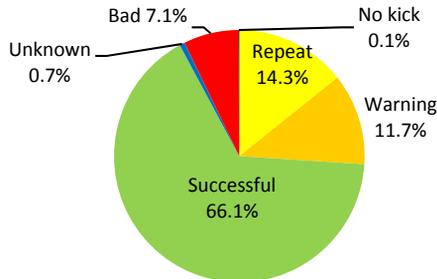

Figure 4: Distribution of IQC results over a period of 60 fills. In total there were 1483 injection events, where 7.9% latched.
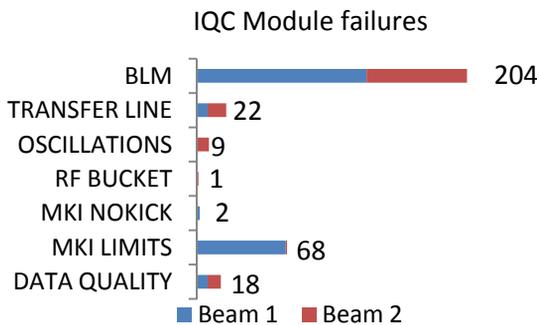

Figure 5: Distribution of module failures over 1483 injections; beam losses, transfer line (BLMs and BPsM), injection oscillations, RF bucket check, MKI not pulsed, MKI waveform out of thresholds, bad data quality. The total number is given right of the plot, the bars indicate the distribution between beam 1 and beam 2.

Data Collection Issues

The IQC is depending on a large number of data sets from many sources. In case of missing data the IQC automatically stops injection. During the commissioning run of 2010 events with missing data were frequent. All data collection problems could be solved during the winter shutdown and the beginning of the LHC run in 2011. The remaining issue is the data quality from the transfer line BCTs we still frequently have issues with the data quality. During the analysed period of above for 47.9% only one of the BCTs produces data or the two BCTs give inconsistent data. For the total of 60 fills analysed for only 18 events (1.2%) a data set was missing and caused an injection interlock.

Beam Quality Issues Discovered

In this section examples are presented where beam quality issues could be discovered due to the IQC results.

At the beginning of injecting full SPS batches into the LHC, consisting of 144 bunches, spaced by 50 ns, the IQC indicated large injection oscillations in the vertical plane for beam 1, see Fig. 6. It turned out that the injection kick length had not been long enough and some of the beam was kicked on the falling edge of the waveform. It was subsequently prolonged.
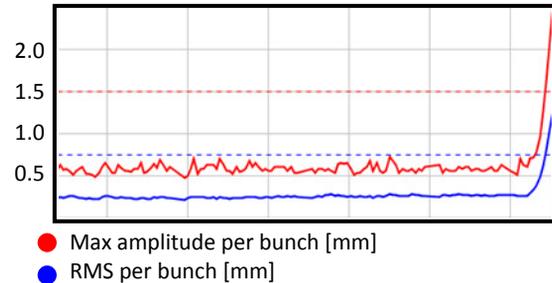

Figure 6: Injection oscillations in the vertical plane for 144 bunches. The last bunches had larger oscillation amplitudes due to too short kicker waveform. [23:21:38 20/6-2011]

The transfer lines suffer from trajectory stability problems in the horizontal plane [6]. Slow drifts, shot-by-shot and also large bunch-by-bunch variations have been recorded. The IQC injection oscillation analysis was very useful to detect the large bunch-by-bunch differences for beam 2 H, see Fig. 7. The source for these is probably the horizontal extraction kicker in the SPS. The issue is still under investigation.
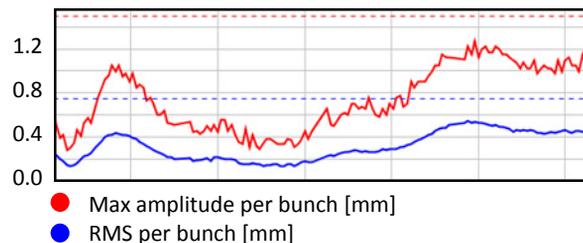

Figure 7: Injection oscillations amplitudes in the horizontal plane for 144 bunches for beam 2. A bunch-by-bunch variation of more than 1 mm was discovered. [01:28:57 25/9-2011]

On 18th of April 2011, 11 magnets were quenched during a high intensity injection attempt when an injection kicker flashover of one of the four beam 2 magnets occurred. The problem could be diagnosed immediately with the IQC MKI analysis indicating the shortened waveform for one of the four kicker magnets, see Fig. 8.

The IQC BLM buffer is now also used for studying very fast beam loss phenomena occurring shortly after injection, called UFOs [7].
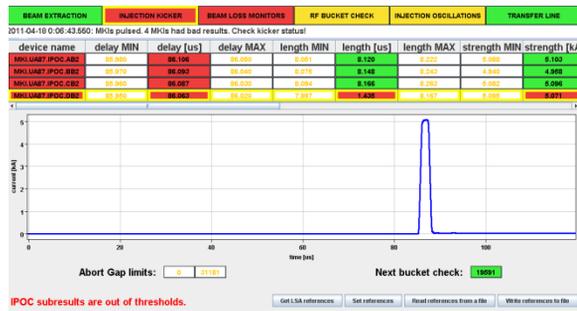
Figure 8: IQC MKI panel showing the MKI waveform of magnet D which had a flashover and had a length of about 2µs only instead of the required 8 µs.

CONCLUSION

The LHC injection quality check has become an important part of the LHC software suite ensuring good quality beams and injection protection. The chosen modular architecture based on the post-mortem framework has proved valuable and allowed stepwise commissioning and easy diversification of the analysis.

The IQC analysis is used offline and online on a routine basis to tune and improve injection. It has played a major role to achieve routine LHC filling with 1 MJ beams.

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