POTENTIAL ISSUES WITH INJECTING UNSAFE BEAM INTO THE LHC

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Abstract

Nominal LHC operation foresees to inject four batches of 72 bunches at the time. Injection of up to 48 bunches per batch has been tested in 2010 and possible intensity limitation and machine protection issues have been highlighted, in view of 2011 run. Beam leakage at LHCb and ALICE during injection and qualification of the provided protection are evaluated. Encountered and potential failures of the injection system are presented together with existing and required redundancy of the injection interlocks. Possible modifications of injection procedure and implication for filling schemes are discussed.

INTRODUCTION

Proton beams are injected into the LHC, at 450 GeV, via the transfer lines TI 2 and TI 8, in the combined experimental and injection insertions IR2 and IR8. The injection system comprises 5 horizontally deflecting septum magnets (MSI) and 4 vertically deflecting kicker modules (MKI) per beam. Any failure of the injection system causes the loss of the beam in a single turn. Typical examples are: wrong machine settings during injection, failures in the extraction from the SPS or in the transfer lines, MKI failures (i.e. BETS [1], erratic or missing kicks, wrong length and timing of the kick, magnet sparks, terminating resistor breakdowns, etc.). A robust interlock system has been put in place to protect the machine in case of injection failures. Tighter interlock thresholds and tolerances are needed when increasing beam intensity. Further passive protection is ensured by the collimators in the transfer lines (TCDI) and in the ring (TDI and TCLI). In particular, the TDI has been designed to withstand the impact of a nominal injection batch (288 bunches). This collimator must be set up correctly to intercept mis-kicked beams that could hit and seriously damage the machine. The TCLIs act as a complement and have to absorb any eventual leakage from the TDI.

2010 OPERATION

The “unsafe beam” limit for the LHC corresponds to $>10^{12}$ protons (10 nominal bunches). A maximum of 48 bunches has been injected during 2010 operation: a factor of 5 above safety. Two examples of failures, when injecting unsafe beam, are presented in the following.

Missing MKI Kick

The protection system prevents the MKI from firing, in case of any fault during extraction from the SPS. On October the 23^{rd}, the Abort Gap Keeper (AGK) stopped the MKI while injecting 32 bunches which, then, impacted on the upper jaw of the TDI. The showers of particles from the TDI induced high losses in IP2 and the dump of the circulating beam.

ALICE experiment is installed in IR2 and LHCb is in IR8. Dedicated simulations were performed, by people from the experiments, to evaluate possible dangers for the detectors when dumping 288 bunches at the TDI. The event presented provided ALICE with an important set of benchmarking data. Further tests were carried out, both for ALICE and LHCb, by changing the delay of the MKI kick, so that the injected beam was grazing on the TDI jaws, and evaluating the leakage at the experiments [2]. According to simulations and test results, no limit is expected on the intensity of the injected beam provided that the TDI is properly set up.

Wrong TCDQ Settings

LHC collimators are movable objects which have to be set up according to rigorous hierarchic rules in order to provide beam cleaning and machine protection. They have to define the smallest machine aperture (6σ = primary collimators half aperture) and follow the adiabatic beam damping during acceleration. One extraction protection collimator (TCDQ) was accidentally moved, trough the ramp function, to the 3.5 TeV settings while still at injection (TCDQ at $\sim 4\sigma$). The interlock system did not record any nonconformity since the thresholds were also changed according to the ramp function. Moreover, no visible loss was observed in the extraction region due to the slowness of the movement and the low intensity of the circulating beam (pilot bunch). The beam was dumped by the losses at the TCDQ when injecting 24 bunches. This incident highlighted the possibility of injecting unsafe beam in a mis-set up machine generating downtime and damage (for example of the tungsten tertiary collimators). Possible solutions to this problem are:

- Implementation of an energy interlock on the minimum allowed gap for collimators. At present, this interlock checks the collimator gap as a function of the energy and gives a fault only if it is bigger than a certain threshold [3].

- On line aperture measurements. This would allow to identify the minimum aperture and highlight eventual anomalies.
- State machine. This function should check any machine component and compare it with well defined references depending on operational conditions, beam process, etc.
- Compulsory re-injection of a pilot bunch after any change in the machine.

In general, the injection system worked as expected. Few failures occurred when injecting unsafe beam and they did not cause any machine damage. These incidents allowed to identify weak points and possible further upgrades of the system and of the injection process. The crucial role played by TDI correct setup in providing the very last protection, in case of any failure, has been highlighted.

INTENSITY LIMITATIONS DURING INJECTION AND POSSIBLE SOLUTIONS

Two main sources of losses were observed which could limit the intensity of the injected beam. Showers of particles, which are generated by the TCDI intercepting the beam tails in the transfer lines, are detected by the ring Beam Loss Monitors (BLM). These showers come from outside the magnet cryostat and do not constitute a danger for the machine, however, they would trigger a beam dump if above BLM thresholds. Losses from TCDI increase linearly with the intensity of the injected beam. A second source of losses is represented by the un-captured beam, from the SPS and the LHC, that is spread onto the TDI jaws. In this case the loss rate depends both on the intensity and the time between two consecutive injections. In both cases any limit in beam intensity is due to operation and not to machine protection issues. It is expected to be able to operate the machine, in 2011, with 108 bunches and to inject up to 144 bunches without mitigation [4]. Possible solutions to mitigate losses from TCDI cross-talks and un-captured beam are presented.

Non Critical

Some mitigation solutions do not present any drawback from the point of view of machine protection. For example, losses from un-captured beam can be reduced with abort gap and injection cleaning, as presented in [5], and by improving diagnostic and beam quality in the injectors. Moreover, the installation of shielding blocks close to the critical regions can help in reducing significantly particles showers. Energy deposition studies showed that an appropriate shielding close to the TDI could reduce the signal at the BLM triplet magnets, in IP2 and IP8, by a factor of 10. Three TCDIs (2 for Beam 1 and 1 for Beam 2) have been identified as critical. Shielding has already been installed in TI2, as illustrated in Fig 1, and is is expected to improve the signal at the ring BLMs by up to a factor of 8. Shielding is more complicated in TI8, due to the small available space, and requires a special support. A factor of 4 gain was calculated for this location.

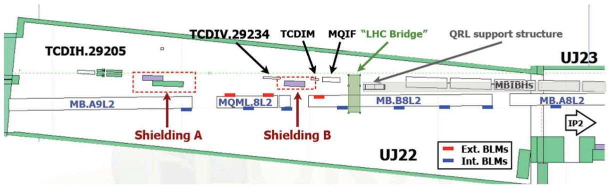

Figure 1: Shielding installed in TI2 to reduce the signal at the BLM in the common region of LHC and transfer line tunnels.

Critical

Supplementary techniques, which could provide a further improvement but might also have an impact on machine protection, are under study.

The TCDIs define a generic single pass protection system and have to provide a full phase space coverage. Due to optics and space constraints, there are only three collimators (double jawed) per plane installed at the end of each transfer line close to the LHC. The settings of these collimators depend on the aperture available for the injected beam. Nominally, the TCDIs are set at 4.5σ to protect a theoretical aperture of 7.5σ. It was shown that a factor of 4 reduction in cross-talks can be obtained by opening the TCDIs by 0.5σ. Moreover, measurements showed that the available aperture is about 10σ but an additional tolerance margin for orbit (2 mm), injection oscillations (1.5-2 mm) and energy offset has to be taken into account. Machine protection validation tests have been performed and showed that the required phase space coverage is obtained with the TCDIs at 5σ. Operation with higher intensity seems feasible with this setting. Further checks are anyhow necessary at the start-up in 2011 and when changing the filling pattern to re-validate the system.

Another promising option consists in the BLM sunglasses. The aim, in this case, is to temporary mask the BLM interlocks affected by cross-talks and un-captured beam losses during injection. A fourth crate should be added to the existing ones and, when receiving the injection pulse event, blind the affected BLMs for a fixed time. This is a critical procedure since the BLMs will be also blind to eventual dangerous losses. Requirements for this system are:

- SIL level equivalent to both BLM and BIS systems
- Fail safe design
- Fixed time-out duration (hard-coded, no remote way to modify it)
- RF pulsed period: maximum repetition rate fixed by hardware

- Cross-check with the energy value
- Remote monitoring of the input and output signals

The definition of the blinding time is crucial since it has to allow the distinction between good and bad injections without compromising machine safety. An example of good injection is shown in Fig. 2 for 36 bunches. The blue line represents the ratio between the losses (black line) and the BLM thresholds (red line) as a function of the integration time. A factor of ten margin between losses and thresholds is required in order to be able to inject a full intensity batch (i.e. blue curve below green line). The signal of the presented BLM should be masked over 80 μs; this is an acceptable time-out since it corresponds to less than 1 turn and the system could not provide any protection for these losses. A full data analysis is ongoing to evaluate if, in case of good injection, the BLM signal stays above thresholds for longer running sums. An acceptable limit for the blinding time has to be defined (320 μs ?). A bad injec-

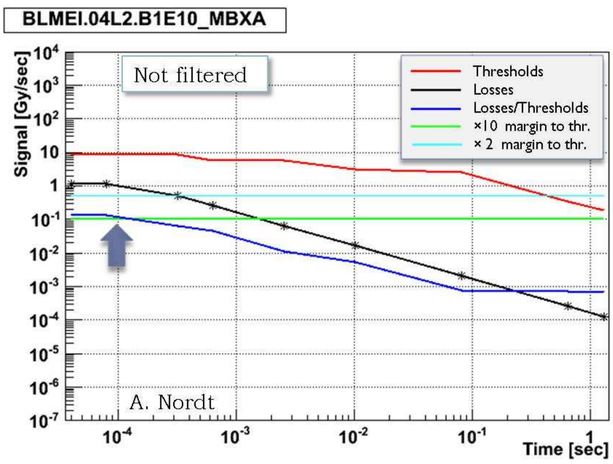

Figure 2: An example of good injection of 36 bunches is shown.

tion is shown in Fig. 3 for a not filtered (top) and a filtered monitor (bottom). A high level of de-bunched beam was in the machine due to an abnormally long waiting time between two consecutive injections. As expected in case of bad injection, the factor of 10 margin is obtained after a considerably long integration time: 655 ms. Filtered monitors need a longer period for collecting the charges and they should not be connected to the sunglasses crate since they would increase the required blinding time.

In total one expects that about 20-30 BLMs should be connected to the new crate (BLM families: TCTVB, MQX, MBX, TCLI, TDI, MQ6, MQ7, MQ8, MSIA and MSIB). The question if it is possible to profit of redundancy from other BLMs, located nearby the masked ones or in the cleaning insertions, to guarantee the required protection in case of losses is addressed. In addition, the possibility of increasing the BLM thresholds for short running sums is considered. The studies presented are very preliminary and effectiveness and reliability of this solution have to be fully

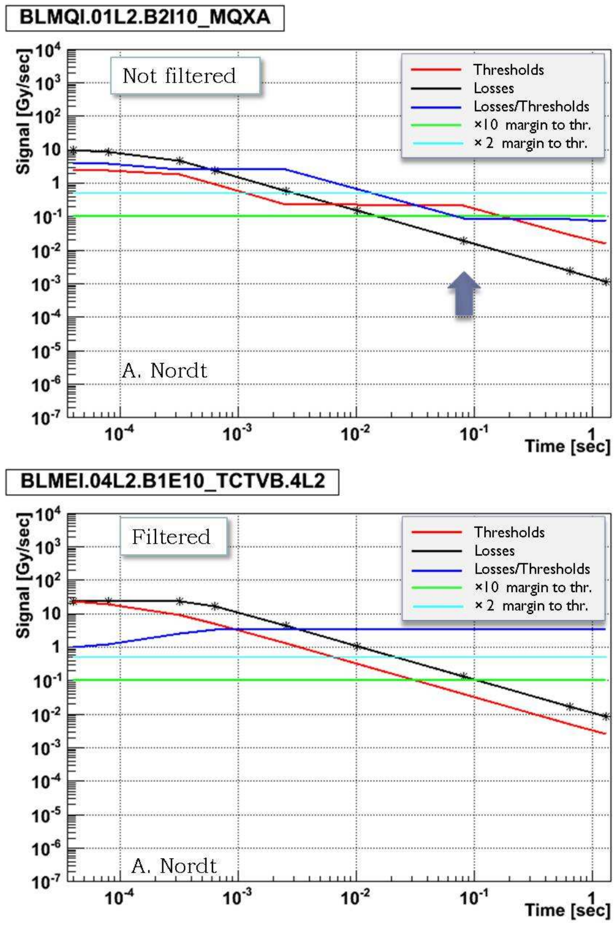

Figure 3: An example of bad injection of 32 bunches is shown for a not filtered (top) and a filtered (bottom) monitor.

probed. A machine protection review will be made after the completion of these studies before eventual implementation and commissioning of the sunglasses (middle/late 2011).

INJECTION SYSTEM UPGRADE

The main change applied to the injection system, during the Christmas technical stop, concerned the position interlocks logic for the injection protection collimators. According to the old logic, common to all the LHC collimators, any jaw movement outside position thresholds would have been stopped inducing an injection inhibit (for TDI, TCLI and TCDI). The collimators have to be moved, for mechanical and operational reasons, during the nominal machine cycle. In particular, TDI and TCLI have to be open to parking position after injection, before the start-up of the energy ramp. This action required to open also the position thresholds to parking with the consequent risk of injecting the beam with the injection protection collimators not correctly set up. The new logic allows to move these collimators outside thresholds, but it prevents the movement of TDI and TCLI into the circulating beam. In this way, thresholds can be kept at injection setting, collimators can be moved according to the operational needs and any injection will be inhibit in case of wrong setup. Moreover, an energy interlock has been implemented, for TDI and TCLI, that forbids injection if the measured gap is bigger than defined thresholds. A software interlock has been introduced that force the MKI to standby before opening the TDI and TCLI. This ensures that the beam is dumped at the TDI in case of an erratic MKI kick.

A new interlock will be added to control injection oscillations when injecting high intensity beams. In particular, in case of bad injection oscillations, it will be possible only to inject an intermediate intensity. A new high intensity injection will then be allowed as soon as good oscillations will be recorded. The implementation of this interlock requires testing and stability of the Injection Quality Check (IQC) module and beam commissioning time.

CONCLUSIONS

The fundamental importance of a correct machine status during injection has been discussed in this paper. In particular, injection protection collimators have to be properly set up to provide the required passive protection also in case of failures of other systems (for example MKI). The LHC ran already with unsafe beam in 2010, and a limit of 144 bunches is expected for 2011 operation. No limitation in intensity is foreseen to come from LHCb and Alice, which are ready for 288 bunches dumped on the TDI. Predicted intensity limitations come mainly from operational more than machine protection related issues. Possible uncritical an critical solutions to go to higher intensity have been presented. The upgraded and safer logic applied for the operation of injection protection collimators has been described. The principles for an interlock on injection oscillations have been introduced.

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