What is required to safely fill the LHC?

V. Kain, CERN, Geneva, Switzerland

Abstract

Machine protection consisting of passive and active systems will be used to prevent damage during the LHC injection process. Concerning beam 2, parts of the SPS extraction and transfer line beam interlock system has already been successfully tested during the TI 8 commissioning. Key elements of the final system for beam 2 will be validated during the LHC Sector Test with low intensity beam, together with parts of the passive protection system, the TDI and at least one transfer line collimator TCDI. The remaining issues after the sector test will be discussed in detail, where the entire injection protection system together with post mortem, management of critical settings, sequencer and software interlocking system must be tested with beam, for different intensities and filling patterns during the LHC beam commissioning. Requirements from other systems and interdependencies for test modes, such as inject & dump, are important input for the overall LHC commissioning strategy and will be discussed.

SYSTEMS CONCERNED

The different systems required for adequate injection protection are described in detail in [1].

Besides the actual injection into the LHC the injection protection system also has to cover extraction from the SPS in LSS4 and LSS6 and the transfer via the transfer lines TI 2 and TI 8, Fig. 1.

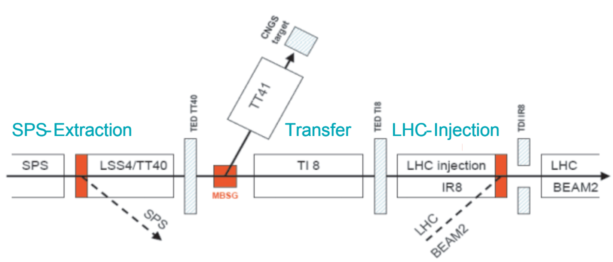

Figure 1: Overview of the injection process: extraction from the SPS in LSS6 and LSS4, transfer via the transfer lines TI 2 and TI 8 and injection into the LHC in IR 2 and IR 8.

The machine protection system consists of active and passive systems - active protection in the form of surveillance systems and interlocking to inhibit extraction/injection in case of failure; - passive protection with collimators and absorbers. The main characteristics of the protection systems are briefly summarised below.

Passive Protection: TCDI

Transfer line collimators (TCDI) are needed to protect the LHC aperture, assumed to be 7.5 σ at 450 GeV, from any failures upstream of the collimation section. They provide full phase space coverage with 3 double-jawed collimators per plane and a setting of 4.5 σ. The expected phase space coverage was simulated including nominal errors for setting-up, optics and trajectory and amounts to about 6.9 σ maximum amplitudes escaping the system, Fig. 2.

In total there will be seven collimators per line. The momentum collimator is at the beginning of the lines and the 6 betatron collimators are located in the last 300 m, mostly downstream of the last beam dump (TED), Fig. 3. This means that these TCDI need the LHC beam permit for setting-up. Concerning the commissioning this means that the LHC has to be ready to complete the beam commissioning of the collimators. In case of TI 8 the TCDI can already be tested with beam during the LHC Sector Test.

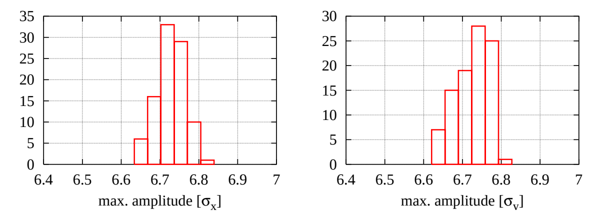

Figure 2: Expected phase space coverage with TCDI collimators as fraction of seeds versus maximum amplitudes escaping the system.

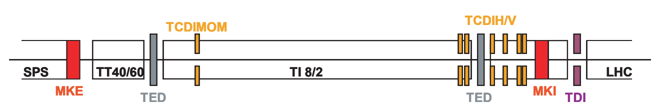

Figure 3: The momentum transfer line collimator is at the beginning of the line, the 6 betatron collimators are located in the last 300 m.

Passive Protection: TDI-TCDD-TCLI

The other passive protection system involved in the injection process is located in the injection regions in the LHC and consists of the 4.25 m long injection stopper TDI, the mask TCDD(M) and the auxiliary collimators TCLIA/B. This system protects the LHC against injection kicker (MKI) failures, the required setting is 6.8 σ.

The TDI will be installed 90° downstream of the MKI, followed by the mask TCDD in front of the superconducting dipole D1, Fig. 4. The TCLI collimators are located on the other side of the IP and complement the protection with the TDI in case of phase changes between the injection stopper and the MKI. TCLIA will be installed downstream of the experimental area close to the D1 and TCLIB close to the Q6 downstream of the insertion. A mask (TCLIM) is required to shield the superconducting quadrupole from possible showers generated in the collimator jaws.

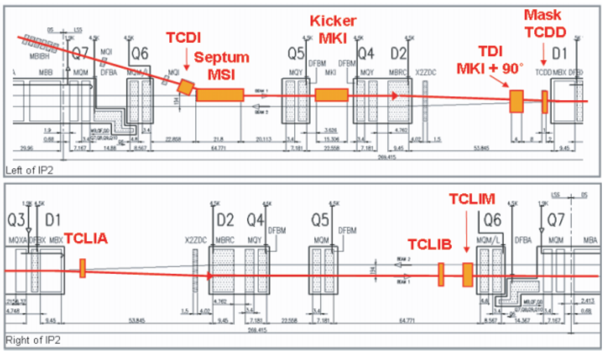

Figure 4: Horizontal overview of the injection region around IP2.

Active Protection

Active protection has to guarantee correct settings for SPS extraction, transfer lines and LHC injection via the surveillance of e.g.:

- magnet currents with ROCS surveillance and Fast Magnet Current Change Monitor (FMCM)
- collimator positions
- beam position in SPS extraction region
- SPS extraction septum girder position
- kicker charging voltage

Active protection also has to make sure that high intensity beam can only be injected into the LHC when beam is already circulating (beam presence condition). BCT signals from the SPS and the LHC are required to verify this condition:

- SPS safe beam intensity
- LHC beam presence

These two intensity signals (in the form of flags) along with the User Inputs from the surveillance systems are input to the Beam Interlock System (BIS) via Beam Interlock Controllers (BIC). A schematic of the BIS for the injection process of beam 2 as well as CNGS can be seen in Fig. 5.

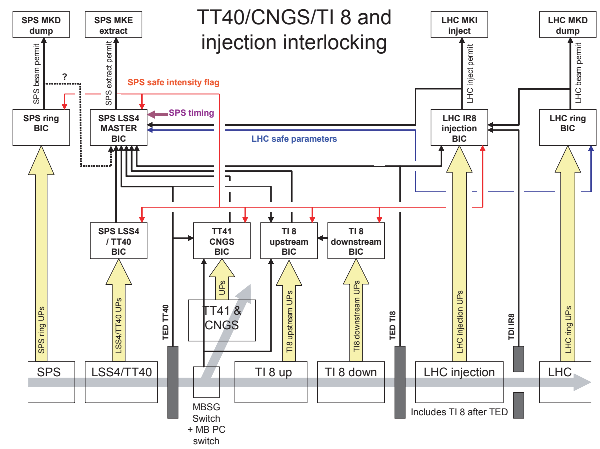

Figure 5: Schematic of the interlock system for the injection process of beam 2 and CNGS.

Software

Besides hardwired active and passive protection also a number of software ingredients are required for adequate injection protection.

Software interlocking system (SIS)
Beam quality aspects like trajectories along the transfer lines, but also screen positions and other less safety critical issues are covered by the software interlocking system.

Management of critical setting (MCS)
The MCS is a software to remotely manage interlock settings in a secure way. It needs the SIS for full functionality. The MCS will be used for a lot of surveillance systems of devices involved in the injection process, examples are the MKI, MKE, TDI, TCLI, TCDI, ROCS, BLMs, BPCE and MSE. The first version of this software is planned to be ready for the extraction and transfer tests in 2006.

Extraction/transfer/injection data analysis and diagnostics
A tool for extraction, transfer and injection data analysis and diagnostics is required. It will have to cover shot-by-shot beam quality checks to allow the next extraction/injection as well as post mortem analysis after abnormal situations e.g. in case of an interlock.

LHC injection sequencer
Setting up of the TDI and TCLI collimators needs to be driven by the LHC injection sequencer to guarantee coherency with the different injection preparation and filling steps. The sequencer will also have to provide the LHC machine mode inject & dump, which is required for setting up the transfer line collimators, as will be discussed below.

WHEN DO WE NEED INJECTION PROTECTION?

Injection protection **must** be in place and working correctly when the injected intensity exceeds the **damage limit**. The damage limit is assumed to be about 2×10^{12} protons at 450 GeV, corresponding to about 5 % of a nominal full batch extracted from the SPS towards the LHC.

According to the "overall commissioning strategy for protons" [2], injection protection is absolutely mandatory from commissioning stage II onwards.

Before a beam intensity above the damage limit can be authorised, formal tests and acceptance of the protection system performance are needed. Injection protection should hence be operational for 156 on 156 bunches and be commissioned at latest during the operation with 43 on 43 bunches.

The only exception are the TCLI collimators. They enhance the protection performance against injection kicker failures, the main protection however is provided by the TDI. The TCLIs are needed above an injected intensity of 50 % of nominal and can be commissioned later than the rest of the protection system.

There will also be some earlier milestones before the LHC start-up. The SPS extraction will be commissioned with high intensity during the commissioning of CNGS in 2006, TI 8 will be commissioned with higher intensity in 2006 and finally the LHC Sector Test will allow to test and verify procedures.

ISSUES AFFECTING THE COMMISSIONING STRATEGY

Before showing the time-line indicating when the different protection systems have to be in place and work properly, issues which might affect the commissioning strategy are discussed.

Transfer Line Collimators

The setting-up procedures for TCDI centering, alignment and beam size measurement for single pass in the transfer lines have to be defined. A possible single-pass method for the alignment was already tested during the TI 8 commissioning in 2004. This method is based on a transmission measurement with BCTs and non-local BLMs. The promising results of the tests can be seen in Fig. 6. In test phase 3 one of the jaws was moved into the beam and its tilt was varied by 300 μrad. This variation had a clear effect on the transmitted intensity on the downstream BCT. For a realistic set-up a complete scan of transmission versus tilt would have to be carried out with about 10 measurement points. The optimum alignment would then correspond to the maximum in the obtained transmission curve [3].

As already mentioned, the TCDIs need the LHC beam permit for setting-up and hence the LHC inject & dump mode. Thus the whole of the LHC has to be ready, the inject & dump mode working (interplay between sequencer, timing, BIS etc.) and the beam dump has to be commissioned, before the TCDIs can finally be commissioned with beam.

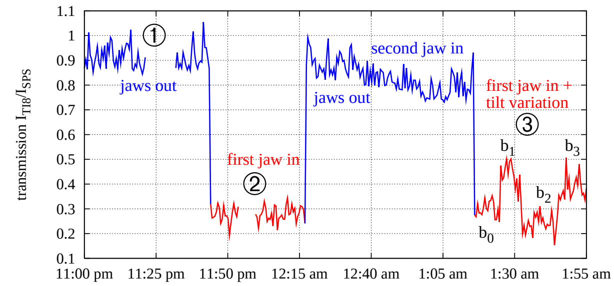

Figure 6: The transmitted intensity at the BCT at the downstream TED in TI 8 during a setting-up test of a collimator.

The transfer line collimators will be installed in the part of the transfer line which is already close to the aperture of the LHC superconducting magnets. Beam losses on the TCDI during nominal operation, during setting-up of the collimators or during accidental loss of a full batch on one collimator jaw could lead to quenches of the adjacent LHC magnets. FLUKA simulations were carried out where 70 m of TI 8 with the adjacent LHC were modeled and loss scenarios studied, Fig. 7. Preliminary results show that even for an accidental loss of a full ultimate batch the LHC magnets do not quench (assuming a quench limit of 38 $\mathrm{mJ/cm^3}$). The results for an accidental loss on TCDIV.87804 can be seen in Figs. 7 and 8.

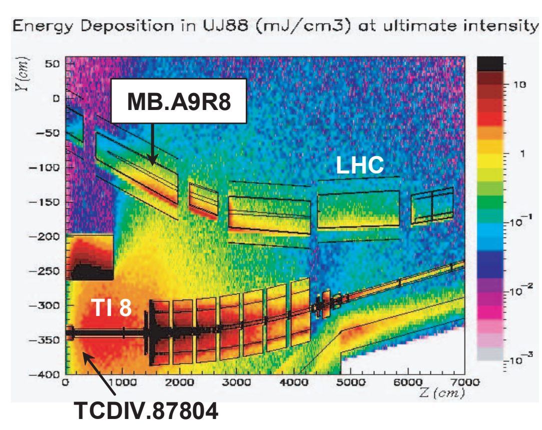

Figure 7: The FLUKA model to study losses on the TCDI and the resulting energy deposition in the adjacent LHC magnets. In this case a full ultimate batch was lost at TCDIV.87804.

TDI

The setting-up procedures for the TDI, the injection stopper, have not been defined yet. As this diluter is already in the LHC it can either be set up on the circulating

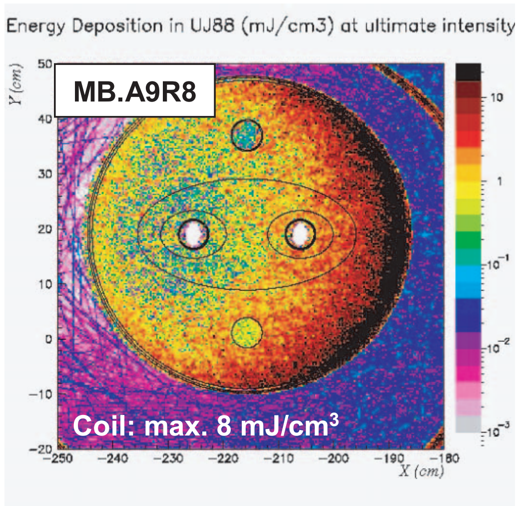

Figure 8: Energy deposition in MB.A9R8 for an accidental loss of a full ultimate batch at TCDIV.87804 in the TI 8 transfer line.

beam or on the injected beam. During the Sector Test it is (obviously) planned to set it up on injected beam.

The halo load on the TDI from the circulating beam is of concern. The baseline TDI does not include cooling and the out-scattered particles could lead to D1 quenches. In case of unacceptable heat load on the TDI or the D1, retracting the TDI further might be considered. In this case the TCLI collimators would be needed earlier than discussed before to provide sufficient protection of the LHC aperture, see also [4].

The reproducibility of optics and orbit at the location of the TDI (TCLI) is an issue and data from the Sector Test is eagerly awaited. Orbit feedback might be necessary.

The TDI is fixed in the horizontal plane and not much space is left for the non-injected beam, Fig. 9. The aperture for the non-injected beam has been validated according to the standard procedure for LHC apertures, Fig. 10, nevertheless care has to be taken as the TDI is a movable device.

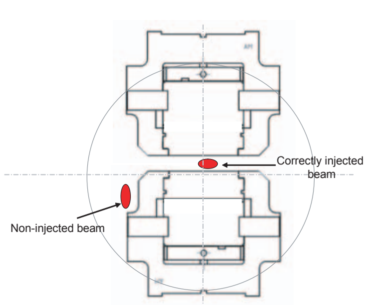

Figure 9: Cross-section of the TDI.

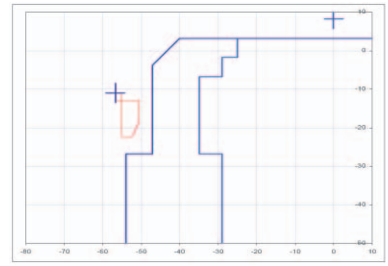

Figure 10: TDI at IP2: the available aperture for the non-injected beam corresponds to n1 > 7.

TCLI

One of the two TCLI collimators per injection insertion, TCLIA, will be installed in an area of the LHC where both beams share a common beam pipe. A special collimator design is required to accommodate two beams in one collimator tank. The TCLIs are vertical collimators, TCLIA however will most probably also need to be set up in the horizontal plane to provide enough aperture for the other beam. Special setting-up procedures will be required, where crosstalk between the beams might be of an issue.

Collimator Control System

All movable devices in the LHC and also the transfer line collimators will eventually be under a common collimator control system. It is not clear yet when this will be available. A rudimentary version of this system is required for the TI 8 tests and the Sector Test towards the end of this year to be able to test the TCDIs and the TDI.

The interplay of the MCS and the collimator control system has to be defined. One question to answer is whether to store absolute or normalised interlock settings for the collimators in the MCS. In the case of normalised settings the orbit at the device locations might be locally folded into the interlock setting.

At a later stage automatic setting-up procedures will be required (e.g. for 43 on 43 bunches). The automatic procedures developed by the collimation project for the ring collimators will be reused as much as possible.

Active Protection

Interdependencies are a general issue. As an example, for the testing of the interlocking functionality of parts of the surveillance equipment, the MCS and also the SIS have to be available.

About 15 magnet families involved in the injection process have to be equipped with FMCMs to guarantee safe injection [5, 6]. Three out of the 5 required for CNGS will be installed for CNGS commissioning, not all are available. TI 8 needs six in total. Whether TI 8 commissioning with higher intensity 2006 should/can take place if not all FMCMs are ready, has to be clarified.

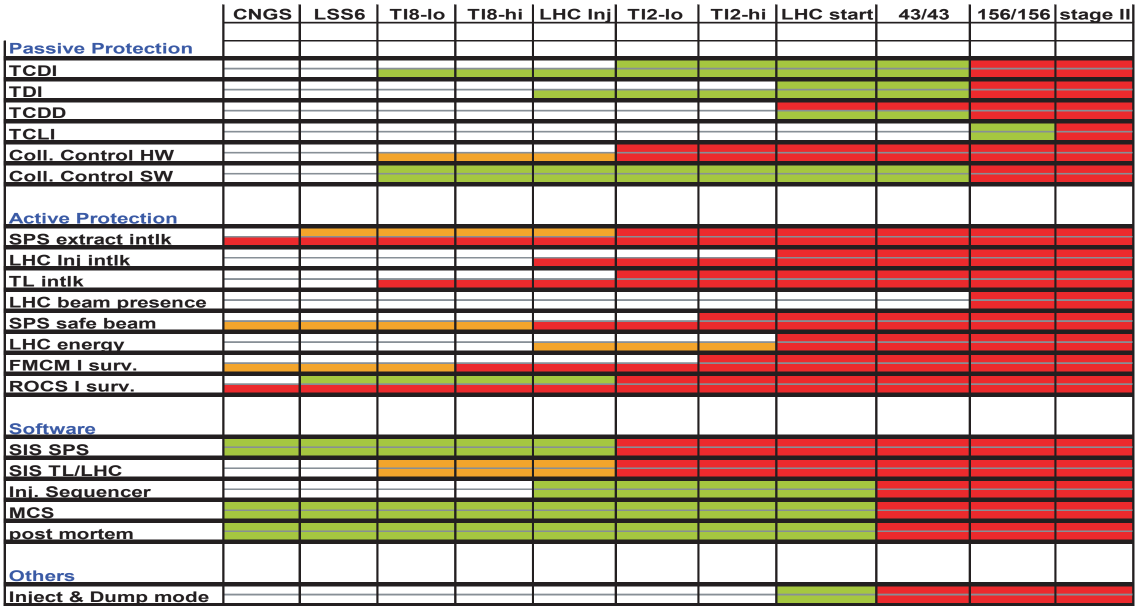

Figure 11: Time-line: systems required for the different commissioning stages. Each row is divided into a beam 1 and a beam 2 row. Colour code: green = installed & prototype test; orange = needed, but may not be fully available; red = installed & fully operational.

The protection level of the TCDIs depends on the momentum offset of the extracted beam. Sufficient phase space coverage can only be guaranteed for a momentum offset $\delta p < 5 \cdot 10^{-4}$, due to the partly large dispersion at the TCDI locations (e.g. TCDIH.87441: $D_x = 1.4$ m). An interlock on the SPS energy has to be in place.

With safe beam intensity, interlock signals like collimator positions can be masked. For the time being the value for the safe beam intensity is set to 1×10^{12} protons at 450 GeV. This leaves more than a factor of 2 margin to the assumed damage limit for nominal emittance. For runs with smaller emittance the safe beam intensity will probably need to be reduced.

SYSTEMS REQUIRED FOR THE DIFFERENT COMMISSIONING STAGES

Fig. 11 shows when the different protection systems have to be ready. On the left side of the table in Fig. 11 the systems involved in injection protection can be found and the top row lists the commissioning stages.

Many injection protection systems will already have to be operational a long time before the actual start-up of the LHC due to the tests in 2006, like the CNGS high intensity commissioning and the Sector Test. The passive protection devices belong to the last systems becoming fully operational, as they need the whole LHC ready for the final beam commissioning.

Discussion

Testing procedures and criteria to declare systems commissioned after each commissioning stage have to be defined (e.g. ready for pilot or ready for 43 on 43 bunches). How and where to represent, store and "move" between the allowed operating conditions (e.g. maximum current in the LHC, minimum emittance, number of bunches) has not been decided yet. A possibility would be to use the MCS to store the operating conditions for the current commissioning stage and the SIS as surveillance system to guarantee that the previously authorised operating conditions are respected.

CONCLUSIONS

Injection protection must be fully operational for 156 on 156 bunches in commissioning stage I. The main unresolved issues concern the machine protection state control and the passive protection system. For the machine protection state control the sequencer, the interplay between sequencer, MCS and SIS and the formalisation of the commissioning pathway have to be defined. The passive protection systems need setting-up procedures and a working collimator control system.

A lot of important tests of the injection protection system and procedures can and will be done during the TI 8 tests in 2006 and the Sector Test. A prerequisite however is that the TCDIs, the MCS, injection post mortem, the collimator control system, the injection sequencer for setting up the TDI, the safe beam intensity flag from the SPS etc. are available.

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