PROTECTION OF LHC AGAINST FAST FAILURES DURING INJECTION AND BEAM DUMP

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Abstract

The LHC transfer lines, injection and beam dump systems are equipped with a series of active and passive protection systems. These are designed to prevent as many failures as possible, for example through surveillance and interlocking, or to absorb any beam which is mis-kicked or mis-steered on passive absorbers. The commissioning, validation tests and performance of the different systems are described, and the implications for the protection of the LHC against different failures during beam transfer are discussed.

PROTECTION AGAINST FAST FAILURES

Transfer Lines

Each transfer line is equipped near the LHC injection with a series of six two-sided collimators TCDI with adjustable jaws, to limit the maximum beam excursion. The collimators are arranged in both planes at 60 degree phase advance, to provide optimum phase space coverage for the single pass [1-2]. The nominal setting of the TCDI jaws is ±4.5 betatron sigma.

Injection System

The injection kicker MKI can fire erratically or a switch can also fail to fire when required. Also a synchronisation failure could lead to the beam not being deflected, or to the circulating beam being kicked by mistake. Finally, the kickers can also fail with high voltage breakdown (flashover), which can in theory give a kick of any amplitude up to 125% of the nominal one.

To protect against these fast failures each injection is equipped with a primary protection device TDI, which is a 4m long two-sided collimator, nominally placed at 6.8 sigma from the beam. The TDI is 90 degrees in phase downstream of the MKI kicker, and therefore intercepts any miskicked injected beam with an amplitude greater that the jaw setting. A fixed 1 m long mask TCDD is placed in front of the superconducting dipole D1, to reduce the beam load on the coils of this magnet. The TDI is supplemented with two auxiliary collimators at phase advances of n×180 ±20 deg, which improve the system performance in the event of phase advance errors between MKI and TDI. The TDI and TCLIs are interlocked such that injection is only possible if the jaws are in position around the beam. After injection the jaws are retracted.

Beam Dump Failures

To protect the downstream elements against a beam sweep from an erratic kicker firing, protection devices are installed. A 6 m long composite fixed absorber (TCDS) is located in front of the extraction septum, and must dilute the impacting ~30 bunches to a level where the septum is not damaged. Another 6 m long single-sided absorber is located in front of Q4, to protect Q4 and also to limit the amplitude of beam escaping into the LHC. For this latter purpose this absorber is movable, and is placed at around 8-10 sigma from the beam. The TCDQ is supplemented by a short 1.2 m long two-sided graphite collimator TCSG which allows an accurate definition of the beam position, and also can be positioned more accurately than the long TCDQ. A fixed 2.4 m long steel mask protects the Q4 magnet coils from the showers from these elements.

The TCSG and TCDQ are closed during the ramp to maintain the correct position with respect to the beam. The jaw positions are ensured by HW interlocks, and an additional interlock is present on the maximum TCSG gap and TCDQ position which depends only on the LHC energy. The beam position at the TCDQ is maintained by the orbit feedback system and interlocked by the SW interlock system SIS. This is presently set at ±1.7 sigma at 3.5 TeV, corresponding to about. ±1.2 mm.

INJECTION PROTECTION SYSTEM COMMISSIONING

TCDI System

The TCDI alignment was made during a dedicated LHC filling sequence, where a minimum number of nominal bunches (to date 1 or 4) was repeatedly injected into the LHC, while the jaw positions were scanned. To avoid the potential danger of opening the jaws, the method used was to scan the jaws only towards the beam. Sample scans are shown in Figure 1, for locations with low dispersion and for large normalised dispersion ($D/\sqrt{\beta}$). The locations with large dispersion have less room for alignment errors, and these collimators are the ones which need to be most frequently adjusted.

Validation checks of the TCDI collimators were made by sending free betatron oscillations with different phases through the system, using correctors upstream in the line, to measure the system opening as a function of phase. A small emittance low intensity 'pilot' beam of about 1 μm normalised in both planes was used, with small bunch length, to accurately probe the acceptance of the system. The position in sigma of the edge of the jaws was then estimated from the fraction of beam lost, scaling the offset by the ratio of the actual to nominal emittances to derive a setting in nominal sigma.

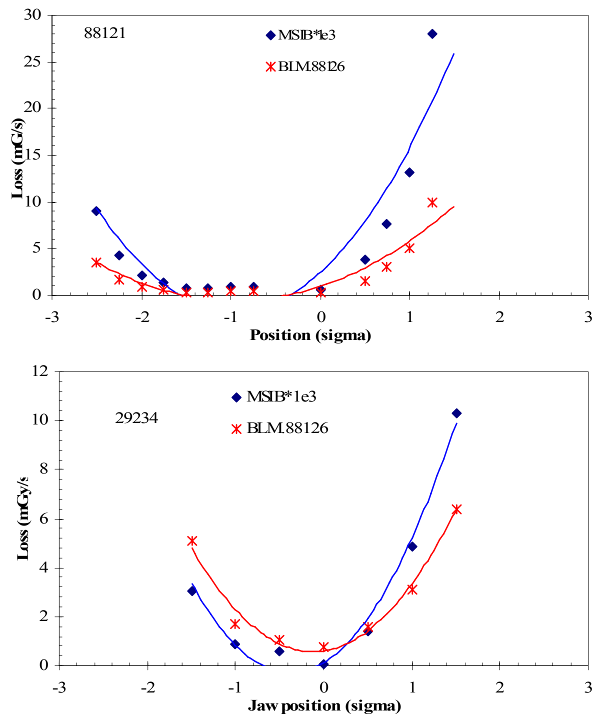

Figure 1. Centring scans with 4 bunches per injection, for TCDIs with low (upper) and high normalised dispersion (lower). The blue curve is for losses measured on LHC BLMs, the red for the local BLMs on the TCDIs.

The results for TI 2 are shown in Figure 2 and for TI 8 in Figure 3. For the validation the jaws were all set at 5 sigma, with the plan to operate at 4.5 sigma and leave a small margin to open selected jaws by 0.5 sigma if needed because of beam losses. The dashed grey line indicates the jaw setting, the solid grey line the setting plus the allocated tolerance of 1.4 sigma, and the red line the effective (target) system protection level. An error of ±0.5 sigma was estimated as the accuracy of the measurement. The results show that the systems all are positioned as expected or better, for all phases.

In addition to the phase scans, loss maps were made with the beam steered at 7.5 sigma amplitude into the collimators at different phases, recording the losses in the LHC and comparing with the generic damage thresholds assumed for the different elements. The losses were scaled to the nominal full batch intensity of $288 \times 1.15 \times 10^{11}$ p+. Typical results for TI 2 and TI 8 are shown in Figure 4. Scaling the losses on the collimators gives numbers well above the estimated damage level – however, these are generic numbers for warm machine elements, and the collimators are designed to intercept a full injected batch. The losses downstream of the collimators are due to the showers – one simulation which still is needed is a full FLUKA check of the effect of impacting the TCLIB with a full injected batch.

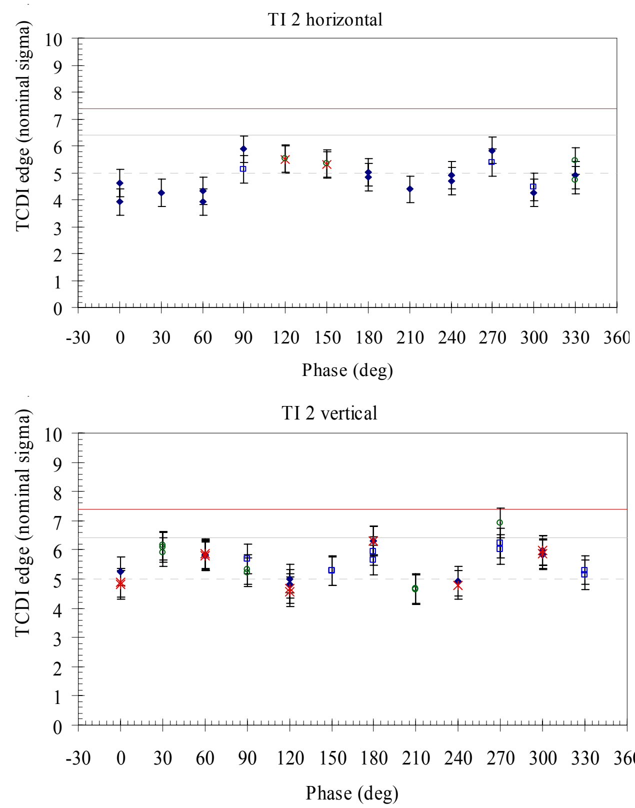

Figure 2. Validation results for TCDIs in TI 2, with measurement of TCDI phase space coverage.

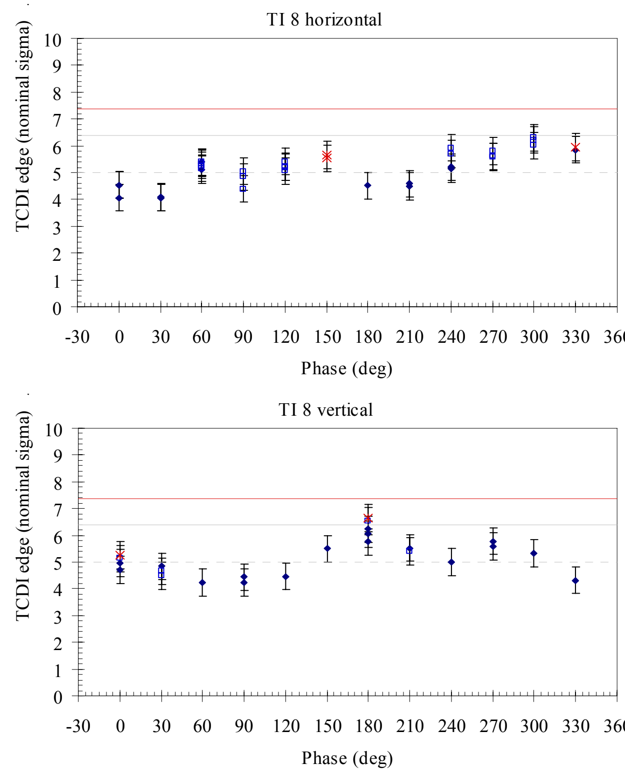

Figure 3. Validation results for TCDIs in TI 8, with measurement of TCDI phase space coverage.

There are no significant losses in the arcs or matching sections; the injection regions are shown in more detail in Figure 5. The main feature is that the MKIs appear over the damage threshold. This was checked in more detail, as the MKIs are known to be sensitive to beam loss – in fact the peaks on the MKI in Figure 5 are because the assumed damage limits for the MKI are taken as a factor of about 50 less than the damage limit for the superconducting magnets, without any specific justification. Examination of the raw loss maps confirms this, Figure 6, where the losses measured on the MKI are not larger than the surrounding elements.

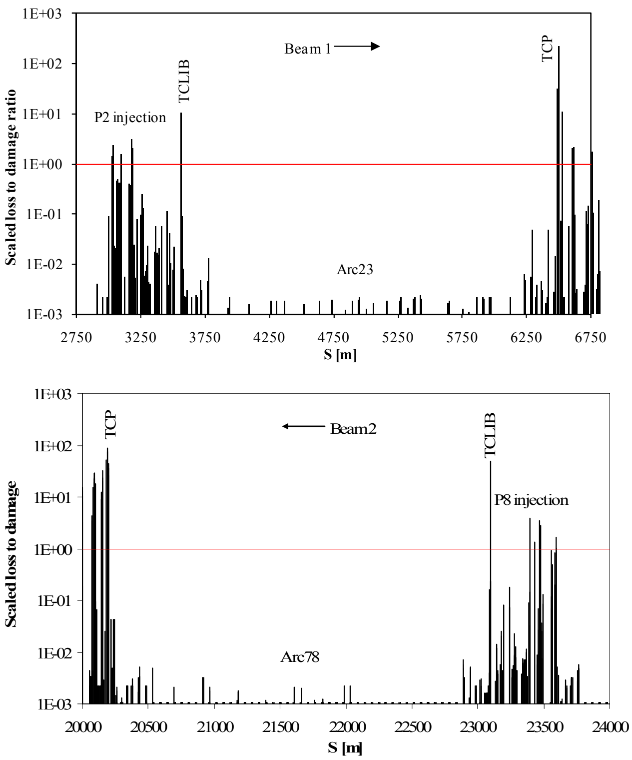

Figure 4. Loss maps for the LHC arc downstream of the injection regions, for 7.5 sigma beam impact on a TCDI in TI 2 (upper) and TI 8 (lower).

TDI and TCLI System

The TDI and TCLIA/B centring was made around the circulating beam, corrected to the reference orbit. This was done by scanning the jaws until the loss signals indicate the beam is reached. The jaws were then set at an offset given by the required number of sigma and the nominal optics. For the TDIs this gave some interesting results; for both beams, the beam size (sigma) as measured at the TDI was found to vary significantly with the setting of the TCP collimator used to define the core of the beam. In a dedicated measurement which was conceived to check that the TDI is correctly aligned the TCP gap was progressively reduced and the TDI opening measured as a function of this gap – the two settings were then translated into beam sigmas and compared, Figure 7. The result should be a straight horizontal line. This is not the case, indicating a scale error in one of the systems.

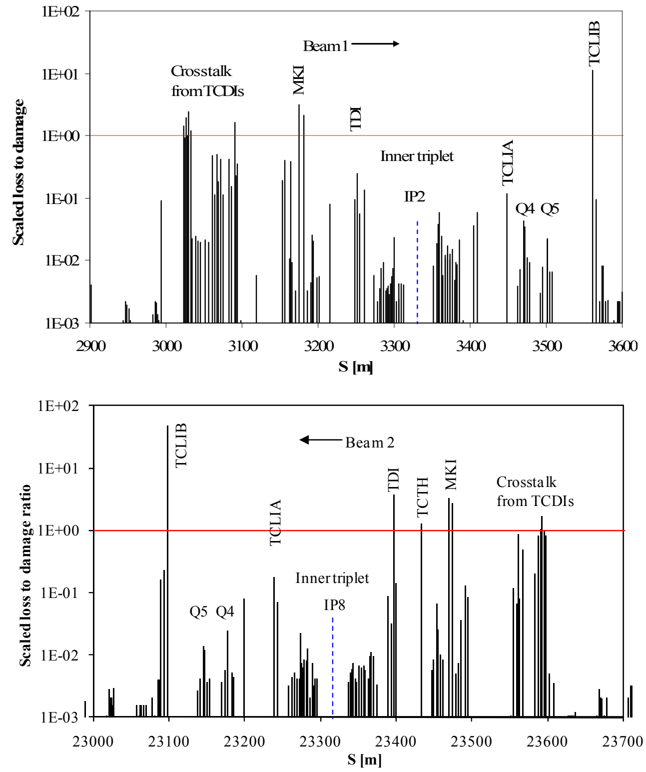

Figure 5. Losses in the injection regions are all on the protection devices and collimators, except for the MKIs, which are a factor 3 above the assumed damage limit.

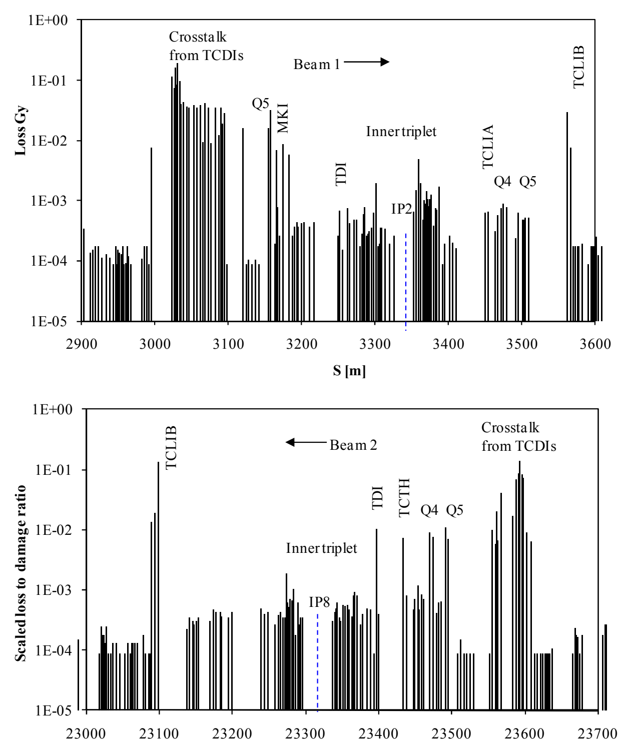

Figure 6. Absolute losses in injection regions for Beam 1 and Beam 2. Losses on the MKIs are lower than those on the adjacent Q4 and Q5.

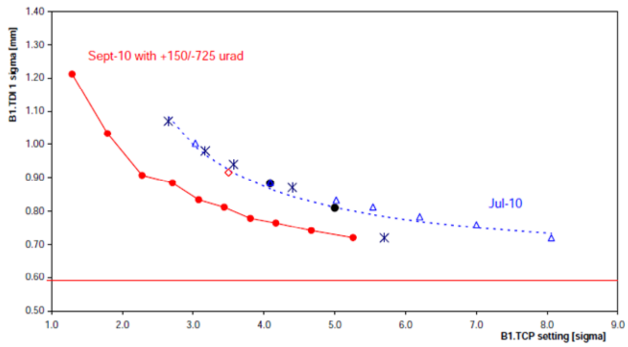

Figure 7. Scale effect between Beam 1 TCP and TDI settings, which could be explained by a TDI gap some 2.4 mm smaller than expected, and the improvement observed when the 900 µrad tilt on the lower TDI jaw was corrected.

Further measurements on the TDI were made, by retracting the jaw by about 0.5 mm from the beam and applying tilts to the upstream and downstream ends of the jaws until losses were observed. It was found that the TDI for B1 had a tilt on the lower jaw of almost 1 mrad, which would explain about half of the observed scale effect.. The tilt was corrected for in the subsequent setting up, checks and operation.

Validation checks of the TDI and TCLI systems were made by injecting low intensity bunches and varying the strength of vertical correctors which gave a deflection calculated to be the same as a fraction of the MKI kick. The scan results are shown in Figure 8. The actual protection levels were then estimated, Table 1. The protection levels measured are in tolerance; however, the relatively large offsets of the TDI centres, especially for Beam 2, mean that the overall protection will be improved for the jaws centred around the injected beam. Loss maps were also made for the extreme impacts on the TDI jaws, and the losses scaled to the assumed damage limit for nominal beam. Two maps are shown in Figure 9.

Table 1. Protection Levels of TDI/TCLI Systems

	B1 (sigma)	*B2 (sigma)*
Centre	0.85	-1.75
Gap	13.53	12.35
Protect +	8.37	5.07
Protect -	-6.55	-8.55
System protection	8.37	8.55
(if centred)	7.46	6.81

The maps show that significant losses escape the TDI/TCLI system for grazing impact on the TDI. Since the losses are above the generic assumed damage levels for several locations for Beam 2, a more detailed study with FLUKA, including the whole geometry of the insertion, is needed to understand whether this poses a real risk to the machine. This situation was simulated in the past to check for the risk of damage to D1, but not for the other downstream magnets.

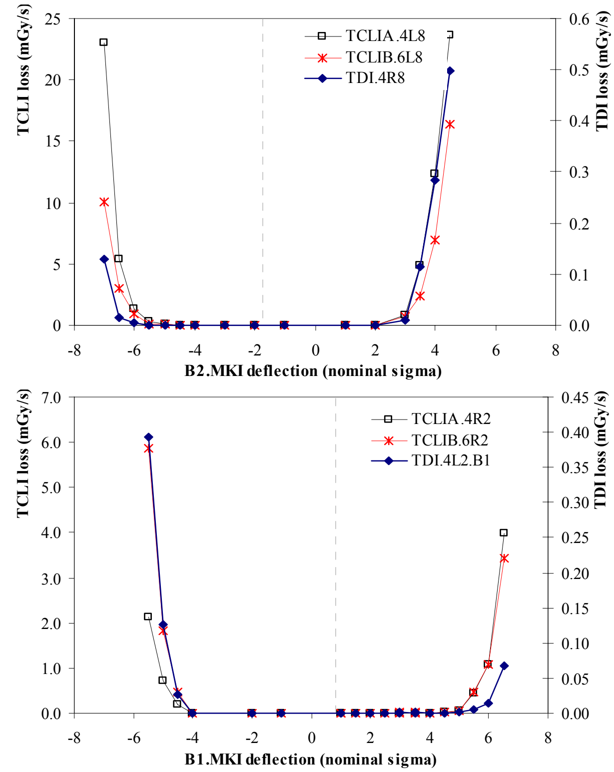

Figure 8. Scans of Beam 1 and Beam 2 TDI/TCLI opening with simulated MKI deflection variation, in sigma. The nominal system opening is ±6.8 sigma.

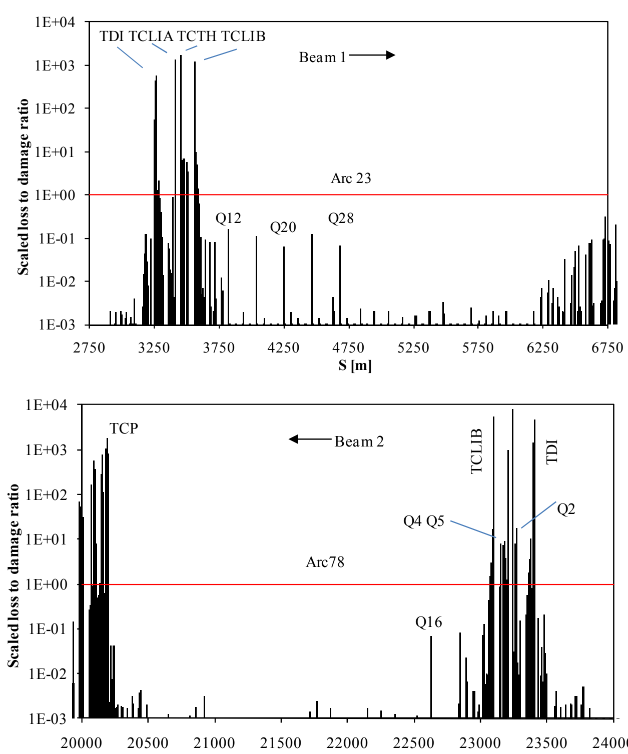

Figure 9. Scaled damage threshold/loss maps for grazing incidence impact on TDIs, for Beam 1 (upper) and Beam 2 (lower).

BEAM DUMP PROTECTION SYSTEM COMMISSIONING

Extracting with 14 out of 15 Kickers

The dump system was designed to be able to extract the beam if one of the 15 extraction kicker magnets does not work. This was tested with low intensity beam at 450 GeV with correctors powered to generate the same offset and angle at the septum as the MKD kickers – the beam was then extracted and the losses checked. The beam was cleanly extracted with one missing kicker.

Positioning of TCSG and TCDQ

The TCSG and TCDQ were positioned as for the other collimators, with the difference that the TCDQ centring is not possible as the device only has one jaw. As the TCSG and TCDQ are adjacent, the relative alignment of TCDQ with the corresponding TCSG jaw is simple, which yields the offset to apply and hence the retraction. The TCDQ is positioned 0.5 sigma further out than the TCSG.

As the TCSG and TCDQ are very important for the machine protection, a cross-check of the alignment was made similar to the TDI, by checking the TCSG opening as a function of TCP setting. In this case the curves were flat, showing that there are no unexpected gap errors.

Asynchronous Dump Tests

A large number of tests were made to test the positioning of the TCSG/TCDQ and to check the loss maps in the LHC with beam in the abort gap. These tests are made by switching off the RF and allowing a bunch to debunch, such that the abort gap fills with particles. The beam is dumped after about 90 seconds, and the total abort gap population has been measured at about 3e10 p+ at the moment of the dump. This is a factor of about 450 lower than the full intensity with 25 ns. The tests and associated simulations are reported in more detail in [3] – an example loss map is shown in Figure 10, showing the expected level of losses on the collimation elements, in particular the TCTs in P5 for Beam 2. To date the asynchronous dump tests have not shown any large losses on elements other than collimators, and the highest losses on the TCTs correspond almost exactly to the expected ~10^{-4} leakage of protons scattered through the short (1.2 m long) jaw of the TCSG, which is exposed for 0.5 sigma behind the TCDQ.

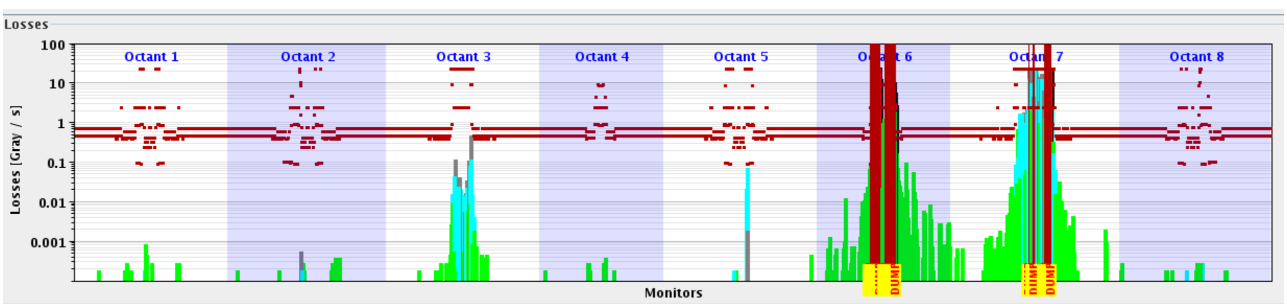

Figure 10. Map of losses through the LHC for asynchronous dump test with about 3×10^{10} p+ in each abort gap. The dumps for Beam 1 and Beam 2 were triggered together. The losses in Octants 3 and 7 are on the collimation insertions, and in Octant 5 on the TCTH which protects the low-β triplets. A dump of the full intensity 25 ns beam will give losses about 500 time higher.

DISCUSSION AND CONCLUSIONS

Commissioning and validation tests of the injection and dump protection systems against fast failures have been made in the first months of LHC operation, and before major increases in stored and injected intensity. The systems have generally been found to work as expected, although the transmission through the rest of the LHC of scattered protons through the graphite jaws needed extra simulation. A number of features of the different systems have been revealed; the unexplained tilt and gap error of the TDI for Beam 1 will need to be checked when the device is next opened, and the loss on the downstream quadrupoles for grazing impact on the TDI needs to be checked in detail with FLUKA, together with the long-pending study of the effect of a full injected beam impacting the TCLIB. The loss levels on the MKIs for the full beam impact on the final TCDIs should also be simulated.

The phase coverage and protection level of the different systems has been measured and agrees with the specifications; for the TDI/TCLI system the protection depends on the amplitude of the injection oscillations in the vertical plane – these need to be corrected if they exceed the tolerance of maximum 2 sigma.

It is to be hoped that the learning curve for the use of these critical elements can keep pace with the progress LHC is making in terms of intensity increase. The risk of the devices being needed to prevent damage to the LHC should continue to be minimised by the comprehensive interlocking and rigour in operational procedures and their execution.

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[2] V.Kain, CERN-THESIS-2005-047, 2005.
[3] C.Bracco et al., Proceedings High Brightness, 2010.