INJECTION PROTECTION – ARE WE TAKING IT SERIOUSLY? HOW CAN WE MAKE IT SAFER?

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Abstract

The experience with the injection protection system during the 2010 run will be summarized, the setting-up times for the transfer line collimators and stability will be evaluated. Weak points of the protections system at injection which became apparent with first high intensity experience will be discussed and solutions for 2011 presented. Improvements for tools and procedures to be implemented during the shutdown will be mentioned.

INTRODUCTION

The LHC is protected against possible failures during the injection process by a dedicated injection protection system. Examples for possible failures are: LHC equipment not at injection settings while beam is injected, power converter failures during SPS extraction or in the transfer lines resulting in wrong injected trajectory, injection kicker (MKI) failures such as synchronisation issues due to timing problems, kicker flash-overs, erratics and missings.

Passive protection through collimators and absorbers and active protection in the form of interlock systems defining injection and SPS extraction permits is in place to cover the above mentioned failures. The "beam presence concept" protects e.g. against injecting high intensity into the LHC not at injection settings, the power converter interlocks in the SPS extraction region and the transfer lines disallow extraction from the SPS in case of power converter trips or wrong settings. There is a generic passive protection system, the transfer line collimation system (TCDI), located at the end of the lines to protect against any problem during the transfer. And the 4 m long absorbers, TDI, plus two auxiliary collimators downstream of the injection kicker cover injection kicker failures. More details on the injection protection system can be found in [1].

NEW IN 2010: INTERMEDIATE INTENSITY INJECTION

Injection of high intensity into the LHC is only permitted by the interlocking system if beam is already circulating. Only probe intensity (currently < 10^{10} charges) can be injected into an empty machine. This is the concept of "beam presence". A number of so-called "safe machine parameters" (different flags derived from beam current measurements in the SPS and LHC and other quantities distributed across the machine) are combined in the permit equation in the master beam interlock controllers for the SPS extraction to guarantee this condition.

The LHC does not change settings when switching from probe beam to nominal beam (except sensitivity settings for some BI equipment). The injectors however are running at different settings and hence different cycles for the different beams. While the "beam presence concept" is vital for protection during the injection process at the moment the beam enters the LHC, it increases the complexity for the SPS to LHC transfer.

Trajectory Correction in the Transfer Lines

The trajectories in the transfer lines are drifting with time even in the absence of changes of magnetic settings. The settings in the transfer lines can therefore not be frozen. Trajectory correction is required every week or so triggered by too large injection oscillations or losses.

During the 2010 run it was noticed that with the same magnetic settings in the transfer lines, the trajectories for the probe beam and the nominal beam averaged over the bunches are significantly different (up to about 500 μm in trajectory). Structures of the kicker waveforms might play a role for the single bunch versus a batch, but also the different shape of the cycle (faster ramp) of the probe and hysteresis. Different BPM sensitivity etc might enter the game as well. Studies in 2011 will be conducted to identify the origin of the discrepancies.

Due to this effect the probe cycle could/can not be used for trajectory correction. Intermediate intensity batches were used for that purpose.

Fewer bunches per batch

In 2010 the LHC was filled with single batch injections from the booster into the PS, with the booster RF running on harmonic 2 (+1). The intermediate intensity batch was generated by injecting a single booster ring into the PS instead of three. The other two were disabled manually followed by adjusting the splitting in the PS. Intermediate intensity batches could not be generated in an automated way.

Following the recommendations of the External Machine Protection Review in September 2010, the physics filling schemes all contained an intermediate batch as first injection after the probe beam as final validation of the injection process. For 75 ns the intermediated intensity corresponded to 8 bunches, for 50 ns to 12 bunches and for 25 ns taking a single booster ring with one injection from the booster it would correspond to 24 bunches. The required manual intervention of the operations crew and the tuning of the splitting

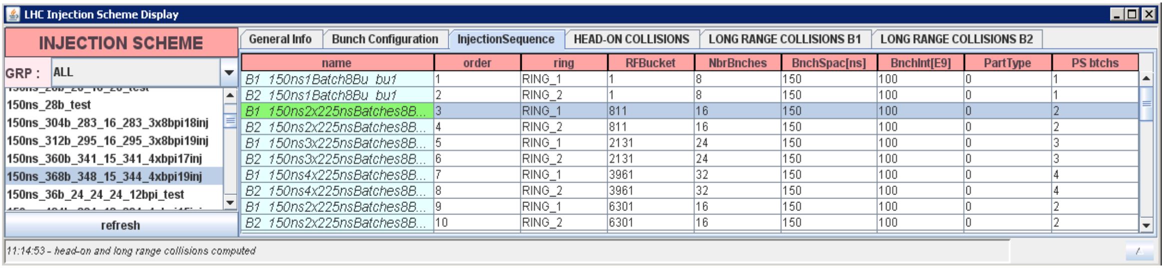

Figure 1: Current injection schemes: The current injection schemes consist of a number of injection requests. An injection request tells the injectors into which LHC ring and into which RF bucket the next injection should occur and how many PS batches should be injected into the SPS. The number of injections into SPS can be controlled on the fly. The same is not possible for the number of booster injections into the PS.

then in the PS before and after the intermediate batch injections caused some considerable holdup during the LHC filling. Improvements of the mechanism to switch to intermediate intensities will have to be put in place for the 2011 run.

Possibilities to speed up switching in and out intermediate batch injections

Two possibilities to make the switching to intermediate intensities more efficient are discussed:

1. Separate user for intermediate intensities
2. New type of LHC injection requests.

<u>Separate user:</u> this approach would not require any modifications of the existing way of controlling the LHC beams in the injectors. Nominal and intermediate intensity would be run on different cycles in the injectors. As the intermediate intensity cycle is used to steer the SPS to LHC transfer lines and to avoid the complication of having to copy the steering settings to the nominal cycle which risks to be forgotten, the same user in the SPS should be used for intermediate and nominal. Only the PS and the booster would run with different users. The drawbacks of the "separate user" solution are the larger number of users locked for the LHC beams, the potential issue of the copy of the transfer line steering in case of different SPS users and that the switching from intermediate to nominal and vice versa cannot be done through LHC injection requests. The timing system would have to be re-configured to play the other user. In this way intermediate intensities could only be used as first injection. Mixed filling schemes using nominal and intermediate intensity injections throughout the filling to optimise the luminosities at the different interaction points would not be possible.

<u>New LHC injection requests:</u> the drawbacks of the first possible solution could all be elegantly avoided by the introduction of more flexible LHC injection requests. An example of a filling scheme with the current type of injection requests is shown in Fig. 1. Note that the number of PS injections into the SPS can be piloted on the fly by the LHC injection request with today's Central Timing. This is not the case with the number of booster rings. However, the concept of different destinations for different booster rings exists. And different PS equipment settings can be associated with these different destinations (double PPM settings). These destinations are static today. The idea behind the "new LHC injection requests" is to use the fact of different settings for different booster ring destinations and upgrade the "LHC injection request" to also pilot the number of booster rings between 1 and 6 (2 x 3 rings for 2 batch injection from the booster).

Despite the obvious advantages for injection protection and overall flexibility of building injection schemes of this proposal, there are some drawbacks. The 2010/11 shutdown is short and this proposal would require a major, but technically feasible, modification of the LHC and Central Timing System. The bigger obstacle however comes from the fact that not all required systems in the PS are double PPM yet, a controls infrastructure upgrade and an efficient way of managing the settings in INCA would have to be organised. Possibilities to exploit the "separate users" proposal will be investigated for 2011. In addition we will study and prepare a new type of LHC injection requests in 2011 to be ready for implementation during the shutdown 2011/12.

TRANSFERLINE COLLIMATORS

The transfer line collimation system has been designed to provide full phase space coverage and protect therefore against any failure leading to large amplitude oscillations from upstream of the collimators. The TCDI collimators are at the end of the lines and due to optics and space constraints only three collimators per plane could be fitted into the lattice. The phase advance between two adjacent collimators is 60°. The settings of the collimators depend on the LHC aperture available for the injected beam, thus the aperture for the circulating beam minus a margin for sources of aperture reduction from injection like injection oscillations. The circulating beam aperture in the LHC at injection energy was measured to be 12.5 σ [2]. The settings of the transfer line collimators are chosen not to let amplitudes through larger than 7.5 σ. This is fulfilled with a setting of 5 σ. Currently the transfer line collimators are at 4.5 σ. The required protection level was validated for 5 σ settings. The results for the maximum amplitudes leaking through the system for different phases are shown in Fig. 2. In summary, the

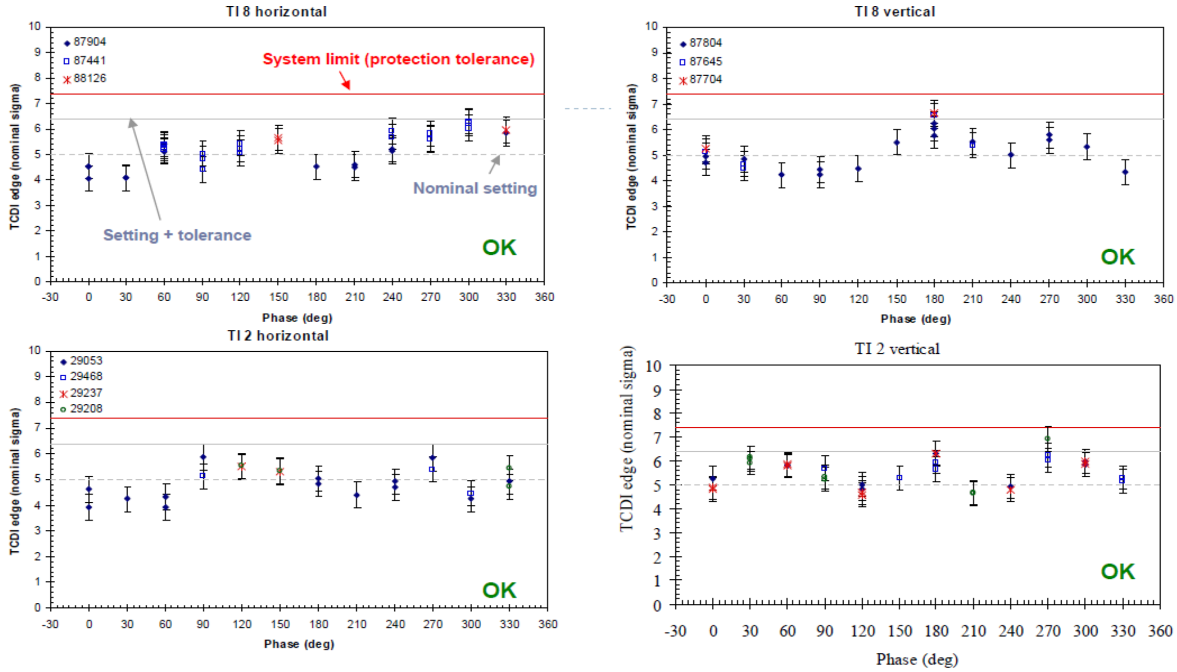

Figure 2: Results of the protection level measurements of the TCDIs for TI 2 and TI 8 on September 15, 2010: The phase space coverage was evaluated. The phase space is covered within the system limit protection tolerance

plots show that for 2010 the system achieved the required phase space coverage.

With the collimators at the end of the lines, close to the LHC, and the tight settings, any losses on the collimators are seen by the sensitive BLMs on the LHC superconducting magnets, see Fig. 3. This was one of the reasons for the partly poor operational efficiency during injection [3,4]. Frequently the showers from the collimators created signals above threshold in these BLMs.

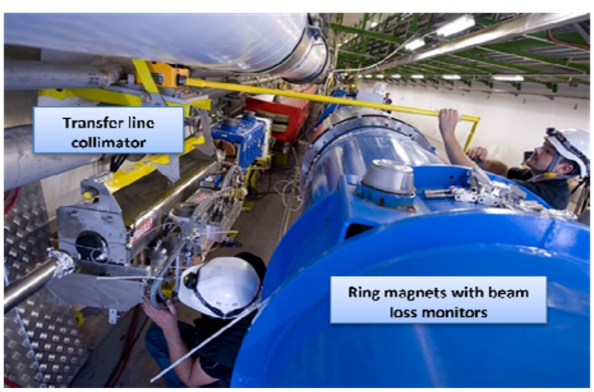

Figure 3: The transfer line collimators are close to the LHC superconducting magnets equipped with sensitive ring BLMs.

Setting-up frequency of the transfer line collimators

All TCDIs were set up middle of March using the old lengthy setting-up method as shown and described in Fig. 4. Until June, 1 to 2 TCDIs had to be adjusted a couple of times (maximum changes of centre positions were of 800 μm). Beginning of July 2010 all TCDIs were re-set up for higher intensities. This time the new method, scanning the jaw gap as described and shown in Fig. 5, was used. With this method the collimators for both lines can be set up within 1 shift.

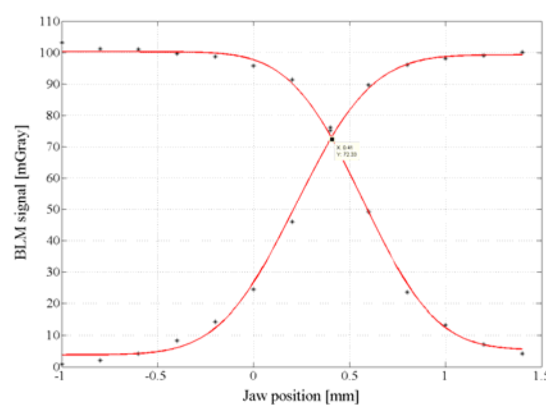

Figure 4: Response of BLM when moving each jaw individually through the beam during subsequent SPS

extractions fitted with the error function to define beam size and centre position between the jaws.

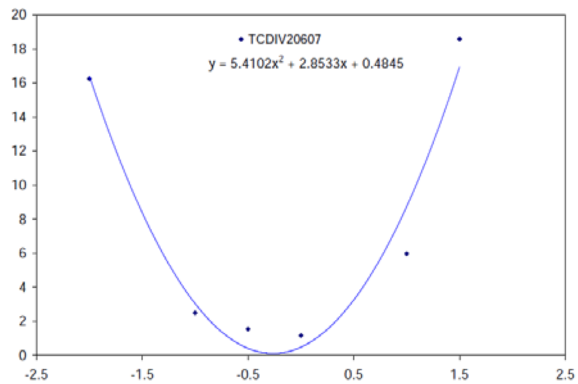

Figure 5: Response of transfer line BLM when moving gap and parabolic fit. This method quickly determines the optimum centre position for the two jaws.

From then on the collimators were only touched to reduce losses on the transfer line collimators when the injected intensities were increased or a new bunch pattern was introduced. Always the same collimators were affected, all of them in the horizontal plane: for beam 1 TCDIH.29050 and TCDIH.29205, for beam 2 TCDIH.87441. Per adjustment 1 to 2 TCDIs had to be touched, the typical changes of the centre position were between 200 to 300 µm. No change was required when switching to 150 ns and 50 ns running or ions.

The last big change of the TCDI jaw positions was caused by the re-steering of the injection of beam 1 due to an aperture bottleneck in the injection septum MSI with RF fingers buckling into the injected beam chamber. No scans for the optimum jaw position were necessary. The trajectory interpolations at the TCDI locations could be used directly to shift the gaps. The centre positions had to be changed by up to 1.2 mm.

Operational margin

It turned out in 2010 that the longitudinal and transverse parameters of the beam extracted from the SPS and the steering in the transfer lines had to be very well under control not to cause collimator losses above threshold on the LHC BLMs. Opening up the transfer line collimators beyond 5 σ was requested several times. The following will summarise the arguments for keeping the transfer line collimators as tight as possible. The TCDI settings contain margin for injection oscillations and LHC orbit.

Orbit bumps can be left in after MDs, be introduced by accident with steering algorithms or on purpose to compensate missing correctors. Currently the software interlock limit for orbit bumps is 1 mm which is frequently not enough in case of missing correctors. The correction of injection oscillations is problematic due to not understood systematic differences between different cycles in the SPS as already mentioned before and the tight collimator settings at the end of the line where the trajectory should not be changed. Injection oscillations are corrected with intermediate intensity. Also they can only be corrected after establishing a well corrected orbit in the LHC. Due to the differences in the orbit reading between high and low sensitivity settings of the BPMs, this is only fully done with nominal bunches in the LHC and not with probe. This is another argument for correcting injection oscillations with nominal bunches even though only a minor uncertainty well within any margin would be expected from this effect if correcting with probe. Depending on the bunch spacing intermediate intensity can already be above setup beam limit. To be pragmatic, trajectory correction in the lines therefore became expert intervention and was done as infrequently as possible in 2010. With the excellent performance of the LHC transverse damper [5] and the larger injection aperture and tight TCDI settings, injection oscillations of more than 1.5 mm were acceptable.

These values for orbit bumps and injection oscillations were comfortable values to work without having to spend too much time on optimisation, sophisticated algorithms and risking machine protection issues. Opening up the TCDIs will reduce these margins. Table 1 summarises the current situation.

Table 1: Tolerances for TCDI setting of 5 σ

	Tolerance [σ]
TCDI setting	5
TL tolreance	1.4
Real setting 1 col	6.4
Phase space coverage	**7.4**
Injection oscillations	2
Orbit	2
Dynamic beta-beat	0.6
Energy	0.5
Max. amplitude in LHC	**12.5**

Required correction during the 150 ns run

Trajectory correction was triggered by high loss levels at the transfer line collimators or significant injection oscillations (> 1.5 mm). The total correction applied in both lines reached about 1 σ at some of the collimators, see Fig.6 to 9.

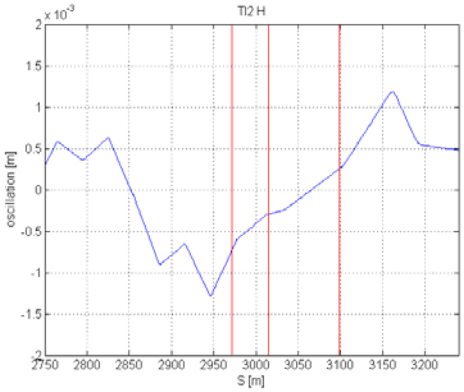

Figure 6: The sum of all corrections applied during the 150 ns proton run in 2010 in the horizontal plane end of TI 2. The red vertical lines indicated the locations of the transfer line collimators.

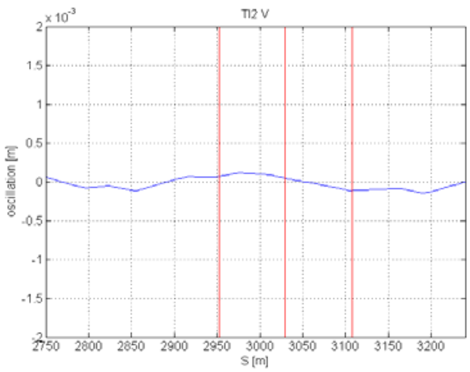

Figure 7: The sum of all corrections applied during the 150 ns proton run in 2010 in the vertical plane end of TI 2. The red vertical lines indicated the locations of the transfer line collimators.

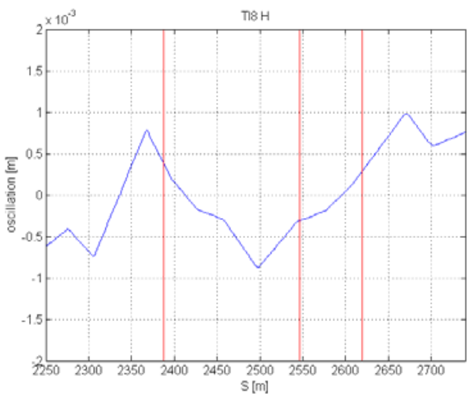

Figure 8: The sum of all corrections applied during the 150 ns proton run in 2010 in the horizontal plane end of TI 8. The red vertical lines indicated the locations of the transfer line collimators.

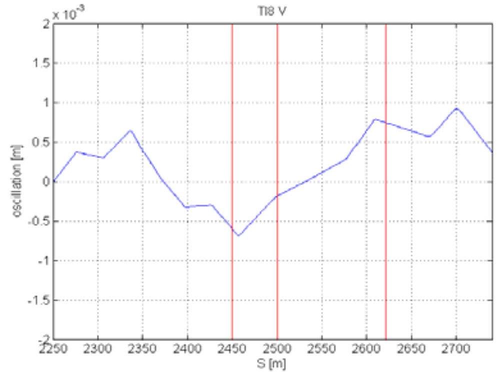

Figure 9: The sum of all corrections applied during the 150 ns proton run in 2010 in the vertical plane end of TI 8. The red vertical lines indicated the locations of the transfer line collimators.

NEW INJECTION SOFTWARE INTERLOCKS

Two new software interlocks will become active for the 2011 run. The software interlock system SIS will allow the injection of high intensity only if intermediate intensity is already circulating. In this way the injection of intermediate intensities will be enforced also through interlocking. Another flag will be introduced in the Injection Quality Check (IQC) [6] analysis checking the injection oscillations of the last injection. The new flag will also be picked up by the SIS. If the injection oscillations in the IQC have returned FALSE, the maximum intensity to be injected thereafter is intermediate intensity. This will be automatically reset, once the injection oscillations are within limits. (A special RBAC role will exist to overwrite the injection oscillation IQC result in case of data availability issues and for debugging.)

In 2011 operations will be responsible for correcting the trajectories in the transfer lines. Correction limits and safety of correction algorithms/tools will be investigated.

ANYTHING WE HAVE FORGOTTEN?

Accidental beam on TDI

At several occasions during 2010 a considerable amount of intensity, 24 to 32 bunches, ended up on the TDI. One failure type could have been avoided and was due to new filling schemes not respecting the abort gap keeper window for the last injected batch (abort gap keeper window: 3 μs abort gap + 8 μs). An automatic check will have to be implemented in the injection scheme editor (together with an unmaskable SIS check). A complication is coming from an unanticipated synchronisation issue. The abort gap keeper window had moved by about 50 RF buckets towards the end of the run. The reason is unclear.

Another unforeseen failure case was the complete loss of the synchronisation between SPS and LHC normally guaranteed through connecting both timing systems to the GPS. The GPS was off at one occasion and the injection pre-pulses had not been sent out at the correct moment with respect to the charging of the PFN voltages of the injection kickers. The whole injected beam was dumped onto the TDI. A surveillance system had been put in place already in 2010. For 2011 another upgrade of the timing system is planned where injection requests will be rejected by the timing system in case problems with the GPS are detected.

Circuits within the transfer line collimation section

The transfer line collimators can only protect against oscillations originating from circuits upstream the collimation section. A small number of circuits is within the collimation section or even afterwards. All have interlocked settings. The dipole chains are interlocked 0.1 to 0.2 % and dipole correctors at 10 μrad. Circuits with small time constants in case of a trip are protected in addition with FMCMs [1], not the dipole correctors or the three MCIAVs which are used as RBEND at the end of TI 8 (the MCIAVs are slow, time constant of 185 ms). Details are summarised in Table 2 and 3. Fig. 10 and 11 show the resulting oscillations in the LHC in case of wrong settings within the currently set interlock tolerances. The current thresholds are sufficient, but could be even further decreased depending on the power converter stability.

Table 2: Circuits within or upstream of the transferline collimation section in TI 2.

Circuit	
MBIBH	FMCM
MCIAV	-
MSI	FMCM

Table 3: Circuits within or upstream of the transferline collimation section in TI 8.

Circuit	
MBIAH	FMCM
3 x MCIAV	-
MCIAH, MCIAV	-
MSI	FMCM

IMPROVEMENTS TO COME

Threshold management of injection protection devices

The settings and threshold management of the injection protection collimators and dumps is implemented following the philosophy of the ring collimators. The ring collimators' motors block if the interlock thresholds are reached to avoid that the jaws accidently run into the circulating beam. The same logic is applied to the transfer line collimators and TDI plus TCLIs. As all these collimators are driven by stepping motors, a periodic cycling of the jaw positions is recommended to guarantee motor precision. Before each LHC fill all collimator positions are opened up and only then moved to their injection settings. Because of the blocking mechanism, the thresholds have to be opened up as well. Thus different sets of interlock thresholds have to be maintained in the control system. They can be loaded at any time with no guarantee for the correct ones to be resident at injection. An additional energy dependent gap interlock which does not have to be changed for cycling the motors, increases the reliability of the system.

In 2010 no energy gaps were implemented in the control system of the TDI. Also, relying on energy gaps only is not sufficient for the transfer line collimators. As the settings are tight and the collimators have to protect in single pass, the correct gap centre positions have to be ensured.

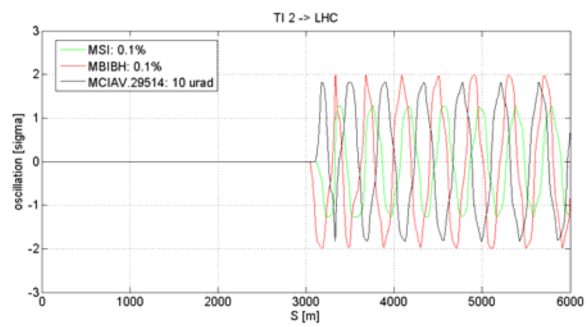

Figure 10: Resulting oscillations into the LHC for the large circuits within or upstream of the collimation section in TI 2 with current errors at the interlock limits.

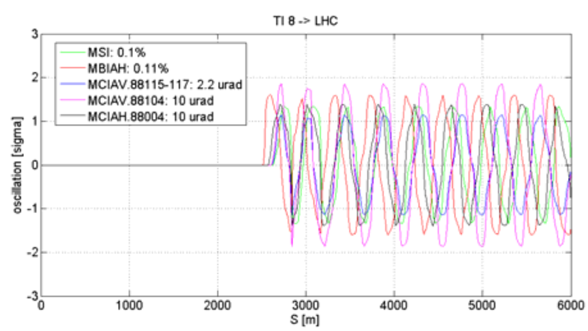

Figure 11: Resulting oscillations into the LHC for the large circuits within or upstream of the collimation section in TI 8 with current errors at the interlock limits.

Several improvements will be put in place during the 2010/11 shutdown. Running of collimator jaws into circulating beam is not an issue for transfer line collimators. It was therefore decided to remove the movement blocking mechanism for transfer line collimators for inner and outer thresholds and for the TDI for going across the outer threshold. The TDI will also be equipped with energy gap interlocks.

Over-injection

In 2010 the probe bunch required for beam presence was injected into RF bucket 1 and then over-injected onto the TDI with the first high intensity injection. If however no beam was extracted from the SPS during an over-injection attempt, the probe beam was kicked out, the beam presence condition was lost and therefore the possibility to resume the filling was lost as well. Cycles in the injectors had to be changed again to switch back to probe beam production etc. and a lot of time was lost.

For 2011 it is therefore planned to place the probe bunch at a better location around the LHC circumference such that over-injection does not occur during the first injection but later.

Keeping the probe bunch as part of the filling scheme as a witness bunch is another possibility.

SUMMARY

The LHC injection protection system is fully operational and is working well. All injection failures problems during the 2010 run were caught. The transfer line collimators could be kept at tight settings of $4.5\ \sigma$ without any major efficiency problems. The LHC has already been saved several times from damage when high intensity batches of up to 32 bunches ended up on the TDI. The injection interlocking system has proved to be very reliable and available. Interlocks on injection oscillations not to compromise the available aperture will be implemented for the 2011 run. In 2010 the concept of injecting intermediate intensity before high intensity had been introduced and will be kept for 2011. Other improvements to tools e.g. the injection scheme editor, unmaskable SIS interlocks and upgrade of the timing system concerning the GPS issue should avoid accidently dumping high intensity beam onto the TDI. An increase of protection reliability will come from the new threshold management of the injection protection collimators. And an improved procedures concerning e.g. over-injection will help to make the restrictions of the injection protection system less cumbersome.

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