SUMMARY: SESSION 4 - MACHINE PROTECTION SYSTEMS

A.L. Macpherson, CERN, Geneva, Switzerland

Abstract

A summary of the Machine Protection System of the LHC is given, with particular attention given to the outstanding issues to be addressed, rather than the successes of the machine protection system from the 2009 run. In particular, the issues of Safe Machine Parameter system, collimation and beam cleaning, the beam dump system and abort gap cleaning, injection and dump protection, and the overall machine protection program for the upcoming run are summarised.

SAFE MACHINE PARAMETERS

Beam Interlock System

As a precursor to the discussion on safe machine parameters and machine protection issues, the Beam Interlock System (BIS) was first presented and discussed. For the BIS, it was clearly stated that the SPS, SPS Extraction, Transfer Lines, Injection and LHC Ring are operating to specification and commissioning is complete for all inputs which are required for 3.5 TeV operations at reduced intensity. Yet it was also noted that there are several ongoing issues that are being addressed, namely:

- The implementation within the BIS of both pre-operational and Internal post-operational checks on both the beam interlock controllers and the beam permit loop generators
- User systems that provide inputs to the BIC are being encouraged to implement automatic interface tests that will allow for verification of functionality of the input on a regular pre-fill basis.

Safe Machine Parameter System

It was clearly stated that the Safe Machine Parameters (SMP) system has been operational in the SPS for the last two years, and has operated without fault or loss of accelerator ability.

For the LHC, a SMP system was installed that met the 2009 run requirements, but suffered limitations that need to be addressed for the 2010 run. These limitations included:

- Lack of a consistency check on the BETS energy at the SMP controller
- Lack of a fully redundant path for producing the SMP flags at the SMP controller
- Lack of a cross check by the SMP Controller on the on the General Machine Timing distribution of parameters
- Lack of an SMP input to the BIS.

To address these limitations for the 2010 run, the following action is to be taken

- An energy consistency check at the level of the Software Interlock System (SIS) is to be implemented to ensure consistency between end-users and main-bend currents.
- During normal physics fills, the LHC Setup Beam Flag (SBF) will be forced false; operation with the SBF unforced will only be permitted in predefined conditions.
- During normal physics fills, the all masks set on the LHC BIS will be removed, so even if the LHC SBF is unforced, channels are taken into consideration.

SMP Development

As it has been identified that the current SMP specifications do not meet with the required functionality needed for the LHC, the LHC SMP system is to be revised and upgraded, with a target implementation date set for the start of the 2011 run. This revision is expected to encompass both revised specifications and the subsequent implementation of design modifications to SMP hardware/firmware/software.

SMP Issues

One point that was clearly made during the course of the presentation was that SMP reliability and performance is in part governed by the reliability of its inputs. In this regard, two key dependencies were identified from the 2009 run, and a clear request from the TE/MPE was made to improve the reliability and internal cross checking of the two associated systems. The two SMP inputs that were identified as having quality/integrity issues were :

1. Intensity information – Beam Current Transformer (BCT).
2. The General Machine Timing (GMT) which is used for transmission of SMP inputs and parameters.

Discussion

Over the course of the presentation it was clear that the reliability and performance of the SMP system is directly linked to the the quality of the input systems that it depends upon. In the case of the BCTs, there is the possibility of arbitration as there are two independent BCT systems. However, it was pointed out by BI that for the upcoming run, this redundancy is not really available, as one of the two BCT systems is needed for development work. Further, with only two BCT systems , it is not clear as to how arbitration would work in all but the most clear cut cases.

In regard to the proposed SMP upgrade, and given that at present the SMP flags are calculated outside the SMP system, the SMP should address how the SMP flags are evaluated and if possible remove critical dependencies on external input systems. This is to be addressed in the specification review.

It was also noted the setting of the SBF to false for normal physics fills but with low beam intensities will make machine checkout and commissioning difficult, as the the machine will be "safe" but in some cases the instrumentation will be blind. A case in point is the TOTEM runs and any other setup that requires the presence of the SBF. The further implication of this is that this constraint on the SBF risks pushing some machine checkout and commissioning activities to be done at higher beam intensities than is normally desired.

The final comment was that in the present state, the SMP cannot achieve the required SIL 2 safety specification that is required for the LHC, and that for the upcoming run, a compromise has had to be made. This compromise has been achieved without significant concessions on safety, but it has to be understood that safety integrity is not restricted to the SMP but has implications to the systems that input into the SMP.

COLLIMATION AND BEAM CLEANING

The performance of the LHC collimation system for both beam cleaning and passive machine protection was reviewed as well as the necessary hardware commissioning required by the collimation system for the 2010 run. Issues of performance, collimation interlocks and operational procedures were addressed in terms of machine protection, and the presentation finished with a discussion of issues related to higher intensity operation and improvements.

Hardware Commissioning in 2009

All LHC collimators were tested in preparation for operations with beam, and an automatic procedure has been implemented to execute interlock checks as part of the machine protection (MP) tests. Additional sequences have been established to drive collimators through nominal operation cycles, and the reproducibility of jaw position has been found to be better than 10 μm, and the movement of all the collimators was triggered within 6 μs and stopped within 10 μs.

Beam Based Alignment

Beam based alignment and centering of a collimator with respect to the beam relies on beam loss measurements correlated with jaw movements, and just such an initial alignment campaign was carried out during the 2009 run.

For this alignment campaign, a reference normalized position (for TCPs it was set at ± 5.7 σ. i.e. nominal TCP half gap at 450 GeV. σ was calculated for ε= 7.28 nm) was set for the last absorber (TCLA) in the plane (relative to beam direction), and then one by one, all other collimators were moved until they located the beam edge. This procedure was used for the horizontal, vertical and skew planes, and based on the resulting the BLM loss maps gave a first estimate of a local cleaning efficiency better than 99.9%.

Once the reference "golden orbit" was established, a second beam based alignment was performed, with 62 collimators were set up to within an accuracy of 50-100 μm. From this alignment, the measured collimator jaw gaps were compared to the expected gaps (calculated from nominal parameters), the resulting difference is shown in Fig. 1.

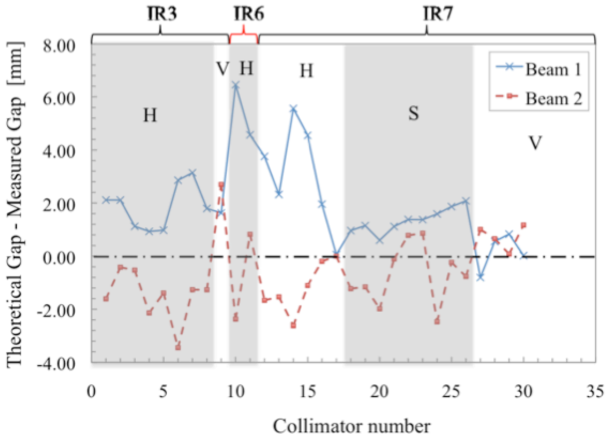

Fig. 1 Difference between theoretical and measured gap of LHC collimators after beam based alignment. Collimators are grouped per IR and divided in horizontal (H), vertical (V) and skew (S).

In addition to beam based alignment measurements, TCLAs were also used to perform a full beam scraping, in order to obtain an independent estimate of the beam centre and beam size at the collimators. Comparison with values calculated from the collimation setup showed a reasonable agreement, but some discrepancies were found on the vertical component of beam 2, and this has to be followed up.

Interlocks and Machine Protection Issues

For the 2009 run with low beam intensities the collimator system operated with static settings during all the phases of the machine cycle, including the ramp up to 1.18 TeV. This meant that static position dependent thresholds were applied. In addition, energy dependent thresholds were also activated albeit with a maximum allowed gap of 60 mm. During the 27 days of machine operations in 2009, collimators generated only six interlock requests, and of these only one interlock was induced by a real hardware problem: all other interlocks due to inappropriate user requests .

In regard to beam loss maps from collimators, a loss map for beam 1 at 1.18 TeV was measured, and was found to be in good agreement with simulation results, but some discrepancies at IR6 collimators and at the cold magnets downstream of IR3 were observed. It is suspected that the losses in IR6 may be due to a tight collimator aperture resulting from the problematic alignment of the TCDQs, while for the losses around IR3 things are not so clear. The observed losses on the right side of IR3 is seen for both beams, but for beam 2 they occur upstream of the primary collimators. Analysis now seems to indicate a problem in the BLM reading rather than actual losses, but further studies are ongoing.

For betatron loss studies carried out by crossing the third-integer tune resonance the highest losses were in the betatron cleaning insertion and the loss pattern showed good agreement with simulation. Moreover, the origin of losses on the cold magnets on the left side of IR6 and IR7 were shown to corresponded either to maximum vertical β-function or to a combined maximum horizontal β-function and dispersion location.

Momentum losses were analyzed by changing frequency of the RF cavities, and in these cases the highest loss rate was recorded in the momentum cleaning insertion.

Plans for higher intensities

For the collimation system a list of commissioning steps to be completed before operating at higher intensities has been presented, and includes the following:

- An accurate definition of BLM thresholds must be setup in order to protect the machine without inhibiting operation.
- The evolution of collimator settings during the energy ramp and the beam squeeze has to be tested.
- Beam based alignment at higher energy has to be accomplished with improved setting accuracy.
- Cleaning efficiency with higher loss rate (500 kW - 1000 kW) has to be checked.
- Effect of collimator impedance on beam stability has to be verified.
- An automatic procedure for MP temperature interlock verification.

Discussion

The discussion focused mainly on the unexplained losses at IR3, and it was questioned whether the lack of an exponential drop off in losses as you moved away from IR3 could be a leftover from the sector 34 refurbishment. If so, it was commented that it does not come from the momentum aperture, but could be related to the off-momentum aperture. Indeed it was not yet clear if the losses were restricted to point losses. The conclusion of this part of the discussion was that a better overview of the situation was needed, and that this should be followed up in the Collimation working group.

Lastly, it was also noted that the rate of filling of the beam tails after cleaning was slower that the SPS.

BEAM DUMP SYSTEM AND ABORT GAP

Performance of the beam dumping systems and the abort gap cleaning as related to machine protection were discussed, with a focus on setting up, equipment problems, the eXternal Post Operational Checks (XPOC), and the importance of operational procedures.

Beam Dumping System

In 2009, the beam dump system correctly dumped 450 GeV beams, with the expected pattern on the beam screen just in front of the beam dump block (BTVDD) and no significant beam losses in the extraction area and beam dump channel. For the dumping of 1.2 TeV beams, the dump pattern was found to be ~8 mm low on the BTVDD for both beams, but this is suspected to be due to a MSD (extraction septum) calibration issue. In scenarios, the aperture of the beam dumping channels were measured for both beams in both planes using all phases and results were as expected, with apertures above 8 σ.

Over the course of the 2009 run, a total 2541 dumps were analyzed but with only 7 of these at 1.2 TeV (both beams). All beam dumping system failures were caught by the XPOC (eXternal Post Operational Check) system and/or IPOC (Internal Post Operational Check) system and there were no beam dump failures which were 'unacceptable', meaning that none would have caused damage with the TCDQ correctly positioned.

As the TCDQ protects the downstream against asynchronous beam dumps, and given that the rate of expected asynchronous beam dumps was once per year, it was initially surprising that the 2009 run yielded 11 asynchronous beam dumps. However, this was related to a TSU (Trigger Synchronization Unit) firmware fault, which was corrected. Once fixed, along with some additional hardware issues, it was noted that for both beams there were no false XPOCs over the last 10 days of operation in 2009. However it was noted that operation above 5 TeV should not take place with unsafe beam until broken resistors used for in the redundancy check of erratic trigger detection are fixed.

It was also noted that while false XPOCs were annoying for both the operators and the experts, it is important to maintain the 'Expert Reset' of any false XPOC as the beam dumping system is a safety critical component.

Abort Gap Cleaning

A first functionality test of the abort gap cleaning was successfully, demonstrating that in principle, abort gap cleaning can be achieved, and now can be commissioned. Fig. 2 show the summary of the abort gap cleaning tests.

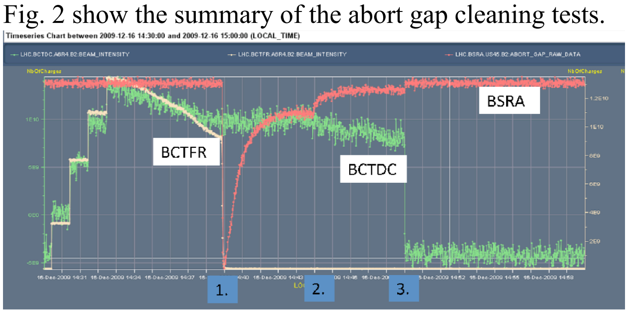

Figure 2: Beam current measurements by the BCTFR and BCTDC together with BSRA intensity measurements (zero intensity at top) as a function of time. After injecting 4 bunches close to the abort gap, the RF is switched off (1) so the abort gap is populated. After 5 minutes (2), cleaning is switched on and an equilibrium between cleaning and abort gap repopulation is obtained after 1 – 2 minutes. At (3) the beam was dumped. During the dump, the losses at the BLMs located at the TCDQ and TCDS

were reduced to 10 – 12 % of the losses at these elements without cleaning.

Discussion

It was noted that there are still a number of MPS checks related to the beam dump system, and it was stated that there is an ongoing programme to finish and optimise a number of XPOC module. These modules extends to checking both the beam dump system itself and the external inputs from other systems (e.g. BI Instrumentation).

Yet, the clear issue that was discussed was the need to have clearly identified procedures for recovery from an XPOC failure, that allows for clear understanding and response by both the XPOC/beam dump experts and the operations crew. It was also pointed out that one vital input to diagnosing and recovery of XPOC faults was the clear logging of the fault and the recovery steps taken by the shift crew/experts. It was also emphasised that at this stage of the machine operation, expert reset on both the XPOC and the LBDS was still very much restricted to a few experts from the beam dump system.

INJECTION AND DUMP PROTECTION

The presentation focused on the setup, commissioning and issues associated with the collimators used for machine protection against fast failures in the injection and dump lines. For injection the devices under consideration are the TCDI collimators in the TI2 and TI8 transfer lines, the injection dump (TDI) which absorbs losses caused by injection kicker failure or over-injection, and the downstream collimators (TCLI) which increase the TDI phase space coverage. For the moveable dump protection, single jaw TCDQ and double jaw TCSG collimators at Pt 6 were discussed, as they protect the downstream LHC ring elements against particle showers originating from asynchronous beam dumps.

Injection Protection: TCDLs, TDIs, and TCLIs

The TCDI, TDI, and TCLI setup was done by

1. Calibrating beam loss signal from losses generated by dumping a full bunch on the jaws and normalizing to the bunch intensity.
2. Aligning the jaws symmetrically around the beam, then scanning each jaw through the beam to determine beam size and position
3. Set the transfer line collimators to 4.5 σ and the passive injection protection elements to 6.8 σ.
4. Test protection settings with a series of orbit kicks at certain phases to verify that the collimators provide full phase space coverage.
5. Check TDI protection by injecting without firing the injection kicker or by over-injecting onto a circulating bunch in the kicker gap.

For the 2009 run this setup procedure was followed but over the course of the setup several issues were noted:

- Normalization of loss maps to beam intensity was difficult due to poor BCT resolution in the transfer line.
- The beam loss monitors with the fastest integration scale (40μs) saturate for low beam intensity.
- Particle showers from upstream collimators overlap and make beam size measurements more difficult due to saturation.

Nevertheless, both TDIs and TCLIs were aligned without major problems. However for beam 2, an asymmetry of a few mm was observed the TDI settings with beam well centered on adjacent BTV screens, and if this misalignment cannot be tracked down by further measurements, a TDI tank opening may be required.

However, as observed from tail scans performed conducted during transfer line sector tests, an exponential horizontal beam shape with significant tail population results in non-negligible losses. It was observed that by increasing the retraction of the horizontal TCDI from 4.5 σ to 6 σ gives a factor 2-3 loss reduction at injection, but a far more efficient reduction of injection losses achieved by scraping the beam in the SPS.

For the case of over-injecting, beam 2 causes losses at one of the triplet quadrupoles in Point 8 (MQXA) which needs to be under- stood.

Dump Lines: TCDQ and TCSG

In a similar setup campaign to that of the injection, the dump lines were set up and commissioned for the 2009 run. Again, there were no major problems, but the following features were noted:

- TCDQ/TCSG setting resolution of 0.1 mm is rather coarse and could be be improved.
- Position reading problems for the TCDQ related to the spring friction of the LVDT. The proposal is to replace this transducer with a potentiometer.
- For the commissioning, the beam size at the TCDQ and TCSG could not be properly measured, and so theoretical beam σ was used for retraction settings.

For the validation of the dump system under an asynchronous dump, de-bunched beam in the abort gap was used, and from Fig. 3 the losses for B1 and B2 on the TCDQ system can be seen to be concentrated on the dump protection devices with 0.1% on the collimators. This is in good agreement with expectations, and the sweep shape on the BTVDD shows the expected dilution on the dump block.

Discussion

The issue of the losses at injection due to significant tail population was discussed, and it was pointed out that the SPS scrapper was not adequate for routine operation at higher intensities. If it is to be used, then additional protection is needed. Further, with up to 30% of the beam is lost at injection, work needs to be done to reduce such losses as the transfer line collimators cannot sustain such abuse over the long term. Certainly opening the TDI to 6σ is not the desired solution.

It was also pointed out that the observed cross-talk in the transfer line BLM signals was not real cross-talk but this then begs the question as to its origin and to how it can be removed.

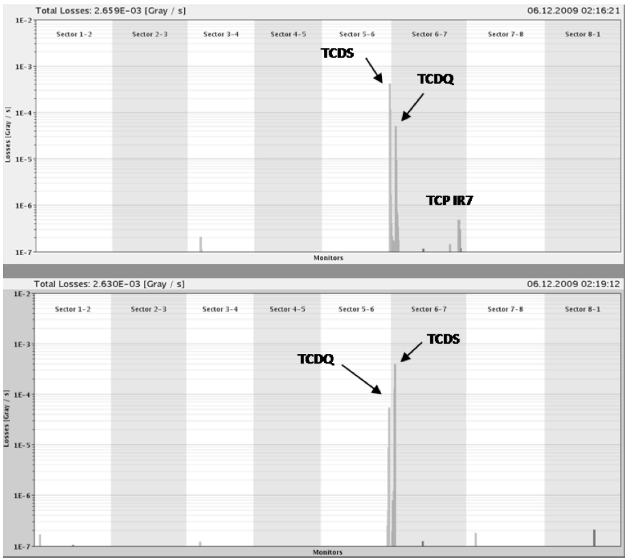

Figure 3: Losses on the dump protection devices during a dump of de-bunched beam in the abort gap. Top: Beam 1. Bottom: Beam 2

OPERATION AND OVERALL MP

An overview of the LHC Machine Protection System (MPS) was given, and the steps in going from the low intensity and low energy beam operation to higher energies/intensities discussed. Given that there is to be progressive steps in intensity and energy with each new step in energy or optics requiring machine protection validation at low intensities, it was clearly stated that a detailed and coordinated checkout programme must be followed. Naturally, each step must include interlock functionality as well as and the conditions for when or if interlocks can be masked.

Machine Protection in 2009

For the 2009 run, MPS tests without beam were almost entirely completed and for the MPS tests with beam, approximately 2/3 of the individual system beam tests were completed. In addition, global setup and tests were performed at injection energy and a partial setup of collimators and absorbers was done. No major problems were identified, however a number of issues were found. The list of MPS issues requiring attention is:

- The lack of an operational abort gap cleaning; it was tested, but was not made operational and not interlocked. This will become critical at high(er) intensity and smaller β*.
- Reliability of the Safe Machine Parameters (SMP) System: Specifically, reliability of the transmitted Safe Energy.
- The Setup Beam Flag (SBF) and Beam Presence Flag (BPF) had reliability issues related to the data transmission from the LHC BCTs.
- BLM signal cross-talk and saturation was observed, mostly in the injection region (TDI and TCDI collimators) and the TCDI-ring BLM shower cross-talk meant that scrapping in the SPS was mandatory already for very small intensities

Evolution towards Unsafe Beams

MPS evolution toward higher energy/intensity operation, given that quench levels decreases with energy, , imply a number of operational conditions for operating at or above the safe beam level. Associated with this evolution is a number of critical issues for the MPS. This list of critical issues includes:

- Setting of safety levels that are either unknown or estimated from reliability analysis.
- Common cause and correlated failure scenarios that leave the machine unprotected in some situations.
- Operational mistakes or controls issues that trigger dangerous situations .
- Non-nominal beam configurations.
- Machine Development (MD) phases which can potentially involve interlock masking or settings changes that are not removed at the end of the MD.

As such, a proposal was made that during standard physics operation sequences and settings be frozen to ensure best possible protection. Further, for each dedicated MD, a designated responsible must restore the machine conditions at the end of the MD. Similarly, “end-of-fill” MDs must be severely limited as the beams will most likely be unsafe.

In regard to interlocks it was noted that masking should be limited to a small set of people. Any masking should in general only be done below the SBF limits and only in well understood scenarios that are uncritical for machine protection.

Finally it was noted that as the Post-mortem (PM) system systematically analyses beam dumps, it can be used to validate the performance of the MPS. It is foreseen that for 2010, the EICs will have to acknowledge every beam dump, and SIS will inhibit injection as long as the last beam dump is not acknowledged.

The 2010 Startup

For commissioning to stable beams at 3.5 TeV (including the squeeze) it was noted that 4 pilot bunches is just at the SBF limit (3E10 p) and so the risk is very limited. As the decisions to increase the beam intensity is based on the performance of the MPS and on operational stability, it was suggested that an intensity increase should only be sanctioned once the MPP (machine protection performance) and MP3 (magnet performance - quenches) panels have given the OK. From the MPS point of view it was stated that the intensity steps should not be larger than a factor f = 2-4, and that the ratio luminosity to stored energy should be maximized through the bunch charge. Finally it was suggested that a long stable running period should be foreseen at a stored energy of 1 MJ.

Discussion

Discussion focussed on how to balance the commissioning and operation of the machine with the establishing and maintaining of an MPS envelope that would provide some level of machine protection. Specifically, it was noted that for example is setting up and using the collimators, some flexibility in collimator settings is needed, and that the no-mask policy at higher intensities may be limiting. It seems that while there is not a single strategy for all commissioning/operation scenarios, there was a general acceptance of the MPS proposals outlined in the talk.

It was also asked how the MPS envelope was to be restored after periods such as an MD, but here the answer was not obvious; part of the solution being looked at is to have the a state machine linked to the sequencer so to allow identification of non-nominal conditions. This idea has not yet been fully developed, and it was not clear to the speaker if this was the way to proceed. It was suggested that the issue of a MPS envelope would benefit from a more formal review once the commissioning has been further advanced.

In relation to the comment on operational/controls issues that trigger dangerous situations, clarification was requested from AB/CO as to the nature of these issues, and it was pointed out that it was not a risk from any individual component, but rather an operational risk from the complex interplay between controls interfaces and machine operation.

As part of the discussion, it was noted that for the experiments, in 2010 no “Quiet beams” fills are to be allowed, as they compromise the machine/experiment protection. In addition, the LHC physics coordinator noted that in order to push the luminosity while respecting MPS aspects of protection, the natural course of action would be to increase the bunch charge. The speaker noted that both bunch and total beam charge have to be considered when applying and adhering to the MPS limits.

Finally, the BLM team asked when the BLM signals associated with collimators should be made unmaskable inputs to the Beam interlock system. It was agreed that a decision on this be made after discussion with MPS and the Collimation team.