Report from the LHC Machine Protection Review

September, 28th, 2010

Submitted by the LHC Machine Protection Review Committee: Jerry Annala (FNAL), Reinhard Bacher (DESY, Chair), Mei Bai (BNL), Doug Curry (SNS), Stefan Lueders (CERN/IT, Co-Chair), Richard Jacobsson (CERN/PH), Jens Stadlmann (GSI), Dean Still (FNAL), Frank Zimmermann (CERN/BE)

Acknowledgement

The committee is impressed by the smooth start-up of LHC beam operation and congratulates the whole team for this great success. The Committee wishes to thank the organizers and all speakers for the careful preparation of their talks and for the lively and detailed discussions.

Introduction

The LHC commissioning with beam has now reached the point where a further increase of the beam intensity will result in a power level sufficiently high to damage accelerator equipment. During the course of 2010 and 2011 it is planned to boost the stored beam energy at 3.5 TeV from about 3 MJ to up to 30 MJ per beam. In order to ensure that this next step does not pose any danger to the LHC, a review of the LHC Machine Protection System has taken place at CERN during September 6 – 8th 2010. Guided by the following questions the Committee was asked to have a close look at the system in its present stage:

- Do you consider the plans for intensity and luminosity increase adequate for machine protection?
- Do you consider the machine protection adequate for increasing the energy stored in the beams up to 30 MJ, based on the proposed operational scenario (beta squeeze, crossing angle...)?
- What could be the main risks?
- Based on experience elsewhere: what is most critical and where have been surprises?

This report presents the outcome of this review.

Conclusions

Based on the present operational experience, the LHC machine protection system has proved to be highly reliable. The total number of protective beam abort events recorded so far is consistent with previous assumptions, even if the relative distribution among the different parts of the machine protection system differs from the expectations. No quenches due to the losses from circulating beam have been observed so far. Most of the beam abort events generated by the machine protection system were caused by direct failures of individual sub-systems. Unexpected beam aborts due to fast local beam losses which are still not fully understood have been handled properly. At the present level of stored beam intensity the experiments seem to be well protected. Powerful post-mortem analysis tools are available.

The highest risk of potential damage is expected to originate from combined failures of several critical protection systems (e.g. erratic discharging of the injection kicker while the hierarchy of the injection absorbers and collimators is not properly established), with the possible exception of firing the beam dump for the wrong beam energy, leading to an improper extraction of the entire stored beam energy in one location. Single-turn loss scenarios at injection due to missing injection kick, asynchronous kick or over-injection might pose a particular risk to the experiments Alice and LHCb.

However, present beam operations and a few machine components that are vitally important for the proper functioning of the LHC machine protection system still reveal deficits or are not fully understood. Therefore the Committee recommends that before reaching 30 MJ various issues should be addressed or further improved. In particular, clear criteria should be established by which steps and under which conditions the beam intensity will be increased. This includes, among other points,

- establishing the necessary operational discipline associated with the potential risks in the new regime of stored energy which to a large extent was promoted during the LHC engineering and construction phase,
- the understanding of the mechanisms populating the abort gap and their scaling as a function of beam intensity,
- consolidation of the beam position monitoring system,
- the improvement of a detailed and comprehensive post-mortem analysis, and
- establishing a robust and rigid set of operating procedures an sequences.

In summary, the Committee feels that the LHC is ready to go beyond 3 MJ. It sees no objection to a relatively fast but successive increase in stored energy. This conclusion is based on what was presented on the machine protection system and its performance. It assumes

- that the improvements are implemented which have been presented by the LHC project team themselves, including the priorities made by the Committee in addition to further recommendations,
- that the machine performance is all the time understood as the stored energy increases and that confidence is gained in all the operational phases, and
- that it is verified that there is no onset of new phenomena affecting the reliability of the machine protection system.

In the following sections, a more detailed description of the Committee's findings and recommendations will be presented.

Findings and Recommendations

1. The Human Factor

High importance was attached to sound conceptual ideas and procedures while designing and installing the components of the LHC machine protection system and its attached user systems. This inherent strictness was driven by the understanding that the LHC was aiming at a stored energy two orders of magnitude beyond that of present day machines and that it has to be protected against beam induced damage at all circumstances.
The Committee strongly agrees with the LHC project team's own admission that the human factor is a weak point. Rigorous discipline associated with the risk level must be reinforced during beam operations, maintenance interventions and component upgrades. The Committee supports all technical and administrative measures to restrict access to accelerator devices and their parameters to authorized and qualified personal only. It recommends establishing clear procedures to make and approve decisions for implementing or changing thresholds, sequences, firmware, etc. Back-door access or by-passing of established procedures must be banned; the amount and the consequences of planned maintenance or repair activities must be understood and communicated.

2. Configuration Control and Requalification

The Committee had many concerns over what was carried out during a technical stop or maintenance period. The concern mainly deals with soundness of the machine protection system when returning to beam operation. Recognizing that this is a complex issue, to the extent that it is possible, an automatic logging of systems which have been subjected to intervention is strongly recommended, e.g. using the Engineering Change Requests employed during hardware commissioning. Each intervention should be followed by significant routine test procedures ensuring requalification of the changed system. Similarly, tracking of software changes and keeping established previous programme versions as part of a secure roll-back scenario is mandatory.
In addition, the Committee recommends to establish test sequences to ensure the overall integrity of the complete machine protection system. These test sequences are required to be executed typically after each technical stop. This would also include verification of threshold sets downloaded to the hardware against the central database.
The Committee strongly encourages that a separate test sequence is executed regularly on a fraction of the beam interlock system inputs, checking the complete signal flow from its source to the release of the beam dump trigger.

3. Sequencer and High-Level Operations Tools

The Committee concludes that today's usage of the sequencer may be a direct source of risk to the LHC operation. Improper handling of the sequences should not be a tool to prove the validity of the machine protection system. It is strongly felt that the increase in intensity requires proper well-defined operation for both luminosity production and commissioning tests of main critical tasks and steps. In order to establish specific operation conditions, e.g. beam collisions, there should be only one set of well-defined steps available to the operator.

Long lists of procedures have been worked out already. However, executing the sequences requires largely manual interventions and the strict processing is thus not enforced. Paper-based lists of instructions should be strictly avoided for crucial steps.

There seem to be many pre-flight checks performed by the sequencer between fills which run serially. In order to decrease the time where the beam is not available, multiple instances of the sequencer are started in parallel each running a single function. This can lead to confusion as to which steps have been completed successfully. Establishing a method for completing these checks in parallel launched from a single sequencer is strongly recommended.

For the aforementioned reasons it should be of highest priority to pursue the work to integrate a state machine concept into the sequencer. A state machine provides an adequate platform to implement automatic flow and progress checking, and embeds rules for prohibited actions, commands, single tasks or sequences, including rules for compulsory steps. In addition, the changes of sequences should be registered into a versioning system which must also tag the timestamp, origin, and purpose of that change.

Various applications routinely used such as the injection sequencer or post-mortem analysis after a beam dump are presently independent tools. It would be advisable to increase the controls integration towards a "top run control" tool. The Committee feels that a conceptual review of the future development of such a tool with external experts on control integration may be advisable.

Besides the sequencer, efficient and reproducible operations should be supported by other high-level tools such as the alarm application. The Committee agrees with the operators that this alarm application is crucial for LHC operation and must become fully operational and usable.

Finally, the Committee was not able to verify whether the sequence to enable the operators to declare “Stable Beam”-Mode has the appropriate levels of protections and recommends reinvestigating this sequence.

4. Abort Gap Monitoring and Cleaning

Since a migration of beam into the abort gap has been already observed, the Committee emphasises the importance of understanding the underlying mechanisms and that a quality observable should be identified to determine the scaling as well as the effect of beam in the abort gap with the increase of beam intensity. The abort gap cleaning will improve the situation and might also relax the demand on the momentum cleaning.

5. Collimator System

The Committee feels that single-turn losses at injection due to missing injection kick, asynchronous kick or over-injection might hold a serious risk. The overall risk here is determined by the beam energy of one SPS injection and not by the total stored LHC beam energy. It recommends revising the leakage through the injection protection devices by means of measurements and simulations. Although it is said that the protection devices are designed to provide sufficient shielding to the machine elements against a full

train of bunches, the effect of the leakage is of particular importance to the Alice and the LHCb experiments.
The Committee also supports the proposal to attempt monitoring the collimator hierarchy based on losses during regular operation (lifetime drops, beam dumps) and making it part of the post mortem analysis. It recommends performing dedicated regular checks of the collimator hierarchy[1]. These checks should further foster the confidence in the collimator system and help identifying how often the dedicated re-setting of the collimators should be repeated. Increasing intensity will naturally increase loss levels to the regime where collimator hierarchy checks can be done during normal operation.
Although clearly the betatron-cleaning hierarchy is of primary importance the Committee supports work to understand and correct the problem of the momentum cleaning hierarchy. It recommends investigating at which point the momentum cleaning becomes significant.

6. Beam Position Monitors

The observed drift of the beam position monitor readings has impact on many systems, including the proper setup of the absorbers and collimators. However, the current accuracy is at the limit for a β^* of 2.5m. The Committee recommends giving a much higher priority to improving this.

7. Movable Devices

The Committee could not evaluate how the position limit of TOTEM and VELO is ensured as a function of the β^*.
The Committee finds it advisable to properly interlock the wire scanner to ensure that it cannot be used with intensities above its breaking limit, which is 7% of the nominal current.
In addition, the Committee recommends disconnecting and interlocking the alignment system of the triplets during beam operation.

8. Beam Loss Monitors

The beam loss monitor thresholds appear to be set conservatively, in particular in view of the fact that no beam induced quenches have yet been observed with circulating beam. As long as this does not affect the availability of the machine, the Committee does not currently see an urgent reason to raise the thresholds. However, the Committee recommends improving the understanding of quench levels and beam loss scenarios, including identifying potential blind spots of the beam loss monitor system based on the present experience with beam. This may prepare for changing the thresholds should an increased rate of unjustified beam aborts due to the beam loss monitor system be observed while increasing the beam intensity. This may include controlled beam induced quench testing. In addition, the fast losses observed recently may also be a reason to produce controlled beam loss induced quenches in order to improve the understanding of

[1] However, the Committee cannot give any recommendation on the checking frequency.

the mechanisms involved. At least one controlled beam induced quench at 3.5 TeV may also provide a good reference event for the post-mortem system. This could provide useful information for comparison when an actual quench occurs. Checking out the post-mortem system on an event that requires diagnosis can lead to uncertain conclusions.
The Committee learned that diamond-based detectors provide a bunch-to-bunch resolution of losses, and, thus, might provide an important complement to the existing beam loss detectors. Experience gained at the Tevatron demonstrates the importance and strength of this type of diagnostics capability. The Committee strongly encourages the installation of fast detectors at significant points around LHC which should be equipped with history buffers for post-mortem analysis.

9. Beam Current Monitors

It was reported that problems have been observed with the "Beam Presence" flag based on the fast beam current transformers, which on one occasion led to a potential risk of over injection of a probe beam on top of already stored high intensity bunches. The Committee recommends removing the intermixture of beam diagnostics and machine protection system by installing and relying on an independent failsafe system based on four button electrodes to measure the beam current.

10. Software Interlock System

The Committee understands that software-based interlocks implemented on the control system level complement the hardware-based interlocks of the machine protection system. Software-based interlocks allow realizing more complex decision logics and are a proper place to handle scenarios which have been overlooked.
The Committee encourages regular reviews of the software interlock system to see which interlocks may require the higher reliability of a hardware implementation. These should subsequently be re-implemented in hardware. An example is the verification of the synchronisation and energy match between SPS and LHC which is presently performed only by the software interlock system.

11. Specific Procedures

The Committee was informed that the injection kicker is designed to be switched off when LHC is not in the injection state to avoid erratic firing. During the review it turned out to be questionable if disabling this kicker will always be performed before retracting the injection absorbers for ramping.
It was also reported that the transfer line collimators will be regularly cycled for maintenance reasons. This procedure requires changing thresholds. The Committee recommends re-investigating this issue since the transfer line set up is critical for a safe injection.

Appendix

Monday 06 September 2010

09:00 - 11:45 Overview LHC

- 09:00 Meeting of the reviewers
- 09:30 Introduction to the review and mandate, Steve Myers (CERN)
- 09:45 Introduction to the LHC, Massimo Giovannozzi (CERN)
- 10:30 Coffee
- 11:00 LHC operation and objectives for 2010/2011, Mike Lamont (CERN)

11:45 - 14:4 5 Overview LHC Machine protection

- 11:45 Introduction to LHC Machine Protection, Rüdiger Schmidt (CERN)
- 12:45 Lunch
- 14:00 Operational experience with LHC Machine Protection, Markus Zerlauth (CERN)

14:45 - 20:00 LHC Machine Protection Systems

- 14:45 Overview of beam interlocking, Bruno Puccio (CERN)
- 15:30 Coffee
- 16:00 Experience with BLMs, Bernd Dehning (CERN)
- 16:30 BLM Thresholds, Eva Barbara Holzer (CERN)
- 17:00 Introduction to the LHC collimation system, Stefano Redaelli (CERN)
- 17:20 Collimation of encountered losses, Daniel Wollmann
- 17:40 Collimation and protection in the experimental IRs, Roderik Bruce (University of Lund)
- 18:00 MP issues from collimation and impact from upgrades, Ralph Assmann (CERN)
- 18:30 Meeting of the reviewers

Tuesday 07 September 2010

09:00 - 12:15 Injection, dumping and other fast systems

- 09:00 Fast kick failures, Jan Uythoven (CERN)
- 09:30 Protection at injection, Verena Kain (CERN)
- 10:15 Coffee
- 10:45 Beam Dumping system, operational experience and validation, Brennan Goddard (CERN)
- 11:30 Asynchronous dumps, Chiara Bracco (CERN)

12:30 - 18:00 Interlocking

- 12:30 Lunch
- 14:00 Magnet powering system, Markus Zerlauth (CERN)
- 14:45 Movable devices, Stefano Redaelli (CERN)
- 15:15 Coffee
- 15:45 Orbit and feedbacks, Jorg Wenninger (CERN)
- 16:45 Machine protection and operation, Laurette Ponce
- 19:00 Review Dinner

Wednesday 08 September 2010

09:00 - 11:00 Discussion session

- 09:00 Interactive session
- 10:30 Coffee

11:00 - 16:00 Interactive session (closed session)

- 11:00 Interactive session
- 14:00 Executive session
- 13:00 - 14:00 Lunch
- 16:30 - 17:30 Conclusion (Open session)