MACHINE PROTECTION SYSTEMS PERFORMANCE AND ISSUES 2012

D. Wollmann*, L. Ponce, R. Schmidt, J. Uythoven,
J. Wenninger, M. Zerlauth, CERN, Geneva, Switzerland

Abstract

Operating the LHC with stored beam energies up to 140 MJ (40% of nominal value) in 2012 was only possible due to the experience with and confidence into the machine protection systems gained in the 2 previous running periods - 2010 and 2011, where the stored beam intensity was slowly increased. In this paper the performance of the machine protection system during 2012 will be briefly discussed and compared to the previous running periods. Issues, which appeared during the operation of the MP systems during 2012 are reviewed. Special attention will be given to MPS issues, which risked compromising the protection of the LHC and, therefore, lead to a stop or delay of the standard operation of the LHC. The immediate actions taken as well as the mid- and long-term mitigations in these cases will be discussed. The efficiency of machine protection procedures during intensity increase, intensity cruise and the preparation of machine development periods will be reviewed. Finally improvements of the MP systems and procedures for operation after LS1 are proposed.

INTRODUCTION

During the 2012 run of the LHC more than 1000 clean beam dumps have been performed. 585 of them have been performed at particle momenta above 450 GeV/c. Note that only dumps before the 10th December 2012 were taken into account here. The majority of these beam dumps have been performed with beam energies above 100 MJ, reaching a maximum stored beam energy of 146 MJ per beam. No beam induced quenches of superconducting magnets have been observed at a particle momentum of 4 TeV/c. Excluding the observed problems of beam induced heating, no equipment damage due to the stored particle beams was observed during the 2012 run of the LHC. The reasons and the response of the machine protection systems for all beam dumps above 450 GeV/c have been analysed in detail, validated and classified by machine protection experts. Figure 1 shows the distribution of the 585 beam dumps classified into five categories (black: external; blue: beam; green: equipment; purple: operations; orange: experiments). These categories contain further sub-classes. False dumps from the machine protection systems - including BIC, BLM, LBDS, PIC, QPS, SIS - account for about 14 % of the beam dumps. This is comparable to their share in 2011 and slightly more than in 2010. A detailed analysis of the dump causes can be found in [1].

* daniel.wollmann@cern.ch

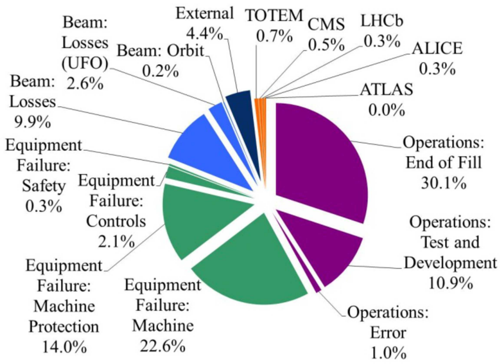
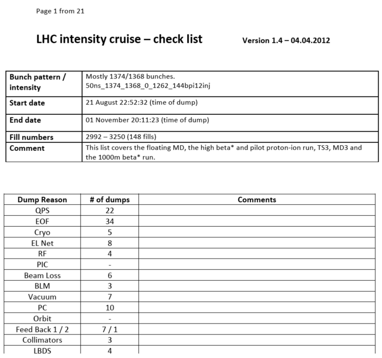


Figure 1: Distribution of Beam Aborts in 2012 (total 585). The dump causes are classified into five categories (black: external; blue: beam; green: equipment; purple: operations; orange: experiment), which contain further subclasses [1].

ISSUES 2012

During machine operation all dumps are stored and documented in the LHC post mortem database and completed with an operator and machine protection expert comment. In addition so-called machine protection check lists including all beam dumps above injection energy during the reference period concerned have been distributed regularly to the different system experts to document issues with the concerned systems. The check lists cover issues in the magnet powering system, beam interlock system, RF system, beam loss monitors, collimation, feedback systems, post mortem system, beam dumping system, issues with the beam orbit, issues during injection and with heating of accelerator equipment. The cover page of such a check list is shown in figure 2. In total 9 check lists have been distributed and filled by the system experts in 2012. During the step-wise intensity ramp up check lists were filled out before each significant step in beam intensity and after accumulating a minimum of 3 successful fills with a minimum of 20 hours operating in the machine mode stable beams with the current beam intensity. Intensity ramp check lists were completed after running with 84, 624, 840 and 1092 nominal LHC bunches per beam. During the following so-called intensity cruise with 1380 bunches per beam check lists have been distributed every 4 to 8 weeks. In total 5 intensity cruise check lists were filled out in 2012. The check lists are documented in EDMS. A list of all machine protection system issues documented in the differ-



Page 1 from 21

LHC intensity cruise – check list **Version 1.4 – 04.04.2012**

Bunch pattern / intensity	Mostly 1374/1368 bunches. 50ns_1374_1368_0_1262_144bpi12inj
Start date	21 August 22:52:32 (time of dump)
End date	01 November 20:11:23 (time of dump)
Fill numbers	2992 – 3250 (148 fills)
Comment	This list covers the floating MD, the high beta* and pilot proton-ion run, TS3, MD3 and the 1000m beta* run.

Dump Reason	# of dumps	Comments
QPS	22	
EOF	34	
Cryo	5	
EL Net	8	
RF	4	
PIC	-	
Beam Loss	6	
BLM	3	
Vacuum	7	
PC	10	
Orbit	-	
Feed Back 1 / 2	7 / 1	
Collimators	3	
LBDS	4	

Figure 2: Screen shot of a machine protection check list during the so-called intensity cruise. The filling pattern, the reference period (time and fill numbers), and a summary table of the false beam dumps are visible here. On the following pages each beam dump above injection energy is mentioned with an operator and machine protection expert comment.

ent check lists during 2012 operation has been presented to the 71st LHC Machine Protection Panel meeting on the 9th November 2012 [2].

In the following the top five machine protection issues in 2012 and their consequences for the operation of the LHC, listed in the sequence of their appearance, are critically reviewed.

OFSU reference problem

During the intensity ramp up in the beginning of 2012 operation it was observed that the reference used by the orbit feedback system was suddenly set to zero along the whole LHC ring during the machine mode squeeze at top energy (see figure 3). This lead to orbit offsets of up to 4 mm in some of the LHC insertion regions, where the orbit feedback compensated the crossing bumps due to the wrong reference orbit. The beams were finally dumped due to particle losses in the vertical B2 tertiary collimator in IR2. Due to this problem the next step of intensity increase was postponed and a new software interlock was introduced, to dump the beam automatically, if the reference settings are not loaded correctly or zeroed. In addition checks in the LHC sequencer and by the operators were introduced to check if the correct orbit reference is loaded before starting the ramp or the squeeze. Due to these measures the problem was reduced to an availability issue. This example shows that also issues in systems, which are not directly part of machine protection can have important consequences.

Powering of the LHC beam dumping system (LBDS)

Two major problems were discovered in the LHC beam dumping system during 2012. On the 13th of April a fault in one of the two redundant WIENER power supplies caused a loss of power in the whole set of general purpose beam dump crates. This would have caused an asynchronous beam dump if beam would have been present at this time. As a short term measure one of the triggering synchronization units was connect to a second independent UPS and fast fuses were introduced. In addition a review of the LBDS UPS powering was scheduled.

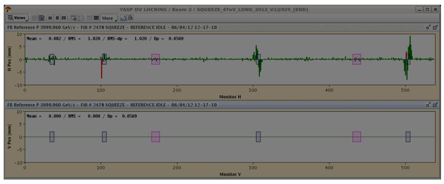


Figure 3: Screen shot of a reference orbit for beam 2 along the whole LHC ring on the 6th of April 2012 (fill 2478) for the machine mode squeeze. The top graph shows the (correct) reference orbit in the horizontal plane. In the lower graph the false reference orbit for the vertical plane is displayed. It is clearly visible that the reference has been falsely set to zero along the whole ring.

During the preparations of this review a common mode failure in the 12V DC powering of the triggering synchronization units was discovered during lab tests. This failure would have made it impossible to dump the beams in the LHC, which is considered to be the worst case failure. As any other problem could then lead to a fatal damage of the LHC. Due to the severity of the discovered common mode failure the operation of the LHC was stopped until a short term mitigation in form of a watchdog to supervise the 12V supply voltage was implemented. In case of a problem in the 12V supply this watchdog would dump the beam before the system would be off.

A fail safe and fault tolerant solution to mitigate the two problems will be implemented during LS1. In addition a redundant channel from the beam interlock system (BIS) to the LBDS re-triggering line will be installed, which will directly trigger a delayed asynchronous beam dump in case of a problem in the triggering synchronization units of the LBDS.

BSRT mirror support degradation

The transverse synchrotron light monitors (BSRT) are an important instrument to measure several critical beam parameters like the change of the beam emittance during a fill, the bunch by bunch beam intensity and information about the population of the abort gap. The latter is of importance for machine protection, as a high particle population in the abort gap may lead to high losses, magnet quenches and possibly damage of accelerator equipment in case of a beam dump.

During 2012 operation a gradual deterioration of the BSRTs due to beam induced heating was observed. On the 27th of August the deterioration suddenly increase in the B2 BSRT and the mirror, which reflects the synchrotron

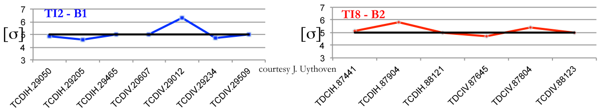


Figure 4: Deviation of TCDI gap openings from the required $5\,\sigma$ due to the change in optics in the tranfer lines after the introduction of the Q20 optics in the SPS. Courtesy J. Uythoven

radiation the instrument's optical installation, threatened to drop from it's support, damage the view port and fall through the beam. Therefore, fill 3012 was dumped to allow to un-install the BSRT and avoid any risk of collateral damage due to this problem.

The BSRT of B2 was re-designed and re-installed in technical stop three. As the observation of the abort gap population was not any more possible during the period before the re-installation the abort gap cleaning was turned on frequently. In addition alternative and redundant solutions to measure the abort gap population are under investigation and should be available after LS1.

False settings of Transfer Line collimators

After the technical stop three (TS3) end of September the so-called Q20 optics has been implemented in the SPS for the injection of beam into the LHC. Therefore the optics, i.e. the quadrupole strengths, in the transfer lines to the LHC had also to be adjusted. On the 19th of November it was discovered that the settings of the transfer line collimators, which protect the aperture of the LHC against too big injection oscillations had not been adjusted accordingly. This caused deviations from the required gap openings ($5\,\sigma$) of up to $1.3\,\sigma$ (see figure 4), which resulted in a reduced protection.

When the problem was discovered by the injection team physics operation was stopped to re-setup the TCDIs and validate their settings with beam. For after LS1 operation it is planned to introduce additional consistency checks between TCDI settings and used optics to avoid a comparable situation with reduced protection in the future.

Injection Issues due to Timing Problems

Tests with the so-called BCMS high brightness beams from the PS lead to a problem with the timing in the SPS. This caused the injection of beam into LHC B1 instead of B2.Thus, the the injection kickers in B1 did not fire and the 20 bunches were therefore injected onto the TDI. After this the tests with the BCMS beams was stopped until the reason for this problem was identified and mitigated.

Shortly after a second problem appeared during injection, when the SPS RF-clock was not synchronized with the LHC, i.e. running on local timing. This caused a mismatch of the kicker firing and the SPS injection and therefore twice 48 bunches were hitting the TDI in IR8.

These issues were a reminder that currently there exists no active protection against timing issues during injection. The passive protection for injection problems, i.e. the correctly positioned TDI, worked as foreseen. As the TDI is currently the only protection for these type of errors it is planned to introduce additional extraction interlocks on the SPS side during LS1.

Other MP issues in 2012

Some other machine protection issues observed in 2012 are listed below. The full list of machine protection system issues documented in the different check lists during 2012 operation has been presented to the 71st LHC Machine Protection Panel meeting on the 9th November 2012 [2].

- False collimator settings of the vertical tertiary collimators in IR2 and 2 collimators in IR3. The false settings were detected on the 17th of April and corrected in LS1.
- Upper corner of the TDI in IR2 was *falling* onto the lower jaw (03.12.2012), when putting it back to injection position due to a loose splinter pin.
- Several MKI.D flash-overs in the beginning of the run. This injection kicker has been replaced during TS3.
- The tune feedback could not be used during the beam mode squeeze due to a poor tune signal, thus operation relied on a feed forward. Since the end of October an additional high gain system, which gates on the first 6 bunches is operational, which mitigated the problem.
- After technical stop two a cabling problem in the QPS instrumentation of RQX.L8 was discovered. The cables had to be changed back to the status before the technical stop.
- Different trips of power converters caused significant orbit drifts. The beams were dumped by the BLM system due to losses. During LS1 these issues will be mitigated by introducing interlocks on these power converters, which will allow to dump on the root cause of the orbit drifts.
  - Fill 3220: Removal of powering permit for the 60A corrector magnets in sector 67.
  - Fill 2985: Trip of LHCb dipole.
  - Fill 2934: Fast discharge of CMS solenoid.
- Heating of different equipment due to beam.

MACHINE PROTECTION PROCEDURES FOR MACHINE DEVELOPMENTS

Machine developments explore per definition new machine territory. Therefore, the requestors of MDs are required to prepare a machine protection document if they are

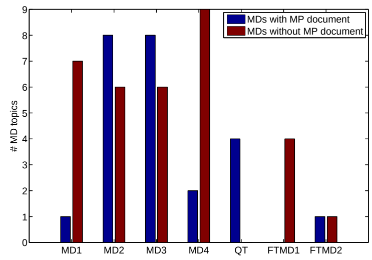


Figure 5: Comparison of the number of MD topics with and without machine protection document

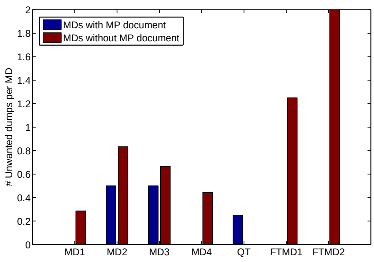


Figure 6: Comparison of number of unwanted beam dumps per MD with and without machine protection document

planning to use unsafe beam intensities with non-standard parameters and settings of machine protection devices. Figure 5 shows the comparison of the numbers of MDs with (blue) and without (red) machine protection documents during the different MD periods. In total 26 machine protection documents were prepared and approved in 2012. The discussions of the MD programs in the preparatory phase has proven to be useful for the MD and machine protection teams. It improves the safety and also the efficiency of the MDs. Figure 6 shows the number of unwanted beam dumps per MD during the different MD periods for MDs with (blue) and without (red) machine protection documents. This comparison indicates that the preparation of a machine protection document can even improve the efficiency of the MD.

Especially during MD4 a number of last minute MD program and parameter changes were requested. The short preparation and discussion time made it difficult to discover possible dangers, perform pre-tests with the requested parameter space in the LHC with safe beam intensities and go through the agreed approval process before the actual MD.

For after LS1 it is therefore proposed to request for every MD an updated program including beam parameters, thresholds and settings for machine protection relevant systems and devices. It is currently under discussion if interlocks on the specified beam parameters could be implemented for each MD in the SIS, to avoid on the spot changes of relevant beam parameters or machine protection device settings.

PROPOSED CHANGES IN THE MACHINE PROTECTION SYSTEMS DURING LS1

Following the discovered issues in the LHC beam dumping system a redundant channel from the beam interlock system (BIS) to the LBDS re-triggering line will be implemented during LS1 to create a redundancy for the triggering synchronization unit of the LBDS. Furthermore it is required to implement a measurement and interlocking on the change of the beam intensity, called DIDT, during LS1. This interlock will bring an additional redundancy for the BLM system in case of fast beam losses. Such a system has already been proposed for the LHC in 2004 and a prototype system has successfully been tested with a detection principle developed by DESY.

Due to the experienced issues with the BSRTs it is proposed to develop a redundant monitoring of the abort gap population during LS1. Studies in ALICE and with diamond particle detectors are ongoing. Furthermore it is proposed to implement automatic consistency checks for collimator settings - in the ring as well as in the transfer lines. These checks should also take the implemented optics into account. Finally it is proposed to automatically monitor the aperture in the LHC ring and transfer lines and warn the operators if defined thresholds are violated.

CONCLUSION

In 2012 more than 1000 clean beam dumps have been performed. The majority of beam dumps above 450 GeV/c have been performed with beam energies above 100 MJ. No beam induced quenches of superconducting magnets have been observed at top energy. These results are mainly due to the reliable and efficient functioning machine protection systems, the due diligence of the equipment teams, operations, (r)MPP and the coordinators.

Still weaknesses in procedures and machine protection systems were discovered during the LHC run 2012. The response of the coordinators, operations and (r)MPP to the discovered issues was adequate.

Machine protection procedures for machine developments worked in general well, but recently too many last minute program and parameter changes were requested. This can potentially put the LHC in unnecessary danger. Machine protection check lists proved their importance as prerequisite during the intensity increase and for documenting machine protection issues of the different systems during the full running period.

REFERENCES

[1] B. Todd et al. A LOOK BACK ON 2012 LHC AVAILABILITY. In *Proceedings of LHC Beam Operation workshop - Evian 2012*, 2012.

[2] D. Wollmann. Machine Protection Systems - Performance and Issues 2012, 71st MPP: http://lhc-mpwg.web.cern.ch/lhc-mpwg/.