MPS issues and MP approach concerning operation and MDs

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Abstract

The performance of the machine protection system with a focus on safety has been studied for the first 3 years of LHC operation. An overview of the remaining limitations, major issues, periods of non-standard operation and the functioning of machine protection organisation as seen by machine protection experts will be presented in this paper and the procedures and processes to handle these will be discussed.

Inferring from the experience gained, proposals to improve said processes and the support to the operation crews during intensity ramp-ups, MDs, and other non-nominal modes of operation will be made for the re-start of the machines after LS1 and the operational period thereafter.

INTRODUCTION

With close to 30 fb^{-1} of integrated luminosity been delivered to ATLAS and CMS during the first 3 years of operation, the LHC machine has surpassed many of the expectations during this first run, despite still operating with 50 ns of bunch spacing and being limited in energy to 4 TeV. At the end of 2012 the machine was routinely operated with bunch currents reaching $2 \cdot 10^{14}$ protons per beam, representing stored beam energies of more than 140 MJ. This was only possible due to the expertise and confidence gained in the two previous years, where the intensity was progressively increased to safely reach the ultimate intensity target. During this first three years of running, the LHC machine protection systems have safely removed circulating beams from the machine 3500 times, whereas for almost half of these dumps (namely 1582) the energy was above injection energy. Even while routinely operating with stored beam energies well above 100 MJ, no unintentional beam induced quenches have been observed with circulating beam, emphasising the dependable protection provided by the different layers of the machine protection system. Likewise no severe equipment damage was recorded during the entire run, apart from some damage recorded in the SDD calibration unit of ALICE [1], a few corrector coils of the inner triplet L2 following kicker erratic's during beam injection and some issues related to beam induced heating of components during 2012.

All beam dump events above injection energy, be it a programmed dump or a premature beam dump request, have been meticulously analysed and validated by the operation crews and Machine Protection System (MPS) experts and have been used to build a knowledge database to assess possible long-term improvements of the LHC machine protection and equipment systems [2]. This database has proven a useful asset in the efforts to understand and improve machine performance throughout the different operational phases as shown at the example of dumps occurred during the operational year 2012 (Figure 1).

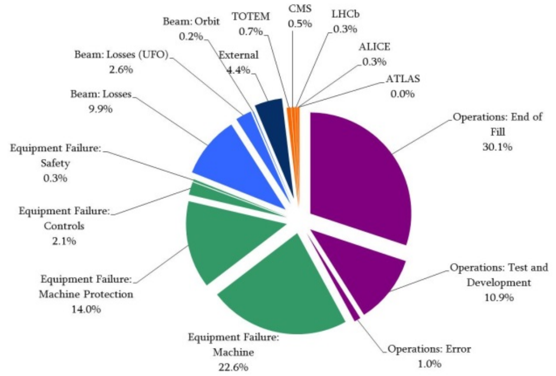

Figure 1: Causes of beam dumps above injection energy of 450 GeV during the operational year 2012

MACHINE PROTECTION ISSUES

The aforementioned database is also extensively used by machine protection experts and rMPP members to assure that potentially dangerous situations are recognised, documented and published as well as concordant actions are being followed up throughout commissioning and operation.

Despite the absence of severe damage to equipment during the first three years of operating the LHC, a number of issues and near-misses have probed the thoroughness of the machine protection architecture and the way the system is used during operation, a selection of which is listed in the following:

- Common cause failure mode of 12V supply in LHC Beam Dumping System (LBDS)
- Quench detection issues on IPQ, 600A EE
- Wrong setup of TL collimators for SPS Q20 optics
- Timing issues when injecting H9 beams
- Wrong collimator settings (2 x TCTV IR2, 2x IR3)
- Roman Pot Controls issues
- BLM High Voltage Cable interruption
- Orbit Feedback System Utility (OFSU) reference problems
- Beam Synchrotron Radiation Telescope (BSRT) beam induced heating
- MDs and other non-standard machine operation
- MKI flashovers
- Tune Feedback System (QFB) not usable in squeeze due to poor signal
- Instrumentation problems in triplet L8 after TS2

- Loss of redundant protection (60A power permits, LHCb dipole, CMS solenoid…)

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 along with describing the actions taken and mitigations put in place [3].

Reference problem in the orbit feedback system

During the intensity ramp up it was observed that the reference used by the orbit feedback system was suddenly set to zero along the whole LHC ring at 4 TeV/c (see Fig. 2). This lead to orbit offsets of up to 4 mm in some of the LHC insertion regions, where the orbit feedback removed the separation bumps due to the wrong reference orbit. The beams were finally dumped due to particle losses in the vertical beam 2 tertiary collimator in IR2. Because of this problem the next step of intensity increase was postponed and a new software interlock was introduced, to dump the beam in case of an orbit reference problem. Due to this measure and additional checks in the LHC sequencer and by the operators the problem was reduced to an availability issue.

Powering of the LHC beam dumping system

Two major problems were discovered in the LHC beam dumping system (LBDS) during 2012. On the 13th of April a fault in one of the two redundant 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 in the LHC 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.

During lab tests a common mode failure in the 12 V DC powering of the triggering synchronization units was discovered. In the LHC this failure would have inhibited the beam dump. This is considered to be the worst case failure scenario, as any other problem could then lead to a fatal damage of the LHC. Due to the severity of the discovered problem the operation of the LHC was stopped until a short-term mitigation in form of a watchdog to supervise the 12 V supply voltage was implemented. This will dump the beams in case of a problem. A fail safe and fault tolerant solution to mitigate the two problems will be implemented during LS1.

Mirror support degradation in synchrotron radiation monitor

Besides other critical beam parameters the LHC Synchrotron Radiation Monitor Light Extraction System delivers information about the population of the abort gap.

This is of importance for machine protection, as a too 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. A gradual deterioration of the two devices due to beam induced heating was observed in 2012 [4]. On the 27th of August the deterioration suddenly increased in beam 2 and the optical mirror, threatened to drop from its support, damage the view port and fall through the beam. Therefore, fill 3012 was dumped to allow to un-install the device and avoid any risk of collateral damage due to this problem.

False settings of Transfer Line collimators

End of September 2012 the so-called Q20 optics has been implemented in the CERN-SPS for the injection of beam into the LHC. The optics, i.e. the quadrupole strengths, in the two transfer lines to the LHC were adjusted accordingly. 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 to the new β-functions.

This caused deviations from the required gap openings ($5\,\sigma$) of up to $1.3\,\sigma$, which resulted in a reduced protection. When the problem was discovered LHC physics operation was stopped to re-setup the transfer line collimators and validate their settings with beam.

Injection Issues due to Timing Problems

Tests with high brightness beams from the CERN-PS led to a problem with the timing in the SPS. This caused the injection of beam into beam 1 instead of beam 2. Thus, the injection kickers in beam1 did not fire and 20 bunches were therefore injected onto the LHC injection beam stopper (TDI). Therefore these tests were stopped until the reason for this problem could be identified and mitigated. Shortly afterwards, a second problem appeared during injection, when the SPS RF-clock was not synchronized with the LHC, i.e. running in local mode. This caused a mismatch between SPS extraction and LHC injection. Therefore, twice 48 bunches hit the beam 2 TDI.

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.

MACHINE PROTECTION ORGANISATION AFTER LS1

Experience over these past three years has shown that a majority of the issues detected where ‘dormant’ failures. Despite the fact that appropriate actions where always taken immediately, the mid-term lessons should be learned and commissioning and operational procedures accordingly modified and tightened up. A few of the issues were allowed to persist for longer periods in time, as the reaction to a certain event varies as a function of the individuals knowledgeable about it. In retrospect it may not always have been easy for the operation crews and Machine Coordinators to assume the double role of optimizing performance of the machine as well as to assure its safety. To increase and facilitate the support to the operation crews the role of a ‘Machine Protection piquet’ is proposed as of the start of commissioning the LHC after LS1. This role could alternate between selected rMPP members on a weekly or bi-weekly basis and would include the follow-up of the commissioning of machine protection systems, operational changes and the necessary revalidations, analysis and documentation of operational runs and beam dumps as well as serving as the contact person (representing rMPP) to operations.

This recommendation results from the experience that, while the initial MPS commissioning phase was prepared and carried out with the required rigor and necessary time available [5], we did not manage to maintain this commissioning mind-set throughout the full running period. Due to various factors such as scheduling pressure, routine, relatively smooth operation of the machine, fatigue and others the initially commissioned safety level certainly degraded towards the end of the running period. Hence possibilities to counter-act such phenomena should be investigated, e.g. to

- Dependably track (relevant) system changes
- Assure a more coherent approach for follow-up of magnet & beam related MPS issues
- Define and enforce a minimum validation cost of changes (following previously defined and agreed procedures) through the use of automatic tools and dependency models
- Introduce the role of a Machine Protection Piquet for non-standard cases

These considerations are particularly important for phases of non-nominal operation of the machine such as special runs or machine development periods, which by definition explore new machine and machine protection territory, often requiring numerous changes to the machine and machine protection systems to allow for the MDs to be performed. In general MD requestors have demonstrated a high level of responsibility by proactively providing the required MP documents, towards the end of 2012 MDs where however planned on shorter notice which sometimes did not allow for an equally thorough preparation of the MDs.

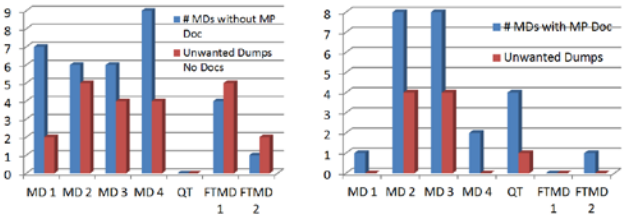

Figure 2: Number of Machine Developments (blue) and unintentional dumps (red) during the different MD blocks in 2012. For MDs without a detailed MP document (left) and where a detailed MP document has been prepared (right).

While an MP document is mandatory when using unsafe beam or a non-operational setup of the machine, Figure 2 shows that in general the preparation of an MD (through a mode detailed document) is beneficial even for the efficiency of the MD (if measured through the number of unintentional losses of beams during the MD). As shown in the figure the likelihood of losing the beam – often because of forgotten interlock conditions, masking of certain system inputs… - is roughly twice as high in absence of an MD document. To further enhance the safety as well as making an optimum use of machine time allocated to MDs, the preparation and approval of a short MD note [6], detailing the program and required changes to the machine setup will become mandatory for the allocation of an MD slot.

CONCLUSIONS AND OUTLOOK

The LHC Machine Protection and Equipment Systems have been working extremely well during the first three years of operating the LHC thanks to a lot of commitment and rigor of operation crews and equipment and machine protection experts. There is no evidence of a major loophole or uncovered risks within the MPS architecture, however a few near-misses have revealed shortcomings in designs, commissioning procedures and operation of the MPS systems which will have to be addressed and mitigated during LS1. The organization and response of coordinators, operation crews, (r)MPP and equipment experts in case of such near-misses was adequate, however the issue of decreasing attention and rigor towards the end of a running period remains to be addressed. Despite the high dependability of the machine protection systems during the past operational years we have to remain vigilant also in the years to come when more emphasis will be given to increase the overall machine availability and when it will become increasingly challenging to maintain the systems at their required level of dependability due to questions of resources and additional operational challenges in the post LS1 era.

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