MACHINE PROTECTION AT THE LHC - EXPERIENCE OF THREE YEARS RUNNING AND OUTLOOK FOR OPERATION AT NOMINAL ENERGY

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Abstract

With more than 22 fb^{-1} integrated luminosity delivered to the experiments ATLAS and CMS, the LHC surpassed the results of 2011 by more than a factor 5. This was achieved at 4 TeV, with intensities of ~2e14 p per beam. The uncontrolled loss of only a small fraction of the stored beam is sufficient to damage parts of the superconducting magnet system, accelerator equipment or the particle physics experiments. To protect against such losses, a correct functioning of the complex LHC machine protection (MP) systems through the operational cycle is essential [1]. Operating with up to 140 MJ stored beam energy was only possible due to the experience and confidence gained in the two previous running periods, where the intensity was slowly increased. In this paper the 2012 performance of the MP systems is discussed. The strategy applied for a fast, but safe, intensity ramp up and the monitoring of the MP systems during stable running periods are presented. Weaknesses in the reliability of the MP systems, set-up procedures, and setting adjustments for machine development periods, discovered in 2012, are critically reviewed and improvements for the LHC operation after the up-coming long shut-down (LS1) of the LHC are proposed.

INTRODUCTION

During the 2012 run of the LHC more than 1000 clean beam dumps have been performed. More than half of those have been performed at particle momenta above 450 GeV/c. 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 [2], 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 MP systems for all beam dumps above 450 GeV/c have been analysed in detail, validated and classified by MP experts. Fig. 1 shows the distribution of the beam dumps classified into five categories (black: external; blue: beam; green: equipment; purple: operations; orange: experiments). These categories contain further subclasses. False dumps from the MP systems, including the Beam Interlock Controllers (BIC), the Beam Loss Monitor System (BLM), the LHC Beam Dumping System (LBDS), the Powering Interlock Controllers (PIC), the Quench Protection System (QPS) and the Software Interlock System (SIS), account for about 14 % of the beam dumps. This is comparable to their share in 2011 and slightly more than in 2010 [3]. A detailed analysis of the dump causes can be found in [4].

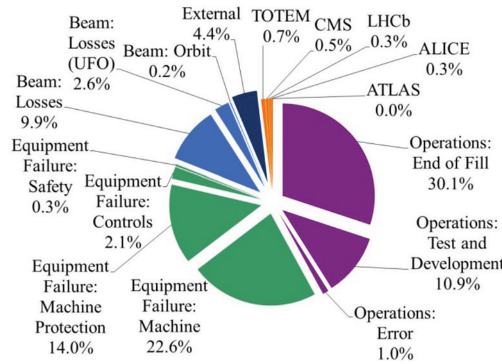

Figure 1: Distribution of Beam Dumps in 2012 (total 585). The dump causes are classified into five categories (black: external; blue: beam; green: equipment; purple: operations; orange: experiment), which contain further subclasses [4].

MACHINE PROTECTION ISSUES 2012

During machine operation all dumps are stored and documented in the LHC post mortem database and completed with operator and MP expert comments. In addition so-called MP check lists have been distributed regularly to the different system experts to document issues with the concerned systems. The check lists include all beam dumps above injection energy during the reference period concerned. They cover issues in the magnet powering system, beam interlock system, RF system, beam loss monitor system, collimation system, feedback systems, post mortem system, beam dumping system, as well as issues with the beam orbit and related to heating of accelerator equipment. As in previous years, the ramp up of the beam intensity at the beginning of the run was performed in steps. Before the beam intensity was increased, a minimum of 3 successful fills with in total at least 20 hours stable beams, i.e. delivering collisions to the LHC experiments, had to be accumulated. In addition intensity ramp up check lists had to be filled to assure that all concerned systems were ready for the next step. 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 were compiled every 4 to 8 weeks. In total 9 check lists have been distributed and filled by the system experts in 2012. In the following the top five MP issues in 2012 and their consequences for the operation of the LHC are critically reviewed.

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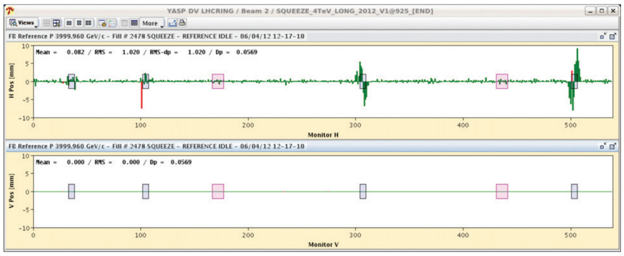

Figure 2: Screen shot of a reference orbit in the horizontal (top) and vertical (bottom) plane for beam 2 along the LHC ring (fill 2478).

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 in the vertical plane 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 compensated the separation bumps due to the wrong reference orbit. The beams were finally dumped due to particle losses from beam 2 at the vertical tertiary collimator in one of the insertions. 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 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 several electronics crates of the LBDS. 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 connected 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. If this failure would have happened in the LHC, it would have been impossible to dump the beam. This is considered to be one of the worst case failure scenarios, as any other problem could then lead to a very serious 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 would 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

The LHC Synchrotron Radiation Monitor Light Extraction System delivers information about beam size and particle 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, in particular since the inter magnet splices were not yet consolidated. A gradual deterioration of the devices due to beam induced heating was observed in 2012 in the two beams [5]. 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 in order 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 [6] 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. As soon as 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 ring 1 instead of ring 2. Thus, the injection kickers for beam 1 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 after 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 mis-match between SPS extraction and LHC injection. Therefore, twice 48 bunches hit the TDI in beam 2.
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.

MP PROCEDURES FOR MACHINE DEVELOPMENTS

Machine developments (MD) explore per definition new machine territory. Therefore, the requestors of MDs are required to prepare a MP document if they are planning to use beam intensities above the limit that is considered reasonably safe with non-standard parameters and settings of MP devices. Fig. 3 shows the comparison of the numbers of MDs with (blue) and without (red) MP documents during the different MD periods. In total 26 MP documents were prepared and approved in 2012. The discussions of the MD programs in the preparatory phase has proven to

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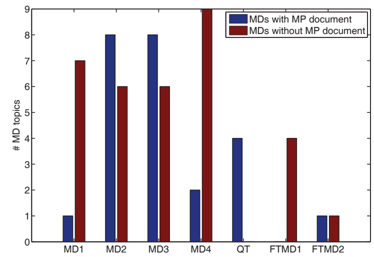

Figure 3: Comparison of the number of MD topics with and without machine protection document.

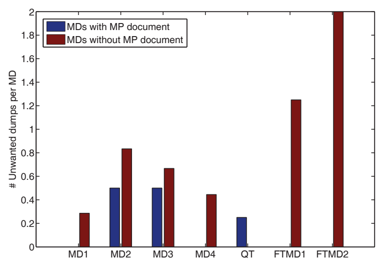

Figure 4: Comparison of number of unwanted beam dumps per MD with and without machine protection document.

be useful for the MD and MP teams. It improves the safety and also the efficiency of the MDs. Fig. 4 shows the number of unwanted beam dumps per MD during the different MD periods for MDs with (blue) and without (red) MP documents. This comparison indicates that the preparation of a MP 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 hazards, 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.

After LS1 it is therefore proposed to request for every MD an updated program including beam parameters, thresholds and settings for MP relevant systems and devices two to four weeks ahead of the MD.

PROPOSED CHANGES IN THE MP 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 units of the LBDS. Furthermore it is required to implement a measurement and interlocking on the change of the beam intensity, called DIDT. This interlock will bring an additional redundancy for the beam loss monitor system in case of fast beam losses.

Due to the experienced issues with the LHC Synchrotron Radiation Monitor Light Extraction System it is proposed to develop and implement a redundant monitoring of the abort gap population during LS1. 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. To improve the protection against timing issues at injection it is planned to introduce additional extraction interlocks on the SPS side during LS1.

CONCLUSION

In 2012 more than 1000 clean beam dumps have been performed in the LHC. 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 MP systems, the due diligence of the equipment teams, operations, the MP team and the LHC machine coordinators.

A few weaknesses in procedures and MP systems were however discovered during the 2012 run. The response of the coordinators, operators and MP experts to the discovered issues was adequate.

MP 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. MP check lists proved their importance as prerequisite during the intensity ramp-up and for documenting MP issues of the different systems during the full running period.

Acknowledgments

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