POSSIBLE CAUSES AND CONSEQUENCES OF SERIOUS FAILURES OF THE LHC MACHINE PROTECTION SYSTEM

J. Uythoven, R. Filippini, B. Goddard, M. Gyr, V. Kain, R. Schmidt, J. Wenninger
CERN, Geneva, Switzerland

Abstract

The LHC machine protection systems, including the beam dumping system, are designed to ensure that failures leading to serious damage to the LHC during its lifetime are extremely unlikely. These kind of failures, for instance requiring a combination of equipment failure and surveillance failure, have to date been considered as being ‘beyond the design case’. However, their consequences need to be evaluated to determine the required safety levels of the protection systems. A second objective is to understand if measures can and should be taken to further reduce the probability of such failures, or to minimise their impact. This paper considers various serious failure modes of the different machine protection systems. The probable consequences and possible ameliorating measures of the worst-case scenarios are discussed. The particular case of having a stored beam with an unavailable beam dumping system is mentioned, together with possible actions to be taken in such an event.

INTRODUCTION

The Large Hadron Collider (LHC) presently under construction [1] has an unprecedented energy stored in its two beams and in the superconducting dipoles. A reliable machine protection system [2] is crucial to its successful operation. A central part of the machine protection system is the Beam Dumping System [3] which is designed to be very reliable, with less than 1 ‘unacceptable’ failure every 100 years, while still guaranteeing a high availability of the system. The beam dumping system comprises, in turn, per ring, 15 horizontally deflecting extraction kicker magnets MKD of which the kick is enhanced by the superconducting quadrupole Q4, 15 vertically deflecting septum magnets MSD, 10 dilution kicker magnets MKB followed by several hundred metres of transfer line before the beam reaches the dump TDE. The system is designed to be tolerant to the most common failure modes [4], nevertheless it is possible that so called ‘beyond design case failure modes’ could occur. The impact of these extremely unlikely failures can be very serious and for this reason must be considered in the design of the machine protection system. In the present paper the causes which lead to these failures and the associated likelihood are not considered in detail.

BEAM DUMPING SYSTEM FAILURES

This section discusses the cases in which the beam dumping system is triggered on request, but the dump action is not correctly executed.

MKD Extraction Angle Failure

In case of a beam dump demand, the beam is extracted from the LHC by the extraction kicker MKD with a nominal system bending angle of 0.275 mrad. Several failure scenarios could lead to a deflection with a different angle, leading to considerable damage to the machine.

One such scenario is the 7 TeV/c stored beam being deflected by 1/15th of the nominal kick. This could happen if the MKD magnets are powered with injection settings. The kick corresponds to a 15 σ excursion and should not damage the cryogenic aperture of the arc magnets. However, calculations of the horizontal displacement of the central beam over subsequent turns show that already after two turns the oscillation amplitude at virtually all the collimator locations is larger than their nominal setting, see Figure 1. The studies were made for LHC optics V6.5 with 24 collimators and absorbers at nominal settings (between 6 σ for primary collimators in IR7 and 15 σ for tertiary collimators). There is a significant risk that many of these objects could be damaged and for a proper assessment material studies need to be taken into account.

For kick angles of the MKD system at about 60 μrad, corresponding to some 50 σ excursion, the beam screen of the immediately downstream quadrupole (Q4) will be hit. For larger angles subsequent parts of the extraction system can be damaged, see Figure 2. No damage occurs around the nominal extraction angle of 275 μrad. The calculations did not take into account that after traversing about 10 – 20 m of heavy material the beam is likely to be significantly absorbed and diluted so it will not damage

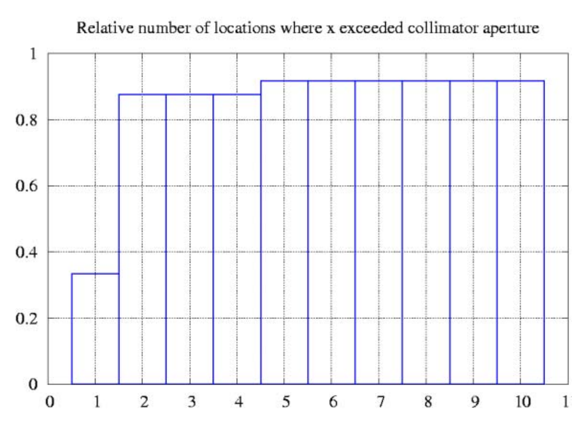

Figure 1: Fraction of collimators and absorbers where the oscillation amplitude exceeds the nominal aperture as a function of the turn number, following a MKD kick excursion of 15 σ.

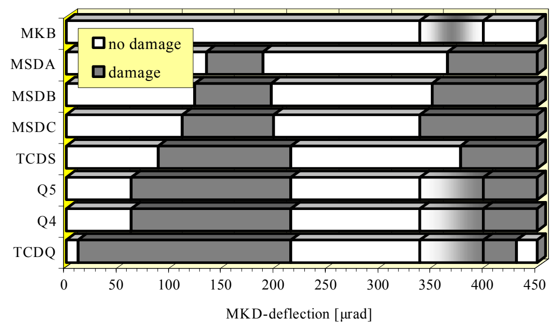

Figure 2: Elements possibly hit as a function of the MKD extraction angle. TCDQ and TCDS are absorber elements, giving protection against asynchronous beam dumps.

equipment, which is further downstream [5]. The quadrupoles Q4 and Q5 can be damaged over a relatively large range of MKD extraction angles because their possible damage depends on the deflection angles in both the horizontal (MKD) and vertical (MSD) plane.

Bad extraction with excursions between 15 σ and 50 σ has not been studied in detail. For these angles serious damage to a substantial number of cryogenic magnets, both quadrupoles and dipoles, distributed over the LHC circumference is expected to occur. A detailed study of this case is planned.

MSD Vertical Bending Failure

Part of the failure scenario of wrong vertical deflection by the septa (MSD) is implicitly treated by the study presented in Figure 2. The failure in the vertical bending over a large angle has the potential of damaging the dilution magnets MKB and the quadrupole magnets Q4 and Q5. A small bending angle failure can damage the dump block enclosure.

Small Extraction Angle Failures

It is possible that the beam is not extracted on the centre of the face of the dump block and hits the steel jacket around the dump core, caused by a relatively small error of the extraction angle in either plane, creating an air leak in the dump line vacuum chamber and the jacket of the target TDE, leading to a possible loss of containment. A sacrificial absorber placed at some distance upstream of the dump and outside the beam pipe could be implemented to cover this scenario.

MKB Dilution Failure

During normal operation 10 pulsed magnets (MKB) will be used to sweep the extracted beam along an "*e*"-shape path on the upstream face of the absorber graphite core. Detailed simulations have been made of the effect of the absence of dilution [6]. No dilution can locally lead to an energy deposition which is above the vaporisation limit of the carbon core. However this failure remains laterally contained within the steel jacket of the dump core. The only loss of containment could be located at the downstream window, where a localised perforation cannot be excluded. However, no significant amount of graphite should be released and the consequences of a complete dilution failure are not expected to be catastrophic for the LHC or its environment.

OTHER SYSTEM FAILURE MODES

Failures of other systems in the LHC can also have serious consequences and will be studied in the future. They are only briefly outlined below.

The transverse feedback system should normally damp any beam oscillations. If the damper works in 'anti-phase' it could excite the beam and possibly lead to a distributed beam loss around the machine. Normally the beam loss monitoring system should catch such a failure and trigger the beam dumping system as the loss is expected to take place over several turns.

The tune and aperture measurement kicker (MKQA) would normally kick the beam corresponding to a maximum excursion of 5 σ (in aperture mode). If a 450 GeV/c beam was kicked with a 7 TeV/c kick strength, the kick would correspond to an excursion of 78 σ, which could not only lead to damage of the collimation system but also of a number of superconducting magnets. As this is a single turn effect, having a highly reliable interlock system, which prevents the MKQA from improper use, can only exclude damage.

In the case that the injection kickers MKI would kick the 7 TeV/c stored beam with a 450 GeV/c kick, the beam would be deflected by 55 µrad in the vertical plane. This corresponds to an excursion of 17 σ, and is similar to the MKD small kick angle error discussed above for the horizontal plane, with the difference that the perturbing kick only acts for 7.8 µs, which reduces the effective intensity of the beam which can cause damage. A 'beam energy interlock' of the injection kickers and the obligatory presence of a pilot beam should prevent this from happening.

Another failure scenario related to the injection kicker system is the injection of a beam into the LHC while it is not at injection settings. With the LHC at 7 TeV/c settings the beam would be lost in the dipoles situated in the downstream octant. The same injection kicker interlocks mentioned above should adequately protect the machine.

The D1 dipoles in the insertions of the LHC are not superconducting and their power converter failure is one of the most critical in the LHC [7]. The signal from the beam loss monitors will be used to dump the beam in this failure scenario.

NON-AVAILABILITY OF THE BEAM DUMPING SYSTEM

Failure scenario I

A specific failure case is considered:

- High intensity beam is circulating at 7 TeV.
- A failure or a quench occurs that normally should result in a beam dump.

- The beam is not dumped, due to a failure in the beam dumping system, the beam interlock system or the system that should have requested the beam dump.

Due to the failure, the beam will move, the emittance will quickly grow, or both. Particles will touch the aperture, most likely in the cleaning section or in the insertions, depending on the optics. Independent of the origin of the failure, beam losses will quench either superconducting magnets in an arc, or quadrupole magnets in an insertion. After a magnet quench all particles would be lost within about 10 ms.

This case is of particular importance because it is the natural 'final state' of many different failure modes. It seems possible to study this case by coupling tracking with full aperture models and energy deposition studies.

Possible upgrades to reduce scale of damage

Although it is very unlikely that such accidents occur, several ideas are being discussed that could reduce the consequences of such events.

Sacrificial Dump: One option is to drive a massive block of material into the beam. The time for blocking the beam passage must be in the order of some ms, in order to be efficient. There is no material that would stand the beam impact without being damaged. Such a sacrificial block would have to be replaced. The block must be long enough to absorb most of the beam energy. From the studies presented in [5], the length of such a block when made out of a heavy material must be at least 10 – 20 m. The challenge is triggering and moving the dump into the beam. When a beam dump request does not trigger the beam dump kicker, it is unlikely that the controls of the sacrificial dump would receive the trigger.

Massive Absorbers Around the Beam: A second option would be installing massive absorbers close to the beam. The distance between absorbers and beam would have to be larger than the position of the collimators (about 10 σ). At least four such absorbers are required, each with two jaws, two for each plane, with 90 degrees phase advance in between. When the beam moves, or the emittance grows, the beam would touch them and most of the energy would be absorbed. They would have to be massive, similar to a sacrificial beam dump. In order not to limit the aperture at injection, the absorbers must be movable. They move towards the beam during the energy ramp, and must be further closed when the beams are squeezed. No trigger is required. Since such absorbers must be further out than the collimator jaws, they cannot protect the collimators.

Failure scenario II

The other failure scenario assumes stable beams but with the knowledge that the beam dumping system is unavailable. In this situation damage is not immanent but it is desirable to dispose of the beam in a safe way. It can be considered to use the collimation system to slowly scrape the beam, while staying below the quench limits of the superconducting magnets. The time required to dispose of the beam in this way is estimated to be about one hour.

CONCLUSIONS

Several unlikely failure modes of the LHC machine protection system have been presented. Depending on the failure scenario, serious damage can occur to the beam dumping block, the LHC collimation system or the (cryogenic) magnets. Several important failure scenarios, which in many cases combine particle tracking and material studies, have been identified and will be studied in the future.

Further work on the reliability of the machine protection system is required, with the objective to establish a credible safety level of the LHC. Together with a study of the efficiency of sacrificial dumps or absorbers around the beam and their merit versus increased risk due to added complication of the machine protection system, a decision could be taken if such devices are really required.

ACKNOWLEDGEMENTS

The authors would like to acknowledge their colleagues of the AB department for the discussions and data leading to this paper, especially L. Bruno and R. Assmann.

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