PROTECTION AGAINST ACCIDENTAL BEAM LOSSES AT THE LHC

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Abstract

Protection of the LHC against uncontrolled beam losses is of prime importance due to the very high stored beam energy. For nominal beam intensities, each of the two 7 TeV/c proton beams has a stored energy of 360 MJ threatening to damage accelerator equipment. At injection a number of passive beam absorbers must be correctly positioned and specific procedures have been proposed to ensure safe injection of high intensity. The LHC beam dump block being the only LHC element that can safety absorb the full LHC beam, it is essential that the beams are extracted unto the dump block in case of emergency. The failure time constants extend from 100 microseconds to few seconds depending on the equipment. Failures must be detected at a sufficiently early stage and transmitted to the beam interlock system that triggers the beam dumping system. To ensure safe operation the machine protection system uses a variety of systems to detect such failures. The strategy for protection of the LHC will be illustrated, with emphasis on new developments and studies that aim at an increased redundancy of the protection system.

INTRODUCTION

The first priority for the LHC protection systems is to prevent equipment damage in the ring and during beam transfer from the pre-accelerator SPS. Uncontrolled release of even a small fraction of the stored beam energy may cause serious damage to equipment. The LHC proton momentum is a factor of seven above accelerators such as Tevatron and HERA, whereas the energy stored in the beams is more than a factor of 100 higher, see Figure 1. The transverse energy density as relevant factor for equipment damage is even a factor 1000 higher than for other accelerators.

The beam intensity that leads to equipment damage depends on impact parameters and on the equipment hit by the beam, see Table 1. The damage level for fast proton losses is estimated to $\approx 2 \times 10^{12}$ p at 450 GeV and to $\approx 10^{10}$ p at 7 TeV. No special protection for the LHC would only be required below these intensities. At 7 TeV the damage level is four orders of magnitude smaller than the nominal beam current. To evaluate the beam intensity to reach the damage level, a dedicated experiment was performed at the SPS confirming the numbers previously assumed for the damage threshold at 450 GeV [1].

The second priority of the machine protection is to protect superconducting magnets from quenching. At 7 TeV

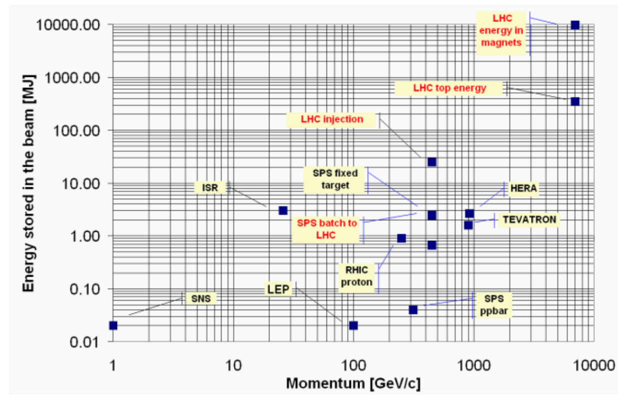

Figure 1: Stored beam energy as a function of the momentum for various accelerators. For comparison, 700 kJ are sufficient to heat and melt one kg copper.

Parameter	No. of protons
Pilot bunch	5×10^9
Nominal bunch	1.1×10^{11}
Nominal beam	2808 bunches = 3×10^{14}
Damage level, 450 GeV	$\approx 2 \times 10^{12}$
Damage level, 7 TeV	$\approx 10^{10}$
Quench level, 450 GeV	$\approx$ 2-3 $\times 10^9$
Quench level, 7 TeV	$\approx$ 1-2 $\times 10^6$

Table 1: Bunch intensities, quench and damage levels for fast proton losses at the LHC.

fast particle losses corresponding to a 10^{-8} - 10^{-7} fraction of the nominal beam intensity may quench superconducting magnets, see Table 1. This value is orders of magnitude lower than for any other accelerator with superconducting magnets and requires a very efficient beam cleaning system. The LHC will be the first accelerator requiring collimators to define the mechanical aperture through the entire machine cycle. A sophisticated scheme for beam cleaning and protection with many collimators and beam absorbers has been designed [2]. Some of the collimators must be positioned close to the beam ($\approx$ 5 - 6σ, σ = r.m.s beam size). For operation at 7 TeV, the opening between primary collimators jaws can be as small as 2.2 mm.

POWERING FAILURES

Failures in the magnet powering system are among the most likely causes of beam losses. After such failures the closed orbit deviations increase everywhere around the

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ring. In addition, both emittance and beam size may growth rapidly. Consequences of many failures can be detected everywhere around the LHC and by a number of different instruments. The aim of the machine protection strategy is to detect such failures with a few redundant protection systems.

Magnet quench

A likely cause for beam loss at 7 TeV is a quench of a superconducting magnet. The quench may be due to particle losses, to a failure of the quench protection system or to a high helium bath temperature. In addition there may also be a spontaneous quench. The current decay in a main dipole magnet after a quench is approximately Gaussian with a time constant of 200 ms. The orbit moves in 4.6 ms by one σ. The orbit movement from 2σ to 3σ takes only about 1.5 ms since the current decay accelerates.

Normal conducting magnet

A failure of a power converter (PC) is most critical for circuits with normal conducting magnets that have the shortest circuit time constants. During luminosity operation at 7 TeV a failure of the normal conducting separation dipole magnet PC is the most critical failure, leading to a fast change of the closed orbit around the accelerator. At nominal intensity and for Gaussian beam profiles, a damaging amount of beam has already been deposited after 3 ms (30 turns) on some collimator jaws, which corresponds to an orbit shift of $\approx$ 2 - 3σ [3].

QUENCH PROTECTION

After a quench, the energy stored in the quenched magnet is discharged into the coils by firing quench heaters. The energy stored in other magnets of the same electrical circuit is discharged into a resistor (energy extraction). Figure 2 shows the time sequence:

- The quench starts. After 3-200 ms the voltage across the magnet exceeds the threshold of the quench detector. After another delay of 10 ms for signal validation, a quench signal is triggered.
- The quench heaters are fired and the voltage across the magnet coils increases. The current remains constant until the power diode in parallel to the magnets opens when the heaters become effective after 15 to 130 ms.
- In parallel the quench detector triggers the energy extraction system by switching a resistor into the circuit. It takes $\approx$ 8 ms to open the switch.
- Finally the quench detector also triggers a beam dump request through the powering interlock system. It takes about 4 ms to complete the beam dump from the moment when the quench signal is triggered. At this time the field is the magnet is not yet affected by the quench.

An important conclusion that can be drawn from this sequence is that the beam is very likely to be dumped before it is affected by the field of the quenching magnet, provided that the quench development is not much faster. Such fast quenches, which might happen in case of massive losses, have been observed at the Tevatron [4]. In such an event the beam loss monitoring system should however react within milliseconds and dump the beam.

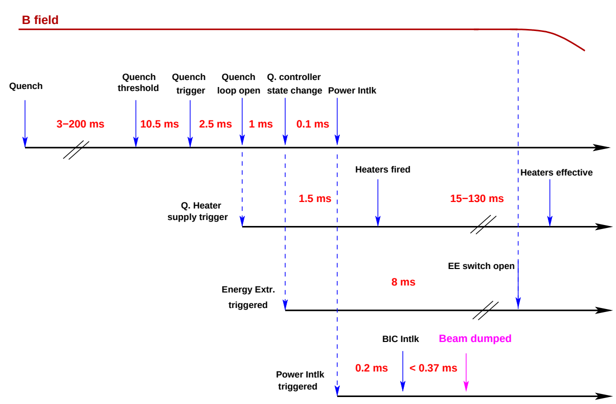

Figure 2: Time sequence of signals following a quench of a magnet until the beam is dumped, the quench heaters are fired and the energy is extracted from the circuit.

FAST CURRENT DECAY DETECTION

For circuits with very short time constants, the detection of a powering failure in time before the beam is affected requires very low detection thresholds and very short reaction times. As an example, for the LHC normal conducting separation dipoles, the detection threshold is $\approx$ 0.05% to 0.1% in 1 millisecond [3].

Recently an instrument for the detection of fast current changes developed at DESY was tested at CERN on some of the most critical circuits, see Figure 3, and found to fulfill the requirements for fast detection [6]. This device generates a fast interlock using a current signal that is reconstructed from the voltage after appropriate filtering. The threshold that may be used is only limited by the power converter ripple which is usually in the range of some 10^{-4}.

It is foreseen to equip all critical circuits of the LHC and of the transfer lines to the LHC with such devices.

BEAM LOSS MONITORING

Since collimators define the aperture, particles will in most cases be intercepted first by collimator jaws. Beam loss monitors (BLMs) in the vicinity must detect the particle shower and request a beam dump when the loss level rises above a preset threshold. To ensure an adequate reaction time to protect collimators against damage from very fast failures, the loss signal integration time is only 40 μs (1/2 turn).

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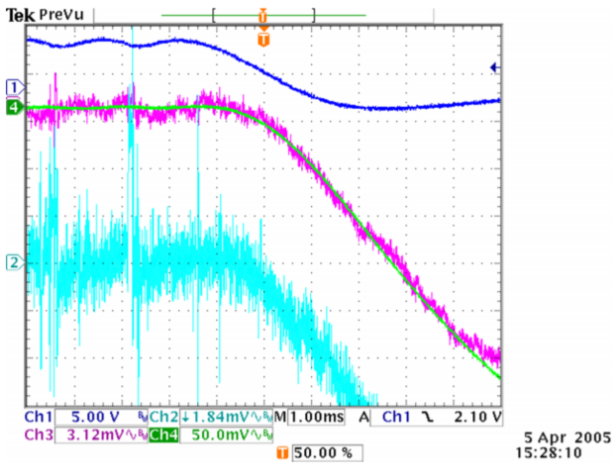

Figure 3: Test of a failure detection on a circuit consisting of a warm LHC separation dipole equipped with a power converter. The top blue curve is the voltage over the magnet, the magenta curve below is the field measured by a Hall probe, the green curve is the current reconstructed from the voltage and the cyan curve at the bottom is the magnet current. The reconstructed current signal is very clean and can be used to trigger on relative current changes of 0.1% or less. Courtesy M. Werner, DESY.

Accidentally applied local orbit bumps may bring the beams close to the aperture, leading to localized beam losses. To protect the LHC against such events, BLMs are installed at very quadrupole around the ring to detect beam losses that are not detected by monitors at the aperture limitations [5]. The total number of loss monitors to be installed in the LHC is around 3600, each monitor consisting of a 1 liter ionization chamber.

BEAM POSITION MONITORING

To provide redundancy for the BLM system, four beam position monitors (BPMs) dedicated to position interlocks will be installed in the LHC. The BPMs are grouped in two pairs for redundancy. The two pairs are separated in betatron phase by 90 ° to allow detection of orbit oscillations of any phase. The betatron function at both locations is large, giving an enhanced sensitivity.

To provide protection against the fast orbit movements due to the most critical powering failures, the position interlock thresholds must be set to 1 mm per ms. To avoid perturbations from slow orbit movements, the interlock logic will be based on the detection of a position change with respect to the last measured closed orbit (average of last 20 ms). Such an interlock also provides protection against failures of the transverse damper system.

The position interlock system will be implemented using a modified BPM acquisition card [7, 8]. The reaction time of the system will be around 1-2 turns.

BEAM CURRENT DECAY

As an alternative to the detection of local losses by BLMs, it can be envisaged to monitor directly the total beam intensity in the machine. A beam current transformer (BCT) able to detect a loss of 10^{11} protons within 1 ms would fully protect the LHC at 450 GeV. At 7 TeV, provided the collimators are correctly positioned and are hit first, there is again good protection, with the possibility of surface damage to some collimators. If the collimators are not in the correct position, then detecting such a loss would still protect the LHC at 7 TeV for many failure scenarios, and could reduce any damage by orders of magnitude.

The most promising option for such a fast loss (lifetime) measurement is based on a fast BCT as installed in the SPS [9]. The noise level over 1 ms that may be expected from this system is around $10^{10} - 10^{11}$ protons. Detection of a loss of around 10^{11} protons in 1 ms seems therefore within reach, albeit with a tight margin based on these SPS figures. It is hoped that with the experience gained in the SPS, the system can be improved for the LHC with a general reduction in this noise figure.

CONCLUSION

Protection of the LHC machine against beam induced damage is a challenge due to the increase by more than 2 orders of magnitude of the stored energy in the beams with respect to existing machines. While the initial protection strategy against uncontrolled beam loss was based entirely on the BLM system, an effort was made in the past year to provide more redundancy for protection. As a result, the most critical electrical circuits of the LHC will be equipped with a fast current decay detection system developed at DESY. At the level of beam instrumentation, a beam position interlock system will be added to the machine protection system. A system based on a fast measurement of the beam lifetime would provide additional protection, but more R&D is required for this system.

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