Concept of a Machine Protection System for the High-Energy LHC

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Abstract

The High-Energy LHC (HE-LHC) is setting new precedents in stored energy in both, the superconducting magnet system (∼ 20 GJ) and the beams (1.34 GJ) as compared to LHC and the LHC upgrade to increase the luminosity (HL-LHC). Therefore, the requirements and performance of the existing machine protection systems have to be reviewed and adapted to the new HE-LHC beam parameters, failure cases and machine availability requirements.

1 Stored energy and risks of equipment damage

The stored energy in the HE-LHC superconducting magnet system will be about 20 GJ. In order to safely handle such energy, the magnets must be powered in several independent powering sectors. In today’s LHC, the energy per sector is in the order of 1.2 GJ. In order to keep a magnet protection system similar to the one of LHC, it implies for HE-LHC to have 16 powering sectors.

Losses of high-energy protons in an accelerator induce temperature rise and thermal stress in the impacted accelerator components. An uncontrolled loss of a small fraction (below 10⁻⁴ [1]) of the 7 TeV LHC beam could already cause damage to equipment and lead to significant downtime. If the entire 7 TeV LHC beam would be deflected accidentally, it can penetrate through 20 m of copper [2].

The stored energy per beam in the HE-LHC is a factor of four higher than today LHC as shown in the comparisons of Fig. 1. Hence the damage potential is increased and the LHC machine protection systems need to be reviewed and adapted the new HE-LHC beam parameters. The first damage limit of HE-LHC can be derived from energy deposition studies [3]. At injection energy of 450 GeV with beam size of σ=0.2 mm, a loss of 1.15×10¹² protons (about 5 bunches) is enough to melt copper. At top energy 13.5 TeV with the same beam size, a loss of 1.6×10¹⁰ protons (equivalent to about 7% of a nominal HE-LHC bunch) would damage accelerator equipments. Hence the protection system must be efficient from the moment the beam is extracted from the injector toward the HE-LHC, throughout the HE-LHC cycle.

2 Strategy for machine protection

The HE-LHC machine protection system (MPS) should be designed to prevent uncontrolled release of the energy stored in the magnet system and damages to accelerator equipment induced by beam losses. The system must be very reliable to limit the amount of false beam dumps to a minimum not to compromise the availability of the machine. In case of failure, the system should provide complete diagnostics data to understand the causes of the failure and to demonstrate that the protection systems functioned correctly. The protection system must also be able to prevent or at least to limit the occurrence of beam induced quenches of the superconducting magnet.

The main principles of the LHC MPS described in Fig. 2, can be applied to HE-LHC. The first principle is to defined the aperture limitation by the collimator jaws in the ring and in the transfer lines, this in order to limit the energy deposited in sensitive accelerator components, i.e. superconducting magnets, throughout the accelerator cycle. The second principle and an essential part of the MPS system is the early detection of failures within equipment that acts on the beam as well as the monitoring of the beam to detect abnormal beam conditions with fast and reliable instrumentation. Once a failure is
Fig. 1: Stored beam energy as a function of beam momentum of HE-LHC in comparison with other particle accelerators.

Fig. 2: Main principles of the Machine Protection Systems throughout the LHC cycle.

detected by any of the protection systems, the information is transmitted via the beam interlock system to the beam dumping system. The beams are then extracted from the LHC via a transfer line into large graphite dump blocks. The third principle is the passive protection by beam absorber and collimator for specific failures cases. The fourth and last principle is redundancy in the protection systems such that failures may be detected by more than one single system.

As for LHC, it is proposed to base the protection strategies on the failure timescales:

- **Ultra-fast failures** - faster than 3 LHC turns (270 µs): Such events can be due to failures at beam injection and at beam extraction, due to the effect of missing beam-beam deflection during beam extraction or due to the effect of quench heater firing on the beam.
- **Fast failures** - several LHC turns (< few milliseconds): Such losses are caused by failures of
equipment with a fast effect on the beam - fast movement of the orbit, beam size growth.
• Slow failures - multi-turn ($\geq$ few milliseconds) can be caused by power converter failures, magnet quenches, etc.

3 Ultra-fast failures

Ultra-fast failures are failures occurring on the timescale of a single turn or couple of turns (less than four turns) which is too fast to be mitigated by an active protection system. In general it is recommended during the accelerator design to avoid as much as possible the implementation of systems that can have a significant ultra-fast effect on the beam. However some failures cannot be avoided, e.g. injection and extraction failures, and require to protect the accelerator equipment with passive protection elements such as collimator and absorbers.

To inject particle in the HE-LHC, a series of fast-pulsed magnet kickers (MKI) will deflect the injected particles coming from a transfer line onto the closed orbit of the accelerator. In case of mis-injection (wrong angle or no deflection of the injected beam) or accidental firing of one of the MKI (deflecting the circulating beam), the deflected beams have to be safely intercepted by a injection protection absorber (TDI) positioned with a phase advance of 90° from the MKI. The TDI should be designed such that it survives the impact of a full injection batch. In addition, it has to be ensured that the accelerator aperture limitations (collimators) survive the worst case injection failure, a grazing impact of a full injection batch on the TDI. If the injection energy remains at 450 GeV, a modest upgrade of the current system should be adequate while an increase of the injection energy (900 GeV or 1.3 TeV) implies to review the robustness of the absorbers and collimators. The preliminary TDI design is based on the design developed for HL-LHC. It is made of segmented jaws of graphite, aluminium and copper (see in Fig. 3) made to withstand the impact of a full injection batch (288 bunches) at 450 GeV. It was shown that it can also survive the impact of 288 bunches at 900 GeV and 1.3 TeV but only under certain conditions on the beam size, $\sqrt{\beta_x/\beta_y}$ must be larger than 100 m for 900 GeV and larger than 500 m for 1.3 TeV [4]. If the beam size conditions can not be fulfilled, the design of the absorber must be reviewed (new absorber materials, longer absorber) or the number of injected bunches per batch needs to be limited below the damage threshold of the TDI [5]. In addition to the passive protections in the accelerator, a set of collimators must be installed in the transfer lines to stop particles with large betatron oscillations before they are injected in the accelerator. If not intercepted in the transfer line, such particles would be lost in the accelerator and could damage accelerator equipment.
Fig. 4: Schematic of the layout of the LHC extraction region for one beam [4].

To extract properly the beams from the accelerators toward the dump block, a series of extraction kickers deflects the beam toward extraction septum magnets which deflect further the beam toward the extraction transfer line. The rising of the extraction kickers must be synchronized with a particle-free gap (abort-gap) to prevent losses in the accelerator. If the kickers field starts rising when particles are present, particle are deflected with a wrong angle and are lost. This is called an asynchronous beam dump. The miss-deflected particle should be intercept by protection devices, the TCDS protecting the extraction septum magnets and the TCDQ protecting the downstream superconducting magnets and collimators as illustrated for the LHC in Fig. 4. With the same extraction kicker rise time and optic as for HL-LHC, the TCDQ might not survive such a failure [4]. To survive a asynchronous dump at 13.5 TeV, different ways are being explored decreasing the kicker rise-time, modifying the optics around the extraction region and upgrading the absorbers. In addition it must be ensured that the downstream superconducting magnets (e.g. triplets) and collimators are protected in case of an asynchronous beam dump.

The absence of beam-beam deflection due to the non-simultaneous extraction of the two beams leads to a deflection of the remaining circulating beam. In the LHC, perturbation of the beam trajectory up to 230 $\mu$m = 0.6 $\sigma_{nom}$ within a single turn have been measured at 4 TeV [7]. Simulations for HL-LHC have shown the perturbations amplitudes are expect to increase up to 1.1 $\sigma_{nom}$. Such trajectory perturbation with a populated beam halo would lead to unacceptable losses on the primary collimator in IR7. To mitigate these losses in the primary collimator, it was proposed to deplete the beam halo population to an acceptable level for the collimator using a hollow electron lens [8]. As a consequence it has been foreseen to monitor the halo population by a reliable diagnostic system, e.g. the synchrotron light monitor and to interlock on the halo population. Similar studies are required for HE-LHC to determine the acceptable level of halo population to survive such a failure case.

Another ultra-fast loss mechanism is the effect of quench heater firing on the circulating beam. When a magnet quench is detected, a current discharge in the quench heater is triggered in order to protect the magnet. This current discharge induces a magnetic field which can affect the beam. An orbit distortion up to 400 $\mu$m was measured in the LHC after the quench of a dipole magnet which is in good agreement with simulations, as illustrated in Fig. 5. Similar simulations performed for current discharge of the HL-LHC triplet quench heater show that the beam will be deflected in the aperture in less than a turn. To mitigate such failures, it must be ensured that the beam is dumped before the current discharge in the quencher is triggered [9].

The installation of dedicated fast beam loss monitors with $\sim$ns resolution close to the injection and extraction absorbers and at the accelerator aperture bottleneck (collimators) would allow to better understand ultra-fast failures and possibly to reduce or even mitigate them. It would also reduce the time
4 Fast failures

4.1 Protection requirements

Equipment failures and beam instabilities appearing in the timescale of multiple turns must be detected and generate a beam dump request via the beam interlock system. The most important signature for failures are beam losses, which in most of the failures are located at the aperture limitation of the accelerators (collimator). From the LHC experience, fast beam losses induced by macro-particles interacting with the beam, so-called unidentified falling objects (UFOs), can also be local.

An important parameter of the MPS system is its response time from failure detection to completion of the beam dump. The MPS response time is the sum of the failure detection time, the time required to transmit the detected failure through the interlock system, the time required to synchronize the firing of the beam dump kickers with the abort gap and the time needed to fully extract the beam from the accelerator. As depicted in Fig. 6, the response time of the MPS of the actual LHC is about 360 $\mu$s equivalent to four LHC turns [10] with the Beam Loss Monitoring System having the fastest failure detection time of 80 $\mu$s. The response time of the MPS must be shorter than the fastest failures not protected via passive absorber. To limit the risk of beam-induced damage, this response time should be...
reduced to the minimum possible. One way to improve the response time is to monitor the beam losses at the aperture limitations and sensitive areas (e.g. triplet) with a bunch-by-bunch resolution and to connect them to the interlock system. Candidates for the nano-second resolution BLM are diamond [12] and silicon detectors. Other ways to reduce the MPS response time is to increase the number of abort gaps or to accept triggering asynchronous beam dumps for dedicated failure cases.

In order to provide redundancy to the fast beam loss monitors, the implementation of fast beam current change monitor [13] should be foreseen.

In case a beam halo cleaning system is required, it must to let some bunches with halo, so-called witness bunches, in order to detect beam losses before they become too critical. Several batches of witness bunches will be present in the accelerator. To ensure that the beam loss signal from one batch of witness bunch is high enough to be detected, a minimum number of witness bunches per batch must be specified.

Beam losses need to be monitored around the accelerator in order to localize the losses (e.g. to resolve UFO losses). It is proposed to use the actual LHC ionization BLM and to investigate alternative technologies such as Cherenkov fibres [14].

4.2 Failure cases

One of the fastest failures with circulating beam observed so far in the LHC are the so-called 16L2 losses. An example of such losses is shown in Fig. 7, it took about 1.3 ms for the losses to reach the dump threshold. The losses detected in the half cell 16L2 had a UFO like signature, however after few milliseconds major losses were observed in IR7 triggering a beam dump. The losses could reach the dump threshold in about 10 LHC turns. The details mechanisms inducing such losses are still under study [15].

Other possible fast failures to be considered are magnet failures, in particular the normal conducting magnets. Powering failures of magnets lead to an exponential field decay with a time constant $\tau$. For normal conducting magnet $\tau$ is typically some seconds while it is much longer for superconducting magnets. For a dipole magnet, the field decay induces a field error $\Delta B_{\text{error}}(t)$ that results in an maximum closed orbit distortion [16]:

$$\Delta x = \frac{\sqrt{\beta_{\text{magnet}} \cdot \beta_{\text{test}}}}{2 \sin(\pi Q_x)} \cdot \left( \alpha_0 \cdot \frac{\Delta B_{\text{error}}}{B_0} \right)$$

where $\beta_{\text{magnet}}$ and $\beta_{\text{test}}$ are the $\beta$-functions at the location of the magnet and the location of observation point, $Q_x$ the horizontal tune, $\alpha_0$ and $B_0$ the magnet nominal deflection angle and magnetic flux density.
In the LHC, a powering failure of the D1 separation dipole magnets in IR1 and IR5 induce, due to their location in areas with high $\beta$-functions and low decay time constants, rapidly increasing beam losses on the collimators. These losses can reach the damage level of the collimators within several tens of turn [17]. There are several ways to protect from such failure, with the so-called Fast Magnet Current Change Monitors (FMCM [18]) or increasing the time constant of the field decay by connecting the normal conducting magnet to a superconducting solenoid in series. For HE-LHC, it is recommended to specify a minimum time constant of field decay in the warm magnets to allow enough time to detect the failure and dump the beam before collimators could be damaged.

Crab-cavities are necessary in HE-LHC to compensate the loss of luminosity due to the crossing angle between the colliding beams. A set of crab cavities installed on each side of the IPs would allow to rotate each bunch such that they collide effectively head on. The failure scenarios are already being studied for HL-LHC [19] [20]. These studies are still under way and require considering details of the final design of the crab-cavities and the corresponding low-level RF system.

A quench protection system proposed to be use for the Nb$_3$Sn magnet is the so-called Coupling-Loss Induced Quench (CLIQ) system [21]. When a quench is detected, the CLIQ unit discharges a current in the order of kilo-Amperes in the magnet coils. It can affect the magnetic field in the magnet. The effect on the beam after a spurious triggering of a CLIQ discharge was studied for HL-LHC Q2 and Q3 triplet magnets. The magnetic flux density in the magnets at the peak current of the CLIQ unit is shown in Fig 8. The discharge in Q2 magnet reduces its focusing gradient inducing a $\beta$-beating up to 20% in 2.2 ms at the collimators resulting in unacceptable losses on the primary collimators in IP7. In Q3, the discharge induces a dipole component in the beam axis, deflecting the beam by $1\sigma_{\text{nom}}$ within 4 ms [9]. Discharge of a CLIQ units must trigger a beam dump.

### 4.3 Quench prevention

Since recovery after a quench to re-establish the conditions for beam operation takes several hours, a system generating a dump request before beam losses reach the quench level of the magnets would increase machine availability.

The majority of the beam induced quenches observed in the LHC arc magnets were caused by beam losses due to UFOs. Theses UFOs are most likely $\mu$m sized dust particles falling into the beam which lead to beam losses in timescale of a few tens of turns when interacting with the beams. As illustrated in Fig. 9, the occurrence of UFOs is evenly distributed around the LHC ring and a conditioning effect during operation is visible. The increased rate in sector 12 visible between end of 2016 and beginning of 2017 can be explained by the replacement of a dipole magnet in this sector [22].

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Fig. 8: Magnetic flux density and flux lines in Q2b magnet (left) and Q3 magnet (right) at the first current peak (12 ms - Q2b, 20 ms - Q3) of a CLIQ discharge [9].
Fig. 9: Spatial distribution by LHC sector of the average number of UFO per hour of stable beam for several period of 2016 and 2017 [22].

Novel concept to prevent or at least reduce beam induced quenches should be investigated. For instance, such system to prevent beam induced quenches would be to insert a superconducting wire along the magnet coil between the cold bore and the coil. The quench level of the wire would need to be slightly lower than the one of the magnet. The detection of a quench along this wire, by measurement of the resistive voltage across the strand, would generate a beam dump request preventing beam losses to develop further inducing a quench of the superconducting magnet. Another possibility to look at, is to interlock on the derivative of the losses measured by the distributed beam loss system of the accelerator. It would allow a faster reaction time and avoid unnecessary preventive dump compare to today’s LHC in which the losses measured by the BLM system are interlocked on their absolute level.

5 Slow failures

Failure beyond the millisecond range are not expected to significantly impact the machine protection considerations for HE-LHC. However with a peak luminosity of $25 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$, the radiation levels in certain underground areas will increase. This must be taken into consideration during the design of the exposed accelerator equipments (e.g. superconducting quadrupole magnets and cold diodes closed to the insertion) and electronics.

References


