Chapter 12

Machine Protection with a 700 MJ Beam

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After the high luminosity upgrade of the LHC, the stored energy per proton beam will increase by a factor of two as compared to the nominal LHC. Therefore, many damage studies need to be revisited to ensure a safe machine operation with the new beam parameters. Furthermore, new accelerator equipment like crab cavities might cause new failure modes, which are not sufficiently covered by the current machine protection system of the LHC. These failure modes have to be carefully studied and mitigated by new protection systems.

Finally the ambitious goals for integrated luminosity delivered to the experiments during the era of HL-LHC require an increase of the machine availability without jeopardizing equipment protection.

1. Introduction

The combination of high intensity and high energy that characterizes the nominal beam in the LHC leads to a stored energy of 362 MJ in each of the two beams. This energy is more than two orders of magnitude larger than in any previous accelerator — and about to increase by another factor of two following the luminosity upgrade for the LHC as shown in the comparisons of Fig. 1. With intensities expected to increase up to $2.3 \cdot 10^{11}$ p/bunch with 25 ns bunch spacing, respectively to $3.7 \cdot 10^{11}$ p/bunch with 50 ns bunch spacing [1], an uncontrolled beam loss at the LHC could cause even more severe damage to accelerator equipment than for today's nominal beam parameters. Recent simulations that couple energy-deposition and hydro-dynamic simulation codes show that already the nominal LHC beam can penetrate through the full length of a copper block 20 m long, in case the entire beam is deflected accidentally. Such an accident could happen if the beam extraction kickers deflect the beam by a wrong angle. Hence, it becomes necessary to revisit many of the damage studies in light of the new beam parameters [2]. In addition, new failure scenarios will have to be considered

Fig. 1. Stored beam energy as a function of beam momentum of HL-LHC in comparison with other particle accelerators.

following the proposed optics changes and the installation of new accelerator components such as crab cavities and hollow electron beam lenses. Special care is required to find a trade-off between equipment protection and machine availability in view of the reduced operational margins (e.g. decreasing quench limits and beam loss thresholds versus increased beam intensity and tighter collimator settings, UFOs at higher energies and reduced bunch spacing, ...).

2. Present Performance of LHC Machine Protection and Future Challenges with HL-LHC Beams

Safe operation of the LHC currently relies on a complex system of equipment protection. The machine protection system (MPS) is designed for preventing the uncontrolled release of energy stored in the magnet system and beam-induced damage with very high reliability. An essential part of the MPS system, the active protection system, is the early detection of failures within the equipment, as well as monitoring of the beam parameters with fast and reliable beam instrumentation. This is required throughout the entire cycle, from injection to collisions. Once a failure is detected by any of the protection systems, the information is transmitted to the beam interlock system that triggers the extraction of the particle beams by the LHC beam dumping system. It is essential that the beams are always properly extracted from the accelerator via 700 m long transfer lines into large graphite

dump blocks, as these are the only elements of the LHC that can withstand the impact of the full beams.

The current machine protection architecture is based on the assumption of three types of failure scenarios [3], namely:

- Ultra-fast failures: failures within three turns, e.g., during beam transfer from the SPS to the LHC, beam extraction into the LHC beam dump channel or the effect of missing beam–beam deflection during beam extraction (1 LHC turn = 89 μ s).
- Fast failures: timescale of several LHC turns (< few milliseconds) as a result of certain equipment failures with fast effect on particle trajectories.
- Slow failures: multi-turn failures on timescales $\geq$ few milliseconds, e.g. powering failures, magnet quenches, RF failures, ...

2.1. Ultra-fast failures

Failures occurring on the timescale of a single turn cannot be mitigated by active protection systems, but require a protection of the vacuum chamber and the accelerator equipment in the vicinity (magnets, cryogenics, instrumentation, ...) by passive protection elements such as collimators and absorbers. In view of the increase in beam energy both for the injected as well as the circulating beams, several consolidation programs are already under way to upgrade the critical elements for injection protection (TDI), dump protection (TCDQ) as well as the LHC collimation system. Several promising novel materials, such as Copper-Diamond, are currently being tested to replace the existing jaws of tertiary collimators, with the aim of rendering them more robust for beam impact in case of asynchronous dumps. The jaws of other collimators could also profit from such materials. Several of the new materials have the additional advantage of reducing the impedance contribution of the collimator jaws, hence having a beneficial effect on beam stability. The simultaneous integration of button pickups into the new collimator jaws will allow for a more accurate, quicker and dependable positioning of the collimator jaws around the beam axis. This will allow maintaining the protection of the aperture while reaching smaller values of β^* in the high luminosity insertions. Operating with reduced β^* requires tighter settings of all LHC collimators with respect to the current operation.

An example of a single turn beam loss mechanism is the absence of the beam–beam deflection due to the non-simultaneous removal of the two LHC beams. Trajectory perturbations of the remaining LHC beam by as much as 230 μ m = $0.60\sigma_{\text{nom}}$ within a single turn have been measured and are in good agreement with simulations, as illustrated in Fig. 2 [4]. When extrapolating the simulations to HL-

Fig. 2. Horizontal trajectory perturbation of Beam1 as measured by the beam position monitors in the LHC ring (blue) and as predicted by simulation (red, green) in the turn directly after the Beam2 dump kickers were fired. The measurement is for bunches with full long-range encounters. Measurement on 13.12.2012 08:26:54. Beam energy: 4 TeV, bunch intensity: $0.9 \cdot 10^{11}$ protons, 84 bunches per beam, 25 ns bunch-spacing, crossing angle in IP5: $\approx 68 \mu\text{rad}$ [4].

LHC beam parameters, the perturbation amplitudes due to this effect are expected to increase up to $0.9\sigma_{\text{nom}} - 1.1\sigma_{\text{nom}}$. This displacement will lead to beam losses around the machine, namely at the primary collimators of IR7. With the present transverse beam distribution, such single turn trajectory perturbations with amplitudes of about $1\sigma_{\text{nom}}$ can lead to beam losses far beyond the specifications of the collimation system and hence imply a significant damage potential.

Since this effect occurs regularly during normal LHC operation, a fast and reliable diagnostics (and interlocking) of the transverse tail population is essential for safe operation in the HL-LHC era. Such a diagnostics could, e.g., be based on the synchrotron light monitor (BSRT) and related studies are strongly encouraged. Furthermore a depletion of the transverse tail population to reduce the number of protons in the beam halo to an acceptable level may be required. A hollow electron-lens [5] would provide this functionality. Dedicated studies are presently on-going and are strongly supported [6].

2.2. Fast failures

Equipment failures or beam instabilities appearing on the timescale of multiple turns allow for dedicated protection systems to mitigate their effects on the

circulating beams. The LHC Beam Loss Monitoring system (BLM) features the fastest failure detection time of $40\ \mu\text{s}$ as illustrated in the comparison in Fig. 3. The BLM system is complemented with fast interlocks on the beam position in IR6, Fast Magnet Current Change Monitors and a beam lifetime monitor (currently under development by the beam instrumentation group at CERN). All of these systems feature similar failure detection times in the $100\ \mu\text{s}$ – $1\ \text{ms}$ range, providing diverse redundancy to the BLM system.

Adding the additional time required to transmit the detected failure through the LHC beam interlock system, the time required to synchronize the firing of the beam dump kickers with the abort gap as well as the time needed to completely extract the beam from the LHC leads to an equivalent worst case MPS response time of three LHC turns as depicted in Fig. 4.

This reaction time is sufficient in the absence of failures occurring on timescales below some 10 LHC turns. The basis for the design of the current MPS system to date has been a failure of the normal conducting separation dipole D1 in

Fig. 3. Failure detection times at the LHC. Shortest failure detection time currently assured by the BLM system, with a fastest integration time of $40\ \mu\text{s}$ = half a LHC turn.

Fig. 4. Current MPS response time from failure detection to completion of beam dump.

P1 and P5 [7], considered the fastest possible failure with circulating beam. These normal conducting magnets induce, due to their location in areas with high beta functions and low time constants, fast changes of the particle trajectory in case of magnet powering failures, which in turn lead to rapidly increasing beam losses on the primary collimators in IR7. At nominal energy and intensity these losses can reach the damage level of collimators within several tens of turns only, hence a dedicated protection system — the so-called Fast Magnet Current Change Monitors (FMCM) — has been very successfully deployed on critical magnets in the LHC and its transfer lines in 2006 [8].

With the HL-LHC upgrade, the optics in the insertion regions will significantly change and the β -function at the D1 separation dipole magnets in IR1 and IR5 will increase up to $\sim 17,000$ m for certain ATS optics. At the same time a replacement of the D1 separation dipole magnets by superconducting magnets is currently considered the baseline for HL-LHC, which would significantly increase the time constants of these circuits, practically mitigating the potential of fast failures originating from these magnets.

In case the D1 separation dipole magnets remain normal-conducting, the increased β -functions imply an increased sensitivity of the beam to corresponding current changes. The expected orbit deviation in the arc would increase within a few tens of turns to $\Delta x_{\max} \sim 230 \mu\text{m} \sim 0.43\sigma_{\text{nom}}$ for a current change of 100 mA, i.e. about 25% more than in 2012 stable beams conditions. This increased sensitivity is still well within the operational reach of the present FMCM system.

For HL-LHC operation, the use of crab cavities will introduce failures that can affect the particle beams on timescales well below the fastest failures considered so far [9]. Studies of different failure scenarios are still underway. These studies require considering details of the design finally to be adopted for the crab cavity and the corresponding low-level RF system. Both have a significant impact on the effect on the circulating beams following, e.g., cavity quenches or trips of the RF power generator. In addition detailed measurements of the quench and failure behaviour of the chosen design have to be conducted. First experience with similar devices at KEK however shows that certain failures can happen within very few turns only as depicted in Fig. 5.

While the protection against failures with time constants > 15 ms is not expected to be of fundamental concern, voltage and/or phase changes of the crab cavities will happen with a time constant τ which is proportional to the Q_{ext} . For a 400 MHz cavity with a $Q_{\text{ext}} = 1\text{E}6$ this will result in a time constant as low as $800 \mu\text{s}$. The situation becomes even more critical for cavity quenches, where the energy stored in the cavity can be dissipated in the cavity walls on ultra-fast timescales. Quenches observed in cavities at KEKB show a complete decay of the

Fig. 5. Schematic overview of crab cavity failure categories [9].

cavity voltage in $100\mu\text{s}$, accompanied by an oscillation of the phase by 50 degrees in only $50\mu\text{s}$. Such crab cavity failures can imply large global betatron oscillations, which could lead to critical beam losses for amplitudes above about $1\sigma_{\text{nom}}$. Highly overpopulated transverse tails compared with Gaussian beams were measured in the LHC. Based on these observations the energy stored in the tails beyond 4σ are expected to correspond to $\sim 30\text{ MJ}$ for HL-LHC parameters. These levels are significantly beyond the specification of the collimation system of up to 1 MJ for very fast accidental beam losses.

Mitigation techniques hence have to include a fast, dependable and redundant detection and interlocking of a crab cavity failure on these timescales as well as taking appropriate measures when designing the cavity and associated RF control to increase as much as possible the failure time constants, namely:

- Avoid correlated failures of multiple cavities (on one side of an IP) through mechanical and cryogenic separation of the individual modules and appropriate design of the low-level RF [10].
- Investigate the use of fast failure detection mechanisms such as RF field monitor probes, diamond beam loss detectors, power transmission through input coupler and head-tail monitors.
- Ensure the depletion of the transverse beam tails to reduce the energy stored in the beam halo which would potentially be deflected onto the collimation system beyond the design value of 1 MJ . For the current baseline this would correspond to an area of $1.7\sigma_{\text{nom}}$ (before reaching the closest primary collimator) as the possible transverse beam trajectory perturbation following an ultra-fast failure of a single crab cavity.

- Decrease the reaction time of the MPS system for such ultra-fast failures by, e.g., increasing the number of abort gaps, accepting to trigger asynchronous beam dumps with potential local damage, add direct beam dump links to IR6 and consider the installation of disposable absorbers.

2.3. UFOs

Besides increasing failure rates of equipment systems when approaching nominal operating parameters, beam losses due to macro particles interacting with the LHC beams could become a performance limitation for nominal and HL-LHC operation. These so-called (un)identified falling objects (UFOs) are most likely μm sized dust particles which lead to very fast beam losses on timescales of a few tens of turns ($\sim 1\text{ ms}$) when interacting with the beams. Following their first identification in July 2010, UFOs have led during the first three years of operational running to 58 premature beam dumps following beam losses above the dump thresholds. As illustrated in Fig. 6 the occurrence of UFOs is, apart for some outliers around the MKIs, distributed all around the LHC ring.

While experience shows a conditioning effect of the UFOs along a machine run and a saturating effect on beam intensity above several hundred bunches, beam losses due to UFOs will most likely increase with beam energy. Extrapolating the current observations to higher beam energies leads to the prediction of expected beam dumps depicted in Fig. 7. Moreover, during initial operation with 25 ns

Fig. 6. Spatial distribution of UFO occurrence around the LHC ring (A total of 7171 UFOs at 4 TeV in 2012 as shown with the blue bars, the red bars show the UFOs for which the BLM signal in the first running sum is exceeding 1% of the dump threshold).

Fig. 7. Expected number of beam dumps by arc and MKI UFOs and the expected scaling of the BLM signal versus threshold as a function of the beam energy. All extrapolations are done relative to the BLM dump thresholds as used for 3.5 TeV operation. Note that at higher energies the BLM thresholds would have to be further decreased to maintain the same level of protection for the superconducting elements.

bunch spacing their occurrence drastically increased up to a level unacceptable for machine operation. For these reasons it is of primary importance to further study the origin and consequences of UFOs to fully understand the limitations they might impose on future operation.

While for the MKI magnet a dedicated consolidation program is already underway during LS1, the main mitigation strategy for the arc UFOs remains the increase of the BLM thresholds towards the magnet quench limit and to profit from the conditioning effect. An additional relocation of BLM monitors from the quadrupole to the dipole magnets will allow for better protection against UFO events whilst maintaining the required BLM thresholds well within a sensible operational range.

A complementary approach is to add a few bunches with large emittance to the filling scheme for UFO detection well before the macro particle reaches the centre of the beam. This could allow a detection of very fast UFO events at higher energies in time to dump the beam before the beam losses exceed the magnet quench margin.

2.4. Slow failures

Failures on timescales beyond the millisecond range are not expected to significantly impact the machine protection considerations for the HL-LHC era. In

several domains, machine protection considerations will however become an increasing challenge for machine availability. The enhanced luminosity of the HL-LHC will increase the radiation levels in certain underground areas like the RR and the dispersion suppressors to levels no longer compatible with the operation of radiation tolerant electronics based on components of the shelf (COTS) installed at present in those areas for the quench protection system (QPS). Based on the progress in electronics, it is probably feasible to re-locate a major part of such protection electronics to low radiation zones or eventually to surface buildings and use long instrumentation cables to link to the protected elements. In addition, equipment such as the new superconducting elements and superconducting links in the high luminosity insertions will require new dedicated protection systems, which are expected to be based on similar principles as already in use for the current LHC magnets and busbars.

Machine availability will be furthermore impacted by the defined quench thresholds of magnets, which will be significantly lower for higher beam energies.

The corresponding reduction of BLM thresholds will represent an increasing challenge in light of higher beam intensities and tighter collimator settings expected for HL-LHC operation. The potential absence of the transverse beam tails in case a hollow electron beam lens will be installed would in addition have a detrimental effect on the efficiency and latency of the BLM system to detect beam losses in the machine. This effect could be mitigated by leaving a low density of particles in the beam tails for detection and machine protection purposes or by leaving the halo along short lengths of the beam.

With the availability of equipment systems and the control of the particle beams already today playing a major role in the physics output of the LHC, the tighter operational margins in the coming years will certainly require to operate the machine with more flexible interlock conditions and less conservative protection thresholds. This has been confirmed by recent simulations which show that, assuming today's operational cycle and availability of the LHC systems, the ambitious goals of integrated luminosity for the HL-LHC cannot be met without a significant increase in machine availability [11].

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