MACHINE PROTECTION CHALLENGES FOR HL-LHC

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ABSTRACT

LHC operation requires the flawless functioning of the machine protection systems. The energy stored in the beam was progressively increased beyond the 140 MJ range at the end of 2012 at 4 TeV/c. The further increase to more than 300 MJ expected for 2015 at 6.5 TeV/c should be possible with the existing protection systems. For HL-LHC additional failure modes need to be considered. The stored beam energy will increase by another factor of two with respect to nominal and a factor of five more than experienced so far. The maximum beta function in the high luminosity insertion regions will increase. It is planned to install crab cavities in the LHC to compensate for the loss in luminosity due to the crossing-angle. With crab cavities, sudden voltage decays within 100 μs after e.g. cavity quenches can lead to large transverse beam oscillations. Tracking simulations predict trajectory distortions of up to 1.5 σ after a sudden drop of the deflecting voltage in a single cavity. Protons in the halo with an energy of several MJ could hit a collimator in case of such event, far above damage level even if the collimator jaws are made of robust material. In this paper we discuss the challenges for machine protection in the HL-LHC era and possible mitigation strategies.

INTRODUCTION

With LHC beam intensities expected to increase for HL-LHC up to $2.2 \cdot 10^{11}$ p/bunch with 25 ns bunch spacing, respectively to $3.5 \cdot 10^{11}$ p/bunch with 50 ns bunch spacing [1], an uncontrolled beam loss would cause even more severe damage than for today's nominal beam parameters. In addition, new failure scenarios will have to be considered following the proposed optics changes and the installation of new accelerator components such as crab cavities. Hence, it becomes necessary to revisit many of the damage studies in light of the new beam parameters. 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 as well as UFOs at higher energies and reduced bunch spacing (UFO: fast beam losses originating from dust particles in the vacuum chamber).

MACHINE PROTECTION AND CHALLENGES WITH HL-LHC BEAMS

The machine protection system (MPS) is designed to prevent 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 systems, aim at an early detection of failures of equipment, as well as monitoring of the beam parameters with fast and reliable beam instrumentation. Once a failure is detected, the information is transmitted via the beam interlock system that triggers the extraction of the particle beams through 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. Active protection is possible for slow and fast failures:

- Slow failures: multi-turn failures on timescales > few milliseconds, e.g. powering failures, magnet quenches, RF failures, …
- Fast failures: timescale of several tens of LHC turns (<few milliseconds) as a result of certain equipment failures with fast effect on particle trajectories (e.g. trip of the normal conducting D1 magnets close to the experiments)

For ultrafast failures during a single turn or a few turns, there is no time to extract the beam in a controlled way. Passive protection with beam absorbers is required.

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 μs. The BLM system is complemented with fast interlocks on the beam position in the beam extraction region, Fast Magnet Current Change Monitors and a Fast Beam Lifetime Monitor (currently under development at CERN). These systems feature a similar time for failure detection in the 100 μs – 1 ms range, providing diverse redundancy to the BLM system for most failure cases.

Adding the additional time required to transmit the beam dump request via 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 determines the equivalent worst case MPS response time of three LHC turns.

This reaction time has been proven sufficient in the absence of failures occurring on timescales below some ten LHC turns. The basis for the design of the current MPS response time has been a failure of the normal conducting separation dipole D1 in IP1 and IP5 [2], considered as fastest possible failure with circulating beam. These normal conducting magnets induce due to their location in areas with high beta function and short

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current decay 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 [3].

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 ~ 17000 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 maximal orbit deviation in the arc would increase within the first few turns up to Δx_{max} ~ 230 μm ~ 0.43 σ_{nom} (σ = standard deviation for the transverse beam dimension) for a current change of 100 mA, i.e. about 25% more than in 2012 when operating with colliding beams. This increased sensitivity is still well within the operational reach of the present FMCM system.

ULTRAFAST FAILURES AT INJECTION AND EXTRACTION

Failures occurring on the timescale of a single turn require the protection of vacuum chamber and accelerator equipment in the vicinity (magnets, cryogenics, instrumentation…) by passive protection elements such as collimators and beam absorbers. Absorbers can protect the aperture, assuming that only a limited amount of energy is deposited (max. 2-3 MJ for a kicker failure at injection). In view of the increased beam energy both for the injected as well as the circulating beams, several consolidation programs are under way to upgrade the critical absorbers for injection protection (TDI), dump protection (TCDQ) as well as the LHC collimation system (TCTs, TCLs). Several promising novel materials such as e.g. 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 [4]. This will allow maintaining the protection of the aperture while reaching smaller values of β* in the high luminosity insertions.

ULTRAFAST FAILURES WITH CIRCULATING BEAMS

The energy stored in the beam tails can be substantial as shown in Fig. 1, assuming a transverse Gaussian distribution. For such distributions, the energy of particles in the tail exceeding amplitudes of 3 σ is about 5.5 MJ. If the entire beam is deflected, part of the distribution risks to hit collimators close to the beam. Highly overpopulated transverse tails compared with Gaussian beams that were measured in the LHC would even be more critical. However, a limited amount of beam in the tail has a positive effect contributing to an early detection of failures: if the beam moves, the halo touches the collimator and BLMs detect the beam losses and can trigger a beam dump before the core of the beam risks hitting the collimator.

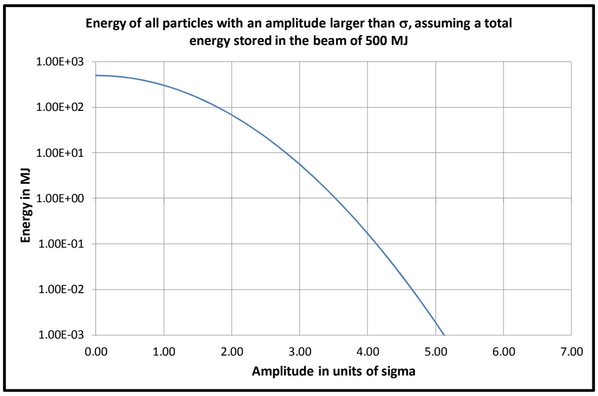

Figure 1: Energy stored in all protons with amplitudes larger than a certain value of σ, assuming a total stored energy of 500 MJ.

Today at LHC there is no failure mechanism that deflects the entire beam on such very short timescales by, say, more than about 0.5 σ. For HL-LHC two mechanisms for beam deflection with a time scale of less than a few turns need to be considered.

Firstly, the absence of the beam-beam deflection due to the removal of only one beam leads to a deflection of the other beam. Trajectory perturbations of the remaining LHC beam by as much as 230 μm = 0.60 σ_{nom} within a single turn have been measured at 4 TeV/c and are in good agreement with simulations (Figure 2) [5]. When extrapolating the simulations to HL-LHC beam parameters, the perturbation amplitudes due to this effect are expected to increase up to 0.9 σ_{nom} – 1.1 σ_{nom}. This displacement can lead to beam losses, namely at the primary collimators of IR7 depending on its position.

Secondly, the use of crab cavities will introduce failure modes that can affect the particle beams on timescales well below the fastest failures considered so far [6]. Studies of different failure scenarios are still underway.

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These studies require considering details of the design 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.

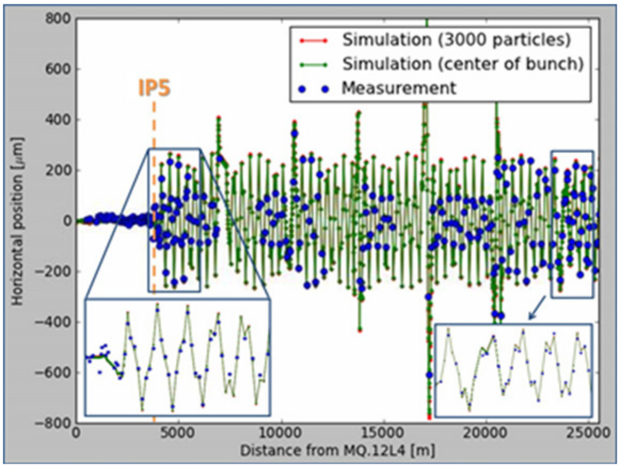

Figure 2: Horizontal trajectory perturbation of Beam1 as measured by the beam position monitors in the LHC ring (blue) and as predicted by simulation (red, green) in the turn directly after the Beam 2 dump kickers were fired. The measurement is for bunches with full long-range encounters. Beam energy: 4 TeV, bunch intensity: $0.9\cdot10^{11}$ protons, 84 bunches per beam, 25 ns bunch-spacing, crossing angle in IP5 ≈ 68 μrad [5].

While the protection against failures with time constants of ~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 Qext. For a 400 MHz cavity with a Qext=1E6 this will result in a time constant as low as 800 μs. 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 cavity voltage in 100 μs, accompanied by an oscillation of the phase by 50 degrees in only 50 μs [7].

RISKS AND MITIGATION

Operation at HL-LHC requires tighter settings of collimators with respect to the current operation. As an example, a collimator at a position corresponding to $5\,\sigma$ and a Gaussian distribution in the transverse planes is assumed. In case of a crab cavity trip and a fast displacement of the beam by, say, $1.7\,\sigma$, all particles above an amplitude of $3.3\,\sigma$ would hit the collimator. If the energy stored in the beam corresponds to about 500 MJ, the energy loss impacting on the collimator would correspond to 2.2 MJ (see Fig. 1). If the beam deflection is larger or the collimator closer to the beam, the energy deposition would increase. There are several ideas to mitigate the risk:

- Controlling the particle density in the transverse tail to reduce the number of protons in the beam halo to an acceptable level. A hollow electron-lens [8] would provide this functionality, ensuring that the energy stored in the beam halo which would potentially be deflected onto the collimation system will not exceed the design value of 1 MJ. For the current baseline this would correspond to $1.7\,\sigma$ (before reaching the closest primary collimator) as the possible transverse beam trajectory perturbation following an ultra-fast failure of a single crab cavity.
- Design the crab cavity system with the objective of limiting any sudden deflection of the beam by more than, say, one σ [9]. Avoid correlated failures of multiple cavities. Investigate fast failure detection. A thin wire at a position closer to the beam than a primary collimator, say, by $1.7\,\sigma$, would deplete the halo and ensure that the collimator is not damaged in case of a sudden deflection to amplitudes of one σ. Other methods for depleting, e.g. by tune modulation are discussed.
- Provide fast and reliable diagnostics and interlocking of the transverse tail population.
- Decrease the reaction time of the MPS for such ultra-fast failures, e.g. increase the number of abort gaps, accept asynchronous dumps, add direct links to the extraction system.

CONCLUSIONS

The existing MPS will cope with slow and fast failures in the order of few ms or more. Beam-beam effects during the extraction of one beam will deflect the other beam by about one σ, this needs to be taken into account.

New ultra-fast crab cavity failures risk deflecting the beam in less than a few turns to an amplitude of more than about $1.7\,\sigma$, requiring the primary collimator to be set far away from the beam. This could limit the β^* reach and therefore the luminosity for future high energy and intensity operation. This is a strong incentive for the design of the crab cavity system to limit beam excursion after a trip.

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