MACHINE PROTECTION ISSUES AND STRATEGIES FOR THE LHC

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Abstract

For nominal beam parameters at 7 TeV/c, each of the two LHC proton beams has a stored energy of 350 MJ threatening to damage accelerator equipment in case of uncontrolled beam loss. The energy stored in the magnet system at 7 TeV/c will exceed 10 GJ. In order to avoid damage of accelerator equipment, operation of the LHC will be strongly constrained. For the first commissioning of the complex magnet powering, quench protection and powering interlock systems must be fully operational. For safe injection, beam absorbers must be in the correct position and specific procedures for safe injection have to be applied. Since the beam dump blocks are the only element of the LHC that can withstand the impact of the full beam, it is essential that the beams are properly extracted onto the dump blocks at the end of a fill and in case of emergency. The time constants for failures leading to beam loss extend from some μs to few seconds. Requirements for safe operation throughout the cycle necessitate the use of beam instrumentation (mainly beam loss monitors), as well as collimators and beam absorbers. Failures must be detected sufficiently early and transmitted to the beam interlock system that triggers a beam dump. The strategy for the protection of the LHC will be illustrated starting from some typical failures.

INTRODUCTION

Protection in high power / high stored energy accelerators became a topic of intense research during the last years [1]. The beam power increases (e.g. SNS), beams become extremely bright (future linear colliders), and both the momentum and the beam intensity increases to unprecedented values (LHC). In accelerators with high power, continuous beam losses must be kept under control to limit radiation exposure of components. Injection must be stopped immediately after any failure. For accelerators with high stored beam and magnet energy, this energy must be safely discharged at the end of a fill or after a failure.

For the LHC, the operation with large stored energy in the beams in the presence of superconducting magnets with a very low quench margin is a particular challenge.

The complexity of the accelerator is unprecedented, with more than 10000 magnets powered in 1612 electrical circuits, complex cryogenics and vacuum systems etc. Repair of damaged equipment would take long, for example, the exchange of a superconducting magnet would take about 30 days.

The first priority for the protection systems is to prevent equipment damage, in the LHC ring, and during the transfer from the pre-accelerator SPS to the LHC. The second priority is to protect superconducting magnets from quenching. Other requirements are taken into account:

- Protect the beam: The protection systems should only dump the beam when necessary. False beam dumps should be avoided.
- Provide the evidence: In case of failure, complete and coherent diagnostics data should be provided, including post-mortem recording.

PROTECTION FOR SUPERCONDUCTING ACCELERATORS

The protection systems proposed in the first LHC design report [2] are similar to other accelerators with superconducting magnets (HERA, TEVATRON, RHIC).

In order to handle the large energy of 11 GJ in the magnet system, the LHC is powered in several independent powering sectors. After a quench, the energy stored in a magnet is discharged into the coils by firing quench heaters. The discharge of the energy stored in the electrical circuit is initiated by opening a switch parallel to a resistor (energy extraction). The energy is safely absorbed in the resistors, heating eight tons of steel to about 300 °C [3].

At the end of a fill and after a failure, the beam is deflected into a specially designed target (beam dump block) thus discharging the energy. The beam dump blocks are the only elements that can absorb the full LHC beam without being damaged. Beam cleaning with collimators limits particle losses around the accelerator. Beam loss monitors detect particle losses, and request a beam dump when losses are too high.

Three of the eight insertions are foreseen for protection, two for beam cleaning and one for the two beam dumping systems. The magnets in the two cleaning insertions are normal-conducting. One insertion has collimators capturing protons with large betatron amplitudes and the other insertion has collimators in locations with non-zero dispersion catching protons with large momentum deviations.

Beam loss monitors are installed at each quadrupole and other aperture limitations around the machine. Additional collimators and beam absorbers are installed in most other insertions and in the transfer lines.

ENERGY IN MAGNETS AND BEAMS

To deliver proton-proton collisions at the centre of mass energy of 14 TeV with a nominal luminosity of 10^{34} $cm^{-2}s^{-1}$, the LHC will operate with high-field dipole magnets using NbTi superconductors cooled with helium at 1.9 K [4]. The most important parameters for the LHC as proton collider are given in Table 1. Whereas the proton momentum is a factor of seven above accelerators such as SPS, Tevatron and HERA, the energy stored in the beams is more than a factor of 100 higher. The transverse energy density as relevant factor for equipment damage is a factor of 1000 higher than for other accelerators (Table 1).

Table 1: LHC Parameters

Momentum at collision	7	TeV/c
Dipole field for 7 TeV	8.33	T
Luminosity	10^{34}	$cm^{-2}s^{-1}$
Protons per bunch	$1.1 \cdot 10^{11}$	
Number of bunches / beam	2808	
Nominal bunch spacing	25	ns
Normalised emittance	3.75	µm
Typical rms beam size in arcs, 7 TeV	200-300	µm
Arc magnet coil inner diameter	56	mm

Table 2: Energy stored in magnets and beams

Energy stored in magnet system	10	GJ
Energy stored in one main dipole circuit	1.1	GJ
Energy stored in one beam	350	MJ
Average power, both beams	~10	KW
Instantaneous beam power, both beams	7.8	TW
World Net Electricity Generation (2002)	1.7	TW
Energy to heat and melt one kg copper	700	kJ

The beams must be handled in an environment with superconducting magnets that could quench in case of fast beam losses at 7 TeV of 10^{-8}-10^{-7} of the nominal beam intensity (see Table 3). This value is orders of magnitude lower than for any other accelerator with superconducting magnets and requires very efficient beam cleaning [5].

Table 3: Bunch intensities, quench and damage levels

Intensity one "pilot" bunch	$5 \cdot 10^{9}$
Nominal bunch intensity	$1.1 \cdot 10^{11}$
Nominal beam intensity, 2808 bunches	$3 \cdot 10^{14}$
Nominal batch from SPS, 216/288 bunches	$3 \cdot 10^{13}$
Damage level for fast losses at 450 GeV	$\sim 1\text{-}2 \cdot 10^{12}$
Damage level for fast losses at 7 TeV	$\sim 1\text{-}2 \cdot 10^{10}$
Quench level for fast losses at 450 GeV	$\sim 2\text{-}3 \cdot 10^{9}$
Quench level for fast losses at 7 TeV	$\sim 1\text{-}2 \cdot 10^{6}$

The beam intensity that could damage equipment depends on the impact parameters and on the equipment hit by the beam (Table 3). Realistic beam intensities above damage levels will be evaluated to update the numbers in Table 3, by simulations and in a dedicated experiment at the SPS. In any case, uncontrolled release of even a small fraction of the beam energy could cause serious damage to equipment:

- The beam from the pre-accelerator (SPS) can already damage equipment.
- For the rise of the extraction kicker, the beam has a 3 µs long particle free "abort gap". After spontaneous kicker firing, or an unsynchronised beam dump equipment could be damaged.

Protection must be efficient from the moment of extraction from the SPS, throughout the LHC cycle.

ACCIDENTAL RELEASE OF BEAM ENERGY

One of the worst case failure scenarios, an accidental release of the entire beam energy into equipment, is considered [6]. The damage has been estimated for a solid copper target hit by the full LHC beam, by carrying out three-dimensional energy deposition calculations and two-dimensional numerical simulations of the hydrodynamic and thermodynamic response.

The beam energy is deposited over 89 µs, long enough to change the density of the target material. The change will strongly affect the energy deposition of the impacting beam.

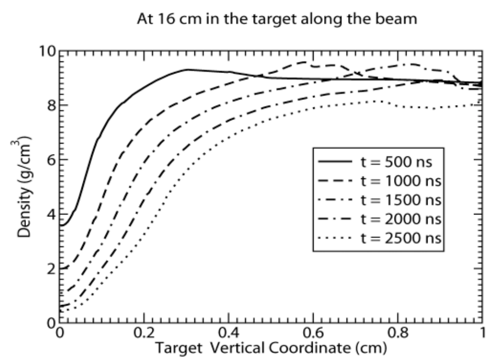

Fig. 1 Density of target material after an impact of 20, 40, 60, 80 and 100 bunches

The calculations indicate that the target density on the axis can be drastically reduced within 2.5 µs, due to the transverse shock wave moving outwards from the beam heated region. In the present results, the density around the beam axis is reduced by a factor of 10, after only 100 LHC bunches out of 2808 have been delivered. Substantial expansion of the material in the inner 0.5 mm beam heated region takes place. The material in this hot inner zone is in a plasma state, with the surrounding target in a liquid state. The protons in the following bunches will therefore penetrate into the target more deeply as they will encounter material with reduced density (Fig. 1). First estimations of the penetration depths are in the range of 10-40 m, to be refined and published in a future report.

PARTICLE LOSSES AND COLLIMATORS

The LHC will be the first machine requiring collimators to define the mechanical aperture through the entire cycle. A sophisticated scheme with many collimators and beam absorbers has been designed [5]. Some of the collimators must be positioned close to the beam, (~6 σ). For luminosity operation at 7 TeV, the opening between two collimators jaws can be as small as 2.2 mm.

Under optimum condition the single beam lifetime could exceed, say, 100 h (Table 4). This would be very comfortable since the beam deposited power into the equipment is only about 1 kW. Still, the cleaning system should capture more than 99 % of the losses. If the lifetime decreases to 10 h, the collimators should capture more than 99.9 % of the beam losses [5]. The collimation system is designed to accept a lifetime of about 0.2 h for a 10 s long transient, e.g. when changing the betatron tune. This corresponds to a power deposition of 500 kW. If the lifetime becomes even smaller, in particular after equipment failure, the beams will have to be dumped immediately. Depending on the type of failure, dumping the beams must be very fast.

Table 4: Lifetime of the LHC beams (7 TeV, nominal intensity)

Beam lifetime	Lost beam power (one beam)	Comments
100 h	1 kW	Healthy operation, cleaning must work and capture >99% of the protons
10 h	10 kW	Operation acceptable, cleaning must work and capture >99.9% of the protons
12 min	500 kW	Operation only possibly for short time, collimators must be VERY efficient
1 s	330 MW	Failure of equipment - beam must be dumped rapidly
15 turns	Several 100 GW	Failure of D1 normal conducting dipole magnet - detect beam losses, beam dump as fast as possible
1 turn	~ TW	Failure at injection or by a kicker, potential damage of equipment, passive protection relies on beam absorbers

FAILURE SCENARIOS AND PROTECTION

Since it is not conceivable to consider all possible failures, mechanisms for particle losses are classified according to the time constant for the loss [7].

Ultrafast beam losses are losses in a single turn or less. Machine equipment is protected with collimators and beam absorbers.

Multiturn losses include very fast losses in less than 5 ms, fast losses in more than 5 ms and steady losses (one second or more).

Ultrafast beam losses

One mechanism for such losses is a wrong deflection of the circulating of injected beam, by an injection kicker, beam dump kicker or a kicker for tune measurements and aperture exploration. Another mechanism is a failure during transfer and injection, such as a wrong trajectory or wrong energy due to equipment failures, or the physical obstruction of the beam passage.

The probability for kicker failures is minimised by using high reliability systems, and by interlocking kicker magnets (for example, for the injection kicker when the LHC is not at injection energy). However, erratic firing of a kicker cannot be fully excluded and additional protection using beam absorbers is required.

Failures at injection

The beam is accelerated in the SPS to 450 GeV, extracted and then sent through ~2.8 km long transfer lines to the LHC [8]. During this process the beam could damage extraction elements, transfer line magnets and the LHC injection septum magnets or kickers. An interlock system verifies a few ms before extraction from the SPS the correct settings of all elements: orbit in SPS before extraction, strengths of kicker and septa magnets, magnet strengths in the transfer line, position of vacuum valves and collimators [9]. In order to minimise risk of quenches in the LHC, the beams are shaped in the SPS by scraping the tails at 3-3.5 σ.

The transfer lines comprise many magnet families. Despite planned power supply surveillance and interlocks, failure modes exist which could result in uncontrolled beam loss. Collimators in the transfer line set to about 5 σ will capture particles that are outside the acceptable trajectory range, to avoid damage of elements in the injection region and the LHC where the aperture at injection is about 7.5 σ. [10]. In this value for the aperture, tolerances for closed orbit, beta beating etc. are included.

The main LHC injection elements comprise injection septa and injection kickers, together with three families of passive beam absorbers. These devices downstream of the kicker magnet will prevent damage in the LHC in case of a beam off axis and will be set to about 7 σ during injection [11].

If one of the magnets in the LHC had a wrong current value, or in case of an aperture problem (for example due to a closed vacuum valve), the beam would be lost. To prevent such accident, only beam with limited intensity can be injected when there is no beam in the LHC. Injection of beam exceeding this intensity requires some circulating beam [12], verified by beam current measurements just before injection.

Failures when dumping the beams

The beam dumping system must function with utmost reliability [13]. For clean extraction of the beam several conditions have to be met:

- The beam dump kicker must be synchronised with the 3 μs long beam abort gap.
- The field of the extraction and dilution elements must be well adjusted to the beam energy.
- The closed orbit errors in the dump insertion must be limited to about 4 mm since the aperture of the beam dump channel is tight.

A likely failure scenario is the pre-firing of one beam dump kicker module. The other 14 kicker modules would be immediately triggered after such failure, but about 94 bunches deflected up to 4 μs after the pre-firing would not be extracted correctly. Bunches having received the smallest kick would travel one turn around the machine, come back and are again deflected by the kicker. These bunches could have a large offset, and absorbers must ensure that no equipment is damaged. About 8 bunches would receive a kick such that they reach the cleaning insertion and impinge on the collimators. Bunches that are deflected with a larger angle would hit a movable absorber in the dump insertion. Some 40 bunches would hit a fixed absorber in front of the septum magnet.

The collimators in the cleaning insertions must be able to withstand at 7 TeV the shock impact of about 8 bunches, as well as continuous beam losses for reduced beam lifetimes [14]. To stand such impact, graphite is used as jaw material. The robustness of a prototype collimator will be tested at the SPS.

A failure in the synchronisation between RF and abort gap has slightly less severe consequences than an erratic firing of the kicker, since the number of bunches that do not follow the correct trajectory is smaller.

The number of particles in the abort gap should be below some critical level defined by quench limits. Debunching caused by RF noise, intrabeam scattering, etc. populates the abort gap [15]. At 7 TeV, non-captured protons will lose energy by synchrotron radiation and therefore be captured in the momentum cleaning insertion. Particles in the gap can be removed with the transverse feedback system [16]. After a failure in the RF system, the beam is dumped immediately.

Whenever a failure during extraction occurs, bunches will oscillate with large amplitudes around the closed orbit. Hence, the closed orbit around the machine must be well controlled [17].

At collision energy the maximum 4 km beta functions in the low beta triplet at the high luminosity experiment insertions lead to a local reduction of the available aperture and hence increased probability for particle impact. Tertiary collimators will be used to shadow the superconducting triplet apertures against the tertiary halo and to provide local protection for irregular beam loss in case of failures [5].

Multiturn failures (fast / very fast losses)

Failures that could drive the beam unstable are mainly quenches of superconducting magnets and other failures in the powering system. There are operational failures and combined failures (for example after mains disturbances).

In [18] several failures were considered. A failure of D1 dipole magnets is most critical leading to a fast change of the closed orbit around the accelerator. Protons in the tails of the distribution would first touch collimator jaws, exceeding more than 10^9 protons after about 15 turns. The losses would be detected by beam loss monitors. Assuming that the collimators can withstand a beam loss of about 10^{12} protons, the jaws could be damaged already after 30 turns. For dumping the beam about 10 turns (1 ms) are available. After a dipole magnet quench, the beam should be dumped within about 5 ms.

The beam loss monitoring system must prevent the machine components from damage and the superconducting magnets from quenches [19]. Monitors close to all aperture limitations, in the cleaning sections, in the insertion with the beam dumping system and in the low-beta triplet will measure the beam losses with a frequency of 20 kHz. Losses at the aperture limits due to very fast orbit movements or beam blow-up can be detected within one turn. Monitors in the arcs at all superconducting quadrupoles will measure beam losses within 2.5 ms, and request a beam dump if a magnet risks to quench.

It is proposed to detect rapid beam position changes. If beam orbit movements exceed a predefined value, say, about 0.2 mm / ms, the beams are dumped. Such a system could detect failures earlier than beam loss monitors and is a redundant system for protection.

Increasing the inductance in the electrical circuit with D1 magnets by about a factor of five, possibly with a superconducting solenoid in series with the magnets, would increase the time constant for orbit changes. This could relax the parameters for the protection system since a failure of D1 causes the fastest multiturn losses.

Steady losses

If the beam cleaning system captures the protons very efficiently, the heat load on the collimators might become unacceptable. Temperature monitoring of collimator jaws is planned. Beam losses and the decay of the circulating beam current (dI/dt) will be measured. If the losses are unacceptable, the beam will be dumped. If steady losses lead to an unacceptable heat load on a superconducting magnet, the magnet would quench. After a magnet quench, protection is as for fast losses discussed above.

AVAILABILITY OF THE PROTECTION SYSTEM

The protection of the LHC relies on a number of systems, including about 4000 quench detectors, about 3800 beam loss monitors, 100 collimators and about 1000 channels in the interlock systems (Fig.2).

Common design principles for the protection systems are being used. No erroneous manipulation on the protection system should compromise the accelerator safety. No single equipment failure should lead to equipment damage. In general, systems should be "Fail Safe": a failure in the protection systems leads to a beam dump and downtime of the accelerator, but no equipment would be damaged. In safety systems, redundancy is widely used. For the LHC, there is redundancy within a system and redundancy across systems. For redundancy within a system, several channels have the same functionality. If one or more channel fail, the "mission" is aborted (…the beam is dumped).

An example for redundancy across systems is the protection from beam losses after equipment failure.

Beam losses will be detected by loss monitors. In general, particles will be lost at different locations around the LHC, and several monitors will detect the loss. Equipment monitoring should also detect the failure and request a beam dump.

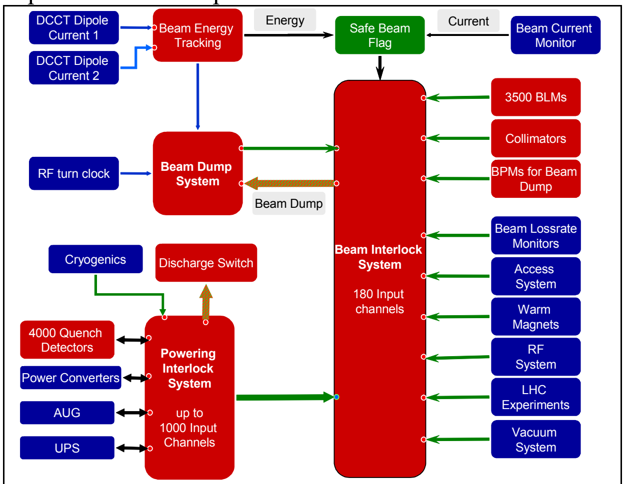

Fig.2: Dependencies of the LHC protection systems

Increasing complexity, for example, by two channels in parallel might increase the number of false beam dumps. Therefore a voting scheme is implemented in some systems [20]. However, this strategy is not always applicable (for example, it is not conceivable to have more than one beam dumping system per beam) and the cost must be kept under control.

The variety of protection systems requires a coherent quantification of risks across systems using industrial standards (SIL = Safety Integrity Level).

It is planned to introduce flexibility by making the system "rigid but flexible". Interlocks will be therefore configurable, with the information on disabled interlock channels in a centralised database. To limit the risks when disabling interlocks, a "Safe Beam Flag" allows disabling only when operating with "safe beam" (beam below damage threshold). This will facilitate bootstrapping of the LHC and allow optimising the protection systems and interlocks during operation.

CONCLUSIONS

Safe operation of the LHC with high intensity beams relies on the correct functioning of several complex protection systems. Protection starts already at extraction from the SPS and collimators must define the aperture in the transfer line and in the LHC during the cycle.

Beam and equipment monitoring will request a beam dump in case of failures. A correct and reliable functioning of all those systems at the start of LHC operation is very challenging. To introduce some flexibility during commissioning period and in case of problems, it will be possible to relax the conditions by introducing a "safe beam" flag permitting the masking of certain interlocks without compromising the safety.

Future work will concentrate on new ideas for detecting failures on the time scale of less than one millisecond [21]. Recently, beam losses on this timescale became of concern for HERA [22]. This observation is a strong incentive to pursue these ideas.

Availability and maintainability of the machine due to the complex protection are issues deserving much more attention. Due to the large energy stored in magnets and beams stringent protection is required: too few interlocks could lead to important damage of LHC components. This requires an unprecedented complexity of the machine protection system, but too many interlocks could prevent the LHC exploitation.

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