LHC MACHINE PROTECTION

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Abstract

The energy stored in LHC magnets presents a considerable challenge for commissioning even before any beam is injected. Furthermore, the energy stored in the nominal LHC beams is such that it presents a serious threat to accelerator equipment in case of uncontrolled beam loss. Consequently the safe operation of the LHC requires the correct functioning, at all times, of several systems which together constitute a complex machine protection system. An overview of this system is presented.

INTRODUCTION

The LHC is a complex accelerator operating close to the limits, both as far as beam energy and beam densities are concerned. Major faults in the complex equipment will result in long repair times. To optimise the operational efficiency of the accelerator, accidents should be avoided and interruptions should be rare and limited to short time. Hence a system is needed that prevents damage to the magnets, the cables and the power-leads, minimises damage due to irradiation caused by beam losses, and provides the necessary tools to implement a consistent and congruent error and fault tracing, throughout the machine. Machine protection is not an objective in itself; it is a mean to maximise operational availability by minimising time for interventions and to avoid expensive repair of equipment and irreparable damage.

This paper is organized as follows. The next section tackles the machine protection subject from the energy stored in the magnets point of view. The following section explains the architecture of the machine protection system. Then, the energy stored in the beams and the protection against the beam damage are discussed in the last two sections. Finally some conclusions are drawn up at the end of this document.

ENERGY STRORED IN THE LHC MAGNETS

At nominal operating current, predominately the dipole magnets store a large amount of energy. The LHC magnets are powered separately in each of the eight sectors in order to reduce the energy stored in a particular electrical circuit. Still, the energy in each sector of the LHC amounts to 1.29 GJ, sufficient to heat up and melt 1900 kg of copper.

During operation without beam, the large energy stored in the magnets presents the main risk. Various reasons can lead to an uncontrolled energy release. Magnets, superconducting bus bars, current leads, or cryogenic infrastructure could in such a case be destroyed. In case of a failure the magnetic energy has to be extracted. Due to the large inductance a response time in the order of 10 ms to abort the power is acceptable for most elements (such as all superconducting magnets).

ARCHITECTURE OF THE MACHINE PROTECTION SYSTEM

General aspects

Some general requirements have to be considered for the machine protection system:

- Protect the machine: In case of fault the necessary steps shall be taken to dump the beam and to discharge the energy stored in the magnets in a safe way.
- Protect the beam: The system shall not generate unnecessary beam dumps.
- Provide the evidence: The system shall help to identify the initial fault, in case of beam dump or power failure.
- Improve the operation: The status of the system must be transparent to the operator at all times.
- Enable tests: Almost all functions must be remotely testable.

This can be achieved by:

- Hardwired abort links protect the equipment (Hard Abort).
- Soft aborts, possibly via computer links, improve the operation efficiency; they may be disabled or may fail.
- The number of channels that may provoke an abort will be minimized to limit the number of superfluous aborts.
- The same structure across different sub-systems in the abort chain will be used.
- All inputs can be simulated or bridged. However, in such a case “permits” are also simulated and not passed to destinations outside of the system.

General Architecture

The architecture of the machine protection system is derived from the structure of the LHC and from operational requirements. It consists of a distributed, globally acting Beam Interlock System that informs the Beam Dump System if any unsafe situation is detected, and of locally acting, distributed, Power Interlock Systems. They cause a safe discharge of the energy stored in the magnet system in case of a quench, or other failures. Interfaces between the Power Interlock Systems and the Beam Interlock System ensure the dumping of the beams, if necessary. A Post Mortem System records data from various systems to understand the cause of a fault leading to a beam dump or power abort.

Architecture of the Power Interlock

The eight sectors in the LHC consist of 44 continuous, largely independent cryostats, and some warm magnets. Powering of one electrical circuit is always limited to one of those cryostats or half-insertions

The powering system for each electrical circuit includes power converters, (warm) cables from power converters to the current feed-through, superconducting bus bars for the current distribution, and finally the superconducting magnets.

In case of a fault in one of the cryostats the energy of some or of all electrical circuits in this cryostat has to be discharged. Each cryostat will have a local Power Interlock System. Hence, any cryostat can be powered irrespective of other cryostats. LHC contains 36 short cryostats requiring one Power Permit Controller (PPC) each, preferentially located close to the power converters.

The eight long arc cryostats span the major part of a sector and are electrically fed from both sides. The energy extraction systems for the main arc quadrupoles magnets are in the even points. The main arc dipole magnets are discharged at both ends of the arc cryostat. Hence the long arc cryostats need Power Permit Controllers (PPC) on both sides and a communication link in between. The quench detection for the main magnets in the arc cryostats comprises about 200 units distributed along the arc.

About 100 power converters installed in the tunnel power the orbit correctors in one sector.

Warm magnets on either side of an interaction point (IP) are treated as if they form an additional “continuous cryostat”.

In total, almost 60 Power Permit Controllers (PPC) are required. They will also be connected to the controls network and the timing system.

QUENTCH PROTECTION SYSTEM

The protection system for superconducting elements in the LHC commonly referred as Quench Protection System (QPS) is attached to all superconducting circuits. To protect a large number of vital components will be a major challenge. More than 8000 superconducting magnets, including about 2000 large dipole and quadrupole magnets, and 6000 corrector magnets, are powered in about 1800 circuits. Several thousand electronic channels may, in case of failure, force a beam dump. To limit the number of superfluous aborts below one per fortnight, the mean time between failures (MTBF) must exceed 100 years for each channel!

The machine downtime depends on the type of faults and their frequency. It could be between two hours and several weeks for one incident. Major accidents may include the partial destruction of a magnet. To warm up the neighbourhood, the repair, and the cool down will require some weeks. Should no spare magnets be available, the repair may last many months.

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). If a quench occurs, the sequence of events that take place is the following:

- The quench starts. It takes some time until the voltage across the magnet exceeds the threshold of the quench detector, plus 10 ms to validate the signal.
- 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 magnet opens at about 6 V.
- The quench detector actuates the energy extraction system by switching a resistor into the circuit. It takes between 5 to 7 ms to open the switch.
- The quench detector sends a signal via the powering interlock system to the beam interlock system. It takes about 4 ms to complete the beam dump. In general, at this time the magnetic field is not yet affected by the quench.

ENERGY STORED IN LHC BEAM

For the LHC both the particle momentum and the beam energy increase to unprecedented values (see Fig. 1 and Table 1). The proton momentum is a factor of seven above accelerators such as SPS, Tevatron and Hera, whereas the energy stored in the beams is more then a factor of 100 higher. Each beam stores energy of up to 0.35 GJ, equivalent to the energy for warming up and melting 500 kg of copper. The stored high beam energy must be safely discharged at the end of the fill or after a failure. If this is not properly done, the complexity of the accelerator is such that the repair of the damaged equipment would take long. For example, the exchange of a superconducting magnet takes about 30 days.

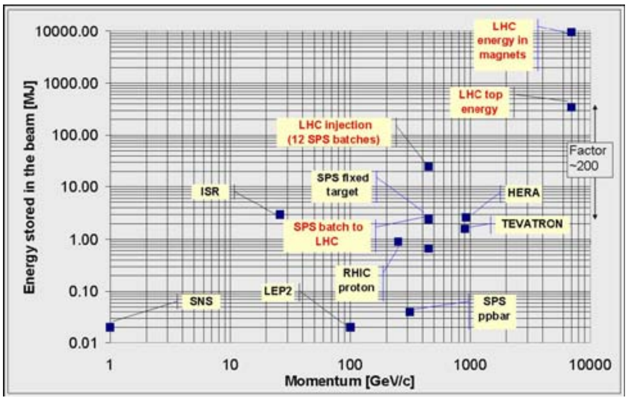

Figure 1: Energy stored in the beam for LHC and other accelerators and energy stored in the LHC magnets.

Table 1: 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	360	MJ
Average power, both beams	~10	kW
Instantaneous beam power, both beams	7.8	TW
Energy to heat and melt one kg copper	700	kJ

The first priority of the protection system is to prevent equipment damage in the LHC ring and during the beam transfer from the pre-accelerator SPS to the LHC.

PROTECTION AGAINST DAMAGE

Protection must be efficient from the moment of extraction from the SPS, throughout the LHC cycle. The beam intensity that could damage the equipment depends on the impact parameters and on the equipments hit by the beam. 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.

The second priority is to protect superconducting magnets from quenching. At 7 TeV, superconducting magnets would quench in case of fast particle losses of ~ 10^{-7} of the nominal beam intensity (see Table 2). This value is orders of magnitude lower than for any other accelerator with superconducting magnets and requires a very efficient beam cleaning system.

Table 2: Bunch intensities, quench and damage levels (for protons)

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	$\sim 1\text{-}2 \cdot 10^{6}$

Particle losses failure and beam dump

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

Most failures would cause particle losses in more than 5 ms. If particle losses during the operation with stored beam become unacceptable, or if there is an equipment failure, the beams must be extracted into a specially designed target (beam dump block) thus safely dissipating the energy. This requires the detection of an unsafe situation, either with beam instruments, or by hardware monitoring. A beam dump request is issued to one of the 16 beam interlock controllers installed around the LHC (two per insertion region, IR). The beam interlock controller transmits this request to the Beam Dumping System.

The beam dump blocks are the only elements that can absorb the full LHC beam if correctly extracted without being damaged. Thus a safe extraction is also required at the end of a normal fill, for example when the luminosity is too low.

The Beam Dumping System has a key role for protection. Before injection, it must be ready. One of the worst failure scenarios is injecting beam into the LHC with the Beam Dumping System not ready, since it could not dump the beams if required.

A likely failure is the pre-firing of one beam dump kicker module or an unsynchronized beam dump. Part of the beam would be deflected by a wrong angle and not travel correctly through the 700 m long extraction channel. To protect the LHC aperture, a movable absorber in the dump insertion (TCDQ) captures bunches deflected by a small angle. The TCDQ must be set close to the beam at injection and with squeezed beams to less than 10σ. Since the position of the TCDQ is very critical it must be interlocked.

Some 40 bunches would hit a fixed absorber in front of the septum magnet and the bulk of the beam travels to the beam dump block.

Architecture of the Beam Interlock

There will be one Beam Interlock System for the LHC. Right and left from each IR one Beam Permit Controller (BPC) will be installed. These controllers are connected to two fast, optical links (Beam Permit Loops) running at 10 MHz (see Fig. 2).

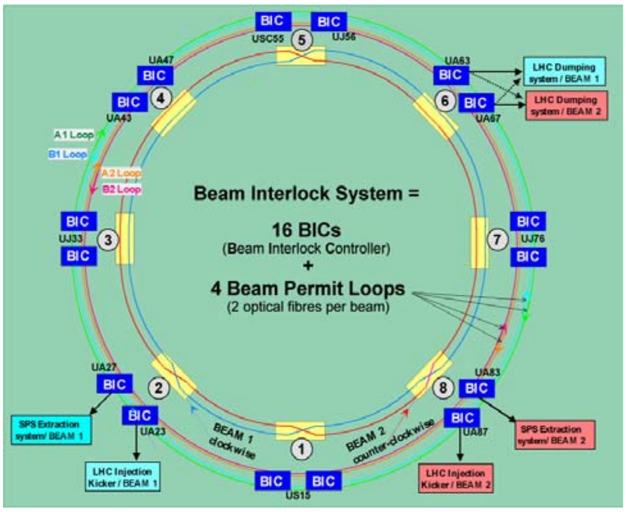

Figure 2: A schematic representation of the beam interlock system.

The two links distinguish between beam I and II. When a link is broken, the corresponding beam is extracted into the beam dump by the Beam Dumping System. In addition, a computer connection to the BPC for monitoring, testing and post mortem analysis is required. Note that Beam Permission is a necessary but not sufficient condition for beam injection. In order to inject, additional conditions have to be met.

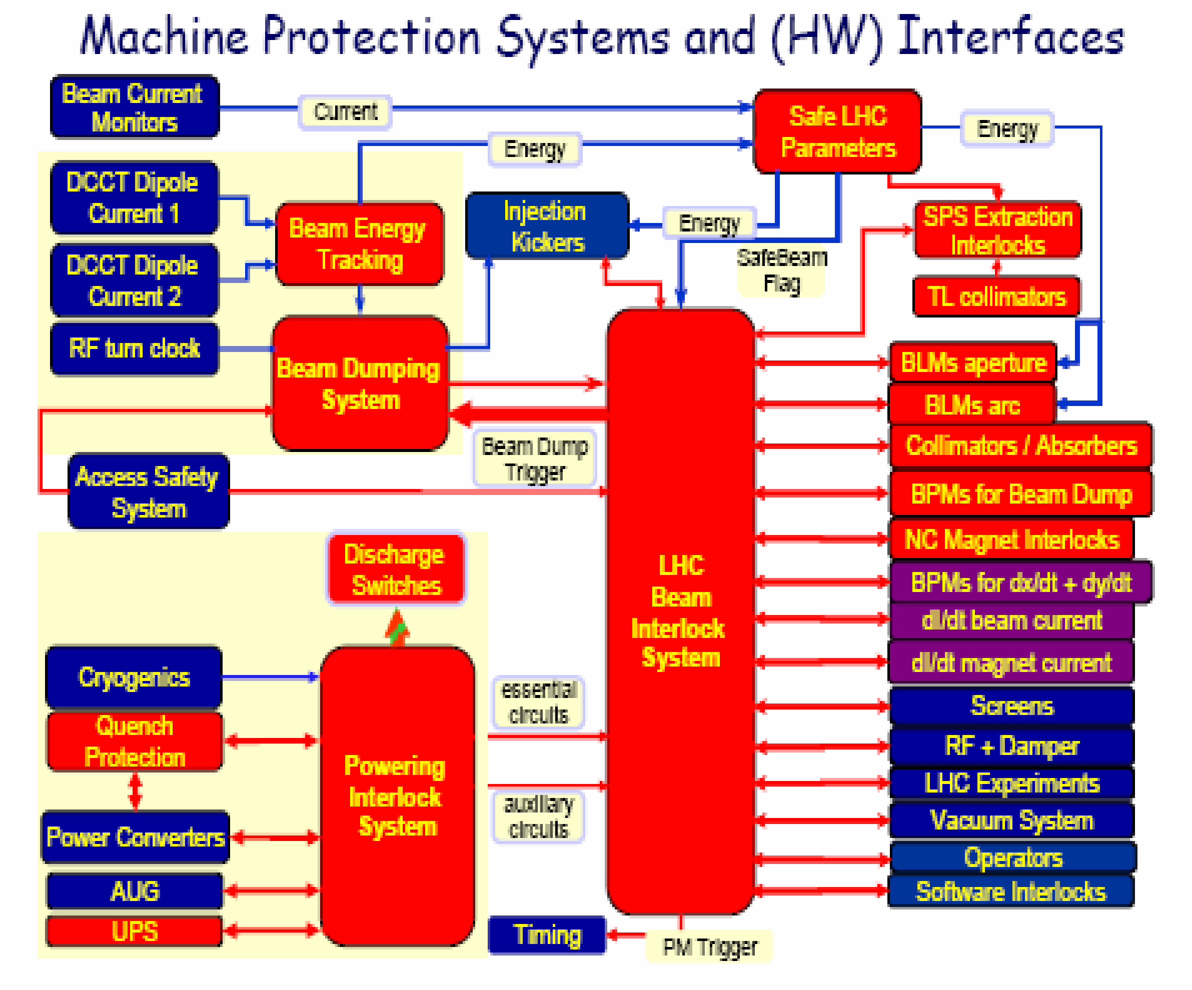

Figure 3: Machine protection systems and hardware links. In red, systems for protection are shown and in blue other systems. Systems that have been recently proposed are in purple.

Fig. 3 shows the hardware links between the machine protection systems and other systems. A correct and reliable functioning of all those systems at the start of LHC operation is very challenging. To introduce some flexibility during the 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. The safe beam flag is based on readings of the main dipole current (approximately proportional to the momentum) and the beam intensities.

CONCLUSIONS

There is no single "Machine Protection System": LHC Machine Protection relies on several systems working reliably together. Construction of the large systems for protection is progressing and smaller systems are in the design phase (for example, the generation and distribution of Safe LHC Parameters).

Prototyping and first experience gained at SPS and elsewhere has been very valuable, for collimators, beam interlocks, beam loss monitors, orbit feedback, etc.

In general, there is a large redundancy for the detection of failures, however: there is only ONE Beam Dumping System, only ONE Beam Interlock System and ONE Energy Tracking System. Reliability and availability of the machine due to the complex protection is an important issue.

Safe operation also relies on operational procedures for commissioning and operation. A "Software Interlock System" is required, managing critical settings, sequencing operational procedures and monitoring critical parameters.

Safe operation of the LHC starts at the SPS, via extraction into TT40/TI8 and TI2, via the transfer lines, via LHC injection and into the LHC itself.

Safe operation does require not only hardware and software interlocks, but also a culture:

- as soon as the magnets are powered, there is the risk of damage due to the stored magnet energy;
- as soon as the beam intensity is above a certain value (that is less than 0.01% of the full 7 TeV beam), there is the risk of beam induced damage.

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