LHC MACHINE PROTECTION

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INTRODUCTION

For nominal beam parameters at 7 TeV/c each of the two LHC proton beams has a stored energy of 362 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, complex machine protection systems are required. Magnet protection and powering interlock systems must be operational already before commissioning the magnet powering system. Beam operation, throughout the operational cycle from injection to colliding beams, requires fully operational protection systems, including beam interlock systems, beam dumping system, beam instrumentation (mainly beam loss monitors) as well as collimators and beam absorbers.

Details of LHC machine protection have been presented on several occasions and the systems involved in protection are well documented [1]. This paper gives an overview of LHC machine protection, discusses the progress with the implementation and presents first results from the commissioning of some systems.

LHC CYCLE AND ENERGY STORED IN THE BEAM

The LHC beam is prepared in the CERN accelerator chain. Before transfer to LHC, the beam is accelerated in the SPS from 26 GeV/c to the LHC injection momentum of 450 GeV/c. During fast extraction, the closed orbit around the extraction point in the SPS must be within predefined limits. When the beam is extracted the strength of all magnets in the transfer line and the LHC must be correct and nothing should block the beam passage.

During the injection phase 12 batches per beam are transferred to LHC (see the LHC operational cycle in Fig.1) via 3 km long transfer lines. The energy stored in a batch with either 216 or 288 bunches exceeds two MJ, in the same order as the energy of the stored beams in TEVATRON or HERA. The LHC is the first accelerator with the intensity of the injected beam already far above damage threshold. Protection during the injection process is mandatory.

The injection process for the two beams will take about 15 min. When filling of the LHC rings is completed, the protons are accelerated to a momentum of 7 TeV/c, with 360 MJ stored in each of the two beams. This is the most critical phase of operation, due to the large energy stored in the beams and the very low quench margin of the superconducting magnets in case of beam loss. Normally, the beams will collide for several hours during a physics fill. At the end of a fill or after the detection of a failure, the beams are extracted into specially designed absorbers (beam dump blocks).

At 7 TeV/c, a fraction of about 10^{-8} of the full beam could already quench a magnet. Fast beam loss with an intensity of about 5% of one single bunch with nominal intensity could damage equipment (e.g. superconducting coils). The only component that can stand a loss of the full beam is the beam dump block - all other components would be damaged. The LHC beams must ALWAYS be extracted into the beam dump blocks at the end of a fill or in case of failure.

The design of the LHC protection elements is based on energy deposition simulations and assumptions for the damage levels. A dedicated experiment was carried out to cross-check the validity of this approach by damaging material in a controlled way with beam [2]. The 450 GeV/c beam with transverse rms dimensions of about 1 mm extracted from the SPS was directed onto a specially designed high-Z target comprising several typical materials used for LHC equipment. The beam intensities were chosen to exceed the damage limits of parts of the target, between $2 \cdot 10^{12}$ and $8 \cdot 10^{12}$ protons. The results of the damage test show good agreement with the simulations, with a damage threshold in the order of some 10^{12} protons, depending on the material.

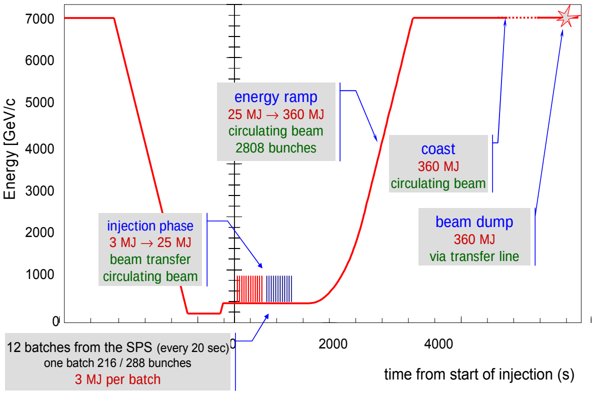

Figure 1: LHC operational cycle and energy stored in the beam

BEAM INTERLOCK SYSTEMS

There are several independent beam interlock systems for the SPS ring, SPS extraction and transfer, LHC injection and LHC ring that are linked to ensure safe operation throughout the operational cycle. The systems are based on hardware that has been developed for the LHC, with the first systems already implemented for the SPS ring and for the SPS extraction system. The interlock

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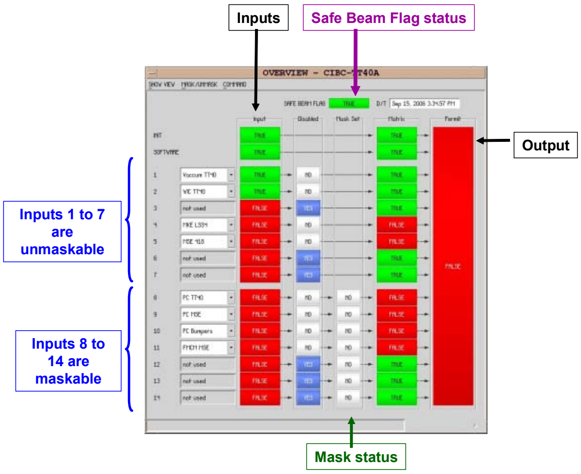
systems are also used for CNGS high intensity operation since one of the SPS extraction zones is used for sending beam to the CNGS target as well as to the LHC.

- The role of the SPS beam interlock system is to concentrate beam dump requests from the various monitoring systems and to transmit such requests to the SPS beam dumping system. Typical inputs come from beam loss monitors, power converters, vacuum equipment etc. When a signal changes from TRUE to FALSE, the beam dump is triggered. A new system with LHC type hardware has been installed for the 2007 run.
- The SPS extraction interlock system allows beam extraction only when the conditions for extraction are valid, and all elements downstream of the kicker magnets are in the correct state. It opens a window of about 3 ms, during which the Pulse Forming Networks of the kicker magnets can be charged, and extraction is permitted during another 3 ms window, when the conditions are still valid.
- The LHC injection interlock system allows beam injection into LHC only when the LHC ring is ready for beam, the injection elements have correct settings and the elements at the end of the transfer line are ready.
- The LHC beam interlock system is similar to the SPS beam interlock system concentrating all beam dump requests and triggering the beam dump, but with many more inputs from the monitoring systems (see later).



SAFE BEAM FLAG TRUE D/T Sep 15, 2006 3:34:57 PM

		Input	Disabled	Mask Set	Matrix	Permit
INT		TRUE			TRUE	FALSE
SOFTWARE		TRUE			TRUE	
1	Vaccum TT40	TRUE	NO		TRUE	
2	WIC TT40	TRUE	NO		TRUE	
3	not used	FALSE	YES		TRUE	
4	MKE L334	FALSE	NO		FALSE	
5	MSE 418	FALSE	NO		FALSE	
6	not used	FALSE	YES		TRUE	
7	not used	FALSE	YES		TRUE	
8	PC TT40	FALSE	NO	NO	FALSE	
9	PC MSE	FALSE	NO	NO	FALSE	
10	PC Bumpers	FALSE	NO	NO	FALSE	
11	FMCM MSE	FALSE	NO	NO	FALSE	
12	not used	FALSE	YES	NO	TRUE	
13	not used	FALSE	YES	NO	TRUE	
14	not used	FALSE	YES	NO	TRUE	

Figure 2: Controls interface for the SPS Extraction Interlock System

A typical interlock controller includes input channels for up to 14 signals (see Fig.2). One additional input is the so-called "safe beam flag" which for the SPS is derived from the beam intensity. If the beam is considered to be safe, part of the signals can be masked. When the beam intensity is above a certain level, the safe beam flag becomes false and masks are not taken into account. For the LHC, the safe beam flag will be derived from beam intensity and energy.

It is possible to extract beam from the SPS without receiving a beam permit from LHC, if for the extraction channel concerned the downstream beam dump block in the transfer line is inserted or the beam is extracted towards the target of the CNGS experiment [3]. The dump blocks are designed to absorb beam with nominal intensity, for example for tests.

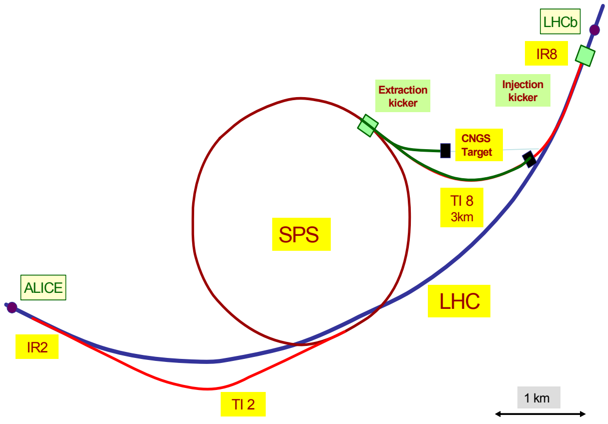


Figure 3: Beam transfer from SPS to LHC and to the CNGS target

MACHINE PROTECTION DURING BEAM TRANSFER

Safe beam transfer and injection into LHC relies on correct settings of all magnet currents, both for slow and fast pulsing magnets. All movable elements must be in OUT position, such as vacuum valves, beam screens, etc. The momentum of beam in the SPS must match the energy of the transfer line, for CNGS (400 GeV/c) or LHC (450 GeV/c). The correct magnet current settings are verified using a permit signal that is TRUE only when the measured magnet current is within a predefined window (see Fig.4). This verification is done in the power converter controller via real time software and takes a few ms [4]. For magnets where the current change can be critical within less than some ms, Fast Magnet Current change Monitors (FMCM) are installed. This is a joint development with DESY based on a system successfully operating at HERA for some years [5]. It allows detecting magnet current changes within a fraction of a ms. FMCMs are installed on critical magnets, the extraction septa and some magnets in the transfer lines. Such monitors will also be installed for some ten electrical circuits with normal conducting magnets in the LHC.

Both the SPS extraction and the LHC injection kicker systems must fire at the correct time with the correct strength. Since a failure of these kicker systems cannot be excluded, a beam absorber is installed downstream of these kicker magnets. Several collimators at the end of the transfer line to the LHC limit the aperture to ensure that the beam enters the LHC correctly. Downstream of the LHC injection kicker several other absorbers are installed, to capture beam in case of a failure of the LHC injection kicker. Beam loss monitors are used for the analysis of the losses during transfer, inhibiting the following extraction if losses exceed a predefined threshold.

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Commissioning of CNGS with high intensity beam was done in 2006. Extraction is via the same transfer line as for LHC up to a switching magnet that separates the CNGS line and the TI8 line for LHC.

During the CNGS run all machine protection devices for the extraction zones and for the common part of the transfer line were commissioned, in particular the beam interlock system. Masking of some interlocks with the “safe beam flag” has been extensively used during commissioning with low intensity beams.

MACHINE PROTECTION FOR CIRCULATING BEAMS IN LHC

The number of possible failures that have an impact on the beam is huge:

- Failure in the powering system (magnet quench, power converter trip, …)
- An object touching the beam (vacuum valve, collimator, experimental detector, bad vacuum, …)
- Operational failure (operator, controls, timing, …)
- Beam instability
- Loss of RF
- Others

For the design of the protection system it is important to understand how fast the beams can become unstable and need to be extracted.

Beam losses during injection, extraction, and by accidentally deflecting the beams with a kicker magnet can occur within a single turn. To protect equipment against some of these failures, safe operation relies on absorbers installed at all critical locations capturing mis-kicked beam. In order to prevent accidental firing of the injection kicker, the injection kicker magnets are switched off and interlocked when injection is finished. Kicker magnets for beam observation, e.g. Q-measurement and aperture exploration, produce either only a small deflection or are interlocked to operate with low intensity beam only.

Extensive simulations have been performed to determine the time constant for the loss of circulating beam after a magnet failure [6,7]. A powering failure for a normal conducting magnet string (D1 magnets) installed in a region with very high beta function leads to the fastest beam loss. The most critical failure at 7 TeV/c is a trip of the power converter, and at injection a failure that sets the voltage of the power converter to the maximum value. It would take between some turns to some milliseconds until particles start to touch the aperture.

For most magnet failures, particles start to be lost after a time between about five ms and several seconds, e.g. after a quench of a magnet or a trip of a power converter.

Considering the different failure scenarios, the machine protection strategy for circulating beams is derived:

- Definition of the aperture by the collimator jaws, with beam loss monitors close to the collimators [8].
- Additional ~3600 beam loss monitors distributed at possible loss locations around the ring [9].
- Early detection of failures within the equipment that acts on the beams, to generate a beam dump request before the beam is affected.
- Active monitoring of the beam with fast and reliable beam instrumentation, to detect abnormal beam conditions and to generate a beam dump request within a very short time, down to one machine turn (89 μs).

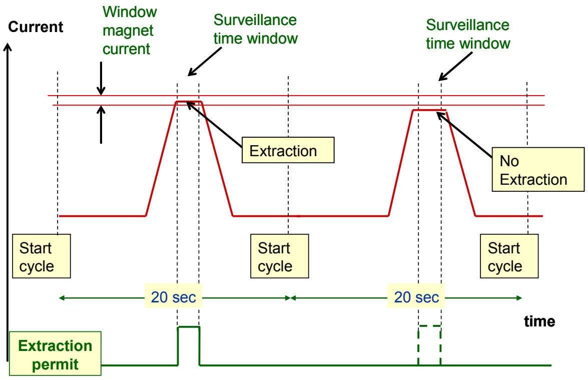

Figure 4: Interlocking of magnet current during cycle

- Reliable transmission of a beam dump request to the beam dumping system by a distributed interlock system. For all interlocks, an active signal is required for operation, and the absence of the signal is considered as beam dump request and injection inhibit [10].
- Reliable operation of the beam dumping system upon reception of a dump request or internal fault detection, to safely extract the beams onto the external dump blocks.
- Passive protection by beam absorbers and collimators for specific failure cases.
- Redundancy in the protection system such that failures may be detected by more than just a single system.
- Very high safety and reliability standards that are applied in the design of the core protection systems, in general done in hardware.

From this strategy the core systems for machine protection are identified:

- The LHC beam interlock system has a specific role since it is connected to all systems for protection (see Fig.5).
- Beam Dumping System: operation with beam is only possible when the beam dumping system is ready and provides a beam permit signal.
- The beam loss monitor system with monitors close to superconducting magnets for quench and damage protection and at all aperture limitations should detect any kind of significant beam losses.
- The collimation system defines the aperture to ensure that particles are lost first on collimators and protects

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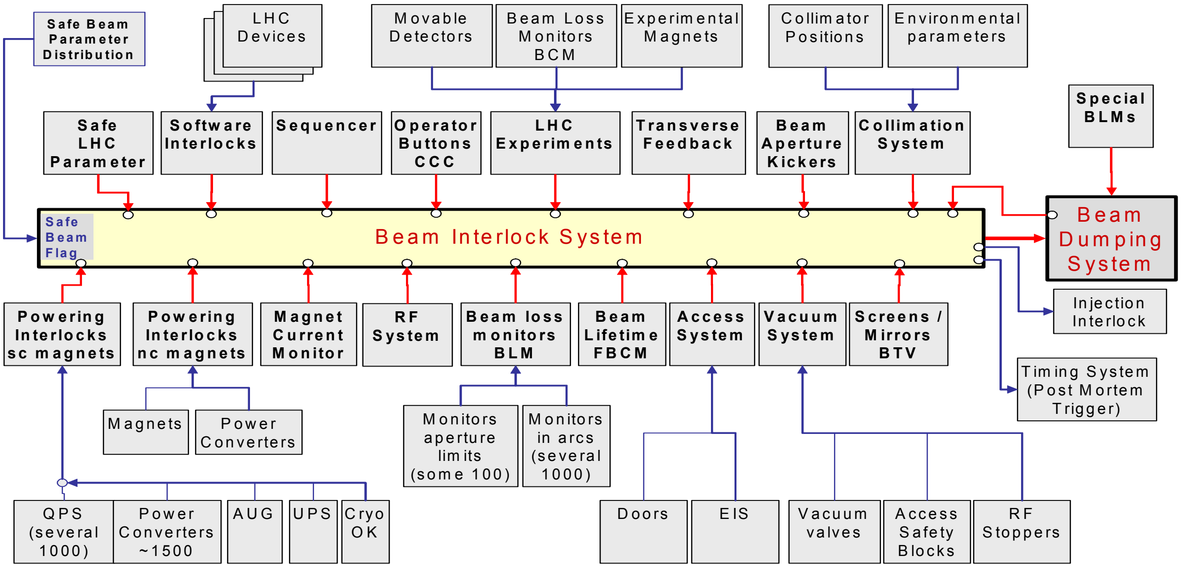

Figure 5: Overview of the LHC Beam Interlock System and its links to other systems

against quenches of superconducting magnets. The collimator jaws (~100) must be correctly positioned.

- The magnet powering system must be fully operational. No fault or quench should be reported by the quench detection system and the Fast Magnet current Change Monitors.

There are several other systems that have links to the beam interlock system:

- Monitors for the beam position, to detect low lifetime, to detect particles in the abort gap, etc.
- The access system must permit beam operation.
- Nothing should block the aperture (vacuum valves, beam screens, experimental detectors, safety stoppers, etc. must be all OUT).
- Several interlocks from operations can inhibit the beam, such as switches in the control room, the software interlock system and software for process control (sequencer).

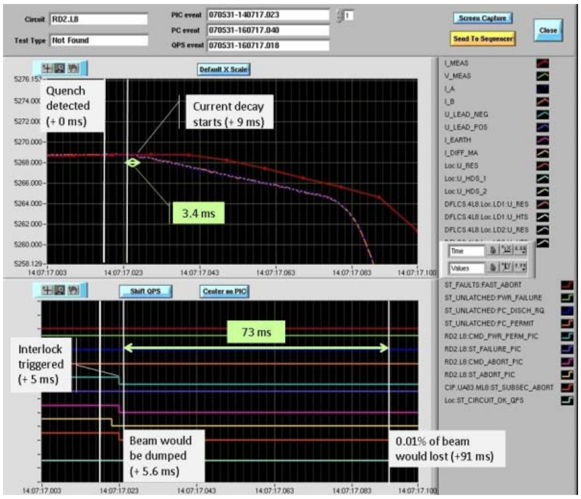
Circuit RD2.L8
Test Type Not Found
PIC event 070531-140717.023
PC event 070531-160717.040
QPS event 070531-160717.018

Figure 6: Signals from different systems after a quench of the D2 dipole magnet: magnet current and interlock signals

- Other inputs include the RF system, transverse feedback, beam aperture kickers and inputs from LHC experiments.

In case of a beam dump request, the beam interlock system provides a trigger via the timing system to many LHC systems for transient recording of the event.

COMMISSIONING STARTED

An interlock system for normal conducting magnets to prevent magnets from overheating has been used for LEIR (Low Energy Ion Ring, an ion accumulator for LHC ion operation) for two years. Recently, a similar system for the LHC was commissioned.

The commissioning of the LHC superconducting magnet powering system [11] started during spring 2007. Powering of superconducting magnets requires operational magnet protection (quench detection and energy extraction) and the powering interlock systems.

When a quench is detected, the signal is sent to the Powering Interlock Controller in the vicinity. This controller receives signals for a large number of electrical circuits, and triggers a beam dump via the Beam Interlock System in case of a failure in one of the circuits. The response after the quench detection is deterministic, since all transactions are done in hardware. The delay from the reception of the quench signal by the Powering Interlock Controller to the completion of a beam dump is about 0.4 ms. During LHC hardware commissioning of the first LHC sector, the quench of one separation dipole magnet (D2) was recorded (see Fig.6). In this case the beam would be extracted before the current in the magnet started to change.

MACHINE PROTECTION AND CONTROLS

Efficient and reliable machine protection relies on the correct operation of all systems involved in protection as

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well as on well-defined operational procedures. The performance of the critical systems must be continuously monitored. In case of a beam dump the event must be analysed to verify if all the systems were operating correctly. The controls system plays an important role, in particular for the recording of data. Software interlocks complement the hardware based protection systems. The procedures during commissioning are executed with software ("sequencer").

Post Mortem Recording and Logging: Data needs to be logged, transient data recording is required after an event such as a beam dump, and software to analyse the data from various systems is required. The data must be accurately time stamped to allow correlating data from different systems. Our initial experience during the powering tests has been positive. Data from power converters, powering interlocks, quench protection and cryogenics are continuously recorded, and in case of quenches or other transient events the required signals were always captured. This allowed analysing various events, such as the quench shown in Fig.6.

The Software Interlock System (SIS) provides additional protection for complex but also less critical conditions, on top of the hardwired interlock systems.

One example is the surveillance of magnet currents at injection and during collisions to prevent failures such as the building up of local bumps that could drive the beam into equipment and would reduce the available aperture. Together with another failure, such as an asynchronous beam dump, this could lead to equipment damage.

The reaction time of the SIS is at the level of a few seconds and it relies on the technical network, databases, etc., clearly not as safe as hardwired systems.

The SIS had been developed with the LHC operation in mind, with the first application for the SPS replacing the outdated system. The new system turned out to be very reliable and easy to use. It is not decided whether the system will be active in the LHC from the beginning since its reliability needs to be checked, to avoid too many false beam aborts. Initially it may be limited to only sending alarms.

Sequencer: The procedures for commissioning of the powering system have been defined in detail. They can be executed by an operator or by a program (the "sequencer") [12]. The sequencer is fully operational and is being used to perform the interlock and powering tests during LHC hardware commissioning. It will be extended to run commissioning and operational procedures during beam operation.

CONCLUSIONS

It is important to understand that there is not one single system for LHC machine protection; safe operation relies on several core systems, such as beam interlocks, beam dumping system, beam loss monitors, collimators and beam absorbers. Machine protection for LHC starts at the SPS, since the beams extracted from the SPS towards LHC have already a substantial damage potential. The different Beam Interlock Systems play a central role since they provides the links between different protection systems in the LHC and the SPS. In addition there are links with other systems required for operation.

Although beam operation is still some time in the future, commissioning of some systems has started. During the commissioning of the LHC powering system, the correct functioning of the magnet protection and powering interlock systems is validated. During the SPS extraction tests and in particular during CNGS operation, the Beam Interlock System and the Fast Magnet Current change Monitors for SPS extraction zone and transfer lines were commissioned. Since 2007 the SPS ring operates with a LHC type Beam Interlock System. Before starting-up with beam, most input channels to the Beam Interlock System will be commissioned during "hardware commissioning" and "cold checkout".

Other systems became operational during 2007: the Software Interlock System, the Sequencer and the tools for transient data recording and analysis.

The early commissioning of core systems allows validating hardware and software design choices and gaining experience with commissioning and operation of systems identical or similar to those to be used in LHC.

To guarantee 'Safe' LHC operation, the commissioning procedures for the different parts of the machine protection systems are being prepared, taking advantage from a similar exercise performed for the Hardware Commissioning.

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