INITIAL EXPERIENCE WITH THE MACHINE PROTECTION SYSTEM FOR LHC

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ABSTRACT

For nominal beam parameters at 7 TeV/c each proton beam with a stored energy of 362 MJ threatens to damage accelerator equipment in case of uncontrolled beam loss. These parameters will only be reached after some years of operation, however, a small fraction of this energy is already sufficient to damage accelerator equipment or experiments. The correct functioning of the machine protection systems is vital during the different operational phases already for initial operation [1]. When operating the complex magnet system, with and without beam, safe operation relies on the protection and interlock systems for the superconducting circuits. For safe injection and transfer of the beams from SPS to LHC, transfer line parameters are monitored, beam absorbers must be in the correct position and the LHC must be ready to accept beam. At the end of a fill and in case of failures beams must be properly extracted onto the dump blocks, for some types of failure within less than few hundred microseconds. Safe operation requires many systems: beam dumping system, beam interlocks, beam instrumentation, equipment monitoring, collimators and absorbers, etc. We describe the commissioning of the LHC machine protection system and the experience during initial operation.

INTRODUCTION

For the 2010/2011 run, the beam momentum will be limited to 3.5 TeV/c. To go to 7.0 TeV/c requires a consolidation of the splices between main dipole and quadrupole magnets. To achieve an integrated luminosity of 1 fb^{-1} requires beams with stored energy of about 30 MJ for 2011, a factor of more than 10 compared to SPS and TEVATRON. It is planned to reach these values gradually, after demonstrating that the machine protection systems are fully understood and performing as expected:

- Before starting beam operation, the interlocks from all system were checked.
- Commissioning started with low intensity beams (no risk of damage).
- Commissioning of the beam dump system at various energies between 450 GeV and 3.5 TeV.
- Commissioning of the beam cleaning system at different energies, and for different optics.
- Specific Machine Protection tests with beam.
- Analyse operation, for all beam dumps, and for beam losses not leading to a beam dump.

COMMISSIONING INTERLOCKS

Several systems ensure early detection of equipment failures and trigger beam dump requests before the beam is affected. The beam interlock system receives these signals (see Fig. 1) and ensures a reliable transmission of the requests to the beam dumping systems. It also prevents that the beam is extracted from SPS and injected into LHC in case of non appropriate conditions.

Failures in the magnet powering system are detected by quench detectors (in case of a quench), by the power converters in case of internal failures of the converter or in the water cooling. The powering interlock system receives these signals and stops beam operation, also in case of a failure in the cryogenics and other service systems. The most critical normal conducting magnets are monitored by **F**ast **M**agnet **C**urrent change **M**onitors (FMCM) [2]. The entire interlock logic including the links with all systems was commissioned before beam operation and fully operational for the first beam [3].

SETUP BEAM FLAG AND MASKING OF INTERLOCKS

Beam below an intensity of about 10^{12} protons is unlikely to cause damage at 450 GeV/c. This limit decreases during acceleration with increasing energy and decreasing beam size. At 3.5 TeV/c it is about $3.14\cdot10^{10}$.

Initial commissioning and most machine protection tests are performed with beam intensity below these values. During this phase, interlocks can be masked, greatly simplifying initial commissioning. In order not to compromise protection, the so-called "setup beam flag" is derived from energy (derived from the dipole magnet currents) and beam intensity. If this flag is TRUE, masking is possible. When the flag toggles to FALSE, for example while ramping the energy, all masks are automatically removed.

MACHINE PROTECTION AND LHC CYCLE

Transfer and Injection: The beam is transferred from SPS and injected into LHC at 450 GeV/c. A beam intensity of 10^{11} protons during transfer is still below damage limit, but already far above the intensity than can quench magnets. The movable LHC injection protection devices in the transfer lines and downstream of the injection kicker in the LHC were commissioned with low-intensity beam, using beam-based alignment measurements that determine beam centre and size [4]. The system was set up with beam to its nominal settings

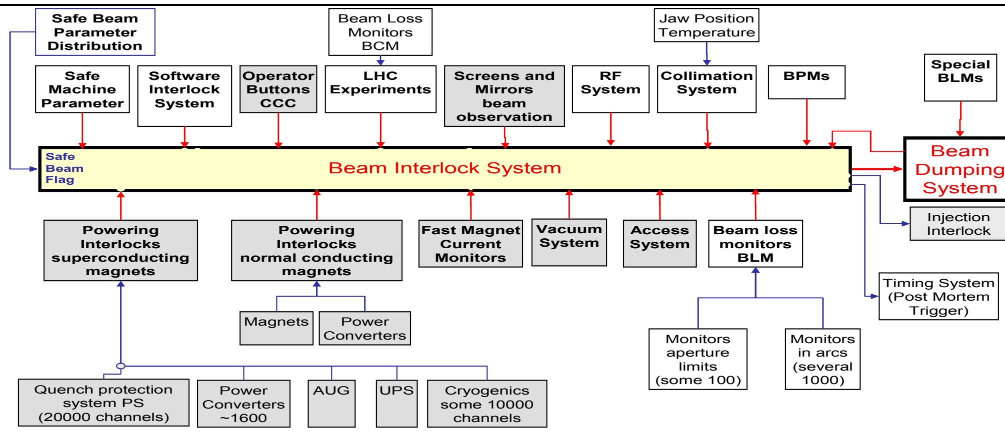

Figure 1: Beam interlock system with connected systems. All systems shown in gray and the related interlock logics were fully commissioned before beam operation.

determined by measuring the transmission and the transverse distribution in LHC as a function of oscillation amplitude.

Extraction into beam dump blocks: In case of failure and at the end of a fill, the beam must always be extracted and transferred into the beam dump blocks. The extraction kickers must deflect the beam with the correct angle synchronized with the revolution clock.

Stored beam in LHC: Filling the LHC takes some minutes. During the ramp, the energy stored in the beam increases by a factor of 8 and the beam size decreases. At top energy of 3.5 TeV/c the beams collide for many hours for physics operation. Any failure generating unacceptable beam loss is detected and the beams are extracted. Most failures are detected before the beam is affected. Some failures lead to movements of the orbit or beam size growth and to particle losses within some ms to many seconds. This is detected by beam loss monitors [5] or by beam position monitors.

BEAM DUMPING SYSTEM

Beam dumps were triggered at different energies, to demonstrate that bunches are correctly extracted via the 700 m long transfer line onto the beam dump block. To reduce the energy density on the dump block, the beam is "painted" by fast deflection of two families of kicker dilution magnets (see Fig. 2). A 3 μs abort gap in the beam structure for the switch-on of the extraction kicker field allows loss free extraction under normal operating conditions. A low number of asynchronous beam aborts is expected. A series of collimators are installed to capture beam deflected with a small angle. Tests were performed with de-bunched beam demonstrating that particles in the abort gap are correctly intercepted by these devices [6]. After each beam dump an automatic analysis checks kicker performance and beam losses. Operation with beam is stopped if any anomalies are detected.

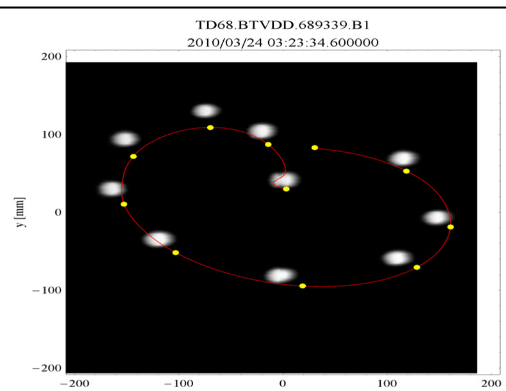

Figure 2: Beam dump of 10 low intensity bunches, recorded with a screen in front of the dump block, compared with their theoretical position.

COLLIMATION SYSTEM

The LHC aperture is defined by collimators to limit beam losses to (warm) collimator regions. Collimators for momentum and betatron cleaning are installed in two dedicated cleaning insertions, and in the experimental insertions to shadow the quadrupole triplet magnets. The cleaning efficiency depends on the precision of the jaw centring on the beam, the accuracy of the gap size and the jaw parallelism with respect to the beam. The collimators are aligned during the different operational phases (injection, top energy, etc.) [7].

The system performance is excellent and there was no quench induced by circulating beam. The efficiency is measured by driving the beam on a resonance (see Fig. 3), losing particles in a few seconds. The beam loss monitors show that losses are concentrated around the collimation regions. Losses in the arc are negligible, with the red lines showing the dump threshold. In a few cases with failures not detected at the hardware level (for example for trips of the orbit dipole correctors in the arcs), the collimators were the first elements to intercept the beam.

SOFTWARE SYSTEMS

Logging and Post Mortem: Data from most systems are continuously logged with a frequency of about 1 Hz. After every beam dump, transient data from many systems is recorded (e.g. beam losses, beam positions, beam and magnet currents, …). An automatic analysis after each dump shows what caused the beam dump, and checks if the protection system reacted correctly [8].

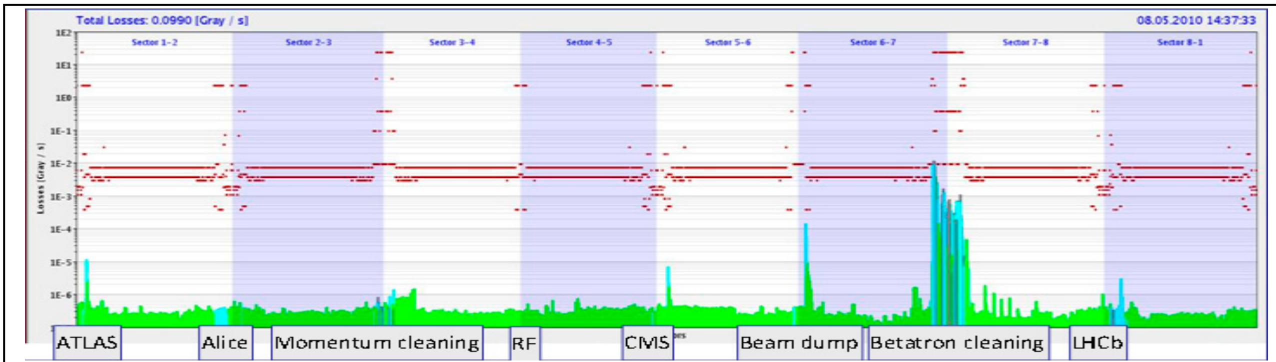

Figure 3: Beam loss map when the tunes are placed on the 1/3 order resonances, to verify the efficiency of the cleaning system. Losses are limited to the betatron cleaning insertions, and to the insertion with the beam dump.

Software Interlock System (SIS): It provides additional protection for complex but also less critical conditions. One example is the surveillance of magnet currents, another example the surveillance of the closed orbit. The response time is about one second.

MACHINE PROTECTION TESTS AND OPERATIONAL EXPERIENCE

A number of specific beam tests were performed to demonstrate effectiveness and redundancy of the machine protection systems. An example is a trip of a power converter for normal conducting magnets close to the experiments, one of the most critical failures leading to fast beam loss. The FMCM detect small current changes within less than one ms. With low intensity beam, this monitor was disabled and a trip of the power converter was triggered. As expected, the beam position changed and beam loss monitors close to collimators detected the loss and triggered a beam dump. The same test was repeated with the FMCM enabled, and the beam was dumped before any effect on the beam position was visible. During several occasions the FMCM detected glitches on the electrical network and triggered a beam dump before the beams were affected.

We distinguish between programmed beam dumps, e.g. at the end of a physics fill, and beam dumps after the detection of a failure. Table 1 shows the reasons for beam dumps, for those dumps after the start of the energy ramp.

Most beam dumps were triggered from monitoring hardware systems. "False" beam dumps are caused by false triggers in the protection systems when there is no real need to dump the beam, contributing to about 20% of all beam dumps. Seven beam dumps were triggered by beam instruments, two by beam loss monitors (particles losses due to wrong value of tune and coupling, particle losses when scraping) and five by beam position monitors when the orbit exceeded the threshold. The reason for each beam dump is understood.

CONCLUSIONS

The stored energy in the LHC beams is increased in steps, with operation for physics in between. This allows validating the machine protection functionality during operational conditions, to verify that the machine protection reacts correctly to different kind of failures and to obtain operational experience. The maximum energy stored in one beam is still limited to less than 100 kJ, and it is intended to increase this value by a factor of 10 during the coming months, and another factor of at least 10 until end of 2010.

ACKNOWLEDGEMENTS

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Table 1: Beam dumps during energy ramp and operation at 3.5 TeV/c

Reason for beam dump	Dumps	False dumps
Magnet Protection System	6	6
Cryogenics	6	
Feedback / Magnet Protection	6	
Experiments	4	
Beam dynamics	5	
Electrical Network	2	
Beam Loss Monitor System	2	2
Beam Position Monitors	5	
Beam Dumping System Internal Failure		6
Operational error	2	
Dump at the end of the fill	2	
Machine Protection Tests	12	
Interlock systems	0	0