# LHC Commitioning

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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..


## 1 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.

Main topics presented during the LHC commitioning are for the purpose of the summary grouped into five categories:

* Energy stored in the LHC magnets
* Protecting Against Damage
* Energy stored in the LHC beams
* Protecting Against Beam Damage
* Summary

## 2 ENERGY STRORED IN THE LHC MAGNETS

Both, the stored magnetic energy and the energy stored in the beams are unprecedented. Moreover, both systems are coupled. Obviously, faults in the magnet system will in general often result in a beam loss, which in turn may induce quenches. The machine protection system has, however, be made to accept that at times the magnets will be powered, without beam in the machine. The opposite case is not possible.

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 [6].

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).

Each beam stores energy of up to 0.35 GJ, equivalent to the energy for warming up and melting 515 kg of copper. A sophisticated collimating system protects the magnets from beam losses.

If the operation of the machine becomes unsafe and beam loss has already been observed by the beam loss monitors, or is imminent due to equipment failure, the beams have to be dumped as soon as possible, in order to prevent radiation damage, quenches, and downtime. However, due to the size of the LHC at least 110µs are required on average to request a beam dump.

## 3 ARCHITECTURE OF THE MACHINE PROTECTION SYSTEM

### *3.1 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 minimised.
● 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.

### *3.2 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 described elsewhere [7] records data from various systems to understand the cause of a fault leading to a beam dump or power abort.

### *3.3 Architecture of the Power Interlock*

The eight sectors in the LHC consist (Version 6.2) of 44 continuous, largely independent cryostats [8], 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 feedthroughs, the current feedthroughs, 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. An example of the architecture between IP1 and IP8 is given in Fig.1

LHC contains 36 short cryostats requiring one Power Permit Controller (PPC) each, preferentially located close to the power converters. Warm magnets on either side of an interaction point (IP) are treated as if they form an additional "continuous cryostat".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 MQ magnets are in the even points. The MB 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 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.

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

### *3.5 The Machine Protection System*

The machine protection system consist of:

● 16 Beam Interlock Controller BIC,

● 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.

## 3 QUENTCH PROTECTION SYSTEM

The protection system for superconducting elements in the LHC [1] 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). Fig. 4 shows the time sequence:
• 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.

## 4 ENERGY STORED IN LHC BEAM

For the LHC both the particle momentum and the beam intensity increases to unprecedented values (see Fig 4) The high stored beam energy must be safely discharged at the end of the fill or after a failure (table1)

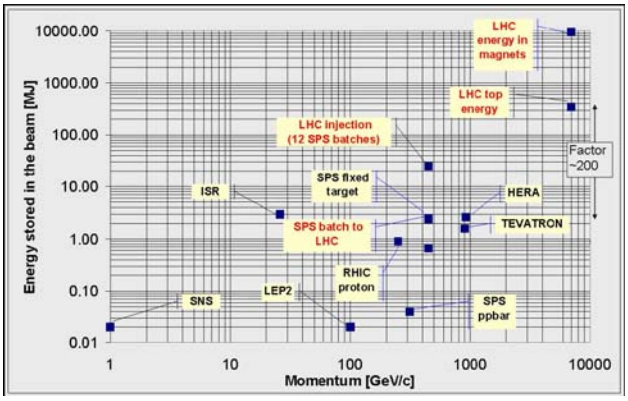


Fig. 1: Energy stored in the beam for LHC and other accelerators and energy stored in the LHC magnets

The proton momentum is a factor of seven above acceleartors such as SPS,Tevatron and Hera, whereas the energy stored in the beams is more then a factor of 100 higher. The complexity of the accelerator is unprecedented and repair of damaged equipment would take long, for example the exchange of a superconducting magnet takes about 30 days. The first priority of the protection system is to prevent equipment damage in the LHC ring and during the beam transfer from the pre-accelerato SPS to the LHC

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 beam intensity that could damage equipment depends on the impact parametrs and on the eqipments hit by the beam. To evaluate the beam intensity to reach the damage level, a dedicated experiment was performed at the SPS [4] 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 $10^{-8}$-$10^{-7}$ 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 [5].

### *4.1 Failure and beam dump*

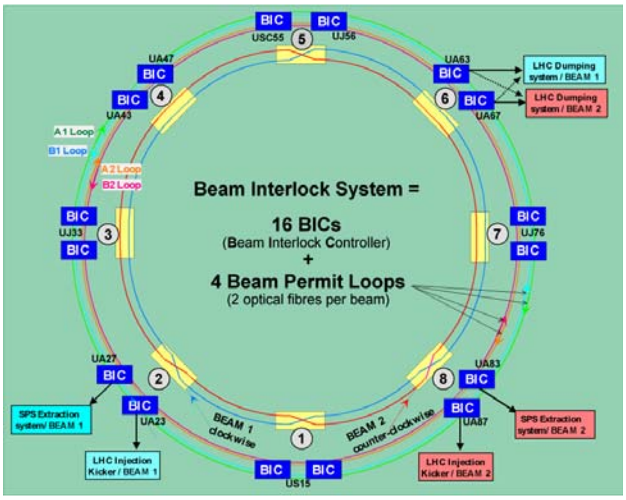
If particle losses during the operation with stored beam become unacceptable, or if there is an equipment failure, the beams must be extracted into a specially designed target (beam dump block) thus safely dissipating
the energy. This requires the detection of an unsafe situation, either with beam instruments, or by hardware monitoring. A beam dump request is issued to one of the 16 beam interlock controllers installed around the LHC. The beam interlock controller transmit this request to the Beam Dumping System (Fig. 2).
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 unsynchronised 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 (see Fig. 3), at injection and with squeezed beams to less than 10 σ (σ is the rms beam size). Since the

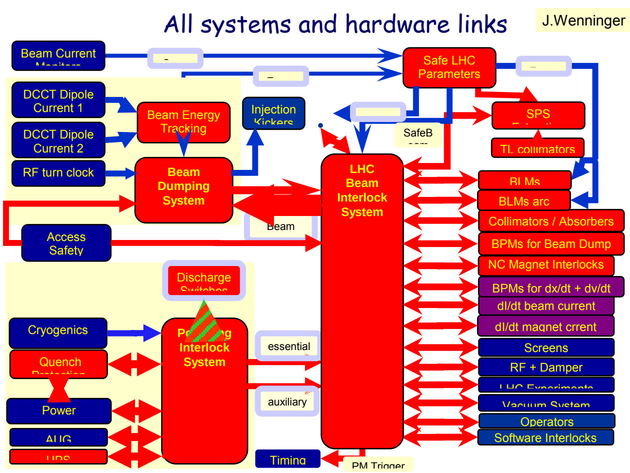
position of the TCDQ is very critical it must be interlocked.
Some 40 bunches would hit a fixed absorber in front of the septum magnet and the bulk of the beam travels to the beam dump block.

### *4.2 Architecture of the Beam Interlock*

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

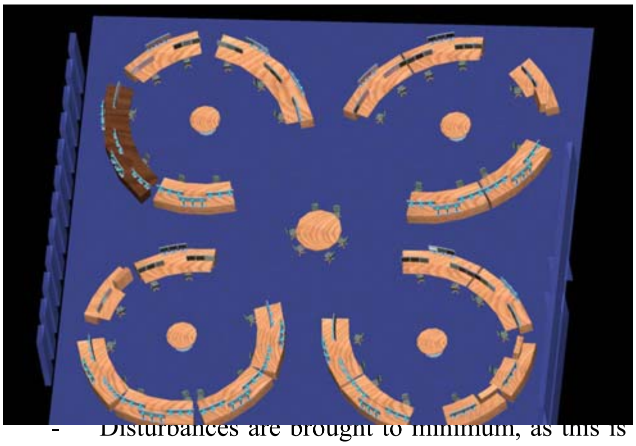
(for example, the generation and distribution of Safe LHC Parameters).
Prototyping and first experience gained at SPS and elsewhere has been very valuable, for collimators, beam interlocks, beam loss monitors, orbit feedback, etc.
In general, there is a large redundancy for the detection of failures, 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 – work is ongoing [18].
Safe operation of the LHC starts at the SPS, via extraction into TT40/TI8 and TI2, via the transfer lines, via LHC injection etc.
Safe operation also relies on operational procedures for commissioning and operational. A “software interlock system” is required, managing critical settings, sequencing operational procedures and monitoring critical
parameters.
Safe operation does requires 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




## 5 CONCLUTIONS

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



- Disturbances are brought to minimum, as this is very important for all users, considering all potential sources like (personal protection control, machine development…)
- A bigger table in the middle is a symbol to increment the common spirit and will encourages the people working in this room to really feel like a team.

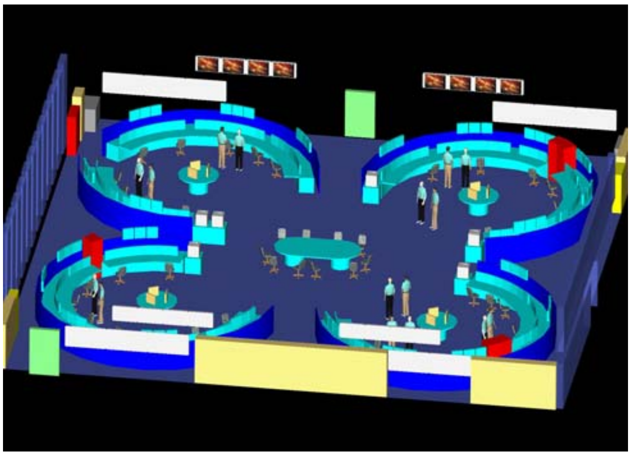


Fig 3

***Temperature***

Along with visual environment thermal factor are subject to the greatest number of operator complains in control rooms. The air-conditioning system for the control room should be designed to cope with the intake of cooler night air and the consequential internal air temperature drops. The ventilation should ensure that the air is distributed effectively within the control room and no stagnant area or large temperature gradients occur. Our system will ensure a mean air velocity of less then 0.15 meter/sec which is a very low value, the range of temperature will be 20-24 degree, and the relative humidity will vary between 40/70%.

***Budget***

A figure of 8.1 MCHF, including 10% contingency, has been allocated for the whole project, divided into :

- 4.9 MCHF civil engineering, ventilation, sanitary, water and electricity.
- 3.2 MCHF for the user's, including furniture, computer systems, ergonomics.

***Timeline***

In order to restart and deliver beam for physics Fixed target and Neutrino Grand Sasso the following deadline had to be met:

- 30/4/2004 the civil engineering committee issue a detailed planning for the work to be performed and confirms the building costs.

- 30/6/2004 the CCC-WG issues the specification for the equipment and start the call for tenders.
- 1/1/2005 start of civil engineering work, SPS dismantled
- 1/11/2005 installation and commissioning CCC.
- 1/2/2006 start up accelerator complex from the CCC.

## 4 CONCLUSIONS

The CERN Control Center will act as master piece, were the physics of CERN will take place. Is not only a technical challenge but also a human interaction were the sense of team will have a vital role to operate LHC and all others accelerators from the same place.

## REFERENCES

[1] Functional specification
Layout and infrastructures of the CERN Control Center
(R.Bailey,M.Batz,B.Frammery,D.Manglunky,R.Saban,L.Serio)

[2] CCD Report on Lighting & Acoustic specification

[3] The CCC Project D.Manlunky at Chamonix workshop 2004