# CHAPTER 15

# MACHINE INTERLOCK SYSTEMS

## 15.1 INTRODUCTION

The energy stored in the LHC superconducting magnets and in the circulating beams is unprecedented. For nominal beam parameters at 7 TeV, each proton beam will have an energy of about 340 MJ. The energy stored in the magnet system amounts to about 10 GJ. An uncontrolled release of energy could lead to serious damage of equipment. Major damage of equipment inside the cryostats will result in long repair times, as the equipment is delicate and difficult to access.

When a failure occurs while powering the magnets, for example in case of a quench or a power converter fault, the energy stored in the magnets must be extracted. For a failure during beam operation, for example when beam losses become unacceptable or after failure of equipment, the beams must be dumped as fast as possible.

The main objective for the machine protection system is to protect the machine in case of failure; the necessary steps should be taken to dump the beam and to dissipate the stored energy in the magnets in a safe way [1]. Furthermore the system should:

- Protect the beam: The system should not generate beam dumps if this is not strictly necessary. Faulty trigger signals that lead to a beam dump should be avoided.
- Provide the evidence: In case of beam dump or failure in the powering systems, correct diagnostic messages should get to the operator. In case of multiple alarms when one initial failure causes subsequent failures, the system should support identifying the initial failure.
- Assist the operation of the machine: The diagnostics for failures should be easy to understand. The status of the system must be presented clearly to the operator in the control room and should be transparent.

## 15.2 MACHINE PROTECTION AND INTERLOCK SYSTEMS

Several systems are required in order to protect the complex equipment of the LHC accelerator. The machine interlocks are part of the protection and include two systems, the powering interlock system and the beam interlock system (Fig.15.1 and [1]).

Protection during magnet powering prevents damage to the elements in the electrical circuits, such as magnets, normal conducting and superconducting cables, current leads and power converters (see Chap. 9). Protection requires dedicated equipment such as the quench protection system, energy extraction system and the powering interlock system. It had also a strong impact on the design of the power converters.

The powering interlock system permits powering of magnets if several conditions are met. In the case of a failure, the powering interlock system must ensure a safe stop of powering (“power abort”) and a discharge of the magnet energy and request a beam dump if necessary.

Magnets can be powered independently of beam operation, for example during commissioning and for tests. The full functionality of the protection systems is required for the start of commissioning the magnet powering system.

The beam interlock system permits beam operation. Firstly, it permits injection into the LHC when all systems are ready for beam. Secondly, with circulating beam, the beam interlock system transmits any beam dump request from other systems to the beam dumping system.

The systems that are essential for protection during beam operation are the beam dumping system, collimators and beam dilutors and beam monitors and all of these have an interface to the beam interlock system. Other systems with an interface to the beam interlocks are the powering interlocks, RF, injection kickers, vacuum system, access safety system, controls system and the LHC experiments.

For the machine interlocks several principles have been adopted:

- To prevent damage of equipment, fail safe hardwired links are used. No interlock signals are transmitted via the control system.

- To understand the current status of the LHC, the general status of the systems connected to the machine interlocks be will displayed.
- To understand the events leading to a power or beam abort, recording of parameters of the interlock systems will be made available for later analysis (Post Mortem). Time stamping of the recording is synchronised across all systems in the LHC by using the same clock [2].

The access safety system and the access control system are separate from the machine interlocks and discussed elsewhere [3, 4].

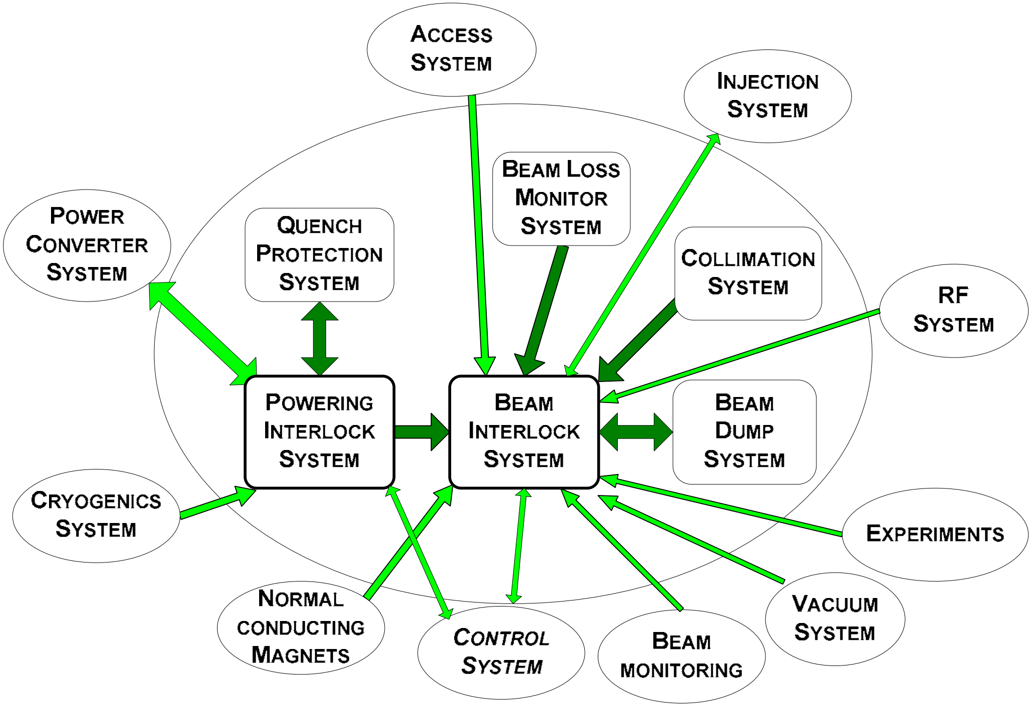


Figure 15.1: Relationship between the powering interlock system, the beam interlock system and other main LHC systems. The systems dedicated to protection are within the grey zone.

## 15.3 THE POWERING INTERLOCK SYSTEM

In the LHC, superconducting as well as normal conducting magnets are used. The requirements for protection from failures are somewhat different. Therefore the powering interlock system is composed of two sub-systems: one is in charge of the protection of the electrical circuit with superconducting magnets, and the other is in charge of the protection of the circuits with normal conducting magnets.

### 15.3.1 Basic Functionality and Response Time of the Interlock System for Superconducting Magnets

The powering interlock system permits powering of an electrical circuit with superconducting magnets when the required conditions are met.

- The superconducting magnets must be at operating temperature.
- The quench protection system must be ready for powering.
- The electrical supplies for the protection systems, backed up by uninterruptible power supplies (UPS), must be fully operational.

In the case of a failure in the electrical circuits, the powering interlock system, together with the quench protection and power converter systems, ensures that powering is aborted correctly:

- The energy stored in the magnets is safely discharged for circuits with large stored energy.
- The power converters are stopped, by removing the permit and issuing a fast abort for the power converters.

- When operating with beam, the powering interlock system informs the beam interlock system of any failures in the powering system. The beam interlock system decides if a beam dump is required.

Numerous failure scenarios were considered during the design phase. The most likely failure is a quench of a magnet. Other failures are quenches of bus-bars, quenches of high temperature superconductor (HTS) current leads, and failures in the powering system for example, a fault in a power converter or in the water cooling of a normal conducting power transmission cable.

As discussed in Chap. 9, in the case of a quench in one of the superconducting magnets with large stored energy, the quenching magnet can absorb its own energy. The energy of the other magnets in the electrical circuit is discharged as fast as possible by switching a resistor into the circuit. The time constant for the current decay is between about 0.1 s for some of the corrector magnet circuits and 100 s for the main dipole magnet circuits. For the electrical circuits with superconducting magnets the response time required to start discharging the energy and stopping the power converters is some tens of milliseconds [5]. In the case of a power converter failure after a water cooling fault, for example, the requirements are similar.

### 15.3.2 Powering Subsectors

The LHC superconducting magnets are powered separately in each of the eight sectors. When operating at 7 TeV, the energy in each sector of the LHC amounts to about 1.2 GJ: sufficient to warm up and melt 1900 kg of copper.

In each sector there are several cryostats, in total more than 40. To simplify installation, commissioning and operation, the electrical circuits with superconducting magnets are grouped into 28 powering subsectors (see Tab. 1Table 1 for the inventory of powering subsectors) [6]. One power converter is always powers magnets that are installed in only one cryostat. There are no electrical circuits powering magnets in several cryostats.

The powering subsectors are defined according to the layout of the cryostats:

- Arc cryostats: Eight long cryostats span the major part of the sectors and are electrically fed from both sides. The MB, MQD and MQF magnets are powered from converters installed at even points, as are the energy extraction systems for the MQF and MQD magnets. For the MB electrical circuit there is one energy extraction system at each end of the arc cryostat. The arc powering subsectors need two powering interlock controllers, one at each side of the arc. In IR3 and IR7 there is only one additional cryostat housing the Q6 magnet left and right of the insertion. Therefore the corresponding electrical circuits in these insertions are interlocked by the controller for the adjacent arc powering subsectors.
- Triplet cryostat: At each interaction point with an experiment, several quadrupole magnets and the D1 magnet (for IR2 and IR8) are installed in a cryostat at each side of the interaction point. Each triplet cryostat is a powering subsector managed by one powering interlock controller.
- Cryostats in matching sections: In some of the long straight sections several other cryostats are installed, with magnets for matching and for separating the beams. These cryostats are combined to one powering subsector with one powering interlock controller.

In total, there are 28 powering subsectors and 36 powering interlock controllers for the superconducting magnets. The powering interlock system must allow for independent operation of each powering subsector.

### 15.3.3 Powering Interlock Controllers for Superconducting Magnets

A powering interlock controller for superconducting magnets is in charge of the interlocks of one powering subsector. It exchanges several hardware signals with the power converters and the quench protection system for each electrical circuit [7]. Each controller also has an interface to the UPS [8] and to the general emergency stop [9]. Other signals, transmitted via the control system, are only used to evaluate if powering of the electrical circuits in the subsector can be permitted:

Table 15.1: List of the Powering Subsectors and Powering Interlock Controllers (for superconducting magnets)

| | **Powering Subsectors** | | **Name of DFB** | **PIC** | | |
|---|---|---|---|---|---|---|
| | **Number** | **Purpose** | | **Name** | **Location** | ***No.Circuits*** |
| Sector 1-2 | 1 | Inner triplet in R1 | DFBXB.3R1 | CIPCX.R1 | UJ16 | *16* |
| | 2 | Matching section in R1 | DFBLB.RR17 | CIPCL.R1 | RR17 | *17* |
| | 3 | Arc 1-2 cryostat (right side) | DFBAB.7R1 | CIPCA.R1 | RR17 | *30+48 (+94)*[1] |
| | | Arc 1-2 cryostat (left side) | DFBAC.7L2 + DFBAC.6L2 | CIPCA.L2 | UA23 | |
| | 4 | Matching sections in L2 | DFBMC.5L2 + DFBMA.4L2 | CIPCM.L2 | UA23 | *17* |
| | 5 | Inner triplet in L2 | DFBXC.3L2 | CIPCX.L2 | UA23 | *16* |
| Sector 2-3 | 6 | Inner triplet in R2 | DFBXD.3R2 | CIPCX.R2 | UA27 | *16* |
| | 7 | Matching sections in R2 | DFBMB.4R2 + DFBMC.5R2 | CIPCM.R2 | UA27 | *17* |
| | 8 | Arc 2-3 cryostat (right side) | DFBAD.6R2 + DFBAD.7R2 | CIPCA.R2 | UA27 | *48+34 (+94)*[1] |
| | | Arc 2-3 cryostat (left side) + Matching section | DFBAE.7L3 + DFBMD.6L3 | CIPCA.L3 | UJ33 | |
| Sect. 3-4 | 9 | Arc 3-4 cryostat (right side) + Matching section | DFBAF.7R3 + DFBMD.6R3 + DFBLC.UJ33 | CIPCA.R3 | UJ33 | *34+44 (+94)*[1] |
| | | Arc 3-4 cryostat (left side) | DFBAG.7L4 | CIPCA.L4 | UA43 | |
| | 10 | Matching sections in L4 | DFBMG.6L4 + DFBMF.5L4 + DFBME.3L4 | CIPCM.L4 | UA43 | *11* |
| Sector 4-5 | 11 | Matching sections in R4 | DFBMK.3R4 + DFBML.5R4 + DFBMG.6R4 | CIPCM.R4 | UA47 | *11* |
| | 12 | Arc 4-5 cryostat (right side) | DFBAH.7R4 | CIPCA.R4 | UA47 | *44+30 (+94)*[1] |
| | | Arc 4-5 cryostat (left side) | DFBAI.7L5 | CIPCA.L5 | RR53 | |
| | 13 | Matching section in L5 | DFBLD.RR53 | CIPCL.L5 | RR53 | *17* |
| | 14 | Inner triplet in L5 | DFBXE.3L5 | CIPCX.L5 | USC55 | *16* |
| Sector 5-6 | 15 | Inner triplet in R5 | DFBXF.3R5 | CIPCX.R5 | UJ56 | *16* |
| | 16 | Matching section in R5 | DFBLE.RR57 | CIPCL.R5 | RR57 | *17* |
| | 17 | Arc 5-6 cryostat (right side) | DFBAJ.7R5 | CIPCA.R5 | RR57 | *30+40 (+94)*[1] |
| | | Arc 5-6 cryostat (left side) | DFBAK.5L6 | CIPCA.L6 | UA63 | |
| | 18 | Matching sections in L6 | DFBMG.5L6 + DFBMG.4L6 | CIPCM.L6 | UA63 | *8* |
| Sect. 6-7 | 19 | Matching sections in R6 | DFBMG.4R6 + DFBMG.5R6 | CIPCM.R6 | UA67 | *8* |
| | 20 | Arc 6-7 cryostat (right side) | DFBAL.5R6 | CIPCA.R6 | UA67 | *40+34 (+94)*[1] |
| | | Arc 6-7 cryostat (L) + Matching section | DFBAM.7L7 + DFBMH.6L7 | CIPCA.L7 | RR73 | |
| Sector 7-8 | 21 | Arc 7-8 cryostat (R) +Matching section | DFBAN.7R7 + DFBMH.6R7 | CIPCA.R7 | RR73 | *34+48 (+94)*[1] |
| | | Arc 7-8 cryostat (left side) | DFBAO.6L8 + DFBAO.7L8 | CIPCA.L8 | UA83 | |
| | 22 | Matching section in L8 | DFBMA.4L8 + DFBMC.5L8 | CIPCM.L8 | UA83 | *17* |
| | 23 | Inner triplet in L8 | DFBXG.3L8 | CIPCX.L8 | UA83 | *16* |
| Sector 8-1 | 24 | Inner triplet in R8 | DFBXH.3R8 | CIPCX.R8 | UA87 | *16* |
| | 25 | Matching sections in R8 | DFBMB.4R8 + DFBMI.5R8 | CIPCM.R8 | UA87 | *17* |
| | 26 | Arc 8-1 cryostat (right side) | DFBAP.7R8 + DFBMJ.6R8 | CIPCA.R8 | UA87 | *48+30 (+94)*[1] |
| | | Arc 8-1 cryostat (left side) | DFBAA.7L1 | CIPCA.L1 | RR13 | |
| | 27 | Matching section in L1 | DFBLA.RR13 | CIPCL.L1 | RR13 | *17* |
| | 28 | Inner triplet in L1 | DFBXA.3L1 | CIPCX.L1 | UJ14 | *16* |

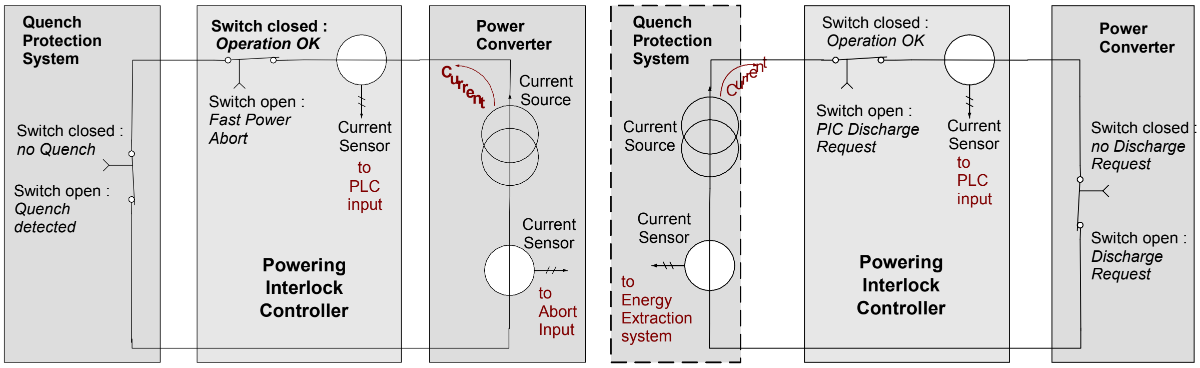
- From the cryogenics system (“Cryogenics OK”) when the operating temperature in the cryostat is reached.
- From the quench protection system (“Quench Protection Permit”) when the quench heater power supplies are charged and the energy extraction system is ready. This also requires that the system is ready to record data in case of failures (“Post Mortem Ready”).

Two types of electrical circuits are defined:

- Circuits with main magnets having large stored energy. This includes all the main dipoles and main quadrupoles in arcs and insertions. In the case of a quench of such a magnet, the quench could travel to magnets or bus bars in other circuits and therefore all circuits in the cryostat will be discharged (fast power abort of all electrical circuits in the subsector).
- Circuits that only include magnets with low stored energy. A quench of a magnet in such circuits would normally not travel to magnets in other circuits (power abort only for the circuit with the quenching magnet).

The powering interlock controller sends the “PC_PERMIT” signal to the power converter to permit powering of an electrical circuit. Absence of this signal causes a slow abort of the power converter.

Most circuits are equipped with quench detectors. In the case of a quench, the quench protection system opens a current loop (see Fig. 15.2 – Circuit Quench Loop). This informs the powering interlock controller and the power converter about the quench. The power converter performs a fast power abort.



**Current Loop for *Circuit_Quench* signal** **Current Loop for *Discharge_Request* signal**

Figure 15.2: Interfaces between powering interlock controller, power converter and quench protection system. Two current loops, the Circuit Quench Loop and the Discharge Loop are shown.

For circuits with high stored energy, the energy is discharged by the quench protection system requiring no action by the powering interlock controller. To avoid quench propagation to other magnets in the same cryostat, all circuits must be discharged. Therefore the powering interlock controller requests a fast abort of all power converters in the subsector, and removes the power permit.

Some circuits have a very long time constant for current decay and it may be necessary to discharge the energy after a failure in the water cooling of the free-wheel diode, for example. To request such discharge, the power converter opens a second current loop (see Fig. 15.2 – Discharge Loop). The quench protection system detects that the loop is open and initialises the energy discharge.

For some circuits with low stored energy, the energy discharge is done either by the power converter or by a system installed in a rack beside the power converter. For these circuits, the power converter triggers the discharge of energy after receiving a request for fast abort.

In the case of a failure detected by the power converter, the “POWERING_FAILURE” signal is sent to the powering interlock controller.

Time stamping of all these events with an accuracy of 1 ms is required, with the common LHC clock derived from the NTP (Chap. 14.5.5).

*Hardware platform*

The powering interlock system will interface with power converters for about 800 electrical circuits, with the quench protection system for 700 circuits, etc. There are about 1400 input signals and 1500 output signals in total. The response time required is ~10 ms. The controllers will be built with industrial PLC's that are well suited for such applications. The exchange of signals with the other systems will use commercial I/O modules.

Since some of the powering equipment is located in tunnel enlargements (RR's) close to the accelerator, a radiation dose in the order of 0.1 Gy/year is expected. It has been shown that the CPU in a PLC does not work correctly in such environment [10]. However, after extensive tests it has been demonstrated that some of the commercially available I/O modules are sufficiently radiation tolerant. The I/O modules are linked via PROFIBUS to the CPU, which is installed in a location better protected from radiation.

*Interface to UPS and general emergency stops*

UPS systems are installed in various underground areas to take over the supply of safety critical systems around the LHC ring in the case of mains failure. In the case of a failure of the redundant UPS system, followed by failure of the mains (for example during a thunderstorm), there will be no safe way to stop the machine as all safety systems will be without power. It is envisaged to transmit a signal to the interlock controller, which will trigger the discharge of energy in all concerned powering subsectors when the redundant UPS system fails [8].

In the case of a general emergency stop, i.e. Arrêts d'Urgence Généraux (AUG), the electrical power and other sources of energy that are likely to present a risk must be stopped. In order to meet this requirement, the magnetic energy of the MB, MQF and MQD must be discharged after a delay of some seconds [9]. For this purpose a link is proposed between the AUG system and the powering interlock controllers involved. As for the UPS link, it is envisaged to transmit a signal which will abort the powering in all the powering subsectors concerned.

*Interface to beam interlock controller*

A failure in an electrical circuit will have an impact on operation with circulating beam and the consequences will depend on the state of the accelerator (beam energy, beam intensity…). Hence, the criticality for beam operation is defined:

- Essential circuits are required for beam operation under all circumstances. In the case of a failure, the beams are dumped. All circuits with main dipole and quadrupole magnets fall into this category.
- Non-essential circuits are not necessarily required. Their use depends on machine and beam parameters. A failure should not automatically generate a beam dump. Examples of such circuits are those of the multipole correction magnets.

Each powering interlock controller will have a link to a nearby beam interlock controller to transmit two separate signals to distinguish the level of criticality. After a failure of an essential circuit, the beam will be unconditionally dumped. After a failure of a circuit that is not considered to be essential, the beam interlock controller will only request a beam dump if continuing operation with beam could endanger machine equipment.

*Interfaces to other systems*

The interlock controllers are linked to the control systems via Ethernet. In order to get precise time stamping information, the synchronisation of the controllers is performed either with Ethernet, or a special link to the LHC timing system. This needs still to be defined. A resolution of about one ms is required.

### 15.3.4 Electrical Circuits with 60 A Orbit Corrector Magnets

In the arcs of the LHC 752 orbit corrector magnets are locally powered by 60 A power converters. In the case of a magnet quench, the power converter switches off due to an over voltage in the circuit. There is no risk for the magnet [11]. There are no hardware links between the converters and the powering interlock controllers.

In order to start powering the orbit corrector magnets, the same external conditions as for other superconducting magnets in the same cryostat are required. The powering interlock control system will inform the power converters via the control system.

The failure of an orbit corrector magnet that significantly deflects the beam can lead to beam losses and to a quench. The beam loss monitor systems are being designed to measure the increased losses and request a beam dump via the interlock system. However, another mechanism of requesting a beam dump might be required. The status of all power converters will be available every 10 ms. If necessary, a beam dump request could be issued if one of the corrector magnet power converters goes to fault state. The details and the time constants that are required have not defined at the time of writing.

### 15.3.5 Programming of the Powering Interlock Controllers

The number of circuits to be managed by one powering interlock controller varies between 8 and 48. Thus the hardware of every powering interlock controller is specific, with between 20 and 160 inputs and outputs managed by the PLC.

To avoid a large number of different programs running in the PLC's, a generic program has been developed. The software will obtain the information about its layout from configuration files located in the LHC Reference Database [12].

Depending on the type of electrical circuit and the circuit parameters, such as the stored energy in the circuit and its importance for beam operation, four different procedures for handling a failure have been defined. For each circuit, the configuration data defines the procedures to be used. Depending on the state of the signals received from the power converter and quench protection system, the powering interlock controller will initiate or remove the signals to permit powering in the circuit, or safely abort powering and discharge the energy.

In the configuration file, two additional parameters for each electrical circuit are included. One parameter defines if the beam will be dumped in case of circuit failure. The other parameter defines if powering abort of all circuits in the powering subsector is required in case of circuit failure.

Starting from the initial state, powering in the circuit can be permitted on operator request if no quench signal is received from the quench protection system and if all other systems are ready. During normal operation powering is permitted until either a request from the operator or a failure in the powering leads to a slow or fast power abort. As soon as one of these abort mechanisms is activated, a beam dump request will be sent to the beam interlock controller and in the case of a fault in a major circuit, the powering of the complete subsector will be aborted.

The input and output states of each circuit will be continuously monitored by the PLC. The cycle time depends on the number of electrical circuits that are managed by the PLC. In each cycle all circuits in the powering subsector are processed sequentially. The maximum response time of the system of about 10 ms will not be exceeded in any of the configurations. All state changes will be recorded in a history buffer together with a time stamp with an accuracy of about one ms.

### 15.3.6 Powering Interlock System for Normal Conducting Magnets

The interlock system is required to avoid overheating water cooled magnets and therefore several temperature probes are installed on each magnet,. If the temperature exceeds a predefined value, a relay opens and the signal is sent to the interlock controllers. The controller has the task of removing the permit for the power converter, thus stopping the converter.

Normal conducting magnets in one electrical circuit which are powered in series by one power converter can be installed at both sides of one interaction point, (for example, the D1 magnets in IR1 and IR5). The interlocks for all normal magnets in one insertion are managed by one powering interlock controller. In IR4 no such controller is required since there are only superconducting magnets.

The required response time for switching off the power converter to avoid overheating is of the order of seconds. In general, normal conducting magnets have a large resistance and a low inductance. The time decay for the current is much shorter than for superconducting magnets and is of the order of some seconds. Switching off such magnets could lead to beam loss within a very short time, for the D1 magnet only a few turns (see Sec. 15.4.1). Before the power converter is switched off, a signal is sent to the beam interlock controller that will trigger a beam dump.

Table 15.2: List of the Powering Interlock Controllers (for normal conducting magnets)

| | Controller | | | Number of | | |
|---|---|---|---|---|---|---|
| | Number | Name | Location | Converters | *Magnets* | Magnets Name |
| IR1 | 1 | CIPW.LR1 | US15 | 1 | 12 | MBXW(2x6) |
| IR2 | 2 | CIPW.LR2 | UA23 | 3 | 3 | MBXWT(x2), MBWMD |
| IR3 | 3 | CIPW.LR3 | UJ33 | 3+12 | 44 | MBW(x12), MCBW(x8), MQWA(x20), MQWB(x4) |
| IR5 | 4 | CIPW.LR5 | USC55 | 1 | 12 | MBXW(2x6) |
| IR6 | 5 | CIPW.LR6 | US65 | 2 | 30 | MSDA(2x5), MSDB(2x5), MSDC(2x5), |
| IR7 | 6 | CIPW.LR7 | UJ76 | 3+12 | 40 | MBW(x8), MCBW(x8), MQWA(x20), MQWB(x4) |
| IR8 | 7 | CIPW.LR8 | US85 | 3 | 3 | MBXWS(x2), MBXWH |

### *Hardware platform for the normal conducting magnet interlock system*

The powering interlock controllers for the normal conducting magnets are similar to those used in the SPS-LHC transfer lines. The powering interlock system will interface to power converters for 40 electrical circuits and 144 magnets (the two main magnets of the ALICE and LHCb experiments are not under the responsibility of the machine interlock and as such are not included in these numbers). There are in total 144 input signals, one for each magnet grouping all thermal switches for this magnet in series. 40 output signals will be transmitted by the system to the power converter. The required response time is of the order of several seconds. As for the interlock controllers for superconducting magnets, the controllers will be implemented with industrial PLC’s. The exchange of signals with the other systems is via input/output modules.

### 15.3.7 Magnet Powering System and Interlocks in the LHC Reference Database

The data for all electrical circuits for powering magnets and their components have been introduced into the LHC Reference Database [12, 13, 14]. The data is used to provide the powering interlock controller with consistent data about the magnet powering system [15].

Every electrical circuit with its electrical circuit elements (power converters, normal conducting cable, current leads, superconducting busbars, magnets, energy extraction facilities etc.) is assigned to one of the 28 subsectors for superconducting magnets, or one of the seven insertions with normal conducting magnets. The LHC Reference Database will provide the interlock controllers with the name and type of all electrical circuits it will have to manage. Four different types have been defined, depending on the hardware interfaces with quench protection system, power converters and energy extraction. Two variables define whether a failure in the powering will lead to a beam dump and an abort of the powering in the complete subsector. This information will be downloaded from the LHC Reference Database to the interlock controllers and to the supervision software. An example of such configuration data is shown here for three circuits of the inner triplet powering subsector right of IP1:

| ID | CIRCUIT NAME | CONFIGURATION_TYPE | PAR_POWSUBOFF | PAR_BEAMDUMP |
|---|---|---|---|---|
| 1 | RQX.R1 | A | 1 | 1 |
| 2 | RCBXH1.R1 | B1 | 0 | 0 |
| 3 | RCBXH2.R1 | B1 | 0 | 0 |

…..etc...

The configuration file is generated taking into account the grouping of signals between the quench protection system and the power converters on one hand, and the powering interlock controllers on the other hand. The information in the LHC Reference Database includes detailed data about the location of quench detectors and power converters as well as the cabling between the three systems.

### 15.3.8 Supervision of the Powering Interlock System

Hardware commissioning of the LHC systems is expected to take about two years. During most of this time, the powering subsectors are independent and individual supervision of each powering subsector is required. The requirements for the supervision of powering interlock controllers for normal conducting magnets are less complex than those for the supervision of the controllers for superconducting magnets.

In order to operate with beam, all electrical circuits for magnet powering must be fully operational. Therefore the supervision system must combine the data from all powering interlock controllers and indicate if the magnet powering system is ready for beam. At this level, the supervision of the powering interlock controllers for normal conducting magnets and superconducting magnets will be combined.

The use of a commercial SCADA system is envisaged, motivated by the following operational and technical requirements:

- The powering interlock system is based on industrial PLC's.
- In total, 36 controllers for superconducting magnets and seven controllers for normal conducting magnets will be supervised using the same tool.
- From the point of view of its supervision, the system is rather complex.
- The time and safety critical control is done in the PLC software and the associated hardware.
- The required response time on the supervision level is in the order of one second.

The tool should be able to provide an interface to the PLC. Database support (ORACLE) and networking (Ethernet, PROFIBUS, etc) is required. The data from the powering interlock controllers will be integrated into the logging, alarm and post-mortem systems.

## 15.4 THE BEAM INTERLOCK SYSTEM

### 15.4.1 Beam Losses and Strategy for Beam Dumps

The most probable causes for beam losses are failures in the magnet powering system, with about 10000 magnets powered in 1612 electrical circuits with 1712 power converters. However, there could be many other types of failures [16, 17]. There could be also aperture restrictions, with two beams circulating through 53 km of beam vacuum pipe containing the beam screen, helium feedthroughs, interconnects, RF shielding etc., many vacuum valves and more than 100 collimator jaws could obstruct the beam passage.

The time after a failure at which particle losses become unacceptable was evaluated for many types of failures. This time depends on the failure and several other parameters such as energy, optics and collimator settings and falls into three categories [18]:

- One turn failures are ultra-fast losses due to a failure during injection or beam dump.
- Very fast losses in less than 5 ms.
- Fast losses in more than 5 ms.
- Steady losses are continuous losses, the lifetime is one second or more.

One turn failures could happen during injection and extraction. Protection relies on collimators and beam dilutors which must be correctly positioned with respect to the beam. The beam interlock system ensures that no beam can be injected if the collimators and dilutors are not correctly positioned.

Very fast losses: The failure of a D1 normal conducting bending magnet in IR1 and IR5 has been identified as the fastest mechanism for multi-turn failures [19]. The beam moves and could touch a collimator after a few turns. Another very fast beam loss is expected after a quench of a superconducting dipole magnet. In this case the beam is expected to touch collimator jaws after several 10's of turns. For failures causing very fast beam movements or emittance blow-up, the beam losses close to aperture limitations (collimators, beam dilutors, low-beta quadrupoles, etc.) are detected by beam loss monitors. The loss monitors request a beam dump if the beam loss exceeds a pre-defined threshold [20, 21]. It is also planned to detect rapid beam position changes. If beam orbit movements exceed a predefined value of say, ~0.2 mm/ms, the beams are dumped.

Fast Losses: Beam loss monitors around the machine and signals from equipment in case of hardware failure will be used to generate beam dump requests and complement fast beam loss and beam position monitors.

Steady losses: the beam losses and heat load at collimators will be monitored. A beam dump in case of unacceptable lifetime is also being considered.

### 15.4.2 Basic Functionality and Response Time

The beam interlock system provides beam permit flags for each beam. It receives status information from many "client systems" that can request the removal of the beam permit flags. Only if all systems indicate that they are ready for beam will the beam interlock system give beam permit. For example, in order to inject beam, the beam dumping system must be ready, all vacuum valves in the beam tube must be in the "open" position and magnets in the LHC and the transfer line must be powered, etc. The beam interlock controllers ensure that these conditions are met before giving beam permit. If the operation of the machine becomes unsafe and beam losses exceed the acceptable threshold or are imminent due to equipment failure, the beams have to be dumped as fast as possible. There is a minimum delay between such requests received by the beam interlock controller and the end of the beam dump [5]:

- The beam interlock system needs to inform the beam dumping system, which takes up to 50 μs if the signal travels half around the ring.
- The synchronisation of the extraction kicker with the particle free gap takes up to one revolution (89 μs).
- It takes about one turn from the start of the extraction to dump all bunches circulating in the LHC.

This determines the achievable response time of up to 270 μs between reception of a beam dump request by the beam interlock controller and the completion of a beam dump.

Systems that are critical for beam operation will always be in the interlock chain. It will be possible to disable some less critical input signals. A so-called "safe beam flag" will be derived from the circulating beam current and the energy and it will be distributed around the machine. If the stored energy in the beam is low and there is little risk of damage, the flag is set to logical one. A beam interlock controller receives the flag. Only when the safe beam flag is one (= safe beam), disabling of inputs is tolerated.

The beam interlock system provides monitoring of all inputs and outputs with precise time-stamps for post-mortem information. The accuracy of the time stamps should be about 1 μs.

### 15.4.3 Architecture of the Beam Interlock System

One beam interlock controller will be installed right of each IP, and one controller left of each IP. The beam interlock system therefore has 16 controllers. The controllers are connected by "beam permit loops" (one redundant loop for beam 1, and one redundant loop for beam 2). A high frequency signal (10 MHz) is transmitted across the loop. The presence of the signal indicates beam permit. If the signal is not present or has a different frequency, this means "no beam permit". If one of the controllers receives a dump request from a client system, it interrupts the loop. Both beam interlock controllers in the insertion with the beam dumping systems (IR6) receive the beam permit signal. When the loops are interrupted, the signal disappears. The two controllers detect the loss of signal, and instantaneously send hardware signals to extract the beam by the extraction kickers (Fig. 15.3).

The beam interlock system allows breaking of only one of the loops leading to a dump of only one beam. As an example, a failure during injection is considered: assume that the first ring has already been filled successfully and the second ring is partially filled. An attempt to inject a batch leads to unacceptable beam parameters for Beam 2. In this case it is sufficient to dump the beam in the second ring. Another example is an obstruction in the beam tube of one ring, when operation with beam in the other ring should still be possible.

Optical fibres will be used for the beam permit loops. Two signals run in clockwise and counter-clockwise direction for each beam. This ensures that the dump signal reaches the kickers as fast as possible, and adds redundancy to the beam interlock system. It is sufficient that one signal is missing in IR6 to dump the beams.

The optical links will only be used for the beam permit signal despite the available bandwidth, assuming that simplicity will lead to enhanced reliability

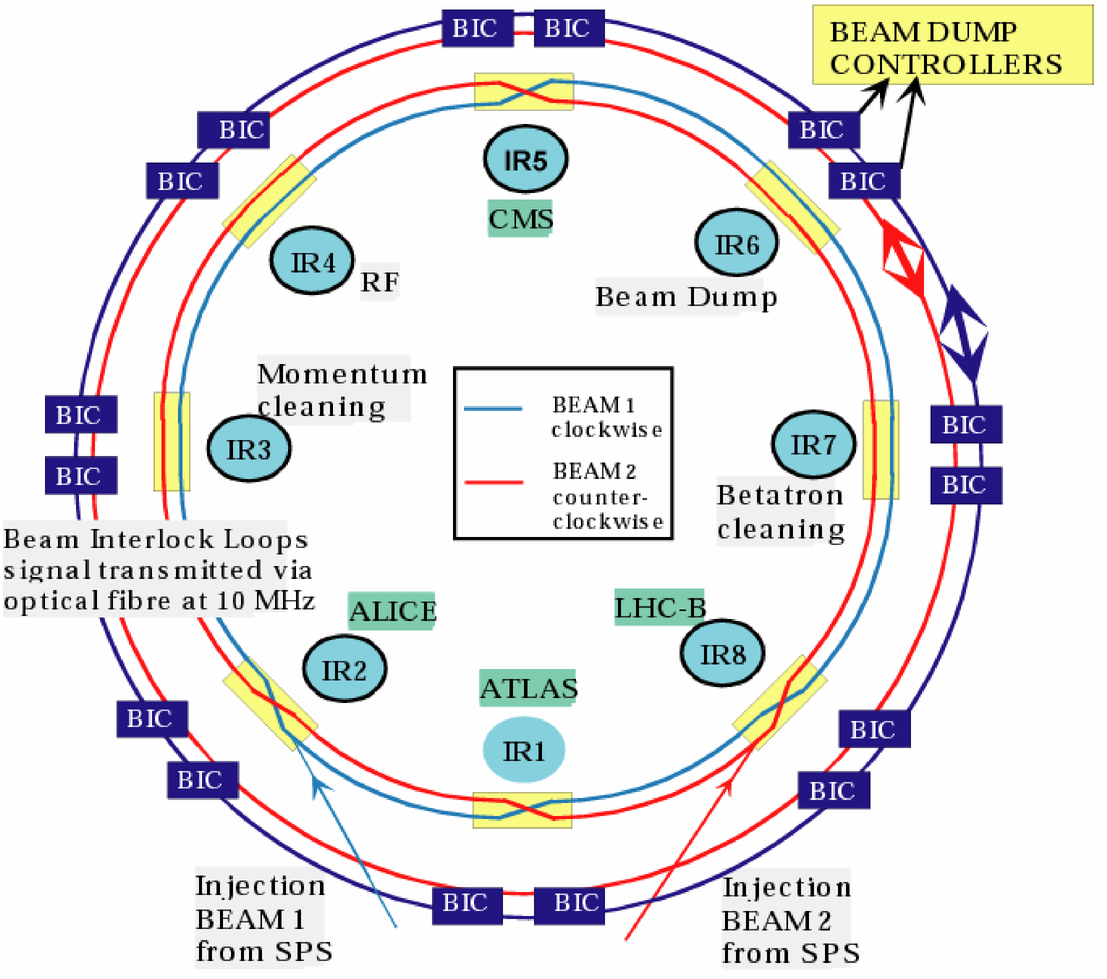


Figure 15.3: Architecture of the beam interlock system with its 16 beam interlock controllers

### 15.4.4 Beam Interlock Controller and its Interfaces

A beam interlock controller receives one signal from each of the following client system in the vicinity:

- Powering interlock controllers for superconducting magnets: each controller sends two signals to the beam interlock controller.
- Powering interlock controllers for normal conducting magnets: a failure of the normal conducting magnets in the insertions could occur due to overheating of the magnet or due to a failure of the power converter.
- Beam dumping system: If it is not ready, injection of beam is inhibited. In the presence of circulating beam, the beam dumping system is continuously monitored. If an equipment fault that could lead to a failure during the next extraction is detected, the beams are dumped immediately.
- LHC experiments: They can prevent beam injection and issue beam dump requests during operation. Injection is only possible if movable detectors (Roman pots, or the LHC-B Velo detector) are in the position far away from the beam centre. During physics operation (top energy, luminosity operation, with stable beams) experiments are authorised to move detectors closer to the beams.

- RF and transverse feedback: A signal to dump the beam is required from the RF system if debunching due to a failure is anticipated. The time constant for debunching is in the order of several 100 ms [22, 23]. A failure of the transverse damper might cause a beam loss within a very short time. Incorrect operation of the transverse feedback must trigger a beam dump.
- Beam loss monitors: There will be many beam loss monitors distributed around the ring close to each quadrupole, each with a response time in the order of one millisecond. Near the collimators and other aperture restrictions the BLMs will have a response time of less than 0.1 ms. The BLMs are the most important monitors for protection against damage from beam losses.
- Access safety system: The system for safety of personnel has to conform to legal requirements, independent of equipment protection considerations. There is a direct link from the access system to the beam dumping systems. For redundancy, the access status is also transmitted to the beam interlock system.
- Vacuum system: There will be many valves that could obstruct the beam passage. If a valve is in a position defined as "not open", beam permit cannot be given. The vacuum system will read the beam permit flags, and only close a valve if there is "no beam permit".
- Input from the beam dilutors and collimators: Collimators and beam dilutor must be in the correct position for each phase of the operation. Only if the conditions are correct will such devices give beam permit to the beam interlock system [24].

Each beam interlock controller knows the state of the beam permit loops: either no beam permit, or beam permit. The status of each beam permit loop (beam permit flags) will be provided for the client systems:

- The beam dumping system for each beam is one client and will receive the beam permit flag from both beam interlock controllers in IR6, for redundancy. If one of the signals disappears, the beam is extracted.
- Each injection kicker is a client. The kicker can only fire if the beam permit is granted.

### 15.4.5 Hardware Platform for the Beam Interlock Controller

VME was selected as hardware platform for the beam interlock controller because:

- The response time required of the order of some µs requires fast processing.
- VME is one of the standards supported at CERN.
- The connection to the control system is simple and supported by the Controls Group.

The VME crate will house several modules (see Fig. 15.4):

- A core module with the central logic for the decision on a beam permit. This will use a module made in-house with programmable logic that can easily be integrated in a VME crate. The interface via the VME bus allows reading of the status and recording the history of state changes. It allows disabling some of the inputs. In addition, the module includes an interface to the LHC timing system.
- The interface to the client modules. This module will also be used to simulate permission from clients during testing of the beam interlock system.
- The link of the controller to the other beam interlock controllers via the optical fibres.

The controller is connected to the control system via Ethernet for monitoring, setting the masks, testing and post mortem data. All input and output state changes and the time of occurrence are recorded and stored into memory.

### 15.4.6 Beam Interlock Client Interface

The beam interlock controllers are distributed around the LHC. The distance to the client systems is between several metres and several hundred metres. For each client, a "beam interlock interface" is provided to be installed in the client's rack (as a one unit, mountable, module). The client's system should provide a signal to this interface box using a TTL level (+5 Volt) or a PLC compatible level (+24 Volt). To be fail safe, the signal must always be present to get the beam permit. If the signal is lost, the beam permit loops will be broken by the corresponding controller and consequently the beams will be dumped.

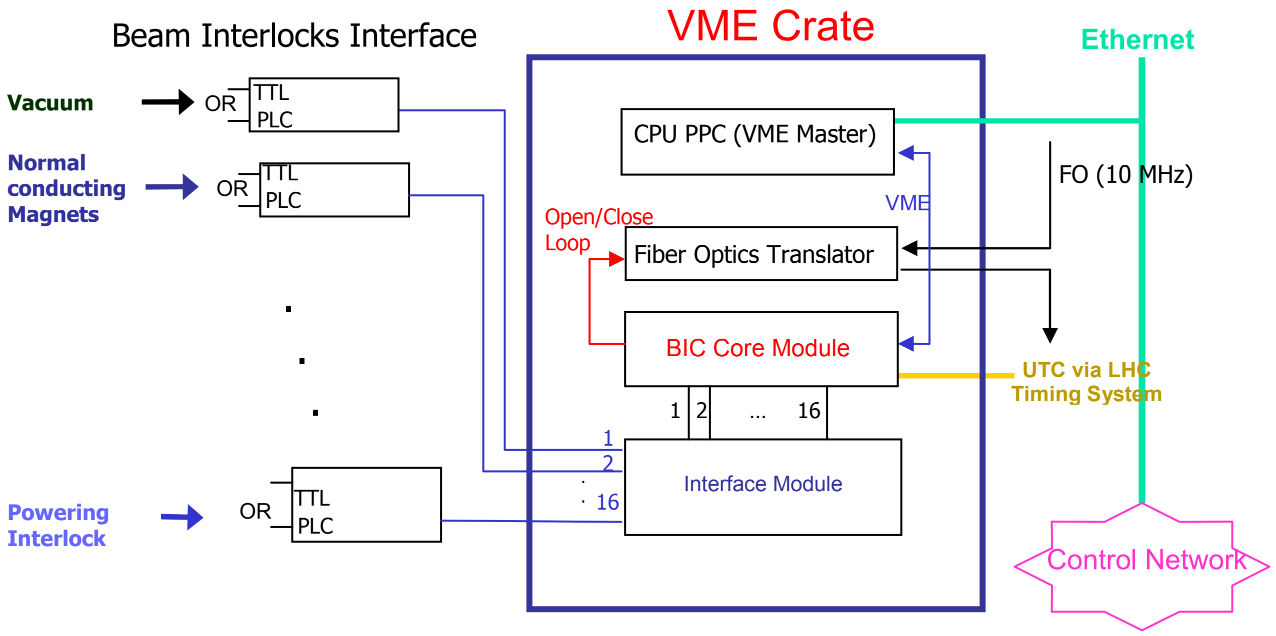


Figure 15.4: Architecture of the Beam Interlock Controller

As each beam interlock controller knows the state of the beam permit loops, the status of each beam permit loop (beam permit flags) will be provided for the client systems via this "beam interlock interface" box. The two status flags are delivered to the user via TTL signals and via PLC compatible signals.

In addition, the "beam interlock interface" box includes some internal self-test parts for remote use via the beam interlock controller.

### 15.4.7 Operation of the Beam Interlock System

Before injecting beam into the LHC, the beam interlock system must receive the beam permit from all client systems that are not disabled. When all clients give permission, the 10 MHz signal on the beam permit loop is established and only then beam can be transferred and injected into the LHC.

It is possible to close one of the two loops for each beam in test mode, by simulating a beam permit for each client system. In this mode the second loop will be forced to remain open, it is not possible to close both loops in this mode at the same time. This facilitates verification of the complete functioning of the beam interlock system without the risk of giving beam permit.

The efficiency of beam operation and the reliability of the protection systems can be improved using beam dump requests or power aborts via the controls system. Such requests can be disabled. If a soft abort is disabled or fails, there is always a second level of protection against damage by the machine interlock system. For example, if the cryogenic system signals that the temperature cannot be kept at the required level, the overall performance is improved by dumping the beam and discharging the circuit before a magnet quenches. This action will reduce the downtime. It is not required that the action is fail safe, since the quench protection system, beam loss monitor and the interlock system would trigger a beam dump and the discharge of the magnet energy.

### 15.4.8 Supervision of the Beam Interlock System

The most relevant information from the beam interlock system to be displayed in the control room is the status of the beam permit for each beam. The supervision for the beam interlock system will also read and display the status of all input signals from the clients for each beam interlock controller, as well as the output status.

The supervision system will allow disabling some of the channels. The status of the hardware will be displayed, showing, for example, which channels are disabled. All state changes and the associated time stamps that are recorded in the controllers will be read and archived via the supervision system.

The beam and powering interlock systems have different requirements and use different hardware platforms. The main operational and technical features of the beam interlock system that determine a proper supervision tool are:

- VME based.
- 16 beam interlock controllers.
- Hardware-based control + embedded real-time application.
- Faster than powering interlock controller (in the order of microseconds).
- Simplicity from the point of view of supervision.

The supervision system must provide the interface to the VME base beam interlock controllers, and to the LHC control system. The data from the beam interlock system will be integrated into the logging, alarm and post-mortem systems.

### 15.4.9 Injection Procedures and Interfaces to SPS

During operation with circulating beam, protection relies mainly on fast monitors to detect beam losses early and issue a beam dump request immediately if the losses exceed the acceptable level.

During injection of high intensity beam there is a risk that equipment in the LHC is not in the correct state. To avoid damage of equipment if there is no beam in the LHC, a procedure for injection has been defined [25]. Without beam, only beam with limited intensity (“pilot beam”) can be injected. The pilot beam is used to verify that there are no obstructions and no magnet wrongly powered etc. The presence of beam in the LHC will be monitored by a beam current transformer. Only when beam is circulating, injection of beam with higher intensity is permitted. If the LHC requests beam with high intensity in the presence of circulating beam, it is still possible that the beam is lost before injection. In this case the beam current transformer will indicate that no beam circulates, and veto injection of high intensity beam. Injection must restart with low intensity beam.

## 15.5 RELIABILITY ISSUES

The correct functioning of powering and beam interlock systems is essential to avoid damage of machine equipment. As such they have to be designed as highly reliable and fail safe systems.

### 15.5.1 Powering Interlock System

Current loops are used to connect the quench protection system, the power converter and the powering interlock controller. If one system opens the loop, the two other systems detect the loss of current, and react accordingly. Fail safe logic is used for the transmission of signals. A faulty system or a cable that is not connected is detected and will result in a fast abort of powering and discharge of the magnet energy. After a complete failure of the PLC used for the powering interlock controller, the equipment would still be protected. The functionality of a power abort in the complete subsector after a quench in a major circuit would be lost, but this is acceptable. The assessment of the Safety Integrity Level (SIL) of the powering interlock system is planned.

### 15.5.2 Beam Interlock System

Beam dump requests will be transmitted via the beam interlock system that must have a similar Safety Integrity Level (SIL) to the beam dumping system. The beam dumping system requires SIL 3 (see Chap. 17).

The beam interlock system is therefore designed in a redundant way. Each client will provide the signal for beam dump requests via a fail safe interface. The beam interlock system provides two independent paths for a dump request including two beam permit loops for each beam. Redundancy is provided for the reception of a beam dump request issued by a client to the beam dumping system.

For most type of failures that have been considered, several beam dump requests will reach the beam interlock system. It is likely that the requests will arrive at several beam interlock controllers. As an example, a quench of a superconducting dipole magnet is considered:

- The beam will be deflected due to the decreasing magnetic field in the magnet. The tail of the beam distribution will touch one of the collimators after several 10 turns. The beam loss monitor close to the collimator will issue a beam dump request.
- Assume that due to an equipment failure the dump request from the first beam loss monitor is not transmitted to the beam dumping system. The beam would move further out and touch another collimator or an aperture limit and another beam loss monitor would request a beam dump.
- The quench protection system will inform the powering interlock system about the quench. The powering interlock system will abort powering in the powering subsector with the quenched magnet and request a beam dump via the beam interlock system.

Several other ideas are being studied to better protect LHC equipment from damage due to beam losses:

- Fast beam position changes could be detected by several beam position monitors covering the horizontal and the vertical plane, installed with a phase advance of 90°. For two rings and two planes, eight of such monitors are required.
- For the D1 normal conducting magnet, the time between detection of a loss of $10^9$ protons and about $10^{12}$ protons hitting the collimator is in the order of 6-10 turns (less than one ms). This time could be increased by about a factor of three by installing industrial superconducting solenoid magnets in series with the normal conducting D1 magnets.
- Several techniques for a fast detection (in the ms range or even below) of a changing magnetic field in the normal conducting D1 magnets are being considered.

For a safe beam operation all systems for machine protection need to operate properly. The Safety Integrity Level for all these systems functioning together will be assessed. After such assessment, a decision will be taken if an improvement of the reliability of the protection systems is required.

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