EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
European Laboratory for Particle Physics

Large Hadron Collider Project

LHC Project Report 521

MACHINE PROTECTION FOR THE LHC: ARCHITECTURE OF THE BEAM AND POWERING INTERLOCK SYSTEMS

F.Bordry, R.Denz, K-H.Mess[1], B.Puccio, F.Rodriguez-Mateos and R.Schmidt

Abstract

The superconducting Large Hadron Collider under construction at CERN is an accelerator with unprecedented complexity. Its operation requires a large variety of instrumentation, not only for control of the beams, but also for the control and protection of the complex hardware systems. Sophisticated protection systems are mandatory to minimise the risk for serious damage caused by a failure. Each proton beam will have an energy of more than 300 MJ, and the energy stored in the magnet system amounts to about 1.2 GJ for each sector. Ideas for the architecture of the interlocks linking the protection systems are presented here.

1 DESY, Hamburg, Germany

Administrative Secretariat
LHC Division
CERN
CH - 1211 Geneva 23
Switzerland

Geneva, 21 December 2001

1 INTRODUCTION

The energy stored in the LHC accelerator, both in the superconducting magnets and in the circulating beams, is unprecedented and an uncontrolled release could lead to serious damage of equipment. Major failures in the equipment inside the cryostats will result in long repair times, because such equipment is delicate and difficult to access.

Preparing the machine for injection requires considerable time due to magnetisation effects of the superconducting magnets. The filling process and the acceleration phase are lengthy procedures. Any interruption during the accelerator operation will reduce the operational efficiency significantly.

To optimise the operational efficiency of the accelerator, accidents should be avoided and interruptions should be rare and limited to a short time. Hence, a system is needed that extracts beam and magnet energy in case of failures as well as:

- prevents damage to all elements in the electrical circuits: magnets, warm and cold cables, current leads and power converters,
- minimises damage due to irradiation caused by beam losses,
- provides the necessary tools to implement a consistent and congruent failure tracing throughout the machine.

MACHINE PROTECTION is not an objective in itself, but should contribute to:

- maximise operational availability by minimising time for interventions,
- avoid causing any damage of equipment.

Major subsystems have been designed to extract beam and magnet energy. The QUENCH PROTECTION SYSTEM [1] and the BEAM DUMP SYSTEM [2], [3], [4] are presented elsewhere. For the diagnostic of losses and to generate a trigger for the BEAM DUMP SYSTEM, the BEAM LOSS MONITOR SYSTEM is being designed [5], [6]. To limit the beam losses around the arc, a sophisticated COLLIMATION SYSTEM has been proposed [7]. Many other subsystems need to be interfaced to the machine protection, such as the ACCESS SYSTEM [8], POWER CONVERTER SYSTEM [9], vacuum valves, RF, collimators etc. In this paper the integration of all subsystems into a common MACHINE PROTECTION SYSTEM is discussed with an interlock system that can be understood as the glue linking and structuring the sub-systems. Since magnets can be powered independently from of operation with beam, we propose two separate systems for powering and beam operation, the POWERING INTERLOCK SYSTEM and the BEAM INTERLOCK SYSTEM. Figure 1 illustrates the relationship between the machine interlock systems and the other systems.

Clearly, personnel safety has the highest priority. The ACCESS SYSTEM for personnel safety is separate and presented elsewhere, however, some ideas about the interface between the ACCESS SYSTEM and the machine interlocks are described here.

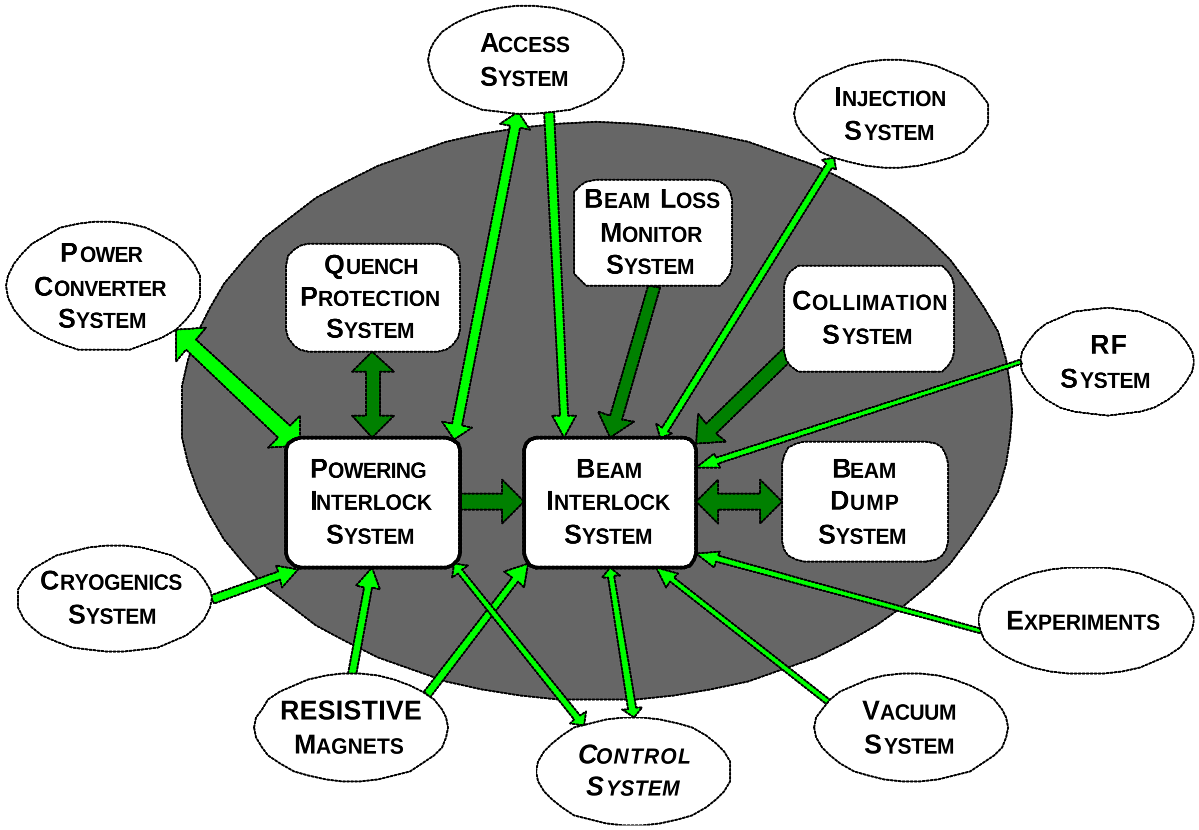


Figure 1: Relationship between powering and beam interlocks and the main LHC sub-systems. The systems dedicated to protection are within the grey zone. Note: Beam loss monitors and collimation systems are also used in regular machine operation.

1.1 Energy stored in the magnet system

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, amongst other reasons, to limit the energy stored in a particular electrical circuit. This precaution causes a substantial increase of the component inventory necessary for the LHC operation (power converters, current feedthroughs, etc.). Still, the energy in each sector of the LHC amounts to about 1.2 GJ, sufficient to heat up and melt 1900 kg of copper [10].

The number of superconducting magnets exceeds 8000, with about 2000 large dipole and quadrupole magnets, and 6000 corrector magnets. The superconducting magnets are powered in about 1800 circuits, with ultimate currents of about 13 kA, 6 kA, 600 A, 120 A and 60 A, respectively. Copper current leads are used to power the 120 A and 60 A circuits. The leads for higher current include high temperature superconducting (HTS) material [11].

The large energy stored in the magnets presents one of the main risks during both, commissioning of the complex hardware and operation with beam. As an example, a quench of a dipole magnet is easily provoked, since the magnets are operating at 1.9 K and at a current where the margin is very small. An energy corresponding to a fraction of some 10^{-7} of the beam energy can quench a dipole magnet that is operating at full current (i.e. close to the critical surface). For the operation without beams in the machine, magnets could quench spontaneously, due to equipment failure, due to faulty connections, or due to a failure in the protection system. Magnets, superconducting bus bars, or current leads that are not properly protected can be damaged.

In case of a failure, the magnetic energy has to be extracted as fast as possible. Since the magnets have a large inductance and the voltages must be limited, the time constant for the current decay can be large. Extracting the energy after switching a resistor in series with the magnets can take several minutes. The time constant for the current decay is between about 0.1 s for some of the corrector magnet circuits, and 100 s for a circuit with main dipole magnets. The required response time to start extracting the energy is in the order of 10 ms or more for most electrical circuits (such as all circuits with superconducting magnets). Failures in circuits with warm magnets might require fast detection in order to abort the beams within a few turns [12].

1.2 Energy stored in the beams

Without beam, normally the magnets should not quench by themselves. Once beam is injected, quenches are much more likely. The energy stored in each beam is up to 0.35 GJ, equivalent to the energy for warming up and melting 515 kg of copper [10]. A sophisticated collimating system captures protons from the tail of the particle distribution, and thus reduces beam losses into magnets and other equipment. The collimators installed in the two cleaning insertions must be close to the beam during injection, ramping and physics coast. The geometric aperture is smaller than for any other accelerator with superconducting magnets. If the operation of the machine becomes unsafe and beam losses are observed by the loss monitors, or are imminent due to equipment failure, the beams have to be dumped as fast as possible to prevent radiation damage, quenches, and downtime. The BEAM INTERLOCK SYSTEM has to collect the information. When a failure is detected, the BEAM DUMP SYSTEM should be informed as fast as possible to dump with minimum delay. The minimum time is given by:

- The BEAM INTERLOCK SYSTEM needs to inform the BEAM DUMP SYSTEM, which takes up to 50 µs if the signal travels half around the ring.
- The synchronisation of the pulsed elements in the BEAM DUMP SYSTEM with the particle free gap could take up to one revolution (89 µs).

This determines the achievable response time between several 10µs and 180µs.

1.3 Number of components

Dealing with the large number of vital components will also be a major challenge. The following table gives an estimate of the number of electronic channels that indicate malfunctioning of LHC equipment, and may cause a beam dump.

Table 1 Approximate number of electronic channels that could request a beam dump.

Protection for main dipole and quadrupole magnets (MB, MQ, MQM)	2000
Protection for current leads for main dipole and quadrupole magnets (MB, MQ)	64
Protection for current leads for MQM, MQX, and other high current magnets	Some 400
Protection for major corrector magnets	400
Protection for current leads for orbit corrector magnets	1800
Protection for current leads for major corrector magnets	800
Power converters	500-800
Beam loss monitors close to collimators	Some 10
Beam loss monitors at quadrupole magnets	3000
Sector vacuum valves	200
Cryogenics system (one signal for each cryostat)	40
LHC experiments	4
Access system	Some 10
Sum	8000-10000

With the objective of less than one faulty ABORT / two weeks, the mean time between failure (MTBF) must exceed 200 years for each channel.

1.4 Downtime

Major accidents may cause the damage of a magnet requiring its replacement. Warming up a part of the machine, the repair, and the cool down will require about four weeks. Such accidents should be avoided by the MACHINE PROTECTION SYSTEM.

To estimate the downtime due to less severe failures, several scenarios quite likely for the operation with colliding beams are considered [13]. Depending on the failure, the downtime is between 1.5 h and up to 7 h in case of quenching magnets (see below).

A power converter failure requires a beam dump, for a circuit including magnets with negligible dynamic effects (no magnet quench)	
Action	**Time [min]**
Beam dump, stop power converter, discharge magnet energy for circuit with faulty power converter, clear failure of power converter	10
Ramp all magnets to injection current	30
Injection of beam	20
Ramp to top energy and preparation for physics	40
Time until physics restarts: at least 1.5 hours	

A power converter failure requires a beam dump, for a circuit including magnets with significant dynamic effects (no magnet quench)	
Action	**Time [min]**
Beam dump, stop power converter, discharge magnet energy for circuit with faulty power converter, clear failure of power converter	10
Switch on power converter, 2 cycles to restore the magnetic history, and ramp to injection current	90
Injection of beam	20
Ramp to top energy and preparation for physics	40
Time until physics restarts: at least 2.5 hours	

Beam loss monitors measure too high beam losses at top energy and request to dump the beam (no magnet quench)	
Action	**Time [min]**
Beam dump and ramp to injection current	30
Injection of beam	20
Ramp to top energy and preparation for physics	40
Time until physics restarts: at least 1.5 hours	

Beam losses cause a quench of a dipole magnet during operation at top energy	
Action	**Time**
Beam dump, stop power converter, discharge magnet energy for circuit with quenched magnet and possibly other circuits	10 min
Cool down from increased temperature (depends on the energy released into the helium) to 1.9 K [14]	3-7 hours
Switch on power converter, 2 cycles to restore the magnetic history, and ramp to injection current	90
Injection of beam	20
Ramp to top energy and preparation for physics	40
Time until physics restarts: at least 5 hours	

2 ARCHITECTURE OF THE MACHINE INTERLOCK SYSTEM

2.1 Main objectives

The main objectives for the MACHINE PROTECTION SYSTEMS are:

- Protect the machine: In case of failure, the necessary steps should be taken to dump the beam and to dissipate the energy stored in the magnets in a safe way.
- 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, the messages should get to the operator. The system should support identifying the initial failure, also in case of multiple alarms (one initial failure that causes subsequent failures).
- Assist improving the operation: The diagnostics for failures should be easy. The status of the system must be clearly presented in the control room and should be transparent to the operator.

From these objectives, the principles for the architecture follows:

- For the protection of equipment, hardwired abort links (“hard aborts”) will be used unconditionally if equipment could be damaged.
- To limit the number of faulty triggers, the number of channels that may provoke an abort will be minimised. This will establish a reasonable compromise between the requirement for protection and the requirement to avoid unnecessary beam dumps. If the required reliability cannot be achieved otherwise, redundancy and majority voting strategies will be implemented.
- The efficiency of the operation can be improved using “soft aborts”, possibly via computer links. Soft aborts can be disabled. If a soft abort is disabled or fails, there is always a second level of protection due to hard aborts. 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 would quench. This action will reduce the downtime.
- To provide the evidence of a failure and assist the operator, the same structure across different systems in the abort chain will be used. For a failure only one abort (or two for redundancy reasons) will be requested, and not many. Synchronised recording of failures leading to an abort will be made available for later analysis (Post Mortem).

2.2 Machine interlocks

The architecture of the MACHINE INTERLOCK SYSTEM is derived from the layout of the LHC and its systems, from operational requirements and from the principles discussed above.

- The POWERING INTERLOCK SYSTEM allows for the powering of the magnets when a number of conditions are met, and causes a safe dissipation of the energy stored in the magnet system in case of a quench or other failures.
- The BEAM INTERLOCK SYSTEM allows beam injection if it is safe to accept beam, and requests a beam dump by the BEAM DUMP SYSTEM if any unsafe situation is detected.

- An interface between the POWERING INTERLOCK SYSTEM and the BEAM INTERLOCK SYSTEM ensures that the beam is dumped at the earliest possible moment for failures that would cause beam losses.
- A POST MORTEM SYSTEM records data from various systems to understand the cause of a failure leading to a beam dump or power abort.

2.3 Architecture of the powering interlock system

The eight sectors in the LHC are largely independent. In each sector several cryostats are installed, in total about 50 cryostats and 42 DFBs (optics version 6.4) [15]. Powering of one electrical circuit is always limited to one cryostat (see Figure 2).

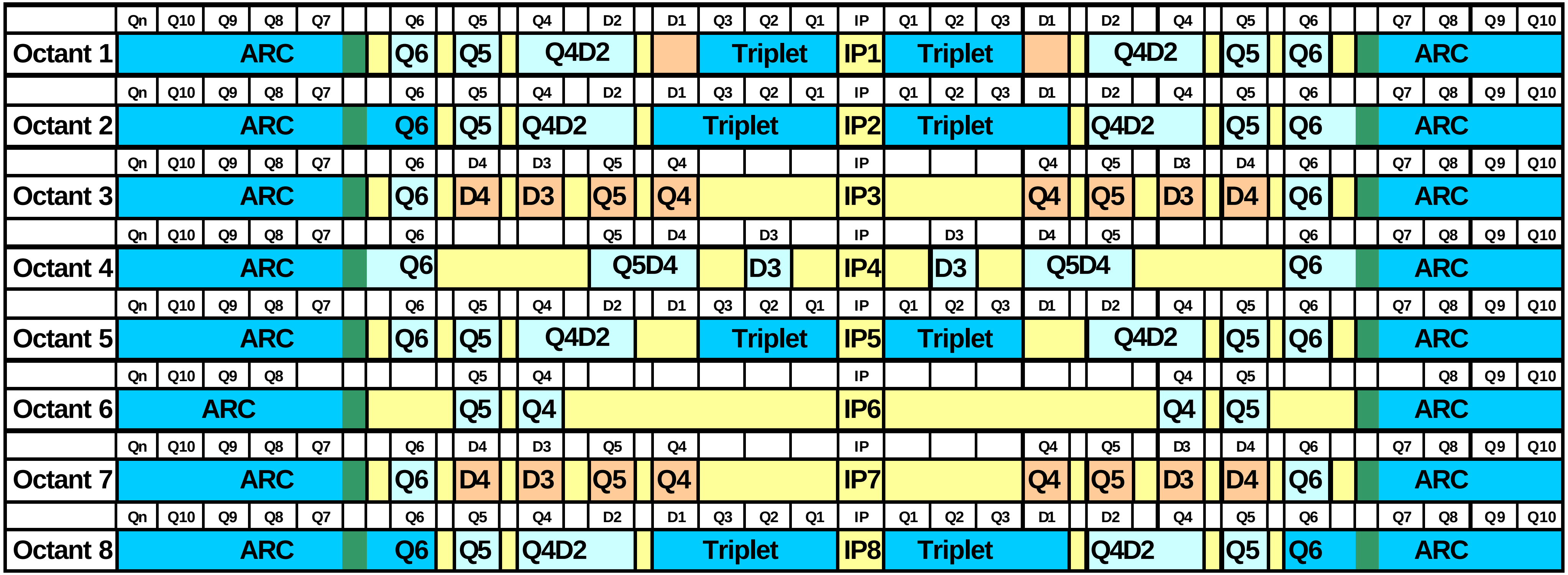
All power converters for superconducting magnets are located in the underground powering areas (UA, UJ, RR). The electrical circuit includes power converters, (warm) cables from power converters to the current feedthroughs, the current feedthroughs from ambient temperature to about 4.2 K (in general two for each circuit), superconducting bus bars for the current distribution, and finally the superconducting magnets (see Figure 3).

The energy stored in either some or all magnets in a cryostat must be discharged in case of a failure. However, the energy of magnets in other cryostats does not have to be discharged. Each cryostat, or the assembly of a few adjacent cryostats, is considered as POWERING SUBSECTOR with one POWERING INTERLOCK CONTROLLER (PIC). This allows powering all circuits in one POWERING SUBSECTOR independent from other electrical circuits, for example during setting up and hardware commissioning. An example of the architecture between IP1 and IP8 is given in Figure 4.

The eight long arc cryostats span the major part of a sector and are electrically fed from both sides. The power converters for the main bending magnets (MB) and main arc quadrupole magnets (MQ), and the energy extraction systems for the MQ magnets are installed in the even points. For the MB there is an energy extraction systems at each end of the arc cryostat. At the odd points power converters for insertion / dispersion suppresser quadrupoles and corrector magnets are installed. Hence the long arc cryostats needs two POWERING INTERLOCK CONTROLLERS, one on each side. The quench detection for main magnets in the arc cryostats comprises about 250 units distributed along the arc. Current loops are connecting all detectors and informing the POWERING INTERLOCK CONTROLLERS about a quench in one of the magnets. To power the orbit correctors, about 100 power converters are installed in each sector in the tunnel underneath the arc cryostat, which will be notified in case of a failure via the control system.

In summary, there are about 36 POWERING INTERLOCK CONTROLLERS in the underground powering areas. There will be some additional POWERING INTERLOCK CONTROLLERS for the electrical circuits operating with magnets at room temperature. The POWERING INTERLOCK CONTROLLERS will be connected to the controls network. One POWERING INTERLOCK CONTROLLER has a functionality that is similar to the interlock system of String 2 [16].

Continuous cryostats in the LHC version 10 November 2001, optics 6.4 **J:\machine-protection\interlocks\[interlocks.xls]cont.cryostats**



	Qn	Q10	Q9	Q8	Q7			Q6		Q5		Q4		D2		D1	Q3	Q2	Q1	IP	Q1	Q2	Q3	D1		D2		Q4		Q5		Q6			Q7	Q8	Q9	Q10
Octant 1	ARC							Q6		Q5		Q4D2					Triplet			IP1	Triplet					Q4D2				Q5		Q6			ARC			
	Qn	Q10	Q9	Q8	Q7			Q6		Q5		Q4		D2		D1	Q3	Q2	Q1	IP	Q1	Q2	Q3	D1		D2		Q4		Q5		Q6			Q7	Q8	Q9	Q10
Octant 2	ARC						Q6			Q5		Q4D2				Triplet				IP2	Triplet					Q4D2				Q5		Q6			ARC			
	Qn	Q10	Q9	Q8	Q7			Q6		D4		D3		Q5		Q4				IP				Q4		Q5		D3		D4		Q6			Q7	Q8	Q9	Q10
Octant 3	ARC							Q6		D4		D3		Q5		Q4				IP3				Q4		Q5		D3		D4		Q6			ARC			
	Qn	Q10	Q9	Q8	Q7			Q6						Q5		D4		D3		IP		D3		D4		Q5						Q6			Q7	Q8	Q9	Q10
Octant 4	ARC						Q6							Q5D4				D3		IP4		D3		Q5D4								Q6			ARC			
	Qn	Q10	Q9	Q8	Q7			Q6		Q5		Q4		D2		D1	Q3	Q2	Q1	IP	Q1	Q2	Q3	D1		D2		Q4		Q5		Q6			Q7	Q8	Q9	Q10
Octant 5	ARC							Q6		Q5		Q4D2					Triplet			IP5	Triplet					Q4D2				Q5		Q6			ARC			
	Qn	Q10	Q9	Q8						Q5		Q4								IP								Q4		Q5						Q8	Q9	Q10
Octant 6	ARC									Q5		Q4								IP6								Q4		Q5					ARC			
	Qn	Q10	Q9	Q8	Q7			Q6		D4		D3		Q5		Q4				IP				Q4		Q5		D3		D4		Q6			Q7	Q8	Q9	Q10
Octant 7	ARC							Q6		D4		D3		Q5		Q4				IP7				Q4		Q5		D3		D4		Q6			ARC			
	Qn	Q10	Q9	Q8	Q7			Q6		Q5		Q4		D2		D1	Q3	Q2	Q1	IP	Q1	Q2	Q3	D1		D2		Q4		Q5		Q6			Q7	Q8	Q9	Q10
Octant 8	ARC						Q6			Q5		Q4D2				Triplet				IP8	Triplet					Q4D2				Q5		Q6			ARC			

Figure 2: CONTINUOUS CRYOSTATS in the LHC, for optics version 6.4.

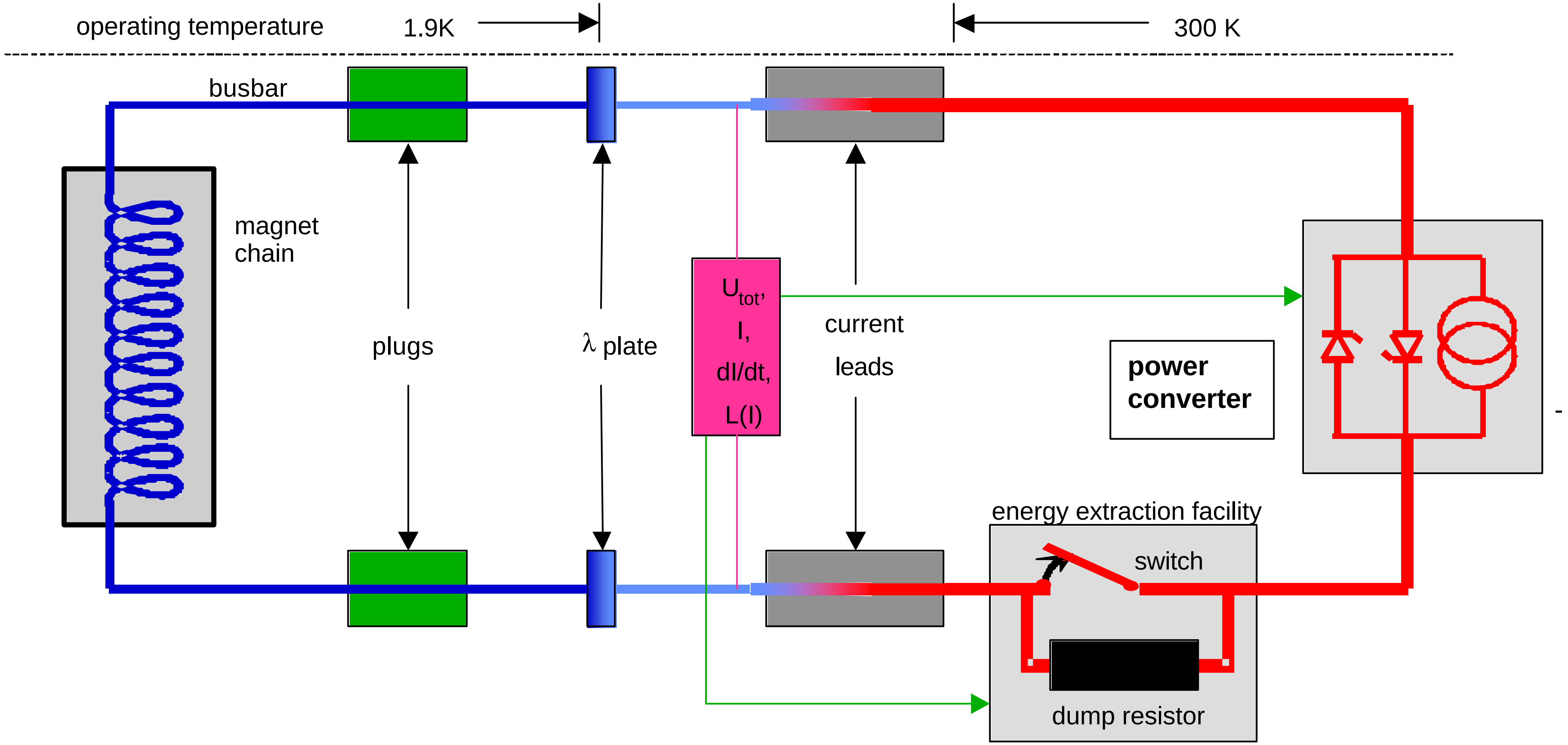
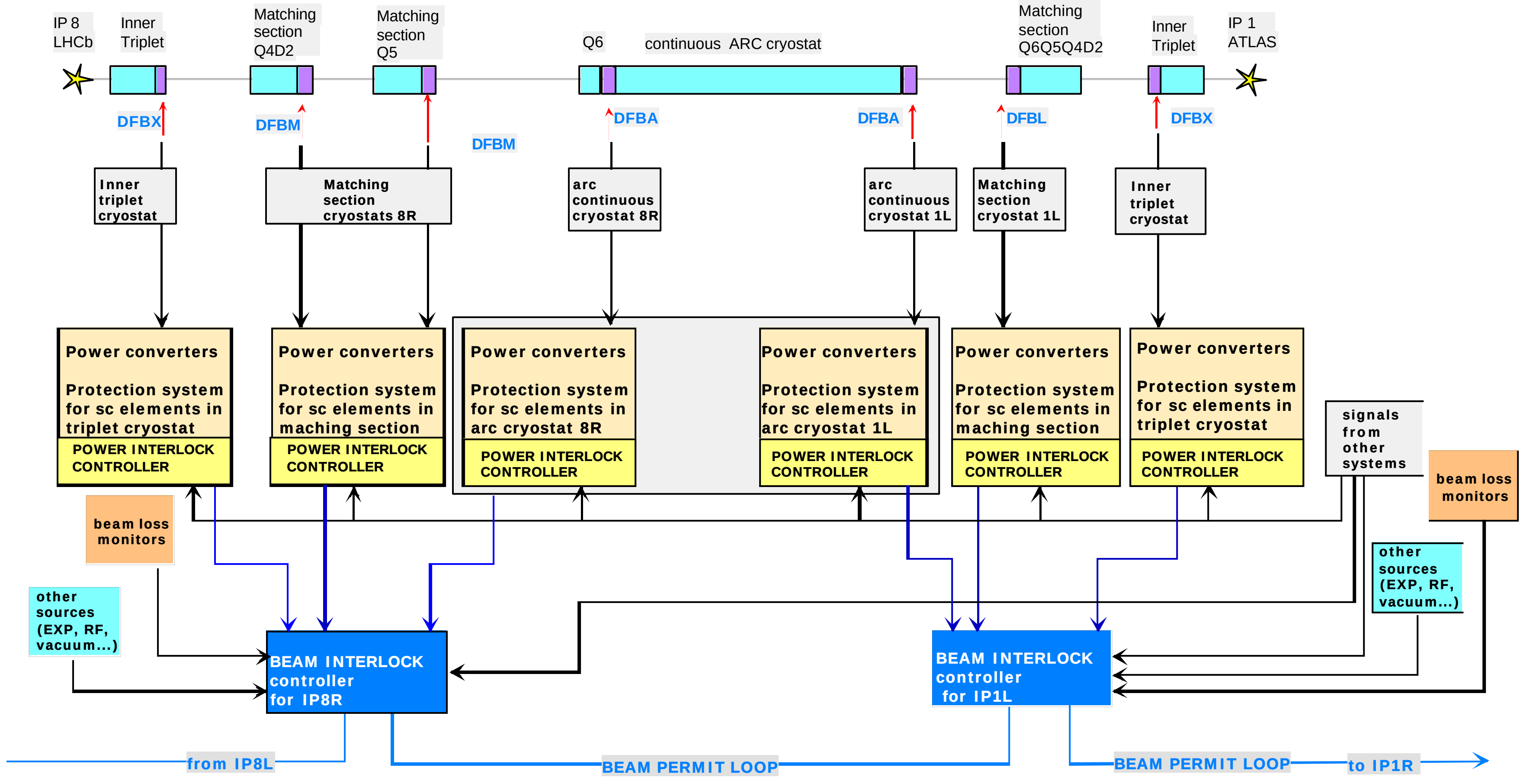


Figure 3: Elements of a circuit with superconducting magnets with a bi-polar power converter.



update 29/11/2001

**Scheme of POWER INERLOCK CONTROLLER
AND BEAM INTERLOCK CONTROLLER
example for sector between IP8 and IP1**

Figure 4: Example for the Architecture of Power and Beam Interlock System in sector 8-1.

2.4 Architecture of the beam interlock system

There will be one BEAM INTERLOCK SYSTEM for the LHC. Right and left from each IP one BEAM INTERLOCK CONTROLLER (BIC) will be installed (see Figure 5). The controllers are connected by two loops (BEAM PERMIT LOOPS). When the loops are broken, the beams are extracted into the beam dump blocks by the BEAM DUMP SYSTEM. A computer connection to the BEAM INTERLOCK CONTROLLERS for monitoring, testing and post mortem analysis is required.

The two loops distinguish between beam I and II. The system allows breaking one of the loops leading to a dump of only one beam, for example during injection: One beam may have been successfully injected. An attempt to inject the other beam leads to a stored beam with unacceptable beam parameters. Another example is a degraded vacuum in one beam tube, when operation with the other beam should still be possible. With the strategy of having a BEAM DUMP SYSTEM for each beam, and a BEAM PERMIT LOOP for each beam, it is possible to dump only one beam.

In order to inject beam, the BEAM DUMP SYSTEM must be ready, all vacuum valves in the beam tube must be in the "open" position, magnets in the transfer line need to be powered, etc. The BEAM INTERLOCK CONTROLLERS ensure that these conditions are met.

POWERING INTERLOCK CONTROLLERS report their state to a BEAM INTERLOCK CONTROLLER in the vicinity.

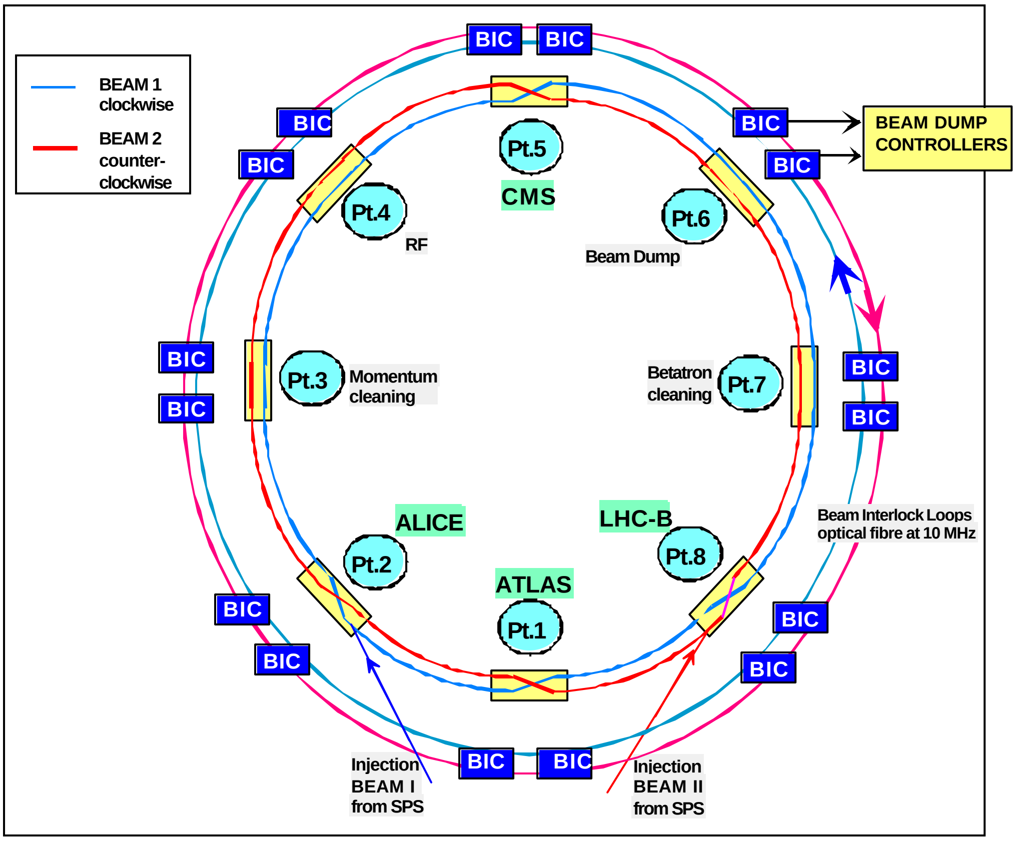


Figure 5: Architecture of the beam interlock system.

3 POWERING INTERLOCK SYSTEM

3.1 Powering interlock controllers

A POWERING INTERLOCK CONTROLLER monitors the powering status of all electrical circuits for one POWERING SUBSECTOR. For each circuit the POWERING INTERLOCK CONTROLLER has an interface to the power converter and the quench protection system. Similar controllers will monitor the powering of all warm magnets in one half-insertion.

Two types of electrical circuits are defined:

- Circuits with main magnets: Circuits that include magnets with large stored energy density, for example all main dipoles, main arc quadrupoles and main quadrupoles in the dispersion / matching section (MQM). In case of a quench, the quench could travel to magnets or bus bars in other circuits and therefore all magnets in the cryostat will be de-excited (SUBSECTOR POWER ABORT).
- Circuits with other magnets: Circuits that only include magnets with little stored energy. A quench of a magnet in such circuits would normally not travel to magnets in other circuits (CIRCUIT POWER ABORT).

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

- Some circuits are essential, i.e. required for beam operation under all circumstances. In case of a failure, the beams are dumped.
- Some circuits are not always required and a failure would not always generate a beam dump.

3.1.1 Electrical circuits with main magnets causing “subsector power abort”

The current loops (QUENCH LOOP) within the quench protection system are connected to all quench detectors for the main dipole and the two main quadrupole circuits in the arc cryostat. The interface from the QUENCH PROTECTION SYSTEM to the POWERING INTERLOCK SYSTEM is via the CIRCUIT QUENCH status. The POWERING INTERLOCK CONTROLLER can break the QUENCH LOOP. The interface to the power converter is via PC PERMIT, POWERING FAILURE, PC FAST ABORT and PC DISCHARGE REQUEST.

In the following several failure scenarios are considered:

Quench of a dipole magnet (or MQ magnet)	Step 1	Quench detector opens the MB (or the MQ) quench loop
	Step 2	Energy of the circuit is extracted by activating the discharge switches directly connected to the loop
	Step 3	The associated POWERING INTERLOCK CONTROLLER is informed, issues a PC FAST ABORT and switches the PC PERMIT off.
	Step 4	The POWERING INTERLOCK CONTROLLER issues a DISCHARGE REQUEST for the other main circuits QF and QD (in case of dipole quench)
	Step 5	All other circuits are discharged via a PC FAST ABORT command that links the POWERING INTERLOCK CONTROLLER to the power converters. For the magnets that require energy extraction, the power converter opens the dedicated extraction switch.

Power converter failure requiring fast discharge	Step 1	Power converter sends a PC DISCHARGE REQUEST to the POWERING INTERLOCK CONTROLLER
	Step 2	THE POWERING INTERLOCK CONTROLLER activates the discharge switch for this circuit by opening the quench loop (Note: for the MQX magnets in the triplet cryostat the heaters are fired, since the time constant for discharge is too long and there is no other system to extract the energy)

Power converter failure requiring slow discharge	Step 1	Power converter sends a POWERING FAILURE command to the POWERING INTERLOCK CONTROLLER
	Step 2	THE POWERING INTERLOCK CONTROLLER takes away the permission to power this circuit (PC PERMIT=OFF)

In case of a failure of a discharge switch that does not open after a request (SWITCH OPEN FAILURE)	Step 1	A number of selected heaters are fired to safely dissipate the energy of the magnets. A large amount of helium would be released. Therefore such event should only occur in emergency situations, and should never be accidentally triggered. This failure is handled within the QUENCH PROTECTION SYSTEM.
	Step 2	THE POWERING INTERLOCK CONTROLLER stops the power converter since the quench loop is broken.

Internal failure of the discharge switch	Step 1	The breakers will be automatically opened and the energy discharged.
	Step 2	A signal is send to the POWERING INTERLOCK CONTROLLER through the quench loop interface.

3.1.2 Electrical circuits with auxiliary magnets causing “circuit power abort”

Such electrical circuits require a QUENCH STATUS, PC PERMIT, POWERING FAILURE and PC FAST ABORT.

If one of the quench detectors for the circuit indicates a quench, the QUENCH STATUS is set to fault state and the power converter is switched off via the POWERING INTERLOCK CONTROLLER (PC FAST ABORT). If the circuit has an extraction resistor, the energy is extracted.

Magnets powered in other electrical circuits do not have to be discharged.

3.1.3 Interfaces of the powering interlock controllers to other systems

Interfaces to the beam interlock controller

From each POWERING INTERLOCK CONTROLLER two signals are input to a BEAM INTERLOCK CONTROLLER: ESSENTIAL CIRCUITS OK and AUXILIARY CIRCUITS OK.

Any failure in the POWERING SYSTEM causes the ESSENTIAL CIRCUITS OK signal or the AUXILIARY CIRCUITS OK signal to the BEAM INTERLOCK CONTROLLER to become false. Internal readable jumper or memory settings in the POWERING INTERLOCK CONTROLLER determine, whether the electrical circuit in question is considered “essential” for operation with beam.

A failure in one of the main magnets, such as dipole or quadrupole magnet or in some of other magnets, would cause a total loss of beam. In case of failure, the signal ESSENTIAL CIRCUITS OK goes to fault and causes a dump of the beams.

A failure in a circuit with a corrector magnet, such as spool piece, does not necessarily cause beam loss. In case of such failure, only the signal AUXILIARY CIRCUITS OK becomes false.

The definition if a circuit is considered as essential will be done in the future.

Interfaces to power converters and quench protection system

Figure 6 sketches the complex example of a long arc cryostat with two POWERING INTERLOCK CONTROLLERS, one on each side of the arc. The signals/links per electrical circuit for a POWERING INTERLOCK CONTROLLER are summarised in table 2. A signal can be logical “1” or “0”. Signals can be AC, voltage, or current. For an AC signal with a defined frequency, “1” corresponds to the presence of the AC signal and “0” corresponds to either no signal or a signal with a different frequency. For a voltage, “1” corresponds to high (defined voltage within a given range) and “0” corresponds to a voltage outside the defined range. For a current, circulating current corresponds to “1”; no current corresponds to “0”.

The hardwired signals between the components in each electrical circuit and the POWERING INTERLOCK CONTROLLER are:

1. QUENCH STATUS
2. POWERING FAILURE
3. PC PERMIT
4. PC FAST ABORT
5. PC DISCHARGE REQUEST (only from PCs for the RB, RQ and RQX circuits)

Interfaces to the control system

The POWERING INTERLOCK CONTROLLER is connected to the control system. Status and memory are readable at any time. Interfaces via the control system are with the cryogenic, quench protection, controls, access and timing systems.

3.2 Loops and Links

Three types of links are required.

- Point to point connections have one source and one receiver.
- Current loops are used to connect many sources to a few receivers.
- A field-bus can be used to create a software-based link in less critical cases, in particular to give permission for powering etc.

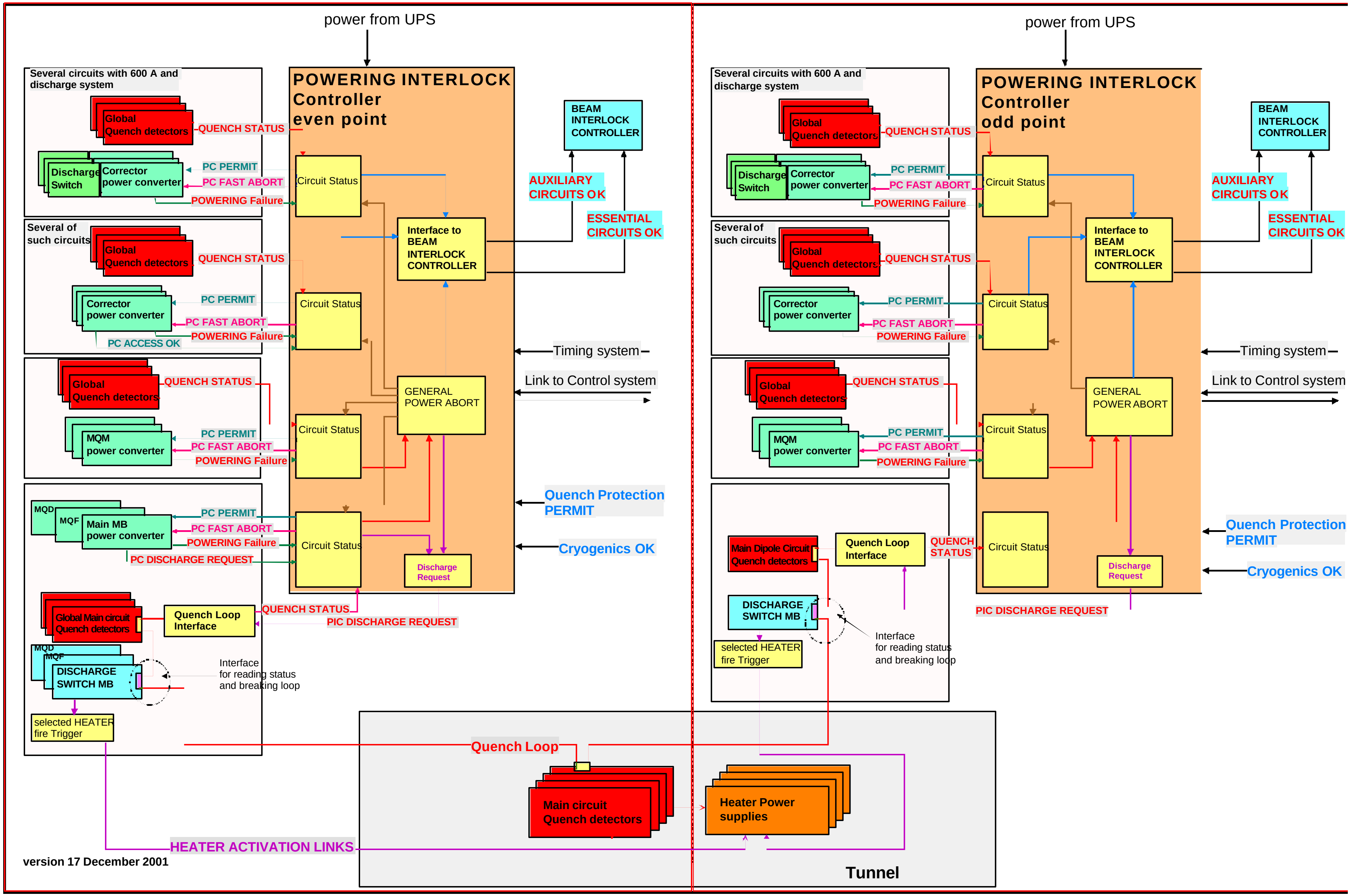


Figure 6: Powering interlock controller for one long arc cryostat.

Table 2 List of the signal names for the POWERING INTERLOCK CONTROLLERS

	Signal Name	Meaning if signal = I	Meaning if signal = 0	From	To	Number
1	CIRCUIT QUENCH	No quench detected	Quench	QPS	PIC	1 per electrical circuit
2	POWERING FAILURE	PC and auxiliaries OK	Failure of PC or other element	PC	PIC	1/circuit
3	PC PERMIT	PC may start	PC start inhibit / slow abort	PIC	PC	1/circuit
4	PC FAST ABORT	PC operation permitted	PC fast off	PIC	PC	1/circuit
5	PC DISCHARGE REQUEST	PC OK, no request for fast discharge	PC failure that requires fast discharge	PC	PIC	1 per PC for RB, RQF, RQD and RQX (fire heaters)
6a	PIC DISCHARGE REQUEST	No action of discharge switch	Discharge switch open request	PIC	Discharge Switch	3 for each even arc, 1 for odd arc, for RB and RQF / RQD
6b	PIC DISCHARGE REQUEST	No firing of heaters	Fire heaters	PIC	QPS	One for each triplet to fire quench heaters, (RQX)
7	AUXILIARY CIRCUITS OK	All auxiliary circuits OK	Failure in at least one auxiliary circuit	PIC	BIC	1 per PIC
8	ESSENTIAL CIRCUITS OK	All circuits essential for beam OK	Failure in at least one essential circuit	PIC	BIC	1 per PIC
9	CRYO OK	Cryogenics ready for powering	Cryogenics Failure	Cryogenics	PIC	1 per PIC
10	DATA I/O			Control System	PIC	1 per PIC
11	TIMING SYSTEM			Timing System	PIC	1 per PIC
12	QUENCH PROTECTION PERMIT	Quench protection system ready	Quench Protection system not ready	QPS	PIC	1 per PIC

3.2.1 Quench loops

For electrical circuits that include magnets with large stored energy there is one current loop connecting all quench detectors and the discharge switches. There is one current bop for the RB circuit and one current loop for both RQ circuits, since both circuits will be discharged in case of a quench of other failure. In case of a quench, the loop informs the equipment connected to the loop, such as discharge switches and POWERING INTERLOCK CONTROLLER. The time between the detection of a quench and the breaking of the loop is about 20 ms. The POWERING INTERLOCK CONTROLLER can give a signal to break the current loops to discharge the circuits, if required.

3.2.2 Heater activation link

If a discharge switch fails to open, the stored magnetic energy is distributed across a large fraction of the magnets by activating a large number of quench heaters. The command is issued by the control electronics of the extraction switches. The stored energy is transferred into the helium, possibly loosing large amount of helium. Hence, this link should not be activated accidentally. The POWERING INTERLOCK CONTROLLER cannot issue this command. In one sector two links for circuits with main dipole magnets and one link for both quadrupole circuits will be available.

3.2.3 Link to the power converters for orbit corrector magnets

Failure of an orbit corrector: 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 break the BEAM PERMIT LOOP. However, another mechanism of breaking to inform the interlock system might be required. The status of all power converters will be available every 10 ms. If it should be required to dump the beam if one of the corrector magnet power converters goes to fault state, this could be done via software. Details and the time constants that are required need to be defined.

Protection of current leads for orbit corrector magnets: The current leads for the orbit corrector magnets are made out of copper. To limit the heat load, the leads are rather thin and thermalised. In case of a thermal runaway, the power converters must be switched off. Therefore an electronic module inside the power converter measures the voltage across the leads, and if the voltage exceeds a threshold, the power converter is switched off.

Power permit for power converter: The power converters for orbit corrector magnets in the long arc cryostat need to know the status of the cryogenics and the main magnet circuits. Permission for powering can only be given if the magnets are cold. After a quench in a main magnet (MB or MQ) the power converters for the corrector magnets should also be switched off. The response time is not critical (some 100 ms). Since every corrector power converter/ magnet assembly is designed to switch off after a quench of the corrector magnet by itself, a dedicated hardware link to each power converter is not required. The information could be exchanged using existing elements of the control system.

4 BEAM INTERLOCK SYSTEM

4.1 Beam interlock controllers

The BEAM INTERLOCK CONTROLLER combines the messages from different systems to one output: BEAM PERMIT, yes or no. The transition of the BEAM PERMIT state from latter YES to NO automatically triggers the BEAM DUMP REQUEST.

The BEAM INTERLOCK CONTROLLER interrupts a pulse train (possibly with a frequency of 10 MHz) transmitted along an optical fibre of the BEAM PERMIT LOOP in case of a failure condition. The absence of the pulse train will be interpreted as no BEAM PERMIT.

Two types of input signals from the equipment systems are possible:

- Unconditional inputs: if such inputs are in fault state, the pulse train will be interrupted. Such inputs cannot be disabled via the control system.
- Conditional inputs: if such inputs are in fault state, the pulse train might be interrupted, depending on other conditions defined by the machine status. Such inputs can be disabled via the control system.
- The pulse train is produced in one BEAM INTERLOCK CONTROLLER only. The setting of the jumper (master/slave) is visible at the front panel and readable from the computer.

All input states and the output state are continuously sampled and stored into a memory at a rate to be defined. The BEAM DUMP REQUEST and the post mortem trigger freeze the state of the memory. It can be considered to employ separate memories for the two cases.

All input states and the output state are displayed on the front panel.

The control system enables/disables the conditional inputs, senses the memory state (frozen or life) and performs the readout.

Table 3 summarises the inputs of the BEAM INTERLOCK CONTROLLER that will be updated according to the definition of the POWERING SUBSECTORS, to be discussed and confirmed later.

Figure 7 depicts symbolically a BEAM INTERLOCK CONTROLLER with all inputs and outputs.

Table 3 Input signals to the BEAM INTERLOCK CONTROLLER (preliminary)

Channel	Name	Possibility to disable input
1	RF system	Yes
2	Loss monitors around the ring	Yes
3	Beam excursion	Yes
4	Spare	Yes
5	Spare	Yes
6	Spare	Yes
7	Spare	Yes
8	Arc powering subsector, auxiliary circuits ok	Yes
9	Triplet powering subsector, auxiliary circuits ok	Yes
10	Spare, depending on powering subsectors	Yes
11	Spare	Yes
12	Spare	Yes
13	Spare	Yes
14	Spare	Yes
15	Spare	Yes
16	Experiment OK	No
17	Loss monitors at collimators	No
18	Collimators	No
19	Access system OK	No
20	Extraction system OK	No
21	Beam Injection Permit	No
22	Vacuum valves beam 1 OK	No
23	Vacuum valves beam 2 OK	No
24	Arc powering subsector, essential circuits ok	No
25	Triplet powering subsector, essential circuits ok	No
26	Spare, depending on powering subsectors	No
27	Spare	No
28	Spare	No
29	Spare	No
30	Spare	No
31	Warm magnets	No

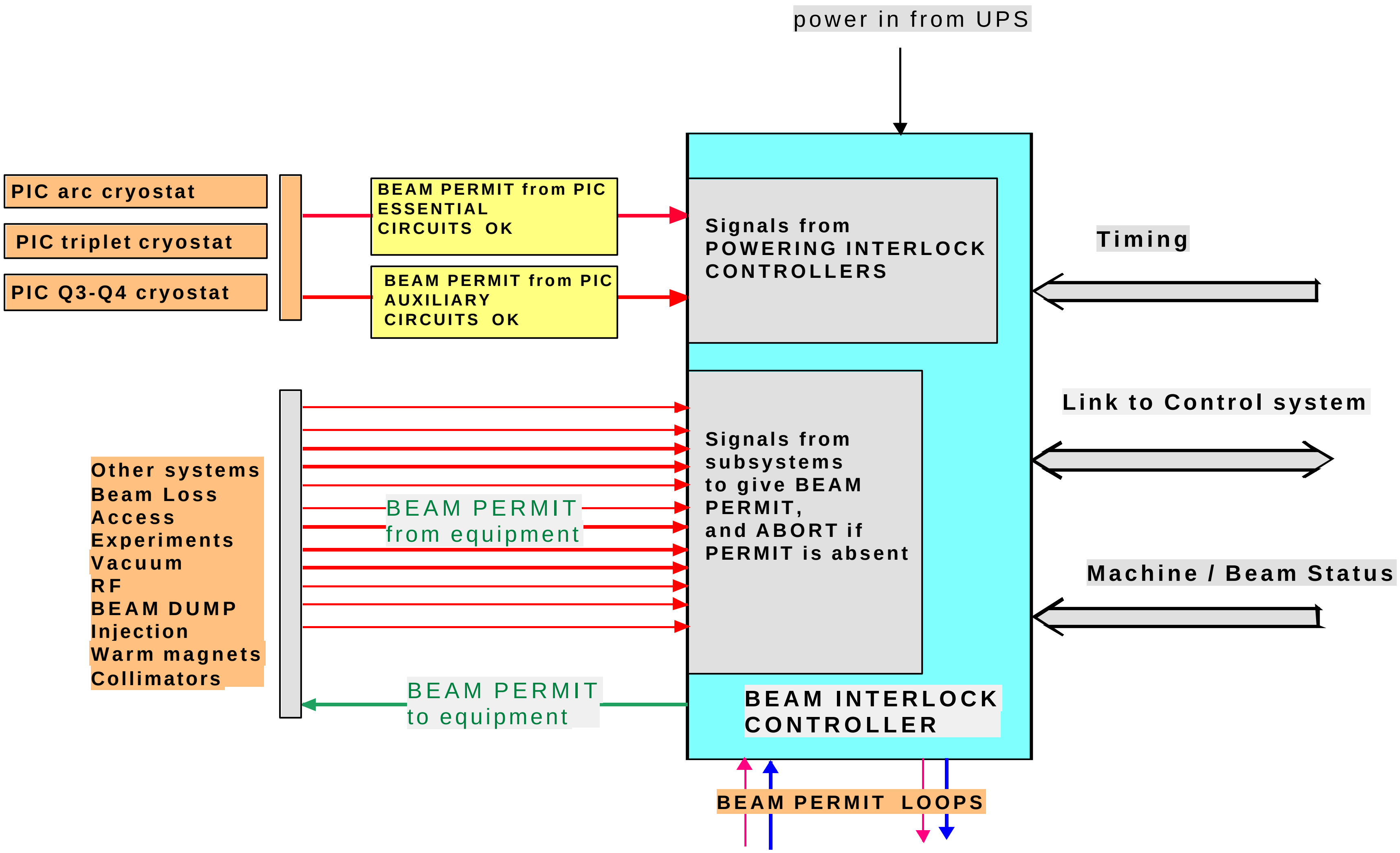


Figure 7: Example for one of the Beam interlock controllers.

4.1.1 Inputs from the powering interlock controllers

Each POWERING INTERLOCK CONTROLLER sends two signals to the BEAM INTERLOCK CONTROLLER (ESSENTIAL CIRCUITS OK, AUXILIARY CIRCUITS OK).

If the signal ESSENTIAL CIRCUITS OK goes to the fault state, the beam is dumped. If the signal AUXILIARY CIRCUITS OK will go to a fault state, this would not necessarily require a beam dump. The required action depends on the machine status. If, for example, the beam intensity is small, there is no need to dump the beams (conditional beam dump).

4.1.2 Inputs from the beam dump system

If the BEAM DUMP SYSTEM is not ready, injection of beam must be inhibited. A breakdown of the BEAM DUMP SYSTEM would present a major hazard, if beams were circulating. Beams must be dumped, as long as the system is still operational. It is not possible to mask the signal.

4.1.3 Input from LHC experiments

The BEAM INTERLOCK CONTROLLER accepts a signal from the LHC experiments. The details will be discussed with the experiments. With physics operation (top energy, luminosity, beams stable) experiments might require moving devices closer to the beams. If such device is not completely in OUT position, any injection must be strictly inhibited.

4.1.4 Input from RF system and transverse feedback

If the RF system does not work correctly, the beam will debunch. The beam dump can not be synchronised with the abort gap in the bunch train and intolerable beam losses would be generated during the dump. A signal from the RF system is required to dump the beam, if debunching is anticipated. The time constant for debunching is in the order of several 100 ms [12].

A failure of the transverse damper might cause a beam loss within very short time. An incorrect operation of the transverse feedback must trigger a beam dump. The details have to be finalised.

4.1.5 Input from resistive magnet system

A failure of the warm magnets in the insertions could occur due to a failure of the magnet itself, for example due to overheating of the coils or a short circuit between turns, or due to a failure of the power converter. The magnets will be equipped with temperature sensors. When the temperature exceeds the permissible value, the beam is dumped and powering is aborted. One dedicated POWERING INTERLOCK CONTROLLER for the each IP could monitor the power converters for warm magnets. Since the power converters are located in the surface buildings, the controller could also be installed in the surface building. Another option is to include the interlocks for electrical circuits with warm magnets into a POWER INTERLOCK CONTROLLER for the cold magnets in the vicinity.

4.1.6 Input from the beam loss monitor system

Beam loss monitors will be distributed around the ring, with a set of monitors close to each quadrupole, as well as monitors close to the collimators for beam cleaning. The signature of a beam loss that should request a beam dump remains to be established.

4.1.7 Input from access system

The ACCESS SYSTEM is a system for the personal safety that needs to follow legal requirements. It needs to be independent from the equipment protection. However, there is an interface between the state of the ACCESS SYSTEM and the actions to be taken by the MACHINE INTERLOCK SYSTEM. The BEAM INTERLOCK CONTROLLER will automatically request a beam dump in case of an access violation. A separate link from the ACCESS SYSTEM to the BEAM DUMP SYSTEM is required that is not part of the MACHINE INTERLOCK SYSTEM.

4.1.8 Other inputs

There will be some elements to prevent the accidental injection and circulation of beam, such as valves in the beam tubes, collimators and some magnets in the transfer line. Such systems are activated if access to the tunnel or the galleries should be given, or after an access violation. Concerning valves, collimators and detectors, injection is inhibited unless they are moved out of the beam.

4.1.9 Outputs

The 10 MHz pulse train that connects the BEAM INTERLOCK CONTROLLERS is one of the outputs. There might be an output required to inform other systems about the status of the BEAM PERMIT LOOP. Finally, there will also be a connection to the computer network.

4.2 Beam permit loop

Two such loops run around the entire accelerator. The signal needs to be transmitted as fast as possible to the BEAM DUMP SYSTEMS. The loop is connected to 16 BEAM INTERLOCK CONTROLLERS around the LHC. Hence, a transmission using optical fibres is proposed.

4.3 Computer link

The BEAM INTERLOCK CONTROLLER is connected to the control system that provides the machine status and the timing information, and reads out the post mortem data.

4.4 Beam abort from the control system

In order to protect equipment from serious damage, hardware interlocks are used. For increasing the operational efficiency, soft aborts are suggested that are generated by software and transmitted via the computer links. For example, in case of a technical problem in one cryo-plant the cooling of the cryostats cannot continue for more than, say, several minutes. In order to prevent magnets from quenching, the information is sent to the control room. This allows the operators to dump the beams and discharge the magnets in this cryostat. If this action would not be taken, the hardwired protection systems would still protect the equipment.

Such soft aborts do not require specific hardware and will be discussed in a future paper.

5 IDEAS FOR THE HARDWARE REALISATION

5.1 Signal transmission

Some general rules need to be applied to all electrical and optical signals, in order to ensure that the interlock system is fail-safe. The presence of a signal represents the safe state (there will be one exception – the signal for firing many heaters if the energy extraction should fail).

- There are several options to exchange electrical signals between systems:

  1. generated by a low impedance voltage source,
  2. generated by a current source with a large compliance to accommodate resistive voltage drops and opto-couplers (current loop),
  3. differential (square waves, RS485 compliant)
  4. A safe condition can be signalled by the presence of a square wave (1 kHz – 10 MHz) or a defined current within a voltage range. The absence of the square wave or of the connection is considered as a failure. Note that a second frequency or a current with a voltage outside a certain range can be used to indicate a TEST state.

- Cables must be shielded. The shield shall be tied to ground at both sides.
- Alternatively industrial compatible logic (24 V) as used by PLCs (Programmable Logic Controllers) can be considered.
- Optical fibre signals need to be square waves (10 MHz or similar). The absence of the square wave is considered as a failure.

For the signal exchange between POWERING INTERLOCK CONTROLLER and other systems one standard will be defined that becomes compulsory. The signal exchange between BEAM INTERLOCK CONTROLLER and other systems must be faster since the beam need to be dumped in a few turns, and an appropriate standard will be defined.

5.2 Beam interlock system

The system consists of 16 clusters (VME Crates or another standard, to be defined). All crates are connected to regularly serviced uninterruptible power supplies (UPS). The power supplies for the interlock electronic have to consist of redundant pairs, connected together with diodes, because power electronics is most likely to fail. Their status must be visible for the control system.

The crate controllers are connected through a field-bus and/or Ethernet to the control system. The crate controllers contain always a mirror of the current states of all components connected to the particular crate and of its history. The time-steps for the history recording depend on the particular data channel. The history recording stops with some delay after the POST MORTEM TRIGGER.

Users of equipment connected to the MACHINE INTERLOCK SYSTEM are responsible for the integrity of their signals up to the input connector or from the output connector of the interlock equipment, including the cables.

The inputs for the BEAM INTERLOCK CONTROLLER must be fail-safe and reliable.

5.3 Beam permit loop

The BEAM PERMIT LOOP must act fast on the dump kickers. We propose to use two optical fibres, one for each beam. This ensures that the dump signal reaches the kickers after at most one turn after the loss at one of the two cleaning sections. Spare fibres are required.

The link will only be used for the BEAM PERMIT signal despite the available bandwidth, assuming that simplicity results in enhanced reliability. A 10 MHz (or similar frequency) square wave signal is sent from the controller IP6L (close to the beam dump) clockwise for one beam around the ring, respectively counter-clockwise.

5.4 Powering interlock controller

Decision logic combined with a computer (VME or PLC) communication port receives and transmits status and commands via input/output sections. As a controller can have several ten I/O subsections, it might be advantageous to arrange the I/O sections outside the crate with the processor.

6 INVENTORY OF THE MACHINE INTERLOCK SYSTEM

An estimate for the inventory of the MACHINE INTERLOCK SYSTEM is:

- sixteen (16) BEAM INTERLOCK CONTROLLERS,
- a global fast link between the BEAM INTERLOCK CONTROLLERS and the BEAM DUMP SYSTEM with at least two channels,
- between 30 and 40 POWERING INTERLOCK CONTROLLERS,
- several POWERING INTERLOCK CONTROLLERS for the warm magnets, with the details to be worked out.

7 CONCLUSIONS

In this paper the architecture of the interlock system for the protection of LHC equipment is discussed, and ideas for the realisation are presented. Since the first application is for the hardware commissioning of one LHC sector in 2004, the POWERING INTERLOCK SYSTEM is required first. An Engineering Specification for this system will be written, followed by a specification for the BEAM INTERLOCK SYSTEM. The interfaces between these interlocks systems and other systems will be discussed in the Working Group on Machine Protection, and specified in the Engineering Specifications. The realisation of the system, using VME, PLCs, or another standard, will be decided later.

Other open questions that will be addressed in the future:

- Definition of the POWERING SUBSECTORS and conditions for access.
- Definition of the machine status.
- Definition of the post mortem recording.
- Beam loss monitor systems and conditions to dump the beam.
- What circuits should be considered to be essential for beam operation?
- Definition of test modes for both, beam interlock and powering interlock systems.

8 ACKNOWLEDGEMENTS

The authors like to thank numerous colleagues that have been involved in the discussions. In particular we appreciate the input of E. Cennini, B. Dehning, Q. King, R. Saban, V. Mertens, E. Weisse and M. Zerlauth.

9 REFERENCES

[1] K. Dahlerup-Petersen et al., The protection system for the superconducting elements of the Large Hadron Collider at CERN, Proceedings of the 1999 Particle Accelerator Conference, New York, p. 3200ff.

[2] J.M. Zazula and S. Peraire, LHC Beam Dump Design Study, Part I: Simulations of energy deposition by particle cascades; implications for the dump core and beam sweeping system, CERN LHC Project Report 80 (1996).

[3] J.M. Zazula and S. Peraire, LHC Beam Dump Design Study, Part II: Thermal analysis, implications for abort repetition and cooling system, CERN LHC Project Report 87 (1996).

[4] L. Bruno et al., LHC Beam Dump Design Study, Part III: Off-normal operating conditions, CERN LHC Project Note 217 (2000).

[5] C. Bovet, A BLM system for the LHC ring, CERN LHC Project Note 220 (2000).

[6] A.A. Garcia and B. Dehning, Configuration of the beam loss monitors for the LHC arcs, CERN LHC Project Note 238 (2000).

[7] J.B. Jeanneret, Handling the proton beams much above the quench limit, 10th Workshop on SPS-LEP Performance, Chamonix, CERN-SL-2000-007-DI (2000).

[8] E. Cennini, LHC Workshop, Chamonix 11 (2001), CERN-SL-2001-003-DI.

[9] F. Bordry, Power Converters, LHC Workshop, Chamonix 11 (2001), CERN-SL-2001-003-DI and “Review of LHC Power Converters”: http://wwwlhc01.cern.ch:8050/lhc_proj/owa/lhcp.page?p_number=7220

[10] Werkstoff Handbuch, Nichteisenmetalle III, H. Stendel (ed.), VDI-Verlag, Düsseldorf (1960).

[11] A. Ballarino, High Temperature Superconducting Current Leads for the Large Hadron Collider, CERN LHC Project Report 337 (1999) and 4th European Conference on Applied Superconductivity, Sitges, Spain, 14-17 September 1999.

[12] O. Brüning, Mechanisms for beam losses and their time constants, LHC Workshop, Chamonix 11 (2001), CERN-SL-2001-003-DI.

[13] General Parameters for equipment installed in the LHC, Engineering Specification, LHC-PM-ES-0002.00.

[14] L.Tavian, LHC Workshop, Chamonix 11 (2001), CERN-SL-2001-003-DI.

[15] LHC Drawing Directory CDD, LHCLSD1_0001 to LHCLSD8_0008, version A, optics 6.3, June 2001.

[16] F. Bordry et al., The Interlock System for String2: Power enable and abort, LHC-XMS-ES-00001.00, January 2000.

[17] R. Lauckner, What data is required to understand failures during LHC operation, LHC Workshop, Chamonix 11 (2001), CERN-SL-2001-003-DI.

10 GLOSSARY

General names of systems	Description
MACHINE PROTECTION SYSTEMS	Generic Name for the systems discussed here dedicated to the protection of the LHC
MACHINE INTERLOCK SYSTEM	Generic Name for the INTERLOCK SYSTEMS discussed here (beam interlock and powering interlock systems)
BEAM INTERLOCK SYSTEM	System including electronics and optical links to enable BEAM PERMIT and issuing BEAM DUMP REQUESTS
POWERING INTERLOCK SYSTEM	System to enable and abort powering of electrical circuits (POWER PERMIT and POWER ABORT)
BEAM DUMP SYSTEM	Includes all elements that are required to dump the beam after receiving a BEAM DUMP REQUEST
POWER CONVERTER SYSTEM	Includes all power converters
POWERING SYSTEM	Includes all power converters and all elements of the circuits to connect a power converter to the current leads on the DFBs
BEAM LOSS MONITOR SYSTEM	System of beam loss monitors present along the arcs and the insertions
ACCESS SYSTEM	System to provide access for people to enter into the LHC underground areas, for protection of personnel
QUENCH PROTECTION SYSTEM	System that protects and monitors all superconducting elements in the LHC, for protection of equipment

Other names	Description
ELECTRICAL CIRCUIT	Includes all elements in one circuit to power magnets: power converters, warm cables, feedthroughs from warm to cold, superconducting busbars and magnets
POWERING SUBSECTOR	Limited stretch of the machine that can be independently powered

Name of hardware	LHC Naming Convention	Description
POWER CONVERTER	**RP**	Power converter to power the magnets in an electrical circuit
BEAM INTERLOCK CONTROLLER	**CIBC**	16 BEAM INTERLOCK CONTROLLERS are installed in the LHC, located left and right from each IP
POWERING INTERLOCK CONTROLLER	**CIPC**	For each POWERING SUBSECTOR there is one such CONTROLLER, except for the arc cryostat with two of such controllers (right and left)
DISCHARGE SWITCH	**DQS**	Switch in order to extract energy, installed in circuits for MB, MQF, MQD and many of the 600 A circuits

Name of a state	Description
CIRCUIT POWER ABORT	State for each individual electrical circuit in a powering subsectors, if power abort for the circuit is activated
SUBSECTOR POWER ABORT	A power abort for all electrical circuits in one of the powering subsectors is activated
BEAM PERMIT	YES: Beam(s) are allowed to be injected / to circulate. NO: Beam(s) are not allowed to be injected / to circulate – the transition from YES to NO generates a BEAM DUMP REQUEST

Signals	From	To	Remarks
ESSENTIAL CIRCUITS OK	CIPC	CIBC	All electrical circuits in the powering subsector that are essential for beam operation are operational
AUXILIARY CIRCUITS OK	CIPC	CIBC	All auxiliary electrical circuits in one powering subsector are operational
PC PERMIT	CIPC	Power converter	Permit to power converter, ok state. If not present => Slow power converter abort
PC FAST ABORT	CIPC	Power converter	Fast power converter abort, fault state
POWERING FAILURE	Power converter	CIPC	Power converter or any circuit component at warm (DC cables, water, etc.) not ok, fault state
PC DISCHARGE REQUEST	Power converter	CIPC	Powering failure that does require fast discharge of the energy in the circuit
PIC DISCHARGE REQUEST	CIPC	Quench Protection System	Signal from powering interlock controller to quench protection system to discharge one of the main circuits (RB, RQ)
CIRCUIT QUENCH	Quench Protection System	CIPC	Signal from quench protection system for every electrical circuit if there is a quench in the circuit
QUENCH PROTECTION PERMIT	Quench Protection System	CIPC	Protection system ready for powering, heaters charged, etc., via network. When it disappears during powering it will not generate any power abort
CRYOGENICS OK	Cryo	CIPC	Cryogenics system ready to power all elements in one powering subsector
BEAM DUMP REQUEST	CIBC	BEAM DUMP SYSTEM	One or both beams are aborted by breaking the BEAM PERMIT LOOP from one of the 16 beam interlock controllers

Loops / Links	Abbreviation	Remarks
QUENCH LOOP	DQPAL	Current loop for the main circuits in the quench protection system
HEATER ACTIVATION LINK	DQHAL	Current loop that activates selected heaters if energy extraction fails
BEAM PERMIT LOOP	CPBPL	Link with optical fibre between the set of 16 beam permit controllers