Chapter 6

Powering and protection

6.1 Overview

A very large number of superconducting and normal conducting magnets will be installed in the LHC, and most magnets of a given type in the same sector will be powered in series families. In total, the LHC will have 1'612 different electrical circuits for superconducting and normal conducting magnets. To limit the stored magnetic energy and the voltages that will be experienced during energy extraction (a quench), magnet families do not extend over more than one sector. In most cases, however, the stored energy is still sufficient to damage superconducting magnets, and hence a sophisticated protection system is essential.

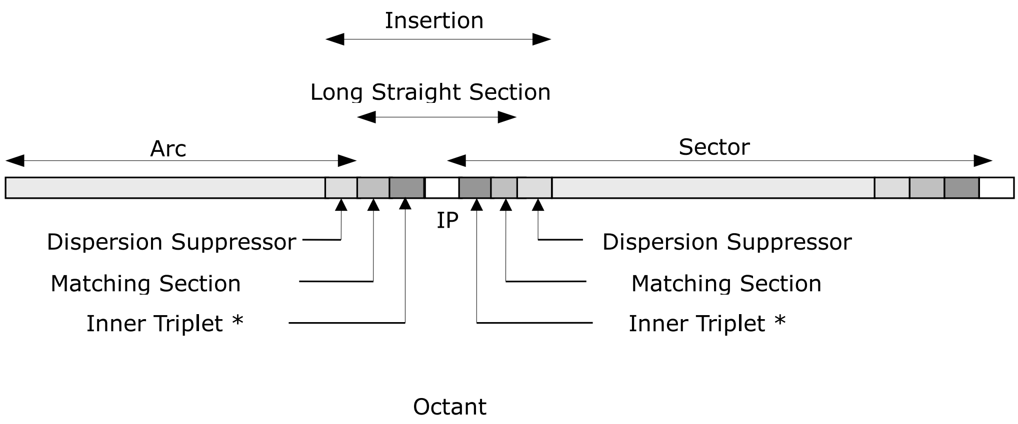
6.2 Powering circuits

The LHC magnets are powered in eight independent and symmetric sectors (see figure 6.1). Within these sectors, more than 40 different cryostats house the superconducting magnets, while the normal conducting magnets are located in the LSSs close to the IPs (except for IP 4, where there are no normal conducting magnets). The higher radiation levels in the cleaning insertions (IR3 and IR7) and around experiments with high luminosity (IP2 and IP8) prevent the use of superconducting magnets. Here normal conducting magnets are employed. Eight long arc cryostats span the major part of the circumference and contain the main bending and focusing magnets. Smaller cryostats located around the interaction points house magnets that are specifically required for each insertion.

The total of 1'612 electrical circuits is composed of 131 types, connecting main bending magnets, magnets for beam focusing, dipole field correctors, or higher order correctors. Some types appear in each of the eight sectors (e.g. the main dipole circuit), while others are only present in dedicated insertions (as, for example, a warm compensator for the ALICE experiment). The detailed description of this complex electrical system is available in the LHC Reference Database [34], which also contains the connection information for all 1'612 electrical circuits.

The eight sectors have been subdivided into 28 powering sub-sectors of four different types, as shown in figure 6.2.

- 8 Arc Powering Sub-sectors, containing all powering equipment related to magnets in the arc cryostats.



* Inner triplets are only present in insertions with physics experiments.

Figure 6.1: Sectors and octants in the LHC.

- 8 Powering Sub-sectors for powering of the inner triplet cryostats, housing the magnets for Q1 to Q3 for the insertions with physics experiments and additionally D1 in the insertions 2 and 8.
- 12 Powering Sub-sectors to power magnets in smaller cryostats in the matching sections, containing individually powered quadrupoles and separation and combination dipoles.
- 7 Powering Sub-sectors for powering of normal conducting magnets left and right of an IP.

Every electrical circuit and the associated electrical components in the LHC tunnel is allocated to a Powering Sub-sector. As such, the powering in each of the powering sub-sectors is independent of the powering of the other sub-sectors.

Each of the eight symmetrical LHC sectors will contain one electrical circuit (called RB), connecting all main bending magnets in series. The main quadrupoles are powered in each sector in two electrical circuits (RQF and RQD) dedicated to focusing and defocusing the two beams. The power converters for these three main circuits in each of the eight sectors are located in an underground area (UA) close to the even insertion regions. The currents enter the cryostat through a nearby DFBA feedbox. The stored energy in these circuits amounts to 1.22 GJ for the main dipole[1] and 20 MJ for each of the main quadrupole circuits. For the main dipole circuit an energy extraction system (consisting of a high current switch in parallel with the extraction resistor) is placed on either side of the arc cryostat, while only one system for either of the quadrupole circuits is sufficient. Figure 6.2 illustrates the powering layout for the eight long arc cryostats.

A number of higher-order correctors are installed in every dipole assembly in the long arc cryostat to compensate the field errors of the main dipoles. Two different types of dipole assemblies are installed alternately in the LHC arcs. In addition to the main dipole coil on each of the two beam pipes the MBA type provides a combined decapole-octupole-corrector (MCDO) at the connection side of the cryo-assembly and a sextupole corrector (MCS) at the far end of the cryo-assembly.

[1] At ultimate energy and using the measured value for the inductance (100 mH).

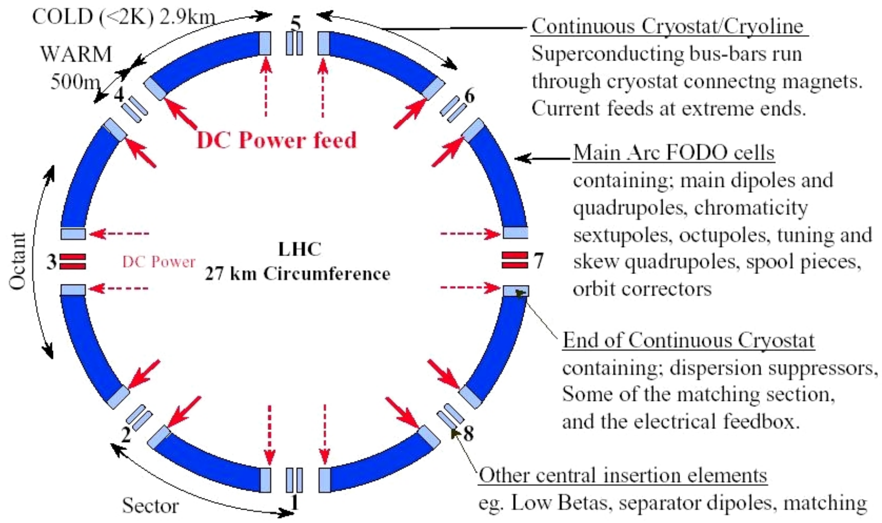


Figure 6.2: Powering of the eight arc cryostats.

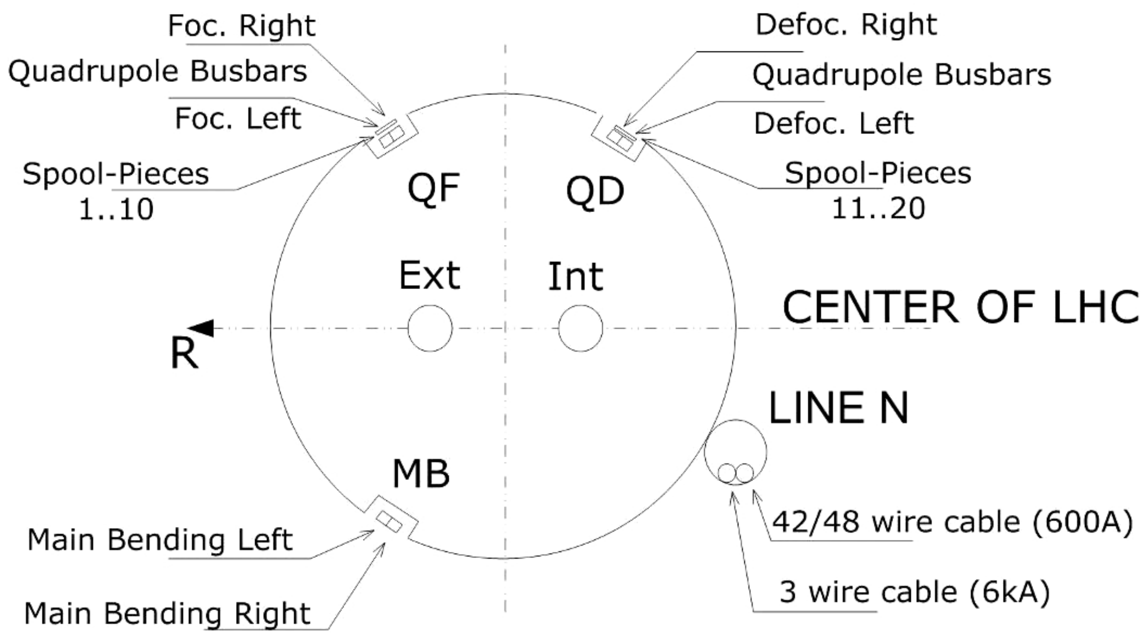


Figure 6.3: Cross-section of LHC arc cryo-assembly with bus-bars.

The MBB type only contains a sextupole corrector at the far end beside the main dipole coil. All correctors of a given family are connected in series for each of the two beams. The circuit families RCS, RCO and RCD (Sextupole, Octupole and Decapole) are connected throughout the cryostat via twenty so-called spool-piece bus-bars, (grouped in bundles of five bus-bars), located on top of the two main quadrupole bus-bars (see figure 6.3).

The SSSs in the LHC arcs contain two independent main quadrupole magnet coils, two higher-order corrector magnets at the upstream connection side, and two orbit corrector dipoles

Table 6.1: Correctors in the arc SSS.

Circuit Function	Families	Magnet Type	Circuit Type
Tuning Quadrupoles	2 families/arc	MQT	RQTF, RQTD
Skew Quadrupoles	In even sectors, Beam 1 & in odd sectors Beam 2: 2 families/arc	MQS	RQS
	In odd sectors, Beam 1 & in even sectors Beam 2: 1 family/arc	MQS	RQS
Chromaticity Sextupoles	4 families/arc	MS	RSF1, RSF2, RSD1, RSD2
Skew Sextupoles	1 family/arc	MSS	RSS
Octupoles	2 families/arc	MO	ROF, ROD

as well as two sextupoles at the downstream side. The orbit corrector magnets are powered with currents of up to 60 A (120 A for SSSs in the DS sections) and are connected to the power converter via current feedthroughs, mounted on a flange on the SSS service module. The correctors on the so-called "connection end" of the SSS are routed throughout the arc cryostat via a special cable, consisting of 42 (sometimes exceptionally 48) superconducting wire cables. This cable does not run through the magnets but through a special pipe (line N), which is attached to the outside of the cold masses. This special cable is connectable only in the upstream interconnection plane of each SSS in the arc (see figure 6.4). To limit the number of wires and hence the size of this cable, each wire will be used in two different electrical circuits, as shown in figure 6.4. An overview of the corrector family types in the arc SSS can be found in table 6.1.

There are also circuits (for mainly individually powered magnets) for the DS and MS regions, the normal conducting magnets in the cleaning insertions, the separation regions, experimental insertion regions including the low-beta inner triplets, and the RF insertion.

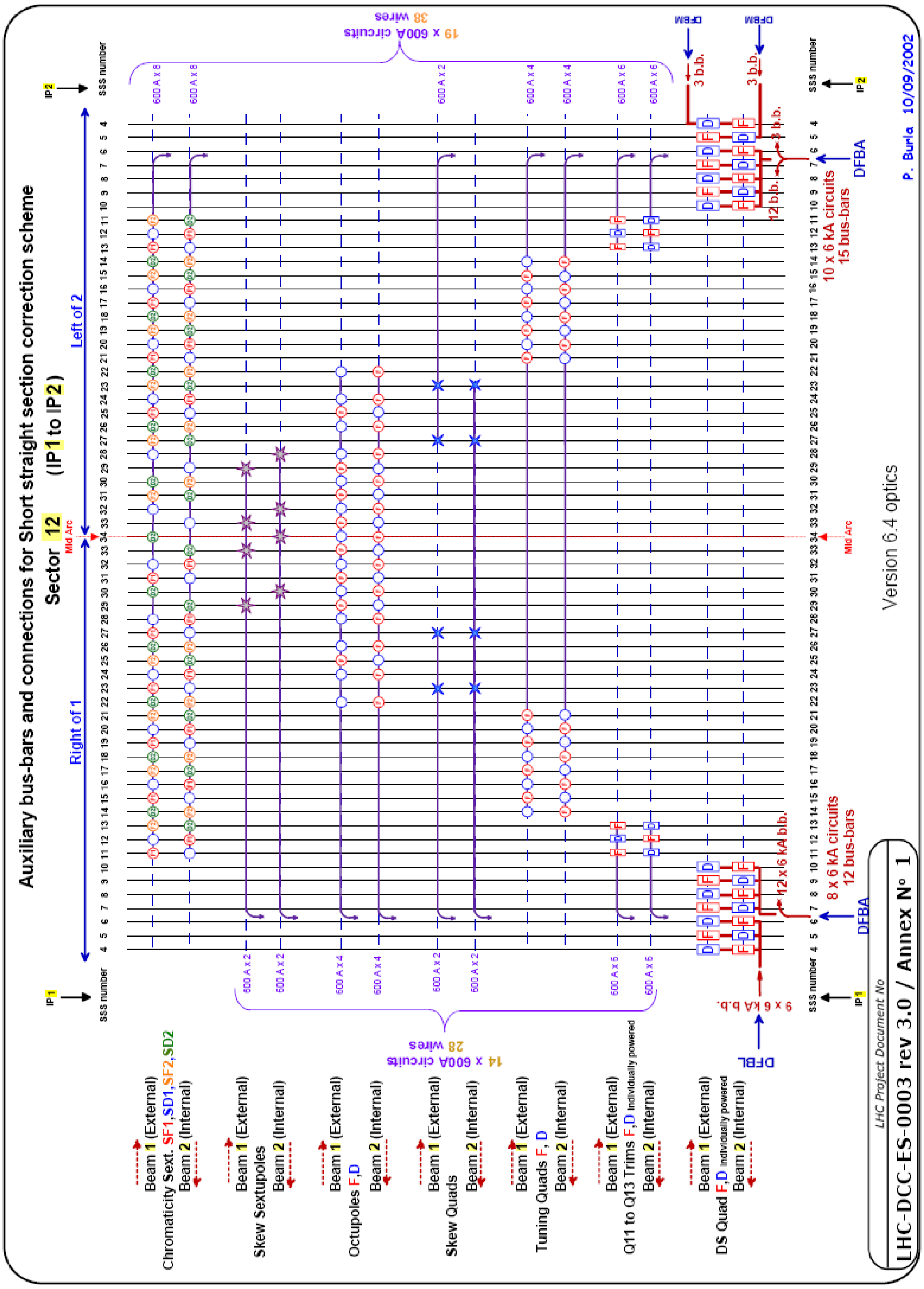


Figure 6.4: Example of the correction circuit layout (sector 12).

Figure 6.5: 13 kA CERN prototype HTS current lead.

6.3 Powering equipment

6.3.1 Current leads

For the 1'612 electrical circuits in the LHC, a total of 3'286 current leads are needed to connect the superconducting wires or cables to the power supply cables, which are at ambient temperature. The design of these leads aims at high reliability and low heat load. A total of 1'070 leads, operating between 600 A and 13 kA, incorporate a section with high-temperature superconducting (HTS) material (see figure 6.5). The higher investment costs are amply compensated by the low heat load. All other leads use copper as conductor. To feed the electrical circuits of the inner triplet magnets with up to 600 A, 112 gas cooled leads are used. The remaining 2'104 leads feed the 60 A or 120 A electrical circuits of the orbit corrector dipoles, the sextupoles of the inner triplets, and the octupole and dodecapole correctors.

6.3.2 Electrical feedboxes

The HTS current leads described above are mounted in cryogenic electrical distribution feedboxes (DFB). The limited space in the LHC tunnel requires the use of two different strategies. If the space is sufficient, the current is transferred to the arc magnets or to standalone magnets through locally installed DFBs. When the integration of a DFB close to the superconducting magnets is not possible, the magnets are powered through superconducting links (DSL) that connect the DFBs and the superconducting magnets at distances between 70 m and 500 m. There are four different types of DFBs listed in table 6.2.

Table 6.2: List of DFB and their current leads.

DFB type	Number	Type of leads (nb/DFB)
DFBA	16	13kA (2-6), 6kA (0-15), 600A (0-52), 120A(0-8)
DFBM	23	6kA (0-5), 600A(0-4), 120A(0-12)
DFBL	5	6kA (0-5), 600A(0-44), 120A(0-12)
DFBX	8	7.5kA (4-6), 600A (10), 120A (14)

Table 6.3: DSL summary.

Name	Description
DSLA	Type-1: connects the DFBLA current feedbox located in alcove RR13 to the three magnet cryostats of Q6, Q5, and Q4D2 in the LHC main tunnel.
DSLB	Type-1: connects the DFBLB current feedbox located in alcove RR17 to the three magnet cryostats of Q6, Q5, and Q4D2 in the LHC main tunnel.
DSLC	Type-2: connects the DFBLC current feedbox located in the UJ33 alcove to the DFBAF current feedbox located in the LHC main tunnel. The routing is from the UJ33 alcove through the UP33 tunnel (about 46 m long) and then through a part of the LHC main tunnel (about 462 m long).
DSLD	Type-1: connects the DFBLD current feedbox located in alcove RR53 to the three magnet cryostats of Q6, Q5, and Q4D2 in the LHC main tunnel.
DSLE	Type-1: connects the DFBLE current feedbox located in alcove RR57 to the three magnet cryostats of Q6, Q5, and Q4D2 in the LHC main tunnel.

The DFBXs electrical distribution feedboxes provided under the USA-CERN collaboration, feed the inner triplets at Interaction Points 1, 2, 5 and 8.

6.3.3 Superconducting links

Whenever it is impossible to mount a DFB close to the magnets, the electrical current is transferred from the DFBs to the LHC magnets through superconducting links (DSL). The links carry currents in the range of 120 A to 6 kA. The nominal operating temperature ranges from 4.5 K to 6 K for the part which houses the superconducting cable and is about 70 K for the heat shielding. Five DSLs of two types will be needed in LSS 1, 3, and 5. Table 6.3 summarises the DSL with some technical details. The four type-1 DSLs are of similar design, differing only in the precise mechanical layout of their routing in the LHC tunnel. Their length is about 70 m, with two intermediate branches of about 3 m. They are located at LSS 1 and 5 on either side of the interaction points and connect a link current feedbox (DFBL) to the Q6, Q5 and Q4D2 magnet cryostats. The type-2 DSL serves as a superconducting power transmission line between two current feedboxes. It is exceptionally long, about 500 m, without any intermediate branches. It is located in Point 3 and connects the DFBLC in UJ33 to the arc current feedbox (DFBAF) on the right side of IP3. In addition to the power transmission function, it provides the cryogenics for DFBLC.

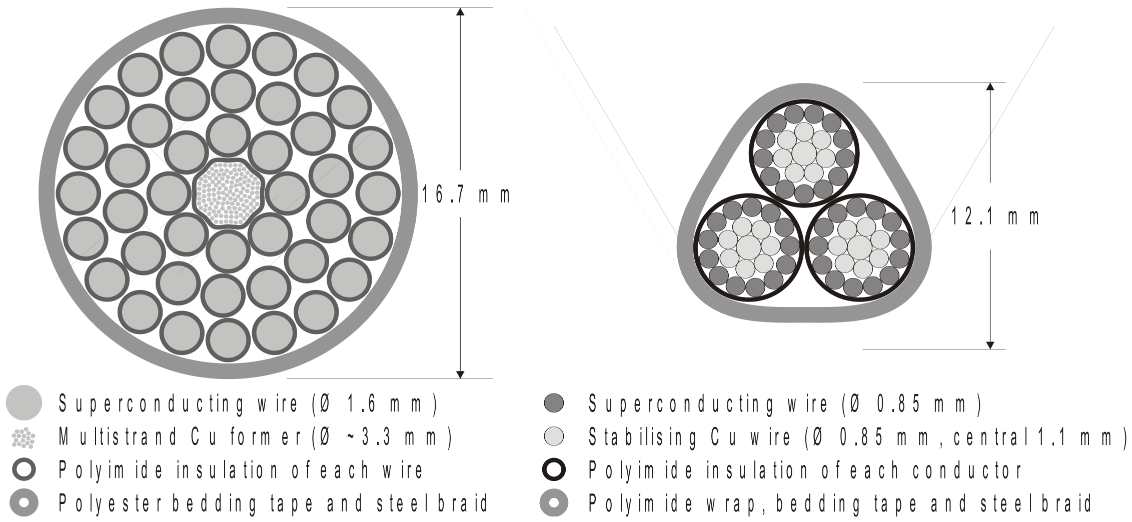


Figure 6.6: Cross sections of the 42 × 600 A cable (left) and the 3 × 6 kA cable (right).

6.3.4 Bus-bar systems

To connect the individual magnets within a family, superconducting bus-bars are used: see figure 6.3. Like the magnets, these busbars may also quench, and hence a protection is needed. There are four distinct classes of bus-bars. The high current connections are highly stabilized and quite rigid. The 600 A connections to the corrector magnets in the SSS are made using a 42 or 48 wire cable running outside the main cryostat in the Line N. The same pipe is also used to hold a cable of 6 kA conductors feeding the individually powered magnets in the continuous cryostat in the matching section and dispersion suppressor: see figure 6.6. Finally, the current for the spool pieces runs through straight wires mechanically attached to the quadrupole bus-bars.

6.3.5 Normal conducting cables

Normal conducting cables are also widely used. The heat losses of all the normal conducting magnets have a major impact on the installed cooling power in the tunnel and underground areas of the LHC. Cables and tubes carrying very high currents for the LHC main circuits and several other connections are therefore water cooled to decrease heat losses into the air.

6.4 Protection equipment

In most circuits, the stored magnetic energy is sufficient to destroy magnets and bus-bars. Protection of the equipment relies on the fast detection of resistive voltages, on a bypass of the current around the quenching parts, and on fast and reliable extraction of as much energy as possible. The large inductive voltages caused by current changes and the electrical noise in an accelerator environment, along with the high level of ionizing radiation, present the basic difficulties for detection. The energy bypass for the main LHC magnets is achieved using cold diodes in parallel with the magnet coils. At low temperatures, the turn-on voltage is normally high enough to prevent a bypass leakage current. However, if the voltage across the diode reaches a few volts, the diode is turned on and heats up. At elevated temperatures, the turn-on voltage rapidly reaches the usual room temperature value of 0.7 V. Here the main difficulty is to avoid a partial overheating of the diode, which would result in an unequal current distribution over the junction area of the diode (current crowding). This, in turn, results in thermal run-away and a fusion of the pn junction. It is necessary to discharge the stored magnetic energy as quickly as possible, mainly to protect the diodes. All parts of the quench protection system are required to be safe and reliable. Moreover, in view of the large number of items, there is a potential problem with false triggers.

The quench detection systems for the main dipoles are based on a floating bridge detector, which continuously compares the voltages of the two apertures. The two magnet apertures of equal inductance and two balancing resistors form the bridge. These resistors also protect against over-currents through the instrumentation wires. The quadrupole magnets have the same kind of detector, comparing the voltage drops across two different poles, because the two apertures are powered separately. In the case of a quench, the floating bridge will become unbalanced, and the detector will activate directly the associated quench heater power supplies. These devices are located in racks under the main dipoles inside the LHC tunnel. In addition, these racks house the quench heater power supplies.

Each of the of HTS current leads is protected by a detector that compares the expected voltages with measured values across the resistive, as well the superconducting part, of the lead. The superconducting bus-bars of the corrector and insertion region magnets are included in the protection of the attached magnets, but the main 13kA bus-bars are a special case and have their own dedicated quench detector. No dedicated quench protection equipment is foreseen for circuits containing superconducting magnets powered with currents lower than 600A. In these cases, the power converter directly protects the magnet by detecting the over-voltage in the circuit caused by a quench.

6.4.1 Quench heater power supplies

The quench heater power supplies (figure 6.7) store enough electrical energy to artificially quench a magnet. The quench heater strips, mounted on the coils of many LHC superconducting magnets, are heated up and spread the quench rapidly. This, in turn, decreases the energy density, and hence the maximum temperature in the quenching coils. Basically a triggered thyristor discharges an aluminium electrolytic capacitor bank, which is normally kept charged. The thyristor has ratings of 1.8 kV and 100 A, while the capacitor bank is formed by 2×3 capacitors of 4.7 mF / 500 V rating. These components have been extensively tested with respect to reliability, useful lifetime and radiation tolerance up to 200 Gy. The useful lifetime of the power supply under radiation is mainly limited by the two thyristors used for the discharge of the capacitor bank. Table 6.4 lists the quantities of electronics needed.

6.4.2 Energy extraction systems

The quench heaters spread the energy released in a quench over a larger volume, thereby reducing the maximum temperature. This is often sufficient to protect a single magnet. However, the energy stored in the other magnets, which are connected in series, might be too large to be absorbed. In

Table 6.4: Quench Protection Electronics, Summary.

Device	**Qty.**
Quench heater power supply	6076
Local quench detector (for MB and MQ magnets)	2016
Protection system for 600A corrector circuits	418
Protection system for insertion region magnets	172
Protection system for inner triplets	8
Protection system for 13kA superconducting busbars	80 slave + 8 master
Protection system for superconducting current leads	1198
Acquisition and monitoring controllers	2070

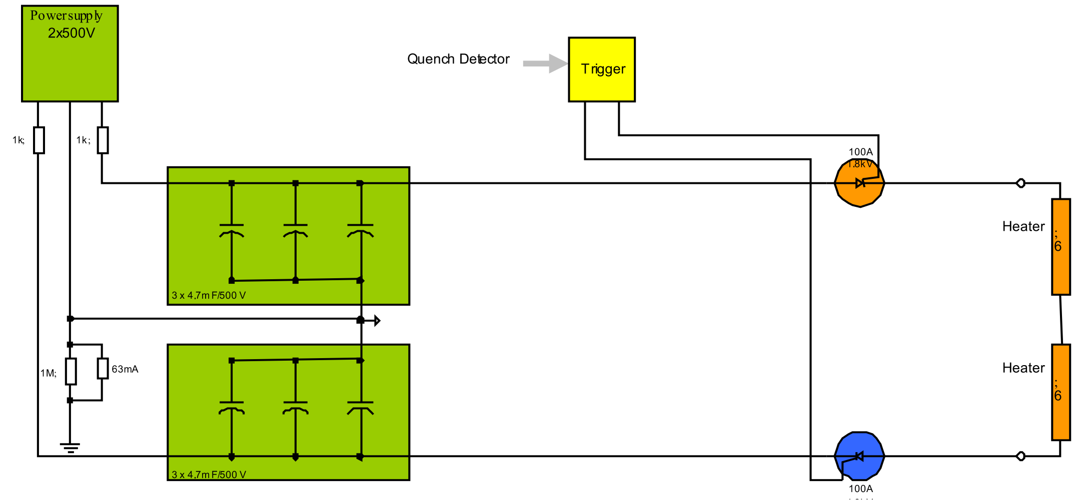


Figure 6.7: Quench heater power supply functional diagram.

this case, as much current as possible has to be routed around the quenching magnet by using a diode, but such a diode may not be able to absorb the total energy of the circuit. Also, energy absorbed by the diode has to be removed at cryogenic temperatures, which is more expensive and time consuming than at room temperature. On top of that, dumping the energy in the diodes takes a very long time. Therefore all major energy dumping systems have an external switch, bypassed by a dump resistor [35].

The energy extraction impacts on other systems in the power circuit. Voltage waves are created by the opening of the switches that sweep through the magnet chains. The amplitudes of the waves would exceed the ramping voltage without individual damping. For the MB strings, 100 Ω resistors connected across the dipole terminals serve this purpose. The effect on the precision of the current due to the leakage during current changes is negligible.

6.4.3 13 kA circuits

The maximum rate of current change must be limited to prevent eddy-current-induced quenches (quench-back), while ramping down the current in the main dipoles. The limit has been estimated to be above 125 A/s for the LHC dipole circuits. Assuming an exponential current decay down from 13 kA, this corresponds to a time constant of 104 s. The inductance of all dipoles[2] in a sector is about 15.1 H. Hence the maximum voltage over a sector would be about 1900 V. With two, identical, series-inserted sub-systems, one with the circuit earthing at its mid-point (through 1 Ω), the maximum voltage to ground is limited to about ±475 V. The system requires the presence of bypass thyristors across the converter terminals to ensure circuit continuity after switch-off of the power source.

The basic criteria for the choice of extraction switches for the various circuits are reliability, lifetime, voltage drop (losses), and radiation hardness (for the units in the tunnel). A CERN/Russia collaboration resulted in a breaker with the following features:

- Two independent release systems: one completely passive, based on under-voltage release, the other active, based on a discharge pulse trigger.
- Magnetic displacement of the arc into the arc-chute, driven by the main current itself, providing fast and reproducible arc extinction, even at low currents.
- No mechanical catch and latch, the 'on' state being maintained entirely by the excitation of the holding coil.
- Arc-free separation of the main contacts, i.e., opening prior to separation of easily replaceable arc contacts.
- High overload and high current breaking capability combined with low 'on'-state losses.

Each extraction facility is composed of eight breakers, in four parallel branches, with two series-connected units each, to recover some of the redundancy lost by the parallel connection. All four branches must be closed in order to generate the 'power permit' for the circuit. A minimum of three branches is required for safe operation of the breakers; consequently, one branch may open accidentally during operation without forcing a beam abort. In case of accidental opening of a second branch, a 'power abort' is generated, opening all the switches for extraction in the circuit and dumping the beam.

In spite of the large energy difference, the dipole and quadrupole extraction resistors have many common design features. The basic principles for both types are:

- The absorber material has a low inductance and a low temperature coefficient.
- The operating temperature stays below 350°C at the end of the energy deposit.
- The equipment must always be available for extraction during powering of the magnet chain. It cannot rely on any external infrastructure, such as mains power or cooling water, for accepting the energy deposit.
- The resistor body is cooled by forced air, and the air is cooled by water. The units contain an air-to-water heat exchanger and a water reservoir, with sufficient capacity to ensure worst-case no-boiling conditions.

[2]Using the measured value of 100 mH per dipole.

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- The cooling period is below two hours. Re-powering of the magnet chain is possible only after cooling of the resistor body.

- The material for the dipole resistors is radiation tolerant.

With an energy deposit of (ultimately) 625 MJ, a single 75 mΩ dipole unit would be 11 m long and have a mass of 8 t. For reasons of handling and space, an alternative solution, with three individual, parallel-connected sub-units of 225 mΩ and 220 MJ has been adopted. The resistor body consists of 84 series-connected stainless steel plates. Particular attention was paid to the need for free expansion-contraction, and for a uniform cooling across the resistor body, to avoid buckling, twisting and other deformation during the fast energy deposit and the slow cooling. The 6.6 mΩ (and 7.7 mΩ), 22 – 24 MJ quadrupole extraction resistor is small enough to be housed in a rack-sized cubicle.

6.4.4 600 A extraction equipment

The MCS, MCD, MO, MQS, MQT, MQTL and MS corrector circuit families are equipped with extraction systems for stored energy ranging from 2 kJ to 108 kJ. In this case, the extraction equipment consists of two series-connected, high-speed electro-mechanical, 3-phase AC breakers, with common and simultaneous operation of the three poles. In addition, the breakers are fitted with special DC arc-chutes. The total opening time is 17 ms (pulsed release) and 25 ms (zero-voltage release). For the corrector magnets and their bus bars the extraction time is a critical parameter, because of the limited amount of stabilising copper in the superconductors. Capacitive snubbers (typically 320 μF, bi-polar) are used for arc suppression, reducing the contact erosion, the total opening time (by 20%), and the acoustic noise (by 15-20 dB). The extraction resistors, 0.7 Ω or 0.2 Ω, are made from a low temperature coefficient material, such as Fe-Cr-Al.

6.4.5 Cold diodes

The main magnets are bypassed, as in HERA and RHIC, by diodes operating at cryogenic temperatures. During normal standby operation, the diodes have a low temperature turn-on voltage of a few volts, sufficiently high for the anticipated ramping rates. Once a quench has created sufficient resistance in a magnet and the corresponding voltage exceeds the diode turn-on voltage, the diodes start to conduct. They warm up and the ‘knee-voltage’ drops to lower values. It is important to achieve a ‘knee-voltage’ and resistance during the bypass operation which is as low as possible. The lower the effective resistance, the more current will be transferred out of the coil.

All dipoles or quadrupoles of a sector may be quenched during a discharge due to a malfunction. The non-uniform quench behaviour will cause the last quenching magnet and its diode to see a reverse voltage of 2’100 V (140 V for quadrupoles). Since there is no diode with such a blocking voltage, the diode will be destroyed. However, it will still protect the magnet. Clearly, the maximum reverse voltage is an important design parameter, along with the resistance to radiation. A special diffused diode was developed with a cold turn-on voltage of about 6 V, which falls to 0.96 V at room temperature (I = 15 kA). The cold reverse voltage is typically around 250 V.

Corrector magnets are protected by parallel resistors. The bypass currents during current changes are negligibly small.

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6.4.6 Controllers

Acquisition and monitoring controllers enable the supervision of all electronic devices belonging to the quench protection system and transfer the data via a fieldbus link to the higher-level LHC control systems. These controllers exist in three different variants, differing only in the number of analogue and digital I/O channels. The hardware is based on a micro-converter of the ADuC831 type, which incorporates a 12 Bit 8 channel ADC with an 8'052 compatible microcontroller core, and an ASIC of the VY27257 type, implementing the WorldFip fieldbus protocol. All controllers are equipped with 62 kByte Flash EEPROM memory and 32 kByte static RAM. All controller boards have been successfully tested with respect to the radiation tolerance levels required in the LHC tunnel of 200 Gy.

6.4.7 Supervision of the Quench Protection System (QPS)

The QPS supervision software layer links the gateways (DQGTW) to the LHC general purpose software modules (LHC Alarms, LHC Logging, LHC Post Mortem, Machine Protection System, etc.). Some key features are listed below:

- The access to the data is based on views.
- It will be possible to access the QPS Supervision from an office with W2000/WXP computers, from the control room, and from the tunnel area.
- The interface to the hardware controllers is done by command/result data.
- This supervision handles the test mode, where all the QPS hardware can be checked with respect to their proper function.
- The QPS Supervision will always be available. Possible upgrades will be planned for shutdown periods.
- The QPS Supervision will be built in stages. The QPS architecture will support this.

6.5 Operational aspects and reliability

6.5.1 Electrical quality assurance

An electrical quality assurance plan is defined for the LHC machine environment in order to ensure the safe and correct functioning of all superconducting electrical circuits during its commissioning and operation. The plan has been worked out in close collaboration with all parties concerned with the installation and commissioning (i.e., the hardware commissioning working group). The steps in the electrical quality assurance plan for the machine assembly, commissioning, operation, and shutdown phases are as follows:

- Continuity, polarity, and electrical integrity verification during machine assembly until the closure of the helium enclosure of each sub-sector.

- Electrical measurements at ambient temperatures of reference parameters for each individual electrical circuit part of a sub-sector. These measurements are performed from the corresponding DFB.
- On-line monitoring during the cool-down of the integrity of electrical insulation of circuits and instrumentation for magnet protection.
- Electrical measurements of reference parameters at cold conditions before the powering of each individual electrical circuit of a sub-sector.
- Diagnostic measurements and verifications during sub-sector commissioning and machine operation.
- Yearly verification during shutdown periods of cold electrical components, such as the bypass diodes.
- Verification of electrical circuit segments after in-situ repairs as well as after an exchange of electrical components.

6.5.2 Quench detectors

In order to increase the availability of each of the detection systems, it is foreseen to use the coherence of the two independent channels continuously, thereby reducing the probability for false quenches. A simulated quench signal can be sent from the control room. If one or more channels fail the test of the coherency it will generate a warning. Since this test implies the discharge of the quench heater power supplies, it can only be performed when the magnets are cold and not powered. When Quench Tests are performed monthly and repairs are carried out before re-powering the circuits (see below), the probability of missing a quench during 20 years of operation is below 1% [36].

The expected number of false quenches is around 10 per year. Since the powering of the detectors is not redundant, it is not possible to improve its reliability via checks. However, the number of false quenches will drop to less than 1 per year, if two supplies are connected in parallel. Due to the large investment required to double all the power supplies, it has been decided to install one power supply per local quench detector and provide the necessary space and cabling to install a redundant unit if operation experience shows it to be necessary.

Table 6.5 summarises the results for all the LHC quench detectors if monthly checks are carried out (see below). The expected probability of not missing any quench along the machine over 20 years is well above 95%.

6.5.3 Quench Heater Power Supplies (DQHDS)

Each of the 6'076 quench heater power supplies contains two banks of three capacitors each, connected in parallel. These are discharged in the quench heaters by triggering two thyristors in series with the strips. Four power supplies are installed per dipole. At least two have to be properly discharged to ensure the integrity of the coil. The quench heaters in the 13 kA and 6 kA quadrupoles are fed by two power supplies (except in the case of the MQY magnets, where four power supplies

Table 6.5: The probability to miss one quench in 20 years (RMQ) and the expected number of false quenches with a 95% confidence level for the different detector families.

Detector		Units	RMQ	False Quenches
DQQDL	Local	2016	0.991	197-238
DQQDI,T	Insertion and Inner Triplets	316	0.991	89-145
DQQDG	Correctors	351	0.997	120-187
DQQDC	Current Leads	1198	0.974	132-165

are required), and at least one of them (two for the MQY) has to be correctly fired to protect the magnet. The reliability analysis of the quench heater power supplies shows that quench tests on a regular time scale improve the reliability of the system. Monthly tests (and repairs) boost the reliability to react properly to all quenches during 20 years to 99.7% (99.9% for the quadrupoles). Incidentally, a high rate of quenches would have a benign effect on the reliability for this highly redundant system.

6.5.4 Energy extraction

As described earlier, the energy extraction systems are based on electro-mechanical breakers with high redundancy, using series and parallel connected current paths. During a machine run, one branch may open by accident without compromising operation. In the case that more than one branch is opened, all the other breakers of the facility will be forced to open. In the case of the main dipoles, the system at the other end of the arc is also opened. In the unlikely, but most dangerous, event that one branch of a system remains closed after an opening command, several cold diodes in the main magnets or resistors in the corrector magnets could be damaged, because the stored energy will not be dumped correctly. In this case, several pre-selected magnets will be fired. This will, unfortunately, lead to a huge load on the cryogenic system. The probability of one such failure in 20 years is about 0.03% in case of the 13 kA energy extraction systems, assuming a realistic failure rate of the breakers of 0.0001. This requires monthly checks and the use of the post-mortem information of all energy extractions which occur. Four power aborts due to quenches in the main magnets per operational week have been assumed. For the 600 A circuits, the space conditions allow the use of a third switch, which decreases the failure rate. In this case, the result is a failure probability of less than 1%.

In summary, only regular maintenance can keep the QPS alert, not to miss a quench, and also not to have a false trigger. Failing to provide regular maintenance means failure in operation of the accelerator. Some checks can be done while running, others require normal operation to be stopped. Finally a check will be done automatically, for example due to “normal” quenches. Table 6.6 summarises the required maintenance policy.

With all maintenance properly done and assuming the parameters mentioned above, an overall main failure probability over 20 years of 0.914 is to be expected.

Clearly, the maintenance will take time. The exact time will depend on the number and distribution of quenches happening during operation, which do not need to be tested any more. The strategy for the quench tests will then fully exploit the cryogenic capacity and the voltage

Table 6.6: Maintenance policy.

		Check	**Inspection**	**Repair**	**Affected**
Quench Detectors	DQQDL	Quench Test	Monthly	Monthly	All
		Post Mortem	After Quench	Before Power Permit	Quenched Magnet
		Coherency Test	On-line	Monthly	All
		Power Permit	On-line	Before Power Permit	Sub-sector
	Other	Quench Test	Monthly	Monthly	All
		Post Mortem	After Quench	Before Power Permit	Circuit
		Powering Test	On-line	Monthly	All
		Power Permit	On-line	Before Power Permit	Sub-sector
Heaters		Discharge Test	Monthly	Monthly	All
		Post Mortem	Quench	Before Power Permit	Quenched Magnet
Extraction	13kA	Open Check	Monthly	Monthly	All
		Post Mortem	Quench	Before Power Permit	Sub-sector
		False Opening	On-line	Monthly	All
		Power Permit	On-line	Before Power Permit	Sub-sector
	600A	Open Check	Monthly	Monthly	All
		Post Mortem	Quench	Before Power Permit	Sub-sector

rating of the various circuits in order to gain time. After a careful analysis of the data, repair or replacement of parts may be needed. Hence, to keep the systems working several days per month of intensive tests and repairs need to be anticipated. It should be noted that access to the sectors under test will normally not be possible.

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