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Chapter 9

Circuit Layout, Powering and Protection

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On behalf of the HL-LHC Magnet Circuit Forum

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The HL-LHC upgrade will impose changes to the magnet circuits in Points 1, 5 and 7 with respect to the present LHC configuration. This chapter describes those changes and describes the powering characteristics and protection strategies applicable to the new magnet circuits. The electrical design criteria for magnets and other elements of the circuit are also presented.

1. HL-LHC Circuits Upgrade

During LS2 and LS3, the HL-LHC upgrade will impose with the installation of new magnets in the high luminosity insertion regions (IR) of ATLAS and CMS many changes to the magnet circuits of the LHC. Figure 1 shows the magnet types and the circuit corresponding circuit layout for the HL-LHC insertion regions. These magnets will be installed in the machine during LS3. In addition to these changes, two main dipole magnets (MB) are planned to be replaced by 11T dipole cryo-assemblies in order to add two additional collimators around Point 7. The two concerned magnets are to be installed in Cell 9 on the left and right side of LHC Point 7. Figures 2 and 3 illustrate the circuit upgrade for one 11T cryo-assembly installed in sectors 67 and 78 of

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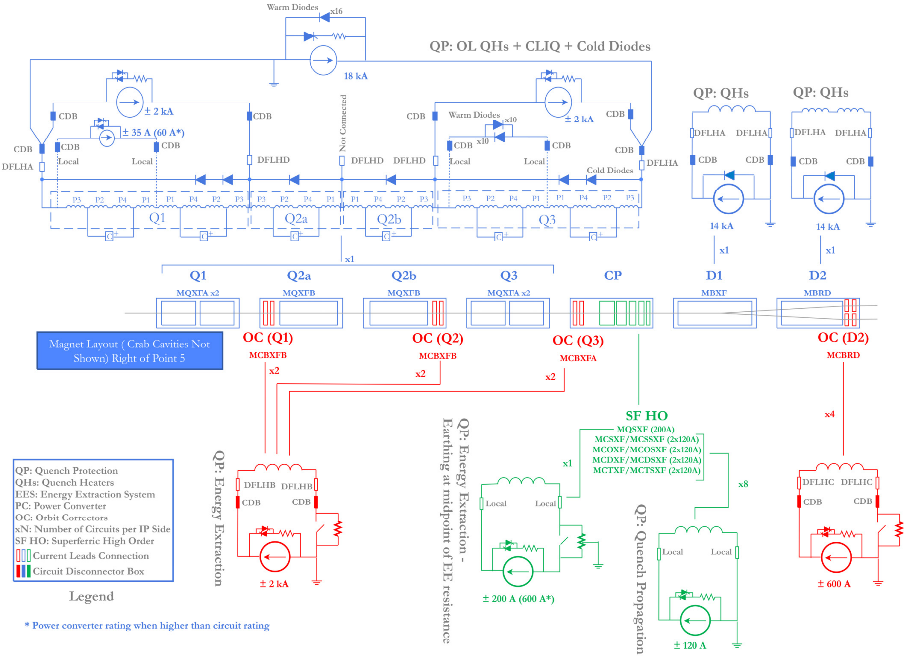

Fig. 1. HL-LHC insertion region magnet and circuit layout the right of Points 1 and 5.

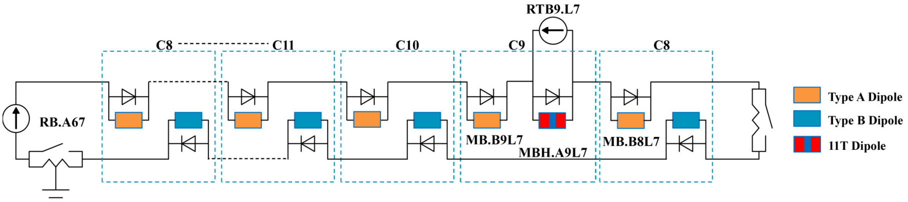

Fig. 2. 11T dipole cryo-assembly replacement of an MB magnet for circuit RB.A67.

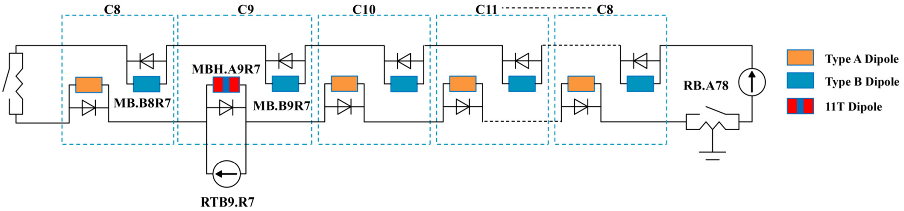

Fig. 3. 11T dipole cryo-assembly replacement of an MB magnet for circuit RB.A78.

the LHC respectively. The next paragraphs will detail each of the concerned circuits.

1.1. *Inner Triplet Main Circuit*

For the HL-LHC, the new inner triplet quadrupoles MQXFA and MQXFB will replace the current MQXA and MQXB magnets in optical positions Q1-Q2a/b-Q3 of the low-β triplet in the LHC IR1 and IR5 (around ATLAS and CMS experiments, respectively). In addition, the circuit configuration relies on having one main circuit with trim power converters acting on half of Q1 (i.e. Q1a), Q1 and Q3 as shown in Figure 1. The circuit powering and protection scheme is composed of the following components:

- **Power Converters:** The main power converter of the Inner Triplet circuit will have a rating of 18 kA. R&D work is well advanced [1] to develop a new type of 2-quadrant power converter in order to apply positive and negative voltage to the magnets which is mandatory to ramp-down the current in the shadow of the main LHC dipole magnets. Two trim power converters will inject or extract currents up to 2 kA in Q1 and Q3. In addition, one 35 A power converter will be connected to the first half of the Q1 magnet (i.e. Q1a) for k-modulation purposes as described in Chapter 5. A decoupling technique with inter power converter communication is applied to the controllers in order to achieve stability [2].
- **Cold Powering:** A superconducting (sc) link, dedicated for the inner triplet circuits (from Q1 to D1) will bring the current to the superconducting magnets through the new UL galleries as shown in Chapter 23. The interface between the sc link and the warm powering is defined at the level of the current leads connected to the distribution feedbox (DFHX) in the new UR galleries (refer to Chapter 23) whereas, the interface between the sc link and the magnets is located at the level of the distribution feedbox (DFX) placed inside the LHC tunnel as described in Chapter 23.
- **Circuit Disconnector Boxes (CDBs):** The CDBs will provide the galvanic separation of the warm powering, i.e. the cables from the HL-LHC current leads respecting the electrical safety standards. The disconnectors will also feature safer and easier execution of the Electrical Quality Assurance tests.

- **DC Connections:** For the 18 kA and the 2 kA trim circuits, water-cooled cables will be installed between the power converters and the CDBs. Air-cooled cables will be installed for the 2 kA trim circuits between the CDBs and the current leads of the DFHX, whereas, copper bus-bars with electrically insulated cooling plates will connect the 18 kA CDBs to the corresponding current leads. All these items are placed inside the UR galleries. For the k-modulation circuit, air-cooled cables connect the power converter to the CDB and then to the local feedthroughs on the Q1 magnet cryostat.
- **Quench Protection**: The triplet magnets will be protected by means of outer layer quench heaters and CLIQ (Coupling Loss Induced Quench) [2] units as described in Chapter 12. Useful to further reduce the hot spot temperature and necessary to mitigate risks in a multiple fault event, the innovative CLIQ system has been adopted in the protection baseline after a series of validation tests on single magnets. The CLIQ units are electrically connected to the circuit as shown on Figure 1. Furthermore, cold diodes are introduced to the Inner Triplet circuit in order to balance voltages during magnet quenches and to mitigate the possible delays in firing the quench protection systems between different magnets. Cold diodes also limit the transient currents through the superconducting link and warm parts of the circuit during asymmetric quenches (that could arise due to different quench resistances in the magnets). The protection strategy of the inner triplet main circuits is based on the simultaneous firing of all the quench protection systems (quench heaters and CLIQ) when a quench is detected in any superconducting element of the circuit (i.e. magnet, bus-bars, sc link and current leads).

1.2. *Triplet Orbit Correctors*

For the inner triplet circuit, there will be a total of 6 orbit correctors (1 vertical and 1 horizontal in Q2a, Q2b and the Corrector Package (CP) cold masses respectively). These dipole corrector circuits have a rating of ± 2 kA. The circuit layout of these correctors, as shown in Figure 1, contains the following components:

- **Power Converters:** One power converter per circuit rated at ±2 kA.

- **Cold Powering:** The MCBXF correctors will be powered via the sc link, the DFHX and the DFX boxes.
- **CDBs:** A CDB will be introduced in each circuit to ensure a safe disconnection of the water-cooled cables from the current leads.
- **DC Cabling:** Water-cooled cables will be installed between the power converters and the CDBs and air-cooled cables will be installed between the CDBs and current leads of the DFHX.
- **Quench Protection:** The baseline for quench protection is energy extraction for the long and the short versions of magnets (MCBXFA/B).

1.3. *Inner Triplet High Order Correctors*

Nine higher order correctors (skew quadrupole, normal and skew sextupole, octupole, decapole and dodecapole) are required to compensate magnetic errors in the inner triplet magnets as shown in Chapter 6. The quadrupole corrector circuit has a rating of ±200 A whereas all the eight other correctors have a rating of ±120 A. The circuit layout of these correctors, as shown in Figure 1, contains the following components:

- **Power Converters:** One power converter per circuit (total of 9 circuits) of ratings +/– 200A or +/– 120A will be used. The power converters will be located in the already existing technical galleries of LHC.
- **Cold Powering:** The cold powering interface of the higher order correctors will be located at the level of the corrector package cryostat (i.e. the magnets will be powered through local current leads penetrating the cryostat walls).
- **DC Cabling:** Air-cooled copper cables will be installed between the power converters and the corresponding current lead feedthroughs, located on the corrector package cryostat.
- **Quench Protection:** All magnets except the skew quadrupole are self-protected. The crowbar resistance of the power converter contributes to dissipate the coil's energy in case of a quench or the detection of other powering failures requiring the extraction of the circuit energy. For the skew quadrupole, an additional energy extraction system is required to protect the magnets, whereas the earthing system is connected to the midpoint of the extraction resistor to limit the magnet voltage to ground during a quench.

1.4. *Separation Dipole D1*

For the HL-LHC, D1 in Points 1 and 5 will become a superconducting magnet in contrast with the LHC configuration where D1 is a series of 6 warm magnets, powered in series between both sides of the IP. The circuit layout contains the following components as shown in Figure 1:

- **Power Converters:** One power converter per circuit rated at 14 kA. This converter will be a 1-quadrant type since the mere presence of the DC cabling resistance leads to a discharge in the shadow of the LHC main dipole circuit.
- **Cold Powering:** The D1 circuit will be powered via the sc link, the DFHX and the DFX boxes.
- **CDBs:** A CDB will be introduced to ensure a safe disconnection of the water-cooled cables from the current leads.
- **DC Cabling:** Water-cooled cables will be placed between the power converters and CDB and copper bus-bars with electrically insulated cooling plates between the CDB and the current leads of the DFHX.
- **Quench Protection:** The baseline for quench protection is quench heaters.

1.5. *Recombination Dipole D2*

The new recombination dipole magnet D2 will be a superconducting magnet with two beam apertures. The two aperture coils are powered in series. The circuit layout contains the following components as shown in Figure 1:

- **Power Converters:** One power converter rated at 14 kA. This converter will be a 1-quadrant type since the mere presence of the DC cabling resistance leads to a discharge in the shadow of the LHC main dipole circuit.
- **Cold Powering:** The D2 circuit will be powered via a second superconducting link, dedicated to the powering of the D2 and its corrector magnets. This includes the DFHM installed in the UR, as well as a DFM module for the connection of the sc link to the D2 magnet in the LHC tunnel.
- **CDBs:** A CDB will be introduced to ensure a safe disconnection of the water-cooled cables from the current leads.

- **DC Cabling:** Water-cooled cables will be placed between the power converters and CDB and copper bus-bars with electrically insulated cooling plates between the CDB and the current leads of the DFHM (matching section electrical feed-box) as described in Chapter 10.
- **Quench Protection:** The baseline for quench protection of the D2 magnet is quench heaters.

1.6. *D2 Orbit Correctors*

Four orbit correctors are needed for the D2 recombination magnets (one vertical and one horizontal for each aperture). These corrector magnets will have a rating of ±600 A. The circuit layout of these correctors contains the following components as shown in Figure 1:

- **Power Converters:** One power converter per circuit rated ±600 A.
- **Cold Powering:** The D2 orbit corrector circuits will be powered via the DFHM, sc link and DFM (dedicated matching section link as for D2).
- **CDBs:** A CDB per circuit will be introduced to ensure a safe disconnection of the DC cables from the current leads.
- **DC Cabling:** Air-cooled copper cables will be placed between the power converters and the CDBs and between the CDBs and the current leads of the DFHM.
- **Quench Protection:** The magnet will be protected by means of an energy extraction system.

1.7. *The Modified RB Circuit with the 11T Dipole and Trim Circuit*

Two main dipole magnets (MB) will be replaced by 11T cryo-assemblies (MBH) in order to allow the introduction of two additional collimators in the dispersion suppressor regions of sectors 67 and 78. Besides this replacement, a trim circuit over the 11T dipole cryo-assemblies will be added to compensate for the differences in transfer function between the MB and the MBH magnets. The MBH magnet will be powered in series with the main dipole circuit of the respective sector, the 11T dipole trim circuit consists of the following components:

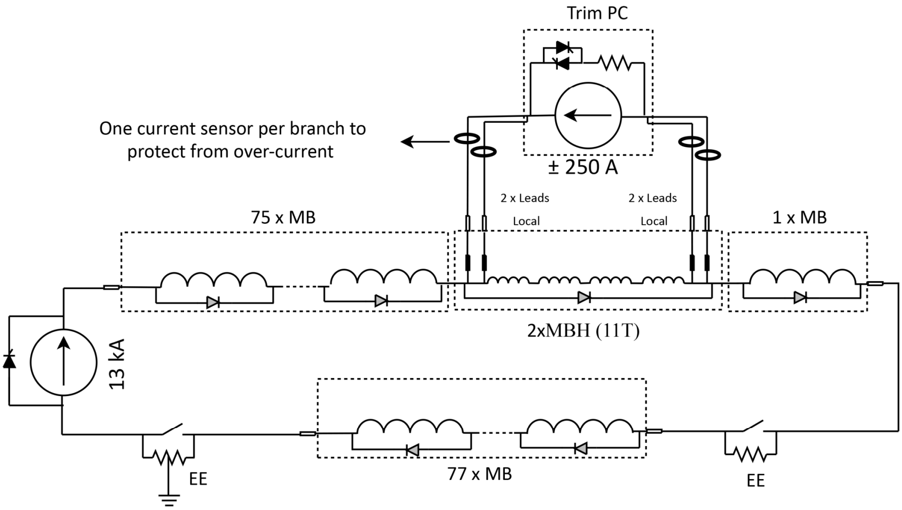

Fig. 4. Circuit layout of the modified RB circuit including the 11T magnet and its trim power converter.

- **Power converters:** One power converter per circuit rated at ± 250 A, see Figure 4.
- **Cold Powering:** The cold powering interface will be at the level of the 11T dipole cryostat (i.e. local powering) with two current leads per polarity.
- **DC Cabling:** Copper cables will be placed between the power converters placed in LHC technical galleries (RR73 and RR77) and the local current leads of the 11T dipole with two cables per polarity due to the number of current leads required.
- **Quench Protection:** The protection scheme used for the 11T dipole magnet is quench heaters. The existing energy extraction system will extract the energy of the RB circuit (the 11T dipole magnet is connected in series with the remaining 153 main dipole magnets). The trim superconducting bus-bars and the current leads are included in the quench protection system of the 11T magnet. When an overvoltage is detected on these elements, the quench heaters of the 11T magnet are fired and consequently the energy extraction systems will be activated.

2. Electrical Test Levels for Magnets and Cold Powering Equipment

Electrical tests are performed in all components belonging to the superconducting magnet chains in order to verify that the integrity of insulation and electrical parameters across the systems are within the expected nominal limits. Electrical tests are also required, among others, in the process to certify acceptance before cryostating, at reception at the test station and before installation of components in the tunnel.

Table 1. Voltage test level requirement for the HL-LHC project

Maximum expected coil voltage at quench (V)	To ground	$V_{sim\,(ground)}$
	To quench heater	$V_{sim\,(heater)}$
Test voltage at NOC at *'Manufacturing Facilities and Test Stations' stage* (V)	To ground	$V_{test1\,(ground)} = 2 * V_{sim\,(ground)} + 500$
	To quench heater	$V_{test1\,(heater)} = 2 * V_{sim\,(heater)} + 500$
Test voltage at warm* before first helium bath (V)	To ground	$V_{test2\,(ground)} = 2 * V_{test1\,(ground)}$
	To quench heater	$V_{test2\,(heater)} = 2 * V_{test1\,(heater)}$
Test voltage at warm* after helium bath (V)	To ground	$V_{test3\,(ground)} = V_{test1\,(ground)}\,/\,5$
	To quench heater	$V_{test3\,(heater)} = V_{test1\,(heater)}\,/\,5$
Test voltage at NOC at *'Tunnel' stage* (V)	To ground	$V_{test4\,(ground)} = 1.2 * V_{sim\,(ground)}$
	To quench heater	$V_{test4\,(heater)} = 1.2 * V_{sim\,(heater)}$

* T = 20±3 °C and humidity lower than 60%.

Table 1 summarizes the test level requirements defined for the HL-LHC project in order to account for different cryogenic conditions and component stages in its lifetime in addition to including safety factors similarly to what was defined for the LHC [2]. The test strategy is equally applicable for coil-to-ground and coil-to-heater voltages. Moreover, the electrical qualification shall be performed in several steps, the entirety of which is denominated as Electrical Quality Assurance (ElQA). In some cases (i.e. MQXF and 11T Dipole magnet), test voltages at intermediate cryogenic levels are proposed. A description of the main inputs for the test voltage requirements defined in Table 1 is presented below:

- **Maximum expected coil voltage at quench** ***(V_{sim})***: This value is obtained by performing simulations on the worst-case scenarios for each magnet or circuit.
- **Test voltage at warm before first exposure to helium** ***(V_{test2})***: the test value that must be applied at warm, after manufacturing and at reception, if the magnet has not been previously immersed in helium. This test value shall not be applied if any magnet component has been previously introduced in helium.
- **Test voltage at Nominal Operating Conditions (NOC) at *'Manufacturing Facilities and Test Stations'* stage** ***(V_{test1})***: the voltage level that the magnet should withstand whenever it is tested at NOC during this stage, in order to make sure that the dielectric material properties are not modified/damaged during the cool down process and after cold test programme.
- **Test voltage at warm after exposure to helium** ***(V_{test3})***: This will be the value to consider whenever the magnet needs to be tested at warm, once the components have been immersed in helium (hence risk of helium pockets).
- **Test voltage at NOC at *'Tunnel'* stage** ***(V_{test4})***: Once the magnet has been tested and qualified at the first stage, this value shall be applied whenever the components need to be tested at NOC in the 'Tunnel' stage.

Figure 5 presents a global flowchart of the test sequences and possible scenarios, starting from the final manufacturing step to machine powering and operation. The flowchart intends to clarify the test levels to apply whenever an ElQA test – represented as hexagons in the flowchart – is required and lists the correct test value. The *final* output of the upper flowchart diagram represents the closure of a short model or prototype magnet test programme, which will not proceed to *'Tunnel'* stage, contrarily to a series magnet.

The flowchart also includes the approach for magnets required to return back to manufacturing for refurbishment or replacement of some parts. To notice that, despite the several flowchart cycles in the *'Manufacturing Facilities and Test Stations'* stage which a magnet could experience, the test level at warm V_{test2} should not be performed except for the first time the magnet is assembled. If testing at warm after helium bath is required, even after returning to manufacturing, it is recommended that the magnet should be tested at the less stringent test level V_{test3}.

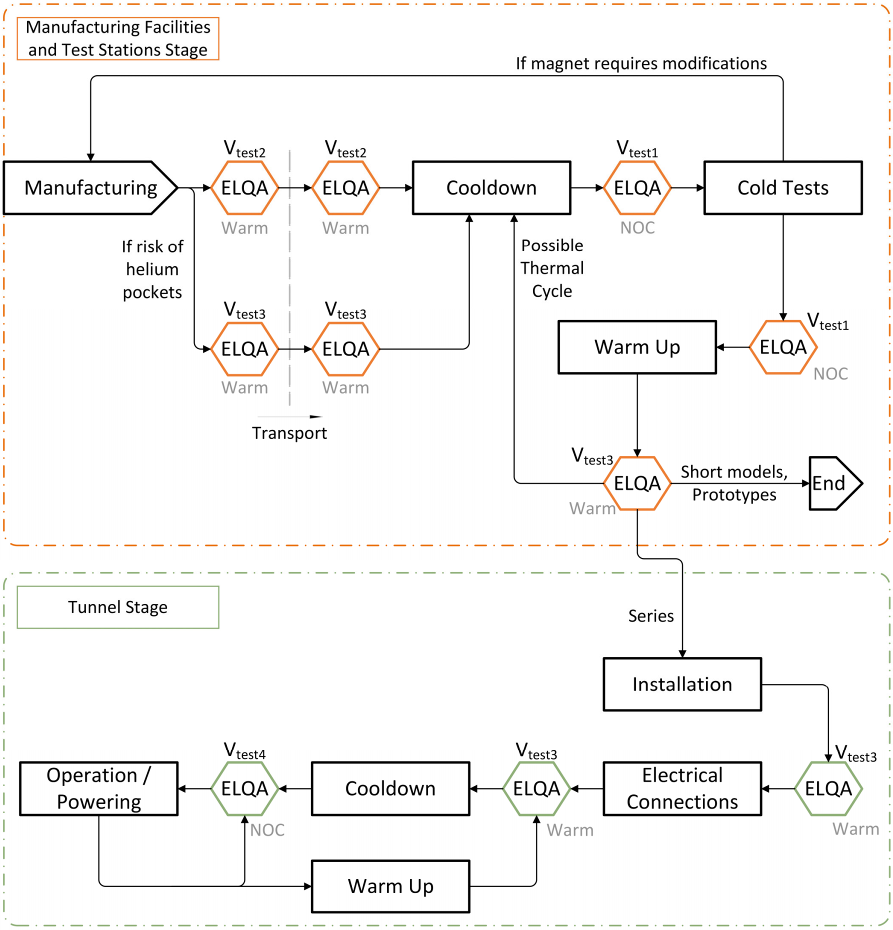

Fig. 5. Flowchart of the defined stages and test levels to apply at each ElQA step.

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