Chapter 6

Circuit layout, powering and protection

F. Rodríguez Mateos[1], T. D. Catalão Rolhas da Rosa[1], F. Menéndez Cámara[1], S. Yammine[1] and M.Zerlauth[1]*

[1]CERN, Accelerator & Technology Sector, Switzerland
[*]Corresponding author

6 Circuit layout, powering and protection

During LS2 and LS3, the HL-LHC upgrade will impose many changes to the magnet circuits of the LHC long-straight sections at points 1 and 5. Figure 6-1 depicts the new layout of magnets as required for the HL-LHC insertion regions. These magnets will be installed in the machine during LS3. In addition to these changes, during LS2, two main dipole magnets (MB) will be replaced by 11T cryo-assemblies (MBH) in order to allow the addition of two extra collimators at warm to intercept dispersive beam losses originating from the collimation system installed in point 7. The two concerned dipole magnets that are to be replaced are MBB.A9L7 and MBA.A9R7. Figure 6-2 and Figure 6-3 show the circuit upgrade for the 11T cryo-assemblies. The next paragraphs will detail each of the circuits concerned.

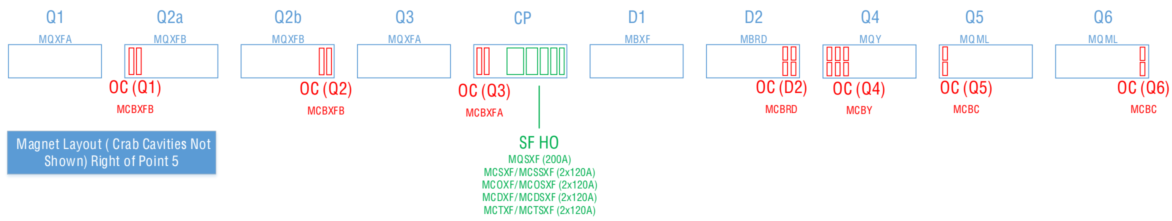

Figure 6-1: Magnet representation for the HL-LHC insertion region at right of point 5.

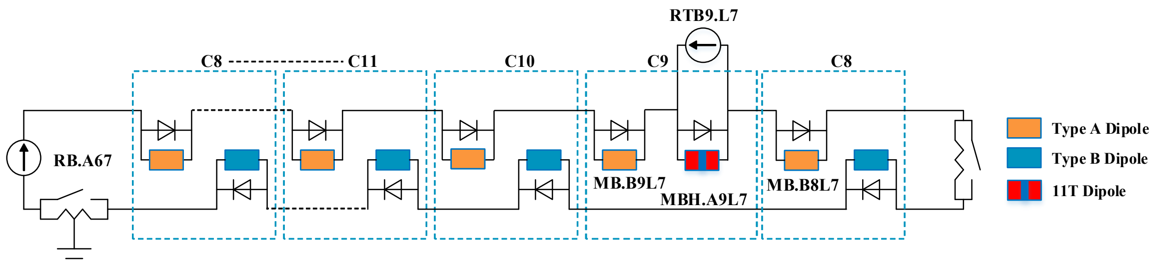

Figure 6-2: 11T cryo-assembly replacement of an MB magnet for circuit RB.A67.

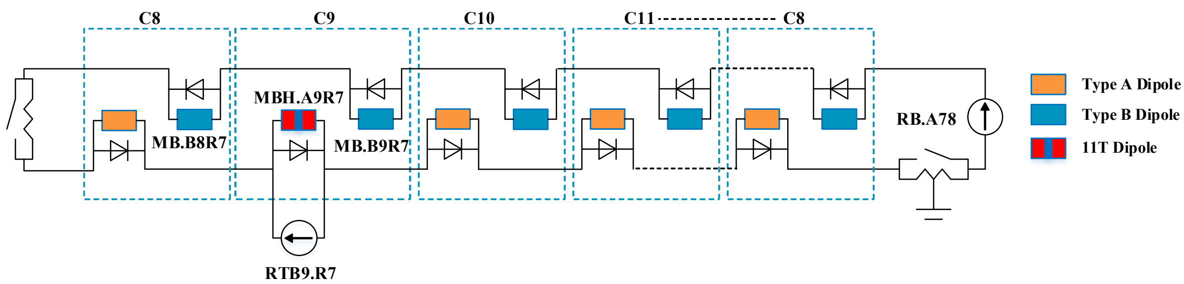

Figure 6-3: 11T cryo-assembly replacement of an MB magnet for circuit RB.A78.

6.1 Inner triplet main circuit

For the HL-LHC, the new MQXFA and MQXFB will replace the MQXA and MQXB magnets as Q1-Q2a/b-Q3 low-β triplet around the high-luminosity experiments ATLAS and CMS. In addition, the layout relies on one main circuit with additional trim circuits for Q1a, Q1 and Q3 as shown in Figure 6-4. Figure 6-5 shows the electrical schematic of the inner triplet main circuit with the main powering components and magnets. The changes of the inner triplet main circuit with respect to TDR V0.1 are summarized in an engineering change request [1]

- **Power converters**: The main power converter of the Inner Triplet circuit will have a rating of 18 kA. R&D work is being done to develop a new type of 2-quadrant power converter in order to apply positive and negative voltages to the magnets which is mandatory to allow for the ramp-down the current in the shadow of the main LHC dipole magnets. Two trim power converters will allow to superimpose trim currents up to 2 kA for Q1 and Q3. In addition, one 35 A power converter will be connected to the first half of Q1 magnet (i.e. Q1a) for K-modulation purposes.
- **Cold Powering:** A superconducting link dedicated for the inner triplet circuits (Q1 till D1) will be used to transport the current to the superconducting magnets through the UL galleries. The interface between the superconducting link and the warm powering is at the level of the DFHX boxes in the UR galleries whereas, the interface between the sc link and the magnets is at the level of the DFX box located in the tunnel.
- **DC Cabling:** Water-cooled cables and copper bus bars will be installed between the power converters, the Circuit Disconnector Boxes (CDB) and the current leads of the DFHX, all placed inside the UR galleries. Cable length and resistance estimations are detailed in Chapter 17.
- **Quench Protection**: The magnets of the main inner triplet circuits will be protected by means of outer layer quench heaters, CLIQ units and cold diodes (CD)[2][3][4]. The CLIQ units are electrically connected to the circuit as shown on Figure 6-4. Quench heaters are the primary baseline protection system. As second protection system, useful to reduce the hot spot and necessary to mitigate risk in a multiple fault event, the innovative CLIQ system is chosen in the baseline after a series of very successful validation tests on stand-alone magnets. Furthermore, cold diodes are introduced to the baseline in order to balance voltages during quench and mitigate the possible delays in firing the quench protection systems between different magnets. The protection strategy of the main inner triplet circuit is 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, current leads). The quench protection details are shown in paragraph 7.3.

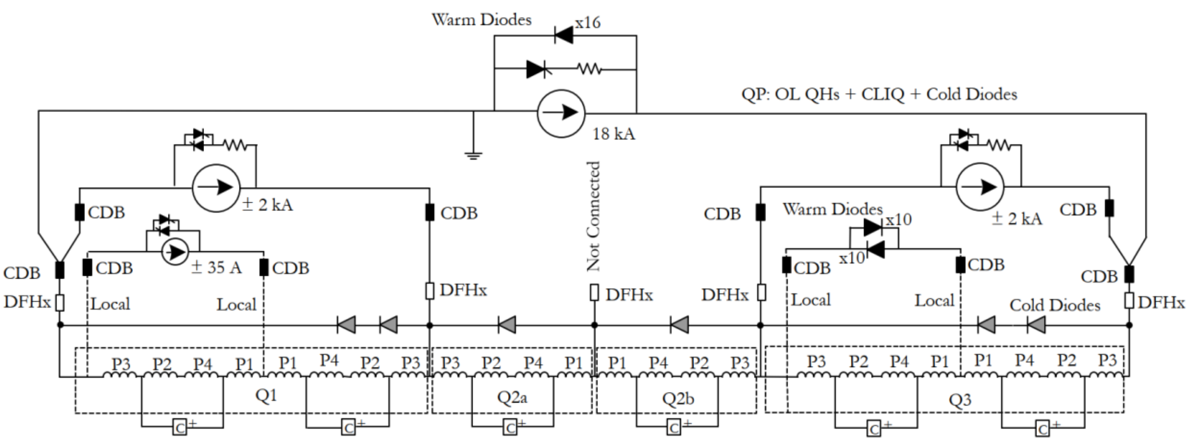

Figure 6-4: Circuit layout of the HL-LHC inner triplet.

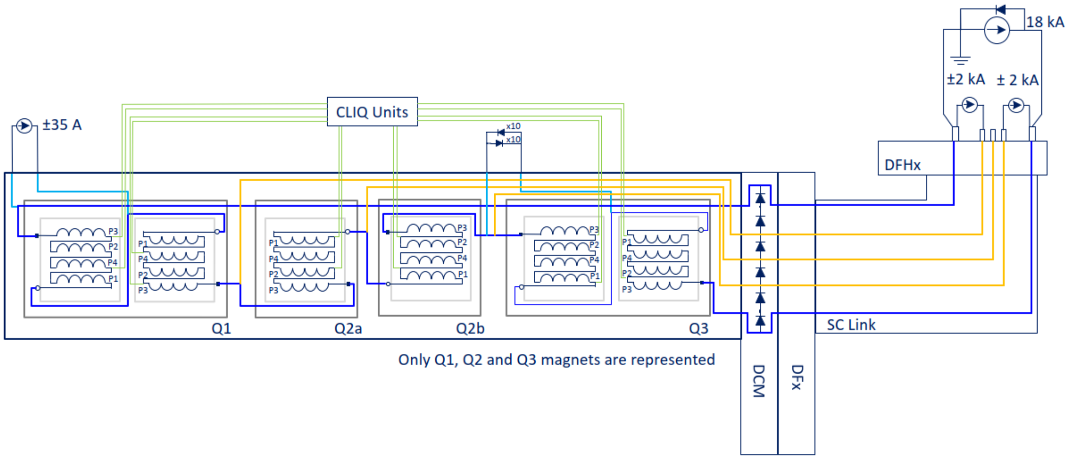

Figure 6-5: General schematic of the HL-LHC inner triplet circuit powering and magnet elements.

6.2 Triplet orbit correctors

For the inner triplet circuit, there will be a total of 6 dipole orbit correctors installed (1 vertical and 1 horizontal in Q2a, Q2b and the corrector package cold masses respectively). These new circuits have a rating of ± 2 kA. The circuit layout of these correctors is shown on Figure 6-6.

- **Power converters:** One 4-quadrant 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.
- **DC Cabling:** Water-cooled and air-cooled cables will be installed between the power converters, the CDB and the current leads of the DFHX.
- **Quench Protection:** The baseline for quench protection includes the installation of energy extraction systems for both, the long magnets (MCBXFA) as well as the shorter magnets (MCBXFB) [5][6].

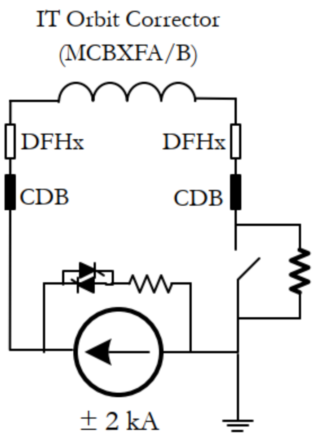

Figure 6-6: Circuit layout of the Inner triplet dipole orbit corrector circuit (MCBXF[A/B]).

6.3 Inner triplet high order correctors

Nine high-order correctors (skew quadrupole, normal and skew sextupole, octupole, decapole and dodecapole) are required for the compensation of magnetic effects in the main inner triplet magnets. 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 is shown in Figure 6-7.

- **Power converters:** One power converter per circuit (total of 9 circuits) of rating ±200A or ±120A will be used. The power converters will be located in LHC infrastructure (UL14, UL16, USC55 and UL557).
- **Cold Powering:** The cold powering interface of the high order correctors will be at the level of the corrector package cryostat (i.e. local powering) [7].
- **DC Cabling:** Air-cooled copper cables will be placed between the power converters and the current lead feedthroughs on the corrector package cryostat.
- **Quench Protection:** All magnets except the skew quadrupole are self-protected. The power converter crowbar resistance (80 mΩ) contributes to the dissipation of the coil's energy in the case of a quench or overvoltage in the current leads. For the skew quadrupole, an energy extraction system is required to protect the magnets with the earth detection system connected to the midpoint of the extraction resistor to limit the magnet voltage to ground during a quench [8].

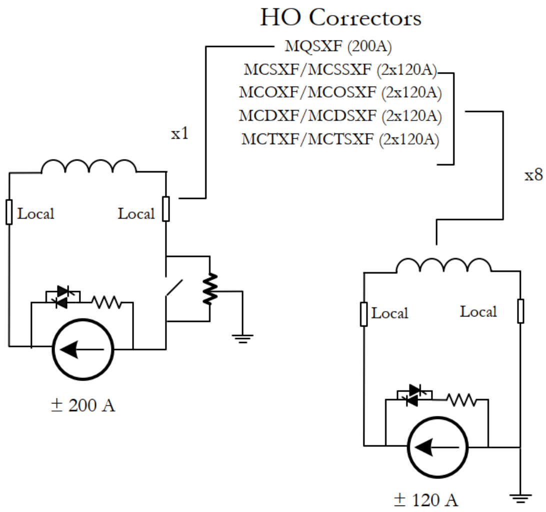

Figure 6-7: Superferric, higher order correctors' circuit layout.

6.4 Separation dipole D1

For the HL-LHC, D1 in points 1 and 5 is a sc magnet in contrast with the LHC configuration where D1 is a series of 6 warm magnets on either side of the IP. The circuit layout is shown on Figure 6-8.

- **Power converters:** One power converter per circuit rated at 14 kA. This converter will be 1-quadrant type since no ramp-down issues are foreseen for this circuit.
- **Cold Powering:** The D1 circuit will be powered via the sc link, the DFHX and the DFX boxes.
- **DC Cabling:** Water-cooled cables and copper bus bars will be placed between the power converters, the CDB and the current leads of the DFHX. Cable lengths and resistances are shown in Chapter 17.
- **Quench Protection:** The baseline for quench protection is quench heaters [9].

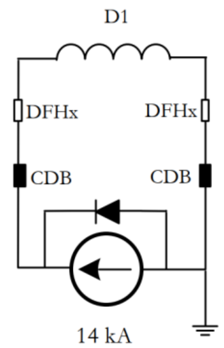

Figure 6-8: D1 magnet circuit layout.

6.5 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 is shown on Figure 6-9.

- **Power converters:** One power converter per circuit rated at 14 kA. This converter will be 1-quadrant type since no ramp-down issues are foreseen for this circuit.
- **Cold Powering:** The D2 circuit will be powered via the DFHM, sc link and DFM (dedicated matching section link).
- **DC Cabling:** Water-cooled cables and copper bus bars will be placed between the power converters, the CDB and the current leads of the DFHM (matching section electrical feed-box), all placed inside the UR galleries.
- **Quench Protection:** The baseline for quench protection is quench heaters [10].

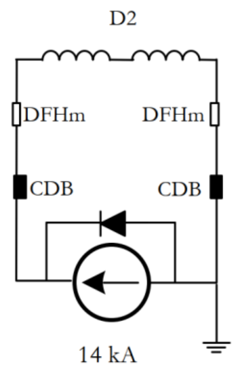

Figure 6-9: D2 magnet circuit layout.

6.6 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 is shown on Figure 6-10.

- **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).
- **DC Cabling:** Air-cooled copper cables will be placed between the power converters, the CDBs and the current leads of the DFHM. Cable lengths and resistances are shown in Chapter 17.

- **Quench Protection:** The magnet will be protected by means of an energy extraction system [11][12].

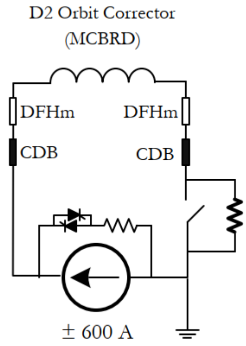

Figure 6-10: D2 correctors' circuit layout.

6.7 Individually powered quadrupoles Q4, Q5 and Q6 and correctors

The Q4, Q5 and Q6 magnets will have the same circuit configuration as in the LHC following the optimization and the introduction of the full remote alignment system to the matching sections [13]. However, since the Q4 and Q5 will be displaced towards the arcs by around 10 m, modifications on the DSL and the corresponding cryogenic infrastructure should be done. Figure 6-11 and Figure 6-12 show the circuit layout of the Q4, Q5 and Q6 magnets and their correctors.

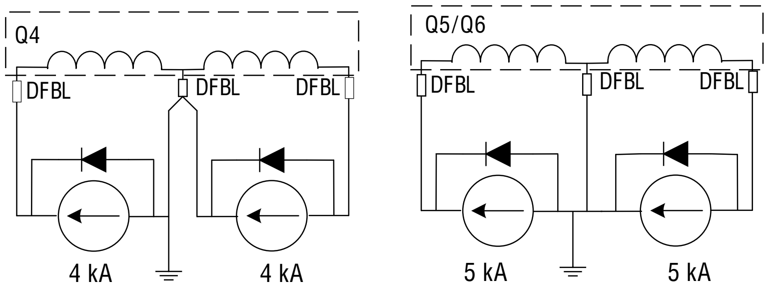

Figure 6-11: Q4, Q5 and Q6 circuit layout (no change with respect to the present LHC layout).

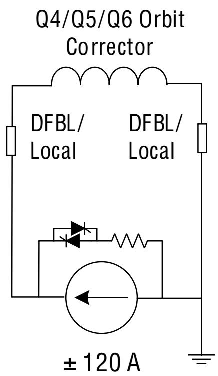

Figure 6-12: Circuit layout of each of the 10 corrector circuits for Q4, Q5 and Q6 (no change with respect to the present LHC layout).

6.8 11T trim circuit

Two main dipole magnets (MB) will be replaced by 11T cryo-assemblies in order to allow for the addition two warm collimators in between the two 5.5 m long 11T MBH magnets. The two concerned magnets are MB.A9L7 and MB.A9R7 (refer to Figure 6-2 and Figure 6-3).

- **Power converters:** One power converter per circuit rated at ± 250 A, see Figure 6-13.
- **Cold Powering:** The cold powering interface will be at the level of the 11T cryostat (i.e. local powering) with two current leads per polarity.
- **DC Cabling:** Copper cables will be placed between the power converters placed in RR73 and RR77 and the local current leads of the 11T with two cables per polarity due to the number of current leads.
- **Quench Protection:** The protection scheme used for the 11T magnet includes solely quench heaters [14][15]. The existing energy extraction system will extract the energy of the RB circuit (11T is in series with the MB magnets in this circuit). The trim superconducting bus-bars and the current leads are included in the quench protection of the 11T magnet. When an overvoltage is detected on these elements, the quench heaters of the 11T magnet are fired as well as the two energy extraction systems of the RB circuit, on either side of the long arc cryostat.

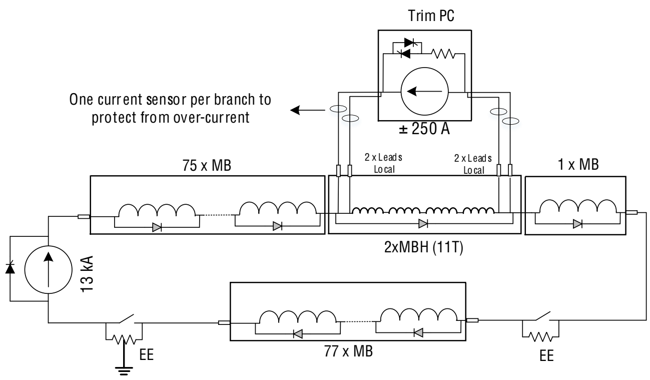

Figure 6-13: Circuit layout of the 11T trim circuit.

6.9 Circuit parameters

Table 6-1 and Table 6-2 regroup the main circuit parameters of the HL-LHC circuits from Q1 to D2 and the 11T circuit. For the complete and dynamically updated set of circuit parameters, please see Ref. [16].

Table 6-1: HL-LHC Circuit Parameters (1/2). (version 9.1)

	Circuits	Magnet Type	Circuit Name	circuits IP side	Number circuits	I_nominal (kA)	I_ultimate (kA)	L per circuit (mH)	R per circuit (mΩ)	Precision Class	Ramp rate (A/s)	Acceleration rate (A/s^2)
Inner Triplet	Triplet Q1, Q2a, Q2b, Q3	MQXFA / MQFXB	RQX	1	4 (IR1/5)	16.23	17.5	255	0.15	0	14.6	0.73
	Trim Q1	-	RTQX1	1	4 (IR1/5)	2	2	69	1.45	2	2.09	0.16
	Trim Q1a	-	RTQXA1	1	4 (IR1/5)	0.035	0.035	34.5	227.08	4	3.32	0.35
	Trim Q3	-	RTQX3	1	4 (IR1/5)	2	2	69	1.3	2	2.09	0.11
	Orbit correctors Q1/2 -H/I	MCBXFB	RCBXH [1,2]	2	8 (IR1/5)	1.625	1.741	58.4	2.38	2	15	5
	Orbit correctors Q1/2 - V/O	MCBXFB	RCBXV [1,2]	2	8 (IR1/5)	1.474	1.579	124.8	2.42	2	15	5
	Orbit correctors Q3 - H/I	MCBXFA	RCBXH3	1	4 (IR1/5)	1.584	1.702	107.1	1.99	2	15	5
	Orbit correctors Q3 - V/O	MCBXFA	RCBXV3	1	4 (IR1/5)	1.402	1.502	232.3	1.98	2	15	5
	Superferric, order 2	MQSXF	RQSX3	1	4 (IR1/5)	0.174	0.197	1530	18.12	3	2.42	0.48
	Superferric, order 3, normal and skew	MCSXF / MCSSXF	RCS[S]X3	2	8 (IR1/5)	0.099	0.112	213	54	4	1.4	0.28
	Superferric, order 4, normal and skew	MCOXF / MCOSXF	RCO[S]X3	2	8 (IR1/5)	0.102	0.115	220	54	4	1.4	0.28
	Superferric, order 5, normal and skew	MCDXF / MCDSXF	RCD[S]X3	2	8 (IR1/5)	0.092	0.106	120	54	4	1.4	0.28
	Superferric, order 6	MCTXF	RCTX3	1	4 (IR1/5)	0.085	0.097	805	54	4	1.4	0.28
	Superferric, order 6, skew	MCTSXF	RCTSX3	1	4 (IR1/5)	0.084	0.094	177	54	4	1.4	0.28
D1	Separation dipole D1	MBXF	RD1	1	4 (IR1/5)	12.11	13.231	24.9	0.41	0	12	2
D2	Recombination dipole D2	MBRD	RD2	1	4 (IR1/5)	12.33	13.343	27.4	0.18	0	12	2
	Orbit correctors D2	MCBRD	RCBRD[V,H]4	4	16 (IR1/5)	0.394	0.422	920	1.36	3	2	1
11T	11T dipole, MBH	MBH	RB.A67-RB.A78	-	2 (IR7)	11.85	12.798	15734	1	1	10	1
	Trim circuit	-	RTBH9	-	2 (IR7)	0.25	0.25	127.1	30.96	3	1	0.1

Table 6-2: HL-LHC Circuit Parameters (2/2). (version 9.1)

	Circuits	Cold powering feedbox	Envelope max currents (kA)	Maximum thermal load [MIIT]	Maximum dI/dt* (kA/s)	PC Location	PC quad number	PC rated current [kA]	Maximum estimated ultimate voltage (V)	PC rated voltage (V)	Crowbar Resistance (mΩ)	Quench Protection
Inner Triplet	Triplet Q1, Q2a, Q2b, Q3	DFHX	17.82	32	250	UR	2	18	6.82	± 10	0.5	OL QHs, CLIQ, CD
Inner Triplet	Trim Q1	DFHX	6.8	5	250	UR	4	±2	4.17	± 10	2	OL QHs, CLIQ, CD
Inner Triplet	Trim Q1a	Local	4.1	1.5	250	UR	4	±0.06	7.99	± 10	2	OL QHs, CLIQ, CD
Inner Triplet	Trim Q3	DFHX	6.8	5	250	UR	4	±2	3.76	± 10	2	OL QHs, CLIQ, CD
Inner Triplet	Orbit correctors Q1/2 -H/I	DFHX	2	1	20	UR	4	±2	5.02	± 10	25	Energy Extraction
Inner Triplet	Orbit correctors Q1/2 - V/O	DFHX	2	1	20	UR	4	±2	5.7	± 10	25	Energy Extraction
Inner Triplet	Orbit correctors Q3 - H/I	DFHX	2	1	20	UR	4	±2	5	± 10	25	Energy Extraction
Inner Triplet	Orbit correctors Q3 - V/O	DFHX	2	1	20	UR	4	±2	6.46	± 10	25	Energy Extraction
Inner Triplet	Superferric, order 2	Local	0.2	0.44	0.01	UL, USC55	4	±0.6	7.28	± 10	50	Energy Extraction with Earth at Midpoint
Inner Triplet	Superferric, order 3, normal and skew	Local	0.12	0.01	0.08	UL, USC55	4	±0.12	6.35	± 10	80	Self-Protected
Inner Triplet	Superferric, order 4, normal and skew	Local	0.12	0.02	0.07	UL, USC55	4	±0.12	6.52	± 10	80	Self-Protected
Inner Triplet	Superferric, order 5, normal and skew	Local	0.12	0.01	0.12	UL, USC55	4	±0.12	5.9	± 10	80	Self-Protected
Inner Triplet	Superferric, order 6	Local	0.12	0.03	0.02	UL, USC55	4	±0.12	6.37	± 10	80	Self-Protected
Inner Triplet	Superferric, order 6, skew	Local	0.12	0.01	0.08	UL, USC55	4	±0.12	5.33	± 10	80	Self-Protected
D1	Separation dipole D1	DFHX	13.3	42.5	130	UR	1	14	5.71	8	-	QHs
D2	Recombination dipole D2	DFHM	13.4	42.5	130	UR	1	14	2.74	8	-	QHs
D2	Orbit correctors D2	DFHM	0.6	1.01	0.04	UR	4	±0.6	2.42	± 10	50	Energy Extraction
11T	11T dipole, MBH	DFBA					2	13	170.14	± 190	-	QHs
11T	Trim circuit	Local	0.25	0.16	250	RR73,RR77	4	±0.3	9.14	± 10	60	NA

6.10 Circuit disconnector boxes

The Circuit Disconnector Boxes (CDBs) have been approved for inclusion into the baseline for the HL-LHC circuits [17]. These systems would provide for an easier connection/reconnection of power cables around the HL-LHC current leads. In particular, the disconnectors would feature safer and easier preparations for the Electrical Quality Assurance tests.

The CDBs are today proposed for the following circuits:

- Inner triplet main circuit (RQX, RTQX1, RTQX3 and RTQXA1)
- Triplet Orbit Correctors (RCBX[V,H] [1][2][3])
- Separation Dipole D1 (RD1)
- Recombination Dipole D2 (RD2)
- D2 Orbit Correctors (RCBRD[V,H]4.B [1][2])

6.11 Electrical design criteria for magnets and cold powering equipment

Electrical tests are performed on all individual 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 or before installation of components in the tunnel. Defining realistic testing conditions requires the understanding of both the design of components and their operational aspects.

Usually insulation materials used in cryogenic systems are highly dielectric, having rather large breakdown voltages, with a large margin with respect to operation (e.g. a layer of 125 μm of polyimide withstands more than 15 kV).

Liquid helium has also a high breakdown voltage. At conditions T = 1.9 K and p = 920 mbar, liquid helium has a dielectric strength of about 10 kV/mm. However, insulation layers are never totally hermetic and creep paths through helium can be created in case of generation of helium bubbles or warm gas volumes (e.g. during a quench). This is particularly relevant in case of resin potted coils when fissures are created in the resin allowing helium to penetrate them.

The voltages that a magnet should withstand at every required Electrical Quality Assurance (ElQA) step is calculated from the maximum voltage that a component is expected to experience during accelerator operation conditions. From this value, the electrical test levels are obtained by applying factors regarding the different environments and temperature-pressure conditions under which the magnet will be tested.

We define two distinct main stages at which the electrical integrity of the magnets must be qualified:

- Manufacturing Facilities and Test Stations: This stage comprises all the tests performed on a single magnet, from the final test after assembly through the reception of the magnet at a test facility up to the acceptance of the magnet in test stations at cold.
- Tunnel: Tests performed on a magnet or a circuit (once the magnet is connected) during installation in the machine and further commissioning and operation.

The electrical qualification shall be performed in several steps, within the two stages, these steps are denominated as Electrical Quality Assurance (ElQA).

6.11.1 Electrical tests strategy

The magnet or superconducting element must be designed according to the voltages that it should withstand during operation. The voltages are calculated through the simulation of worst-case conditions, including single failures of some of the protection elements.

It is important to mention that worst-case calculations are conducted at nominal current. It is a policy stated by the HL-LHC Project that conditions at ultimate current should be covered by the margin in the design of components without applying safety factors.

Moreover, we have considered that some exceptional conservative cases will follow the same rule as ultimate conditions, i.e. no safety margins will apply onto those extreme (realistic but with very low likelihood of happening) cases.

From worst-case simulations, during a quench at nominal current, maximum coil-to-ground and coil-to-heater voltages (if applicable) are calculated and used as reference for the test voltages defined.

6.11.2 Test conditions

The ElQA tests required to qualify the magnet shall be performed at two different conditions, equally valid for both stages:

- at Nominal Operating Conditions (NOC). These conditions are the ones equivalent to 1.9 K superfluid helium in the cold mass, with all the ancillary components (e.g. instrumentation capillary tube and feedthrough) at the corresponding local conditions;
- at warm (room temperature in air with T = 20±3 °C and humidity lower than 60%) (RT).

An additional test step at gaseous helium conditions is included for the qualification of the 11 Tesla dipole and the Main Inner Triplet magnets. The temperature of gaseous helium is obtained from simulations, according to the expected worst-case conditions during a quench, while the pressure is derived \ from discussions with the magnet designers and tests on short models. For the 11 Tesla Dipole magnet the reference value is T = 200±20 K and the pressure during tests shall be 3.0±0.2 bar. For the Inner Triplet Main magnets, the test shall be performed at T = 100±20 K and 1.2±0.2 bar. This test is only applicable within the test stations stage.

To qualify the electrical integrity of the components under test, several factors are applied to the maximum expected coil voltages during quench, henceforth named V_{sim} both for coil-to-ground and quench heater for the purpose of explaining the rationale behind the test voltages. These factors consider either the safety margins or the scaling ratios that changes in test conditions (e.g. presence of helium) bring together.

6.11.2.1 Test levels at NOC

Electrical qualification at NOC shall be performed by applying the test levels defined in this Chapter. The test voltage to apply depends only on the stage.

At *'Manufacturing Facilities and Test Stations'* stage, the test voltage shall follow the formula $V_{test1} = a * V_{sim} + b$, with *a* equal to 2 and *b* to 500. These values are based on the IEEE Standard 95-177 which suggests the same factor *a* equal to 2 and *b* between 1000 and 2000 V. This norm has been frequently applied to superconducting systems, although it was defined for electrical devices in general. Nevertheless, in the case of the LHC [18], CERN followed already the latter standard. For the HL-LHC Project, it has been agreed that the same standard, with the same minor modifications, shall be followed:

$$V_{test1} = 2 * V_{sim} + 500 \ \ [V] \tag{6-1}$$

This value should be used whenever the magnet needs to be qualified at NOC in test stations.

For series magnets, once they have been through the acceptance tests at the previous stage and proceed to *'Tunnel'* stage, V_{test1} shall no longer be applied. Therefore, whenever the magnet needs to be tested at NOC in the machine, the following test voltage shall be applied:

$$V_{test4} = 1.2 * V_{sim} \ \ [V] \tag{6-2}$$

6.11.2.2 Test levels at warm

For testing the magnet at room temperature two values are also defined. The chosen test value must consider the presence of helium in the magnet due to previous tests in a helium bath.

Prior to the first time the magnet is immersed in helium, i.e. after assembly and at reception of the magnet assembly at test stands, qualification at warm shall be performed at $V_{test2} = c*(a*V_{sim} + b)$, whereby *c* is a scaling factor to consider the influence of density according to Paschen's law, between nominal cryogenic conditions and room temperature in dry air. A scaling factor of 2 has been proposed, hence the voltage level at warm for a magnet which has not yet been in a helium bath is:

$$V_{test2} = 2 * (2 * V_{sim} + 500) = 2 * V_{test1} \ \ [V] \tag{6-3}$$

Once the components have been exposed in a previous stage to helium, V_{test2} cannot be longer applied as the presence of helium may weaken the insulation by creating creepage paths. Thus, a second test at warm is defined for whenever the magnet needs to be tested at room temperature after being operated in helium, which shall be applied at acceptance after cold testing and during the following stages of installation and commissioning in the machine. This value, V_{test3}, is also obtained from a scaling of the value at NOC, V_{test1}. Nonetheless, due to the risk of helium pockets, a factor *c* of 1/5 is applied:

$$V_{test3} = \frac{(2*V_{sim}+500)}{5} = \frac{V_{test1}}{5} \ \ [V] \tag{6-4}$$

The test voltage V_{test3} shall also be applied after assembly and at reception, if the magnet returned from a test station to manufacturing for modifications.

6.11.2.3 Test level at gaseous helium conditions

The test in gaseous helium intends to qualify the magnet on the test stations at conditions closely resembling the ones encountered during a quench. This test shall be performed after the magnet has been immersed in superfluid helium, during the magnet warm up, in order to guarantee that only gaseous helium is present within the magnet, including possible pockets inside the insulation. The specified temperature and pressure conditions shall be kept stable during the execution of the test.

The test value is calculated following a different rationale than the already mentioned tests and shall cover the value at ultimate current without margin, $V_{sim\ (I\ ultimate)}$. The test level, V_{test5}, is therefore calculated from:

$$V_{test5} = \max\{\ 1.2 * V_{sim(I\ nominal)}\ ;\ V_{sim(I\ ultimate)}\ \}\ [V] \qquad (6\text{-}5)$$

6.11.3 Diagram and flowchart for the test strategy

Figure 6-14 summarizes in a block diagram the strategy for the calculation of test voltages (it is important to note that it does not reflect the temporal sequence of tests which is instead detailed in Figure 6-15). The diagram allows to identify the factors between different test levels and the stage in which they shall be applied. It should be noticed that the test voltage at warm after the magnet has been in presence of helium – V_{test3} – is applicable for both stages.

Figure 6-15 presents a summarized flowchart of the test sequences and possible scenarios over time, 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 [19] – represented as hexagons in the flowchart – is required, and the applicable test value. The *End* output 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 initial test after magnet assembly. If testing at warm after prior immersion in a helium bath is required, even when returning to manufacturing, it is recommended that the magnet should be tested at the less stringent test level V_{test3}.[*]

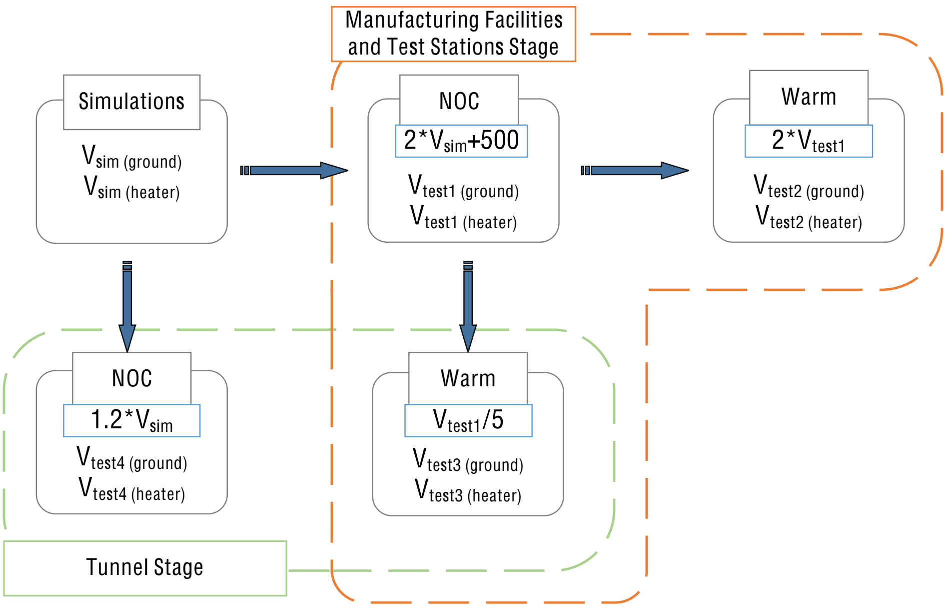

Figure 6-14: Test voltages diagram.

[*] The test levels at room temperature for a refurbished magnet, where part of the coils have been in helium and another part has not, needs to be addressed in the future after proper studies are conducted. As for today there is no final decision on the applicable procedures.

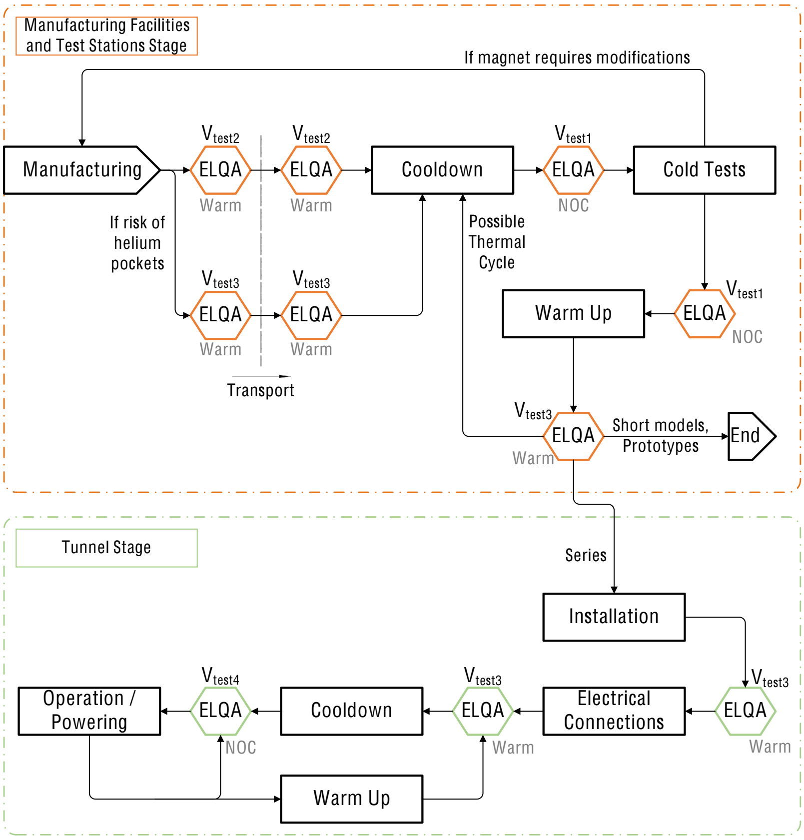

Figure 6-15: Flowchart of the defined stages and test levels to apply at each ElQA step.

6.11.4 Summary of test levels

Table 6-3 summarizes the rationale behind the test levels previously defined. As mentioned, the test strategy is equally applicable for coil-to-ground and coil-to-heater voltage. A description of the table inputs is below presented:

- **Maximum expected coil voltage at quench**: This value is obtained running simulations on the worst-case scenarios for each magnet or circuit.
- **Test voltage at NOC at *'Manufacturing Facilities and Test Stations'* stage**: Is 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 cooldown process and after the cold test programme.
- **Test voltage at warm before first helium bath**: It is 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 warm after helium bath**: This will be the value to consider whenever the magnet needs to be tested at warm once the components have been immersed in helium (risk of helium pockets).
- **Test voltage at NOC at *'Tunnel'* stage**: Once the magnet has been tested and qualified at the first stage, this will be the value to consider whenever the components need to be tested at NOC in the 'Tunnel' stage.
- **Test voltage at gaseous helium conditions:** It is the test value at which the magnet shall be qualified in helium gas conditions at the test station. The test shall be performed after the magnet has been

immersed in liquid helium to ensure the presence of gaseous helium within the coils and insulation layers.

Table 6-3: Expressions to obtain the test voltage levels.

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(1) 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	$V_{test4\,(heater)} = 1.2 * V_{sim\,(heater)}$
Test voltage at gaseous helium conditions (V)	**To ground**	$V_{test5} = \max\{1.2 * V_{\max(I\,nominal)}; V_{\max(I\,ultimate)}\}$
	To quench heater	

(1) Air at T = 20±3 °C and humidity lower than 60%.

The detailed test levels for the HL-LHC magnets (including short models, prototypes and series) and cold components are defined in Refs. [20][21][22][23][24][25][26].

6.12 References

[1] F. R. Mateos et al., "HL-LHC ECR WP3. Baseline for the Inner Triplet Main Circuit", EDMS: 1832082.

[2] M. Mentink, "Conservative Quench Scenario Considerations in the IT Main Circuit and Impact on Voltages to Ground", presented at HL-MCF Meeting no.29, INDICO: 704894.

[3] E. Ravaioli, "Quench Protection Studies for the HL-LHC Inner Triplet Circuit", EDMS: 1760496.

[4] E. Ravaioli, "Table with voltages and temperatures on QXF magnets", presented at the International Review of HL-LHC Magnet Circuits, INDICO: 835702.

[5] S. Yammine, "HL-LHC ECR - WP7. Energy Extraction Systems for HL-LHC RCBX Circuits", EDMS: 2360296.

[6] E. Todesco, "Modification of the Energy Extraction Resistance for the MCBXF Magnets", presented at HL-MCF Meeting no.60, INDICO: 896408.

[7] F. R. Mateos, "HL-LHC ECR - WP6A Local Powering of Correctors in the Inner Triplets of HL-LHC", EDMS: 1832068.

[8] M. Prioli, S. Mariotto, M. Sorbi and M. Statera, "Quench Protection Study of High Orbit Corrector Magnets", EDMS: 2370274.

[9] S. Kento, "Quench simulation and results for the MBXF magnet", EDMS: 2257328.

[10] P. Fabbricator, "Quench and Protection of D2 Magnet (MBRD) for the High Luminosity Upgrade of LHC", EDMS: 2222536.

[11] M. Mentink, "Quench Protection of the HL-LHC RCBRD Circuits", EDMS: 2222746.

[12] E. Ravaioli, "HL-LHC magnet Circuit Forum Meeting no. 58: Update on the RCBRD Protection Studies and Circuit Layout", Minutes in EDMS: 2360705.

[13] S. Claudet, B. Delille and P. Fessia, "HL-LHC ECR - WP1. Full Remote Alignment and New Matching Section Optimisation", EDMS: 2083813.

[14] M. Maciejewski, "Modified RB with 11T Dipoles and Trim Circuit Simulations," presented at HL-MCF Meeting no. 44, INDICO: 777024.

[15] M. Maciejewski, "Updated Quench Simulation Results on the 11T MBH," presented at HL-MCF Meeting no.59, INDICO: 892290.

[16] "HL-LHC Magnet Circuit Forum - Reference Circuit Parameters Table," [Online access].

[17] S. Yammine, "HL-LHC ECR WP6B - Circuit Disconnector Boxes", EDMS: 2317207.

[18] F. R. Mateos, "Voltage Withstand Levels for Electrical Insulation Tests on Components and Bus Bar Cross Sections for the Different LHC Machine Circuits", EDMS: 90327.

[19] M. Bednarek *et al.*, "ElQA Qualification of the Superconducting Circuits During Hardware Commissioning", EDMS: 788197.

[20] T. D. C. R. da Rosa and F. Rodríguez Mateos, "HL-LHC Electrical Design Criteria for the IT magnets", EDMS: 1963398.

[21] T. D. C. R. da Rosa, "HL-LHC Electrical Design Criteria for the D1 Dipole", EDMS: 2187266.

[22] T. D. C. R. da Rosa and M. J. Bednarek, "INFN - MBRD - D2 - Electrical Design Criteria", EDMS: 2363904.

[23] T. D. C. R. da Rosa, F. Menendez Camara and F. Rodríguez Mateos, "Electrical Design Criteria for the HL-LHC 11T Dipole", EDMS: 1995595.

[24] T. D. C. R. da Rosa and M. J. Bednarek, "CIEMAT - MCBXF - Electrical Design Criteria", EDMS: 2363905.

[25] T. D. C. R. da Rosa and M. J. Bednarek, "IHEP - MCBRD - Electrical Design Criteria", EDMS: 2363906.

[26] T. D. C. R. da Rosa and M. J. Bednarek, "HL-LHC Electrical Design Criteria for the High Order Corrector Magnets", EDMS: 2060633.