



EDMS NO. 1963398	REV. 1.0	VALIDITY DRAFT
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REFERENCE :

US HL-LHC-AUP#: US-HiLumi-doc-879

ENGINEERING SPECIFICATION

ELECTRICAL DESIGN CRITERIA FOR THE HL-LHC INNER TRIPLET MAGNETS

Abstract

This document describes the strategy applied in order to define the voltage withstand levels programme for the superconducting magnets manufactured under the US HL-LHC Accelerator Upgrade Project. The values presented here will be the reference to be used during the reception tests. The document gives an outlook into values to be used during installation and during commissioning as systems in the LHC tunnel.

TRACEABILITY

Prepared by: F Menendez Camara, F Rodríguez Mateos

Date: 2018-03-28

Verified by: P Ferracin, M Mentink, S Yammine

Date: 20YY-04-13

Approved by: G Ambrosio, S Feher, E Todesco, D Wollmann

Date: 20YY-MM-DD

Distribution: to be defined

Rev. No.	Date	Description of Changes
0.1	2018-02-09	First draft version
0.2	2018-02-22	Second draft version including corrections and changes to text by M Mentink
0.3	2018-03-28	Third draft version including corrections and changes to text by G. Ambrosio
0.4	2018-03-28	Fourth draft version after meeting on prototype tests in BNL
0.5	2018-04-10	Fifth draft after proposal of changes by G Ambrosio



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1 INTRODUCTION

Electrical tests are performed in components belonging to the superconducting magnet chains in order to verify that the integrity and insulation 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 or before installation of components in the tunnel.

In general, components must be designed according to voltages that they should withstand during operation. Test levels are usually fixed according to some worst conditions that can be encountered during operation and are something intrinsically linked to the design of components. Already from the early phases in the design of a superconducting component, electrical withstand levels must be considered with the same priority as their quench protection or the magnetic design. Defining realistic testing conditions requires the understanding of both design of components and the very operational aspects.

This document applies principally to insulation impedances from the active element to ground. Whenever applicable, numbers are related to insulations from the active parts to the protection systems (e.g. quench heaters). Some indications are presented also for voltages appearing between turns of the same coil.

The rationale behind is that if V is the maximum voltage that a component is expected to withstand during normal accelerator operation, $V_{\text{test1}} = a \cdot V + b$ will be the test voltage at the same operational (i.e. cryogenic) conditions. The IEEE Standard 95-177 suggests $a=2$, and b from 1000 to 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 already [1], CERN followed the latter standard applying it as $V_{\text{test1}} = 2 \cdot V + 500$. For the HL-LHC Project, it has been agreed that the same standard, with some minor improvements, be followed.

If the tests are performed at different ambient and temperature-pressure conditions than the nominal ones, the rule is to apply a so-called "scaling factor" to consider the influence of density in Paschen's law. This results into a new test value $V_{\text{test2}} = c \cdot (a \cdot V + b)$, c being that scaling factor.

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

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 gas volumes (e.g. during a quench).

2 ELECTRICAL TESTS STRATEGY

For the scope of this document, we define two stages at which to verify the electrical integrity of the components belonging to the electrical magnet circuits:

- (1) test voltages at acceptance/reception,
- (2) test voltages at installation and further commissioning.

These are not the only holding points, but this document focuses into these two stages for simplicity.



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Regarding the tests at reception, these qualify the equipment for the machine operation according to the defined safety factors. At this reception stage, it is worth to distinguish between two different levels, which are:

- 1) tests at Nominal Operating Conditions (NOC),
- 2) tests at warm (e.g. room temperature in dry air).

Once the components have been exposed in a previous stage to helium, reception values cannot be longer applied as the presence of helium may weaken insulations by creating creepage paths. The same scaling factor of 5 should be then applied as in Table 3 if the temperature for hi-pot tests is ambient one.

Concerning test voltage values during the installation stage, as it was stated for the reception values, they are also considered both at NOC and at warm. The conditions will be less stringent than in the reception case for the reason mentioned above (presence of helium). The reduction of test values must be applied at any hi-pot test which occurs after the magnet has been immersed in a helium bath.

Table 1 contains the information on how the calculations are made for the different test levels. Under nominal operating conditions, voltages are calculated by applying the modified IEEE Standard mentioned above. The coil-to-ground and heater-to-ground voltages are calculated assuming some worst conditions, including failure of some of the protection elements. For the MQXFA magnets under consideration here, it is assumed that two quench heater circuits are not operational at the moment of quench. Values for tests at room temperature in dry air, are obtained by applying a scaling factor from the ones at nominal cryogenic conditions. In the particular case of the HL-LHC inner triplet magnets, a factor of 2 has been proposed. The same scaling factor is used for the quench heater to coils.

Initial parameters		$U_{Coil_to_ground}$ & $U_{Heater_to_ground}$	
Minimum design withstand voltage (Acceptance/Reception)	Coil	Nominal operating conditions	$U_{test_NOC_GND} = 2 * U_{Coil_to_ground} + 500$
		Warm conditions	$U_{test_warm_GND} = 2 * U_{test_NOC_GND}$
	Heater	Nominal operating conditions	$U_{test_cold_Heater} = 2 * U_{Heater_to_ground} + 500$
		Warm conditions	$U_{test_warm_Heater} = 2 * U_{test_NOC_Heater}$
Test voltage to ground (After Acceptance)	Coil	Nominal operating conditions	$U_{TO\ GROUND\ @\ NOC} = 1.2 * U_{Coil\ to\ gnd}$
		Warm conditions *	$U_{TO\ GROUND\ @\ RT} = \frac{U_{test_NOC_GND}}{5}$

Table 1. Expressions to obtain the test voltage levels

* After tests in helium and during installation



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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 ultimate conditions should be covered by the design of components without contingency (hence without the safety margins which are applied at nominal conditions).

Moreover, we have considered that 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. Among these conservative cases, one would consider rather exotic beam losses scenarios provoking instantaneous quenching of inner layers only. This is a key point, and one has to make sure that the reception/qualification levels and procedures consider –but without margin- those rare cases.

3 DEFINING THE HIGH VOLTAGE TEST LEVELS

The following Table gives worst case voltages under nominal current with some failures as indicated:

Table 2. Worst case voltages in MQXF magnets during quench under different scenarios

Sim #	Quench Scenario	Peak voltage to ground [V]
201	Q2a, stand-alone, nominal current, no faults	680
202	Q2a, stand-alone, nominal current, single heater failure, no CLIQ	680
203	Q2a, stand-alone, nominal current, double heater failure, with CLIQ	730

These values come from [2] which contains results very closely consistent with previous calculations as in [3].

Table 3 contains the values for the test levels to be applied during the different stages. It presents the following data:

- The maximum expected coil voltage at quench: This value is obtained running simulations on the worst-case scenario.
- Minimum design withstand voltage at room temperature: It is the test value that must be applied after the component has been manufactured for qualification at warm. Warm conditions should be taken as follows: $T = 20 \pm 3$ C and humidity lower than 60%.
- Minimum design withstand voltage at nominal operating conditions: After checking that the component withstand the test values at warm it should be tested at NOC in order to make sure that the dielectric material properties are not modified/damaged during the cooldown process and remain within the acceptable limits. This test is the first one that will introduce helium in the tested magnet.
- Test voltage to ground for systems at warm: This will be the value to take into account whenever the component needs to be tested at warm after reception, once the component has been tested in helium (risk of helium pockets). This value is also used during the installation checks.



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- Test voltage to ground for systems at nominal operating conditions: Once the component has been tested at the reception stage, this will be the value to take into account whenever the component needs to be tested at NOC.
- Maximum leakage current to ground: It is the maximum value accepted. Limits to the actual current must be set during application of the voltage. These values come from experience on models and prototype magnets.
- Test voltage duration: Duration to perform the test, taking into account the leakage current value.

Recent simulations (ref. 2) show that the worst-case scenario involving a MoGR collimator may potentially lead to very large instantaneous normal zones throughout the triplet magnets with the potential for large voltages to ground. Assuming that copper-diamond is used instead of molybdenum-graphite, FLUKA calculation results (provided by A. Lechner [5]) indicate a heat load magnitude that is approximately a factor 10 lower. At this level only a fraction of the inner layer turns will quench, resulting in a reduced peak voltage-to-ground. If we assume a worst-case conductor property distribution (i.e. RRR and Cu:nonCu ratio) for Q2b, with correctly functioning quench protection, and assuming a regular quench at ultimate current, then we get a peak voltage to ground of 1650 V (calculated with LEDET [6]). Adding the instantaneous normal zone due to the asynchronous beam dump (assuming a full bunch impacting on TCT6 made from CuD, also see [7]), where the heat load is applied over the entire length of Q2b magnet, in addition to a worst-case single heater failure, then the peak voltage to ground increases to 1880 V [2]. These are voltages that could appear under very rare conditions and are not assumed to be operational worst cases but conservative cases for which no margin applies.

Considering all the above, Table 3 contains the electrical test values for the MQXFA magnets. All the circuit parameters can be found from the reference HL-LHC Circuit Table [4].

Table 3. MQXFA electrical test values

The maximum expected coil voltage at quench (V)	To ground	670
	To quench heater	900
Minimum design withstand voltage at nominal operating conditions (V)	To ground	1850
	To quench heater	2300
Minimum design withstand voltage at room temperature (V)	To ground	3700
	To quench heater	4600
Test voltage to ground for installed systems at nominal operating conditions (V)		840
Test voltage to ground for installed systems at warm (V)		380
Maximum leakage current to ground (μ A) – not including leakage of the test station		10
Test voltage duration (s)		30

4 REFERENCES

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 [3] E Ravaioli, " Quench Protection Studies for the HL-LHC Inner Triplet Circuit".
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- [6] E. Ravaioli et al., Cryog. 80, p 346, 2016.
- [7]. A. Tsinganis, F. Cerutti, "Consequences of asynchronous beam dump on TCTs 4 & 6 of IR5", presented at the 7th HL-LHC workshop, Madrid, Nov. 13 2017.