Circuits description and requirements

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(on behalf of the HL-LHC Magnet Circuit Forum)

HL-LHC Cold Powering Review – 3rd July 2017

Outline

1. Introduction to the HL-LHC Circuits' powering and protection
   - Circuits' layouts, schemes and key parameters
   - The role of the Magnet Circuit Forum
2. Baseline and inputs to cold powering design (Inner Triplet quads circuit)
   - Current ratings, quench loads, dI/dt
   - Voltage withstand levels
   - Documentation
3. Some (other) follow-ups from the Internal Circuits Review
4. Conclusions

Introduction

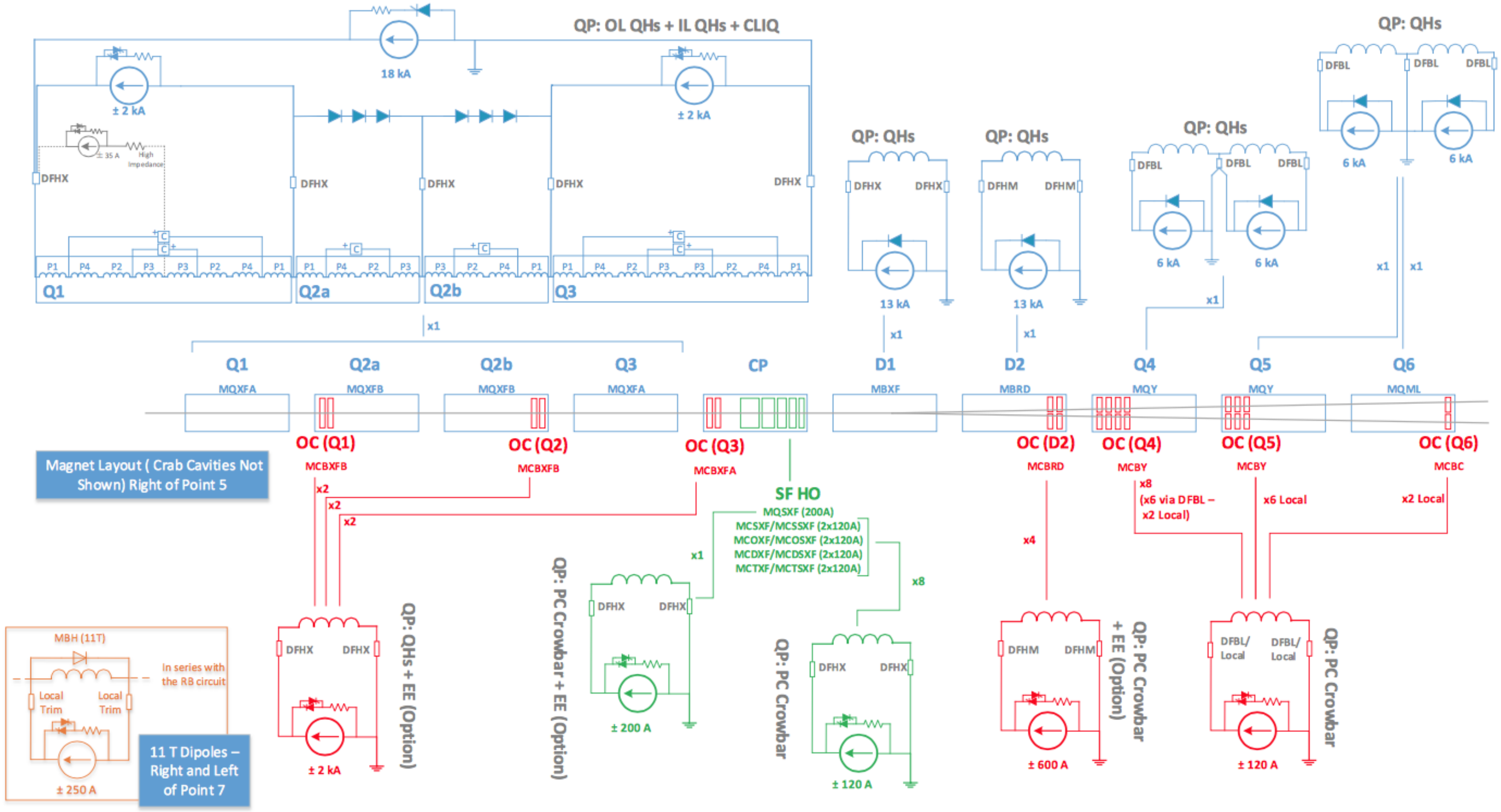
- The definitions and optimization process for the HL-LHC superconducting magnet circuits started in the fall of 2015
- Since then, two reviews have taken place:
  - Conceptual Design Review of the Magnet Circuits for the HL-LHC (**21-23 March 2016**); https://indico.cern.ch/event/477759/
  - HL-LHC Magnet Circuits Internal Review (**17 March 2017**);https://indico.cern.ch/event/611018/

Through the last months, since the second review, a considerable effort has been delivered in order to advance finalizing the configuration of HL-LHC magnet circuits

The work together with the WPs involved is done within the framework of **Magnet Circuit Forum (MCF)**, [26 meetings have taken place so far since July 2016, including some topical meetings]

All this work has produced a baseline that is going to be outlined throughout this presentation

The focus will be set on aspects directly impacting the cold powering.



Cold powering via DFHX
2 leads 18 kA
2 leads 13 kA
3 leads 7 kA 5 MIITS
12 leads 2 kA
2 leads 0.2 kA
16 leads 0.12 kA

Cold Powering via DFHM
2 leads 13 kA
8 leads 0.6 kA

Cold powering of Q4/Q5/Q6 via DFBL+DSL
Cold powering for correctors:
- Q4 MCBYs powered via DFBL+DSL (x6) and locally (x2)
- Q5 and Q6 MCBYs powered locally

9 leads 6 kA (+2 spares)
32 leads 0.12 kA

QP: Quench Protection
QHs: Quench Heaters
EES: Energy Extraction System
PC: Power Converter
OC: Orbit Correctors
xN: Number of Circuits per IP Side
Current Leads Connection

Legend

HiLumi HL-LHC PROJECT

Circuits Layout Version 2.0

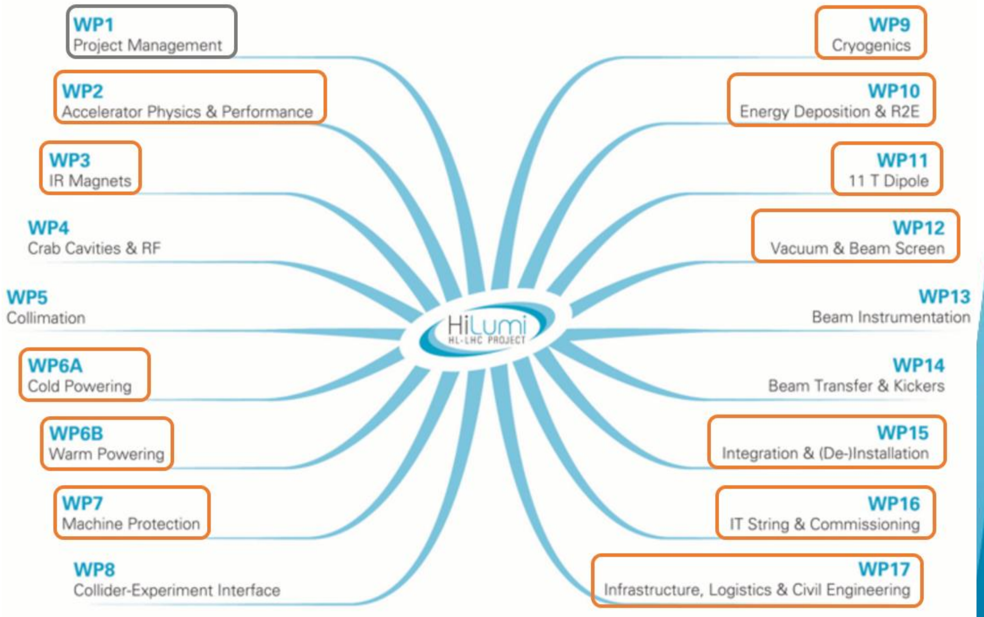
The HL-LHC MCF (Magnet Circuit Forum)

One of the recommendations of the March 2016 review on HL-LHC Magnet Circuits was:

"… to realize close and regular interaction (communication) between the involved experts and work-packages. This could be possibly done by setting-up of a dedicated working group or by using existing structures to discuss circuit integration and protection on a regular basis and to identify the optimum scheme for each magnet circuit system."

Mandate

- The Magnet Circuit Forum (MCF) is a **regular meeting where all aspects related to powering and protection of the HL-LHC circuits are discussed**, in particular the ones pertaining to the optimization of circuit layouts and definition of protection means.
- Subjects in the agenda are defined in **close collaboration with the relevant WPs.**
- **Interface aspects between systems** are clarified through meetings at the forum. To this end, a **documentation plan** has to be developed and completed.
- The aim is to prepare a set of **functional interface specifications** that can be used as input for the design (technical specifications) of the different systems.
- Assessment on **realistic failure scenarios and required mitigation strategies** on a global basis is part of the activities of the MCF.
- The MCF is the meeting where aspects related to **high voltage withstand levels** are discussed and harmonized in order to define an Electrical Quality Assurance plan globally
- The MCF reports regularly to TCC and takes up any relevant discussion within the domain of cold/warm powering and protection of the HL-LHC circuits in collaboration with the relevant WPs .

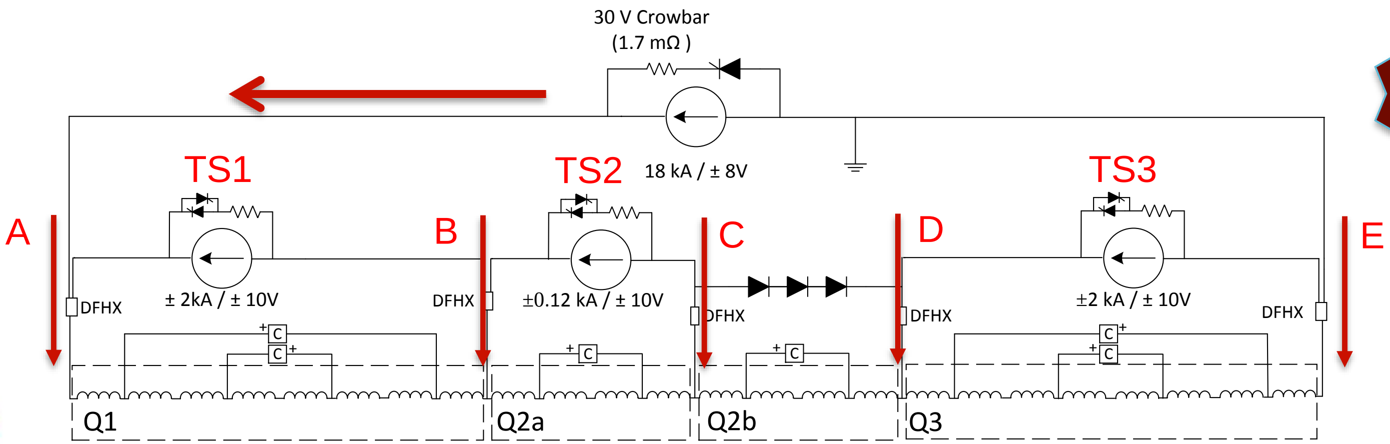


[MCF's website]

Inner Triplet Circuit

Definition of a conservative scenario

- Q2b quenches suddenly and completely (4 poles)
- 15 ms detection and validation
- 1 ms CLIQ firing
- 5ms heater firing
- *Sensitivity analysis w.r.t. parameters*



Nov 2016

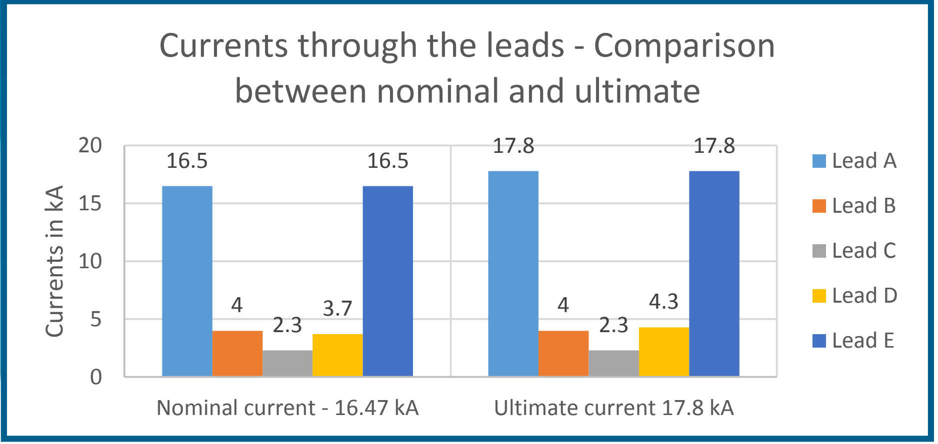
Standard quench case

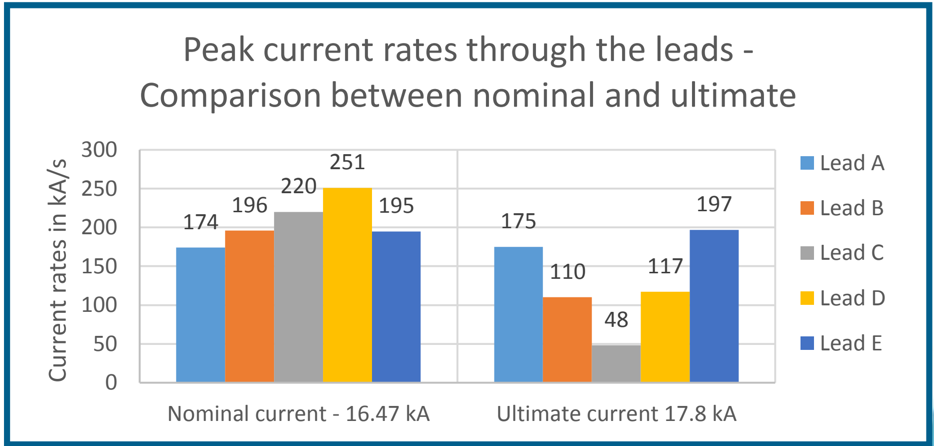
- **Quench occurring in a spot of a magnet** followed by quench detection and validation (15 ms) and quench protection triggering (1 ms, Outer QH+CLIQ)
  - Initial conditions: Worst case of current in trims, nominal and ultimate currents
  - Sensitivity analysis: Influence of the worst distribution of strand parameters (RRR and Cu/non-Cu ratio)
  - CLIQ delays: Influence of a delay in the triggering of one CLIQ unit

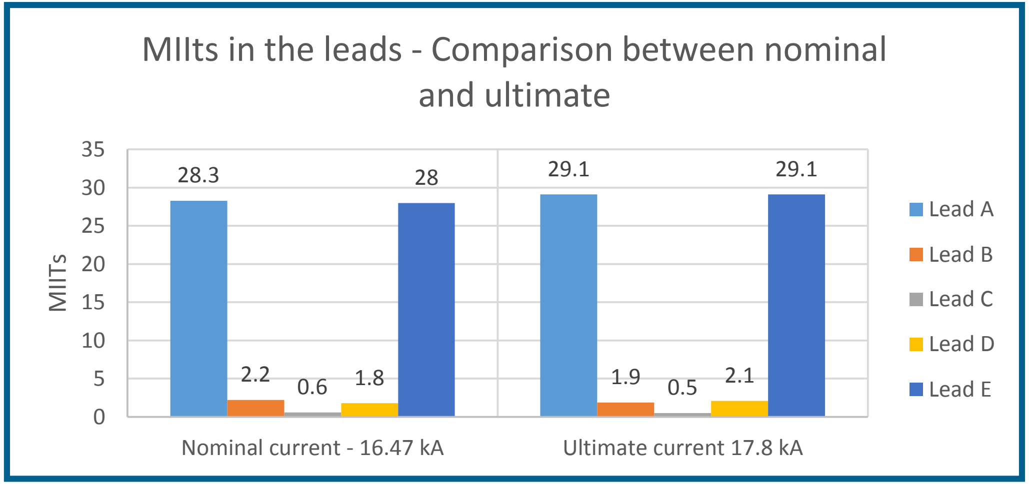
Conservative quench cases

- **Quench occurring suddenly in one entire magnet** followed by quench detection and validation (15 ms) and quench protection triggering (1 ms, Outer QH+CLIQ) leading to the quench of the other magnets
  - Initial conditions: Worst case of current in trims, nominal and ultimate currents
  - Sensitivity analysis: Influence of the worst distribution of strand parameters (RRR and Cu/noCu ratio).
    - For the case at ultimate current (representing the highest values reached in all simulations), less conservative (more realistic) cases of sudden quench of parts of one magnet: inner layers of all four poles in one magnet; a few turns on the horizontal mid-plane.
  - Quench detection time: changing the 15 ms reference time to see effects

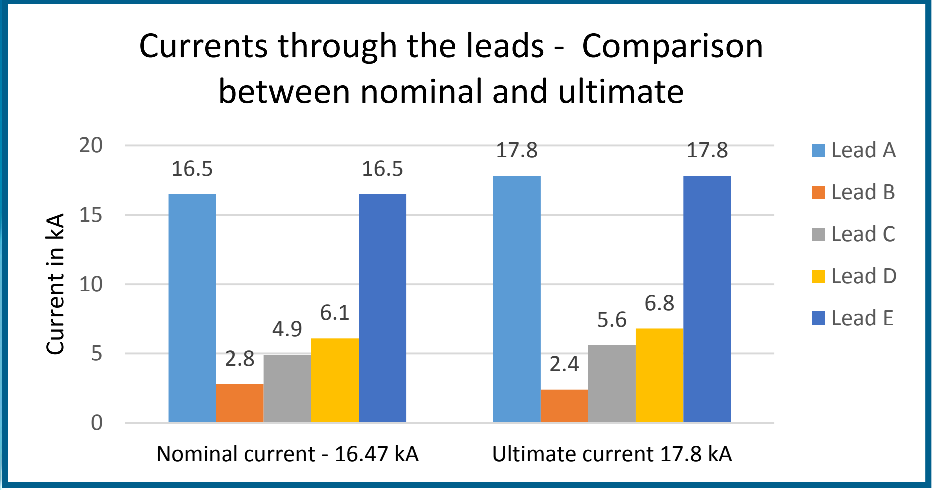
Peak Values @ Standard cases - Nominal I vs Ultimate I

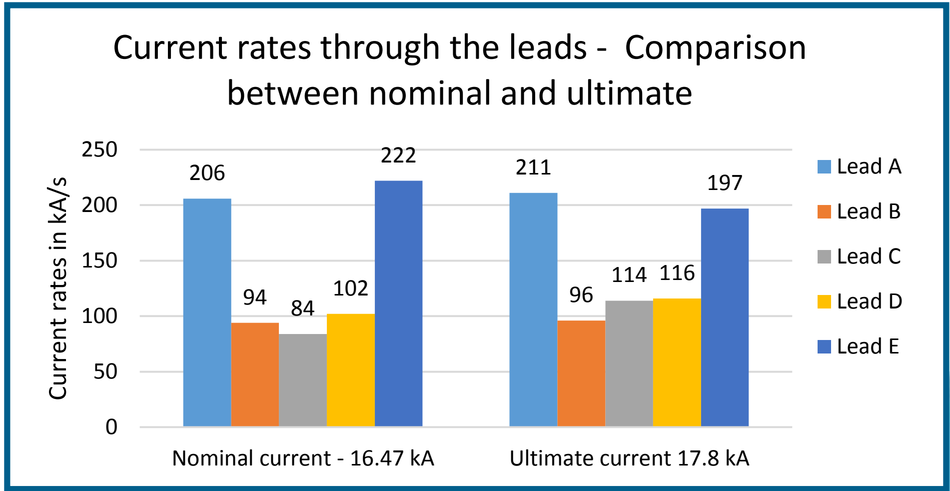


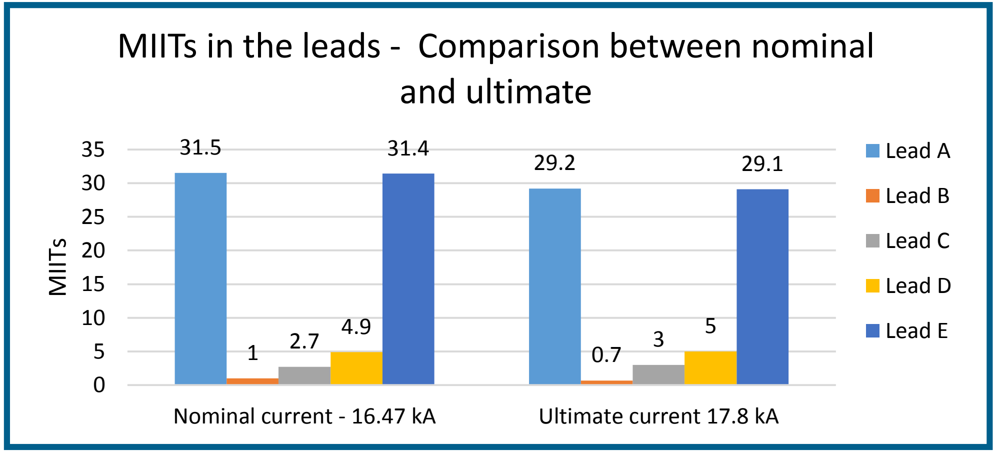




Peak Values @ Conservative case - Nominal I vs Ultimate I







Conclusions from IT simulations & analysis in a nutshell

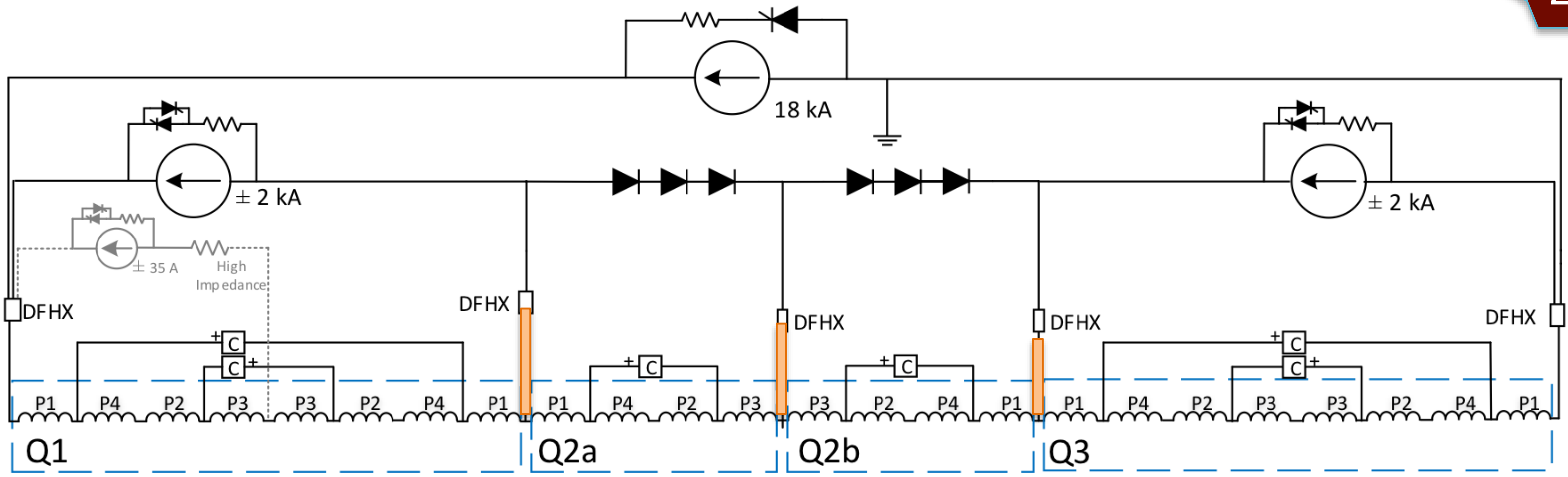
- for **standard** cases, over-currents can go up to 4.3 kA and 2.2 MIITs (approx. nominal and ultimate currents included)
- for the **conservative scenario**, those values could go up to 6.1 kA (nominal) and 6.8 kA (ultimate), and 5 MIIts (nominal and ultimate approx.)
  - these numbers are obtained considering a full magnet suddenly quenching in its whole volume

- **7 kA** current capability in s.c. would suffice for not quenching the conductors within the s.c. link or bus bars
- **5 MIIts** is the highest quench load the s.c. link or bus bars would see

- **The analysis covers the whole spectrum of operating conditions, from low to ultimate current**

Inner triplet – Baseline

May 2017



*"The panel considers that the presented powering circuit is a **robust** solution, provided the 2 kA and 120 A SC trim cables in the superconducting link can be upgraded to a rating of about **5-6 kA and 5 MIITs**"*

*Trim cables will be designed for **7 kA** and **5 MIIts***

Cold Powering Functional Specification for HL-LHC Inner Triplets and D1

A reference document has been prepared with the main parameters related to

- The Inner Triplet electrical circuits
- Ratings as defined by transient studies
- Voltage Withstand Levels for electrical insulation

EDMS NO.	REV.	VALIDITY
1821907	2.0	APPROVED

REFERENCE :

FUNCTIONAL SPECIFICATION

NUMBER OF COMPONENTS AND CURRENT RATING OF THE CURRENT LEADS AND SUPERCONDUCTING CABLES FEEDING THE HL-LHC TRIPLETS AND D1

Abstract

This document summarizes the total number of High Temperature Superconducting (HTS) current leads and cables, the latter contained inside the Superconducting Link, needed for the powering of the HL-LHC Triplets and D1. The design current rating of both leads and cables is also indicated. The values reported in this document reflect the modifications introduced in the HL-LHC Cold Powering System in June 2017 in order to take into account the changes in the magnet circuits announced after the HL-LHC Magnets Circuits Internal Review (EDMS N. 1807471, May 2017). The components described in this document are part of the WP6a Cold Powering system. Circuits simulations providing the input for transient modes, protection and high voltage insulation tests are part of the Magnet Circuit Forum activity [1], [2]. The input is used for the design of the Cold powering System.

APPROVED

TRACEABILITY

Prepared by: A. Ballarino, S. Yammine	***Date:*** 2016-06-12
Verified by: F. Rodriguez Mateos, F. Menendez Camara	***Date:*** 2016-06-21
Approved by: A. Ballarino [WP6a Leader]	***Date:*** 2016-06-23

Distribution: L. Bottura, O. Bruning, S. Claudet, R. Denz, P. Ferracin, Y. Leclercq, V. Parma, P. Retz, L. Rossi, A. Siemko, E. Todesco, D. Wollmann, M. Zerlauth

Rev. No.	***Date***	***Description of Changes*** *(major changes only, minor changes in EDMS)*
X.0	2017-06-22	First version

Inner triplet circuits – Baseline ratings

	Magnet	Cold Powering				
	I_{ult}(kA)	I_{peak}(kA)	I_{lead} (kA)	I_{cable}(kA)	N_{leads}/N_{cables}
MQXF	17.82	-	18	18	2
Trim Q1	2	2.4	2*	7	1
Q2a/Q2b	Protec.	5.6	2*	7	1
Trim Q3	2	6.8	2*	7	1
MCBXFB	1.73	-	2	2	2+2
MCBXFB	1.59	-	2	2	2+2
MCBXFA	1.73	-	2	2	2
MCBXFA	1.59	-	2	2	2
MQSXF	0.2	-	0.2	0.2	2
MCSXF/MCSSXF	0.12	-	0.12	0.12	2+2
MCOXF/MCOSXF	0.12	-	0.12	0.12	2+2
MCDXF/MCDSXF	0.12	-	0.12	0.12	2+2
MCTXF/MCTSXF	0.12	-	0.12	0.12	2+2
D1	12.96	-	18	18	2

Rating (kA)	MIITs $(M.A^2 \times s)$	dI/dt (kA/s)	t_n (no quench of magnets) (s)	t_Q (quench of magnets) (s)	Equivalent time (s)
18	32	250	130	0.2	0.1
7	5	250	130	0.2	0.12
2 *	1	20	20	0.5	-
0.2 *	0.02	0.25	21	0.8	-
0.12 *	0.02	0.22	5	0.8	-

* Conservative numbers, they require detailed simulations

A recap on the definition of voltage withstand levels from previous Reviews:

Test voltage procedure

Acceptance /Reception

Manufacturer & 1st test at arrival to test bench

300 K, 1 bar , AIR

$V2$

$$V2 = 2 * V1$$

1st test at cold in the test bench

Nominal operating conditions

$V1$

$$V1 = 2 * U_{Coil\ to\ gnd} + 500$$

Installation

1st test after cold test in air but possibly with He gas

300 K, 1 bar , He (gas)

$V3$

$$V3 = \frac{V1}{5}$$

Test at cold after acceptance or reception test

Nominal operating conditions

$V4$

$$V4 = 1.2 * U_{Coil\ to\ gnd}$$

Electrical insulation test levels for link and bus bars

Rating (kA)	Worst case voltage to ground during operation (V)	Acceptance tests of components to ground (V)		Insulation test voltage of system to ground (V)		Leakage current per component (µA)	Test duration (s)
		RT	NOC	RT	NOC		
18	900	4600	2300	460	1080	≤10	30
7	900	4600	2300	460	1080	≤10	30
2	540	3160	1580	316	648	≤10	30
0.2	540	3160	1580	316	648	≤10	30
0.12	40	1160	580	220	360	≤10	30
0.035	900	4600	2300	460	1080	≤10	30

Table: Test voltage of leads and cables and calculated highest voltage to ground during operation. For the 18 kA and 7 kA cables, the highest voltage is estimated to be 700 V (across the high resistance of Q1a trim) + 100 V (sum of voltages across crowbar and cables resistances) + 100 V (superconducting cable in the link resistive along the full length). For the 2 kA and 0.2 kA cables, an energy extraction of 500 V is considered (worst case scenario). For the 0.12 kA circuits the crowbar voltage across the power converter is taken into account for the calculations.

RT: Room temperature
NOC: Nominal operating conditions

Other follow-ups from the recent Review

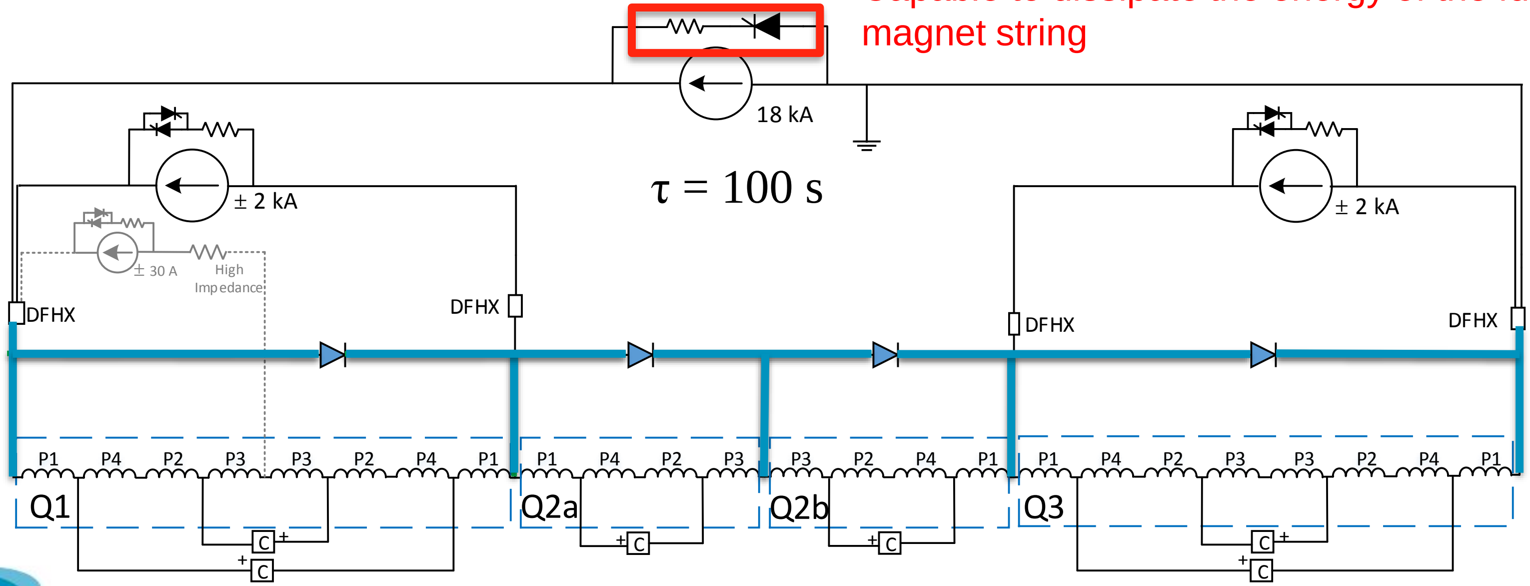
Optimization: Cold Diodes

2 options $\left\{ \begin{array}{l} \tau = 100ms \\ \tau = 100\ s \end{array} \right.$

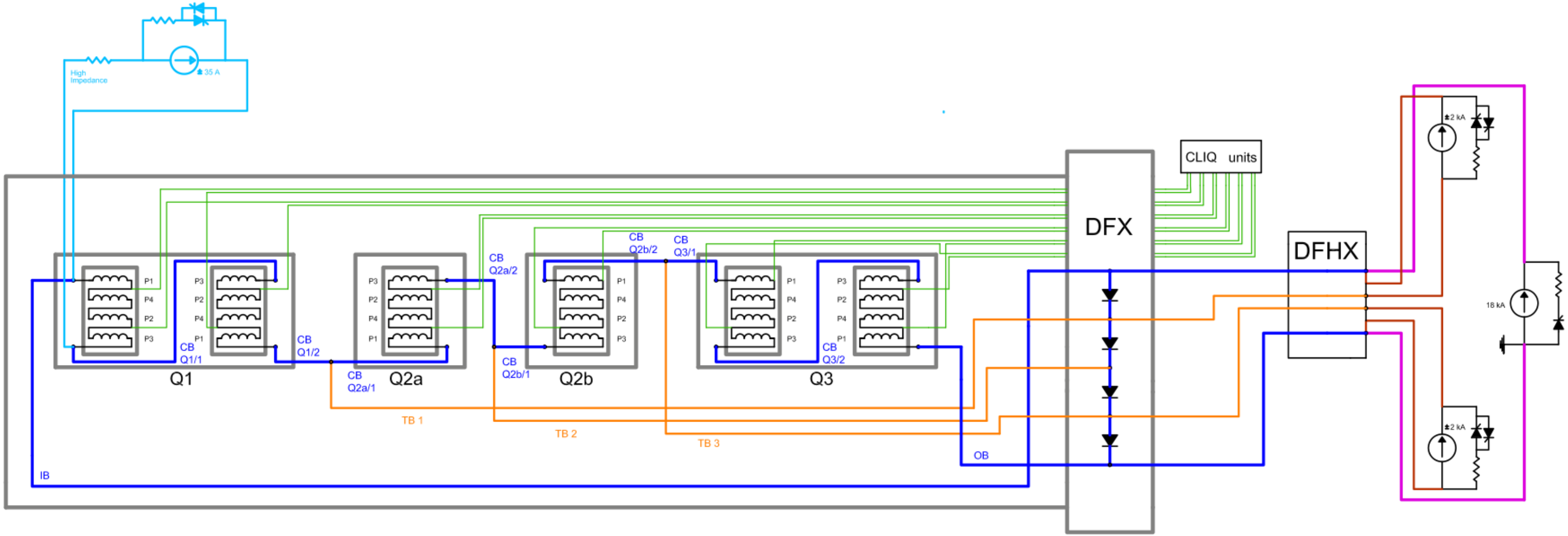
— 7 kA

— 18 kA

Capable to dissipate the energy of the full magnet string



- The Internal Review Panel (March 2017) recommended to carry out studies related to the integration of cold diodes in a way to further optimize the circuit as cold diodes would bring in clear advantages:
  - Decoupling of warm and cold parts of the circuit
  - Avoiding the large current unbalances flowing through the sc link
  - Making the circuit more robust with respect to variability of scattering of quench resistances in the different magnets due to delays in protection actions and/or inherent magnet properties (RRR, Cu/non-Cu, strand diameter, quench location, etc)
- But diodes have to be qualified with respect to:
  - Integration in the cold environment (bus bar section for options being studied at present)
  - withstand the current pulses according to the circuit time constants
  - tolerate with margin the radiation doses expected at their final position (roughly 1 order of magnitude above LHC)

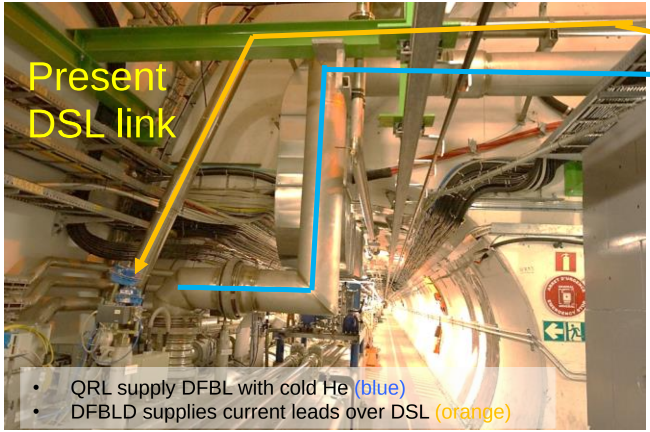


Follow-ups from Internal Review – Matching section

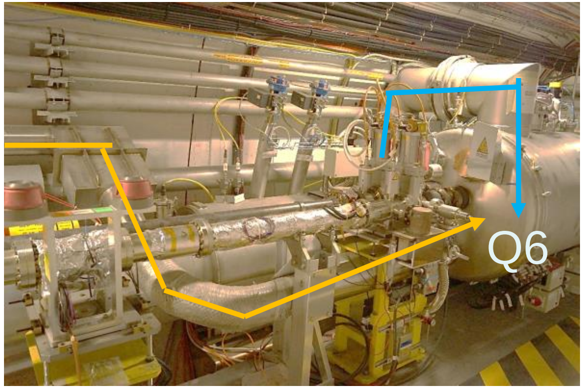
Item	Action
1. The relevant groups (TE-MSC, TE-CRG) should launch a task force effort in order to agree on the requirements and the procedure for the dismantling and the reassembly of the DSL [In case of a dismantling of the DSL, the corrector SC cables should be kept at a rating of 600 A to include a possible change from MCBY correctors to MCBYY correctors]	**WP6a**
2. Connection in series for four Q4 corrector magnets (2 circuits with two magnets [illegible]	[illegible]
3. [illegible] leads	**WP6a**

After discussions with work packages involved, it has been agreed that both Q5's and Q4's correctors will be powered individually

Some illustrative pictures *(not necessarily IR5R)*



Courtesy:
S. Claudet (TE-CRG)
and V. Parma (TE-MSC)



- Not in the scope of this Review
- Studies will start with the goal of a final decision by end of 2017

Conclusions

- The HL-LHC circuits baseline in terms of powering and protection has been consolidated through two Reviews and the teamed work within the Magnet Circuit Forum where all the relevant WPs are represented
- Inputs to the design of cold powering have been defined and are documented
- Optimization in the case of the inner triplet main circuit is ongoing and should not have a major impact into the cold powering baseline (provided decisions are taken with sufficient anticipation)
- A few open points require a follow-up but there is no showstopper identified as of today

Thank you very much for your attention