Engineering changes and advances in the HL-LHC s.c. circuits

[since the last Internal Circuit Review in March 2017]

Felix Rodriguez Mateos for the MCF

TCC – 2nd November 2017

Content

1) Background and global current status
2) Changes to the IT
3) Changes to the MS
4) Changes to the 11T dipole
5) Conclusions

Background

The last Internal Circuit Review that took place on the 17th of March 2017, turned out to be a really useful exercise that provided many recommendations and statements. Now, after months of common work together with the relevant work packages at the **M**agnet **C**ircuit **F**orum (MCF) (since the review the MCF has hosted more than **10** regular meetings and **7** topical meeting), there have been changes applied with respect to the previous baseline. This presentation summarizes the status of advancements on the different circuits and the follow-up points from the Review.

Follow-ups after the review

Circuit	Item	Action	Status
11T dipole	• Trim crowbar resistance is required to limit the currents to 250 A in case of power abort (it is proposed to take 250 A as nominal design value for the trim leads)	WP6a, WP6b	**Implemented**
	• Study the impact of the trim PC on the QDS in case of power abort on the 11T and neighbouring MB magnets in SM18, feasibility study	TE-MSC-TF, WP11, WP7	**Not adopted**
	• Test the full-length prototypes in order to elaborate a suitable quench detection strategy	WP7, WP11	**Work in progress**
	• Qualify the present (conduction-cooled) current leads or make a new design	WP6a	**Work in progress**
	• Decision on the qualification of the trim circuit in terms of HVWLs	WP6b	**Implemented**
Matching section	• 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	**Work in progress**
	• Connection in series for four Q4 corrector magnets (2 circuits with two magnets each) be adopted in order to reduce the leads from 16 to 12 and hence eliminate the local powering	WP3, WP6a, WP6b, WP7	**Implemented**
	• Q5 correctors to be powered individually by providing local powering for the missing leads	WP6a	**Implemented**
Inner triplet	• Only one between IQH and CLIQ is needed (the decision is to be taken after the test of the first long prototype)	WP3	**To be decided**
	• Updates on the trim to be placed on Q1a	WP2, WP3, WP6b, WP7	**Well-advanced**
	• Consequences of the upgrade the 2 kA and 120A sc trim cables in the sc link to a rating of about 5-6 kA and 5 MIITs	WP6a	**Implemented**
	• Studies on cold diodes (development, tests up to 18 kA, radiation levels qualification, etc.)	WP7, WP6b	**Work in progress**
	• Integration of cold diodes	WP3	**Work in progress**
	• Studies to be carried out on the connection of D1 magnet to the inner triplet using both a three-cable configuration or a nested connection	WP7	**Well-advanced**
	• Design and integration of the bus-bars	WP3	**Work in progress**
	• Design and integration of the cables and feedthroughs for CLIQ	WP3	**Work in progress**
	• Design and implementation of interconnects and splices	WP3, WP6a	**Work in progress**
	• Design and integration of the instrumentation	WP3, WP7	**Work in progress**
	• An internal staffer to be designated to take full responsibility for the required studies including benchmarking	WP7	**Implemented**
	• Follow-up on crowbars maximum voltage	WP6b	**Implemented**
	• Follow-up on circuit separators	WP6b	**Work in progress**

Open Issues & Class of Uncertainty

Estimate classification	% of complete definition
Class 1	50 – 100
Class 2	30 – 70
Class 3	10 – 40
Class 4	1 – 15
Class 5	0 – 2

Section	Open issue	Class
IT	Study on the IT alternative configurations from WP6a	1
	Q1a k-modulation circuit follow-up	2
	Bus-bars design	3
	Circuit separators follow-up	3
	Design and integration of the cables and feedthroughs for CLIQ	3
	Study on the polarities for test campaigns	3
	Study on the polarities of the connection between quench heaters and CLIQ	3
	Local integration of leads for corrector package	4
	Cold diodes project as recommendation from the Internal Circuit review	4
	Design and implementation of interconnects and splices	4
	Design and integration of instrumentation	4
MS	Local integration of 120A leads in the HL-LHC cryostats	3
	Follow-up on the DSL	4
11T	Official statement regarding 11T interlock strategy	1
	Test the full-length prototypes in order to elaborate a suitable quench detection strategy	3
	Current leads for 11T trim	3
	Study the impact of the trim PC on the QDS in case of power abort on the 11T and neighbouring MB magnets in SM18	4

2) Changes to the IT

a) Counter-check simulations on the IT. Simulations on Q1a k-modulation circuit
b) Bus-bars
c) Circuit separators
d) Cold diodes project
e) Document co-authored by WP6a and MCF
f) Current leads for the IT correctors

2.a) Counter-check simulations on the IT. Simulations on Q1a k-modulation circuit

Conclusions from simulations & analysis in a nutshell

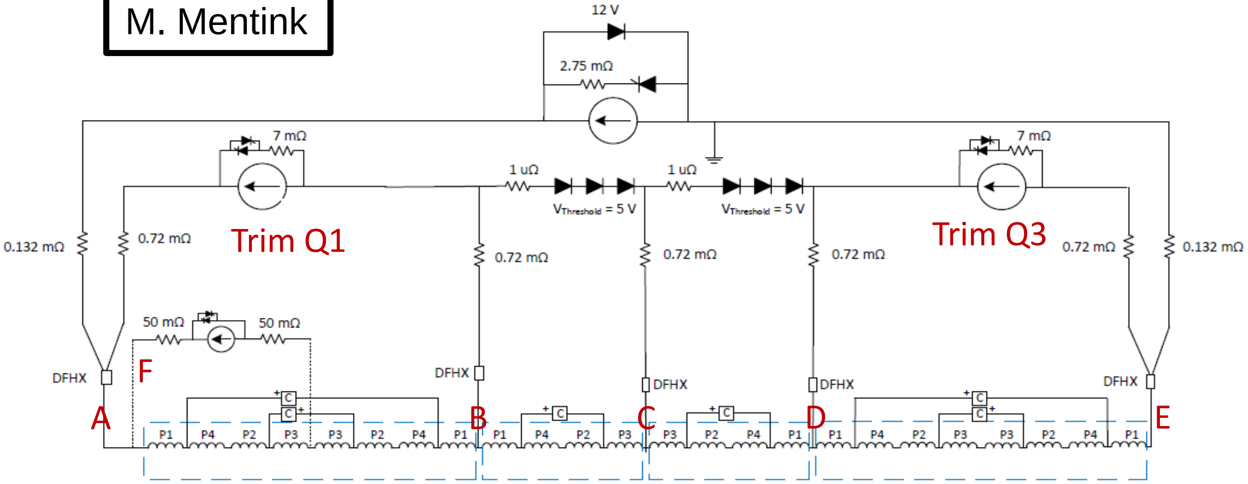
- For **standard** cases, over-currents can go up to 4.3 kA and 2.2 MIITs (approx. nominal and ultimate currents included) => **5 kA** current capability in s.c. would suffice for not quenching the conductors within the s.c. link
- For the **very conservative scenario**, those values could go up to **6.1 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
- **the analysis covers the whole spectrum of operating conditions, from low to ultimate current**

May
2017

October 2017

Counter-check simulations

M. Mentink



Highest values	Leads A / E	Leads B / D	Lead C	Lead F	Trim Q1	Trim Q3
Current [kA]	17.8	6.1	4.3	4.1	5.1	4.2
Ramp rate kA/s	250	170	100	70	160	160
MIITs	32.6	3.8	1.9	1.5	2.9	1.9

Assumptions

- **Maximum current, ramp rate, and MIITS evaluated under different scenarios** (Reference cases provided by E Ravaioli)
- Regular quench: **Detection + validation time = 15 ms**
- Global magnet quench: **Detection + validation time = 10 ms**

Generally **consistent results** compared to previous TALES calculations (Some differences due to circuit modification / starting assumptions)

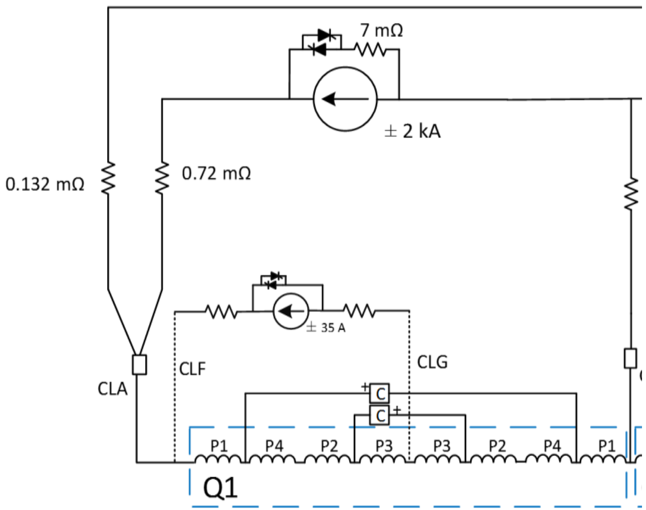
Q1a k-modulation circuit simulations

Developed simulations on

- Current profile during magnet quench
- Current profile during power aborts (without quench)
- Required PC voltage
- Control performance during operation
- Copper cable section for cold powering

Summary of the simulations

- DC cable resistance (resistance during operation) value of less than 265 mOhm is optimal from a powering point of view (PC voltage and design)
- DC cable resistance + Crowbar resistance should be at least 230 mOhm to limit current looping above the DC design value of the circuit
- Overcurrent due to quench for the 'most conservative scenario' generate a hot spot temperature of 314 K.
- If integration accepted, it is fairly straightforward to define the parameters of the circuit (2x20mm2).
- Standard HL-LHC-60A-10V can be therefore used.



Current proposal

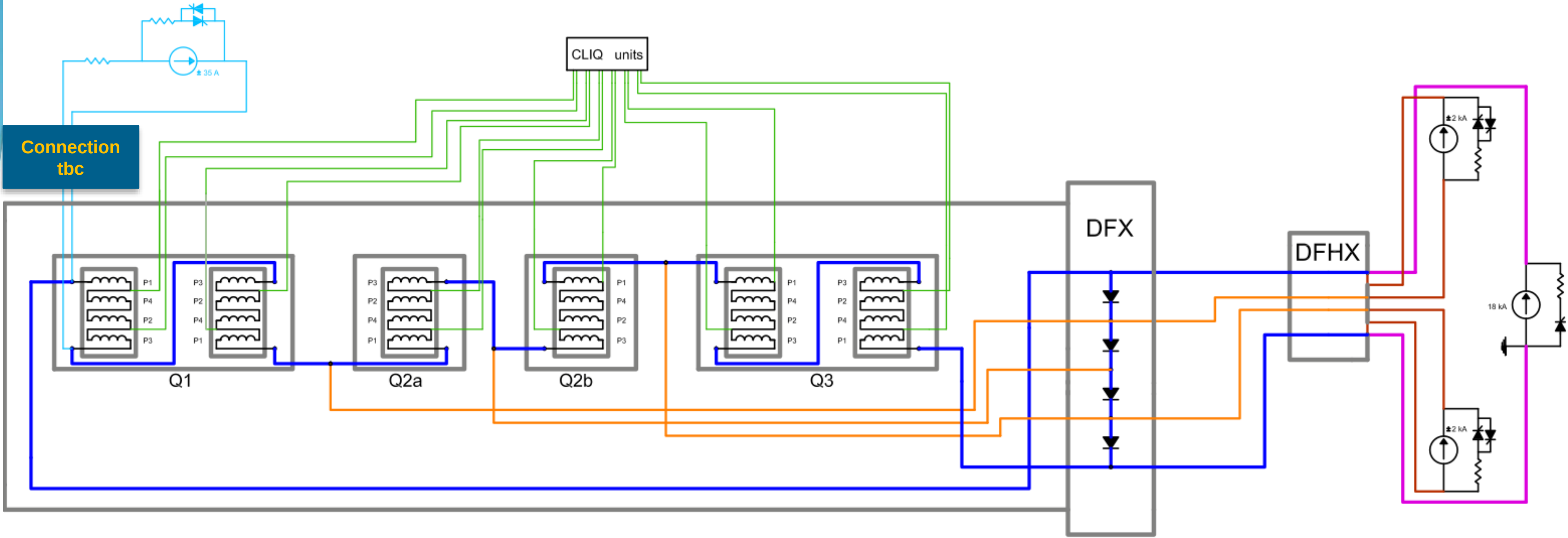
Circuit resistance: 230 mOhms

- Max current: 4.2 kA
- Max MIITs: 1.66
- Copper cable section: 20 mm2
- Hot-spot temperature: 314 K

2.b) Bus-bars for the IT main circuit

Circuit with Cold Diode Option

More Detailed Schematic of the Circuits :



Connection tbc

Under study: Insertion of a cold diode across Q1a k-modulation circuit

Options to protect bus-bars

Protection baseline: Any quench in any element → Fire all the QHs/CLIQ systems

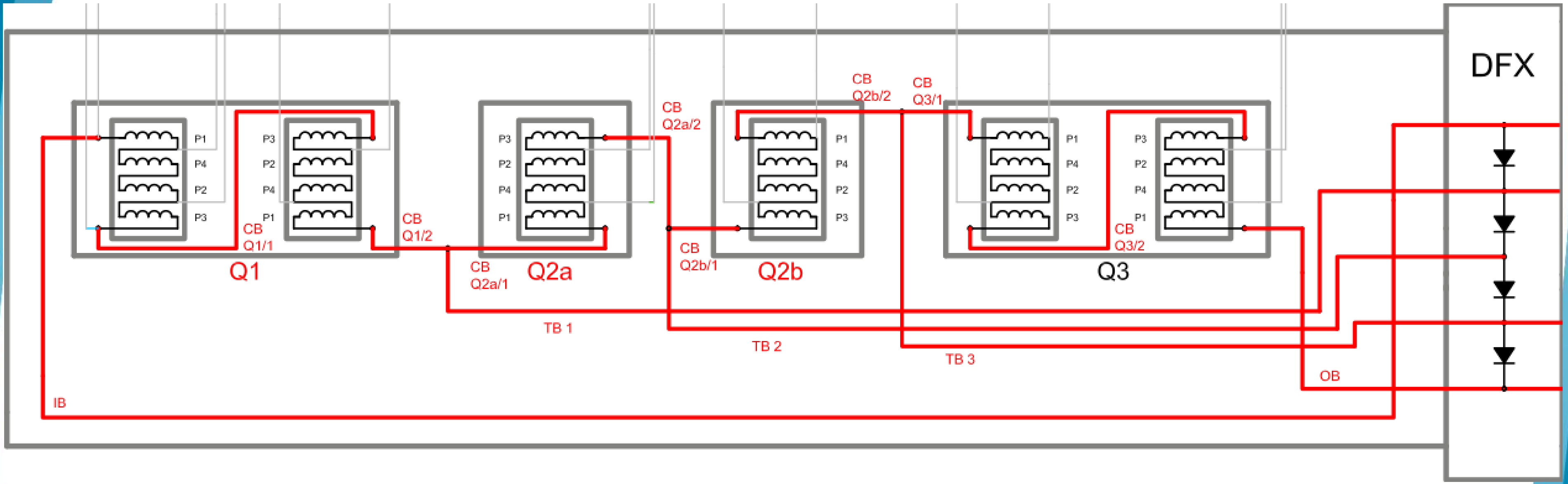
When introducing the cold diodes, two possible strategies:

1. One element quenches → **All QHs/CLIQ systems will be fired**. Diodes carry only the over-currents (7 kA or less) for an equivalent time = 100 ms
2. One element quenches → **Selective QHs/CLIQ fired**. Diodes carry 18 kA, time constant = 100 s

Possible advantage for option2: If a quench of the other magnets following the first cannot be completely avoided, these would happen at lower current, reducing the stress on the magnet and the heat introduced into the cryogenic system, which will allow a faster recovery.

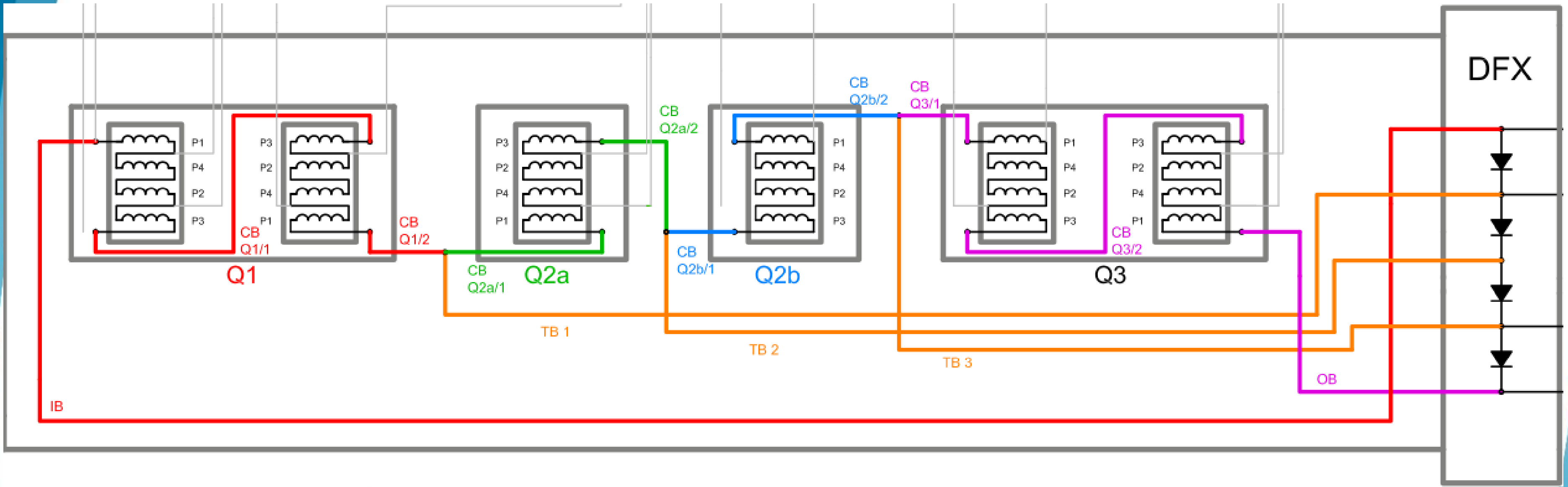
Time of discharge of circuit with 50V RQX Crowbar = 350s.

Option 1 – Quench Protection Strategy



- Any busbar quenching → Firing all protection systems
- Diodes carry only the over-currents (7 kA or less) for time constant or equivalent time = 100 ms

Option 2 – Quench Protection Strategy



Protection strategy

- If any of IB, CB Q1/1 and CB Q1/2 quenches → QPS of Q1 will be triggered
- If any of CB Q2a/1 and CB Q2a/2 quenches → QPS of Q2a will be triggered
- If any of CB Q2b/1 and CB Q2b/2 quenches → QPS of Q2b will be triggered
- If any of OB, CB Q3/1 and CB Q3/2 quenches → QPS of Q3 will be triggered
- If any TB1, TB2 and TB3 quenches → QPS of the two adjacent magnets will be triggered

Conclusions

Option 1: One element quenches → All QPS systems will be fired

Advantages to WP3:

- Bus-bar integration in the cryostat is less complex
- No need to size the trim bus bars to 18 kA (sc state and quenching state
- No need to integrate heat sinks for diodes

Advantages to WP7:

- Keeps the QDS reliability like in the LHC's IT circuit
- The triplet circuit in itself is the most complex HL-LHC circuit. Option 1 does not add further complexity from the QDS point of view.
- The use of the LHC diodes if qualified for radiation levels.

Disadvantages:

- When quench, no quick distinction between quench in coil and bus-bars in terms of detection

Option 2: Selective quench strategy

Possible advantages of the selective quench protection:

- Triggering of the QHs/CLIQ of the other (not initially-quenching) magnets at a lower current (expected ca. 10% less from one magnet to the adjacent one)
- It will allow more energy to be dissipated in the crowbar of the RQX PC

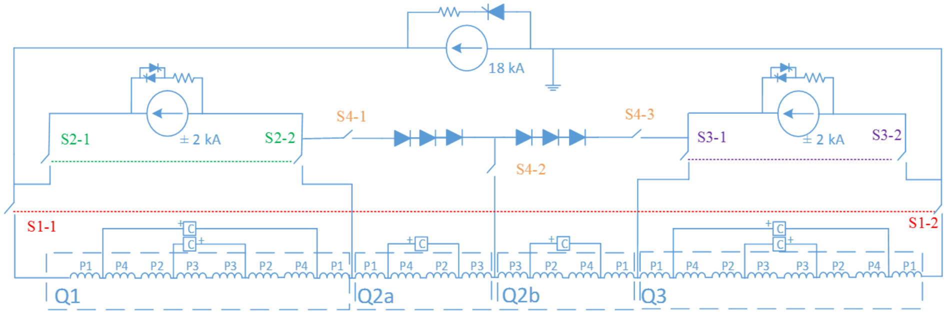
Disadvantages:

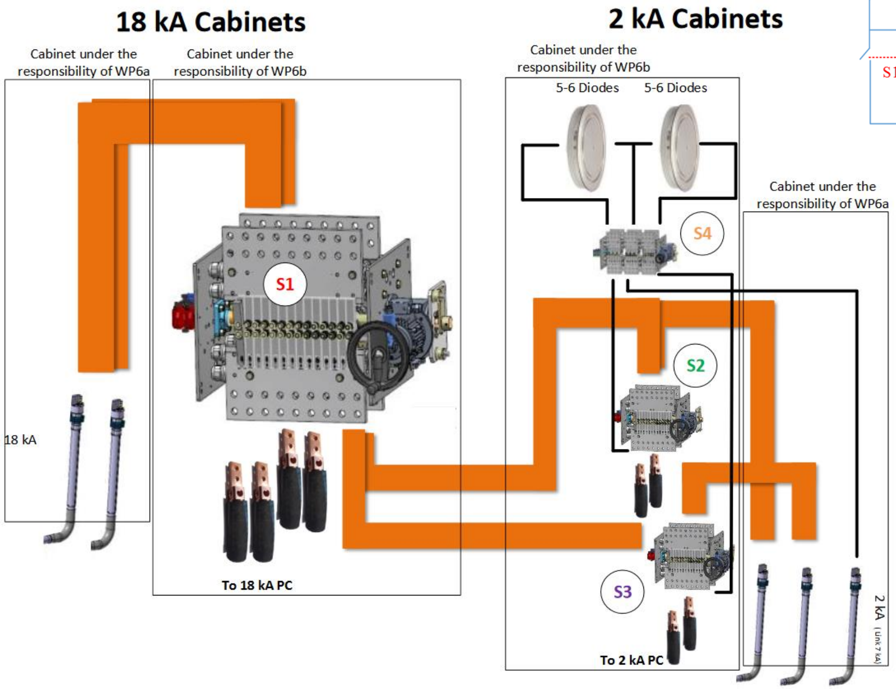
- It includes complexity in the implementation of the QDS which leads to a less reliable system.
- Due to the quench propagation, all the magnets could eventually be fired (in the order of ten seconds between the quench of the different magnets)
- Diodes (+heat sinks) and bus-bars will be significantly bigger
- Imposes new (non-LHC) diodes to support the current of 18 kA

After discussions, MCF considers option 1 as more adequate

2.c) Circuit Separators

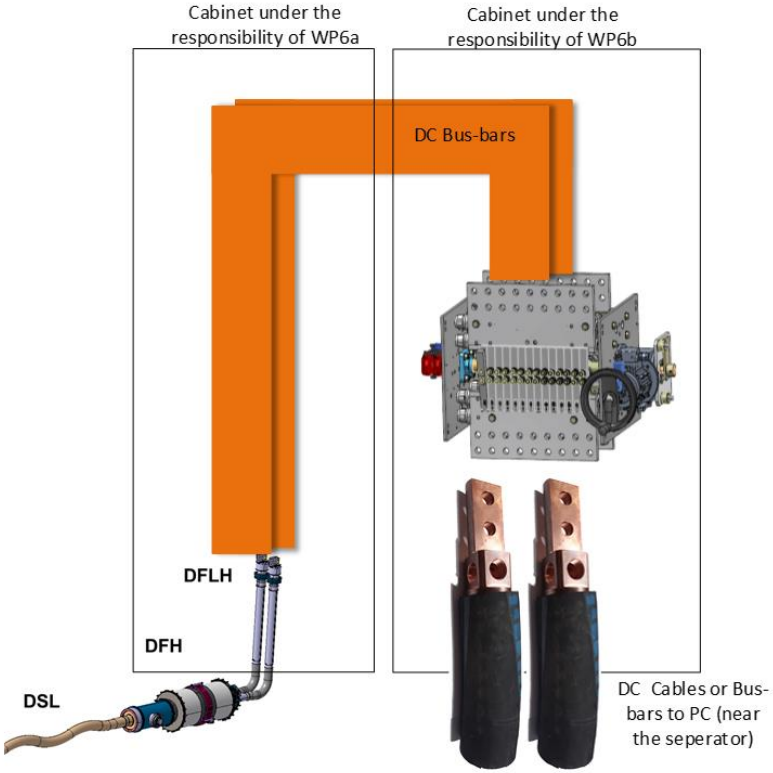
Proposal for Separators for the IT Main Circuit



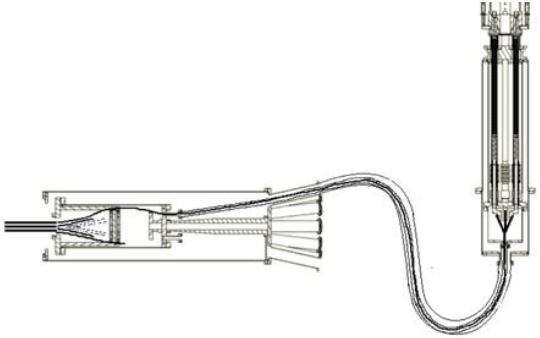


- Number of cabinets is preliminary and needs to be studied in details
- We can have short circuit positions on the three sub-circuits
- Circuit of Q1a not shown for simplification but can have the same principle
- Four separators in total (could be reduced to 3 [2x2 poles + 1x3poles] if short circuit position is not needed)

Proposal for Separators for D1/D2/OCs



- 13 kA or 2 kA OC separators
- 8 separators
- Can we integrate 2x2 kA separators per cabinet?
- 3 positions: connected, disconnected and short-circuit

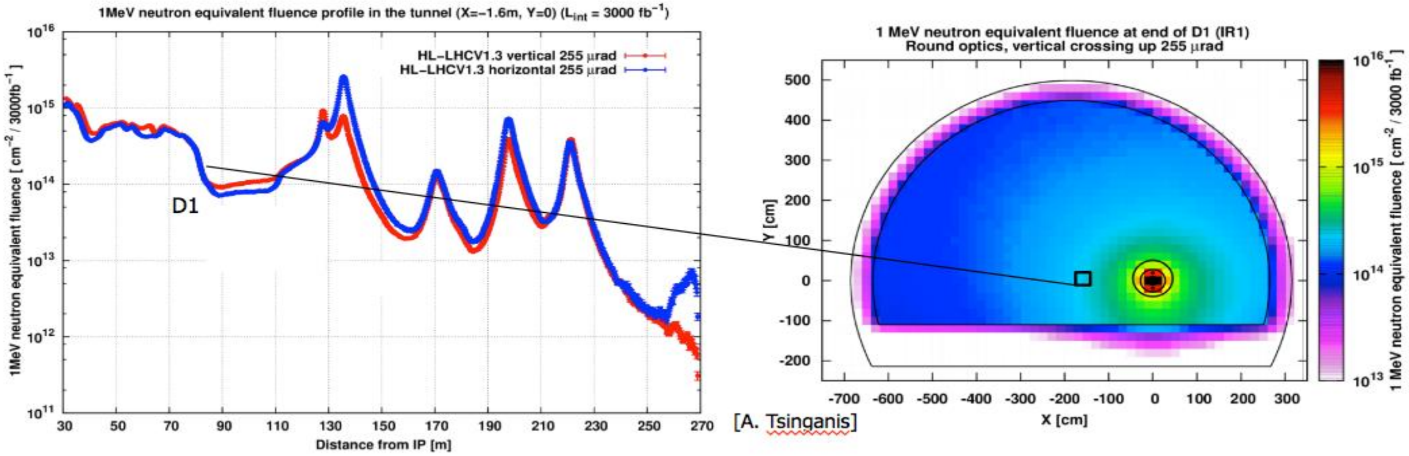


DFLH close to PC → distributed leads: Is this feasible?

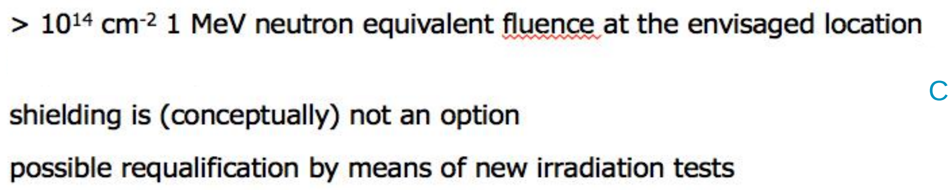
HiLumi
HL-LHC PROJECT

2.d) Cold diodes project (Follow-up from internal circuit review)

Radiation



[A. Tsinganis]



> 10^{14} cm^{-2} 1 MeV neutron equivalent fluence at the envisaged location

shielding is (conceptually) not an option

possible requalification by means of new irradiation tests

Courtesy F. Cerutti, R2E Cost and Schedule Review, 12.10.2017

- LHC type diffusion diodes tested (15 years ago) up to ~2 kGy and 3x10^{13} n cm^{-2} (LHC project Report 688)
- Qualification required up to 30 kGy and 10^{15} n cm^{-2}

Qualification of cold diodes for HL-LHC triplet circuit

- **Adapting the** LHC type diffusion diodes for triplet currents and time constants (18 kA, ~100 s or 7 kA, ~ 100 ms)

- **Qualification** for HL-LHC radiation levels required

- **Staged approach**:
  1. Irradiation and in-situ testing in CHARM in 2018 to reproduce earlier results
  2. Depending on results further testing in CHARM or other facility OR modification of diodes and re-testing

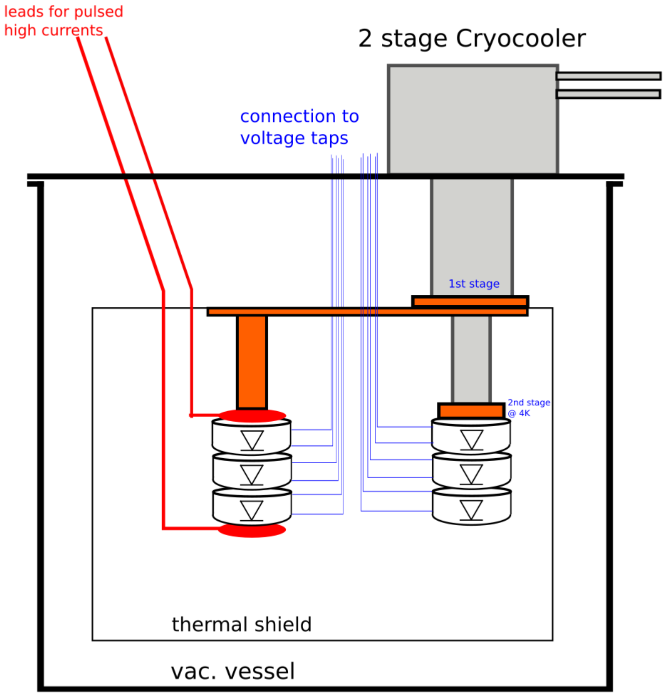
Experimental setup

Two stage Pulse Tube cryocooler

- Simultaneous operation at
  77K (1st stage) and 4K (2nd stage)
- Temperature on both stage controlled via heaters
- metal seals, no electronics in cold head
- Cooling power of 1W@4K, ~90W@77K

Vacuum vessel

- Aluminium
- EPDM seals for radiation hardness
- Multi pin feed throughs
- Two stage interface for sample mounting
- Leak tightness for ~ 6 months
- Thermal shields + MLI

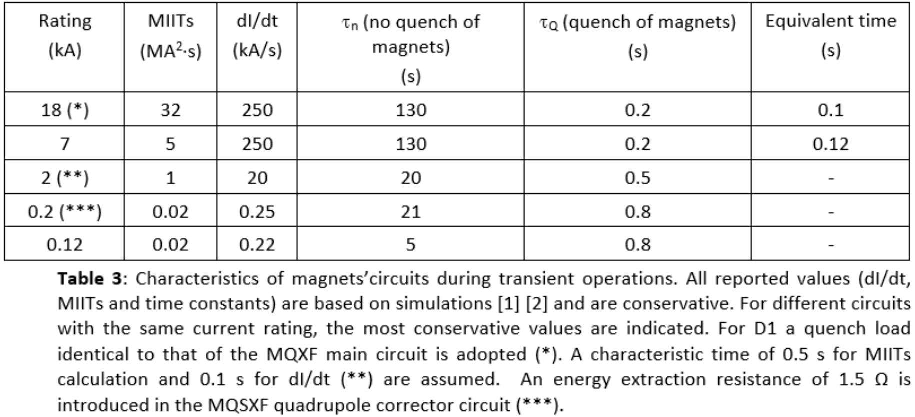


2.e) Document co-authored by WP6a and MCF

Document co-authored by WP6a and MCF - IT

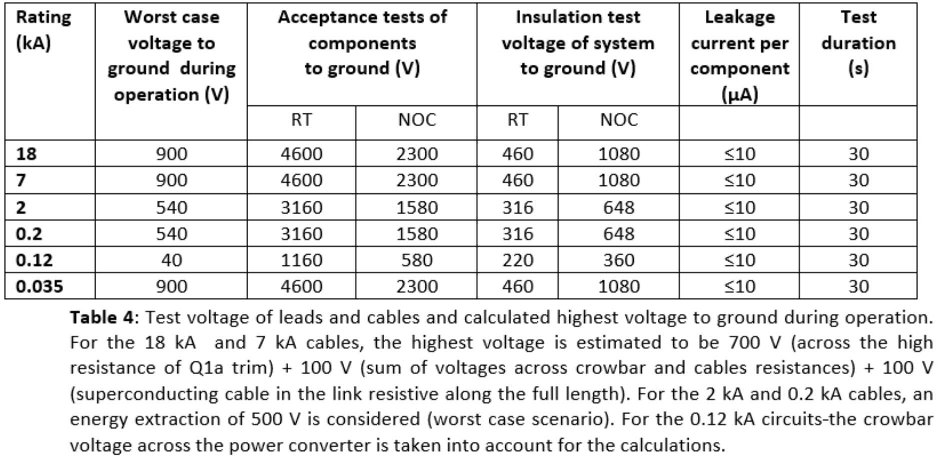
This document summarizes the total number of High Temperature Superconducting (HTS) current leads and cables, the latter contained inside the Superconducting Link, needed for the powering of the HL-LHC Triplets and D1. The design current rating of both leads and cables is also indicated. The values reported 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. The input is used for the design of the Cold powering System.



Rating (kA)	MIITs ($MA^2\cdot s$)	dI/dt (kA/s)	τ_n (no quench of magnets) (s)	τ_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	-

Table 3: Characteristics of magnets'circuits during transient operations. All reported values (dI/dt, MIITs and time constants) are based on simulations [1] [2] and are conservative. For different circuits with the same current rating, the most conservative values are indicated. For D1 a quench load identical to that of the MQXF main circuit is adopted (*). A characteristic time of 0.5 s for MIITs calculation and 0.1 s for dI/dt (**) are assumed. An energy extraction resistance of 1.5 Ω is introduced in the MQSXF quadrupole corrector circuit (***).



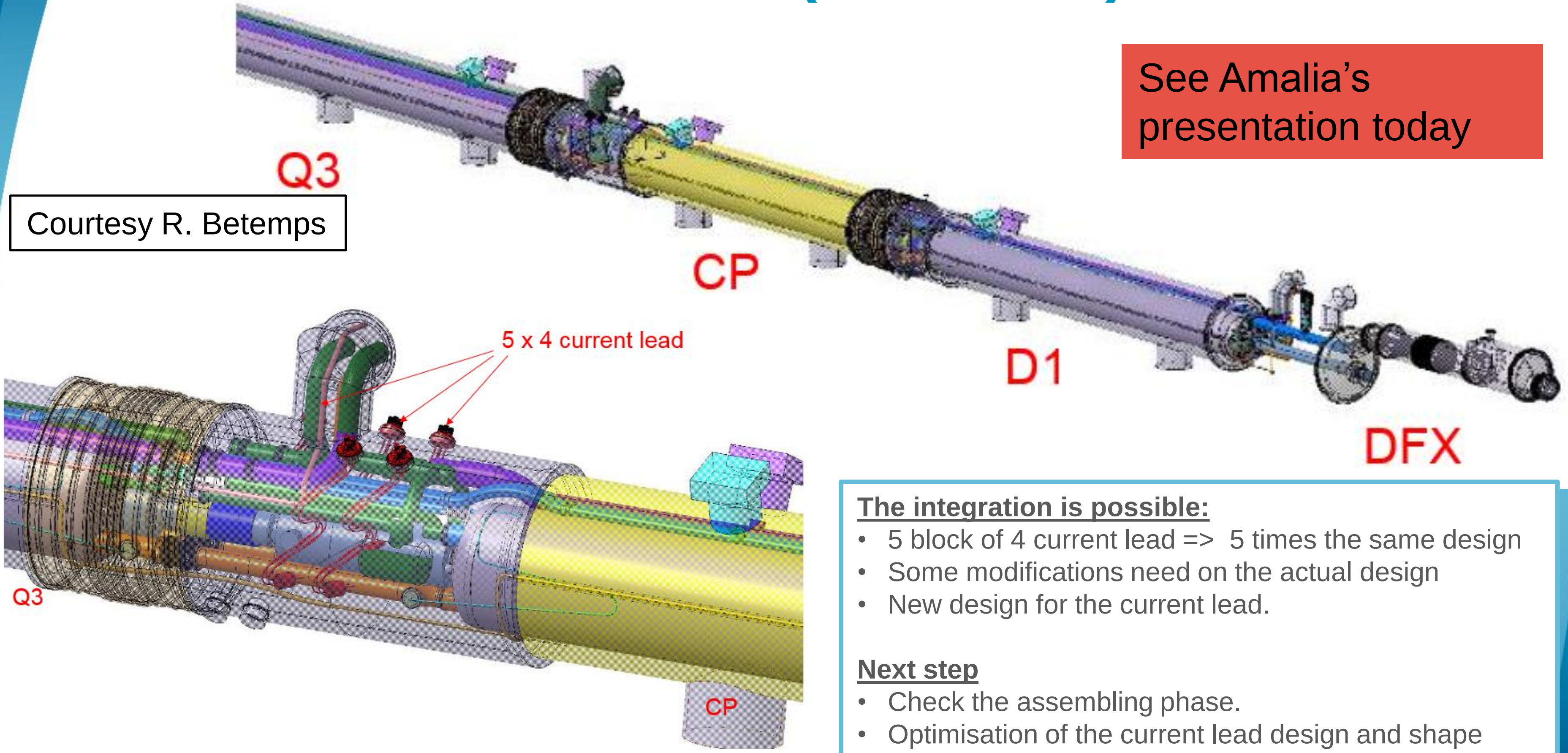
Rating (kA)	**Worst case voltage to ground during operation (V)**	**Acceptance tests of components to ground (V)**		**Insulation test voltage of system to ground (V)**		**Leakage current per component (µA)**	**Test duration (s)**
		RT	NOC	RT	NOC		
18	900	4600	2300	460	1080	≤10	30
7	900	4600	2300	460	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 4: 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.

2.f) HL-LHC IT correctors (120A-200A) current leads integration

Current leads for the IT (12A-200A) correctors

See Amalia’s presentation today



Courtesy R. Betemps

The integration is possible:

- 5 block of 4 current lead => 5 times the same design
- Some modifications need on the actual design
- New design for the current lead.

Next step

- Check the assembling phase.
- Optimisation of the current lead design and shape

3) Changes to the MS

Status

- Q4 and Q5 correctors will be powered individually

- Upon a request by WP6b (transmitted to the MCF), WP6a has accepted to provide enough leads to feed **individually the corrector MCBY magnets of Q4 and Q5**. This means that 1 set of local four-lead assembly will be integrated in the Q4 cold mass and 3 sets in the cold mass of Q5. This will mitigate the development of a new family of power converters to deal with the high energy and the inductance of two MCBYs in series.

- The decision on the necessity of **dismantling the DSL during LS3 should be taken by the end of 2017**. By then, a roadmap on the strategy will be proposed to MCF and TCC.

Document co-authored by WP6a and MCF - MS

Magnet	Circuit type	Current (A)	Feedbox Type	Lead Type	N_{TOT} leads	SC Link Type	N_{TOT} cables in the SC link
MQY	Q4 Quadrupole	6000	*DFBL	HTS*	3	*DSL	3*
MCBY	Q4 Correctors	120	*DFBL	Resistive*	12	DSL	12*
		120	-	Local**	4	-	-
MQY	Q5 Quadrupole	6000	*DFBL	HTS*	3	*DSL	3*
MCBY	Q5 Correctors	120	-	Local**	12	-	-
MQML	Q6 Quadrupole	6000	*DFBL	HTS*	3	*DSL	3*
MCBC	Q6 Correctors	120	-	Local**	4	-	-
MCBRD	D2 Correctors	600	DFHM	HTS***	8	DSH	8***
MBRD	D2 Recombination Dipole	13000	DFHM	HTS***	2	DSH	2***

Circuit	Rating (A)	Worst case V to Gnd (V)	Acceptance		Installation		Current (µA)	Time (s)
			RT	NOC	RT	NOC		
D2	**13000**	**110**	**1440**	**720**	**335**	**705**	**10**	**30**
D2 Corr.	**600**	**660**	**3640**	**1820**	**364**	**792**	**10**	**30**
Q4	**6000**	**110**	**1440**	**720**	**150**	**150**	**15**	**30**
Q4 Corr.*	**120**	**160**	**1640**	**820**	**300**	**600**	**3**	**30**
Q4 Corr.**	**120**	**60**	**1240**	**620**	**300**	**600**	**3**	**30**
Q5	**6000**	**110**	**1440**	**720**	**150**	**150**	**15**	**30**
Q5 Corr.	**120**	**60**	**1240**	**620**	**300**	**600**	**3**	**30**
Q6	**6000**	**110**	**1440**	**720**	**260**	**480**	**15**	**30**
Q6 Corr.	**120**	**60**	**1240**	**620**	**300**	**600**	**3**	**30**

4) Advancements on the 11T dipole

a) 11T interlock system

b) 11T current leads

c) 11T dipole – powering and protection document

4.a) 11T dipole interlock system

Proposed implementation of 11T trim

- Hardware connection to the PIC main dipole quench loop
- Separate the 11T trim and the RB circuit → easier diagnostics in case of trip
- SPA request could be implemented via the PIC, if required, as a function of the main RB circuit status → requires change of safety critical code

4.b) 11T dipole trim current leads

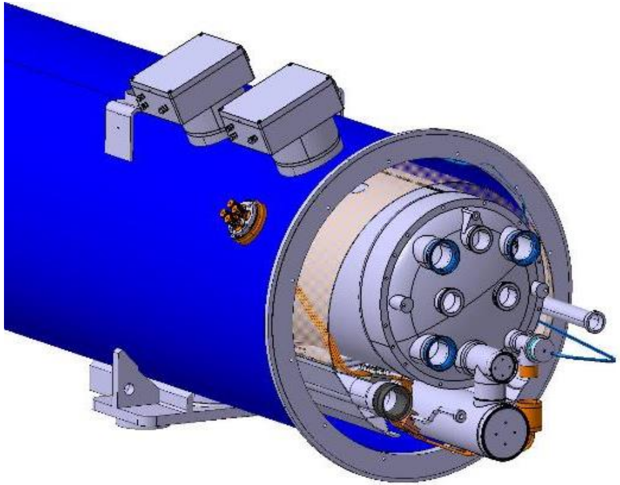
11T dipole trim current leads

WP6a has confirmed that they will "re-use" the LHC 120 A conduction-cooled leads

WP6a presented that they have already launched:

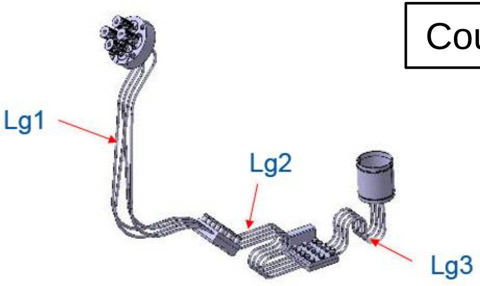
- Proposal of powering one polarity via two leads (to make feasible-flexible-the conduction-cooled option);
- Discussion with TE-EPC for protection of leads against over-heating and possibility of identifying non homogenous current distribution;
- Initiative to re-make an integration study with the objective of keeping as much as possible the existing LHC solution;
- Integration work carried out by R. Betemps (in interface with SCD and CMI). Found solution for keeping the same length of each lead, i.e. same design of leads and thermalization blocks, but different shape. Responsibility under MSC-SCD.

Current leads actual design



120 A **LHC** currents leads

- 1 bloc => 2 circuit with 120 A (4 leads)
- Reserve parts existing.



Courtesy R. Betemps

Status

- ~ Same parts as LHC 120A current lead.
- Change the flange position.
- Add a slit on the thermal screen.

Next steps

- Final design.
- New bending Tools.

See Amalia's presentation today

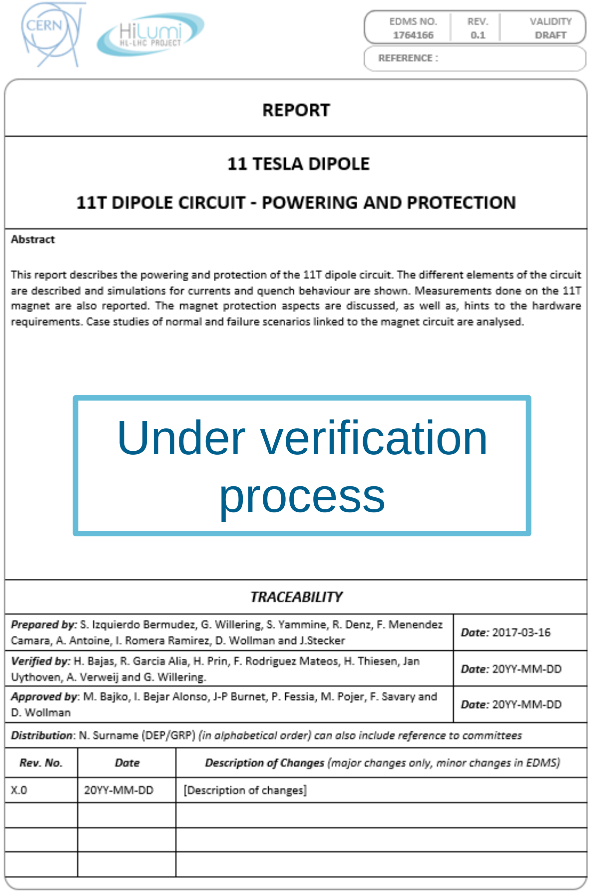
4.c) 11T dipole powering and protection document

11T dipole powering and protection

This report describes the powering and protection of the 11T dipole circuit. The **different elements of the circuit** are described and **simulations** for currents and quench behaviour are shown. **Measurements** done on the 11T magnet are also reported. The magnet protection aspects are discussed, as well as, hints to the hardware requirements. **Case studies of normal and failure scenarios** linked to the magnet circuit are analysed.

EDMS no: **1764166** (Link)

Authors: **S. Izquierdo, G. Willering , S. Yammine, R. Denz, F. Menendez, A. Antoine, I. Romera, D Wollman and Jens Steckert**



EDMS NO.	REV.	VALIDITY
1764166	0.1	DRAFT

REFERENCE :

REPORT

11 TESLA DIPOLE

11T DIPOLE CIRCUIT - POWERING AND PROTECTION

Abstract

This report describes the powering and protection of the 11T dipole circuit. The different elements of the circuit are described and simulations for currents and quench behaviour are shown. Measurements done on the 11T magnet are also reported. The magnet protection aspects are discussed, as well as, hints to the hardware requirements. Case studies of normal and failure scenarios linked to the magnet circuit are analysed.

Under verification process

TRACEABILITY

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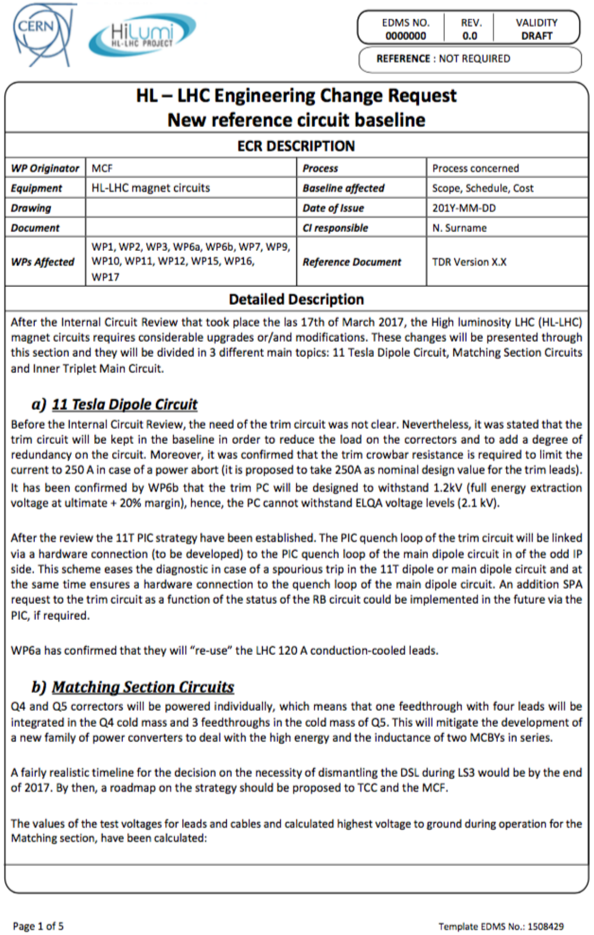
Distribution: N. Surname (DEP/GRP) *(in alphabetical order) can also include reference to committees*

Rev. No.	***Date***	***Description of Changes*** *(major changes only, minor changes in EDMS)*
X.0	20YY-MM-DD	[Description of changes]

5) Conclusions

Conclusions

- ✓ Great effort carried out with the different work packages
- ✓ A great deal of advancements to optimize the circuits
- ✓ Recommendations from the review taken into account
- ✓ Draft ECR on the modifications →
- ✓ Good status with respect to the open issues



EDMS NO.	REV.	VALIDITY
0000000	0.0	DRAFT

REFERENCE : NOT REQUIRED

HL – LHC Engineering Change Request
New reference circuit baseline

ECR DESCRIPTION

WP Originator	MCF	***Process***	Process concerned
Equipment	HL-LHC magnet circuits	***Baseline affected***	Scope, Schedule, Cost
Drawing		***Date of Issue***	201Y-MM-DD
Document		***CI responsible***	N. Surname
WPs Affected	WP1, WP2, WP3, WP6a, WP6b, WP7, WP9, WP10, WP11, WP12, WP15, WP16, WP17	***Reference Document***	TDR Version X.X

Detailed Description

After the Internal Circuit Review that took place the las 17th of March 2017, the High luminosity LHC (HL-LHC) magnet circuits requires considerable upgrades or/and modifications. These changes will be presented through this section and they will be divided in 3 different main topics: 11 Tesla Dipole Circuit, Matching Section Circuits and Inner Triplet Main Circuit.

a) 11 Tesla Dipole Circuit

Before the Internal Circuit Review, the need of the trim circuit was not clear. Nevertheless, it was stated that the trim circuit will be kept in the baseline in order to reduce the load on the correctors and to add a degree of redundancy on the circuit. Moreover, it was confirmed that the trim crowbar resistance is required to limit the current to 250 A in case of a power abort (it is proposed to take 250A as nominal design value for the trim leads). It has been confirmed by WP6b that the trim PC will be designed to withstand 1.2kV (full energy extraction voltage at ultimate + 20% margin), hence, the PC cannot withstand ELQA voltage levels (2.1 kV).

After the review the 11T PIC strategy have been established. The PIC quench loop of the trim circuit will be linked via a hardware connection (to be developed) to the PIC quench loop of the main dipole circuit in of the odd IP side. This scheme eases the diagnostic in case of a spourious trip in the 11T dipole or main dipole circuit and at the same time ensures a hardware connection to the quench loop of the main dipole circuit. An addition SPA request to the trim circuit as a function of the status of the RB circuit could be implemented in the future via the PIC, if required.

WP6a has confirmed that they will "re-use" the LHC 120 A conduction-cooled leads.

b) Matching Section Circuits

Q4 and Q5 correctors will be powered individually, which means that one feedthrough with four leads will be integrated in the Q4 cold mass and 3 feedthroughs in the cold mass of Q5. This will mitigate the development of a new family of power converters to deal with the high energy and the inductance of two MCBYs in series.

A fairly realistic timeline for the decision on the necessity of dismantling the DSL during LS3 would be by the end of 2017. By then, a roadmap on the strategy should be proposed to TCC and the MCF.

The values of the test voltages for leads and cables and calculated highest voltage to ground during operation for the Matching section, have been calculated:

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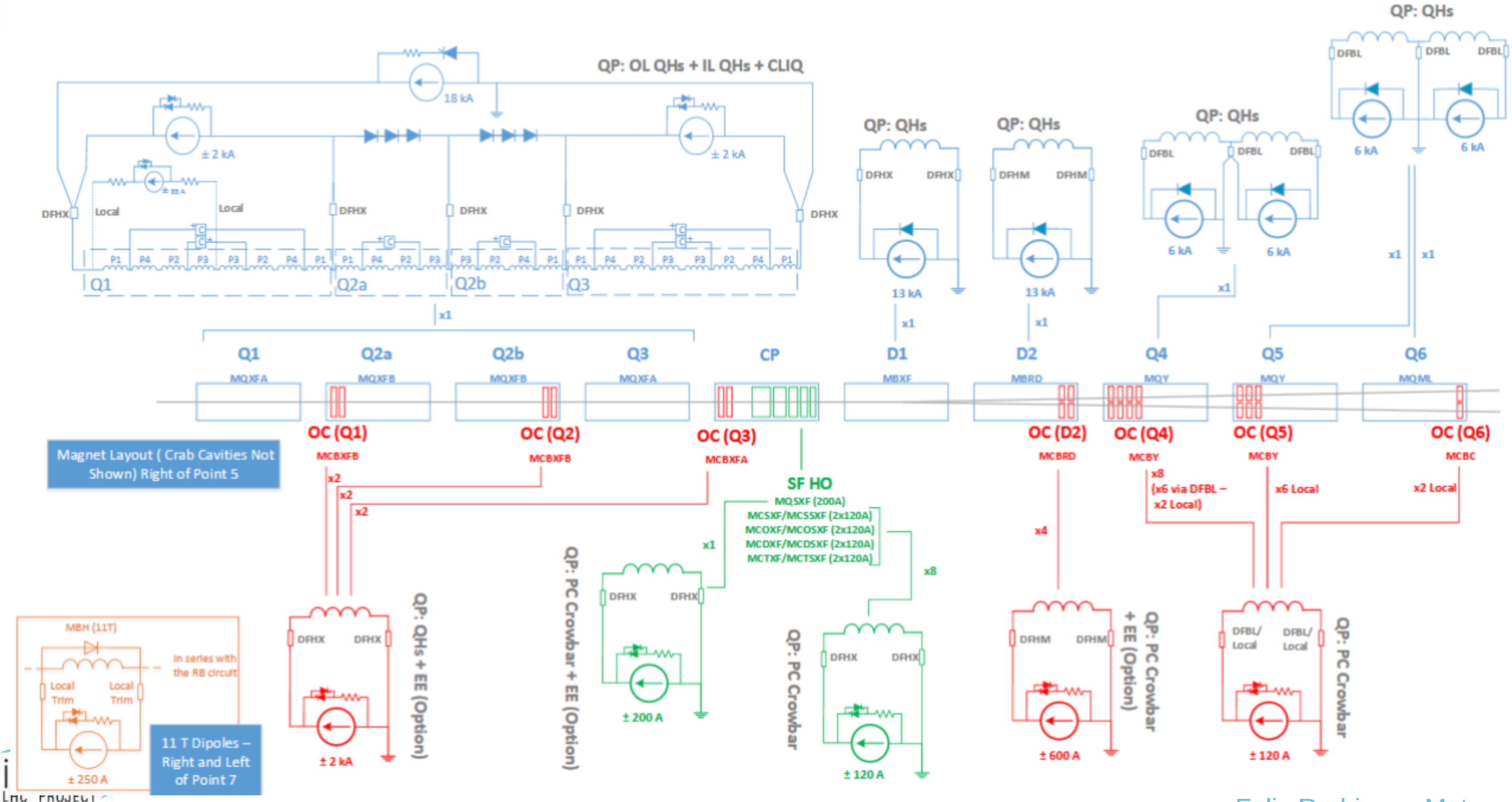
Template EDMS No.: 1508429

Thanks for your attention

Spare slides

Circuits Layout



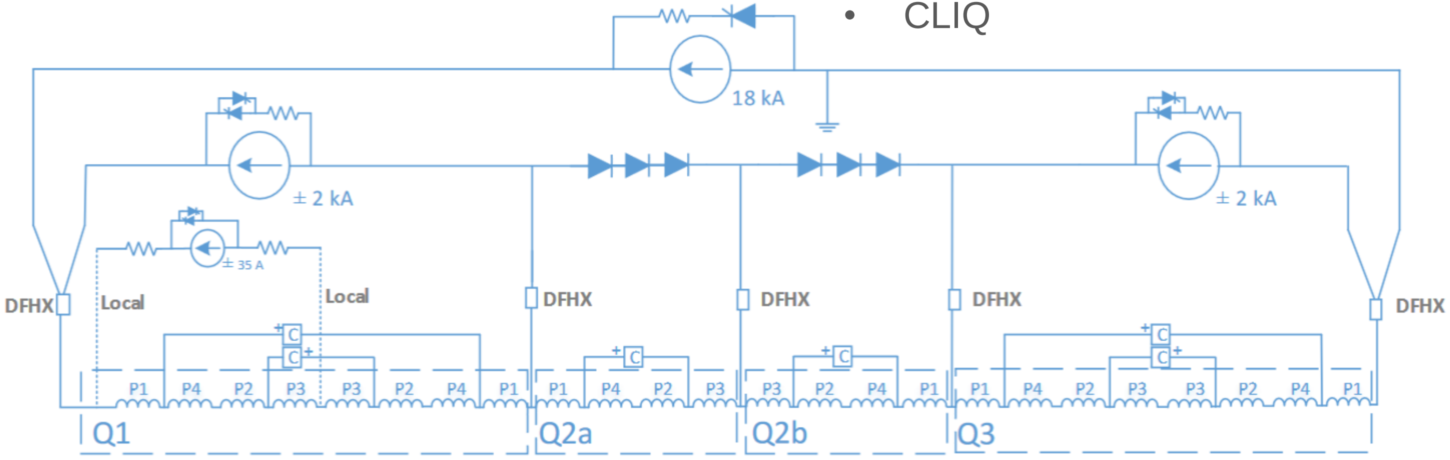
Magnet Layout (Crab Cavities Not Shown) Right of Point 5

11 T Dipoles – Right and Left of Point 7

Inner triplet circuit

- 1 Circuit per IP side
- Power converters (located in the UR):
  - 1 x 18 kA (2quad)
  - 2 x 2 kA (4quad)
  - 1 x 60 A (4quad) tentative

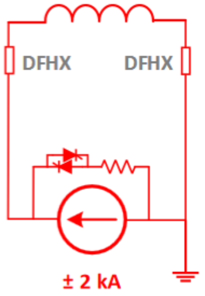
- Cold Powering (feedbox: DFHX at UR):
  - 2 x 18 kA leads
  - 3 x 2 kA leads
- Quench protection:
  - Outer-layer heaters
  - Inner-layer heaters
  - CLIQ



Correctors for the IT main circuit

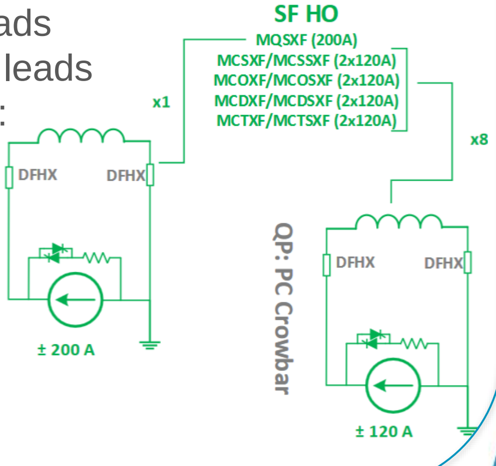
Orbit correctors

- 6 Circuits per IP side
- Power converters (located at UR):
  - 6 x 2 kA (4quad)
- Cold powering (feedbox: DFHX at UR):
  - 12 x 2 kA leads
- Quench protection:
  - Quench heaters (baseline)
  - EE system (option)



High order superferric correctors

- 9 Circuits per IP side
- Power converters (located at UR):
  - 1 x 0.6 kA limited to 0.2 kA (4quad)
  - 8 x 0.12 kA (4quad)
- Cold powering (feedbox: DFHX at UR):
  - 2 x 0.2 kA leads
  - 16 x 0.12 kA leads
- Quench protection:
  - PC Crowbar
  - EE system (dump resistor 1.5 Ohms) for Quadrupole



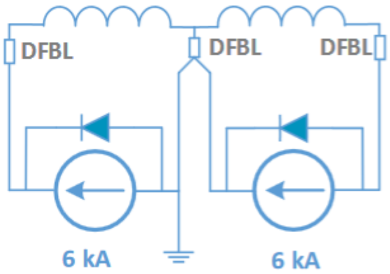
<u>Proposal</u>

Corrector Package (CP) – Locally powered for 120 and 200 A circuits

Quadrupoles Q4, Q5 and Q6

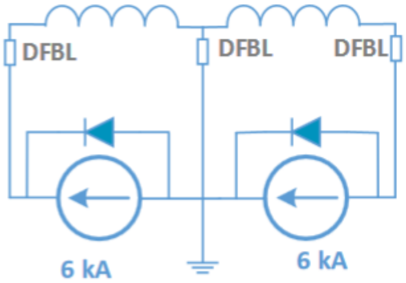
Quadrupole Q4

- 1 Circuits per IP side
- Power converters (located at RR):
  - 2 x 6 kA (1quad)
- Cold powering (feedbox: DFBL at RR):
  - 3 x 6 kA leads
- Quench protection:
  - Quench heaters



Quadrupoles Q5 and Q6

- 2 Circuits per IP side
- Power converters (located at RR):
  - 2 x 6 kA (1quad)
- Cold powering (feedbox: DFBL at RR):
  - 6 x 6 kA (1quad)
- Quench protection:
  - Quench heaters



Q4, Q5 and Q6 correctors

Q4 correctors

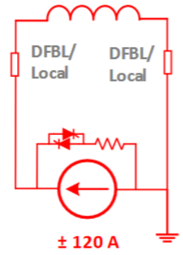
- 8 Circuits per IP side
- Power converters (located at RR):
  - 8 x 0.12 kA (4quad)
- Cold powering:
  - 12 x 0.12 kA leads via DFBL
  - 4 x 0.12 kA leads in local powering
- Quench protection:
  - PC crowbar

Q5 correctors

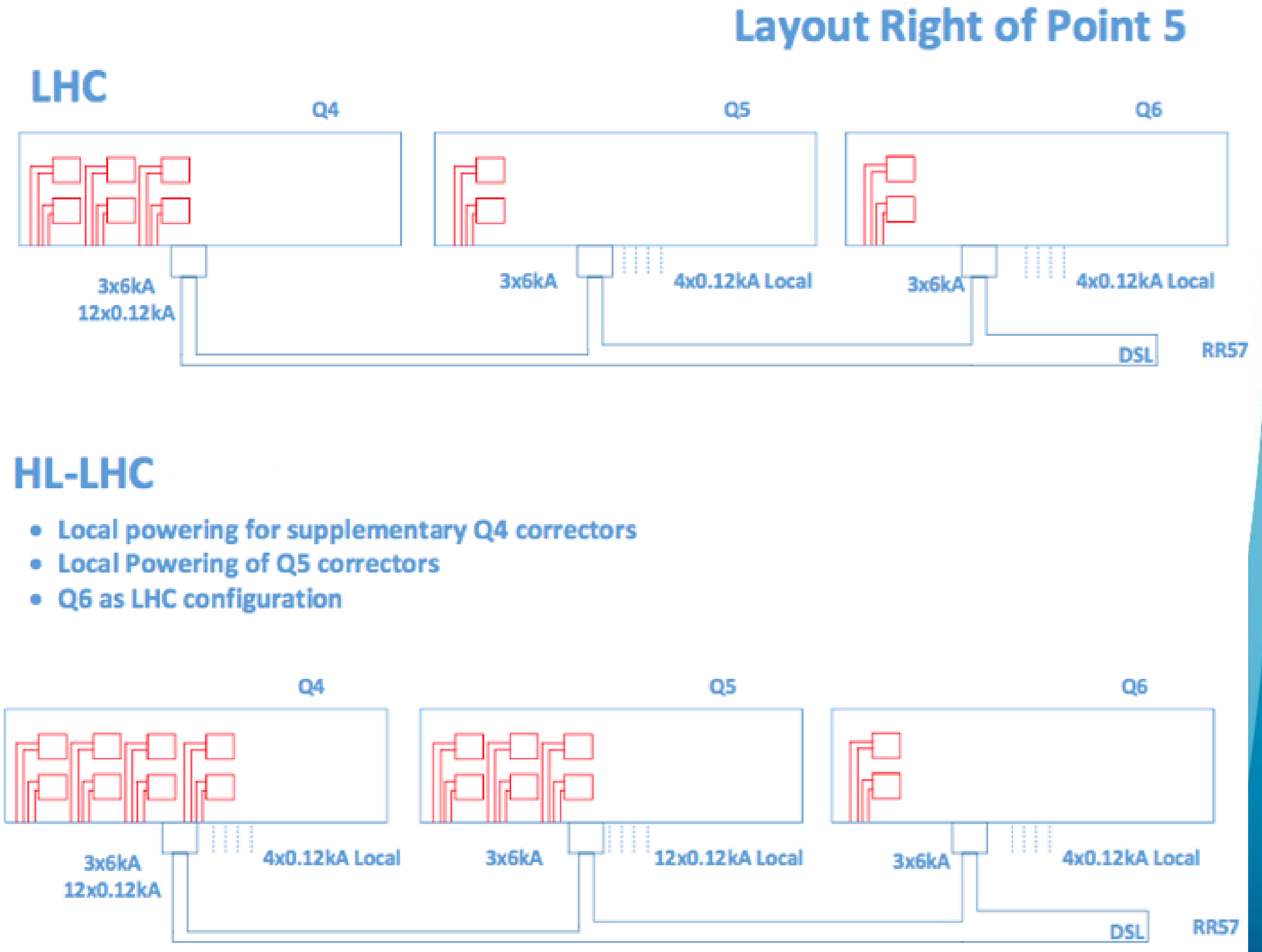
- 6 Circuits per IP side
- Power converters (located at RR):
  - 6 x 0.12 kA (4quad)
- Cold powering:
  - 12 x 0.12 kA leads in local powering
- Quench protection:
  - PC crowbar

Q6 correctors

- 2 Circuits per IP side
- Power converters (located at RR):
  - 2 x 0.12 kA (4quad)
- Cold powering:
  - 4 x 0.12 kA leads in local powering
- Quench protection:
  - PC crowbar



Q4, Q5 and Q6 correctors



Layout Right of Point 5

LHC

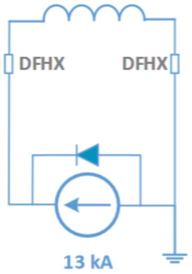
HL-LHC

- Local powering for supplementary Q4 correctors
- Local Powering of Q5 correctors
- Q6 as LHC configuration

Dipoles D1, D2 and D2 correctors

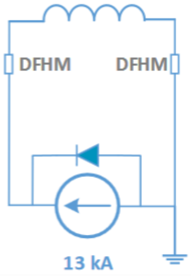
Dipole D1

- 1 Circuits per IP side
- Power converters (located at UR):
  - 1 x 13 kA (1quad)
- Cold powering (feedbox: DFBL at UR): :
  - 2x 13 kA leads
- Quench protection:
  - Quench heaters



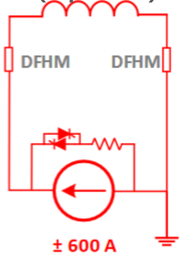
Dipole D2

- 1 Circuits per IP side
- Power converters (located at UR):
  - 1 x 13 kA (1quad)
- Cold powering (feedbox: DFHM at UR):
  - 2x 13 kA leads
- Quench protection:
  - Quench heaters



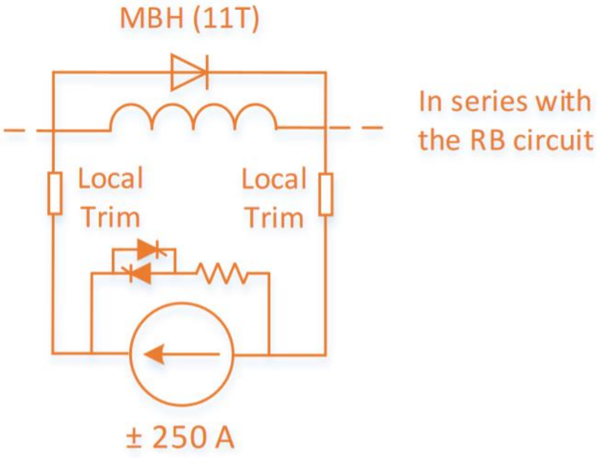
D2 correctors

- 4 Circuits per IP side
- Power converters (located at UR):
  - 4 x 0.6 kA (4quad)
- Cold powering (feedbox: DFHM at UR):
  - 8 x 0.6 kA leads
- Quench protection:
  - PC crowbar
  - EE (option)



11T dipole

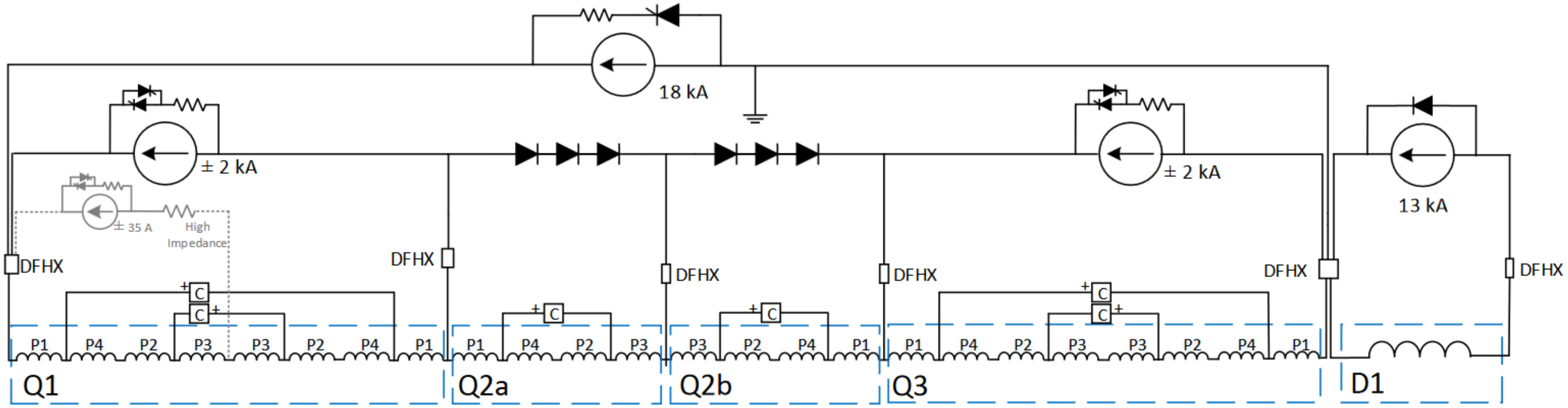
- Power converters (located in the RR):
  - 1 x 250 kA (4quad)
- Cold Powering (local – 2 leads per polarity as tentative):
  - Current leads: LHC DCFs as tentative
- Quench protection:
  - Quench heaters
  - EE from RB circuit



3.e) Quantitative studies on alternative solutions (WP6b and WP7)

- Three-cable configuration
- Four-layer nested configuration

Scheme of the three-cable configuration



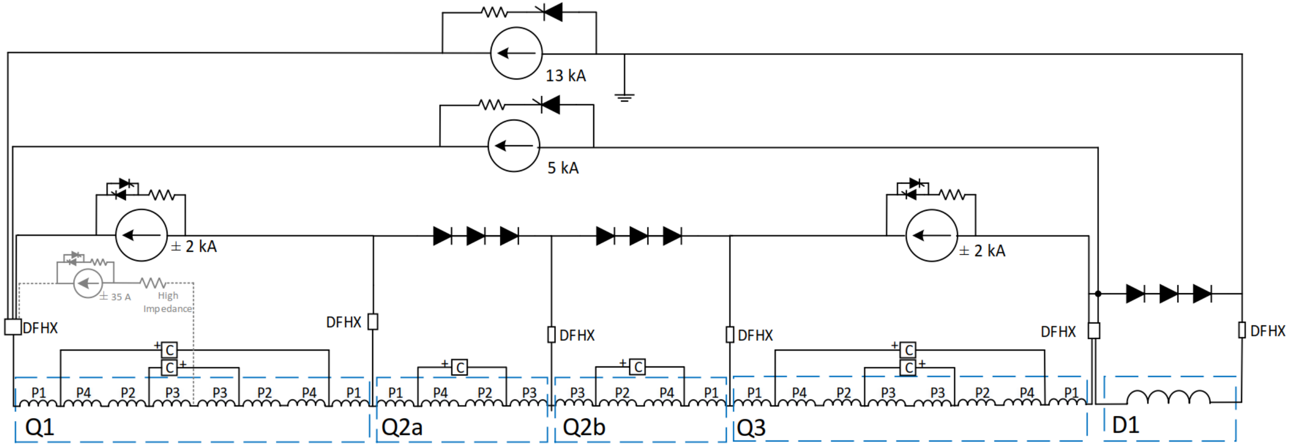
WP6b

Advantages	Disadvantages
1. No clear advantages for WP6b (Transparent to control, same number of power converters, etc.).	1. Electrical common point for two different circuits
	2. Additional complexity in searching for earth faults
	3. Longer estimated MTTR time for TE-EPC (12 hours + 50 %)
	4. Electrical issue on D1 circuit impacts IT circuit and vice et versa
	5. Four cables connection on the current leads (or circuit separator) (2 for 18 kA – 1 for 13 kA and 1 for 2 kA)

WP7

Advantages	Disadvantages
1. 1x 18 kA lead less	1. ELQA to be performed all together (incl. higher voltage withstand requirements of triplet on D1, ...)
	2. Quench cross talk between triplet and D1
	3. PC regulation more complicated
2. 1x spare lead / link	4. 4th cable at warm
	5. Commissioning more complicated
	6. More simulations required to study failure cases etc. (→ manpower)

Scheme of the three-cable configuration



WP6b

Advantages	Disadvantages
1. Lower current ratings for main power converters (13 kA still needed for D2)	1. Even more electrical coupling between IT main quadrupole sub-circuits and D1 circuit
	2. Even longer MTTR for TE-EPC (+200% estimated) (higher intervention time to repair in case of failure since multiplying the sources of failures in one circuit).
	3. Increase in the need for spare parts since more of them are used during interventions
	4. Additional constraints on the circuit control and precision: 4 layer nested circuits and additional source of noise
	5. Additional complexity • Decoupling matrix implementation (Ethernet communication, algorithms, etc.) • For commissioning and operation • For circuit protection (current looping, crowbar definition, etc.) • In the reconstitution of failure events

WP7

Advantages	Disadvantages
1. 1x 18 kA, 1x 13 kA, 1x 5 kA leads → gain 18 kA	1. ELQA to be performed all together (incl. higher voltage withstand requirements of triplet on D1, ...)
	2. Quench always triplet and D1 together
	3. Longer quench training
2. Lower PC rating	4. PC regulation much more complicated & no experience at CERN with four layer nesting
	5. Commissioning more complicated
	6. New failure scenarios with D1 (diff. inductance to Q1/Q3 and Q2a/b) □ imbalances, over voltages, over currents
	7. More simulations required to study new failure cases etc. (→ manpower)
	8. Re-do studies already performed for baseline (→ manpower)