HL-LHC Circuits and Report from 2019 Circuits Review

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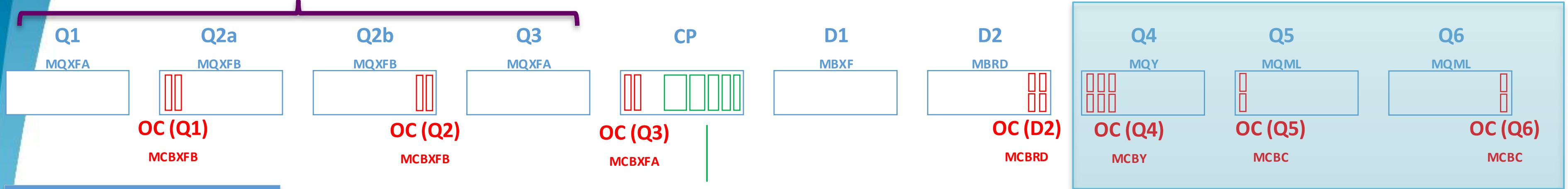
9th HL-LHC Collaboration Meeting, Fermilab 14th October 2019

Outline

- Update on the HL-LHC Circuits
  - Inner Triplet
    - design of the 35A k-modulation feeders
    - cold diodes
    - changes to the circuit
  - HO Correctors powering
- Preliminary Outcome of the International Circuits Review on 9-10 September 2019

Layouts in HL-LHC



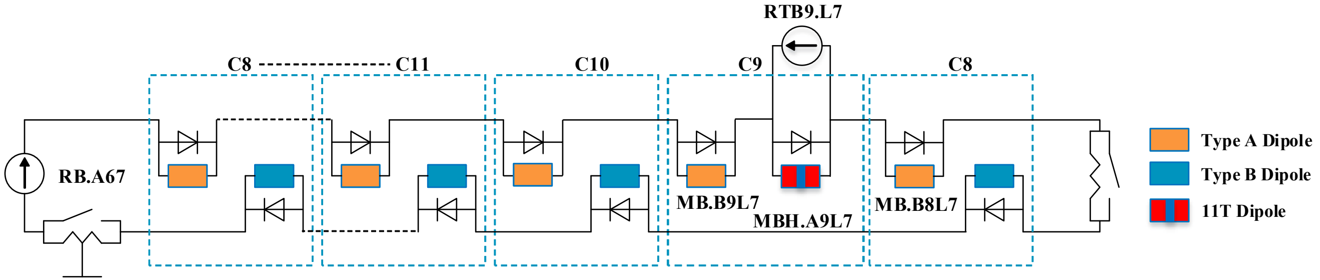
Magnet Layout (Crab Cavities Not Shown) Right of Point 5

Interaction region

SF HO
MQSXF (200A)
MCSXF/MCSSXF (2x120A)
MCOXF/MCOSXF (2x120A)
MCDXF/MCDSXF (2x120A)
MCTXF/MCTSXF (2x120A)

From the circuits point of view this part of the Matching Section is not modified

LHC Dipole circuit in S67 and 78



Changes to the Inner Triplet circuits

A. As a recall from previous HL Annual Meetings:
   1. Addition of a k-modulation circuit across Q1a magnet
   2. The use of very-thin base cold diodes
   3. Suppression of Q2a trim circuit
   4. Update of the ratings of the superconducting elements of the main circuit of the Inner Triplet

B. **New pole order and implications on the circuit polarity.**

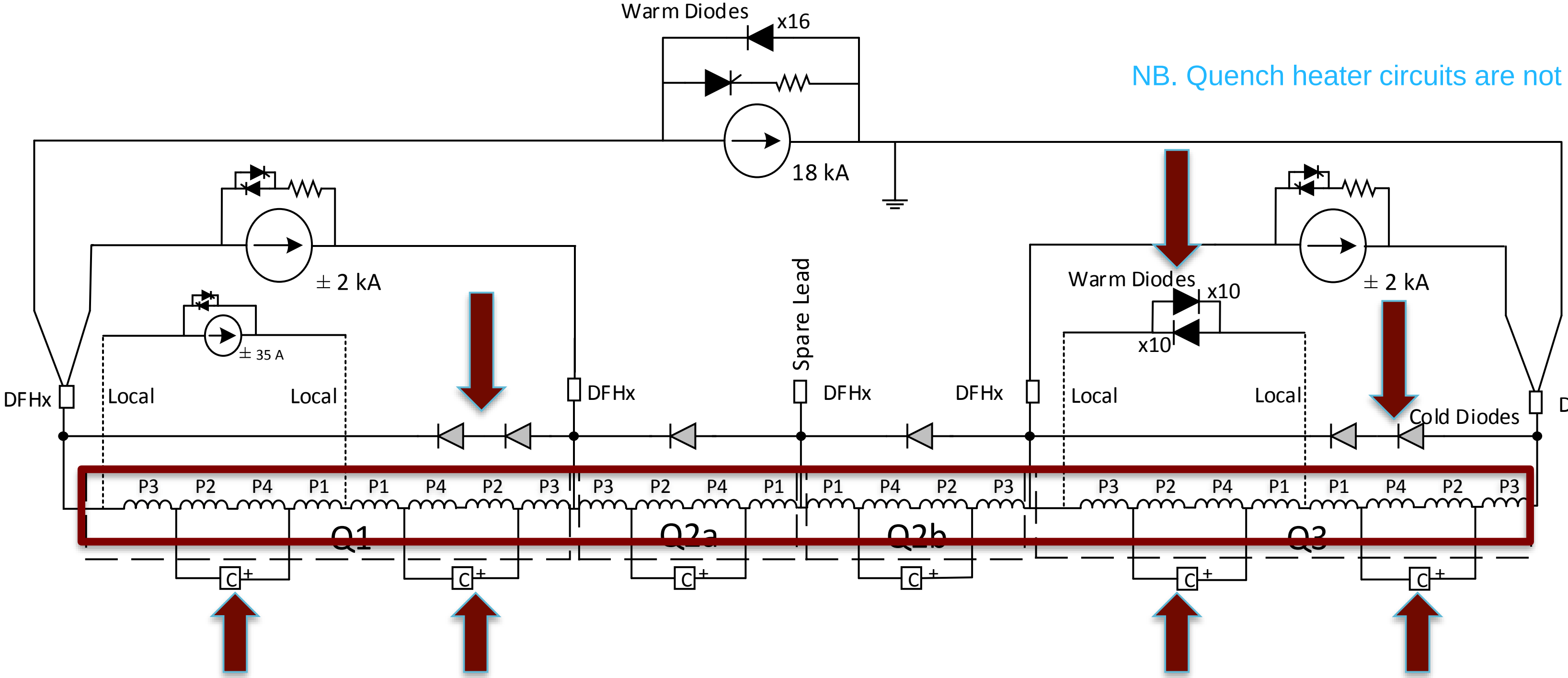
C. **Number of cold diodes across Q1 and Q3**

D. **Connections of CLIQ on Q1 and Q3**

E. **Additional warm diodes for CLIQ discharges on Q3**

Inner Triplets – the new scheme

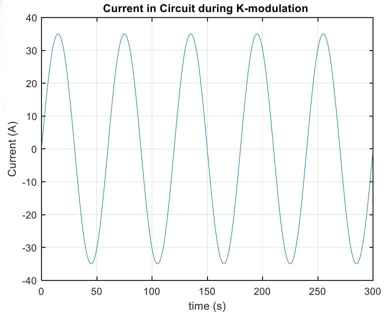
NB. Quench heater circuits are not shown

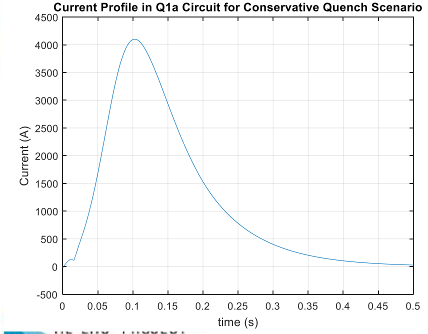


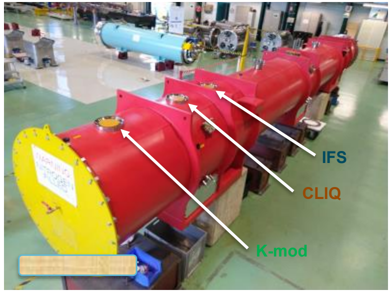
The **quench protection strategy** for the inner triplet of the HL-LHC is such that any quench in a superconducting element of the circuit will trigger the quench protection of all the elements of the circuit (switching off all the power converters, firing quench heaters and CLIQ units in all magnets).

A1. Design of feeders for the Q1a k–modulation circuit

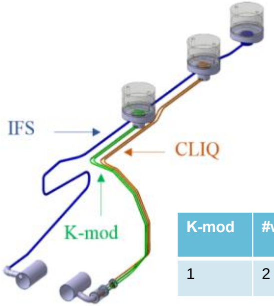
- The requirements from beam optics to apply only on magnet Q1a a sinusoidal modulation in order to measure up to 0.01 tune variation, i.e. measuring the β*-function by k-modulation, have been translated into a 35 A circuit,
- This k-modulation circuit will be powered using local feeders and feedthroughs, which means that it will not be powered through the superconducting link.
- Moreover, this 35 A circuit will be fed by a standard HL-LHC-60A-10V power converter with a specific crowbar system.
- It has been agreed with the relevant WPs (6b and 7) to keep the k-mod circuit permanently connected.

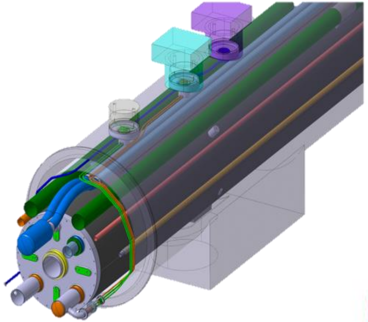






Integration





K-mod	#wires	Cond x-section OFHC Copper	L tube	L cond	Tube Dia	#tubes
1	2	2x10 mm2	1.7m	~2 m	8/6 mm	2

Requirements

Electrical Parameters
- HVWL to ground: 5kV at leakage current below 15μA
- CLIQ: maximum feeder branch resistance: 2.5 mΩ, 5mΩ total

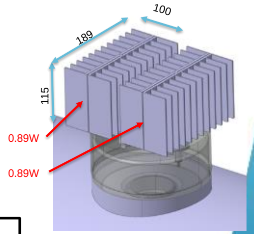
Maximum Conductor Insulation Temperatures
- Limited to about 350K with respect to a glass transition temperature between 630 and 680K* for Polyimide insulation

Minimum Conductor Warm End Temperature
- Not below 288K for a nominal air temperature of 290K sourced from cryogenics experts with LHC operational experience.
- This general rule is confirmed by analysis of the dew point data obtained for one sector in the LHC tunnel over one complete year, where a minimum temperature above the dew point of 2.6 K has been measured.

Ionizing Radiation Resistance
- The increase in luminosity at the interaction points 1, ATLAS and 5, CMS that will be provided by the HL-LHC Triplets, leads to a roughly equivalent increase in activation of all LHC machine equipment on each side of these interaction points.
- All HL-LHC equipment in the long straight sections to the left and right of ATLAS and CMS must withstand an integrated dose of 1 MGy.

Activated Environment
- Installed in highly activated and less well ventilated zones of the LHC, consequently all three feeder systems may exploit only the available natural heat convection to prevent the formation of condensation on their warm ends.

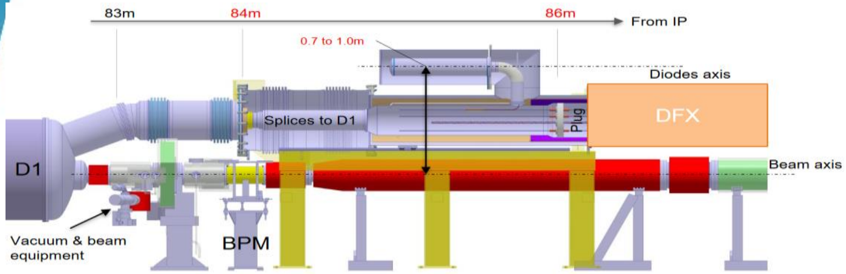
* Dupont data sheet for Kapton® NH

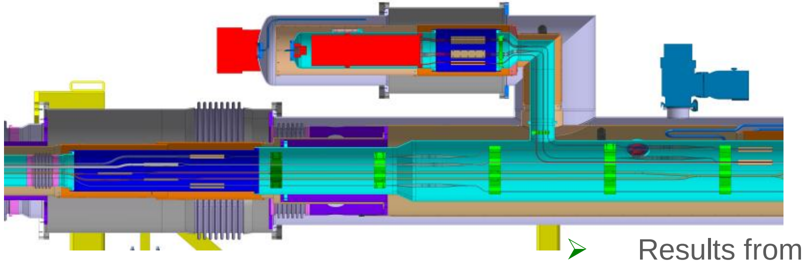


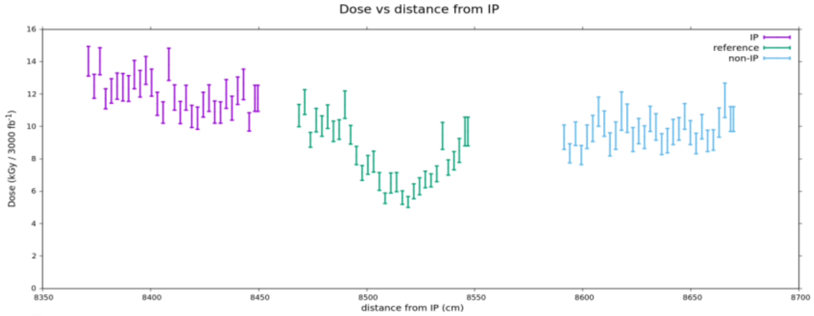
Ref. L R Williams, F Pasdeloup

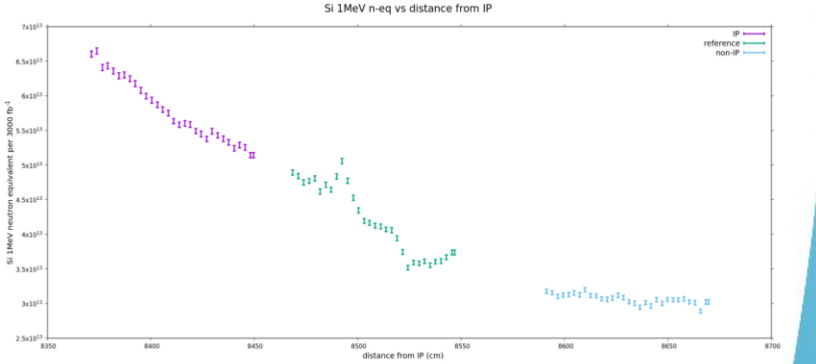
Design

A2. Cold diodes









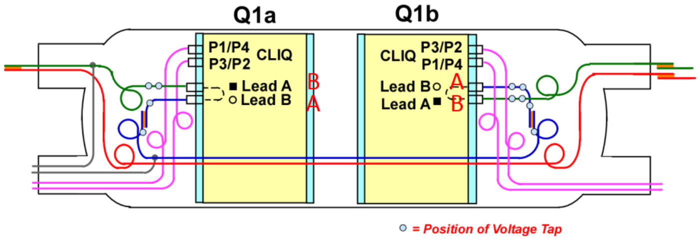
Ref. Yann Leclercq et al.

- Results from FLUKA simulations on radiation levels at the DCM proposed location, normalized for the nominal HL-LHC scenario (3000 fb^{-1}).
- The upper limits at the reference position are 12 kGy and $5x10^{13}$ cm^{-2} for the dose and fluence, respectively [16].
- **The dose/fluence obtained during the CHARM irradiation campaign (between 10 and 12 kGy and about 2.10^{14} n/cm^{-2}) are compatible with the simulation results, hinting that the cold diodes may have been already fully validated. To be followed in detail.**

[Ref. G Lerner, M Sabaté Gilarte, R García Alía, F Cerutti ; EDMS # 2201836]

B. Change of pole order and implications on the circuit polarity

- To **eliminate additional splices in the Q1/3 cold masses** and to be able to **perform vertical tests of MQXFA magnets at BNL**, it was proposed to change the pole order of the triplet magnets.
- To maintain the field **polarity** as in the HL LHC baseline, the connection scheme on Q2 magnets as well as the main circuit, CLIQ, HDS and instrumentation wires have to be adapted accordingly.

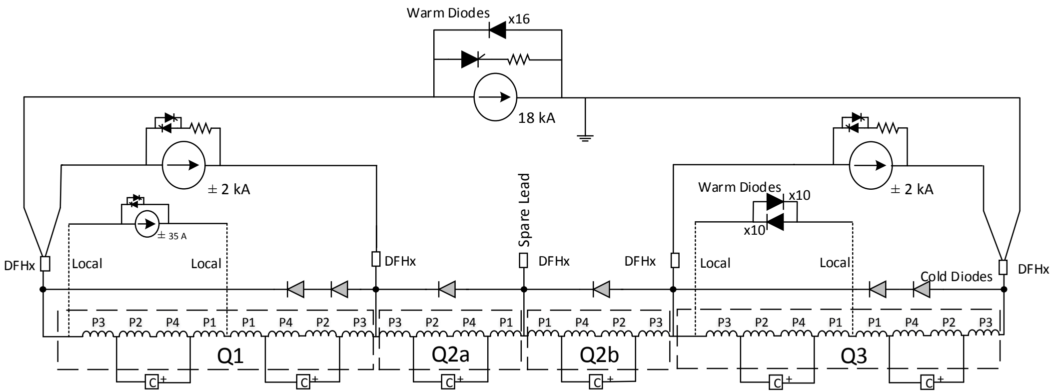


Courtesy S. Feher

C. Number of cold diodes

- *Cold diodes provide **decoupling** between cold and warm parts*
- *… **limit** the over-currents in the superconducting bus bars and link conductors*
- *… provide higher **immunity** in front of unexpected delays in the quench detection and protection systems.*

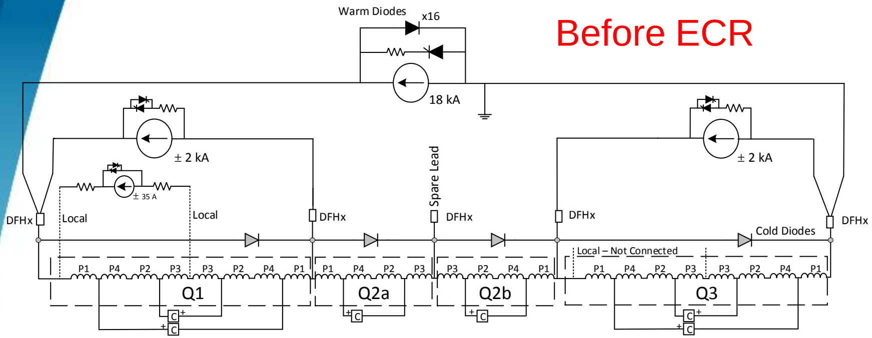
- **One diode** across each magnet, did not provide enough **margin** between the cold diode turn-on voltage and the voltage developed by the power converter crowbar during a power abort.
- If the diode is turned on in conduction, such a process leads to a **high dI/dt** in the circuit which could trigger a **spurious quench detection** and consequently **firing** CLIQs and heater power supplies
- In addition, turning-on of a cold diode leads to the dissipation of around 40 kJ heating the helium bath and the copper connections. **Risks to quench bus bars**.
- **To avoid unnecessary turning-on of cold diodes, the number of diodes increased from four to six per circuit: 2 diodes in series across each of Q1 and Q3, and 1 diode across each of Q2a and Q2b. In this case, the margin between the crowbar voltage and the threshold of the cold diodes increases from 1 V to 7 V.**

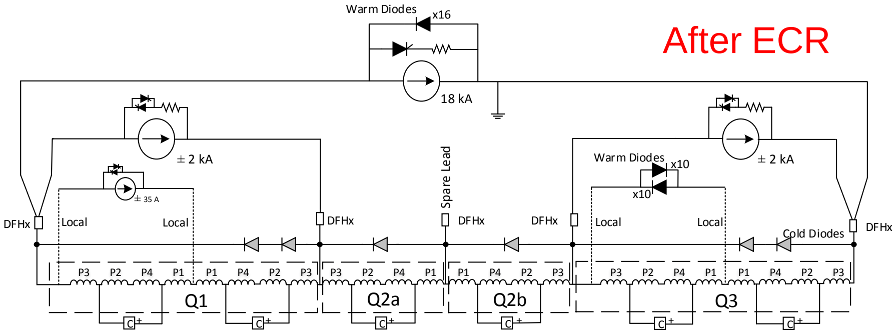


D. Modifications to the warm part

- Modifications only apply to the use of existing instrumentation therefore, **no change to the cold-mass manufacturing baseline**.
- Proposed changes are:
  - Modification of the **connection scheme of the CLIQ units** protecting the Q1 and Q3
  - Addition of a **parallel electrical path across magnet Q3a**, using the warm lead already present in the baseline. This path includes two strings of ten diodes, connected back to back, in series to the 200 mΩ of related cables
- This arrangement prevents the occurrence of a severe failure caused by asymmetric magnetic fields in Q1 or Q3 coils. **See D Wollmann's talk**

HiLumi HL-LHC PROJECT





Implications of the change to quench protection

Hot-spot temperature **BASELINE + ECR**	• No failures • Reference, uniform parameters	• 1 CLIQ and 1 QH failures • Unfavorably distributed realistic* parameters • **With ordering the four coils within a magnet**
Before ECR ≡ After ECR MQXFB, 1x 7.15 m	231 K	<403 K
After ECR MQXFA, 1x 4.20 m	234 K	<401 K

@ I nom = 16.5 kA

(it was 284 K)

Voltages to ground **BASELINE + ECR**	• No failures • Reference, uniform parameters	• 1 CLIQ and 1 QH failures • Unfavorably distributed realistic* parameters • **With ordering the four coils within a magnet**
Before ECR ≡ After ECR MQXFB, 1x 7.15 m	594 V	≤657 V
After ECR MQXFA, 1x 4.20 m	316 V	≤353 V

@ I nom = 16.5 kA

(it was 1132 V)

Ref. E Ravaioli

"This value could be considered as acceptable for an event with low probability of occurrence" (ECR draft)

"Local" powering of HO correctors

EDMS NO.	REV.	VALIDITY
1832068	1.0	VALID

REFERENCE : LHC-D-EC-0002

HL – LHC Engineering Change Request

LOCAL POWERING OF THE HIGH ORDER CORRECTOR MAGNET CIRCUITS IN THE HL-LHC INNER TRIPLETS

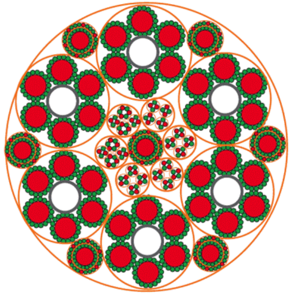
ECR DESCRIPTION

WP Originator	WP6a	***Process***	Engineering
Equipment	DSH, DFX, DFH,	***Baseline affected***	Cost
Drawing	NA	***Date of Issue***	2019-03-26
Document		***CI responsible***	A. Ballarino
WPs Affected	WP3, WP6a, WP6b, WP7, WP9, WP15, WP17	***Reference Document***	TDR Version 0.1

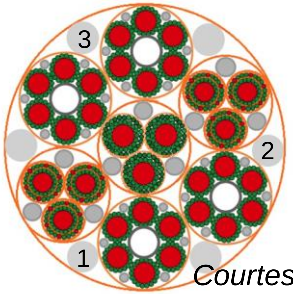
Detailed Description

The HL-LHC Cold Powering baseline envisaged powering the Inner Triplet Corrector circuits rated at 200 A and below [1] via the HL-LHC MgB_2-based Superconducting Link with the related power converters in the UR gallery. The present ECR proposes the local powering of those circuits via LHC-type conduction-cooled current leads integrated in the magnet cryostats [2]. The quench protection system has to be adapted to this change. The proposed change simplifies the HL-LHC Cold Powering System. The global impact of the change is described in detail in this document. More specifically, the local powering of the corrector circuits is achieved by re-locating the power converters in the UL14, UL16, UL557 and USC55 as presented and endorsed in 65th TCC (2019-01-17).

Layout in 2016



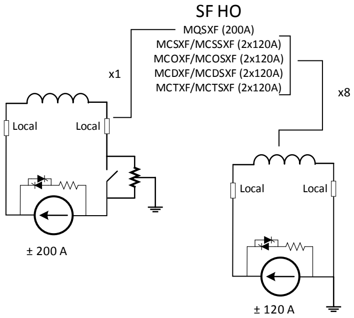
Layout in 2018



Base cable

18-strand cable

Courtesy A. Ballarino



The proposal is to use the LHC design - and associated integration strategy - for feeding the HL-LHC corrector circuits rated at DC current of 200 A and below. The circuits concerned are: MQSXF, MCSXF/MCSSXF, MCOXF/MCOSXF, MCDXF/MCDSXF and MCTXF/MCTSXF

Main points during discussions

- Simplification of the link favoring reliability - endorsed
- Feasibility of integration of the local feedthroughs - assessed
- Study of different alternative options coordinated by WP15:
  - A: Power converters in UR
  - A’: Power converters in UR, modified core to allow the warm copper cable to cool in air and the CV installation in the UL
  - A”: Power converters in UR, water cooled cables, ElQA implications
  - B: Power converters in UL14, UL16, USC55 and UL 557 – retained option
- Access to power converters during operation - accepted

Decision

TCC endorsed the presented solution at the 65th TCC meeting (17/01/2019), after discussions of the several solutions including keeping the power converters within the HL-LHC gallery. The solution shows several major advantages most prominently on cost, without any major disadvantage.

International Magnet Circuits Review

- Dates: September 9-10, 2019
  - At CERN: Auditorium Kjell Johnsen (30-7-018)

- Panel
  - **Hans-Jörg Eckoldt DESY**
  - **Paolo Fessia CERN**
  - **Steve Gourlay LBNL**
  - **Neil Mitchell ITER**
  - **Jim Strait FNAL**
  - **Akira Yamamoto KEK - chair**

- Scientific Secretary: Samer Yammine
- Link person: Felix Rodriguez Mateos
- Secretary: E Kurzen

Indico

Panel's Charter given by the Project

- *"Review the **final layout (design)** of the HL-LHC magnet circuits including the aspects related to **powering and quench protection** strategies, making sure that the right choices have been made both in terms of **circuit optimization and protection reliability**;*
- *Review the **adequacy of the protection** of the circuits for the different configurations that are adopted in order to assure **safe commissioning and operation with beam**. This aspect includes protection in case of quenches, failures of various components or of systems, effects of protection equipment to beam, protection of power converters, etc.;*
- *Review the **integration of equipment** respecting **installation & maintainability** requirements;*
- *Review the proposed **instrumentation for protection** and the ancillary equipment (feeders, feedthroughs, etc.) and their **test in operational conditions in the IT String***
- *Assess on the **Electrical Quality Assurance** strategy of cold/warm equipment and circuits, making sure that insulation coordination is properly established.*

- *While this is mainly a technically oriented review, (managerial aspects are reviewed by special Cost & Schedule Reviews) the **Panel may comment on the level of integration and collaboration between various Work Packages and Teams** participating to the circuits design and realization."*

Structure of the Review - I

I. Setting the scene – the magnets and the circuits

HiLumi Status and Charge to Review – L Rossi
Quick Overview on the HL-LHC Magnets Characteristics – E Todesco
Introduction to the HL-LHC Circuits and Report from Previous Review – F Rodriguez Mateos

II. Powering layouts

Warm Powering and Adequacy with Respect to Requirements – M Martino
Cold Powering – A Ballarino
Superconducting Bus Bars inside Cryostats – E Todesco

III. Protection and hardware

Quench Protection Strategies – A Verweij
Quench Detection, Related Hardware and Required Instrumentation – R Denz
Quench Protection Hardware – D Carrillo
Feeders for k-mod and CLIQ Applications – L Williams
Contribution of Power Converters to the Protection of the Circuits – S Yammine
Effects of Protection Equipment on the Beam and Reliability Studies … – D Wollmann

Structure of the Review - II

IV. Integration in the HL-LHC environment

Integration Studies – M Modena

V. Electrical Integrity and Quench Protection Tests

Voltage Withstand Levels – F Rodriguez Mateos
11T MBH: Electrical Integrity and Quench Protection Test Results – F Savary
MQXF: Electrical Integrity and Quench Protection Test Results – G Ambrosio
NbTi Magnets: Electrical Integrity and Quench Protection Test Results – A Foussat

VI. Documentation

Document Plan, Management of Change – S Yammine

VII. The system of systems real validation

The HL-LHC Inner Triplet String – M Bajko

VIII. Safety

Safety Aspects – T Otto

Special Closed Session

- Risk analysis of the IT String– M Bajko
- Voltages and temperatures on QXF magnets – E Ravaioli
- Voltage withstand levels and quench heater position for QXF and 11T MBH – G Ambrosio, P Ferracin & F Savary
- How are the electrical splices made in HL-LHC cryostats – H Prin
- Reliability studies on the complete inner triplet circuit protection – A Apollonio
- Feedback from LHC and MDs done with respect to effects to beam from misfiring of protection units – D Wollmann
- How to guarantee security of firmware in quench detection and potential protection implications – R Denz

20+7 contributions in total

Preliminary Outcome

The Chair of the Panel presented a preliminary report to TCC on 10 October 2019

- *"The review panel has recognized that the HL-LHC s.c. magnet circuits' design has been much advanced since the reviews held in 2016 and 2017 and has been matured to execute the construction.*
- *Advices from previous magnet circuit reviews have been well implemented in the design and recent development, and they are carefully reflected in the reports presented at the review.*
- *The Panel supports the magnet circuit concepts presented.*
- *The Panel strongly supports the IT String test plan, as a critical milestone of the project to be completed before LS3.*
- *A well-developed set of required voltage withstand levels was presented. As an open question, an additional, intermediate temperature test in gas for Nb_3Sn magnets was proposed. The usefulness of such specific test is not fully demonstrated, but if it can be integrated in the production flowchart without major impact, no counterarguments have been found.*
- *Safety and risk analyses have been carefully assessed, in particular, importance and effectiveness of the beam abort action in case of misfiring of the quench protection system has been well understood."*

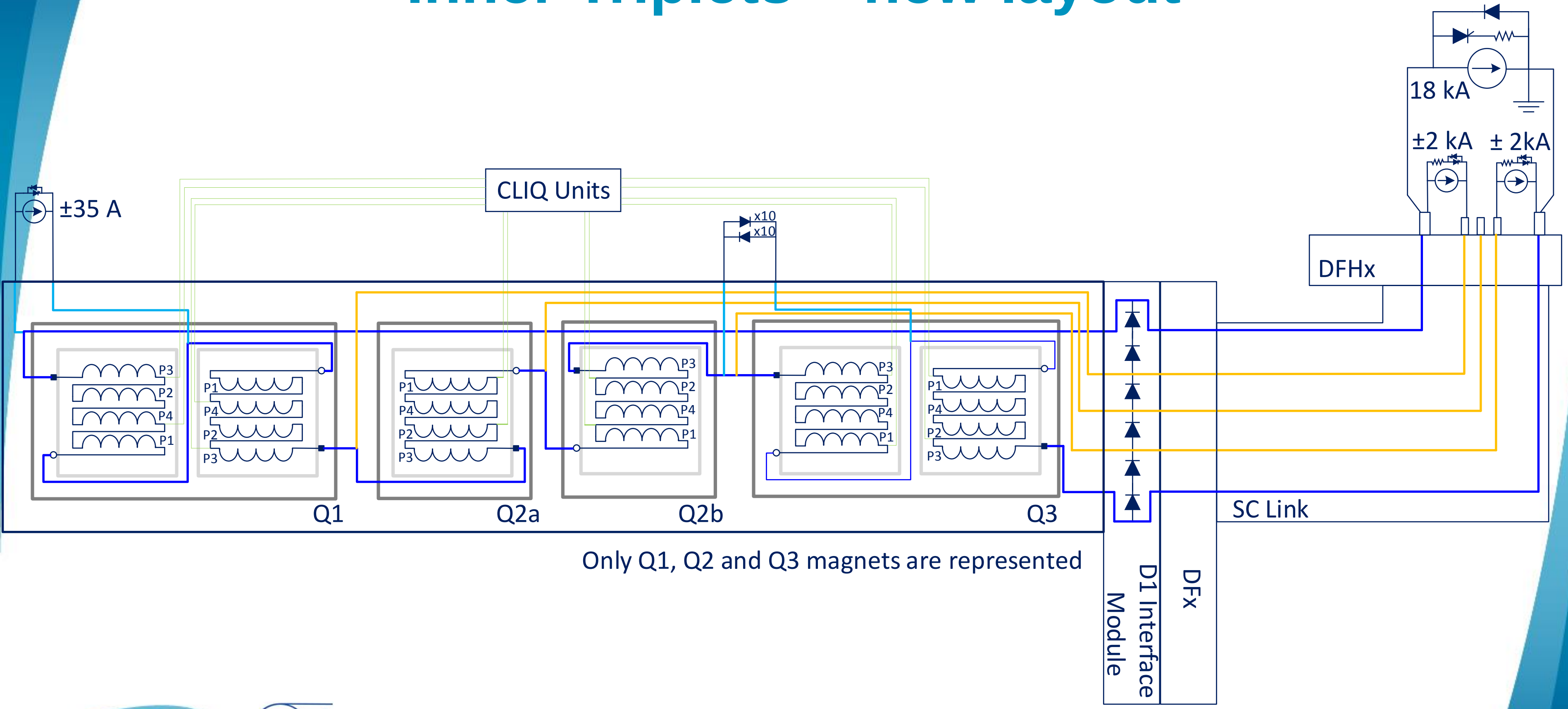
Key recommendations

- *“**Address** the two recommendations from the MQXF Review in July 2019 regarding the quench protection heaters (QPHT) :*
  - *“Assess the QPHT design including the assembly process, to justify the current baseline design, and prepare for any unexpected incidents during production”*
  - *“Assess the long-term stability of the quench heaters including epoxy impregnation issues (elimination of bubbles, dry spots, and cracks)”.*
  - ***Provide** solid justification and decision commonly in the HL-LHC magnet and circuit team**,** if any change in the MQXF-QPHT configuration is proposed.*
- ***Improve** understanding of the significantly different results obtained from different quench simulation codes and make the reasons for the differences clear. Experimental comparison shall be well documented. In case the design process relies more on a code than another, the technical reason for the choice shall be clearly stated and traced.*
- ***Verify** the newly proposed Distribution Feedbox HTS-end (DFH) concept and **ensure** the impacts and dependencies to/from other systems.*
- ***Complete** the electrical quality assurance plan. **Ensure** the documents are efficiently shared and adopted across the HL-LHC magnet and circuit teams. **Reinforce** the voltage withstand test plan, including the additional intermediate-temperature voltage test in helium environments, in addition to the three categories already established.*
- ***Establish** the IT+D1 string test plan and **execute** it within the planned period between now and LS3, in particular for verifying the IT nested circuit characteristics.*
  - ***Reinforce** the string test team to accomplish the goal within the limited time.”*

HiLumi HL-LHC PROJECT

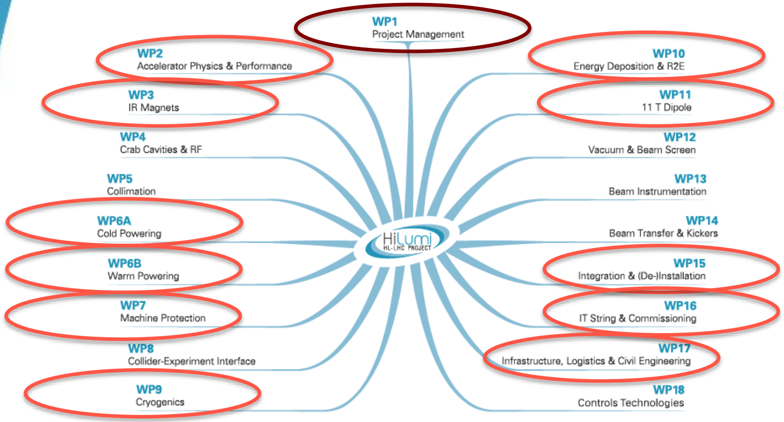
Many thanks

Inner Triplets – new layout



Only Q1, Q2 and Q3 magnets are represented

Magnet Circuit Forum



Mandate

- The Magnet Circuit Forum (MCF) is the 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.
- 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 has the responsibility to keep up to date the circuit configurations and parameters. This is done through updates of the Circuit Table and the electrical schemes (see MCF Sharepoint)
- So far 54 meetings, properly documented with minutes, follow up of actions, etc
- MCF is also organizing topical meetings with reduced attendance, 27 meetings have taken place so far
- The Forum has taken the lead in the preparation of some Engineering Change Requests and other documents related to circuit aspects
- About 50 Members are regularly invited