State of discussions in preparation for the HL-LHC Circuits Review

F. Rodriguez-Mateos

with inputs from G. Ambrosio, **B. Auchmann**, J.-P. Burnet, A. Fernandez Navarro, E. Ravaioli, G.-L. Sabbi, E. Todesco, A. Verweij, **D. Wollmann**,

and many other CERN and colleagues outside

Outline

- The Review Programme
- Rationale for baseline
- Main proposals:
  - Inner Triplet
  - D1/D2

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- **The Review Programme**
- Rationale for baseline
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- https://indico.cern.ch/event/477759/

Review panel:

Akira Yamamoto (CERN & KEK, Chair),
Guram Chlachidze (FERMILAB),
Arnaud Devred (ITER),
Chen-Yu Gung (ITER),
Davide Tommasini (CERN),
Rudiger Schmidt (CERN),
Markus Zerlauth (CERN, Sc. Secretary).

The review is scheduled on 21st to 23rd March 2016 with the **close-out on 23rd March at CERN at 16:00**

Review Organization Office: Julia Cachet & Cecile Noels

Mon 21/3

08:00				
	Closed session (30')		*Kjell Johnsen Auditorium, CERN*	08:30 - 09:00
09:00	**Welcome and scope of the review (10')**	*Lucio ROSSI*	*Kjell Johnsen Auditorium, CERN*	09:00 - 09:10
	The HL-LHC Magnets: Status report (20'+10')	*Ezio TODESCO*	*Kjell Johnsen Auditorium, CERN*	09:10 - 09:40
	HL-LHC Circuits: Global view and open questions (20'+10')	*Felix RODRIGUEZ MATEOS*	*Kjell Johnsen Auditorium, CERN*	09:40 - 10:10
10:00	**Coffee break**			10:10 - 10:40
	Integration of powering and protection systems (30'+10')	*Paolo FESSIA*	*Kjell Johnsen Auditorium, CERN*	10:40 - 11:20
11:00	**SC links (30'+10')**	*Amalia BALLARINO*	*Kjell Johnsen Auditorium, CERN*	11:20 - 12:00
12:00	**Bus Bars (20'+10')**	*Herve PRIN*	*Kjell Johnsen Auditorium, CERN*	12:00 - 12:30

Monday (cont.)

	The principles of the Cliq System (10'+5')	*Emmanuele RAVAIOLI*
	Kjell Johnsen Auditorium, CERN	13:30 - 13:45
	The 11 T Dipole Magnet and protection (15'+5')	*Susana IZQUIERDO BERMUDEZ*
14:00	*Kjell Johnsen Auditorium, CERN*	13:45 - 14:05
	The 11 T Dipole Circuit(s) (15'+5')	*Samer YAMMINE*
	Kjell Johnsen Auditorium, CERN	14:05 - 14:25
	The inner Triplet Magnets and protection (15'+5')	*Giorgio AMBROSIO*
	Kjell Johnsen Auditorium, CERN	14:25 - 14:45
	The Inner Triplet Circuit (15'+5')	*Emmanuele RAVAIOLI*
15:00	*Kjell Johnsen Auditorium, CERN*	14:45 - 15:05
	D1 (10'+5')	*Tatsushi NAKAMOTO*
	Kjell Johnsen Auditorium, CERN	15:05 - 15:20
	D2 (10'+5')	*Pasquale FABBRICATORE*
	Kjell Johnsen Auditorium, CERN	15:20 - 15:35
	D1&D2: Circuit Aspects (10'+5')	*Felix RODRIGUEZ MATEOS*
	Kjell Johnsen Auditorium, CERN	15:35 - 15:50
16:00	**Coffee break**	15:50 - 16:20
	Triplet Orbit Correctors (20'+10')	*Fernando TORAL*
	Kjell Johnsen Auditorium, CERN	16:20 - 16:50
17:00	**Triplet High Order Correctors (20'+10')**	*Giovanni VOLPINI*
	Kjell Johnsen Auditorium, CERN	16:50 - 17:20
	Matching section correctors (20'+10')	*Gijs DE RIJK*
	Kjell Johnsen Auditorium, CERN	17:20 - 17:50

Tue 22/3

08:00		
	Operation requirements (30'+10') *Kjell Johnsen Auditorium, CERN*	*Massimo GIOVANNOZZI* 08:30 - 09:10
09:00	**Power converters: operational aspects (30'+10')** *Kjell Johnsen Auditorium, CERN*	*Jean-Paul BURNET* 09:10 - 09:50
10:00	**Quench detection (30'+10')** *Kjell Johnsen Auditorium, CERN*	*Jens STECKERT* 09:50 - 10:30
	Coffee break	10:30 - 11:00
11:00	**CLIQ & HDS Units (20'+10')** *Kjell Johnsen Auditorium, CERN*	*Knud DAHLERUP-PETERSEN* 11:00 - 11:30
	Warm cabling, cooling and ventilation (20'+10') *Kjell Johnsen Auditorium, CERN*	*Laurent Jean TAVIAN* 11:30 - 12:00
12:00	**Lunch break**	

Tuesday cont.

		12:00 - 13:30
	Electrical Quality Assurance (20'+10') *Kjell Johnsen Auditorium, CERN*	*Felix RODRIGUEZ MATEOS* 13:30 - 14:00
14:00	**Diagnostics and Analysis: The point of view of MP3 (20'+10')** *Kjell Johnsen Auditorium, CERN*	*Arjan VERWEIJ* 14:00 - 14:30
15:00	**Inner Triplet String (30'+10')** *Kjell Johnsen Auditorium, CERN*	*Luca BOTTURA* 14:30 - 15:10
	Coffee break	15:10 - 15:40
16:00	**Document Plan (20'+10')** *Kjell Johnsen Auditorium, CERN*	*Reiner DENZ* 15:40 - 16:10
	Roadmap for decisions (20'+10') *Kjell Johnsen Auditorium, CERN*	*Daniel WOLLMANN* 16:10 - 16:40

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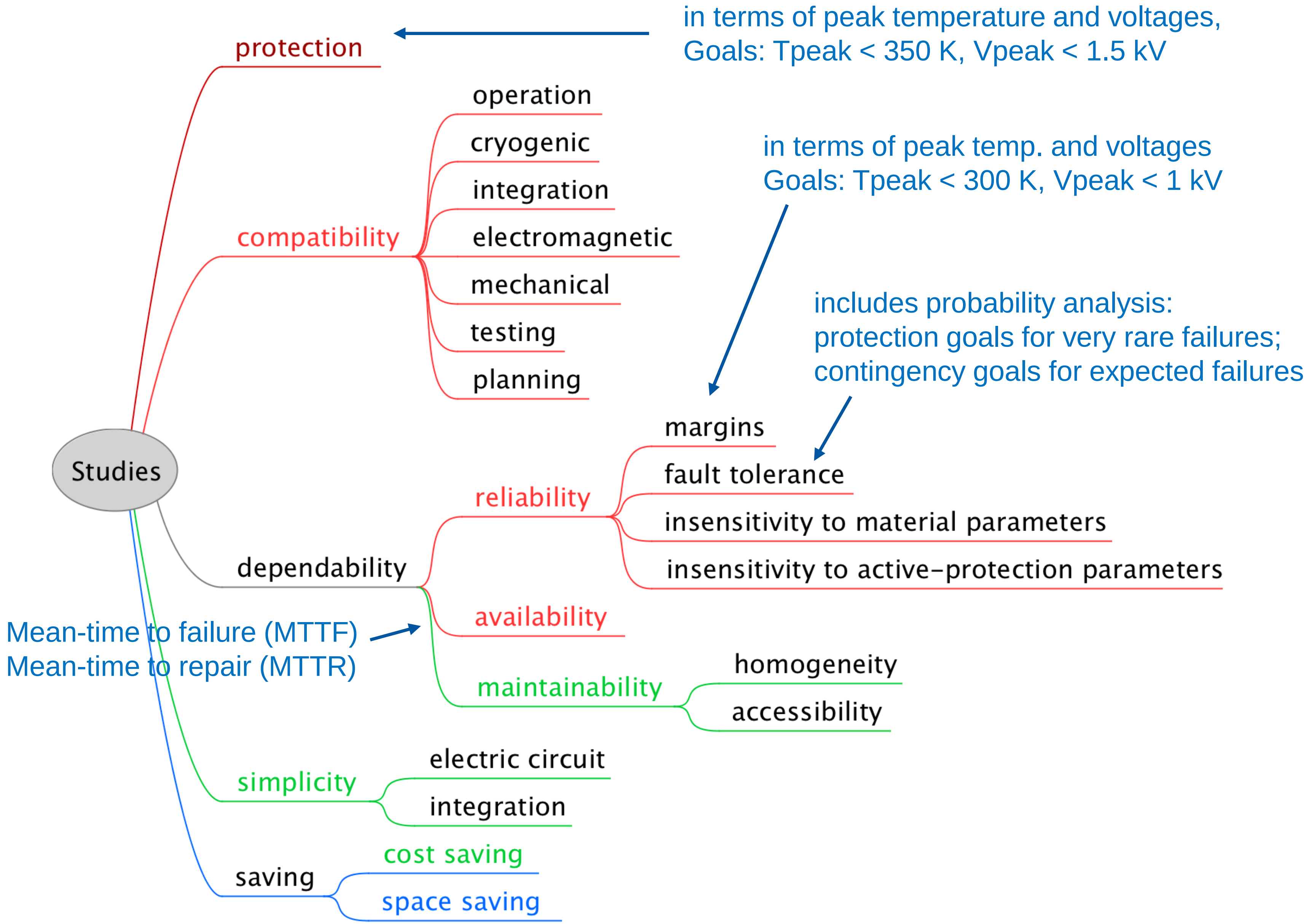
- The Review Programme
- **Rationale for baseline**
- Main proposals:
  - Inner Triplet
  - D1/D2



B. Auchmann, D. Wollmann

Some questions for a new baseline (1/2)

- Number of circuits
- Ramp-down speed
  - Power converter technology issues
  - Losses in passive elements
- Protection means
  - Number of heater strips in active use, how many as spares
  - HDS parameters, redundancy (capacity, triggering)
  - Number and connection of CLIQ units
  - CLIQ parameters, redundancy (capacity, triggering)
  - Parallel elements
  - Lead design (CLIQ, bypass and heaters)
  - Heater & CLIQ polarity assignment

Some questions for a new baseline (2/2)

- Detection and related instrumentation
  - Taps (incl. symmetric detection)
  - Logic (voting, redundancy)
  - Variable thresholds
- Monitoring
  - Online monitoring, interlocking
  - Post-mortem data
- Test and reception criteria
- …

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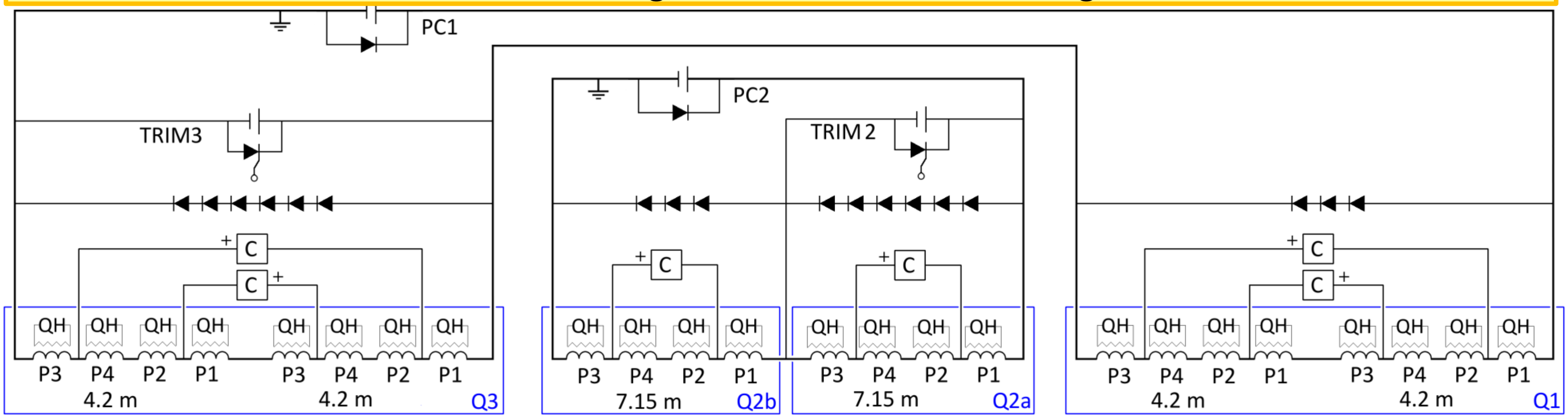
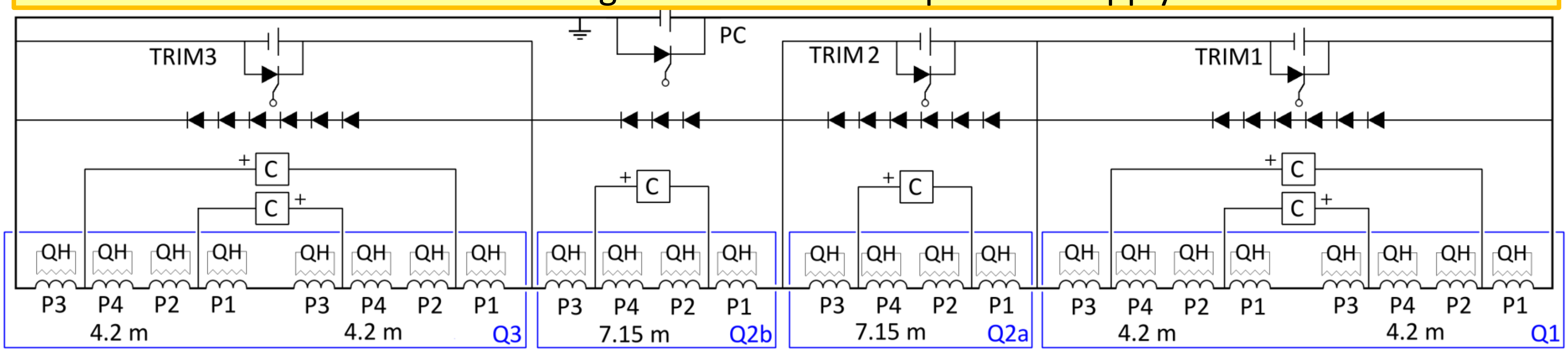
Powering scheme

Baseline: Two main 1-quadrant power supplies + 2 trim power supplies
Slow discharge with free-wheel discharge



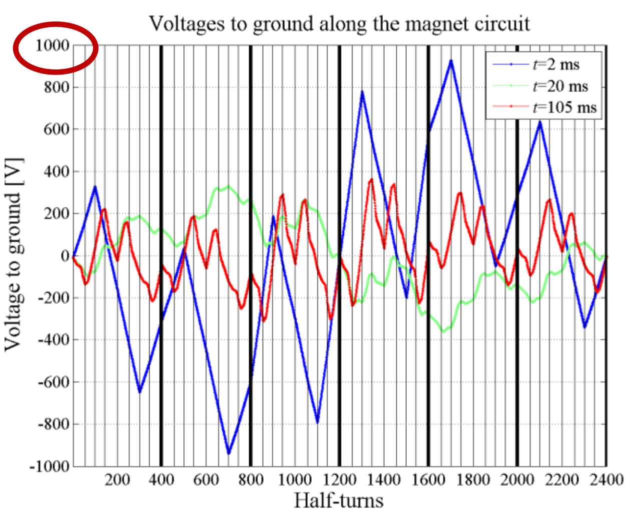
Proposal: One main 2-quadrant power supplies + 3 trim power supplies
Slow discharge achieved with 2-quadrant supply



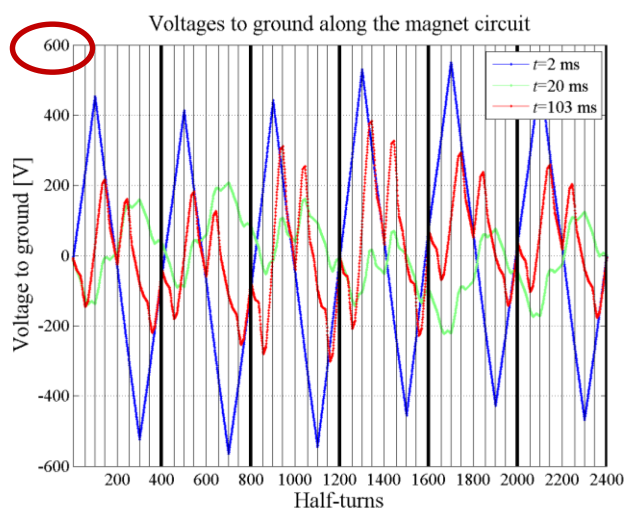
Why do we need parallel elements?

- Voltages to ground reduced by means of parallel elements across parts of the circuit which equalize the voltage distribution
- Avoid very high voltages to ground in several CLIQ failure cases
- Cold parallel diodes are probably incompatible with the very high expected radiation dose in the interaction regions
- Proposed solution: Warm parallel diodes utilizing existing leads of the trim supplies (but needs different connection schemes for Q1/Q3 and Q2a/Q2b)
- Back-up solution: 1Ω parallel resistors (but leakage currents, cryo loads)

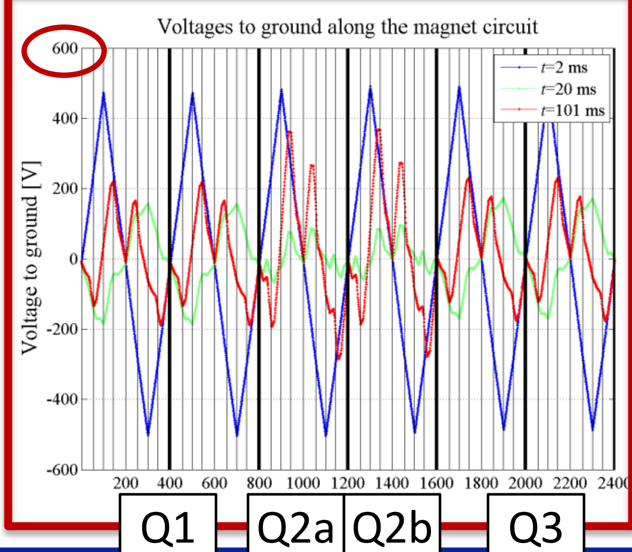
No parallel elements



1 Ω resistors

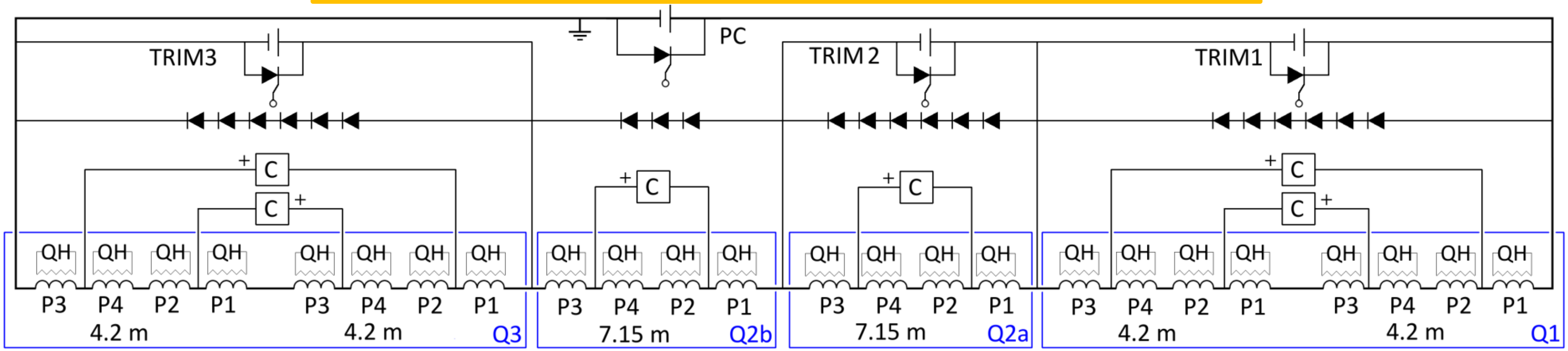


Warm diodes



CLIQ configuration

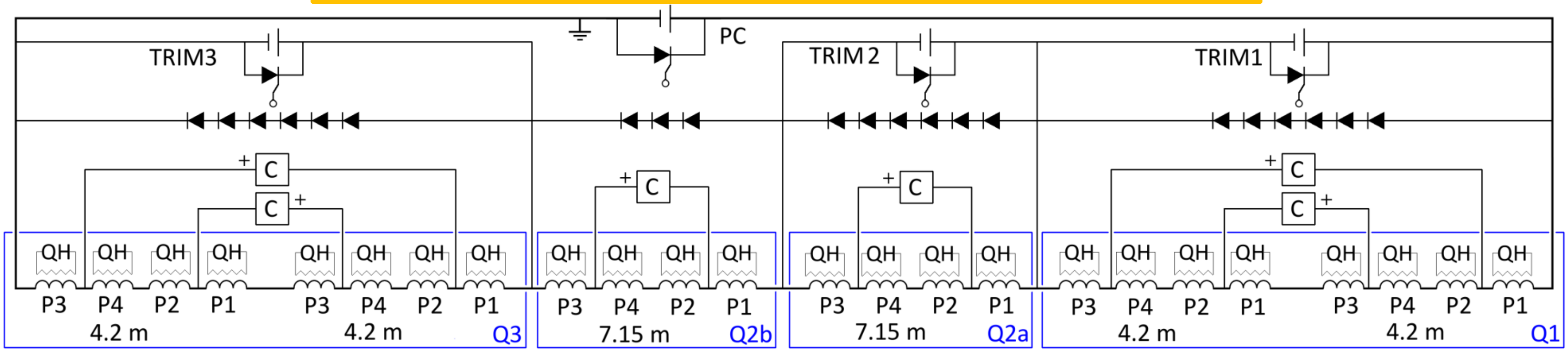
6 CLIQ units and 4 warm diode strings per triplet



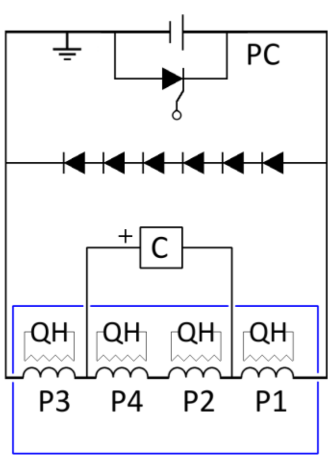
- Electrically equivalent to the previous 6-CLIQ configuration, but voltage to ground greatly reduced in the case of misfiring of one CLIQ unit
- Hence, additional current lead between the 2 magnets of Q1/Q3 not needed
- All parallel elements can be installed to the leads already foreseen for the trim power supplies
- Polarities of the CLIQ units is a key ingredient! (QA, testing at 50 V)
- All CLIQ units have the same capacitance (easier to design, manufacture, maintain the units). Units connected to Q1/Q3 can be charged to a lower voltage (600 V? 800 V?)
- Warm diodes are preferred over resistors (no leakage current during ramps, better control of the voltages to ground in failure cases)

Test of magnets and cold masses

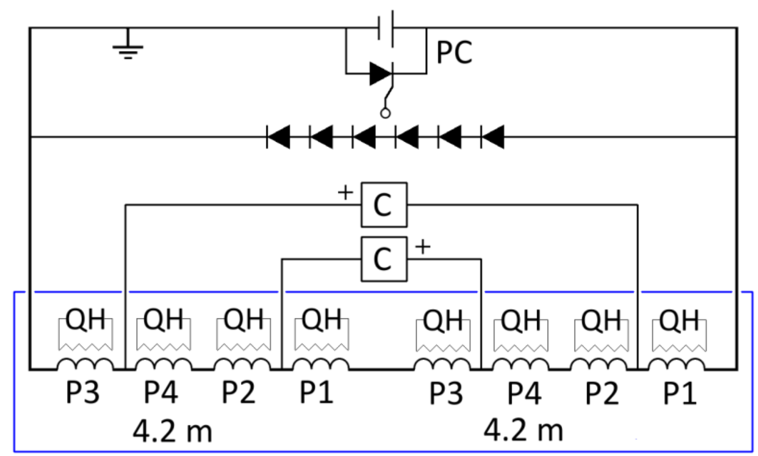
6 CLIQ units and 4 warm diode strings per triplet



Magnet test (7.15 or 4.2 m long)



Cold mass test (2x 4.2 m long)



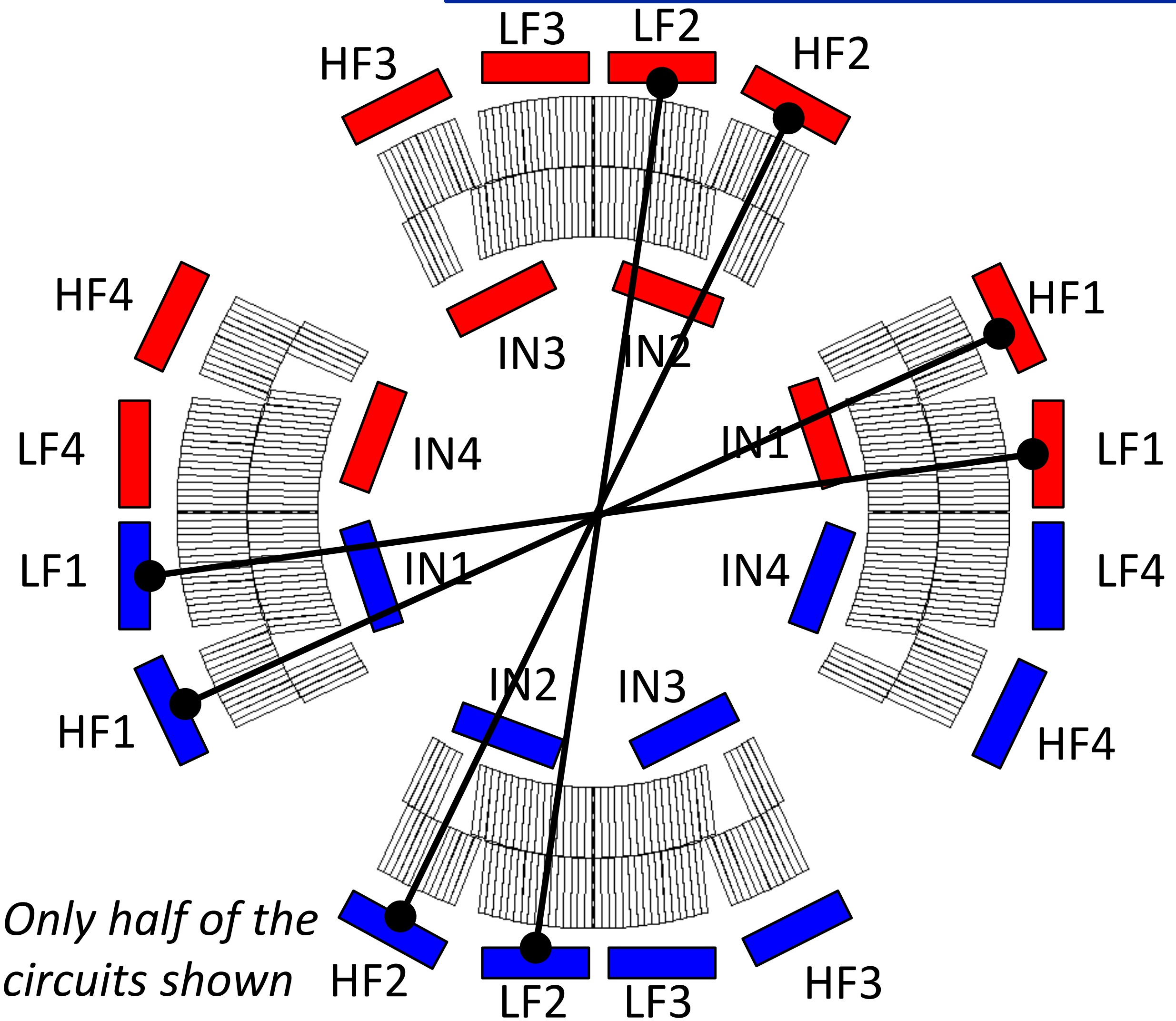
Replies to open questions

Open question	Option 1	Option 2	Option 3
How many main power supplies per triplet?	2 PC	1 PC	
Slow circuit discharge	Free-wheel	2-quadrant PC	
Energy-extraction system?	YES	NO	
CLIQ connection	6-CLIQ, 6 Diodes	4-CLIQ, 4 Diodes	6-CLIQ, 4 Diodes
Type of parallel elements	None	Warm Diodes	Warm Resistors
CLIQ parameters for the units of Q1/Q3	Same C, Same U0	Same C, Different U0	Different C, Different U0
Level of redundancy - CLIQ	Full CLIQ capacitance	Reduced CLIQ capacitance	
Level of redundancy - QH	Trigger Out-HF, Out-LF, In QH	Trigger Out-HF, Out-LF	Trigger Out-HF
QH connection scheme	See next		
Failure cases to consider	See next		
Specifications CLIQ terminals/leads	On going		

Modified from a slide by E. Ravaioli/G.L. Sabbi

Proposed QH connection scheme

Assuming each QH supply is connected to 2 strips in series (other options are possible)



Only half of the circuits shown

- Connection scheme that compensates the voltages induced by CLIQ and QH
- Connecting in series 2 strips attached to different poles reduces the effects of failures (hot-spot temperature, voltage distribution)

Worst-case analysis

The probability of particularly dangerous failure cases can be almost nullified by implementing the proposed mitigations.

In the remaining "realistic" failure cases, the worst-case analysis yields

- Peak hot-spot temperature: 305 K
- Peak voltage to ground: 520 V
- Peak coil-to-QH voltage: 500 V
- Peak mid-plane voltage: 500 V
- Peak layer-to-layer voltage: 500 V
- Peak turn-to-turn voltage: 50 V

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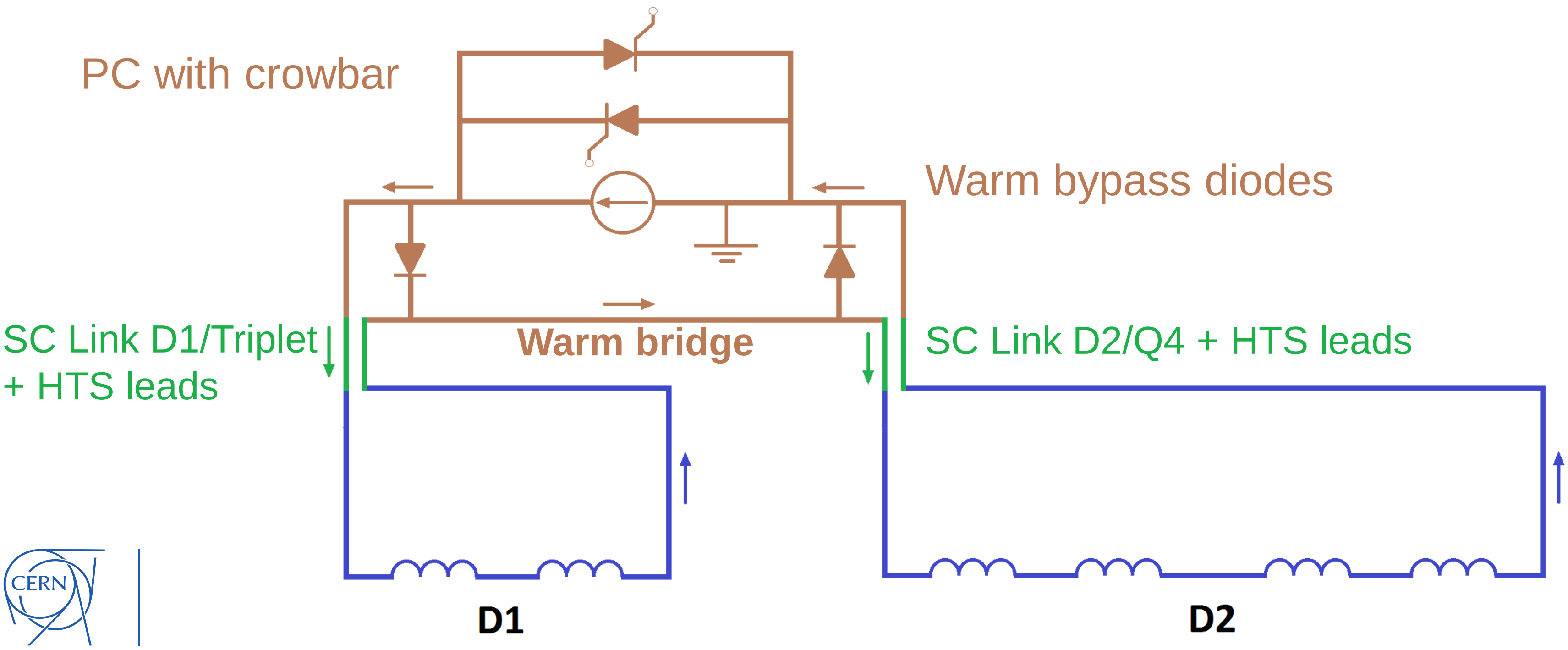
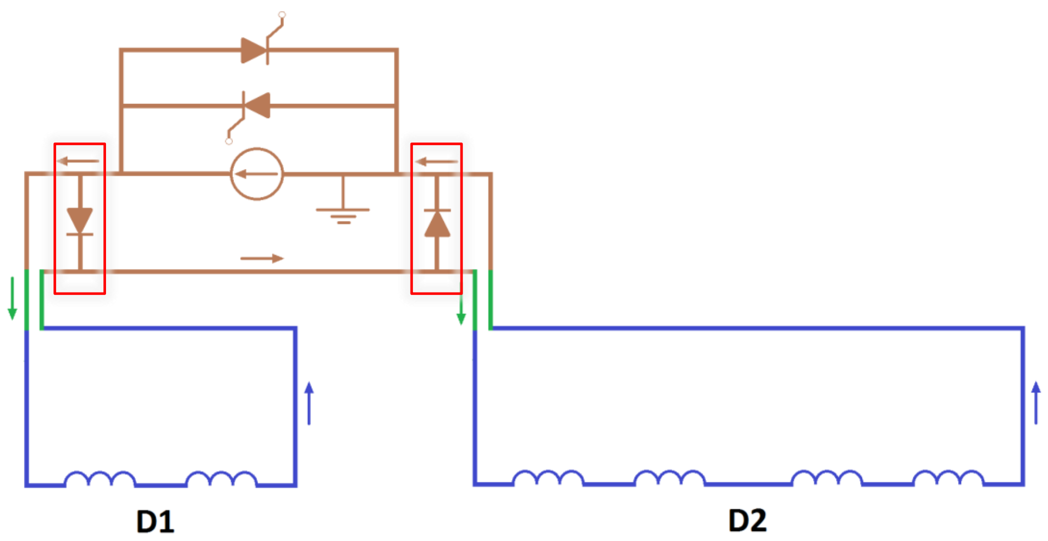
1 or 2 Circuits

- **The proposed single-circuit configuration differs from a two-circuit solution only on the warm side. A change between configurations is possible.**
- The powering through a single 13-kA PC brings substantial cost savings.
- No trims are necessary (E. Todesco).
- Warm bypass diodes decouple the protection of D1 and D2. There are no unprotected cold busbar segments/splices.
- The bridge should be done close to the PC, not close to the DFB, in order to avoid creating a large inductive loop, i.e., the circuit should look as closely as possible as the two-circuit solution with only a short bridge on the PC side (J.P. Burnet)
- The warm diode must be connected as close as possible to the DFB, otherwise the diode would see the voltage across the warm busbars, i.e., several volts in opening direction (J.P. Burnet)



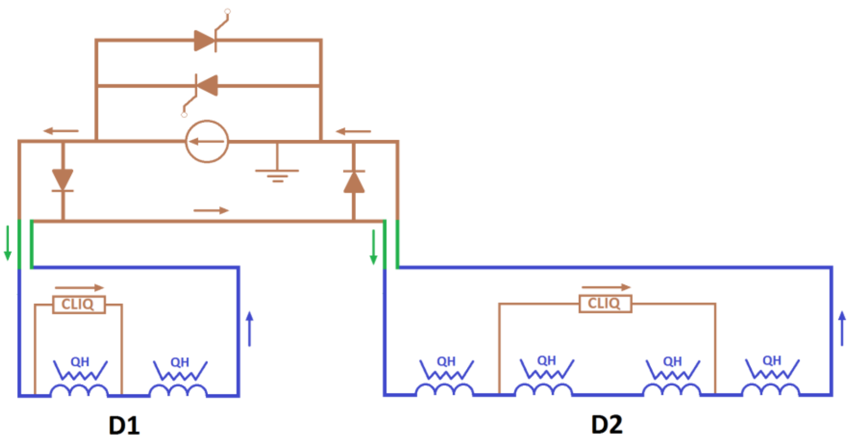
Warm Bypass Diodes

- + Warm bypass diodes decouple the protection of D1 and D2.
  - + Without bypass diodes, small differences in protection efficiency make one magnet absorb stored energy of the other magnet.
- + In failure scenarios, diodes reduce voltages to ground.
- – The warm bypass diode represents a new critical protection element that needs to be developed and tested with its heat sink and leads.

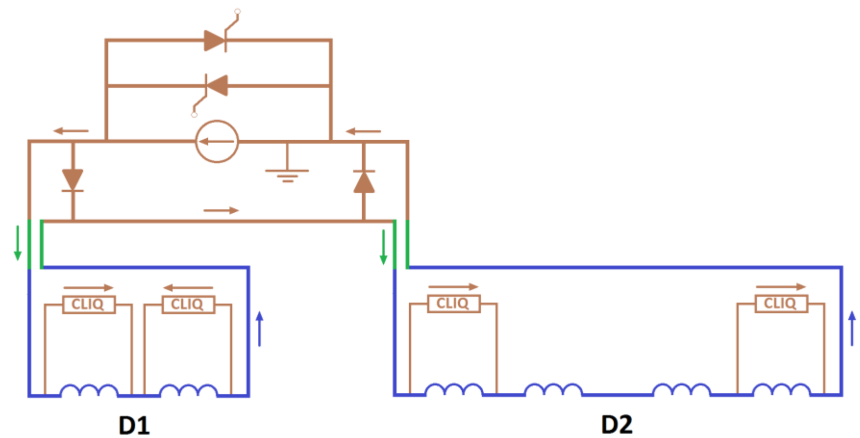


Heaters or CLIQ?

- Both systems effectively and redundantly protect the magnet.
- Being single-layer coils, the difference between CLIQ and heaters in terms of hot spot temperature is small (~270 K hot spot in D1, lower in D2).
- Voltage to ground during nominal operation is higher with CLIQ (~700 V).
- Heater power-supply failures lead to comparable voltages to ground.
- Main difference between CLIQ and heaters is that CLIQ is a new system.
- We propose redundant heater-protection, the installation of CLIQ leads, and high-voltage reception tests compatible with the use of CLIQ.



Heaters with optional non-redundant CLIQ.

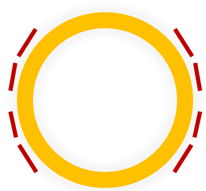


Fully redundant CLIQ-only protection

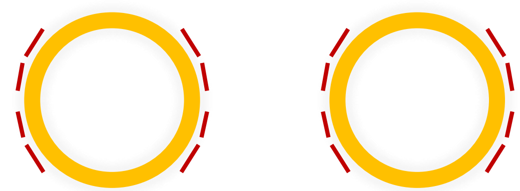
Heater Redundancy

- (Very) worst case assumptions:
  - up to two heater power-supply per magnet might fail during operation.
  - heater strips might fail due to open-circuit or short to ground.
- During operation 4 high-field heater circuits per magnet are needed, with 2oo4 enough for protection.
- Redundant low-field strips to provide redundancy.
- As an alternative (later on if needed) to the low-field circuits, CLIQ could be connected, leads for this required.

Nominal heater-circuit configurations


D1

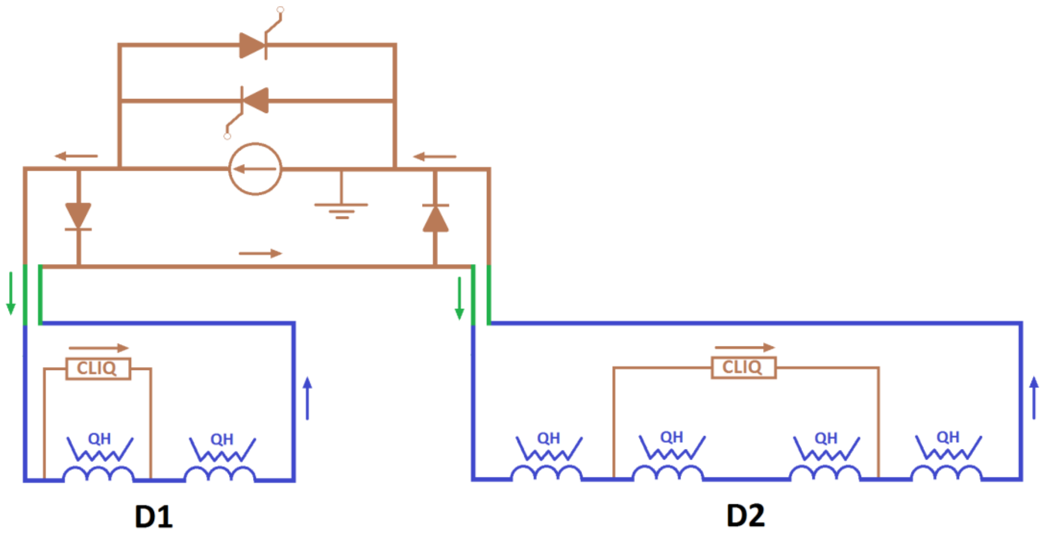
1 circuit per HF heater or
HF and LF heaters in series.


D2

1 circuit per HF pair of heaters
on either side of each aperture.
(Same as MB.)

Quench Detection

- D1 being a single-aperture dipole, it cannot be protected from (top/down-) symmetric quenches by comparison of pole voltages
- A combination of pole voltages and a induction-compensated detector are proposed, i.e., two fully independent systems. A high-current dI/dt sensor needs to be developed / procured



Summary for D1/D2

- We tend towards
  - a single circuit
  - with warm bypass diodes (to be developed),
  - 4(+4 spare) heater circuits per magnet,
  - CLIQ leads for unforeseen events on heaters,
  - Tests of CLIQ-only protection in an accelerator environment could be considered,
  - and a dual quench detection (comparison and active inductive compensation).

Many thanks for your attention!