Update on circuit protection simulations of the HL-LHC Inner Triplet circuit

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STEAM support: Marco Prioli, Lorenzo Bortot, Michal Maciejewski

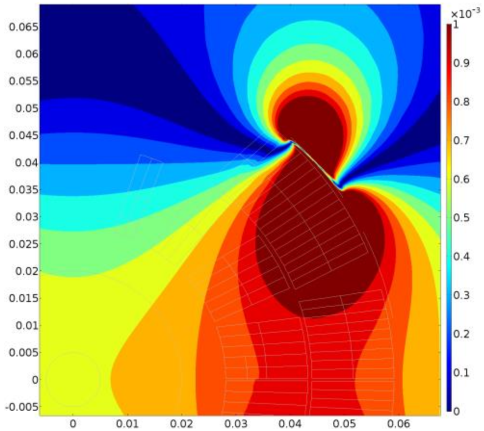
7th HiLumi meeting – Madrid - 16 November 2017

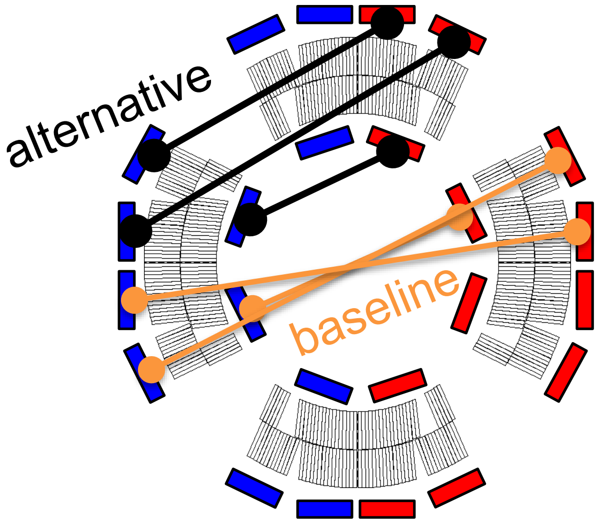
Overview

- Recent changes to the inner triplet
  - Proposed revision of MQXF heater strip powering
  - Revised warm resistance of the 35 A trim circuit
- STEAM co-simulation of the inner triplet baseline circuit
- A first look at the inner triplet circuit with cold diodes
- Summary

Proposed revision of MQXF heater strip powering

QH induced magnetic field





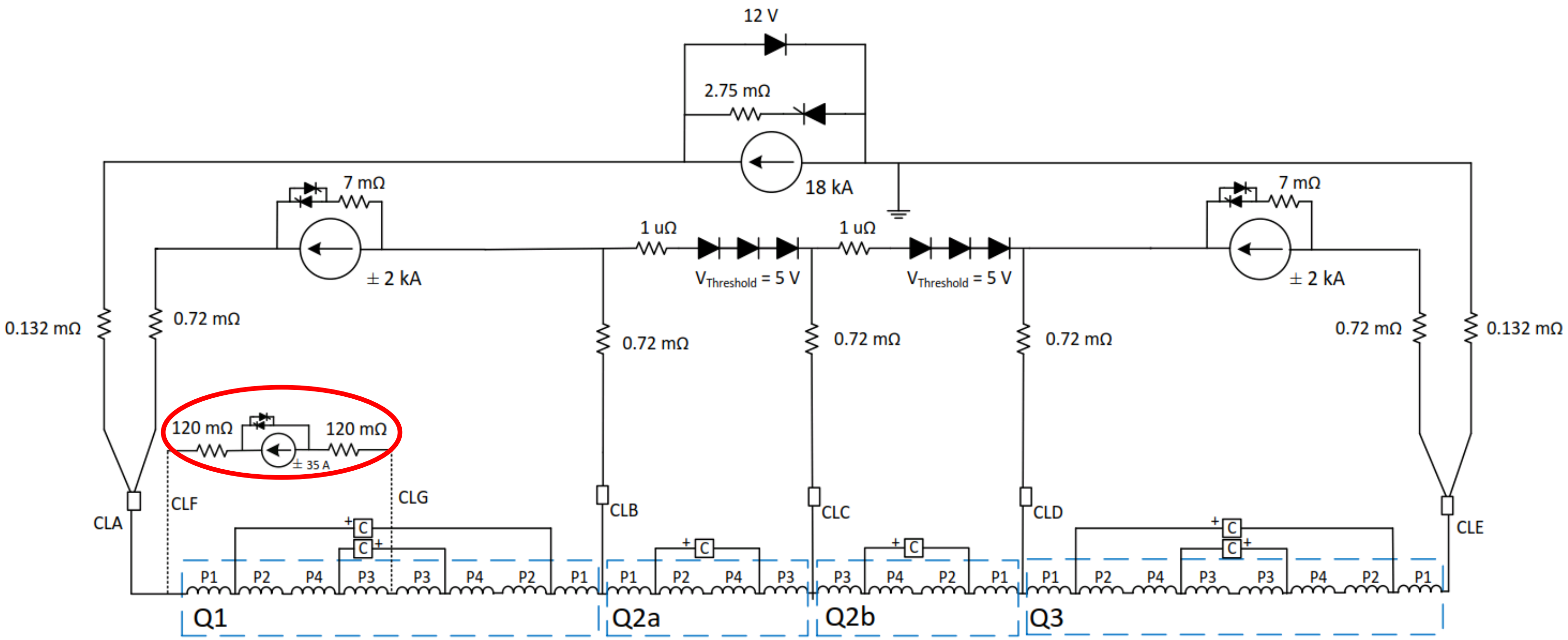
How is the beam affected by QHs and CLIQ? [1] (Courtesy: Valette / Ravaioli / Wollmann)

- Spurious QH firing produces dipole field → Beam kick → Potential for very high losses, after ~35 µs
- Revised heater connections → Beam kick from spurious QH firing reduced
- Spurious CLIQ unit discharge → Beam defocussing, with some dipole components (Q1/Q3), potential for very high losses after 2 ms
- Baseline combined QHs and CLIQ discharge → Potential for damage to the experiments, if the beam is not dumped before the discharge

→ A beam dump has to be triggered before CLIQ units and QHs are discharged

[1] M. Valette – "CLIQ and quench heater firing on the beam", 7th HL-LHC collaboration meeting, 15-11-2017

Revised warm resistance of the 35 A trim circuit



Investigation of 35 A warm resistance implications

- Considerations:
  - Power supply voltage
  - Current looping
  - Peak temperature during a very conservative quench scenario
- Result: Warm resistance should be between 230 and 270 mΩ → 240 mΩ

[2] S. Yammine – "Considerations on the Q1a K-modulation Circuit Powering and Protection", HL-MCF, Oct. 17, 2017

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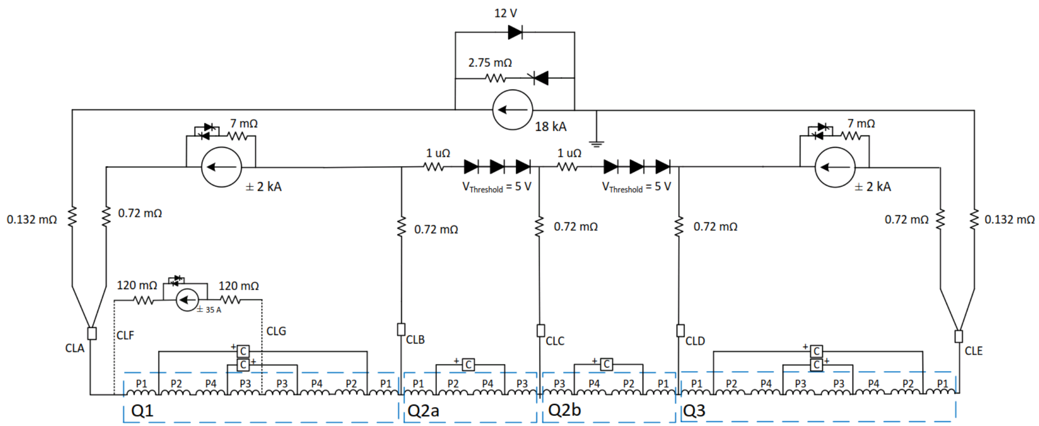
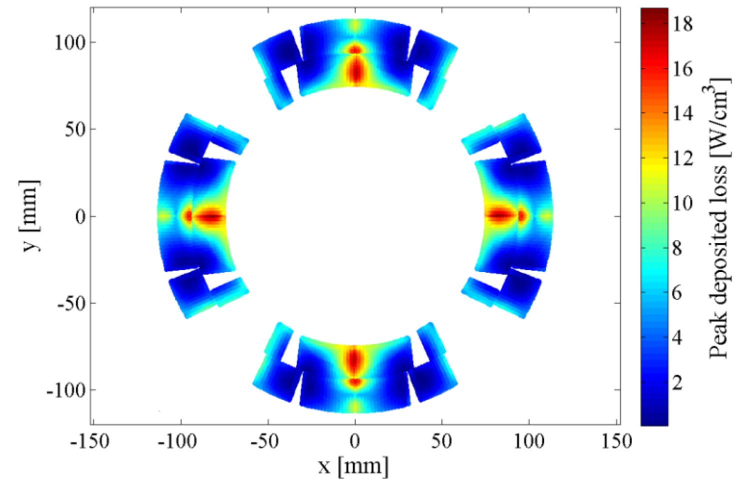
Motivation



HL-LHC inner triplet circuit



Coupling losses in MQXF magnets (LEDET)

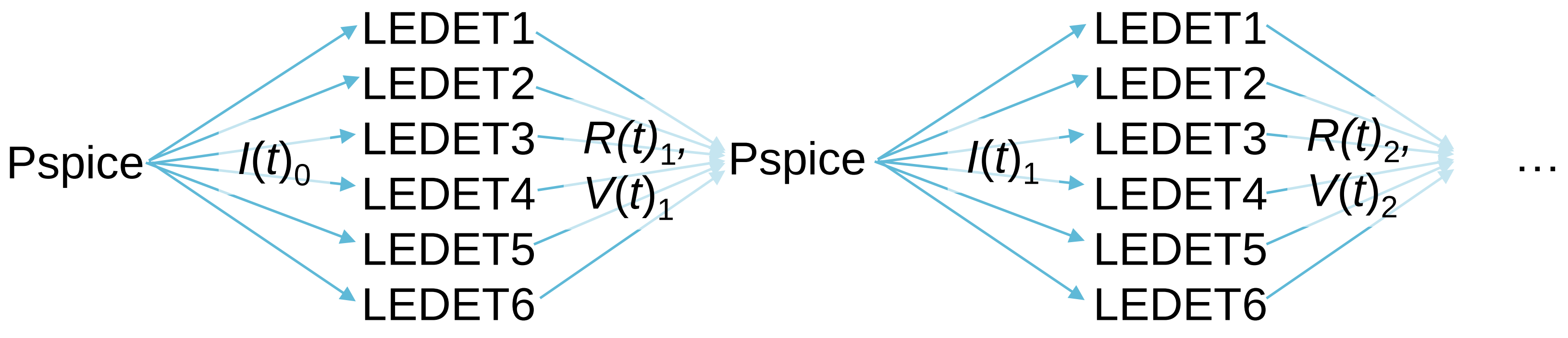
Why co-simulation?

- HL-LHC inner triplet: Complex circuit featuring four nested power supplies and six superconducting magnets
- Quench in one magnet affects all other magnets, as well as the power supplies, crowbars, diodes, etc.

→ Simultaneous transient simulation of quenching magnets, power supplies, switches etc. is needed

STEAM co-simulation: How does it work?

For a given time window $t = t_{start} - t_{end}$:



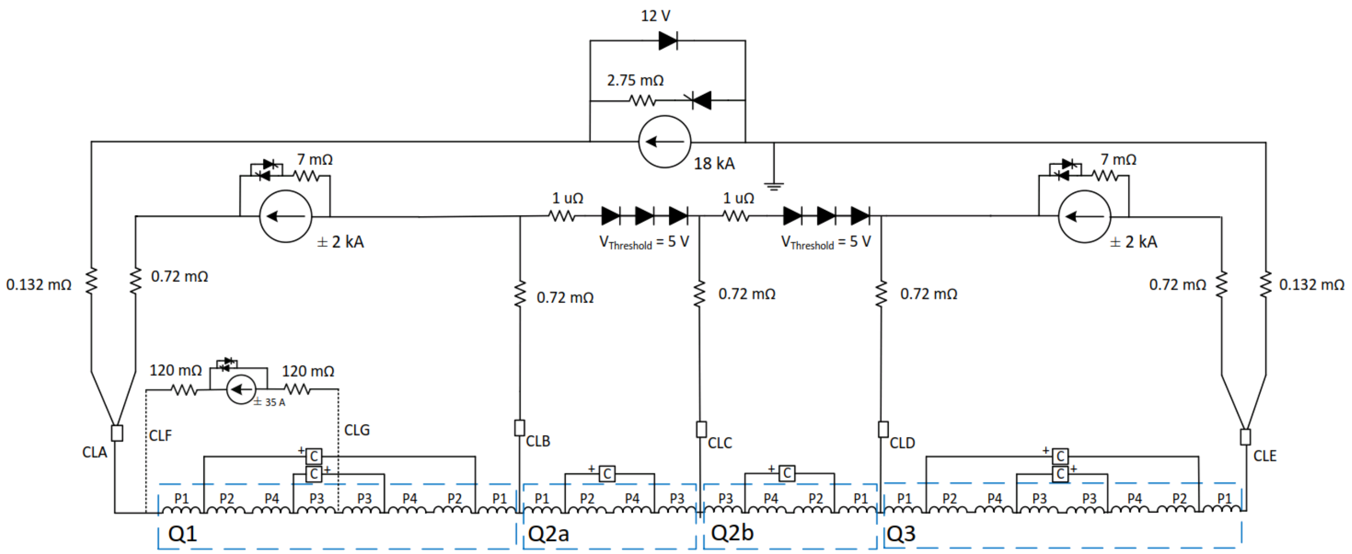
Keep iterating until max($I(t)_{i+1}$-$I(t)_i$) falls below convergence threshold
→ And then move on to next time window

STEAM co-simulation of the HL-LHC triplet circuit

- STEAM Implements wave-form relaxation method: Solution of circuit solver is input for quench models, and vice versa
- Sub-modules: Pspice circuit solver + LEDET quench simulation tool [3]
- Keep iterating until convergence is achieved and then move on to next time window

[3] Ravaioli *et al.* – Cryog. 80, p 346 (2016)

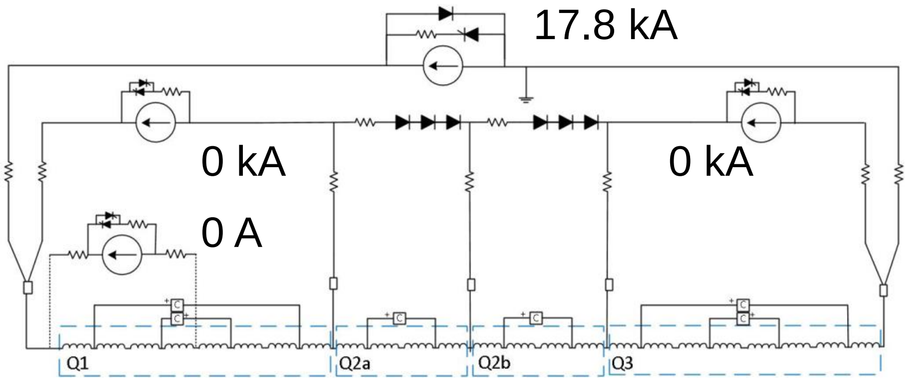
Inner triplet simulation assumptions



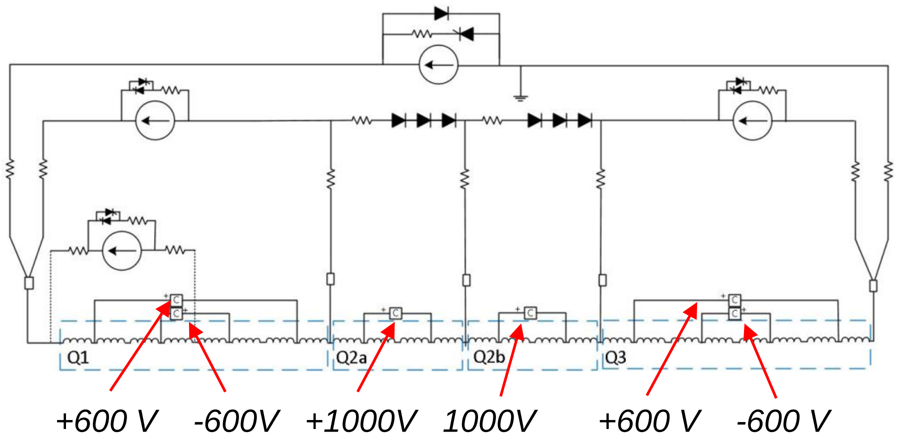
- Quench detected and validated after pre-determined time → Deactivation of power supplies, CLIQ units discharged after 1 ms, QHs discharged after 5 ms
- Whenever voltage over a power supply reaches 10 V → Individual deactivation of power supply
- Whenever voltage over a crow-bar reaches 10 V → Individual closing and latching of crow-bar switch
- Filters parallel to each power supply (not shown here): capacitor (0.48 mF) and capacitor + resistor combination (1.96 mF + 0.1 Ω)

Scenario #1: Localized quench, all magnets operating at 17.8 kA

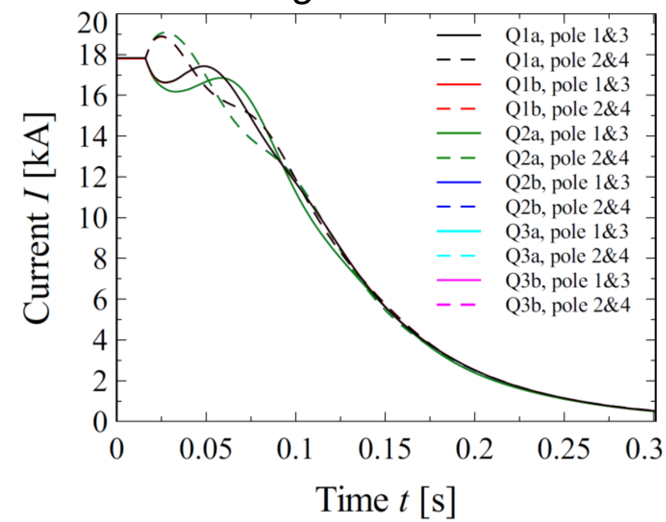
Initial conditions



After quench detection (5 ms) + validation (10 ms):
Capacitive discharge over poles of magnets (CLIQ) + QH firing



Magnet currents



- Starting conditions: 17.8 kA in all magnets
- Nominal conductor parameters
- Quench detected and validated after 15 ms
- Quench protection: CLIQ + quench heaters
- Maximum magnet MIITs: 31.7

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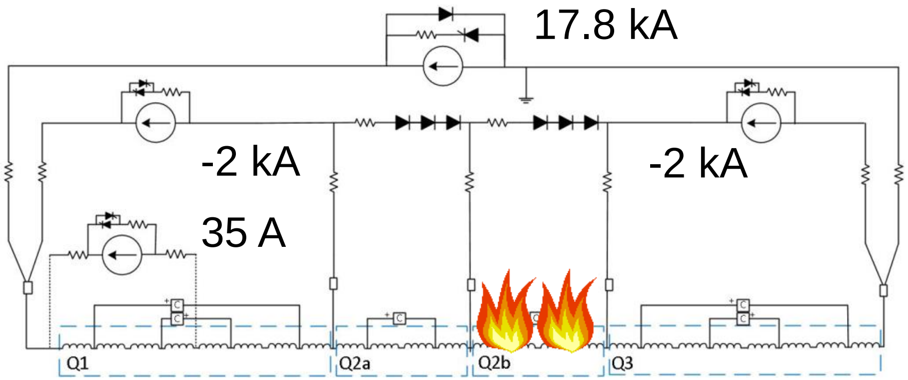
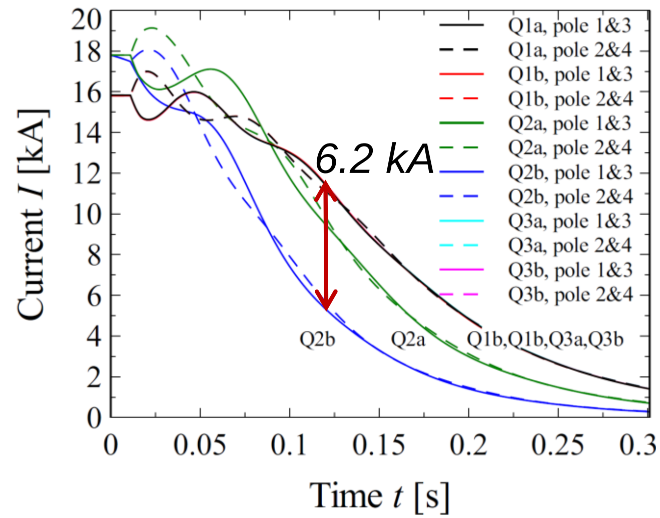
Scenario #2: Instantaneous global quench in Q2b

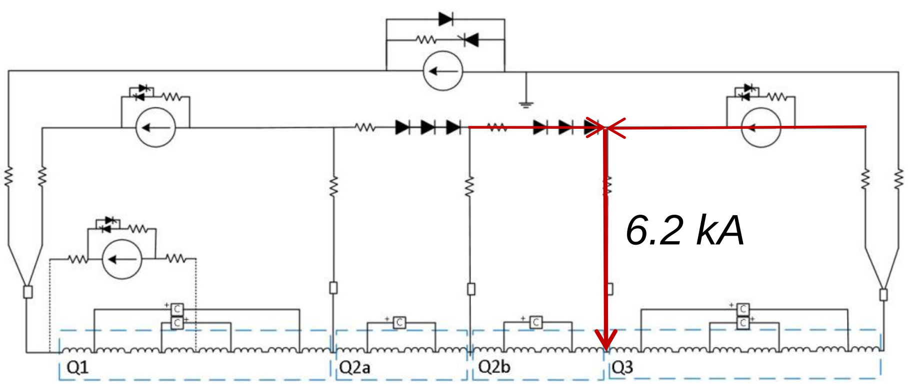
Initial conditions



Magnet currents

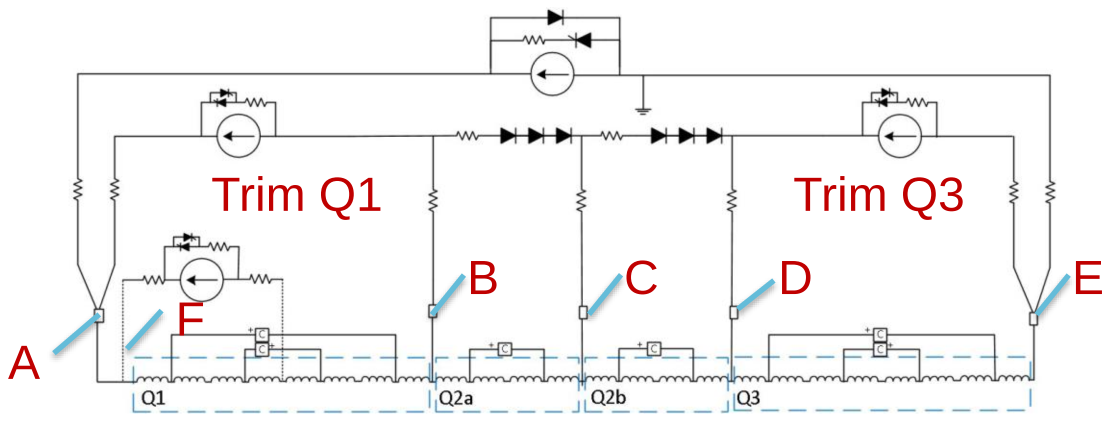


120 ms after quench occurrence



- Initial current Q1/Q2/Q3: 15.8/17.8/15.8 kA
- RRR_{Q2b} = 100, RRR_{Others} = 300, $Cu/nonCu_{Q2b}$ = 1.1, Others: 1.3
- Quench detected and validated after 10 ms
- Difference in currents between magnets is carried by leads (6.2 kA maximum)

What are the maximum values in the leads / trim circuits?



Highest values	SC link A / E	Sc link B / D	Lead C	Lead F	Trim Q1	Trim Q3
Current [kA]	17.8	6.2	4.4	3.5	4.9	4.2
Peak ramp rate kA/s	250	160	100	60	160	160
MIITs	32.6	3.8	2.0	1.1	2.7	1.9

- Maximum current, ramp rate, and MIITS evaluated under different scenarios (Reference cases provided by E. Ravaioli)
- Consistent results with TALES calculations
- Maximum current in the diodes located between SC links B&C, and C&D: 4.4 kA

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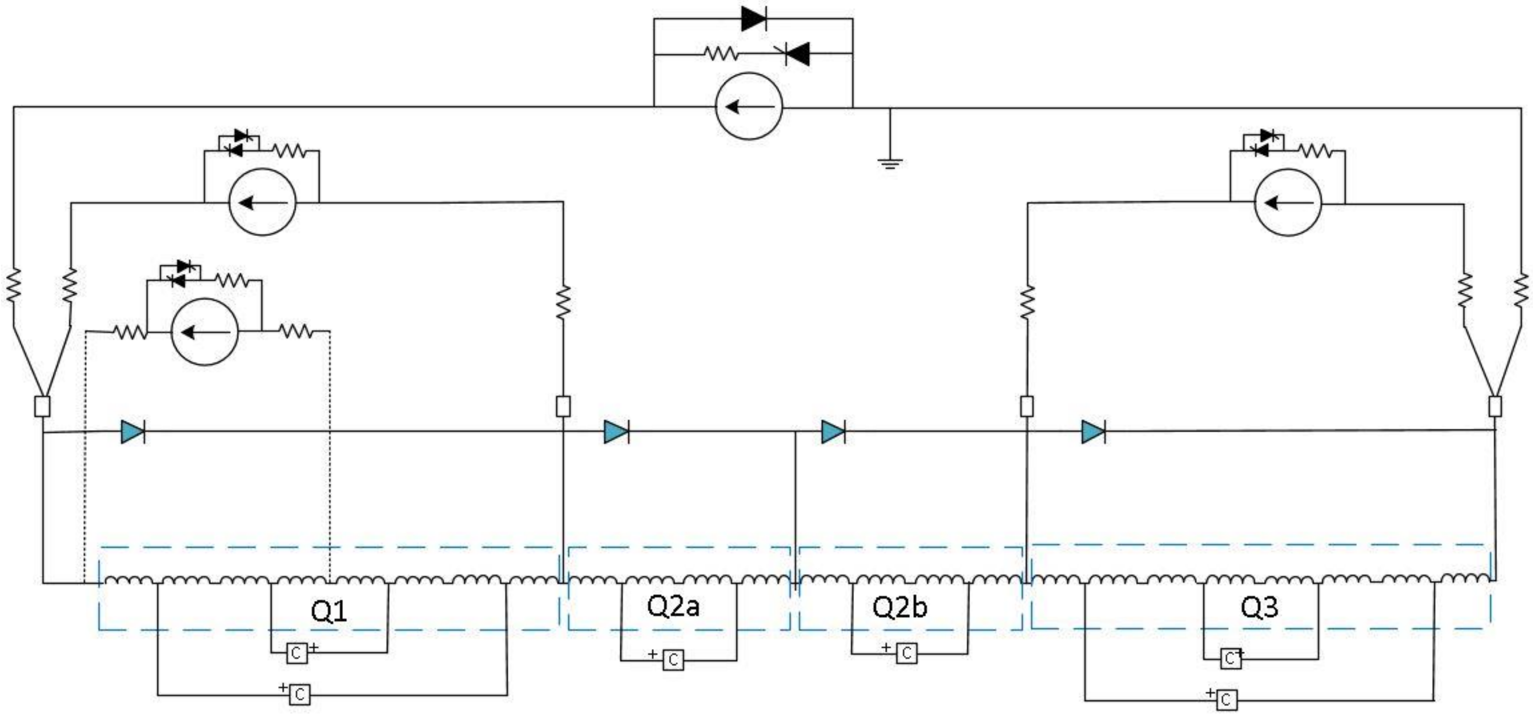
A first look at the inner triplet circuit with cold diodes

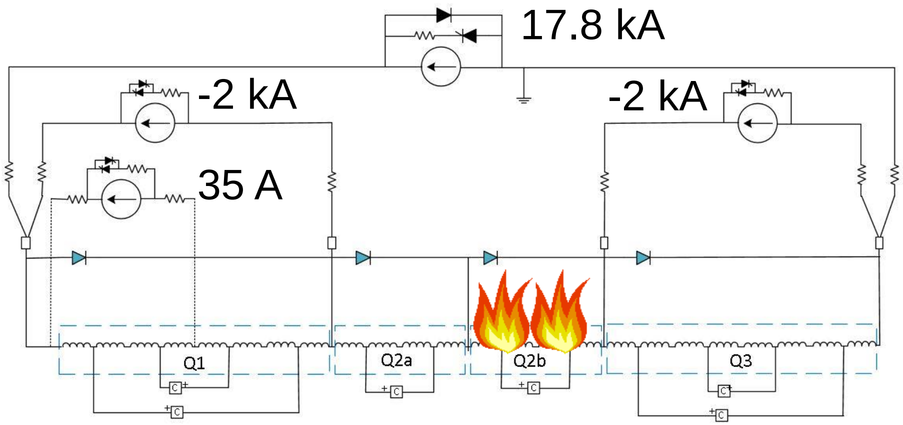


Inner triplet circuit with cold diodes

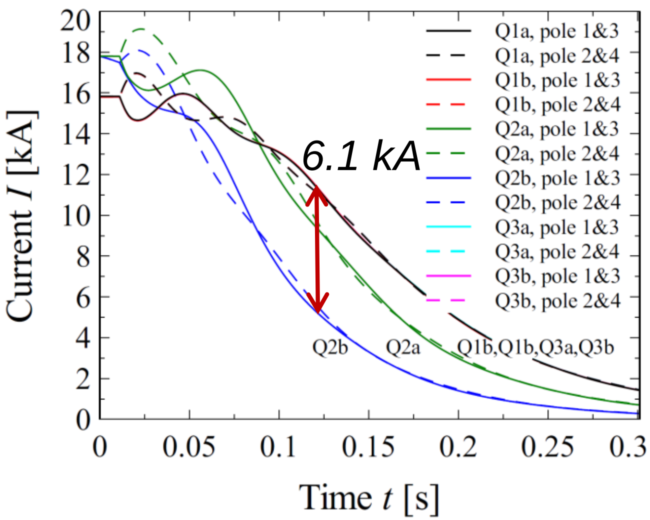
- Parallel cold diodes for Q1, Q2a, Q2b, and Q3
- All CLIQ units and QHs are fired whenever a quench is detected and validated

Scenario #3: Q2b instantaneous global quench, with cold diodes

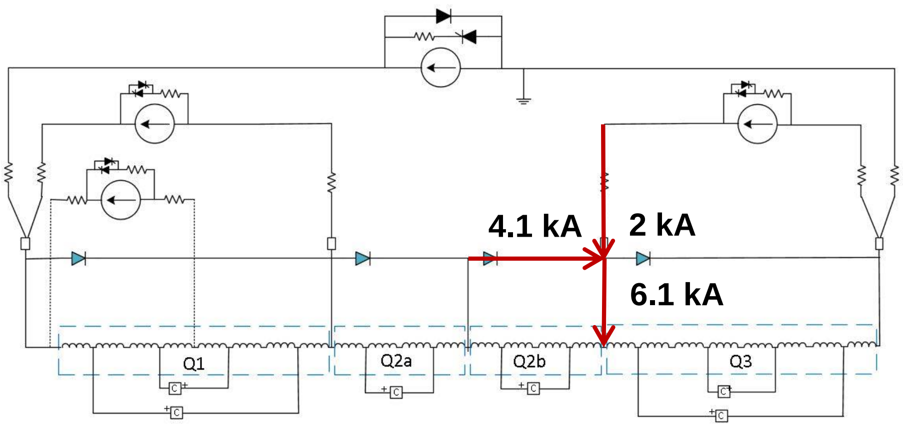
Initial conditions



Magnet currents



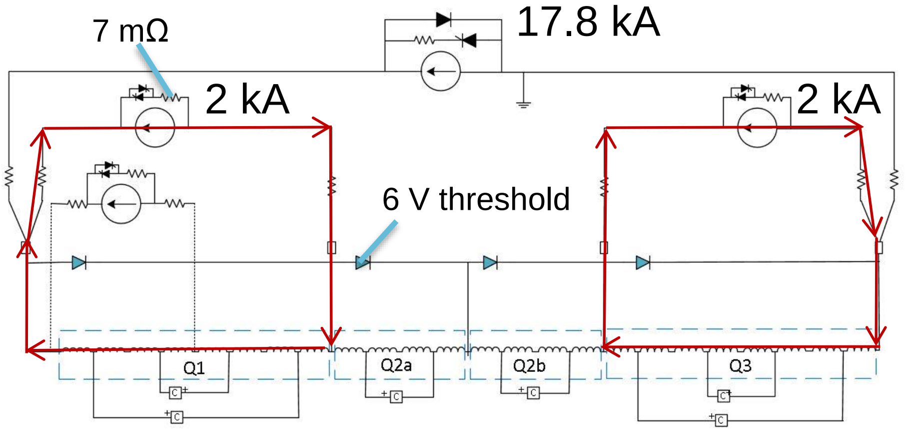
120 ms after quench occurrence



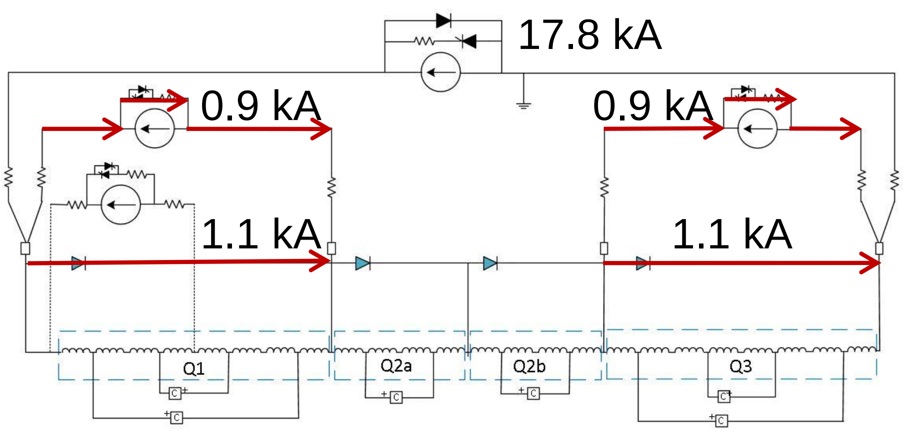
- Same as scenario #2, but with added cold diodes
- Very similar current discharge of magnets
- Peak current in trims and superconducting links B and D reduced to 2 kA
- Promising, but …

Scenario #4: Power failure without quench

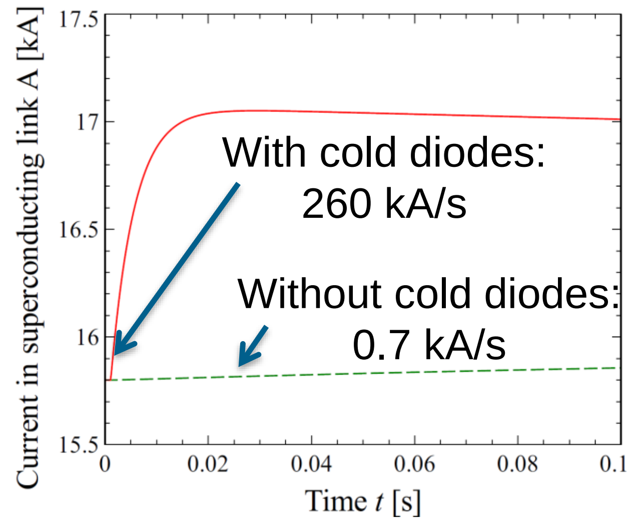
Initial conditions



20 ms after power failure



Resulting current discharge

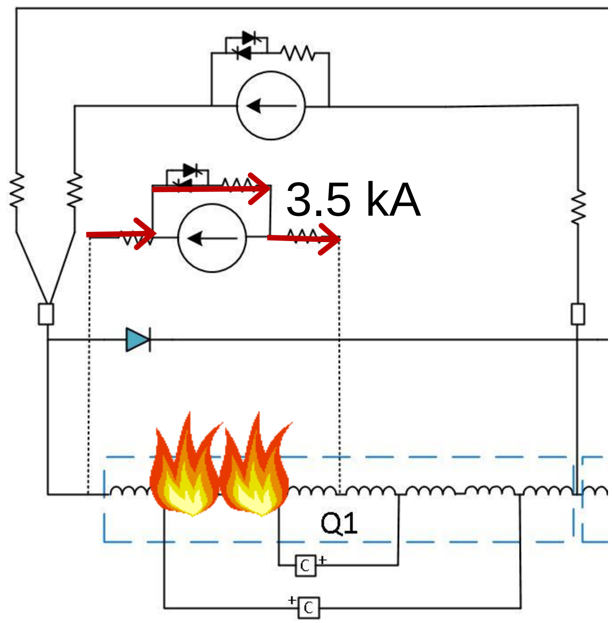


- Same as previous scenario, but without quench
- Power failure → Q1 and Q3 diodes short inductive loads of Q1 and Q3 PCs
- Estimated 40 µH cable inductance

  → **Resulting ramp rate: 260 kA/s**

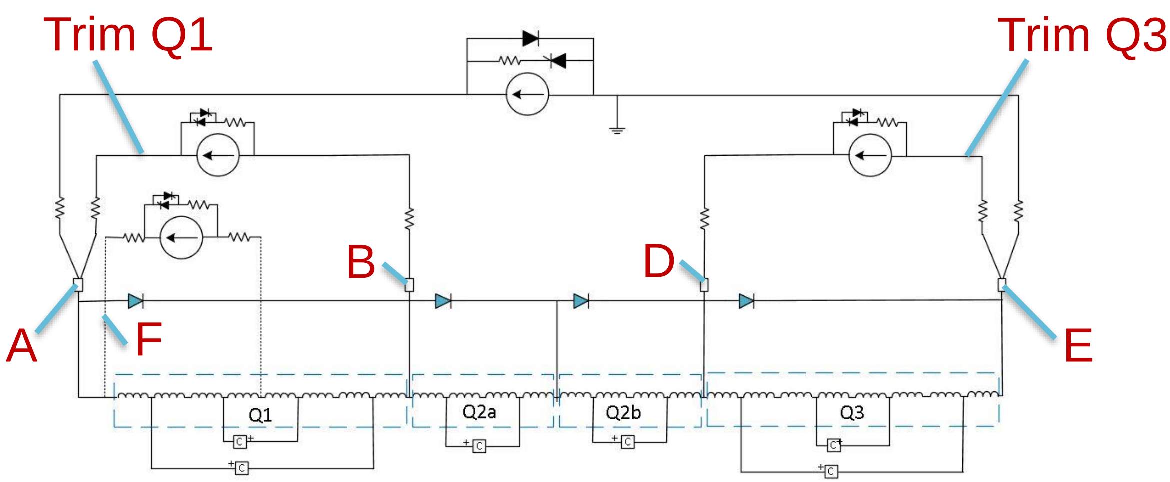
  → **Spurious QPS trigger?**
- Possible solution: Reduce crowbar resistances (Q1/Q3/main) so that at 2000 A the Q1/Q3 resistance voltage is just below diode threshold → No current redistribution for *I* ≤ 2000 A

What about the 35 A trim circuits?



- Instantaneous global quench in Q1a → 3.5 kA peak current in the 35 A trim circuit
- Instantaneous global quench in Q1b → -3.5 kA peak current in the 35 A trim circuit
- To prevent over-current in 35 A trim circuit: Bypass diodes for both Q1a and Q1b are needed

What are the maximum values in the leads / trim circuits?



Highest values	SC Links A / E	SC Links B / D	Lead F	Trim Q1	Trim Q3
Current [kA]	17.8	2.6	3.5	2.6	2.6
Peak ramp rate kA/s	Given by cable inductances and crowbar resistances (to be investigated further)				
MIITs	34.7	0.5	1.1	0.5	0.5

- Maximum current, ramp rate, and MIITS evaluated under different scenarios (Reference cases provided by E. Ravaioli)
- Maximum current in the cold diodes: 4.4 kA

Summary

- Extensive set of STEAM co-simulations performed to study the transient behavior of the inner triplet circuit (Peak currents / ramp rates / MIITs)
- Without cold diodes: Currents as high as 6.2 kA may be expected in the superconducting links B & D after a very conservative quench scenario
- With cold diodes and global QPS activation whenever a quench is detected and validated:
  - Peak current in the superconducting LINKs B & D and Q1 and Q3 trim circuits reduced to 2.6 kA
  - A circuit adjustment should be considered, to avoid very high ramp rates over the superconducting links after a power failure
  - Further studies are needed to understand the behavior of the circuit with cold diodes