Quench protection: CLIQ and Quench heaters

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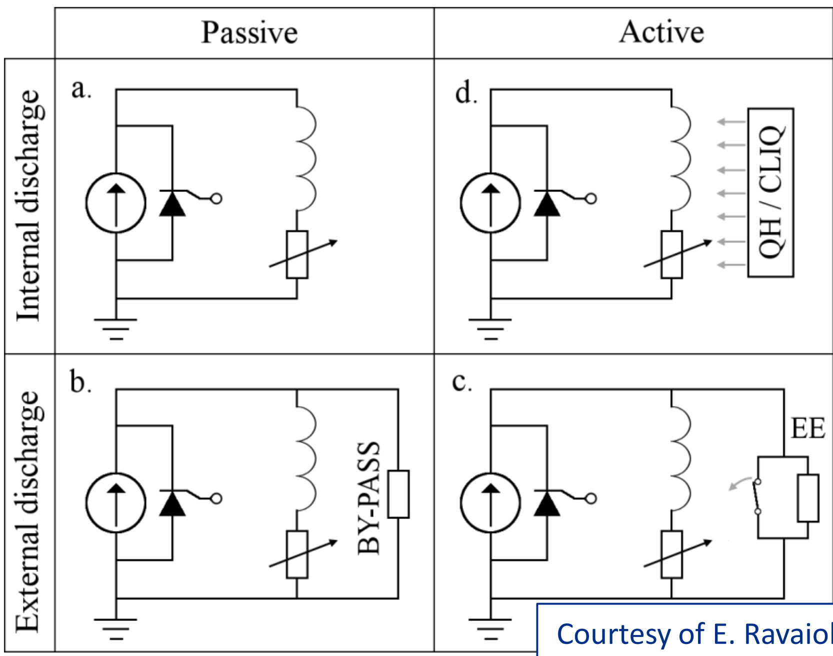
Outline

- Quench protection of high-energy magnets
- Quench heaters: working mechanism
- CLIQ: working mechanism
- Quench heaters vs CLIQ
- Conclusions

Quench protection of high-energy magnets

- During a quench, the electromagnetic energy stored into the magnet is dissipated into the normal zone (usually, small volume)
- First approach: extract the energy



Courtesy of E. Ravaioli

- EE is limited by the voltage (~ 1 kV)
- For high-energy magnets, this method is generally not sufficient to ensure protection
- Need of active methods: CLIQ and quench heaters

Quench protection of high-energy magnets

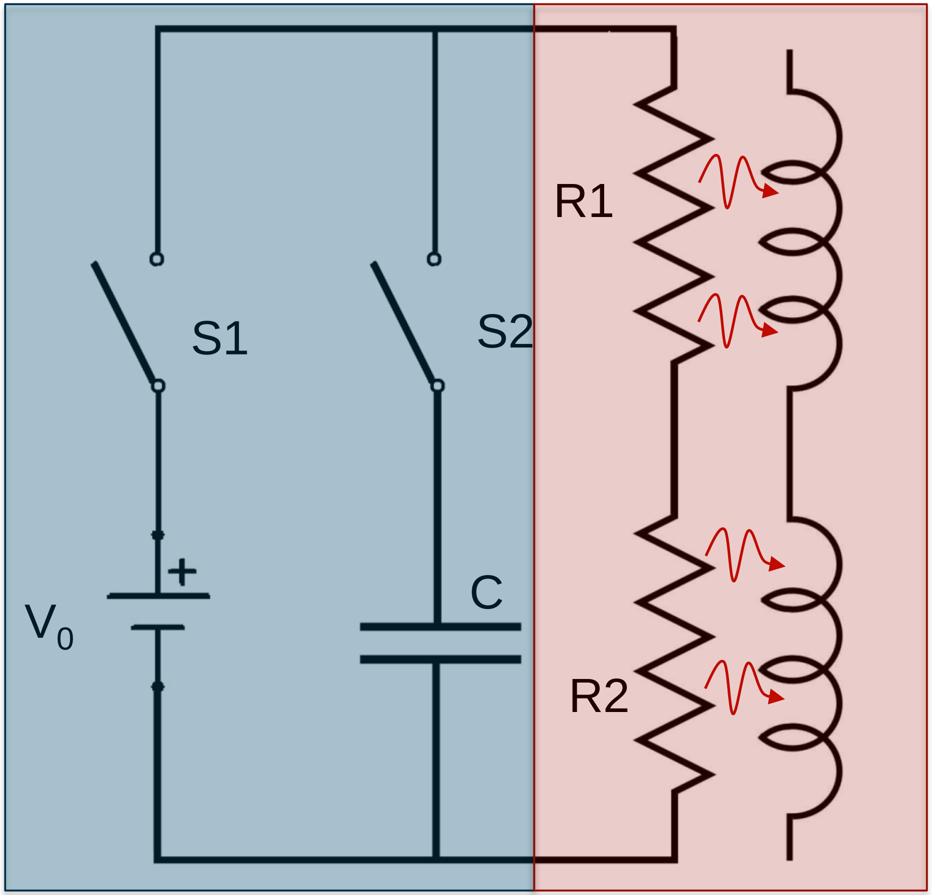
- CLIQ and quench heaters are active methods to protect the magnet
- Main goal: induce a quench in the largest volume as possible
- Energy is not extracted, but it is dissipated inside the magnet
- Average temperature is increased, but hot spot temperature is reduced

Quench Heaters: working mechanism

- Quench heater is basically an RC circuit

Heater Firing Unit (HFU)

Test station



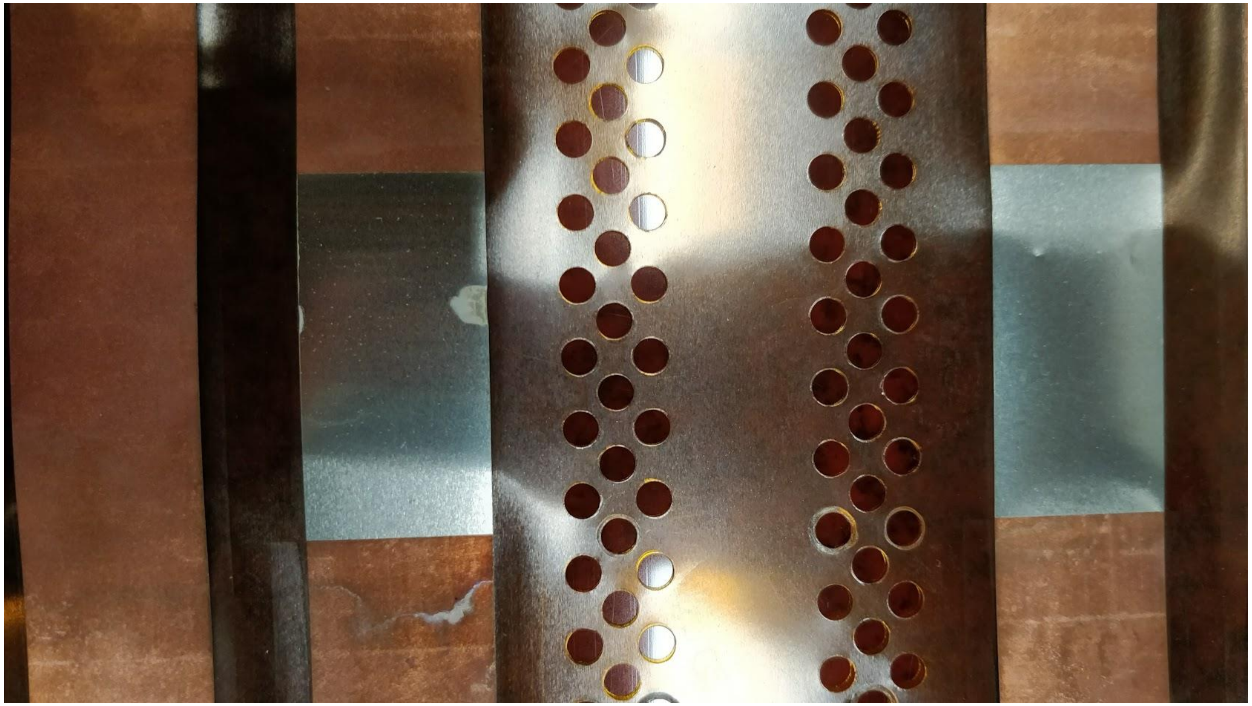
$I \approx$ 100-500 A

$\tau \approx$ 100 ms

Coil

Magnet

Quench Heaters: working mechanism



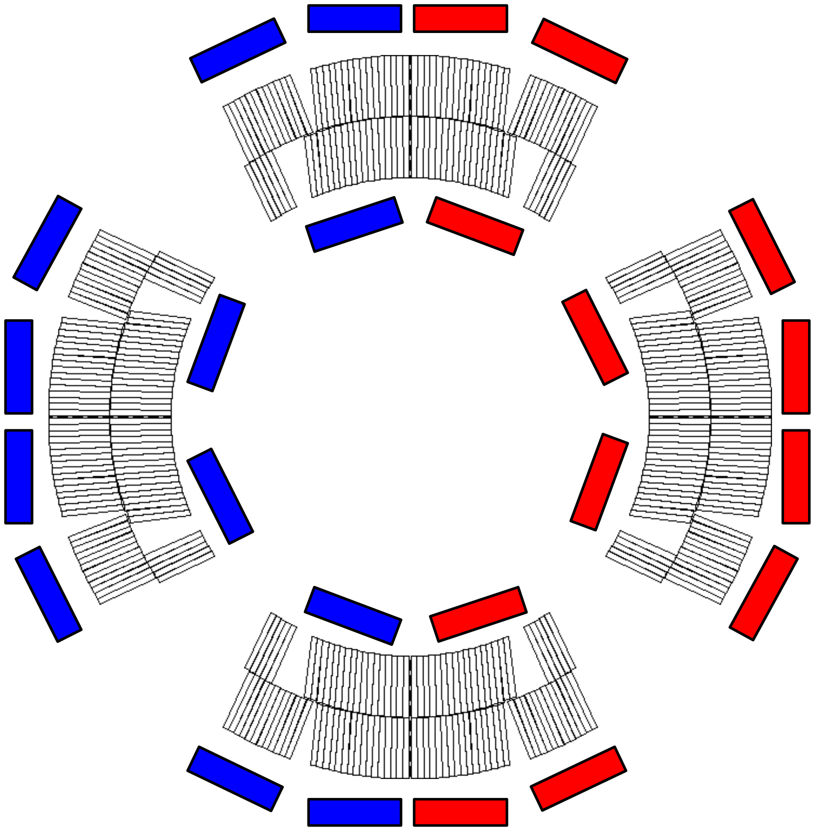
Quench Heaters: working mechanism

- The quench heater efficiency depends on:
  - HFU capacitance
  - Voltage
  - Number of HFUs
  - Heater-coil insulation thickness
  - Heater strips resistance
  - Heater strips design and position
  - Heater strips degradation
  - Conductor properties

- Combination of test stand availabilities and magnet design

Quench Heaters: working mechanism

- Example: MQXFAP1 at BNL



- 24 heater strips
- 12 HFUs
- HFU voltage: 600 V (± 300 V)
- HFU capacitance : 12.4-14 mF
- Heater strip resistance: 1.7-1.1 Ω (10 K)
- Peak power density: 100 - 210 W/cm^2
- Time constant: 50-30 ms
- Insulation thickness: 50 µm
- Quenching time: 7 - 30 ms

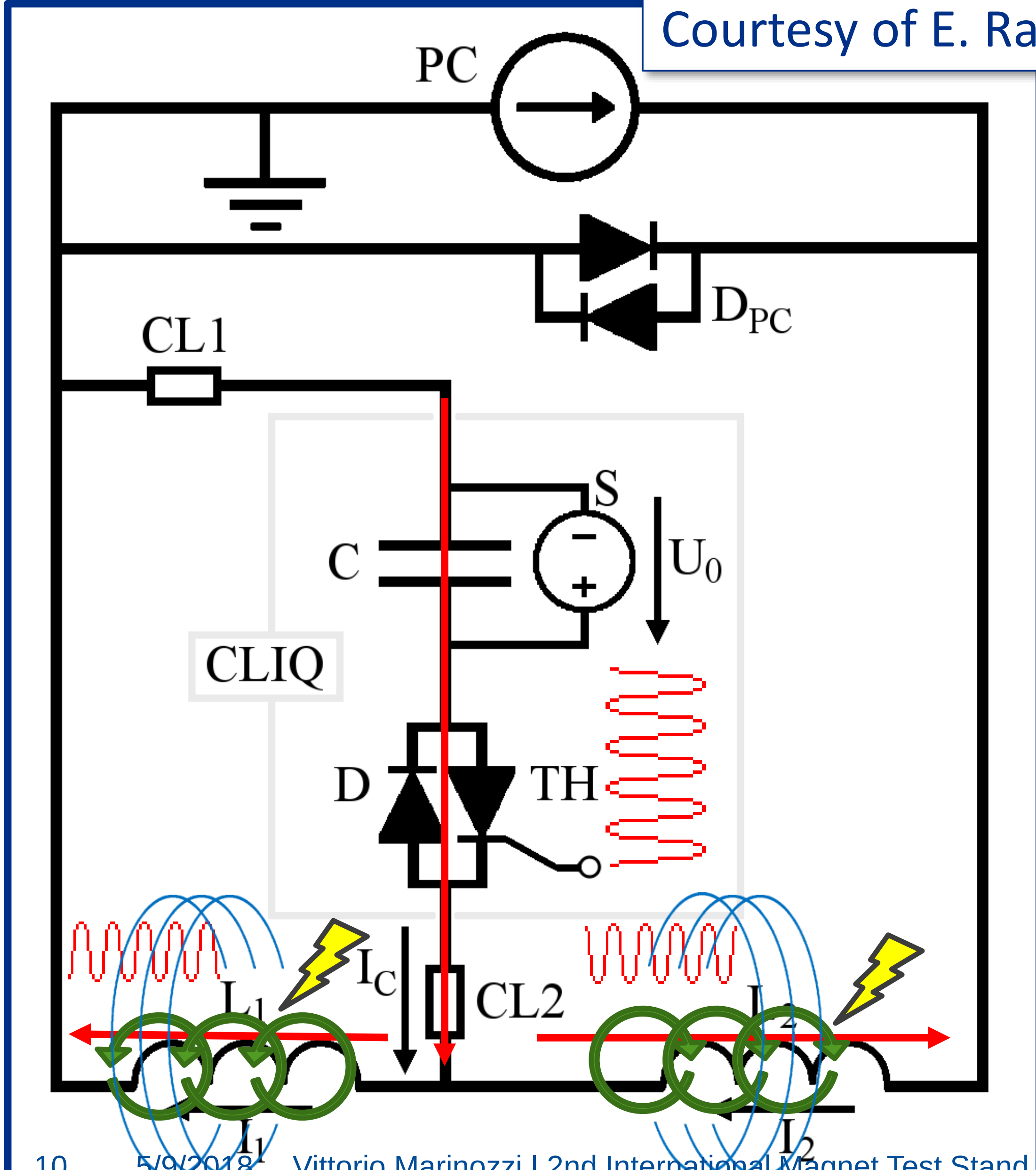
CLIQ: working mechanism

- CLIQ: Coupling Loss Induced Quench
- CLIQ exploits the coupling currents between filaments and strands, in order to induce a spread quench in the whole magnet
- Main advantage: more effective heat deposition with more robust electrical circuit

CLIQ – Coupling-Loss Induced Quench system

Patent EP13174323.9

Courtesy of E. Ravaioli



Current change

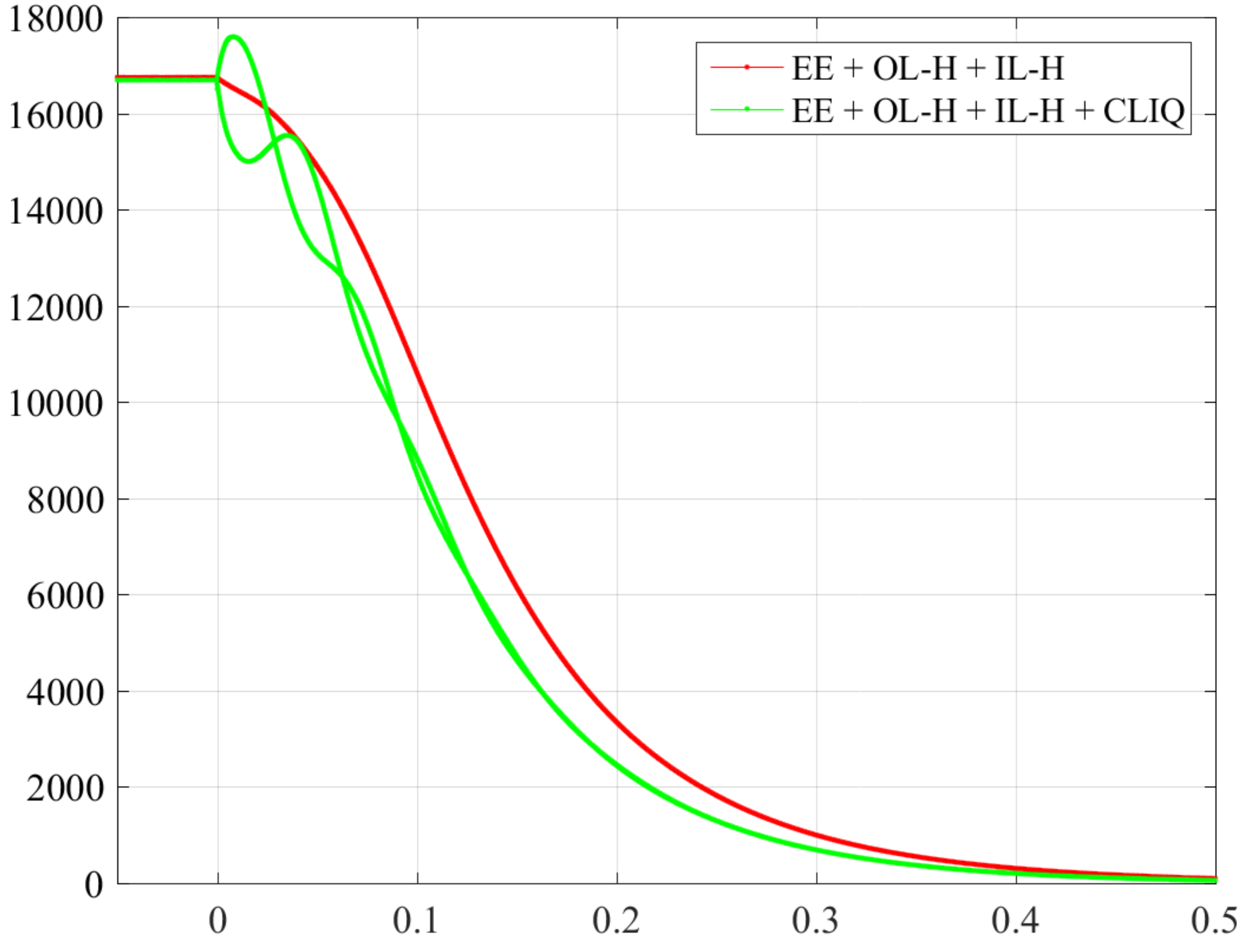
Magnetic field change

Transitory losses (Heat)

Temperature rise

QUENCH

CLIQ: working mechanism



I ≈ 1-2 kA

τ ≈ 100 ms

CLIQ: working mechanism

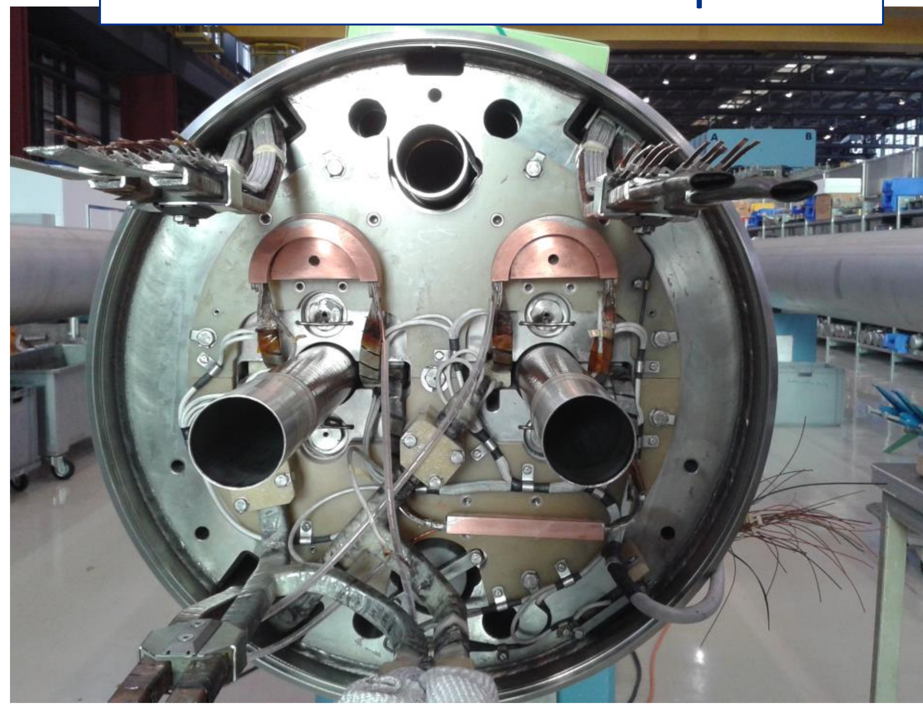
- The CLIQ efficiency depends on:
  - CLIQ capacitance
  - CLIQ charging voltage
  - Number of CLIQ units
  - Number and position of the CLIQ connections on the magnet
  - Magnet size
  - Magnet geometry

- Combination of test stand availabilities and magnet design

CLIQ: working mechanism

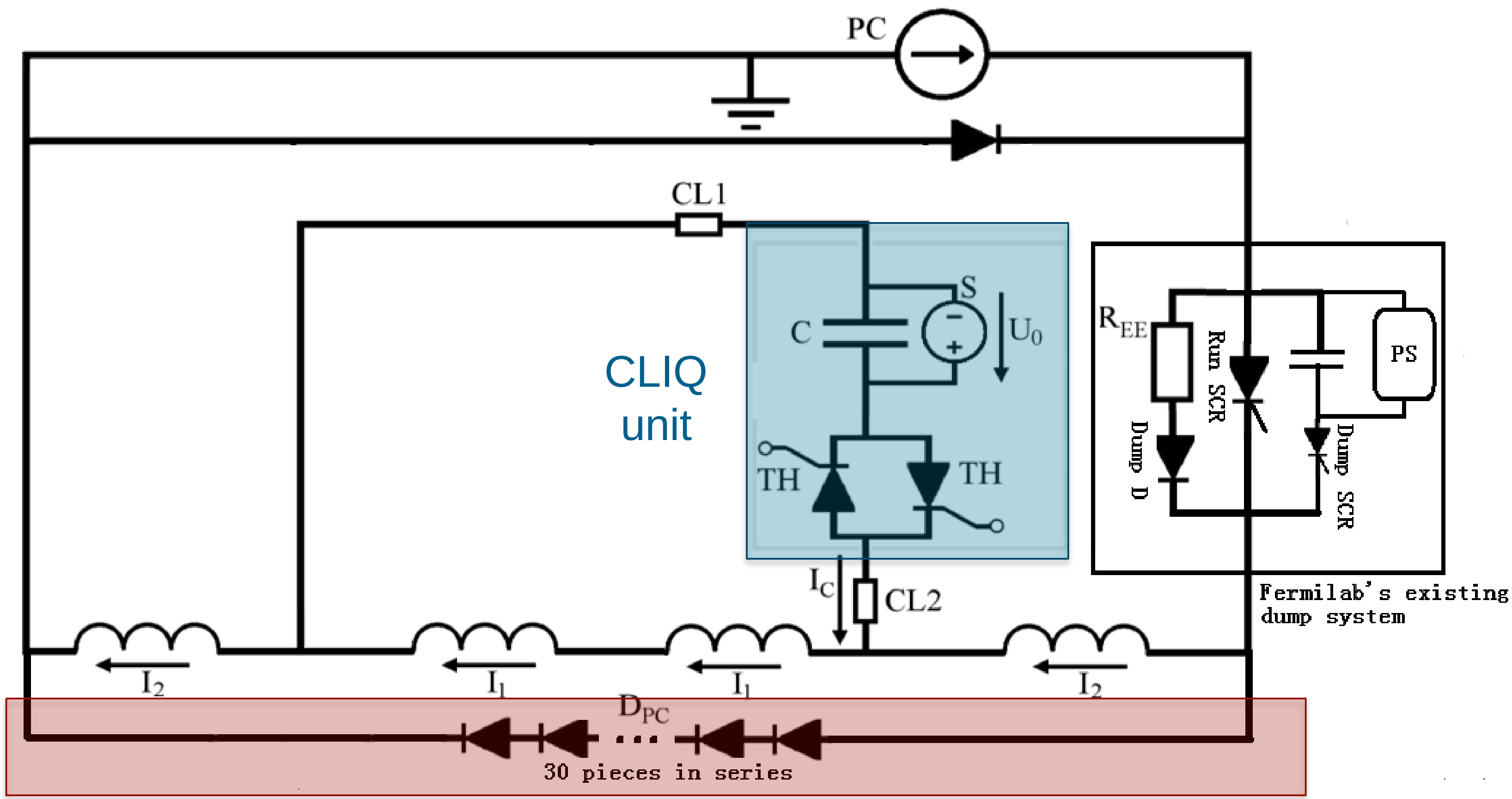
CLIQ UNIT

LHC full size main dipole



CLIQ: working mechanism

- Example: commissioning at FNAL for MQXFS



Diodes to avoid reverse current in PS during CLIQ test

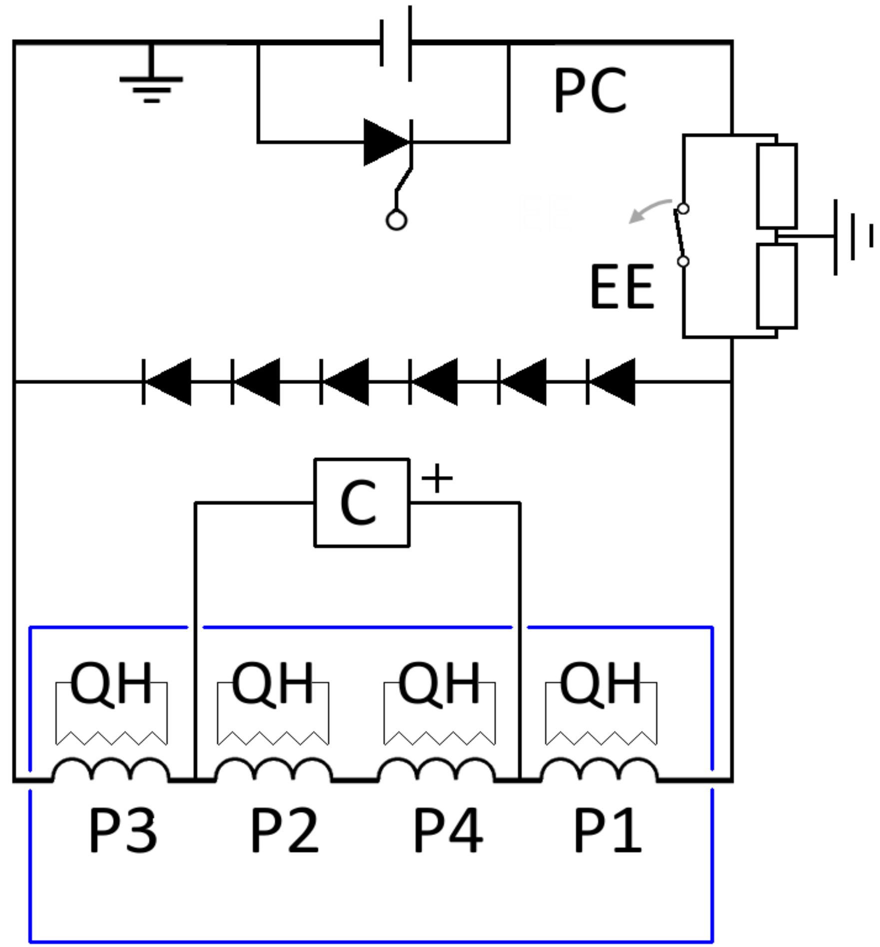
CLIQ: working mechanism

Cliq has been successfully tested on several magnets:

- MB (spare LHC main dipole)
- MQY (spare LHC individually powered quadrupole)
- MQXC
- HQ02
- MQXFS1, MQXFS3, MQXFS5
- MQXFAP1
- 11 T dipole
- Small-scale solenoid
- Small-scale HTS coil

CLIQ: working mechanism

- Example: MQXFAP1 at BNL
  - 1 CLIQ unit
  - CLIQ capacitance: 40 mF
  - CLIQ charging voltage: 500 V
  - MIITs reduction respect to QH: ~15 %



Quench Heaters vs CLIQ

	Pros	Cons
QUENCH HEATERS	▪ Simple implementation in the test station ▪ Quench heater circuit independent on the magnet circuit ▪ Redundant ▪ Independent on length	▪ Damaged strips cannot be repaired ▪ High voltage components very close to coils ▪ Risk of shorts with coils ▪ Bubbles when in contact with helium
CLIQ	▪ More efficient to induce quench ▪ Electrically robust ▪ External to the magnet ▪ Easy to repair ▪ Slightly dependent on conductor properties	▪ Need to implement parallel components in the test station ▪ Implementation in the circuit not trivial (especially with EE) ▪ 1 unit is fully not redundant ▪ Effectiveness reduced with magnet length (short models do not fully demonstrate protection)

Conclusions

- CLIQ and Quench Heaters are active protection systems, needed to protect high energy magnets
- Quench Heaters implementation in a test station is relatively simple, but probability of electrical issues is larger
- CLIQ is more robust and efficient, but the implementation in the test station circuit is not trivial
- Just one CLIQ is not completely redundant, so it should be implemented together with a quench heaters system, or with other CLIQ units (complexity of circuit/connections)
  - "Third generation" CLIQ units will ensure redundancy of all internal components
- Presence of HFUs in a test station today is mandatory to test large magnets. Adding a CLIQ unit ensures more efficiency and redundancy, and possibility to test more performing magnets in the future.