Triplet circuit protection with heaters and CLIQ

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on behalf of WP7, WP3 and CERN-TE-MPE-PE

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with inputs from

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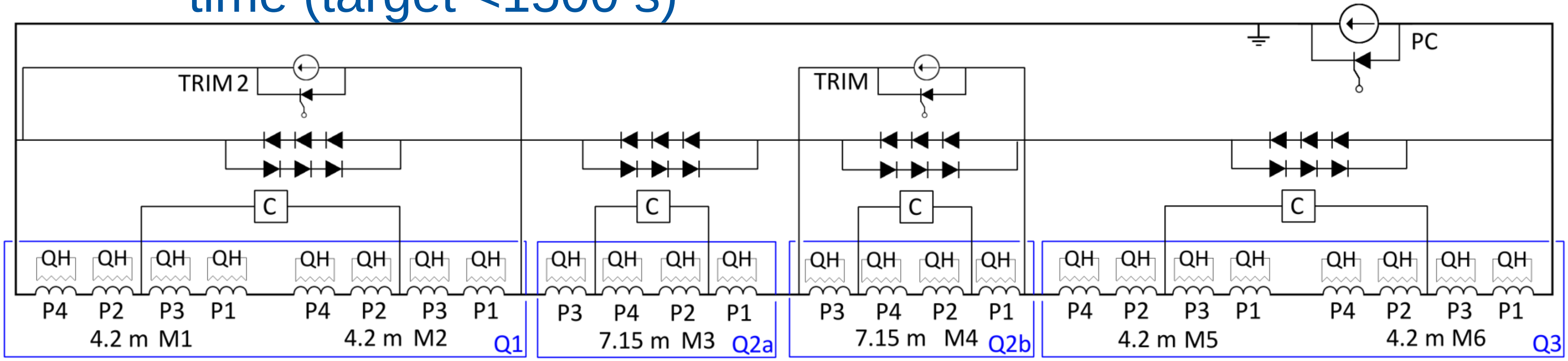
Outline

- Powering options
- Quench protection options
    - (What is CLIQ)
- Simulations
- Failure cases
- Conclusions and ongoing studies

Powering options

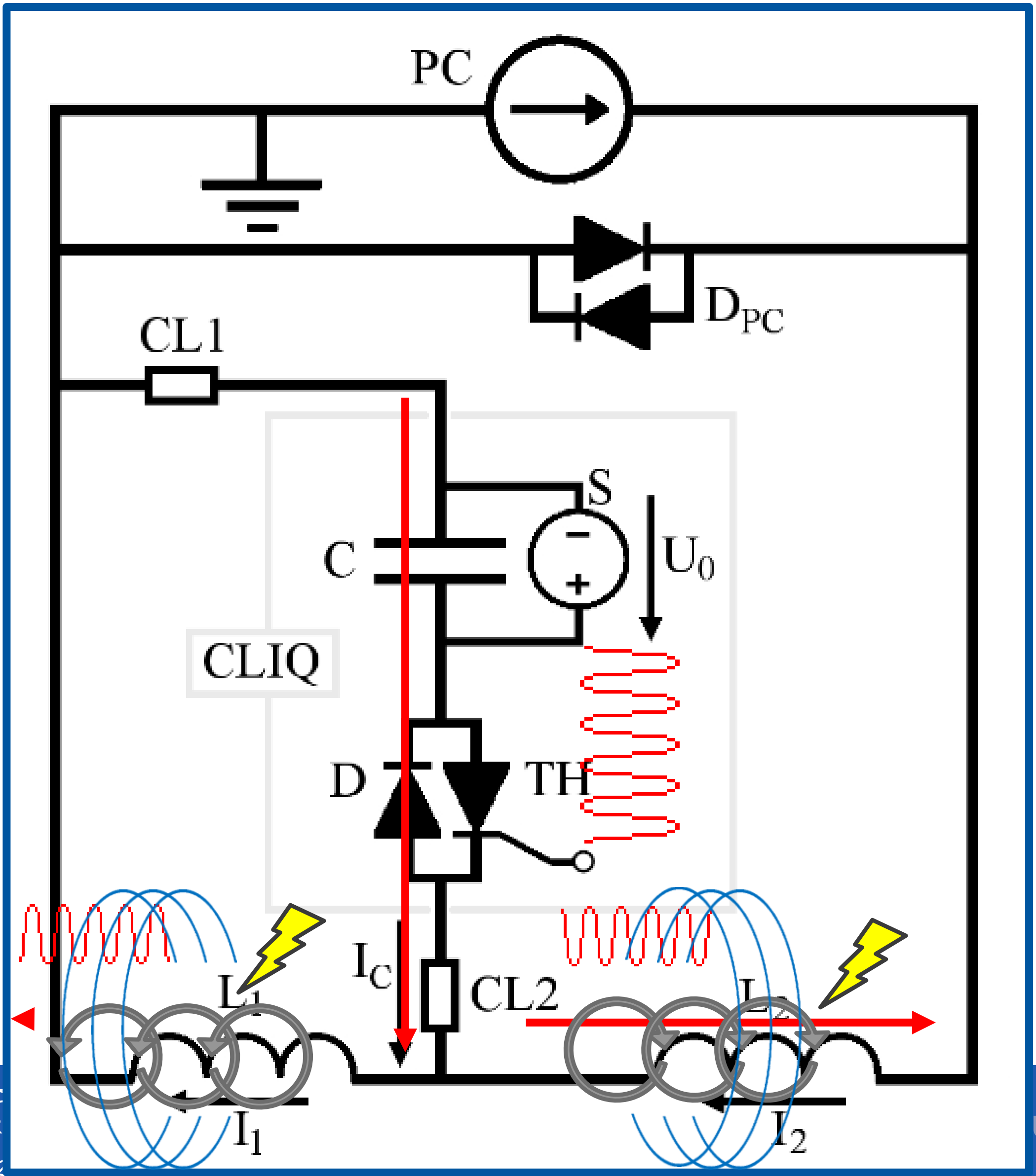
- Two power supplies feeding the Q1-Q3 and Q2a-Q2b magnets, respectively
- One power supply feeding all magnets; 2-quadrant supply preferable; 1 or 2 trim power supplies can be added
  - Pros: less expensive, fewer high-current leads, smaller differences in the magnet currents
  - Cons: voltage-to-ground distribution, longer ramp-down time (target <1500 s)



Quench protection options

- Energy-extraction
- Quench Heaters attached to the outer layers
- Quench Heaters attached to the inner layers
- CLIQ (Coupling-Loss Induced Quench system)
- …and combination of these

CLIQ (Coupling-Loss Induced Quench)



Current change

Magnetic field change

Coupling losses (Heat)

Temperature rise

QUENCH

The ideal protection system…

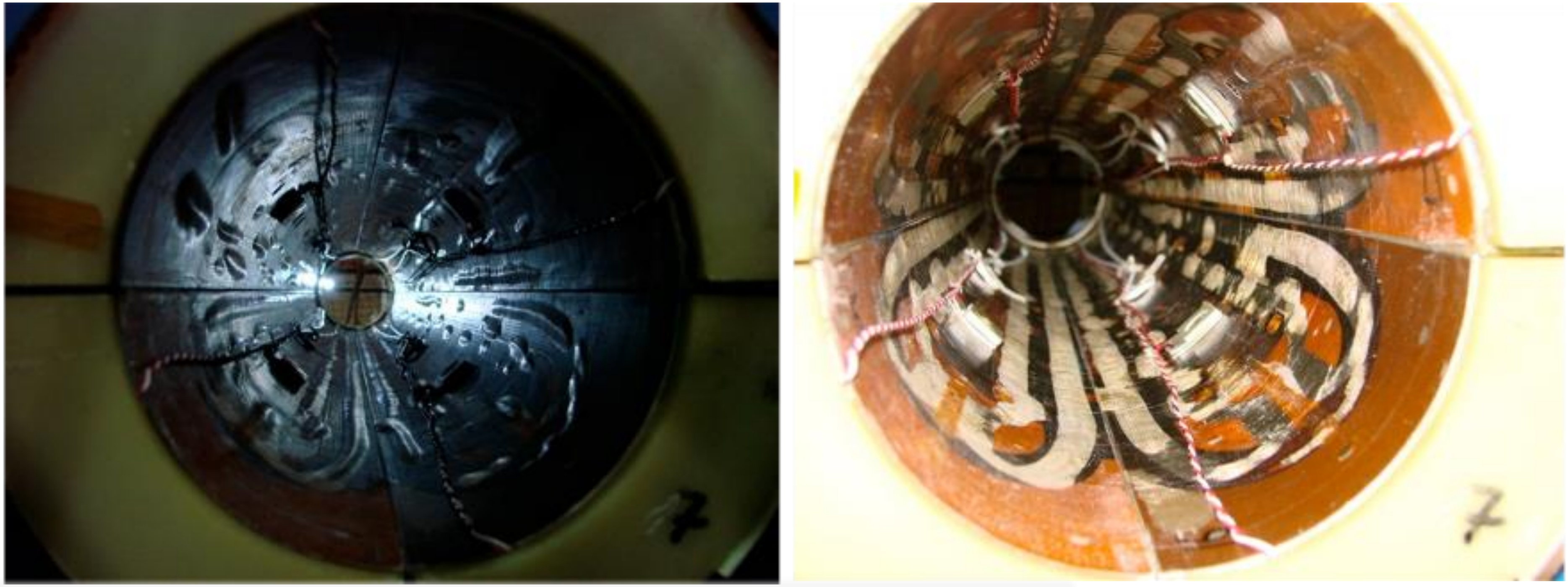
- Minimizes the hot-spot temperature in the coil
- Minimizes the temperature gradients in the coil
- Minimizes the voltages to ground
- Minimizes the voltages between system elements
- Maximizes reliability and redundancy
- Minimizes complexity
- Minimizes sensitivity to magnet/cable/strand parameters
- Maximizes the margins for operation (e.g., allows for threshold increase in case of EM perturbations)

Choice of quench protection -1

- ~~Energy extraction~~: hardly effective without increasing the voltage to ground >1 kV (e.g. V. Marinozzi); poor efficiency for money; developing 20 kA circuit breakers needs high investment; very expensive; voluminous; expensive maintenance (hardware and knowledge)
- ~~Outer QH only~~: well-known technology; hot-spot temperature very close to unsafe levels (360 K without quench-back, 300 K with quench-back); no margin; failure cases are critical

Choice of quench protection -2

- Outer and Inner QH: hot-spot temperature ok; well-known technology; reliability is still an issue (bubbles, detachment)



From G. Ambrosio, 2015 LARP collaboration meeting

Choice of quench protection -3

- CLIQ only: hot-spot temperature ok; very robust system; insensitive to magnet/cable/strand parameters; first-of-a-kind system; voltages to ground to study more carefully
- CLIQ and outer QH: hot-spot temperature ok; very robust system; insensitive to magnet/cable/strand parameters; high level of redundancy; smaller temperature gradients; voltages to ground to study more carefully; high coil-to-QH voltages

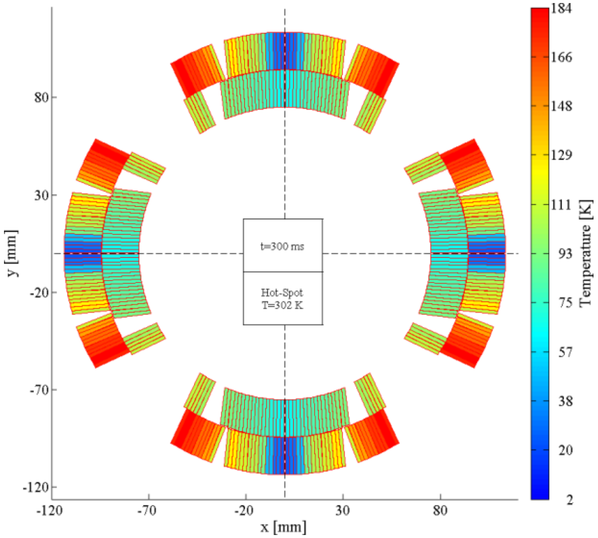
MQXF quench protection studies

- QH simulations performed with four different codes by S. Izquierdo Bermudez, T.Salmi, V.Marinozzi, and E.Ravaioli
- Good agreement between four simulations
- To be validated with measurements on the first MQXF model magnet (especially at low current)
- From quench propagation simulations, ~5 ms to detect a quench at nominal current (S. Izquierdo Bermudez)
- Simulated QH delays benchmarked against more accurate QH model (T. Salmi)
- Study of QH failure cases (V. Marinozzi, E. Ravaioli)
- Circuit-level simulations performed with the software TALES developed in the MPE-PE section (E. Ravaioli)

Simulated temperature distribution

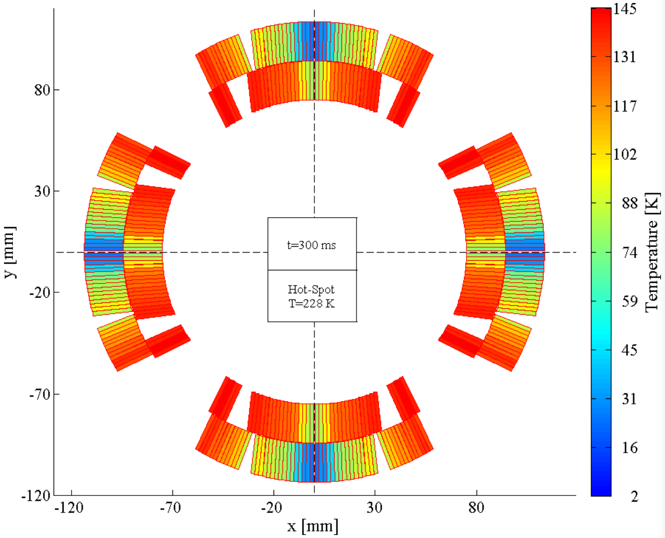
- CLIQ + Quench Heaters assure the most homogeneous temperature distribution in the coil windings at the end of a discharge
- Reducing the thermal gradients reduces the thermal stress

Outer QH



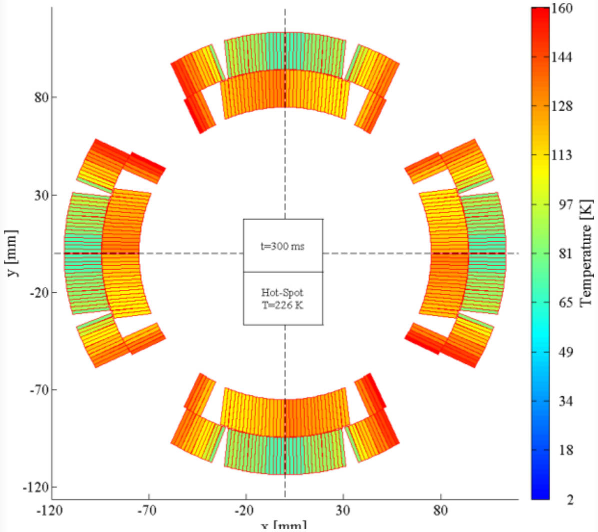
ΔT=140 K

Outer+Inner QH



ΔT=100 K

CLIQ + Outer QH

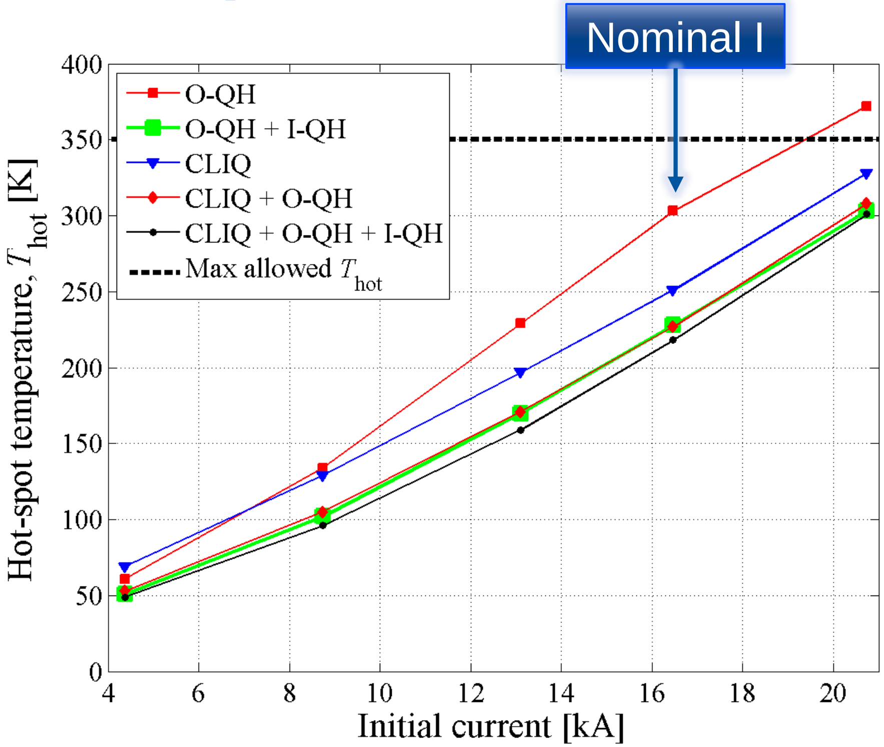


ΔT=85 K

Simulated hot-spot temperature

Protection system	Hot-spot T
CLIQ	250 K
CLIQ+8 outer QH's	230 K
CLIQ+8 outer QH's+4 inner QH's	220 K
CLIQ+4 outer QH in HF region	240 K

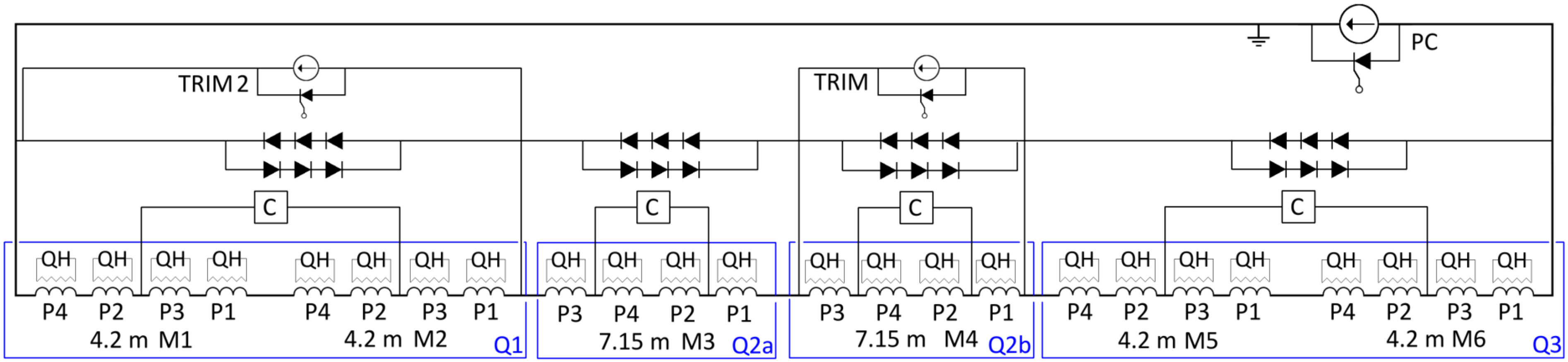
The more QH units are triggered, the higher the probability of degrading the electrical insulation



CLIQ+4 HF outer QH's seems the best compromise for reducing hot-spot temperature and thermal stress, and increasing redundancy and robustness.

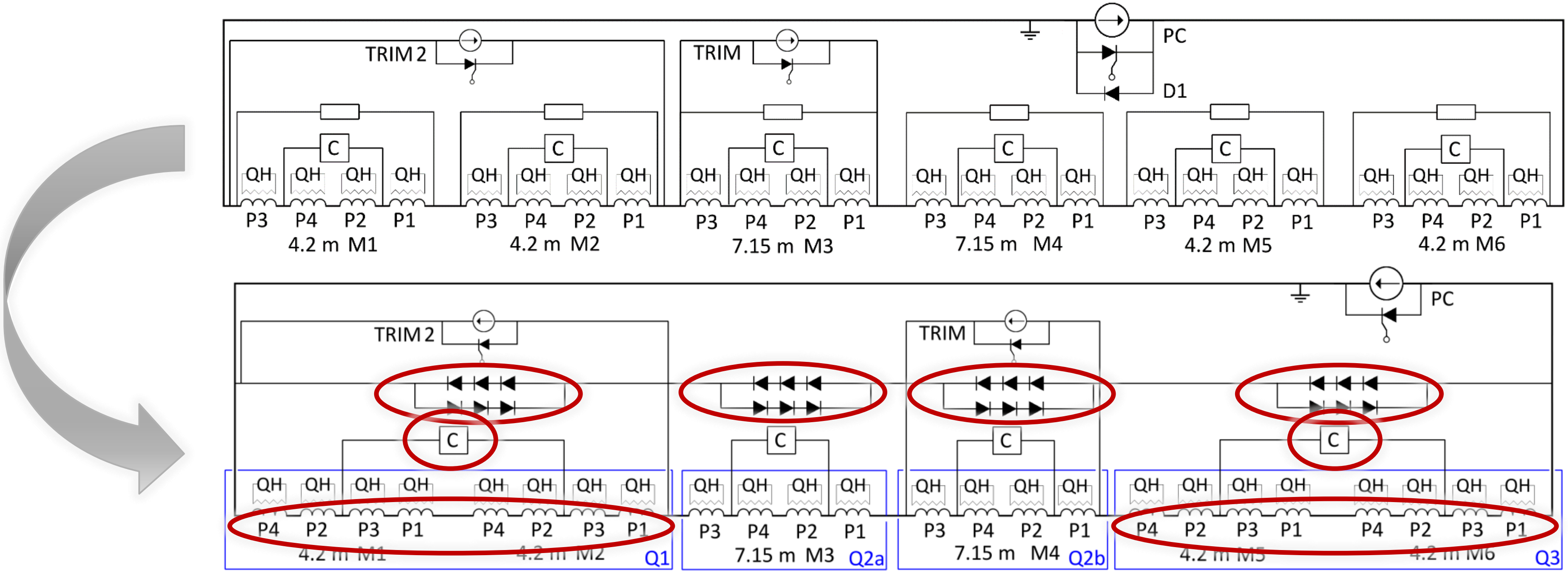
Proposed quench protection

- Hybrid system: CLIQ + Quench Heaters
- One CLIQ unit per cryostat
- Four QH circuits per magnet (4 HF outer)
- Eight QH circuits per magnet (4 LF outer + 4 inner), not triggered, kept as spares
- Warm diodes across Q1, Q2a, Q2b, Q3 (final design of the diodes not yet finalized!)

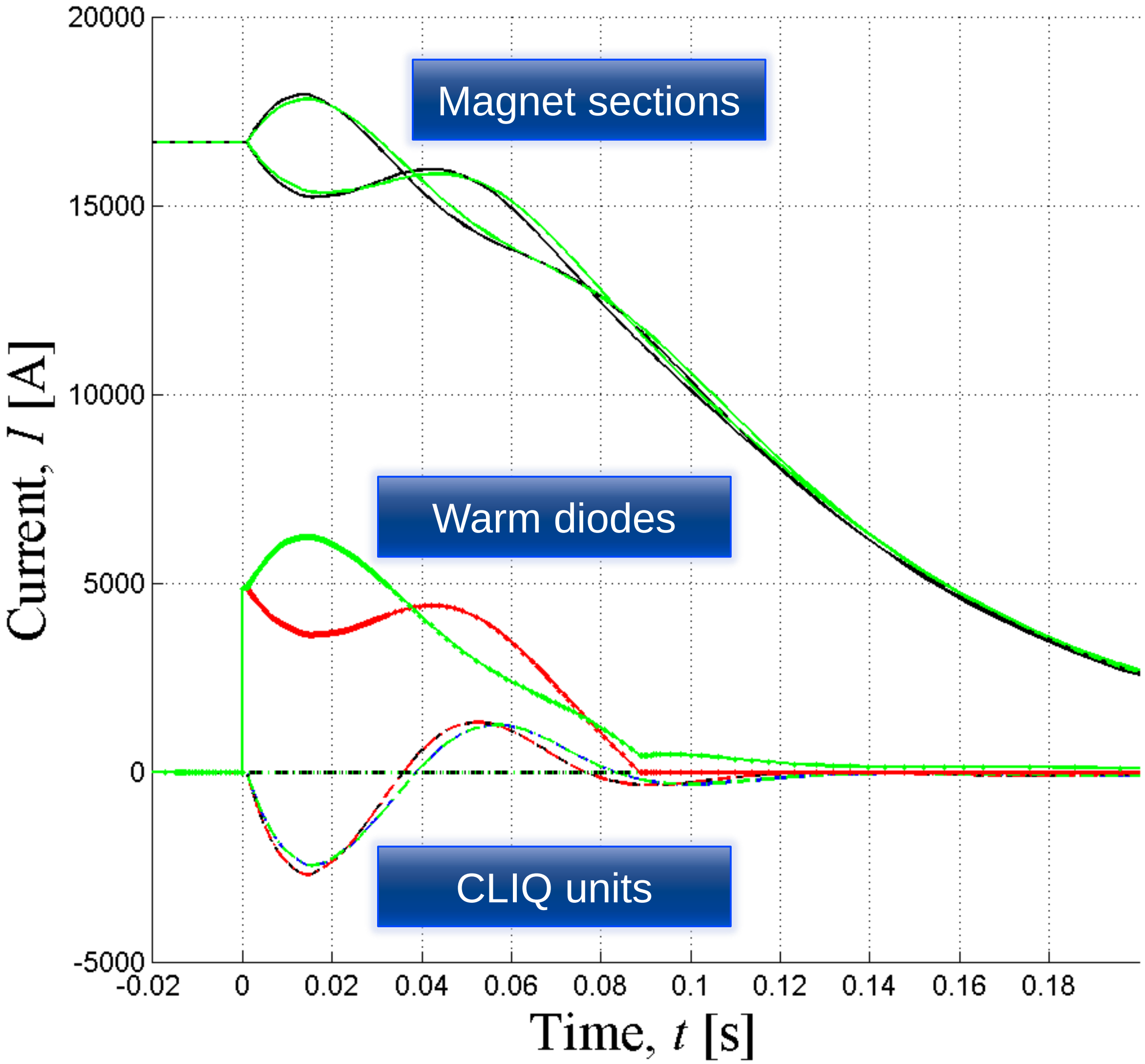


With respect to previous proposal

- 4 CLIQ units per triplet circuit instead of 6
- Different connection schemes for Q1/Q3 and Q2a/Q2b
- Warm diodes across Q1, Q2a, Q2b, Q3 (instead of 1 Ω resistors in parallel to each magnet)
  - No leakage currents, Better control of the magnet currents



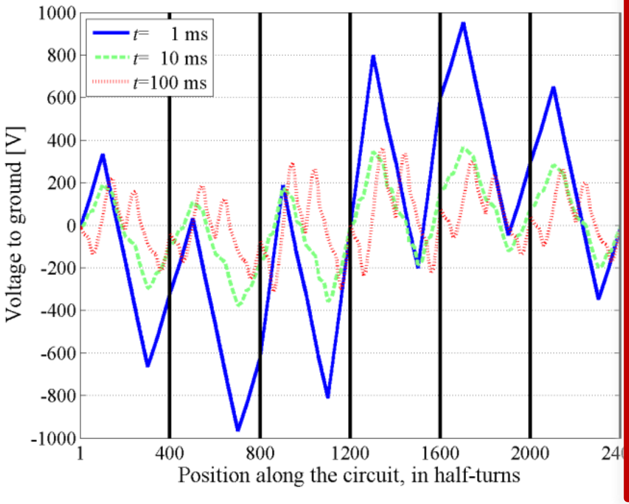
Simulated circuit discharge



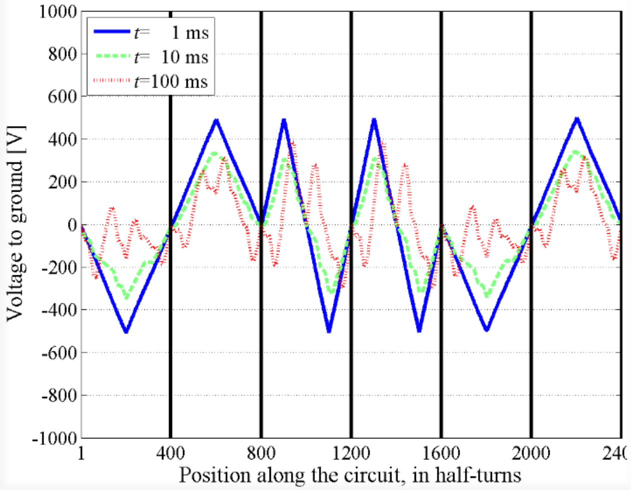
Parallel elements

- Voltages to ground reduced by means of parallel elements across parts of the circuit which equalize the voltage distribution
- 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)

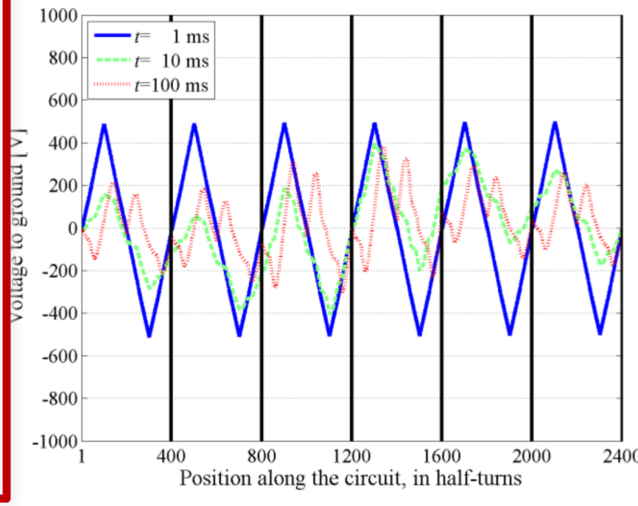
No parallel elements



Warm diodes

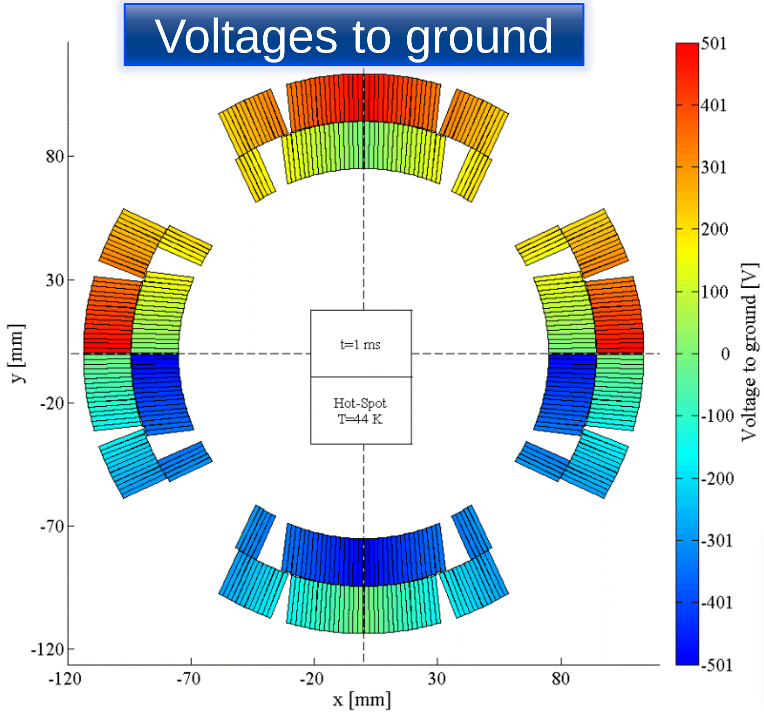


1 Ω resistors



Superposition of CLIQ and QH peak voltages

- Just after triggering CLIQ, voltages to ground as high as ±500 V develop in the coil for a few ms
- Just after triggering QH, the voltage in the QH strips reaches ±450 V, then decreases exponentially with a time constant of 40-55 ms
- If QH and CLIQ are triggered simultaneously, the peak voltage between the windings and the QH strips reaches ±500±450 V ~ ±950 V


Voltages to ground

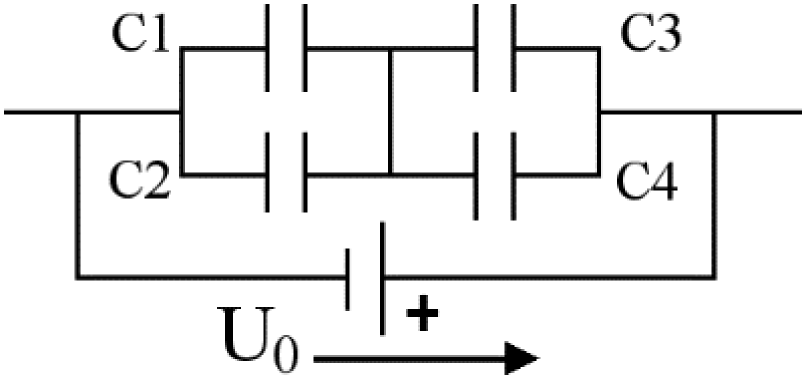
Proposed mitigation strategies	Coil-to-QH Voltage [kV]	Hot-spot T [K]
Default CLIQ + Outer QH	0.95	230
Delay QH by 10 ms	0.75	<250
Delay CLIQ by 10 ms	0.87	<250
Increase QH insulation thickness	0.95	<250

QH failure cases

- Charging voltage of each unit monitored during operation; after each discharge, “as new” analysis
- Under these assumptions, realistically only 1 charging unit at a time can fail
- Based on the LHC experience, the monitoring itself can fail; in this case, up to 2 units can fail
- Worst case: 2 failing units of the same magnet

CLIQ failure cases

- The CLIQ units are connected to the coils
  - They are part of the electrical circuit
  - They are physically attached to the conductor
  - Consequences of a failure are more serious than QH
- A higher level of redundancy is required for CLIQ units
- Combining CLIQ and QH mitigates the failure consequences



Conclusions -1

- The proposed powering scheme includes one power supply (preferably 2-quadrant) and no EE
- The proposed quench protection includes 1 CLIQ unit per cryostat and various QH circuits per magnet (some circuits may be used as spares)
- Peak hot-spot temperature around 230 K
- Need to study quench protection at low current
  - Fully redundant CLIQ units are about 4 times more expensive and voluminous
  - CLIQ performance at high current is almost independent of the capacitance
  - QH optimized for low current, CLIQ optimized for high current

Conclusions -2

- Circuit simulations showed the need for parallel elements across parts of the circuit to equalize the voltage distribution (during CLIQ discharges or during failure cases)
- Peak voltage to ground in absence of failures about ±500 V
- Coil-to-QH voltage after simultaneously trigger CLIQ and QH reaches ~950 V; possible mitigation by delaying QH by 10 ms; or (preferred) by reducing the risk of shorts by increasing the thickness of the QH-coil insulation layer
- Failure cases identified, need for a proper failure analysis with statistics
- Which level of redundancy for CLIQ and QH systems?

Ongoing studies

- Study failure cases
  - With reduced capacitance of CLIQ units
  - With reduced number of QH circuits
  - With increased thickness of the QH-to-coil insulation layer
- Reduction of coil-to-QH voltages
- Reliability and risk analysis
  - Study more in detail the consequences of failures
  - Avoid overdesign
  - Identify further failure cases and weak points
- Dimensioning CLIQ lead cross-section and length
- Dimensioning and designing the warm diodes and their leads

Annex

Proposed quench detection

- Quench detection based on differential voltage monitoring (2 poles Vs 2 poles, pole Vs pole)
- Symmetric quench detection on a 1-magnet basis
- Double, independent voltage taps (1-2 cm apart)
- Two separate detection boards per magnet (2x6 boards per triplet)
- All boards added to the PIC loop
- Threshold and validation time as tight as possible
- Voltage thresholds adapted to the current level (due to flux jumps)
- All protection units interlocked: if one is triggered, all are triggered

CLIQ system

- One CLIQ unit per cryostat (4 per triplet circuit) OR magnet (6 per triplet circuit)
- Each unit connected across two/four poles not physically adjacent
- Max charging voltage: 1 kV
- Target peak voltage to ground just after triggering: 500 V
- Capacitance of the bank: 40 mF (Variant 1) or 10 mF (Variant 2)
- CLIQ terminals with robust connection (soldering, secure bolting, reinforcement)
- Redundant CLIQ terminals not deemed necessary

CLIQ units

- **Avoid short circuit across the unit at all costs**

(the unit is directly connected to the magnet!)

  → Capacitors in series (in the very rare case of short across capacitor, the other assures electrical separation)

  → Back-to-back thyristors to assure galvanic insulation between units and coils when the units are not triggered

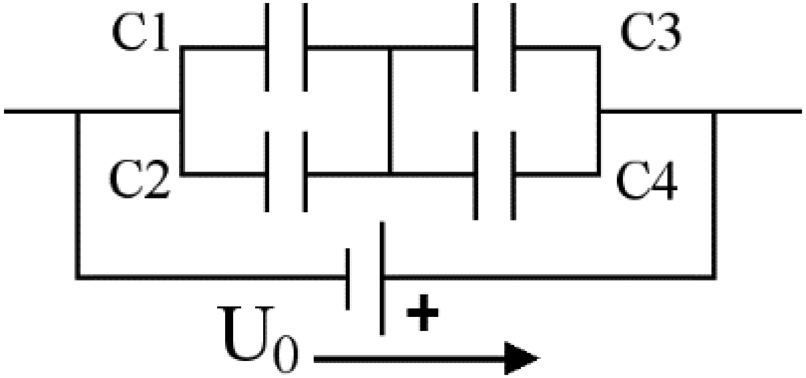
  → Charging supply protected against short by diode and fuse

- Use of film capacitors (suitable for AC applications, digital alert in case of degradation of the electrical insulation)

- During the electrical quality assurance procedure, the entire circuit is tested at a voltage of **X V (?)**. Thus, capacitors must be able to withstand this voltage level (between either terminal and ground)

CLIQ redundancy

- Two independent trigger loops to assure thyristor activation
- Optional: two separate pairs of back-to-back thyristors in parallel, to improve the redundancy of the discharge system
- A fully redundant CLIQ unit is composed of 4 capacitors, each rated for U_0 and with a capacitance 1.5 times than needed
- This high level of redundancy is expensive in terms of money and space (units roughly 4 times larger and more expensive)



- Is this high level of redundancy needed?
- Performance at high current almost independent of the capacitance (10 mF instead of 40 mF is still ok)
- Very expensive to design a redundant system effective at low current (relying on QH?)

CLIQ terminals and leads

- CLIQ terminals with robust connection (soldering, secure bolting, reinforcement)
- Redundant CLIQ terminals not deemed necessary **(?)**

- The internal resistance of the unit and the resistance of the CLIQ leads must be minimized; Target value: 10 mΩ
- The CLIQ leads internal to the cryostat must be dimensioned so as to carry the pulsed current introduced by CLIQ (peak 5 kA, damped sinus, <100 ms)
- Leads connecting the units to the cryostat: copper cross-section of 350 mm^2, length of 2x80 m, resistance ~8 mΩ at room temperature

- Apart from the terminals connected to the coils, all system components are easily accessible and replaceable

QH system

- Four QH circuits per magnet (HF outer)
- Four QH circuits per magnet (LF outer), not triggered, kept as spares
- Four QH circuits per magnet (inner), not triggered, kept as spares
- Each circuit is triggered and discharged independently
- Design of the strips yet to be decided **(?)**, design considered so far: “Copper-plated heater design 2 (OL)”
- Connection of the QH strips to be optimized
- QH kapton insulation layer: 50 μm **(?)** (+145 μm G10 cable insulat)
- Max charging voltage: 900 V (±450 V to ground)
- Capacitance of the banks: 19.2 mF **(?)**, discharge time constant 40-55 ms
- Use of electrolytic capacitors: mono-polar; less expensive; more compact
- Increasing the capacitance of the QH banks is less expensive than CLIQ banks (film capacitors, rated for double voltage)
- Simulations performed with four different codes by Susana, Tiina, Vittorio, and Emmanuele
- Good agreement between simulations; To be validated with measurements on the first MQXF model magnet

Voltage-to-ground distribution

- From magnet-level simulations to circuit-level simulations using the software TALES, developed in the CERN-TE-MPE-PE section
- If no parallel elements are installed across each magnet
  - Just after triggering CLIQ, the inductive voltages distribute across the magnets according to their lengths; this unbalanced voltage distribution generates peak voltages to ground of about 1 kV (instead of 500 V)
  - In case of QH or CLIQ failures, again unbalance voltages arise across magnets of different lengths

- Note that powering magnets of different lengths in different circuits would significantly limit the unbalanced voltage distribution. However, two supplies needed instead of one.

1 Ω parallel resistors

- Cold parallel diodes would force the voltage across each magnet to the diode opening voltage, hence equalizing the voltage distribution
- However, diodes are probably incompatible with the very high expected radiation dose in the interaction regions
- Possible alternative solution: 1 Ω parallel resistors installed across each magnet (resistance value chosen as a compromise between effective voltage equalizing Vs leakage currents / cryogenic load)
- During magnet operation, at the nominal current change of 16.5 A/s, leakage currents of about 965 and 565 mA are expected through 1 Ω resistors mounted across the long and short coils, respectively, resulting in cryogenic loads of 930 and 320 mW.
- These leakage currents are very well reproducible and can be easily corrected by the power supplies.
- During the CLIQ discharge, pulsed currents of about 220 and 120 A are pushed through the resistors across the long and short coils, respectively, resulting in power dissipations of 3.2 and 0.8 kJ.

QH/CLIQ failure cases (with 1Ω parallel resistors)

Failure	Consequences	Probability	Mitigation
CLIQ capacitor in open circuit	Hot-spot T = Voltage to ground +20 V 2.4→3.4 kJ in parallel R	Low	Capacitors in parallel Parallel resistors
CLIQ capacitor in short circuit	Hot-spot T = Peak voltage to ground = 2.4→3.4 kJ in parallel R	Very low	Capacitors in series Parallel resistors
One QH supply not triggered	Hot-spot T = Peak voltage to ground = 2.4→2.7 kJ in parallel R	Low	Parallel resistors
Two QH supply not triggered	Hot-spot T = Peak voltage to ground = 2.4→2.7 kJ in parallel R	Very low	Parallel resistors
Combined CLIQ/QH failures?		Very low	

CLIQ mitigated failure cases (1 Ω parallel resistors)

- Various CLIQ failure cases have serious consequences and must be avoided
- The proposed mitigations make the occurrence of such events extremely unlikely

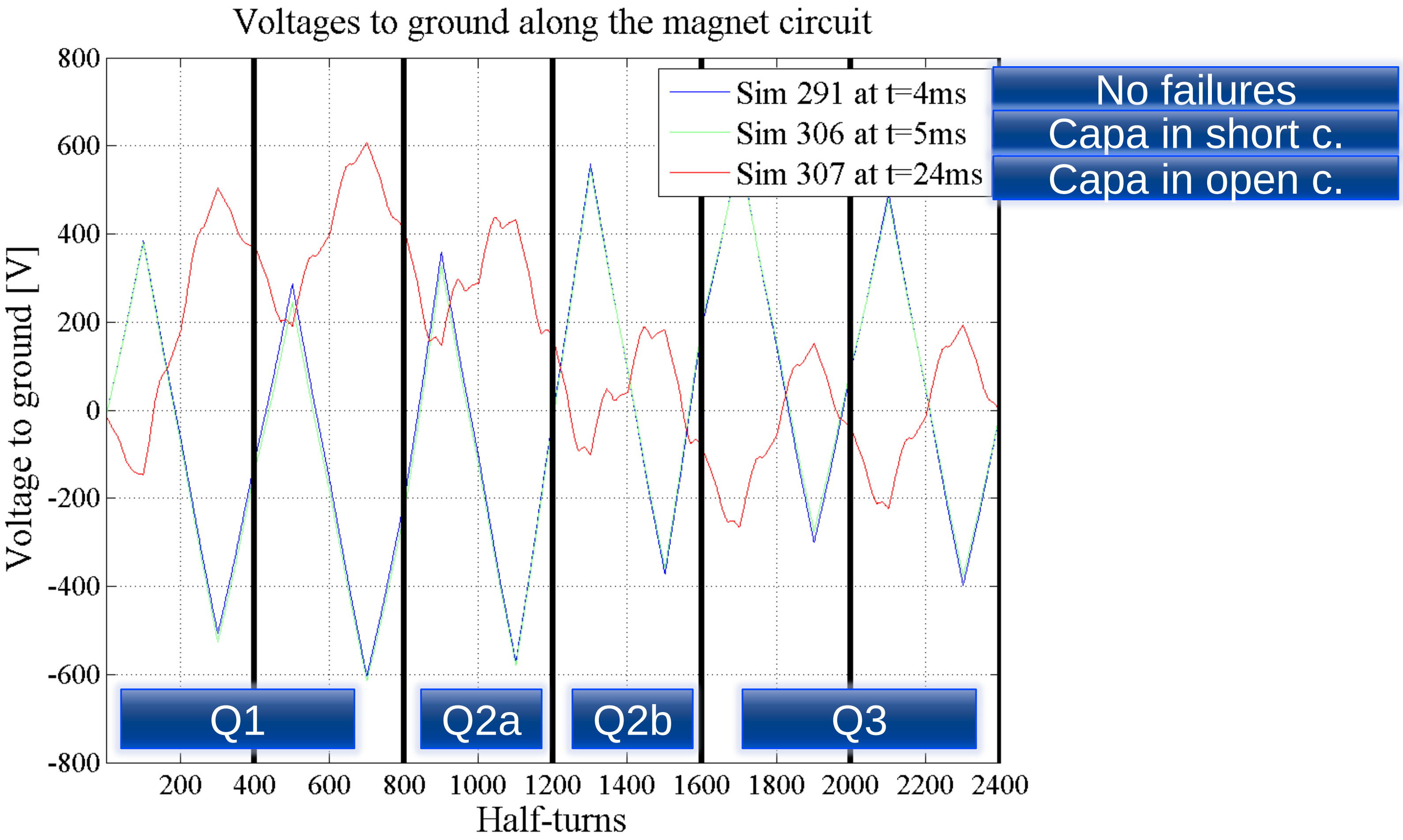
Failure	Consequences	Probability	Mitigation
One CLIQ unit triggered spuriously	Hot-spot T = Peak voltage to gnd +300 V 2.4→6.2 kJ in parallel R	Very low	Units interlocked Parallel resistors
One CLIQ unit not triggered	Hot-spot T +20 K P. v. to gnd +480 V (1070 V) 2.4→73 kJ in parallel R	Very low	Double triggers Voltage monitor Parallel resistors
Entire CLIQ unit in short circuit	Hot-spot T +60 K (280 K) Peak voltage to gnd +125 V 2.4→56 kJ in parallel R CLIQ unit to replace	Nihil	Capacitors in series Charger protected

Failure cases

Failure	Consequences	Probability	Mitigation
CLIQ capacitor in open circuit	Hot-spot T ↑ Voltage to ground =	Low	Capacitors in parallel Parallel resistors
CLIQ capacitor in short circuit	Hot-spot T ↑ Voltage to ground =	Very low	Capacitors in series Parallel resistors
One CLIQ unit not triggered	Hot-spot T ↑ Voltage to ground ↑↑	Very low	Double triggers Voltage monitor
Entire CLIQ unit in short circuit	Half magnet in short CLIQ unit destroyed	Nihil	
One QH supply not triggered	Hot-spot T ↑ Voltage to ground ↑	Low	Parallel resistors
Two QH supply not triggered	Hot-spot T ↑ Voltage to ground ↑	Very low	Parallel resistors
Combined CLIQ/QH failures?	Hot-spot T ↑ Voltage to ground ↑	Very low	
One CLIQ unit triggered spuriously	Voltage to ground ↑	Low	Parallel resistors

Example of CLIQ failure cases

Capacitor in open or short circuit



Previous quench protection proposal

- Hybrid system: CLIQ + Quench Heaters
- One CLIQ unit per magnet
- Four QH circuits per magnet (HF outer)
- Four QH circuits per magnet (LF outer), not triggered, kept as spares
- 1 Ω resistors in parallel to each magnet