Towards an optimized Coupling-Loss Induced Quench protection system (CLIQ) for quadrupole magnets

Emmanuele Ravaioli[a,b]

V. I. Datskov[a], V. Desbiolles[a], J. Feuvrier[a], G. Kirby[a], M. Maciejewski[a,c], K. A. Sperin[a,d], H. H. J. ten Kate[a,b], Arjan P. Verweij[a], G. Willering[a]

[a] *CERN, Geneva, Switzerland*
[b] *University of Twente, Enschede, The Netherlands*
[c] *Lodz University of Technology, Lodz, Poland*
[d] University of Birmingham, Edgbaston, Birmingham, United Kingdom

9 July 2014 ICEC/ICMC

CERN

UNIVERSITY OF TWENTE.

Towards an optimized CLIQ - Outline

CLIQ

- Coupling-Loss Induced Quench
- Working principle and Advantages

Test Results

- CLIQ performance on a 2 m quadrupole magnet
- Comparison with conventional Quench Heaters

Optimization Strategy

- The challenge of protecting full-size magnets
- CLIQ optimum configuration
- Multi-CLIQ

Quench Protection in a Superconducting Magnet

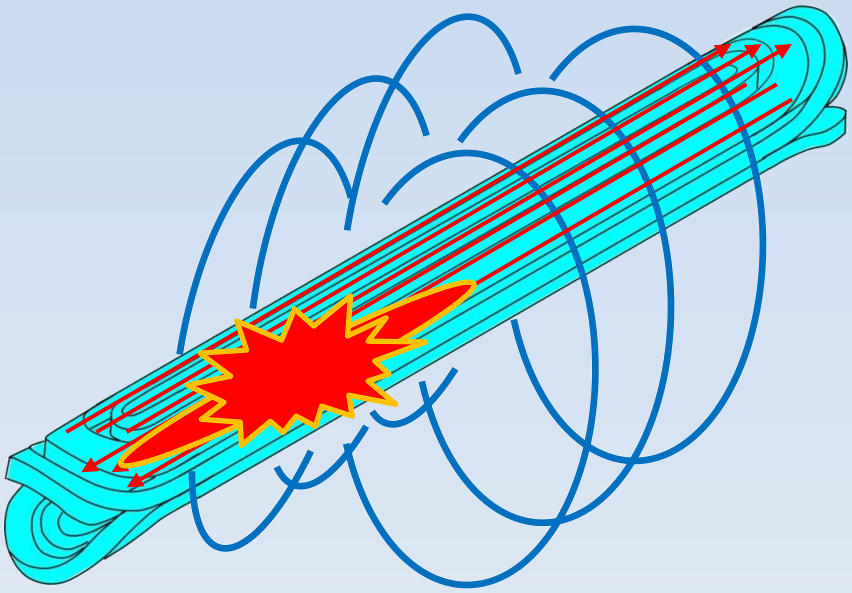
High Current Density
$J \approx kA/cm^2$

High Magnetic Field
B = 5-10 T

High Energy Density
$e = B2/(2\ \mu 0) \approx 10\text{-}40\ MJ/m3$

Quench
If of a portion of cable suddenly becomes non-superconducting, it starts heating up

The energy stored in the magnet is usually sufficient to melt kilos of Copper and destroy the magnet!



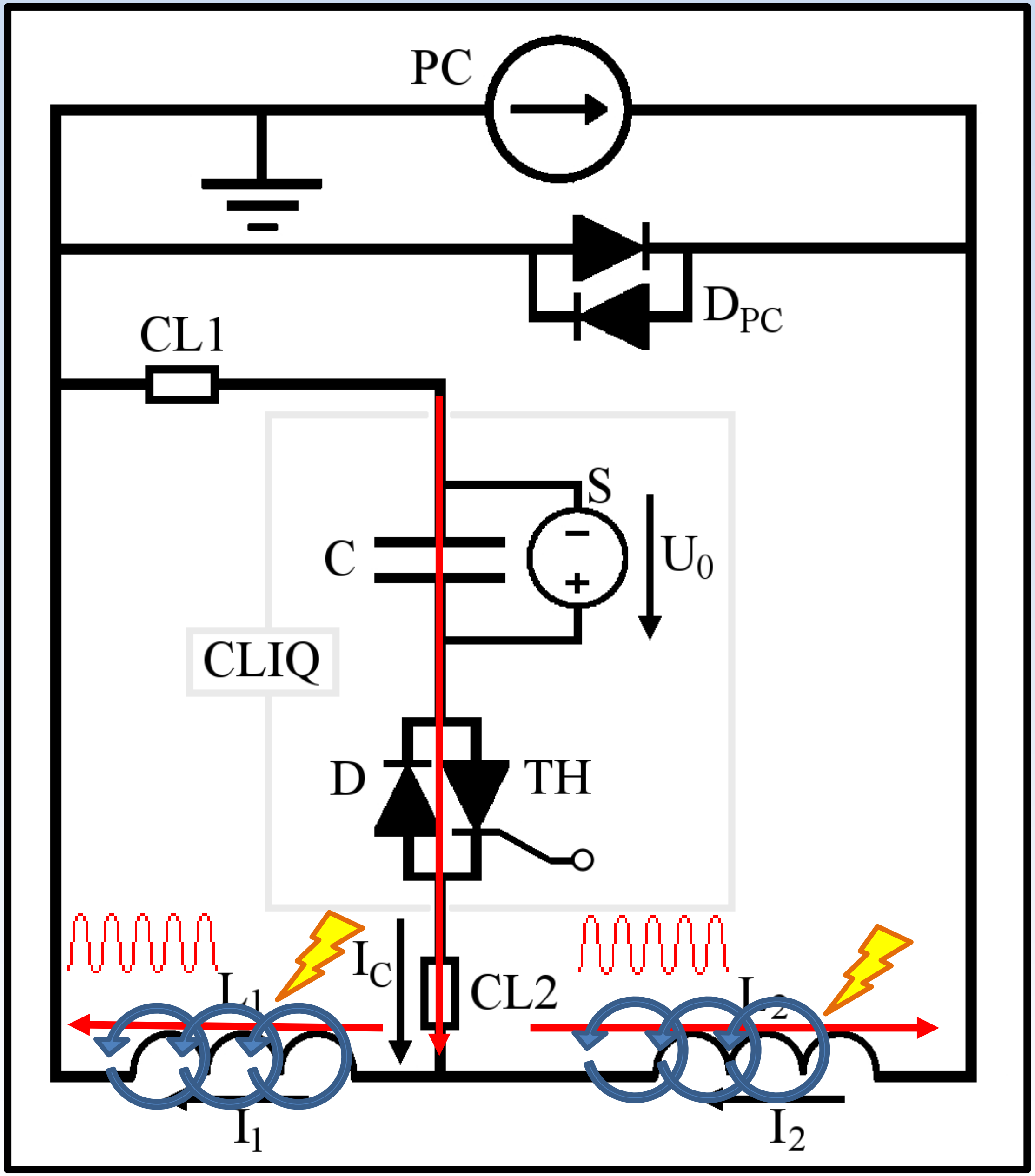
Quick propagation of the quench needed

Homogeneous distribution of the quench energy

Coil resistance **discharges** the magnet current

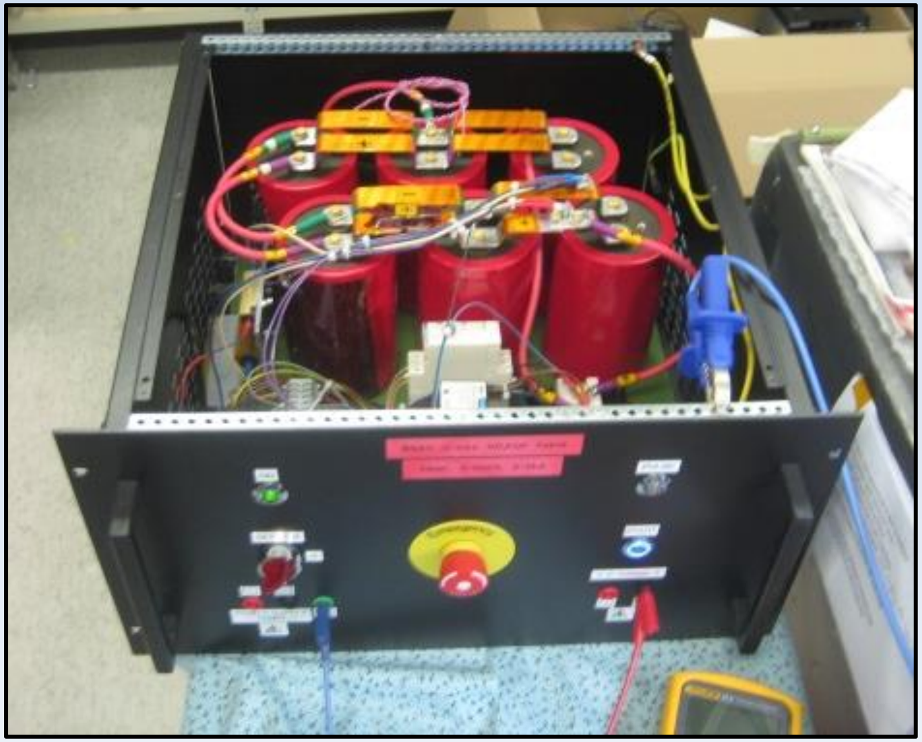
Conventional **Quench Heaters** rely on thermal diffusion across **insulation** layers and are prone to **electrical breakdown**

CLIQ – Coupling-Loss Induced Quench



- **Current Change**
- **Magnetic Field Change**
- **Coupling Losses (Heat)**
- **Temperature Rise**
- **QUENCH**

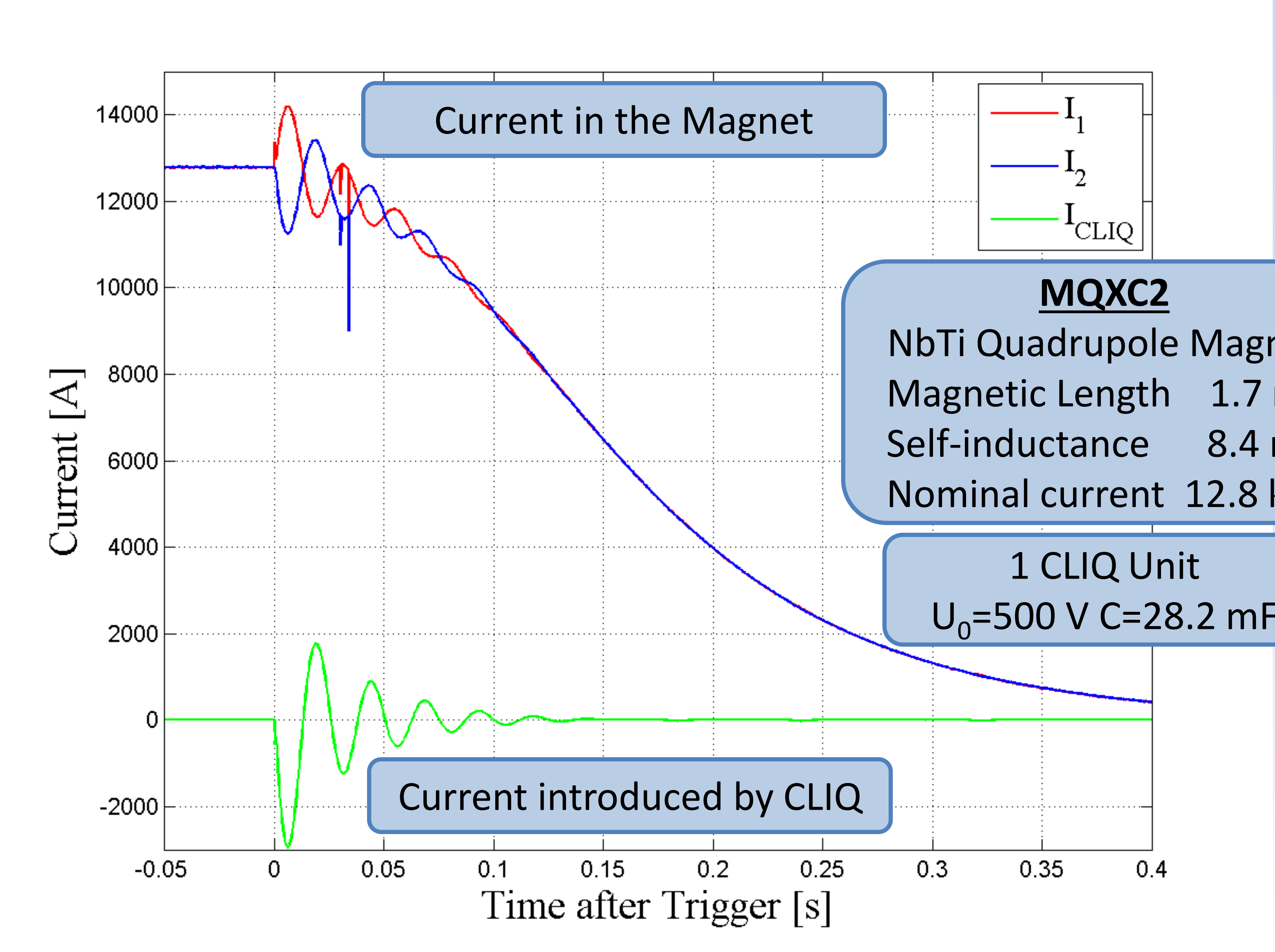
CLIQ – Main Advantages



- More **efficient** energy deposition
- **Faster** and more **homogeneous** quench initiation
- **Easier** to implement and repair
- **More robust** design
- Lower **failure rate**
- **External** system not interfering with the coil winding technology
- Possible to use CLIQ as a **back-up solution** for protecting magnets with failing quench heaters

All you need is an available **connection to the middle of the magnet** (a few mm^2 of copper) and a good understanding of **how CLIQ works**

CLIQ at nominal current (no Quench Heaters, no Energy Extraction)



MQXC2

NbTi Quadrupole Magnet

Magnetic Length 1.7 m

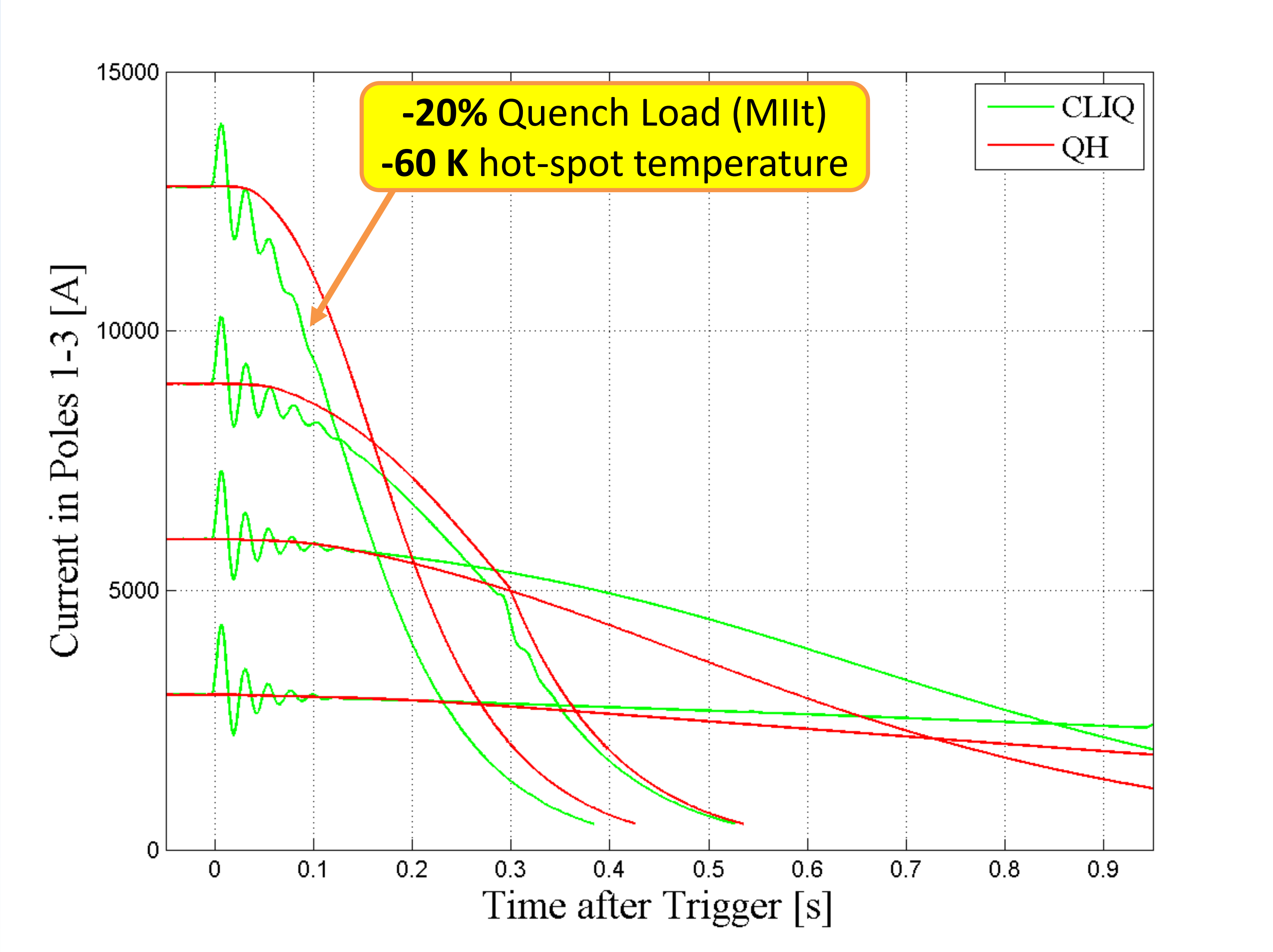
Self-inductance 8.4 mH

Nominal current 12.8 kA

1 CLIQ Unit

U_0=500 V C=28.2 mF

Comparison with Quench Heaters performance

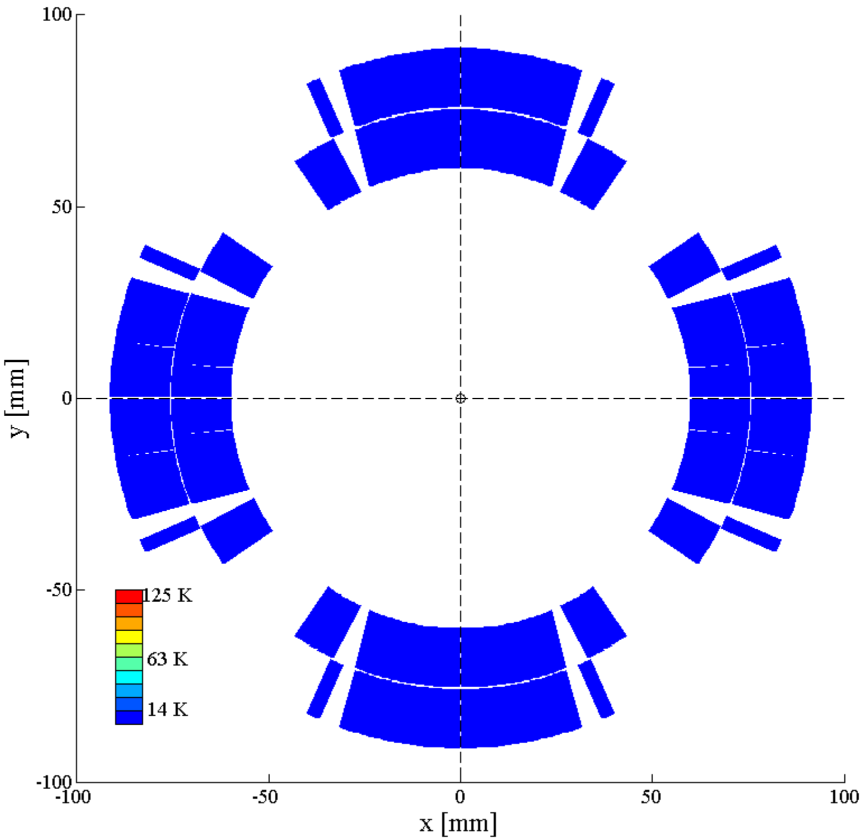


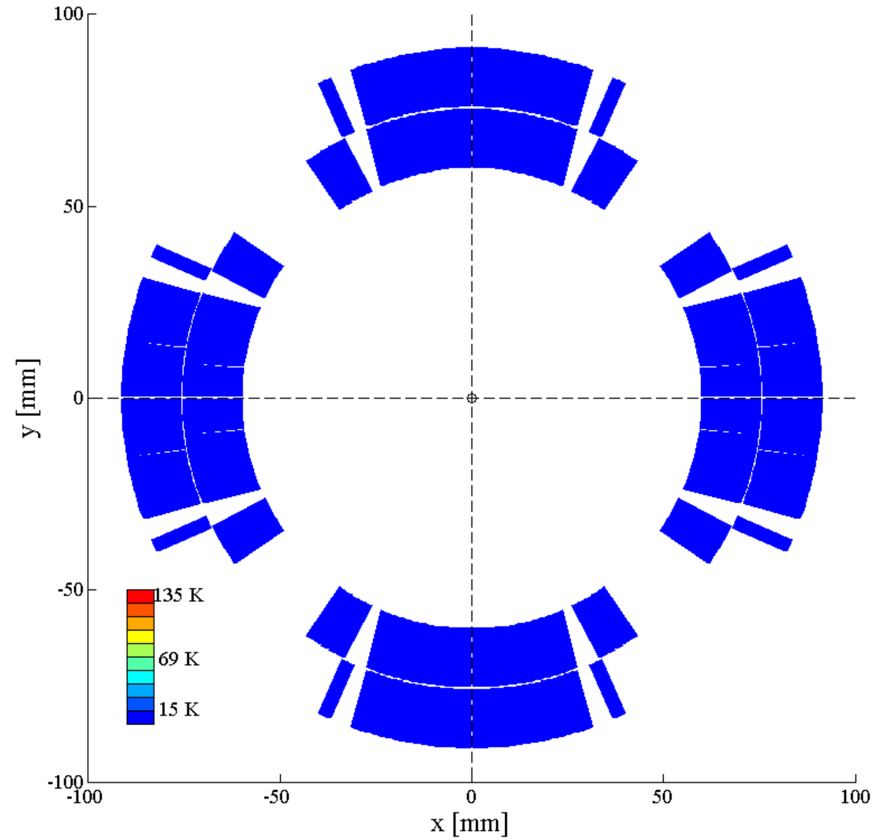
Simulated temperature profile – CLIQ cpr QH

Very fast quench initiation

CLIQ

QUENCH HEATERS

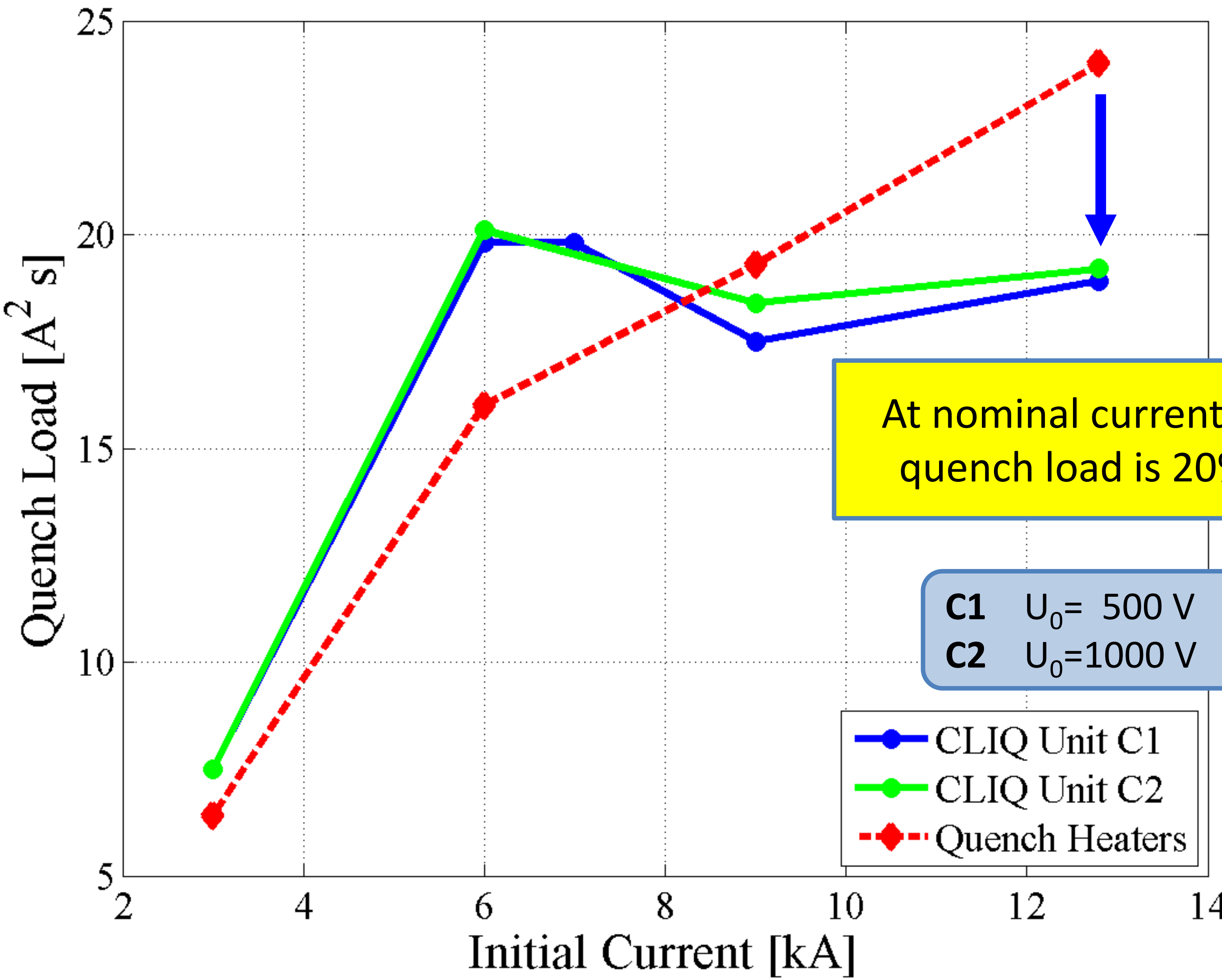




Quench starts at t~0-10 ms
Hot-Spot Temperature ~155 K

Quench starts at t~30-50 ms
Hot-Spot Temperature ~210 K

Summary of CLIQ and QH performance on the 2 meter long magnet



At nominal current with CLIQ quench load is 20% smaller

C1 U_0= 500 V C=28.2 mF
C2 U_0=1000 V C= 8.8 mF

Protecting full-size magnets with CLIQ – The strategy

$$\frac{P_{IF}}{vol} \propto \left(\frac{dI}{dt}\right)^2 \propto \left(\frac{U_0}{L_{eq}}\right)^2$$

CLIQ performance depends on the inter-filament loss (**IFCL**)

The same CLIQ unit discharged on a magnet **10 times longer** will deposit **~100 times less peak power**…

Strategy for existing magnets	Strategy for future magnets
	Optimize **filament twist pitch** and **RRR**
Add CLIQ connections between **poles** (typically a few mm² of copper)	Add CLIQ connections between **poles** and between **inner/outer layers**
Select optimum CLIQ **configuration**	Select optimum CLIQ **configuration**
Increase charging **voltage U_0** (limited for safety) and **capacitance**	Increase charging **voltage U_0** (limited for safety) and **capacitance**
Multiple CLIQ units (for quadrupole magnets up to **2 units**)	**Multiple** CLIQ units (for quadrupole magnets up to **4 units**)

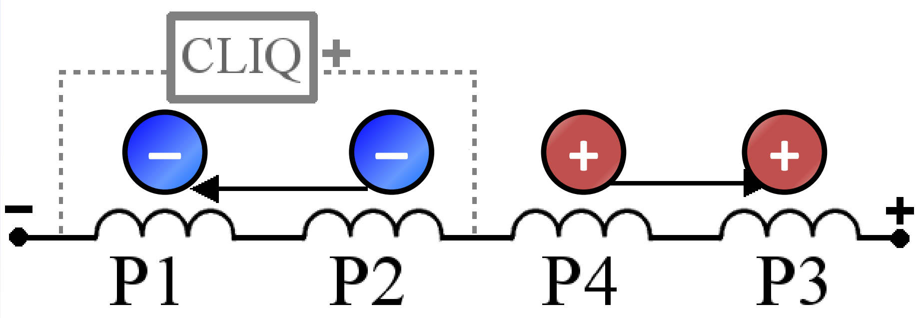
Optimum CLIQ discharge configuration -1

Golden rule for optimizing any CLIQ discharge circuit

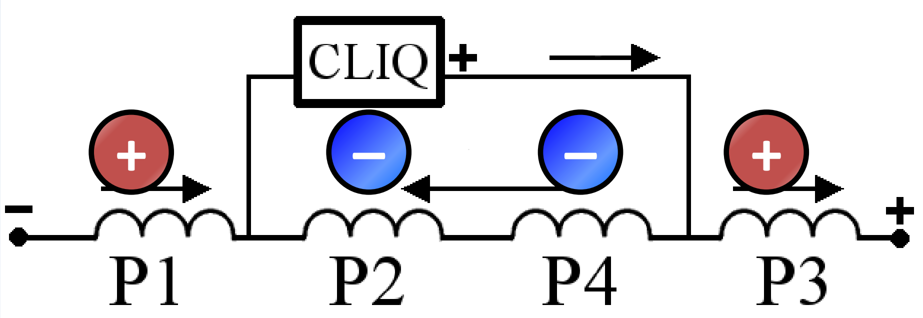
Introduce opposite current change in coils which are physically adjacent

Example:
Quadrupole geometry

Not Optimized



Optimized



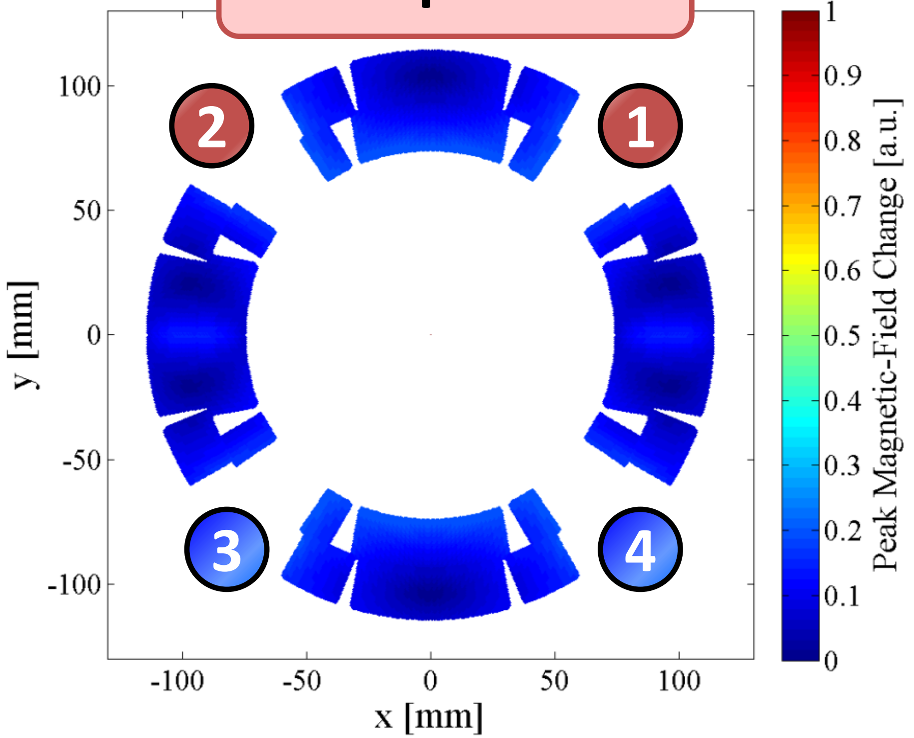
Significant **reduction** of L_{eq} (2.5-9 times!) & **Efficient** magnetic-field change

Optimum CLIQ discharge configuration -2

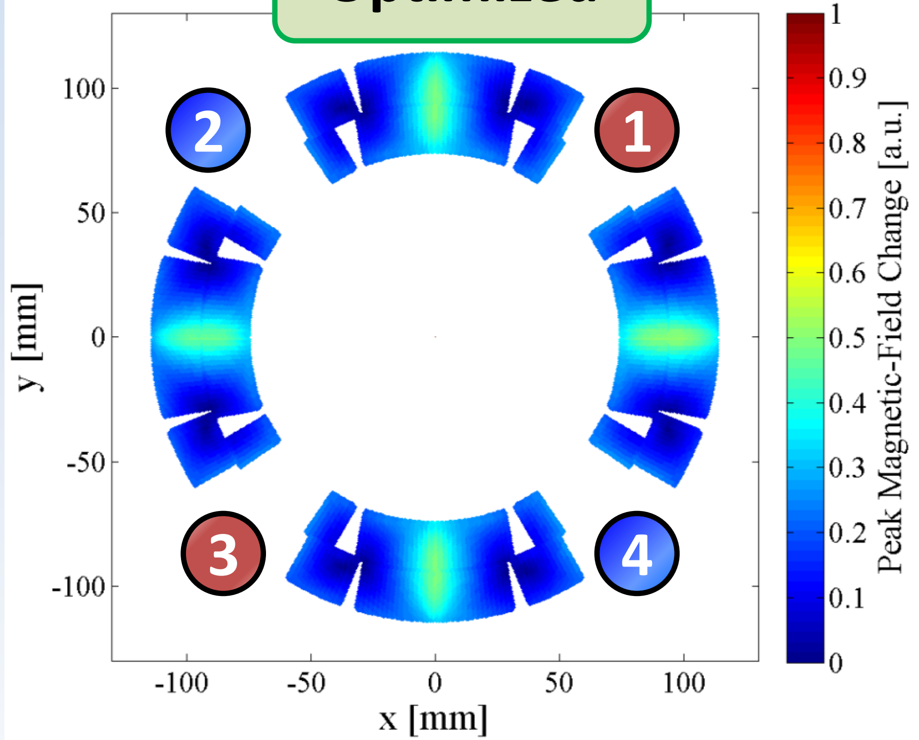
<u>Golden rule for optimizing any CLIQ discharge circuit</u>

Introduce opposite current change in coils which are physically adjacent

Not Optimized



Optimized

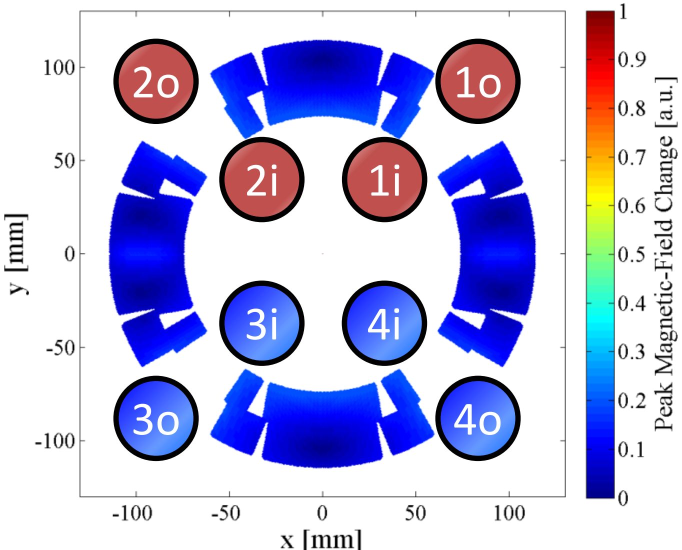


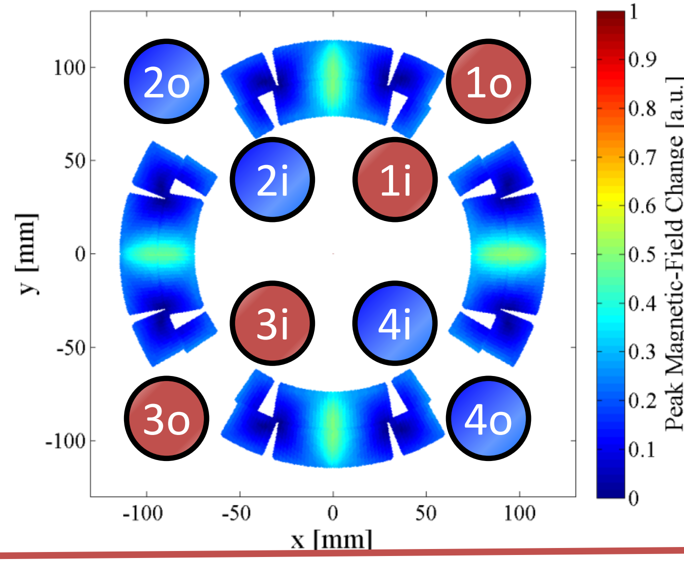
Significant **reduction** of L_{eq} (2.5-9 times!) & **Efficient** magnetic-field change

With CLIQ connections at the joint between inner/outer layers

Golden rule for optimizing any CLIQ discharge circuit

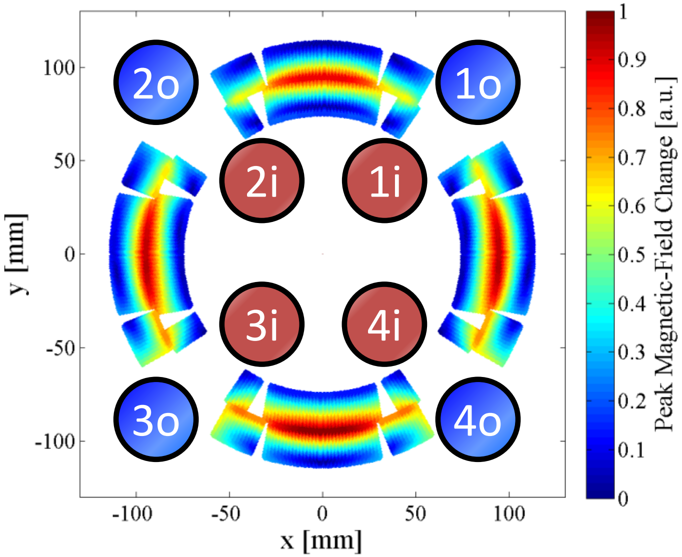
Introduce opposite current change in coils which are physically adjacent

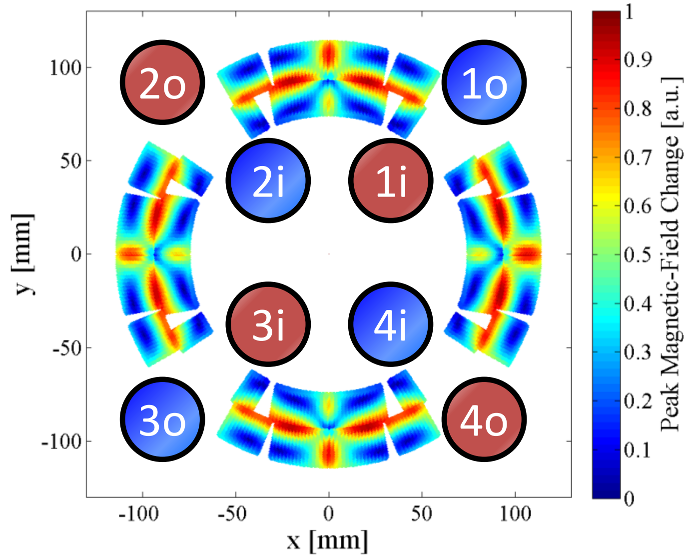




Existing magnets

Configurations **easy** to implement on most existing magnets





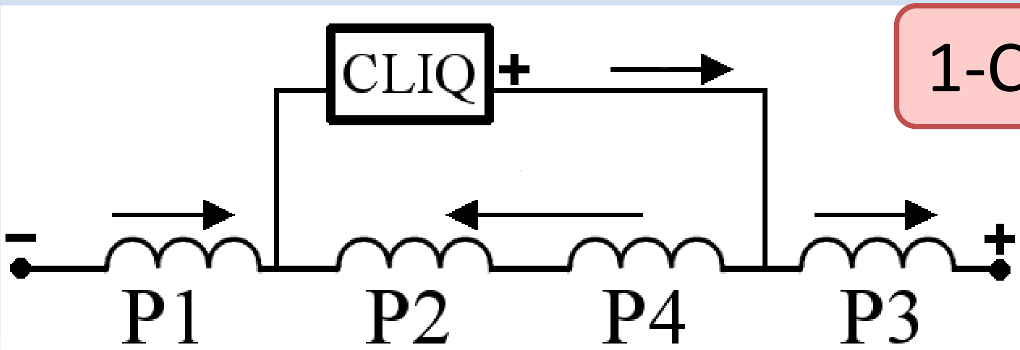
Future magnets

With connections between **in/out layers**

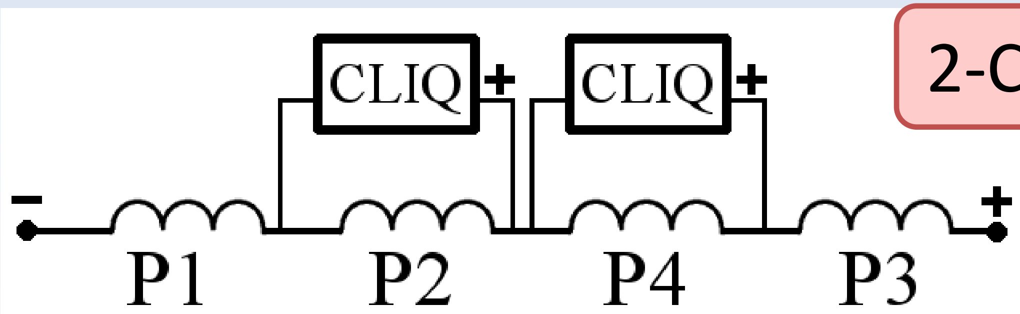
Multi-CLIQ – 2 CLIQ units, 4 CLIQ units, N_C CLIQ units… -1

L_{eq} can be reduced by further **subdividing** the electrical circuit into N_E elements, effectively in parallel when CLIQ is triggered.
They can be **magnets** in a chain, **poles** of a magnet, or **inner/outer layers** of each pole.

1-CLIQ



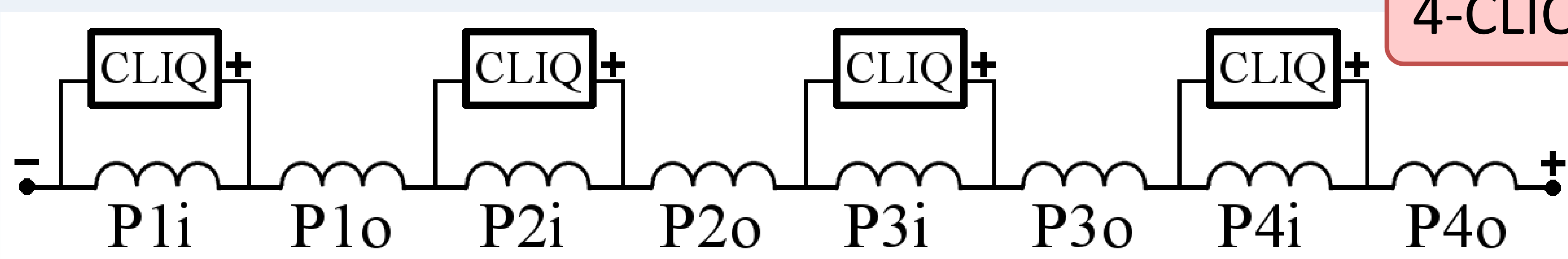
2-CLIQ



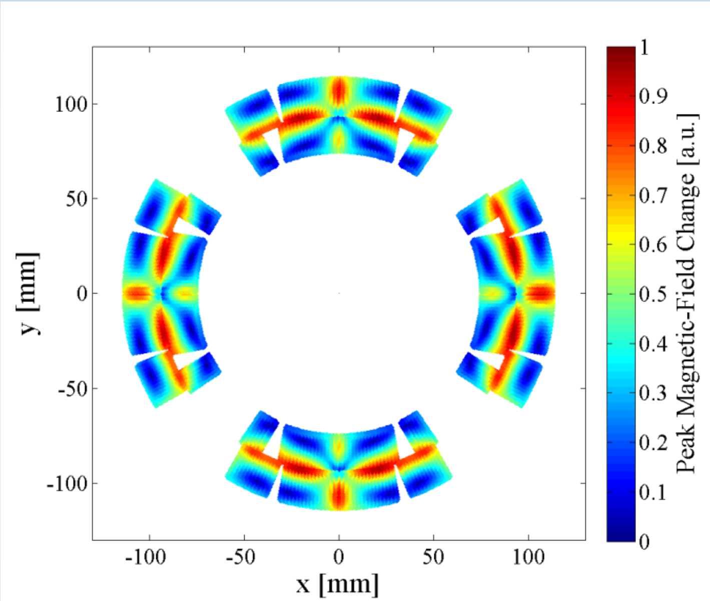
Peak **power deposition** proportional to the square of CLIQ units

$$\frac{P_{IF}}{vol} \propto \left(\frac{U_0}{L_{eq}}\right)^2 N_C^2$$

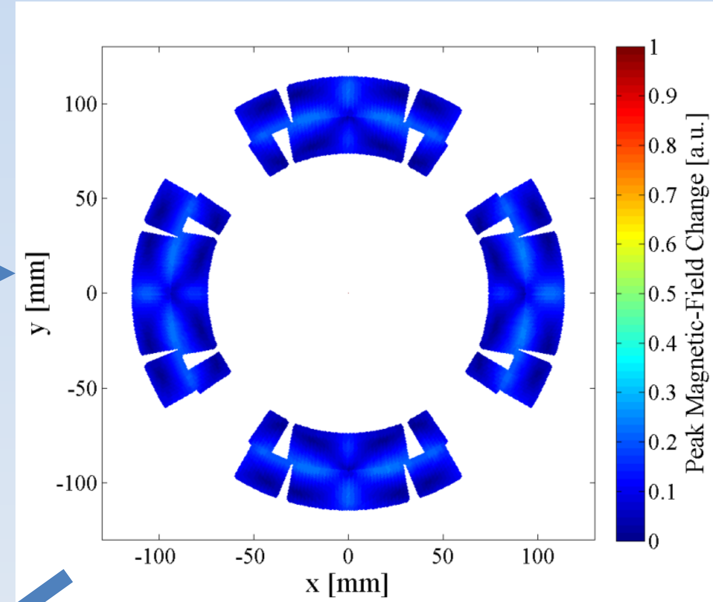
4-CLIQ



Multi-CLIQ – 2 CLIQ units, 4 CLIQ units, N_C CLIQ units… -2

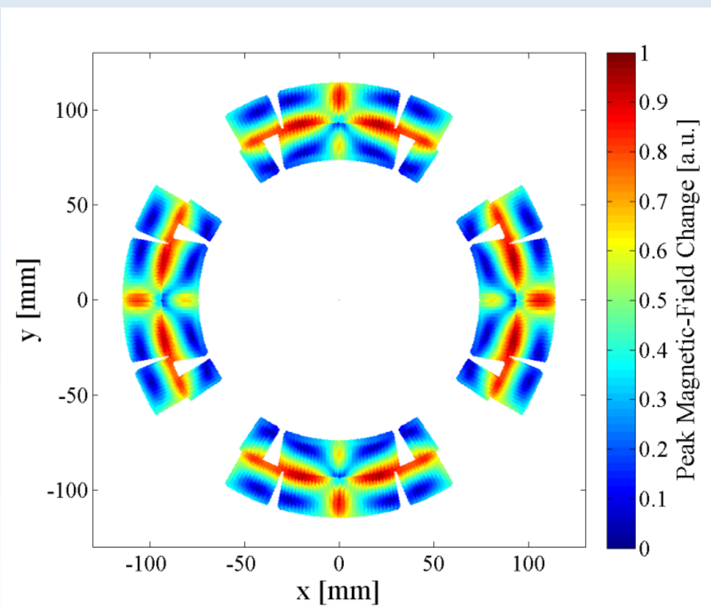


4 times longer magnet



4 times Longer magnet

4 CLIQ



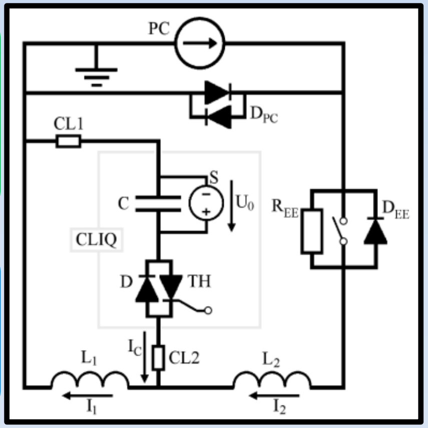
Peak **power deposition** proportional to the square of CLIQ units

$$\frac{P_{IF}}{vol} \propto \left(\frac{U_0}{L_{eq}}\right)^2 N_C^2$$

Towards an optimized CLIQ - Conclusion

CLIQ

CLIQ is a very good solution for the protection of superconducting magnets: efficient, low hot-spot temperature, robust, easy to repair, less failures



Tests

CLIQ discharged a 2 meter long NbTi quadrupole magnet faster than conventional Quench Heaters

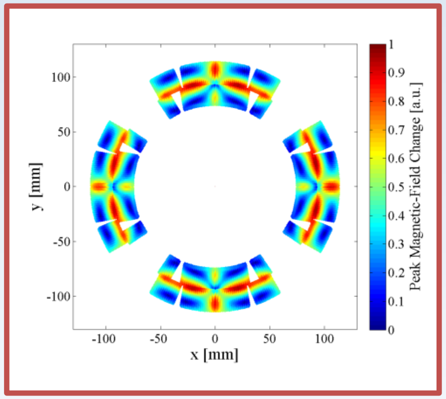
CLIQ Optimization

1 CLIQ unit is sufficient to effectively protect most **existing** magnets

Optimization strategy for new-generation **full-size** magnets

0. *(Optimize* ***filament twist pitch*** *and* ***RRR****)*

1. Select **optimum** CLIQ **discharge circuit**
2. Increase charging **voltage** and **capacitance**
3. **Multiple** CLIQ units (Multi-CLIQ)



Next CLIQ test campaigns: Nb_3Sn quadrupole for LHC High-Luminosity Upgrade, 15 m LHC Main Dipole, LHC individually powered quadrupoles, 11 T dipole, Nb_3Sn solenoids from Oxford Instruments, …?

QUESTIONS?

References

EU Patent EP13174323.9, June 2013.

E. Ravaioli et al., MT23, 2013.

E. Ravaioli et al., EUCAS11, 2013.

E. Ravaioli et al., CHATS-AS, 2013.

E. Ravaioli et al., Cryogenics, 2014.

E. Ravaioli et al., SuST, 2014.

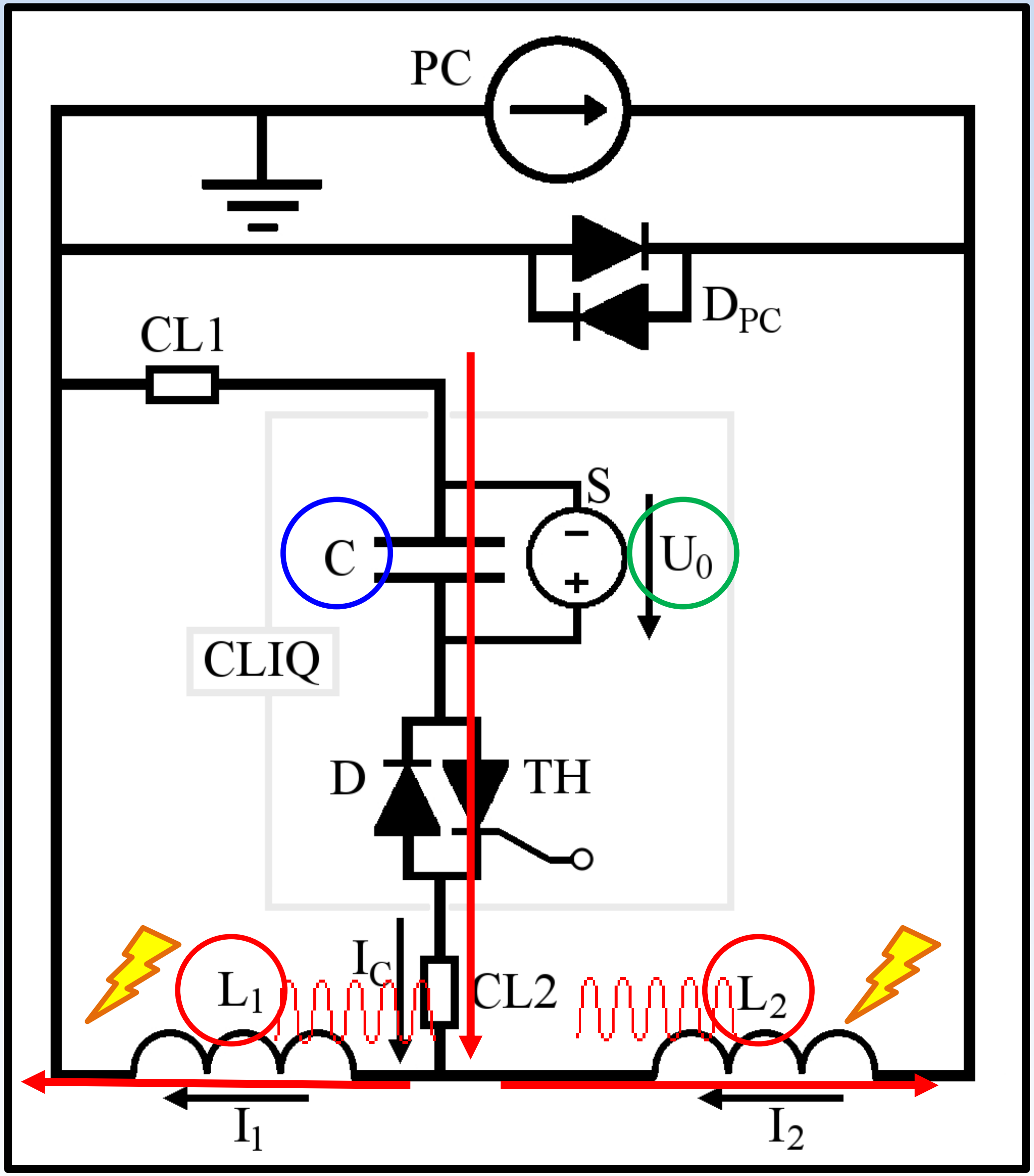
E. Ravaioli et al., ICEC/ICMC, 2014.

E. Ravaioli et al., ASC, 2014.

Ask me the CLIQ Recipe!

Emmanuele.Ravaioli@cern.ch

CLIQ – Coupling-Loss Induced Quench



- Current Change
- Magnetic Field Change
- Coupling-Losses (Heat)
- Temperature Rise
- QUENCH

$$I_C(t) \approx -U_0 \sqrt{\frac{C}{L_{eq}}} \cdot \sin\left(\frac{t}{\sqrt{L_{eq}C}}\right)$$

$$I_{C,peak} \propto U_0 \cdot \sqrt{\frac{C}{L_{eq}}}$$

$$\frac{dI_C(t)}{dt} \approx \frac{U_0}{L_{eq}} \cdot \cos\left(\frac{t}{\sqrt{L_{eq}C}}\right)$$

$$\frac{dB_t(t)}{dt} = f_m \frac{dI_C(t)}{dt}\left[1-\exp\left(-\frac{t}{\tau_{IF}}\right)\right]$$

$$\frac{P_{IF}}{vol} = \beta_{IF}\left[\frac{dB_t(t)}{dt}\right]^2 \propto \left(\frac{U_0}{L_{eq}}\right)^2$$

$$\tau_{IF} = \frac{\mu_0}{2}\left(\frac{l_p}{2\pi}\right)^2 \frac{1}{\rho_{eff}(B)}$$

$$\beta_{IF} = \left(\frac{l_p}{2\pi}\right)^2 \frac{1}{\rho_{eff}(B)}$$

Principle: When subjected to a magnetic field change, **coupling losses** occur in superconducting wires and cables. These losses are **heat** generated directly in the superconductor to quench!

CLIQ – Advantages & Drawbacks (compared to Quench Heaters)

Advantages

- Heat generated directly in the superconductor to quench (not relying on thermal diffusion)
- Robust electrical design, easier implementation and repair
- Faster quench initiation
    - More homogeneous temperature distribution
    - Lower hot-spot temperature
- Lower failure risk
- Easy repair solution for a magnet with damaged quench heaters
- For the same price and size of conventional quench heater systems
- Possible to avoid the installation of quench heaters

Drawbacks

- Additional current lead(s) connected to the magnet (pulse current for <100 ms)
- High voltage introduced in the circuit
    - If applied to a magnet which is part of a chain, additional studies have to be carried out (how to implement, transient waves, avoid resonances, etc)
    - Integration with an energy-extraction system is possible but it needs to be carefully studied
- Additional mechanical stresses due to the introduced current need to be analyzed

Protecting long magnets with CLIQ – Issues & Solutions

Issues	Possible Solutions
Integration with an energy-extraction system: Avoid too high voltage to ground due to voltage superposition	Delaying the triggering of the energy-extraction system to wait the damping of the CLIQ oscillation (30-100 ms?)
If “1 CLIQ” solution is chosen, high voltage to ground (up to 1 kV?)	Increasing insulation thickness would not decrease the CLIQ performance
If “Multi-CLIQ” solution is chosen, three current leads connected to the magnet (pulsed current for t<100 ms)	
Redundancy	More then one trigger thyristor in parallel (2?) More than one CLIQ unit connected in parallel (2?)
Use of CLIQ to protect a magnet which is part of a chain or of a nested circuit	Use by-pass elements (pair of diodes or parallel resistor) to allow introducing an AC current on a single magnet of the chain
Integration with Quench Heaters	No problem

CLIQ – How is the energy deposited? with Inter-Filament Coupling Loss

The current introduced in the magnet coil generates a change in the local magnetic field. When a superconductor is subjected to an applied magnetic-field change, an induced magnetic field is generated which opposes to the applied field.
For fast transients, the actual magnetic field does not change much, because the applied and induced magnetic field almost cancel out.
The presence of the induced field generates currents between superconducting filaments and between superconducting strands. These currents flow through the copper matrix of the conductor, thus they generate loss (=heat) inside the cable.

For typical ranges of magnet inductance (5-100 mH) and CLIQ capacitance (5-50 mF), the range of the **CLIQ oscillation period is 10-100 ms** (frequency range 10-100 Hz)

Inter-Filament Coupling Loss

For typical filament twist-pitch and Cu transverse resistivity, time constant in the order of tens of ms
High energy deposition with CLIQ discharge

Inter-Strand Coupling Loss

For typical strand twist-pitch and cross-contact resistance, time constant in the order of hundreds of ms / seconds
Limited energy deposition with CLIQ discharge

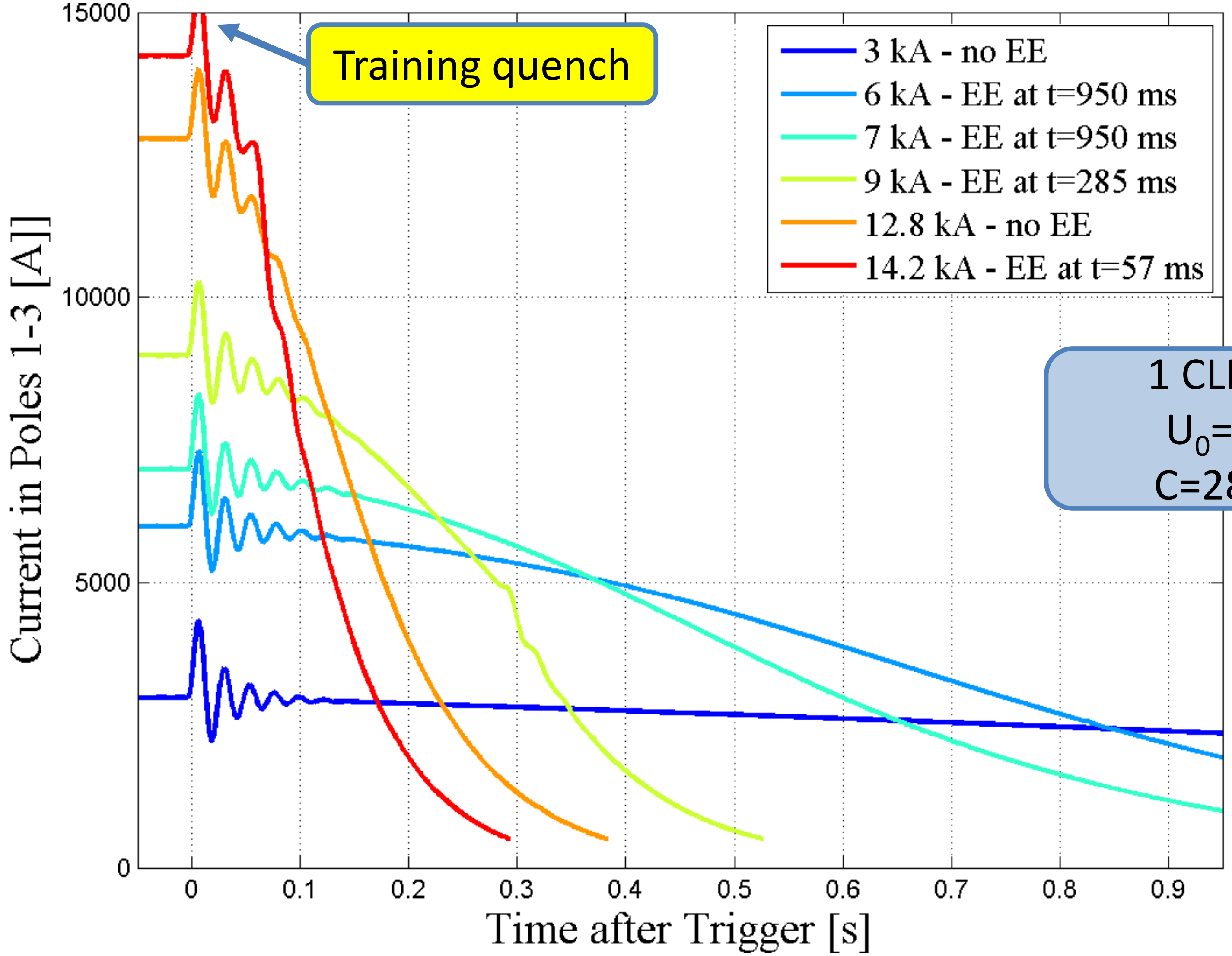
Magnetization Loss

Very limited change in the local magnetic field, hysteresis loops are small

Limited energy deposition with CLIQ discharge

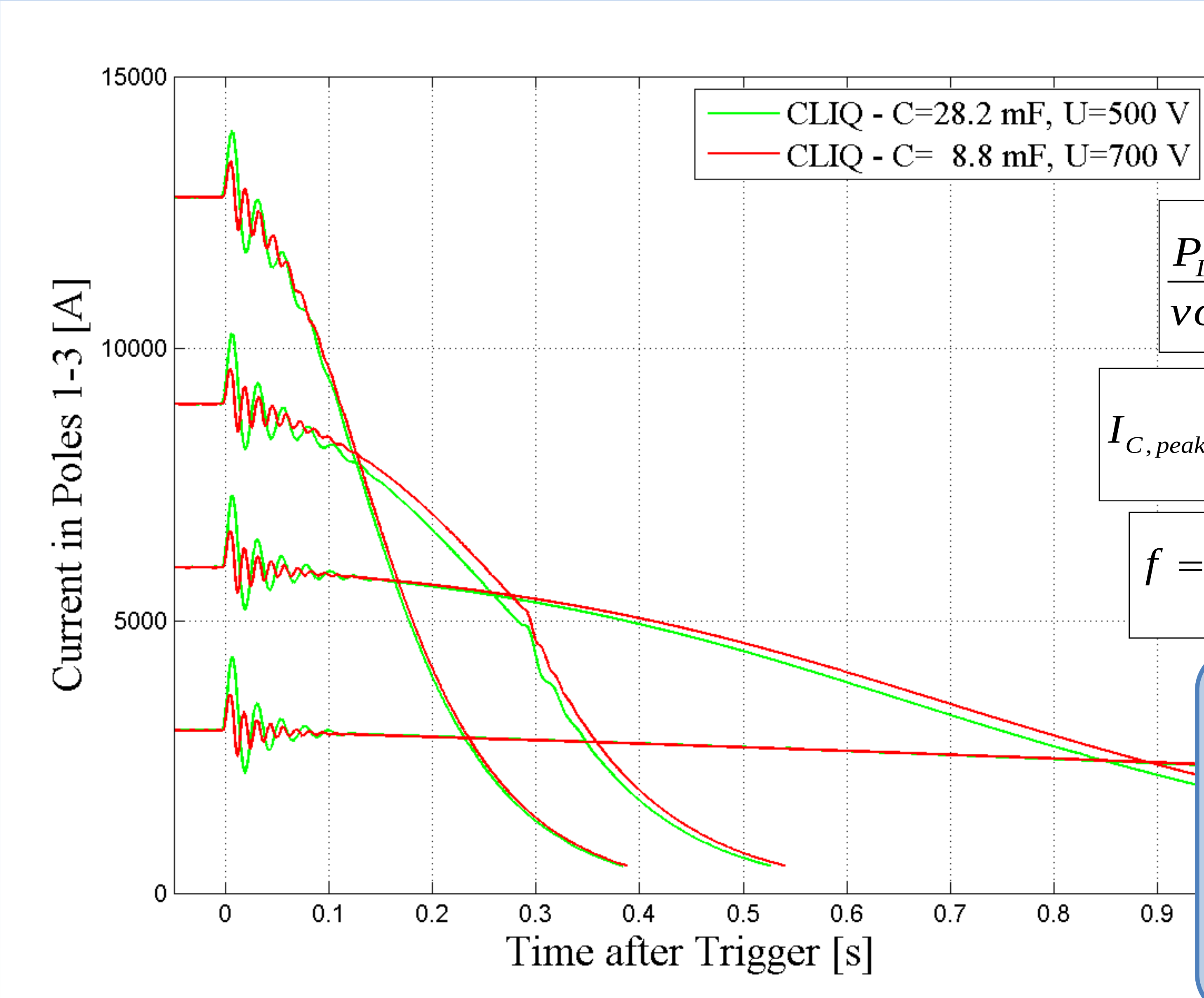
MQXC2

CLIQ protects the magnet **at any current level**



1 CLIQ Unit
U_0=500 V
C=28.2 mF

Very similar performance **varying C and U_0**



$$\frac{P_{IF}}{vol} \propto \left(\frac{U_0}{L_{eq}}\right)^2$$

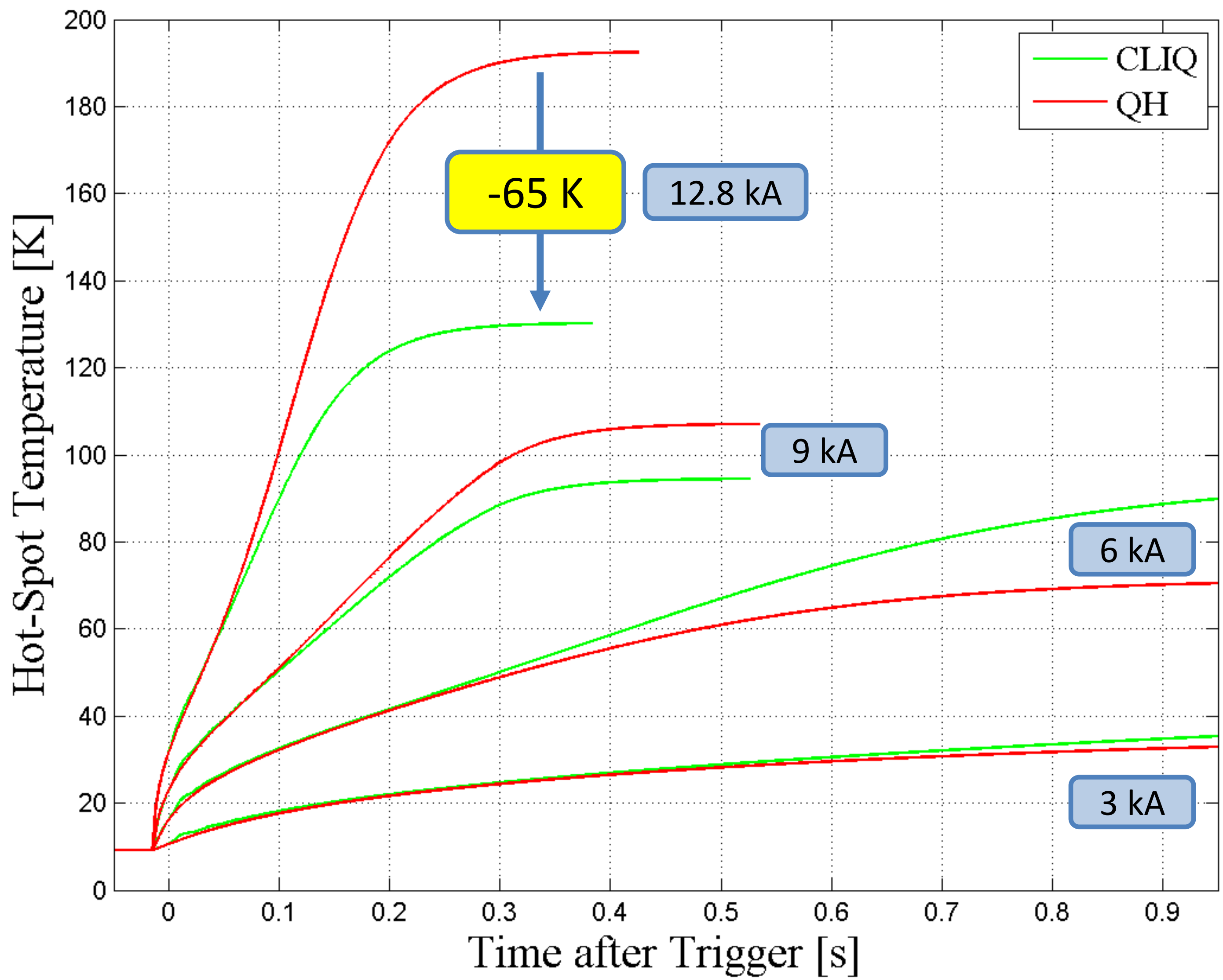
$$I_{C,peak} \propto U_0 \cdot \sqrt{\frac{C}{L_{eq}}}$$

$$f = \frac{1}{2\pi\sqrt{L_{eq} \cdot C}}$$

Energy stored in CLIQ-C2 is about 60% less than CLIQ-C1, but similar performance

MQXC2

Significant reduction of **hot-spot temperature**



Optimum CLIQ discharge configuration – 1-CLIQ

	P1	P2	P3	P4
P1	Ls	Mc	Mf	Mc
P2	Mc	Ls	Mc	Mf
P3	Mf	Mc	Ls	Mc
P4	Mc	Mf	Mc	Ls

Self and Mutual inductance of the 4 poles of a quadrupole magnet

$$L_{mag} = 4L_s + 8M_c + 4M_f$$

8.4 mH

Ls Self inductance of one pole

Mc Mutual ind between close poles

Mf Mutual ind between front poles

Ls > Mc

Mc > 0

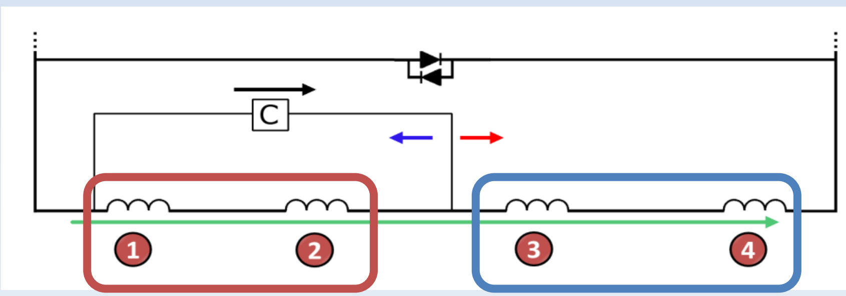
Mf < 0

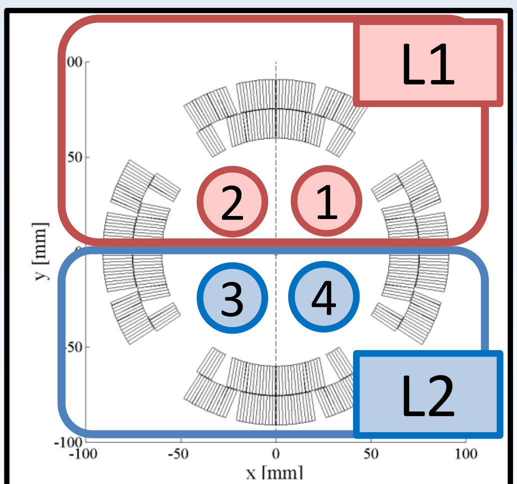
MQXC2

+1.6 mH

+0.4 mH

-0.2 mH



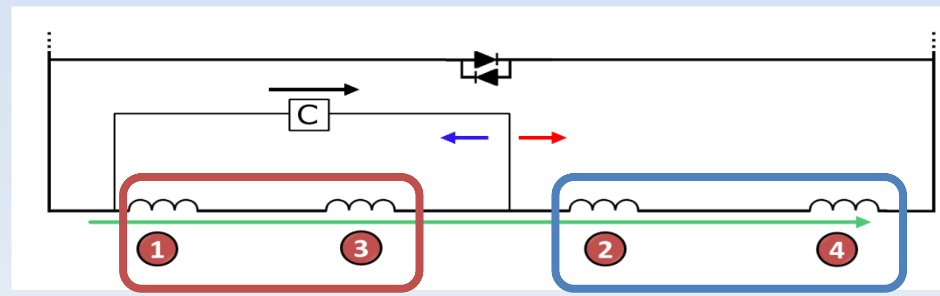


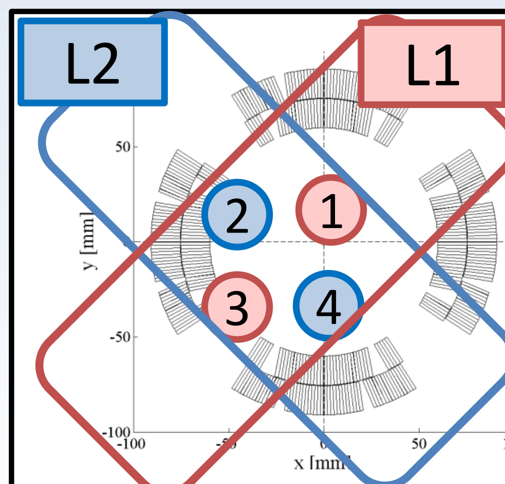
P12-P34

$$L_{eq} = L_s - M_f$$

MQXC2

1.8 mH





P13-P24

$$L_{eq} = L_s - 2M_c + M_f$$

MQXC2

0.6 mH

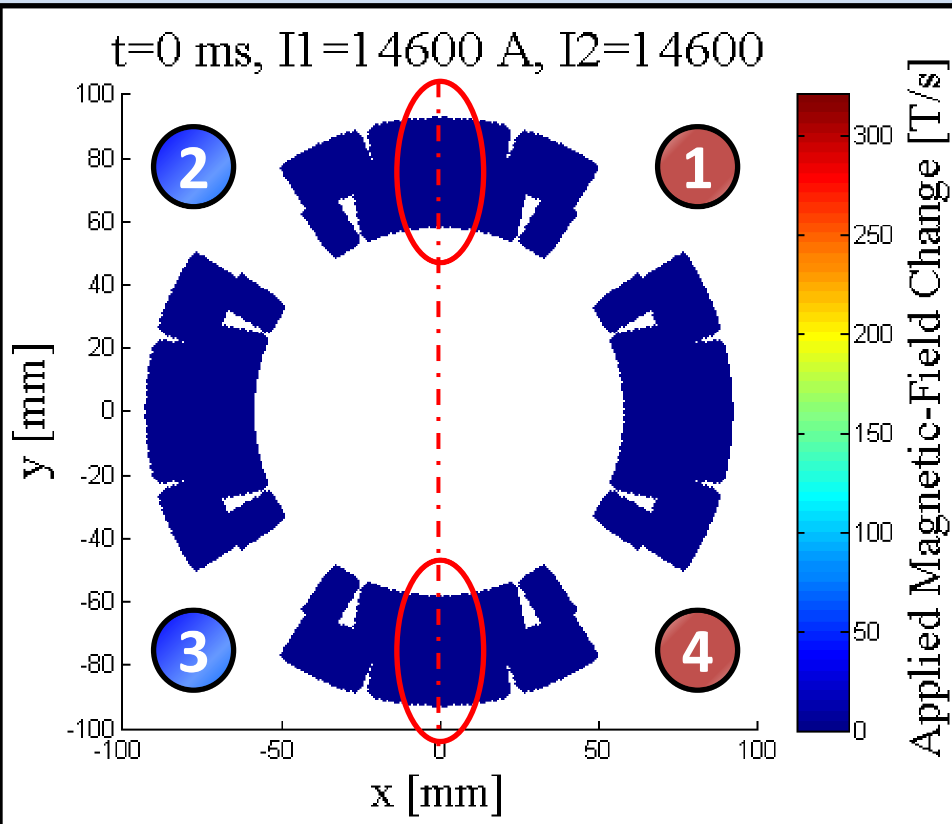
3 times smaller

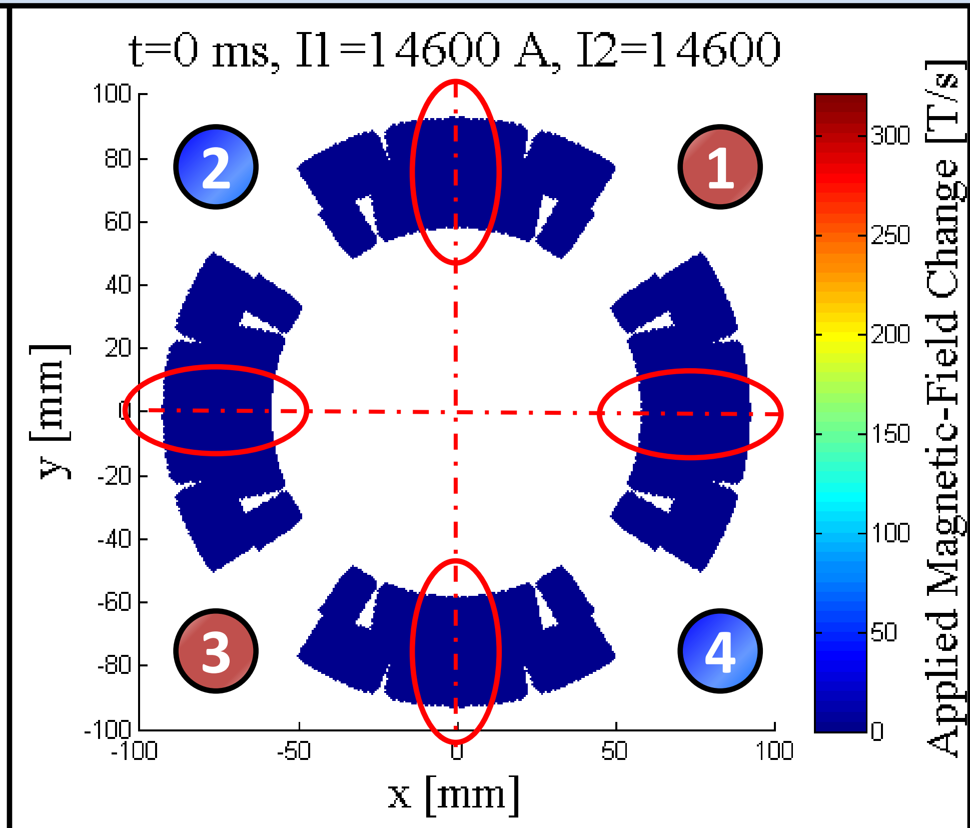
Optimum CLIQ discharge configuration

Efficient magnetic-field change

P12-P34

P13-P24



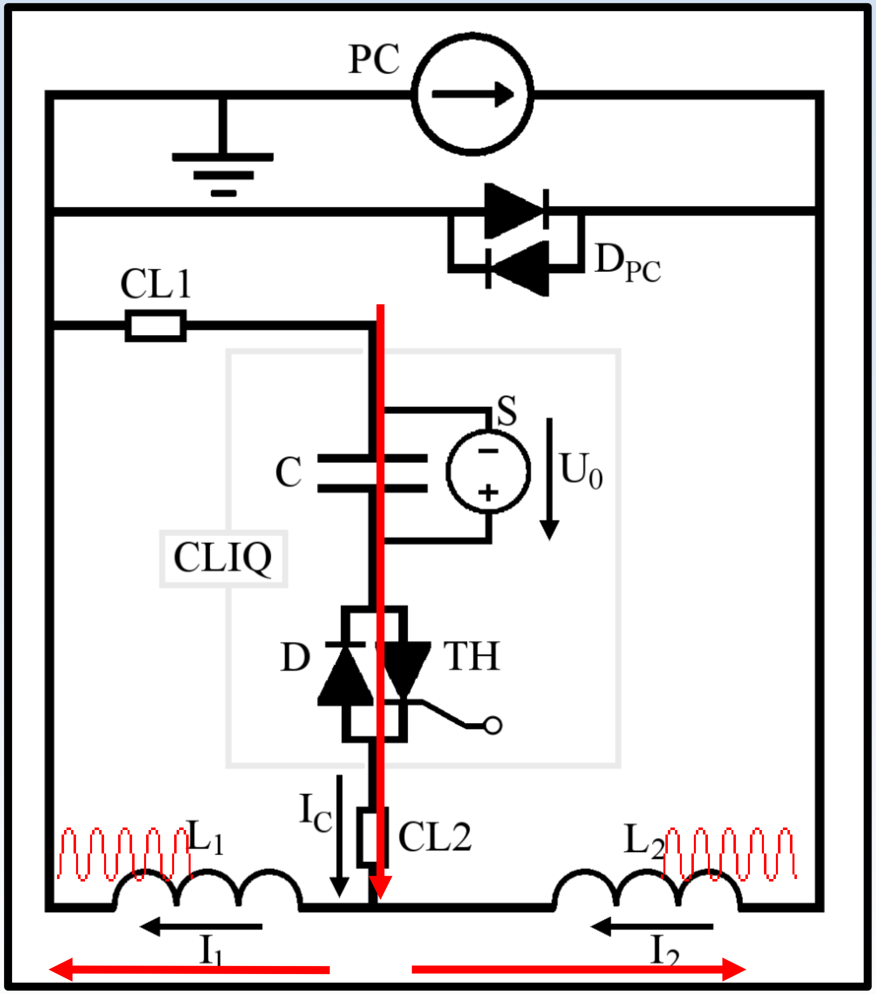


At the edges of two coils with opposite current change the magnetic-field change generated by the two coils superpose, thus creating a region with **very high local magnetic-field change**. Choosing configuration **P13-P24** creates **4 such regions** (instead of 2). This result, combined with the reduced equivalent inductance of the circuit, greatly enhances the CLIQ performance.

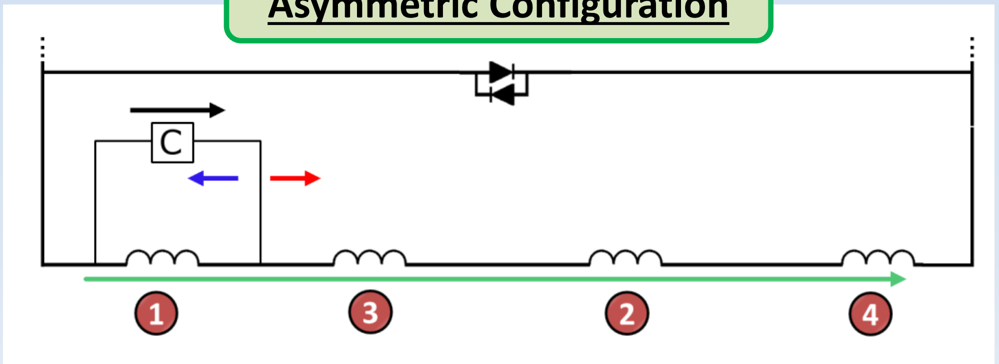
CLIQ Symmetric/Asymmetric Configuration

CLIQ
Coupling-Loss Induced Quench

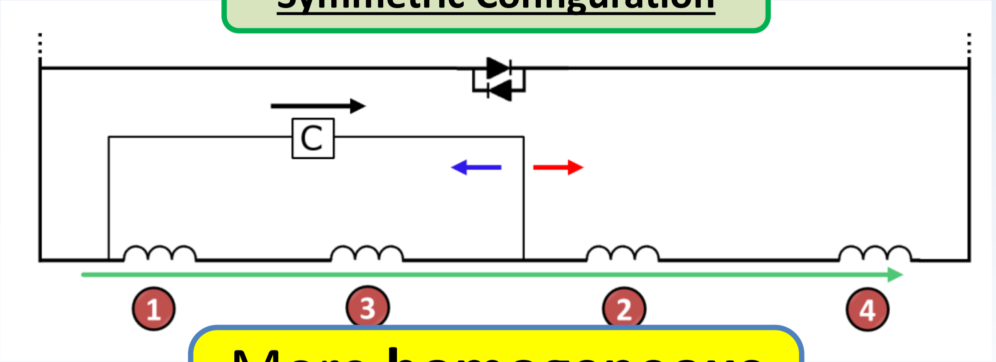
Principle: When subjected to a magnetic field change, **coupling losses** occur in superconducting wires and cables. These losses are **heat** generated directly in the superconductor to quench!



2013 Test campaign
Asymmetric Configuration



2014 Test campaign
Symmetric Configuration



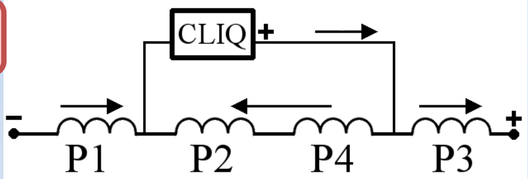
More **homogeneous** energy deposition

Multi-CLIQ – 2 CLIQ units, 4 CLIQ units, N_C CLIQ units…

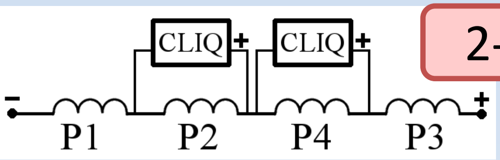
L_{eq} can be reduced by further subdividing the electrical circuit into N_E elements, effectively in parallel when CLIQ is triggered.
They can be **magnets** in a chain, **poles** of a magnet, or inner/outer **layers** of each pole.

Peak power deposition proportional to **N_C^2**

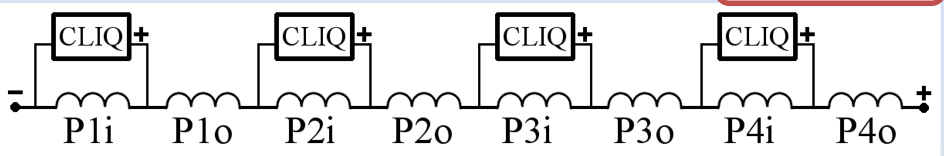
1-CLIQ



2-CLIQ

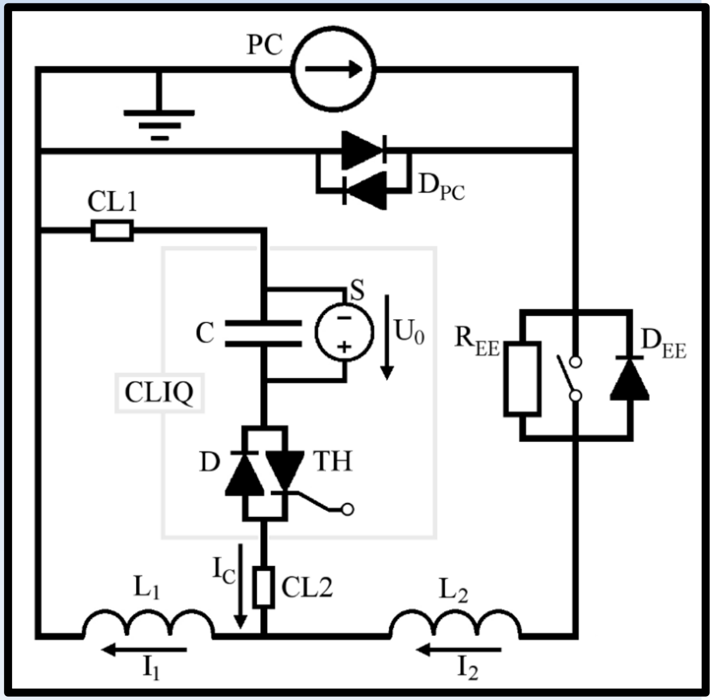


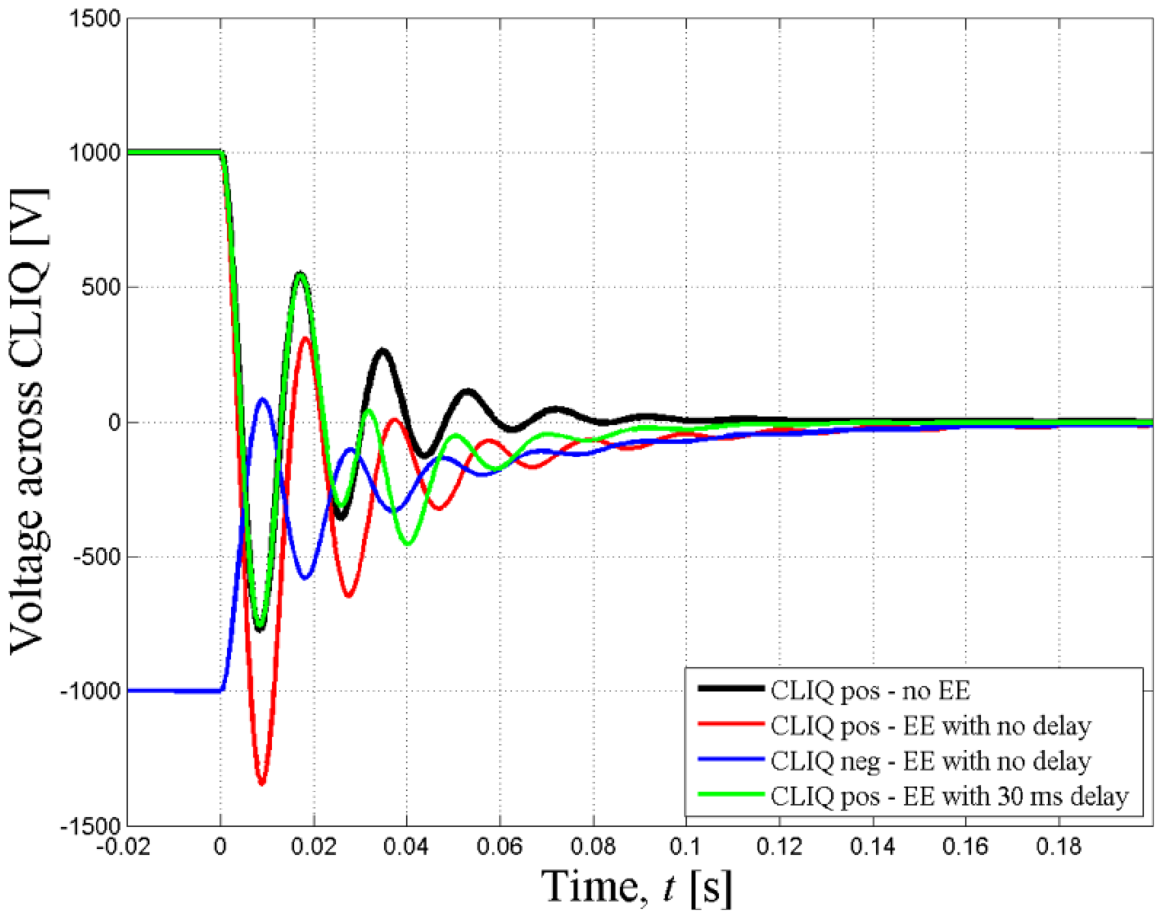
4-CLIQ



Parameter	1 CLIQ	1 CLIQ 2xU_0	2 CLIQ	4 CLIQ	N_C CLIQ
Number of elements, N_E	2	2	4	8	2 N_c
Equivalent inductance, L_{eq}	L_{eq}	=	÷4	÷16	÷N_C^2
Total capacitance, C_{eq}	C	=	x2	x4	xN_C
Charging voltage, U_0	U_0	x2	=	=	=
Peak current change, dI/dt	$U_0/L_{eq}/N_E$	x2	x2	x4	xN_C
Peak deposited loss	∞$(U_0/L_{eq}/N_E)$^2	x4	x4	x16	xN_C^2
Peak AC current, I	∞U_0*sqrt(C_{eq}/L_{eq})/N_E	x2	x$2^{0.5}$	x2	x$N_C^{0.5}$
Frequency, f	1/2/π/sqrt(L_{eq}*C_{eq})	=	x$2^{0.5}$	x2	x$N_C^{0.5}$

Why do we need to delay the triggering of the extraction-system?

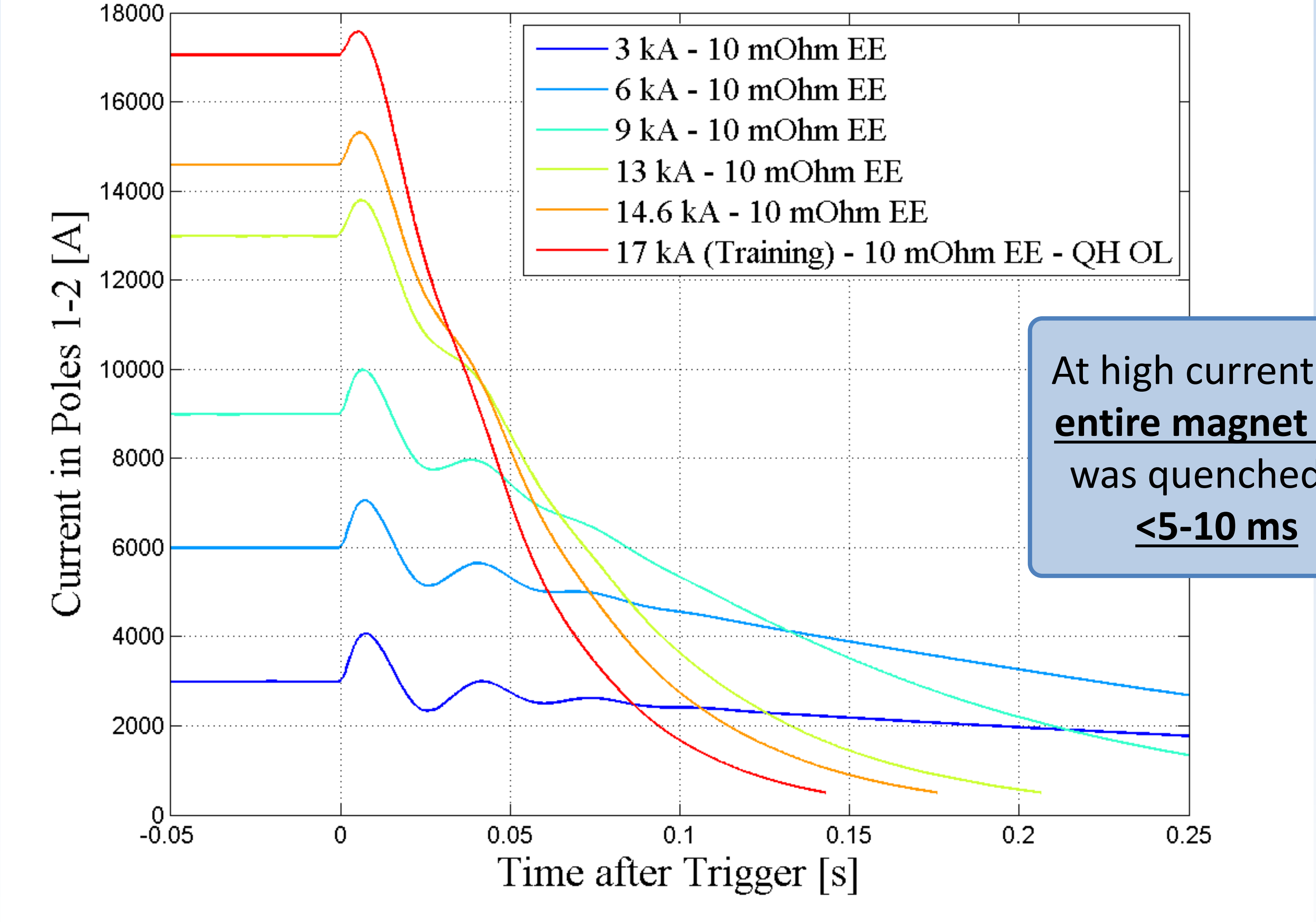




Avoid interference between CLIQ and EE system

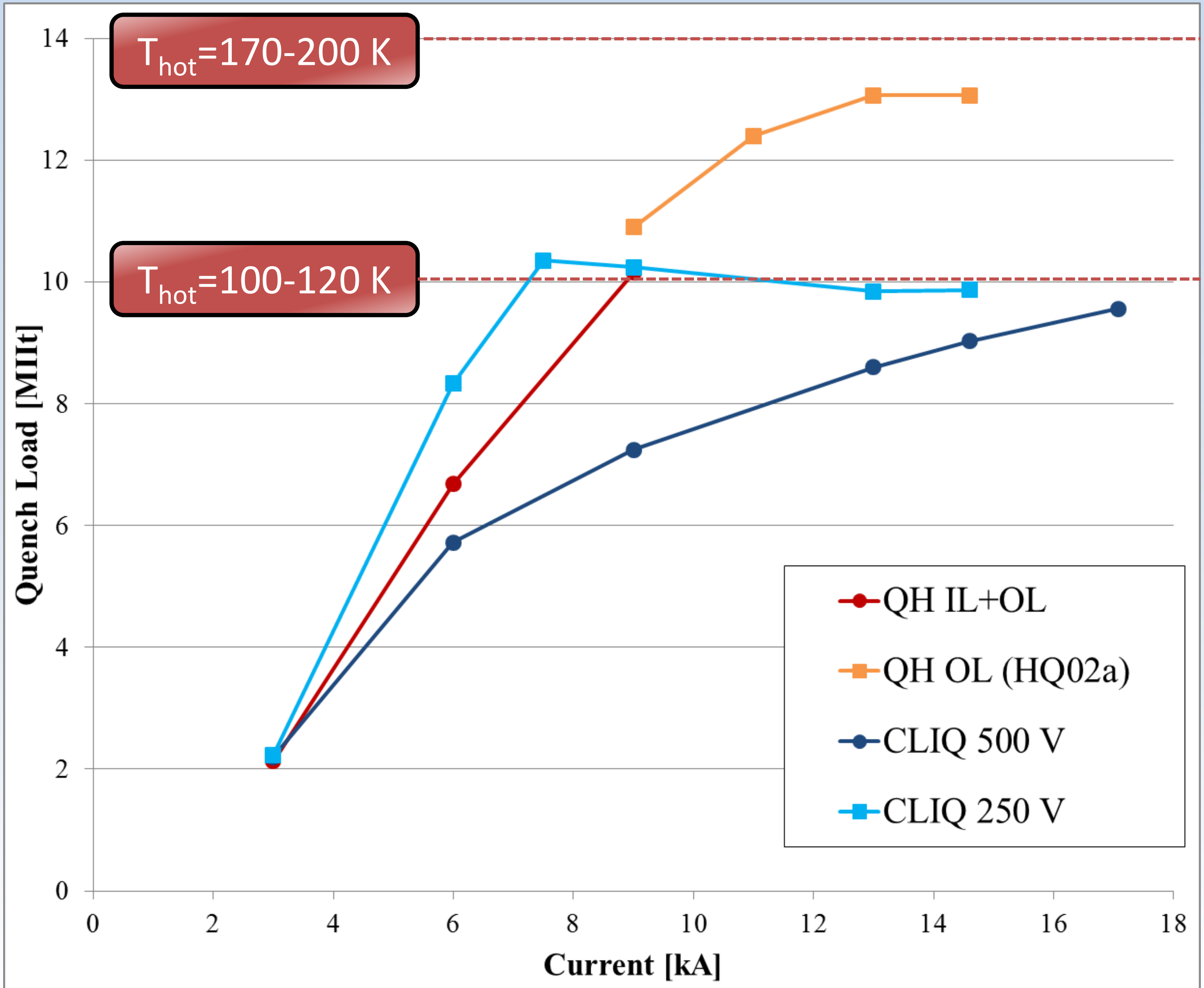
- Avoid superposition of voltage across CLIQ and across EE resulting in voltage too high
- Avoid reducing CLIQ performance

Nb_3Sn Test Results | HQ02b – Nb_3Sn 0.8 meter long quadrupole magnet



At high current the **entire magnet coil** was quenched in **<5-10 ms**

Nb_3Sn — Excellent CLIQ performance (**quench load reduced by 40%)**



CLIQ charged with 500 V shows great performance!
QL<10 MIIt
T_{hot}<100-120 K

CLIQ charged with 250 V (25% nominal power) also shows very good performance
QL<11 MIIt
But below 9 kA quench was difficult to initiate (max QL at 7.5 kA)

No detraining was observed after CLIQ

This performance was achieved with a **not optimized** CLIQ discharge circuit!