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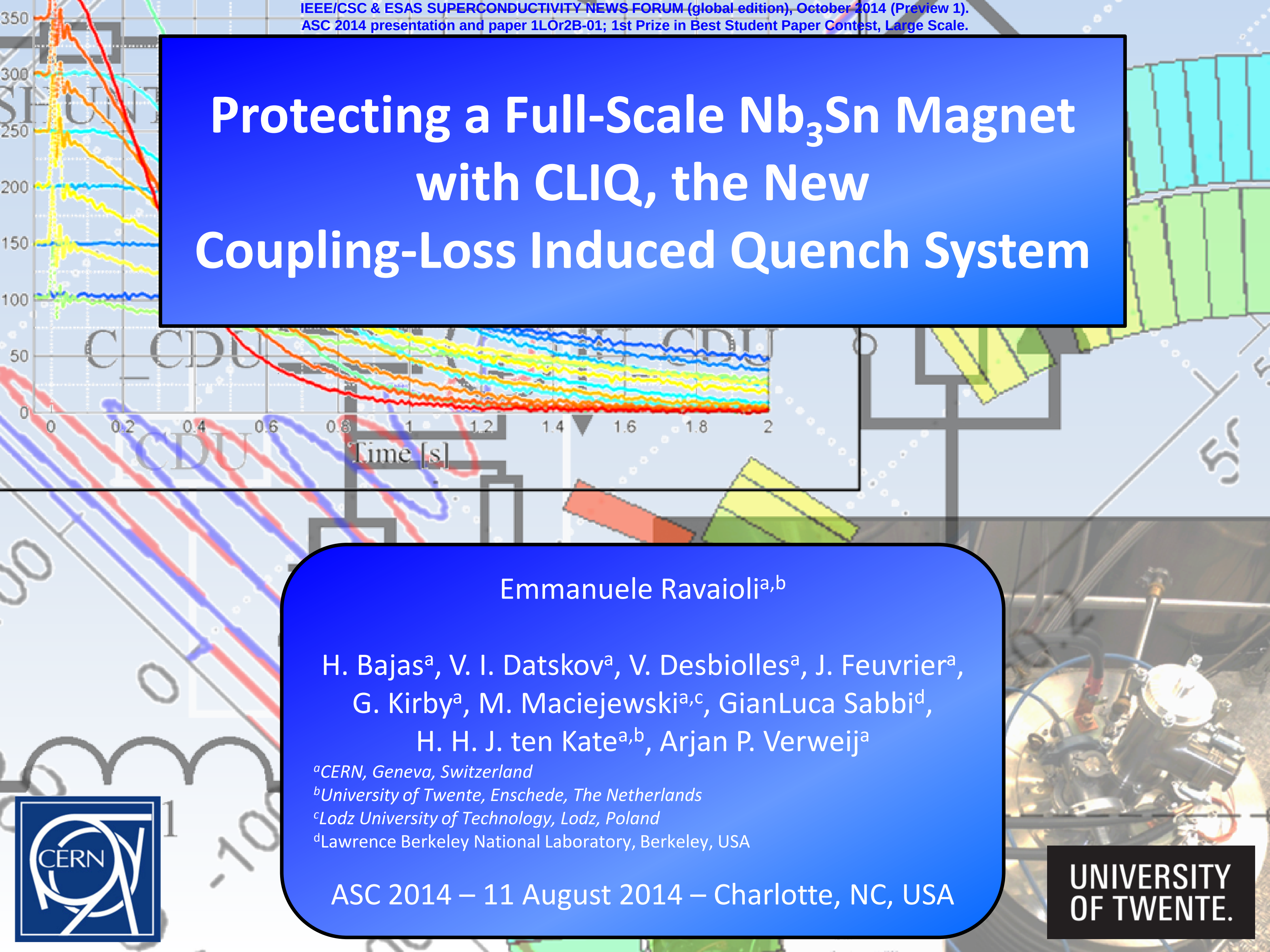

Protecting a Full-Scale Nb_3Sn Magnet with CLIQ, the New Coupling-Loss Induced Quench System

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ASC 2014 – 11 August 2014 – Charlotte, NC, USA

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Protecting a Full-Scale Nb_3Sn Magnet with CLIQ

CLIQ

Coupling-Loss Induced Quench

First CLIQ tests on a Nb_3Sn magnet

Validation of the simulation tools

Optimization strategy

CLIQ-based solution for the protection of full-scale quadrupole magnets

Analyzed case: Quadrupole magnet for the LHC high luminosity upgrade (US-LARP collaboration)

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Quench Protection in a Superconducting Magnet

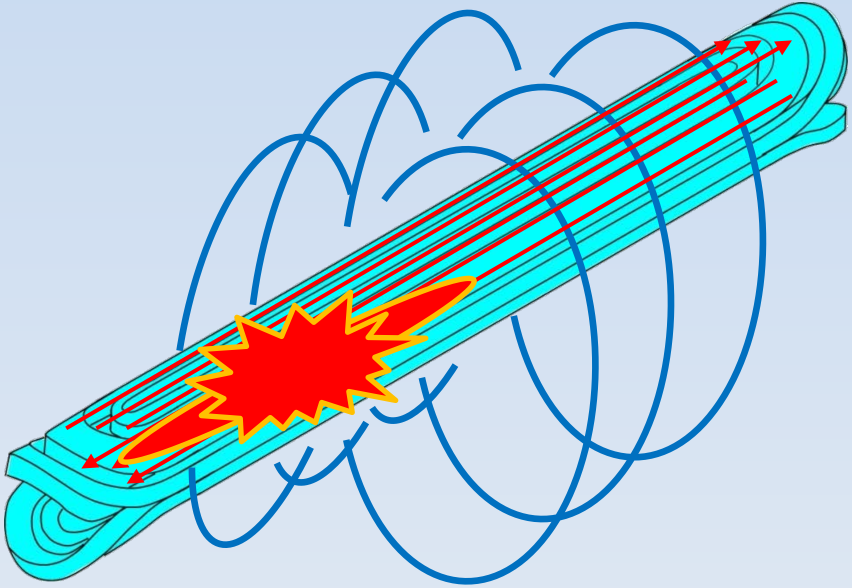
High Current Density
$J \approx kA/cm^2$

High Magnetic Field
B = 5-10 T

High Energy Density
e = B2/(2 μ0) ≈ 10-40 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!



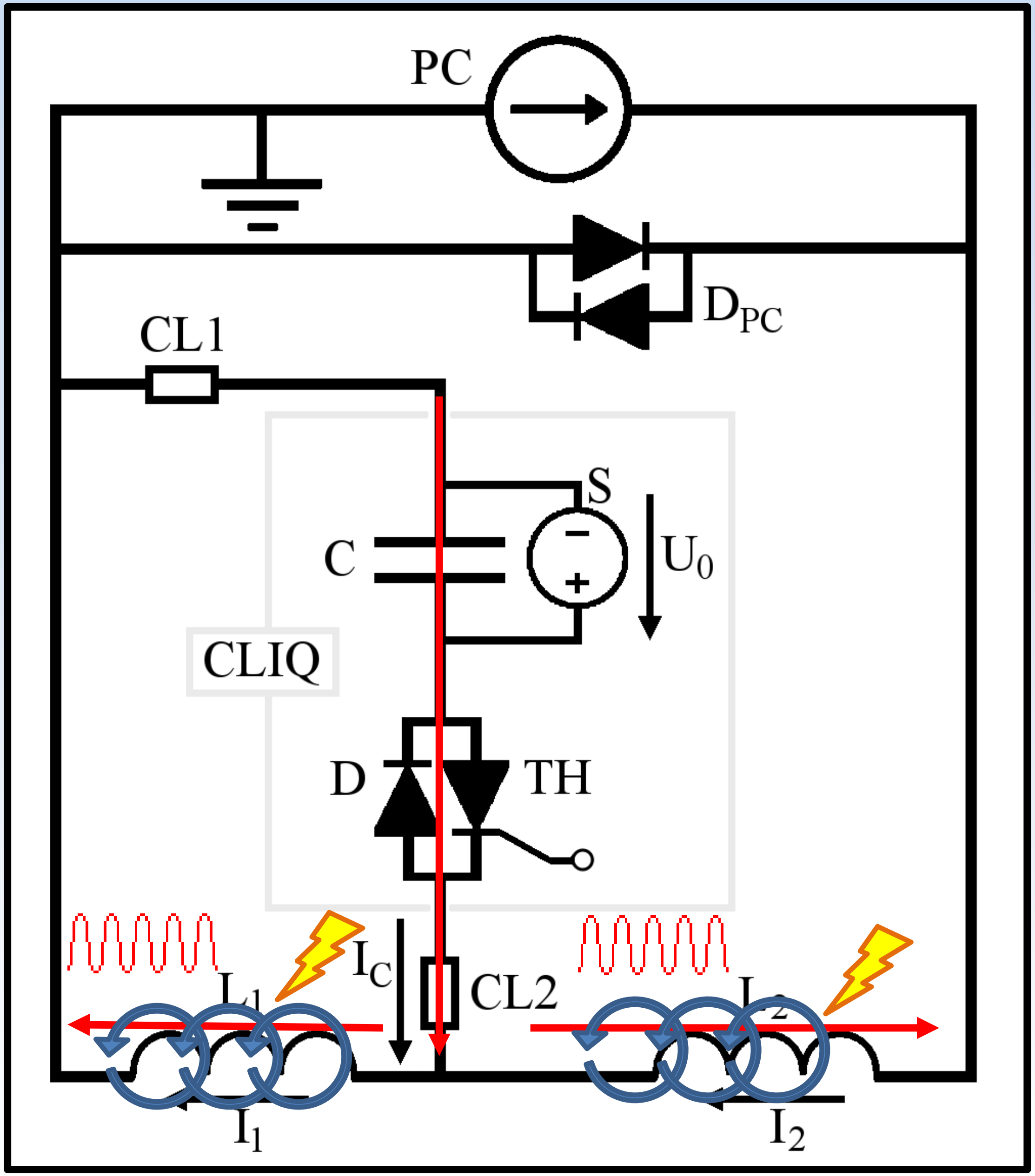
Quick propagation of the quench needed

Homogeneous distribution of the quench energy

Discharge of the magnet current with coil resistance

Conventional **Quench Heaters** may be too **slow** (relying on thermal diffusion across insulation layers) and are prone to **electrical breakdown** (thin insulation)

CLIQ – Coupling-Loss Induced Quench



Current Change

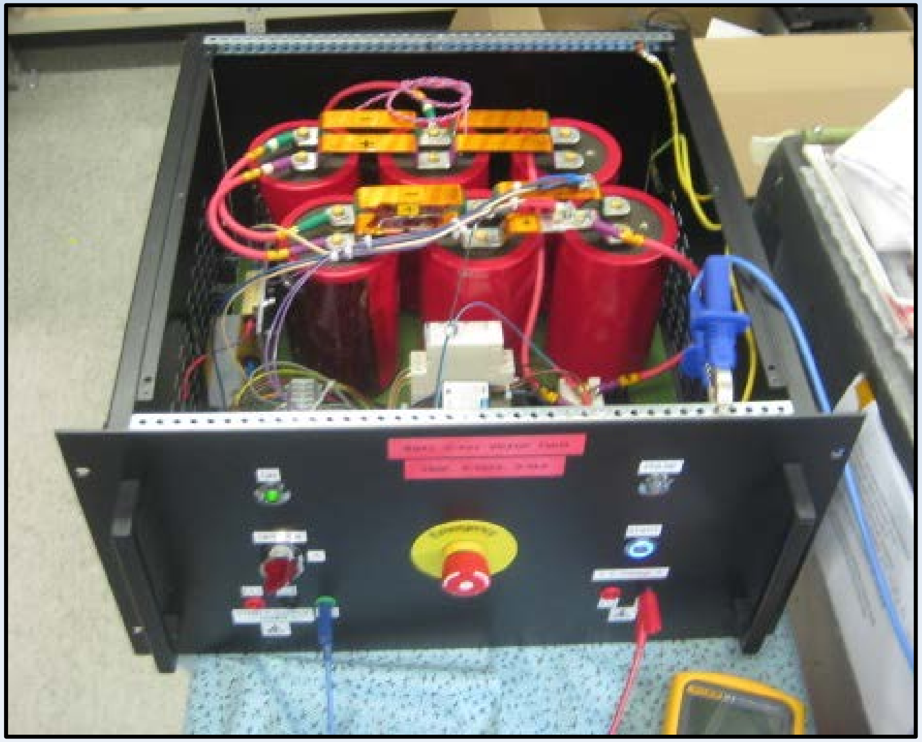
Magnetic Field Change

Coupling Losses (Heat)

Temperature Rise

QUENCH

CLIQ – Main Advantages



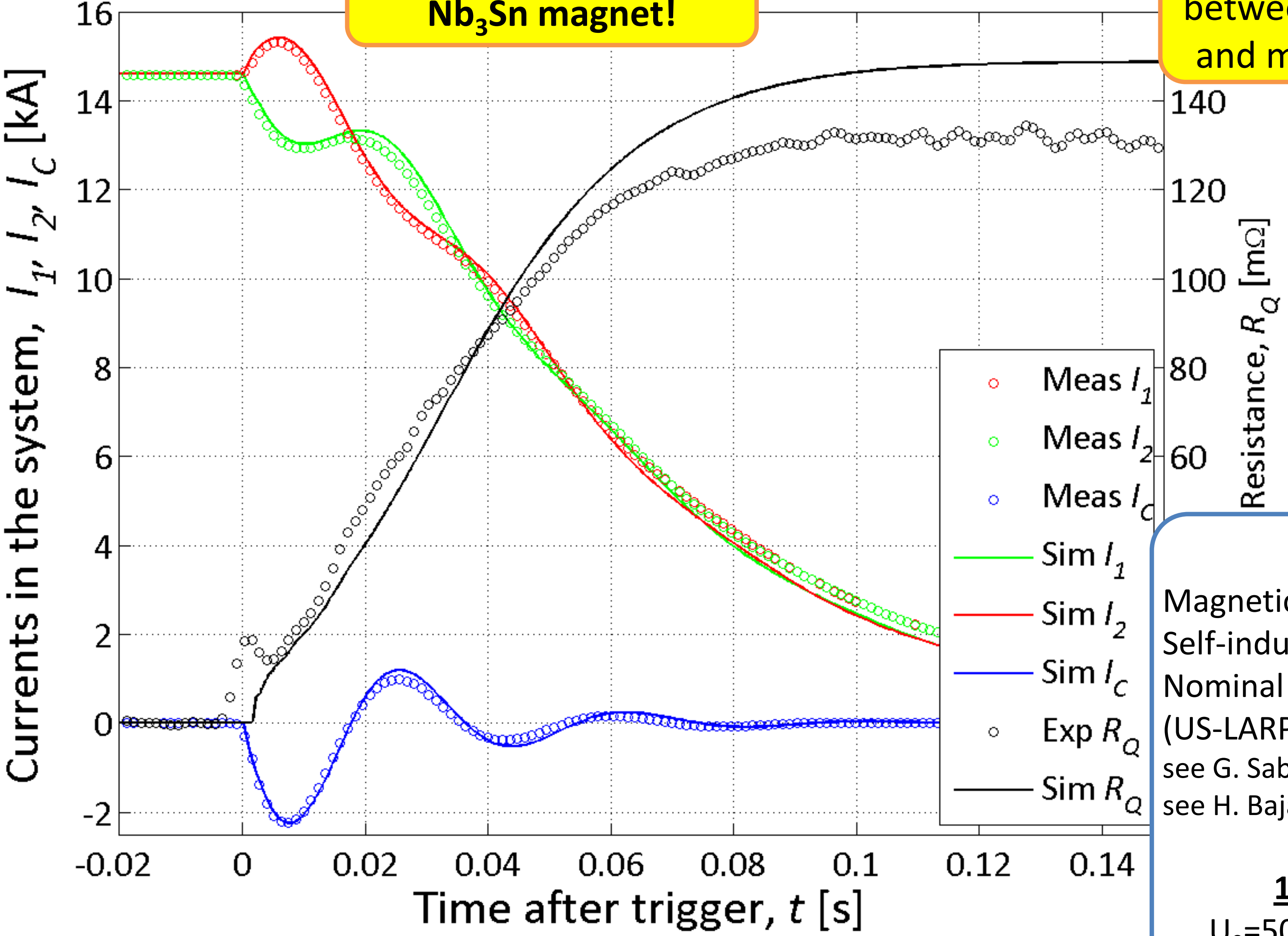
- More **efficient** energy deposition
- **Faster** and more **homogeneous** quench initiation
- **More robust** design
- **Easier** to implement and repair
- Lower expected **failure rate**
- **External** system not interfering with the coil winding technology
- Possible to use CLIQ as a **back-up solution**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

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

CLIQ tests on the model magnet for the LHC high luminosity upgrade

First CLIQ tests on a Nb_3Sn magnet!

Excellent agreement between simulations and measurements



HQ02b

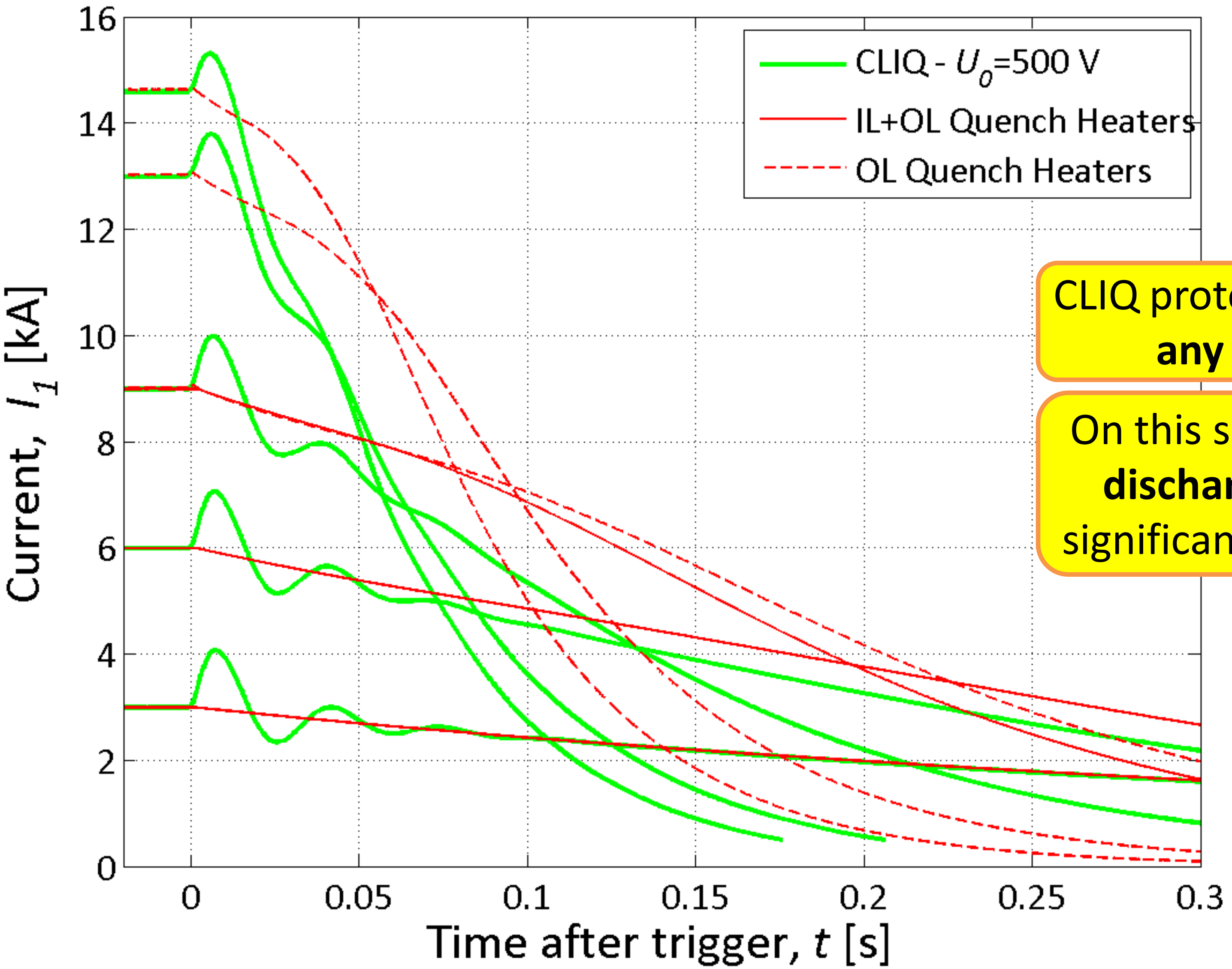
Magnetic Length	0.8 m
Self-inductance	6.4 mH
Nominal current	14.6 kA

(US-LARP collaboration)
see G. Sabbi, 1LOr2B-02
see H. Bajas, 4LPo2E

1 CLIQ Unit

U_0=500 V C=28.2 mF

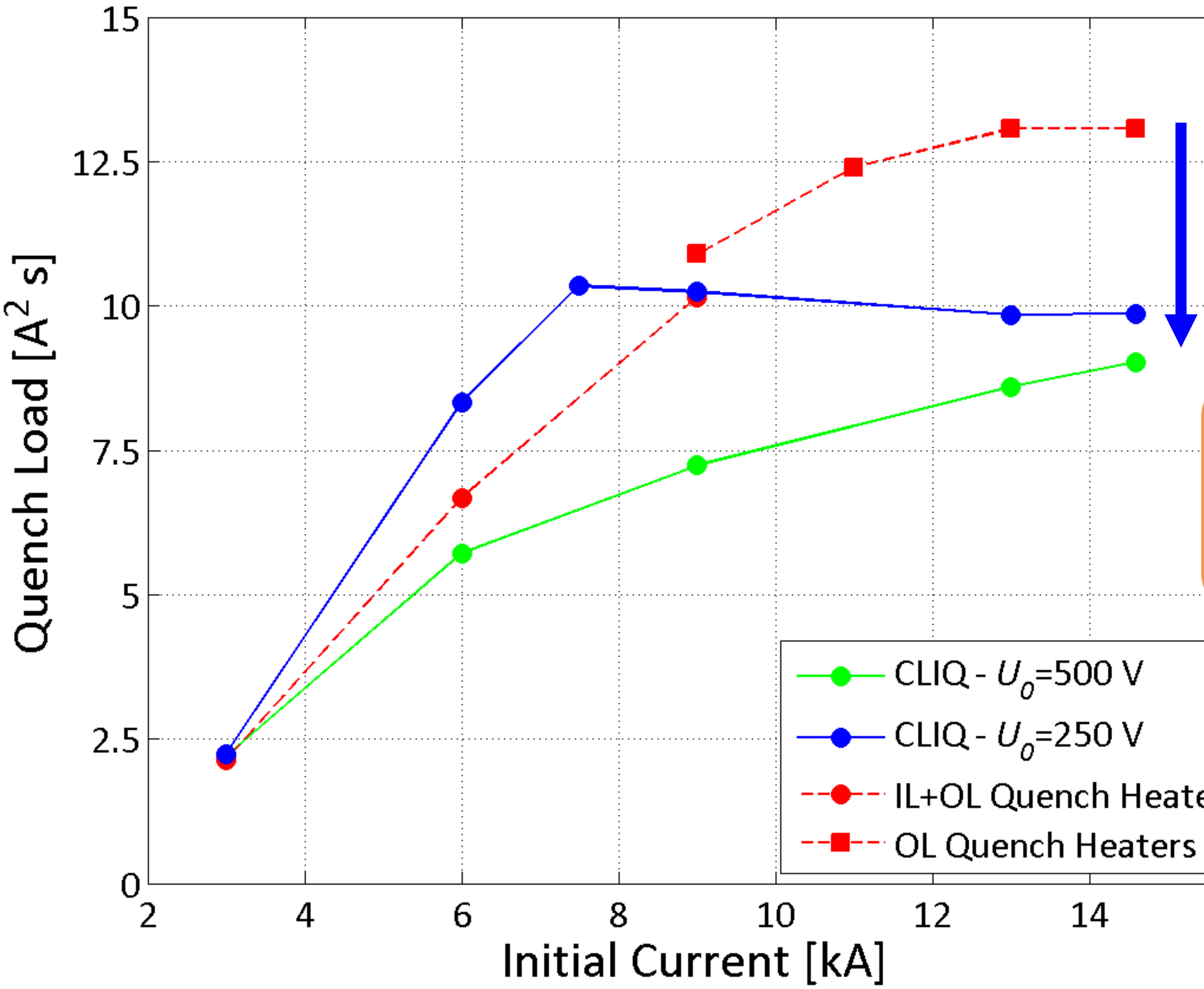
Comparison with Quench Heaters performance



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

On this short magnet CLIQ **discharges** the magnet significantly **faster** than QH

Summary of CLIQ and QH performance on the model magnet



At nominal current quench load **reduced by ~30%** using CLIQ

However, CLIQ performance strongly depends on the magnet length

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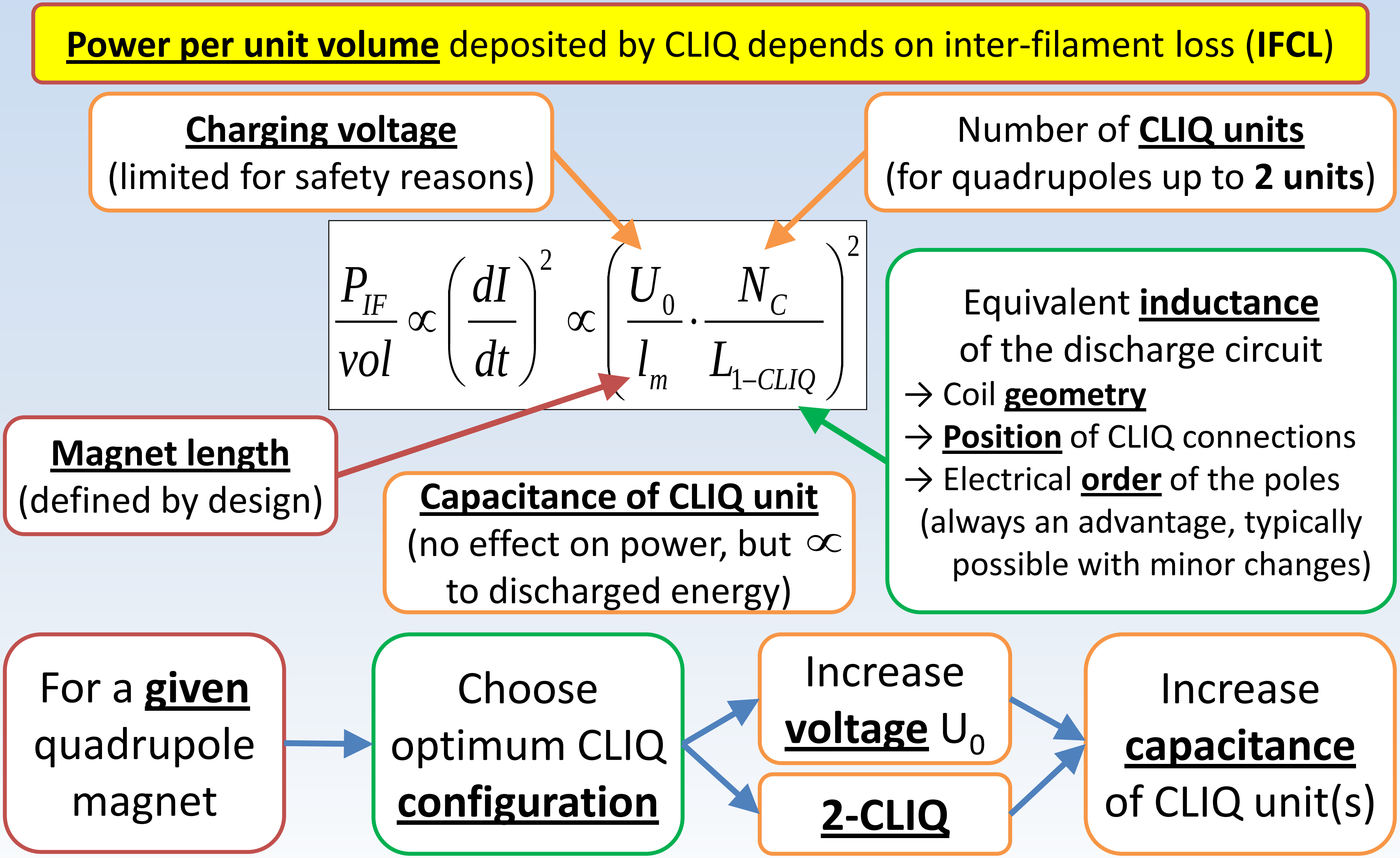
Protecting full-scale magnets with CLIQ – The strategy



<u>Power per unit volume</u> deposited by CLIQ depends on inter-filament loss (**IFCL**)

<u>Charging voltage</u>
(limited for safety reasons)

Number of **<u>CLIQ units</u>**
(for quadrupoles up to **2 units**)

$$\frac{P_{IF}}{vol} \propto \left(\frac{dI}{dt}\right)^2 \propto \left(\frac{U_0}{l_m}\cdot\frac{N_C}{L_{1-CLIQ}}\right)^2$$

Equivalent **<u>inductance</u>**
of the discharge circuit
→ Coil **<u>geometry</u>**
→ **<u>Position</u>** of CLIQ connections
→ Electrical **<u>order</u>** of the poles
(always an advantage, typically possible with minor changes)

<u>Magnet length</u>
(defined by design)

<u>Capacitance of CLIQ unit</u>
(no effect on power, but $\propto$ to discharged energy)

For a **<u>given</u>** quadrupole magnet

Choose optimum CLIQ **<u>configuration</u>**

Increase **<u>voltage</u>** U_0

<u>2-CLIQ</u>

Increase **<u>capacitance</u>** of CLIQ unit(s)

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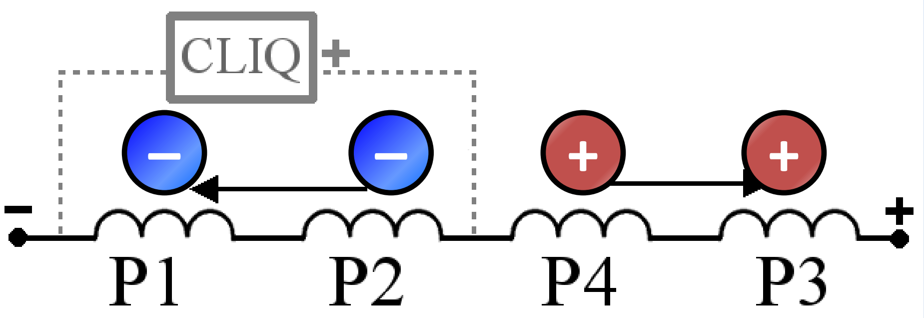
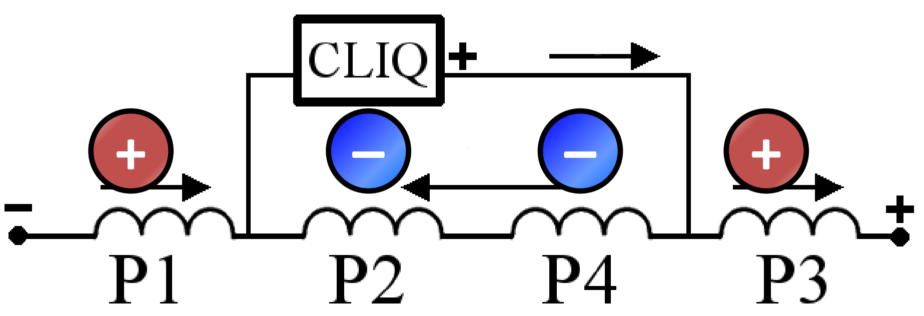
Optimum CLIQ discharge configuration -1

Not Optimized



Optimized



Significant **reduction** of L_{eq} (2.5-3 times!)
→ Increase of deposited loss (6-9 times!)

$$\frac{P_{IF}}{vol} \propto \left(\frac{dI}{dt}\right)^2 \propto \left(\frac{U_0}{l_m} \cdot \frac{N_C}{L_{1-CLIQ}}\right)^2$$

Golden rule for optimizing any CLIQ discharge circuit

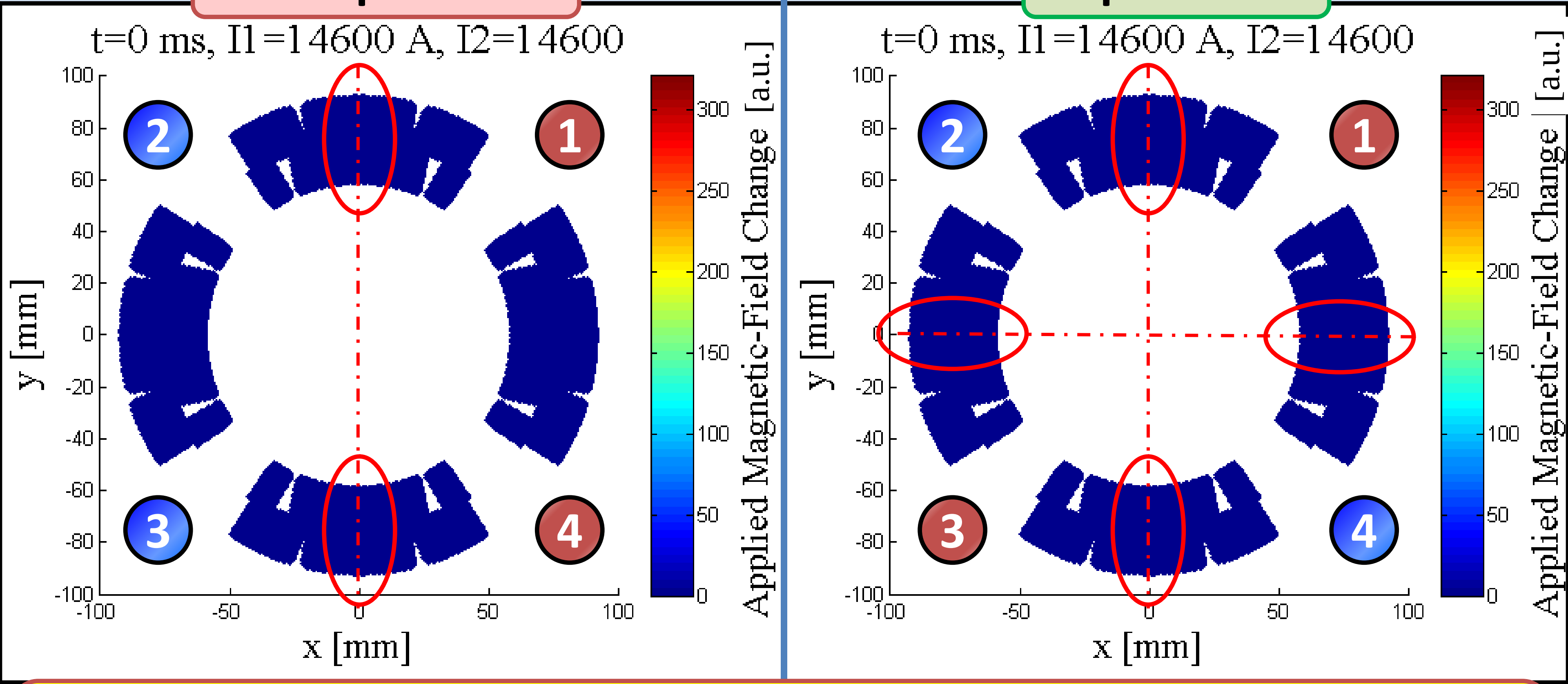
Introduce opposite current change in coils which are physically adjacent

Optimum CLIQ discharge configuration -2

Efficient distribution of magnetic-field change

Not Optimized

Optimized



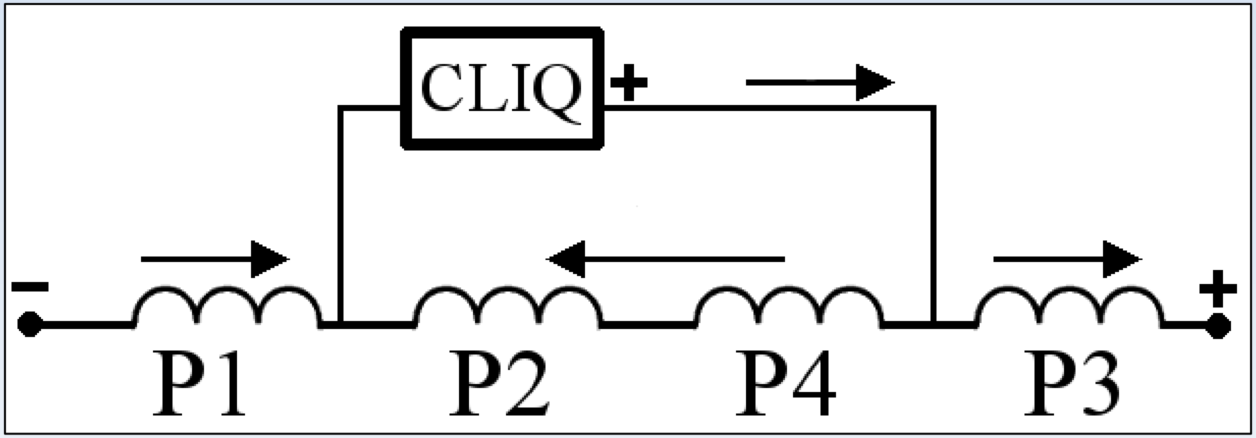
<u>Golden rule for optimizing any CLIQ discharge circuit</u>

Introduce opposite current change in coils which are physically adjacent

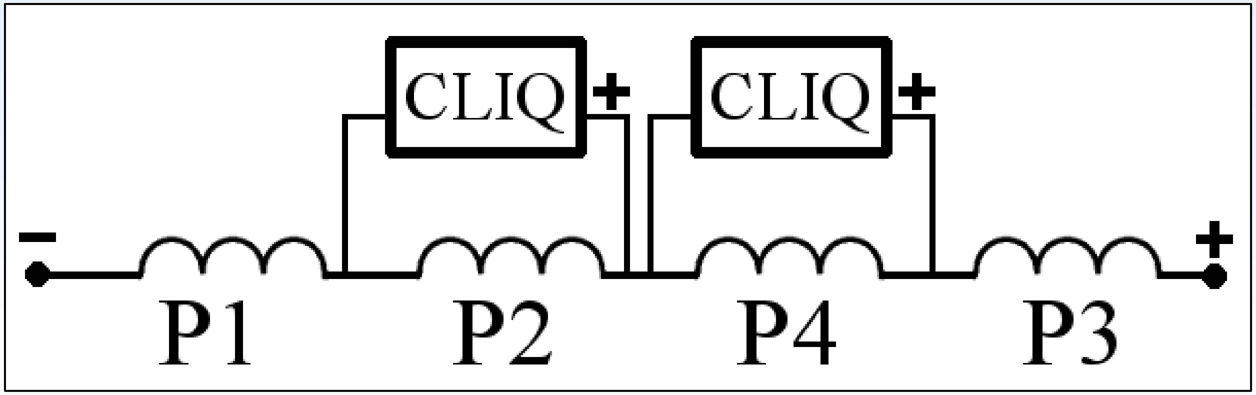
Multi-CLIQ

Further decreasing the impedance of the circuit can be reduced by **subdividing** the electrical circuit into 2xN_C elements, effectively **in parallel** when CLIQ is triggered.

$$\frac{P_{IF}}{vol} \propto \left(\frac{dI}{dt}\right)^2 \propto \left(\frac{U_0}{l_m}\cdot\frac{N_C}{L_{1-CLIQ}}\right)^2$$



1-CLIQ



2-CLIQ

Protecting a Full-Scale Nb_3Sn Magnet with CLIQ

CLIQ tests on the model magnet (HQ02b, 1 m)

Validation of the simulation tools

Optimization strategy

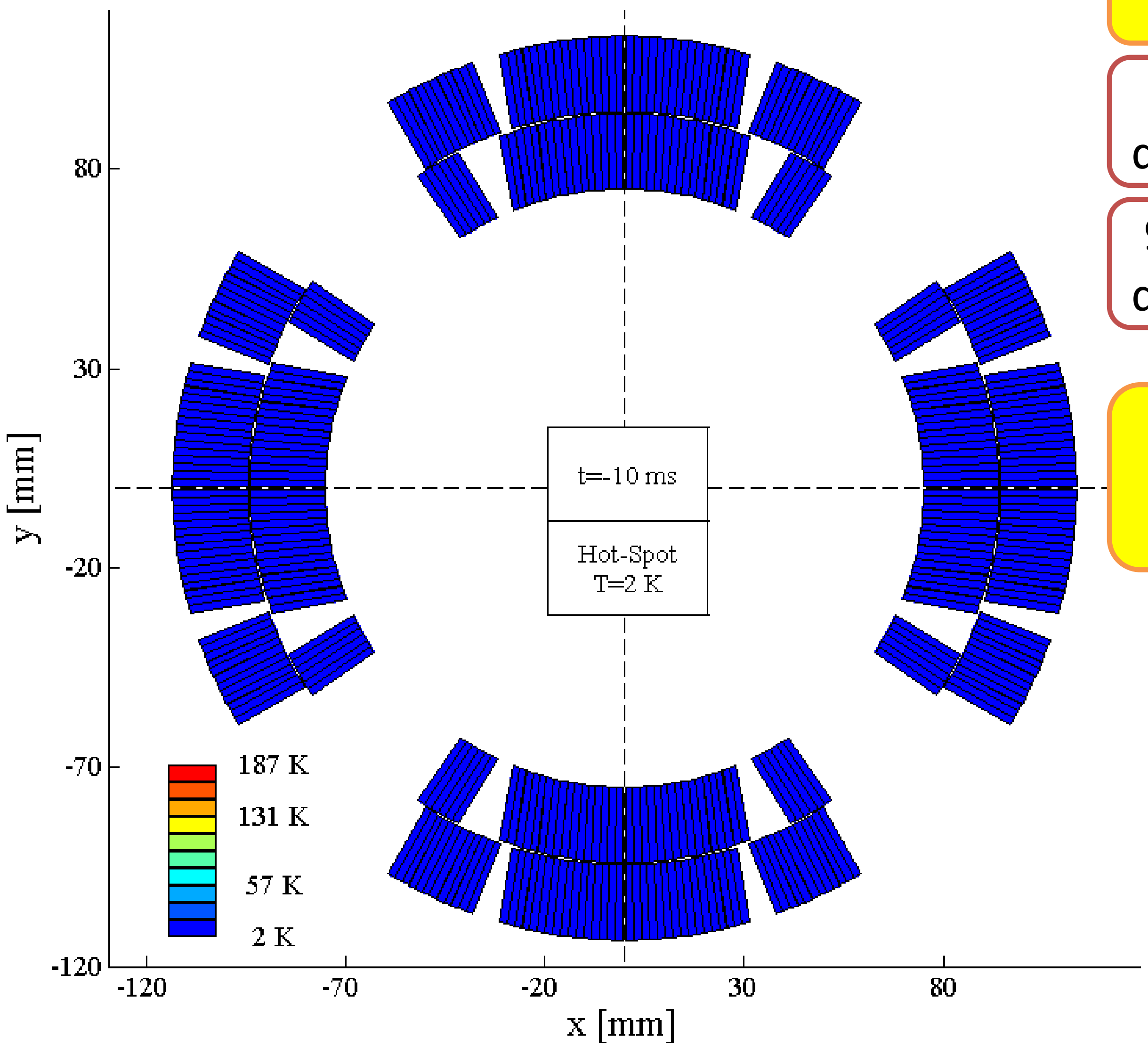
Simulations of the protection the full-scale magnet (MQXF, 7 m) using CLIQ

4 tested configurations

1-CLIQ, 500 V
2-CLIQ, 500 V

1-CLIQ, 1 kV
2-CLIQ, 1 kV

Simulated T profile – I_0=17.3 kA (I_{nom}) – 2-CLIQ, U_0=500 V, C=120 mF



Very fast quench initiation

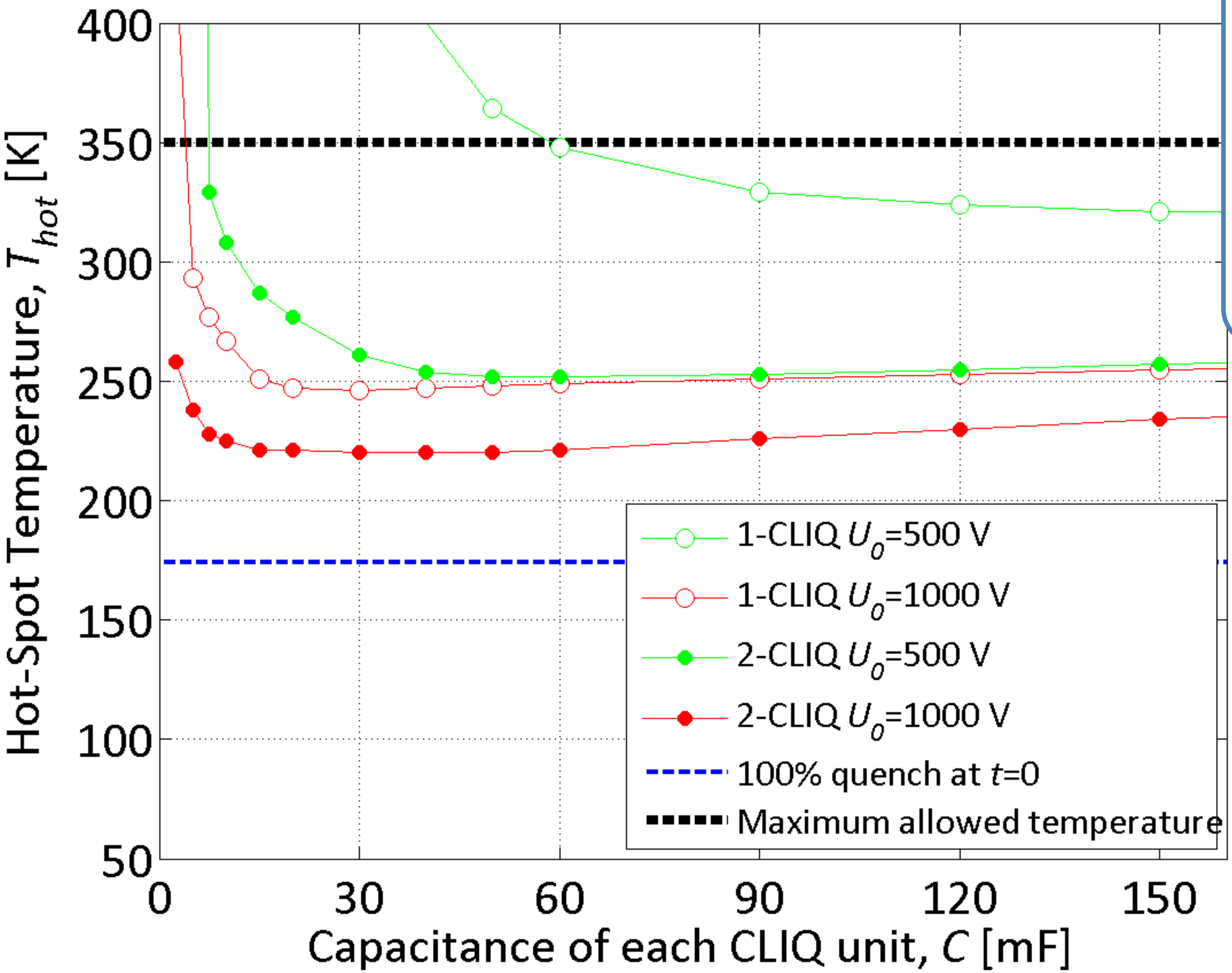
Entire inner layer quenched in **<10 ms**

90% of the magnet quenched in **<40 ms**

Homogeneous temperature distribution

Assumptions: no QH; no EE; RRR=140; 10 ms detection time

Simulation results – I_0 = 17.3 kA (I_{nom})



MQXF

Magnetic Length	6.8 m
Self-inductance	70 mH
Nominal current	17.3 kA

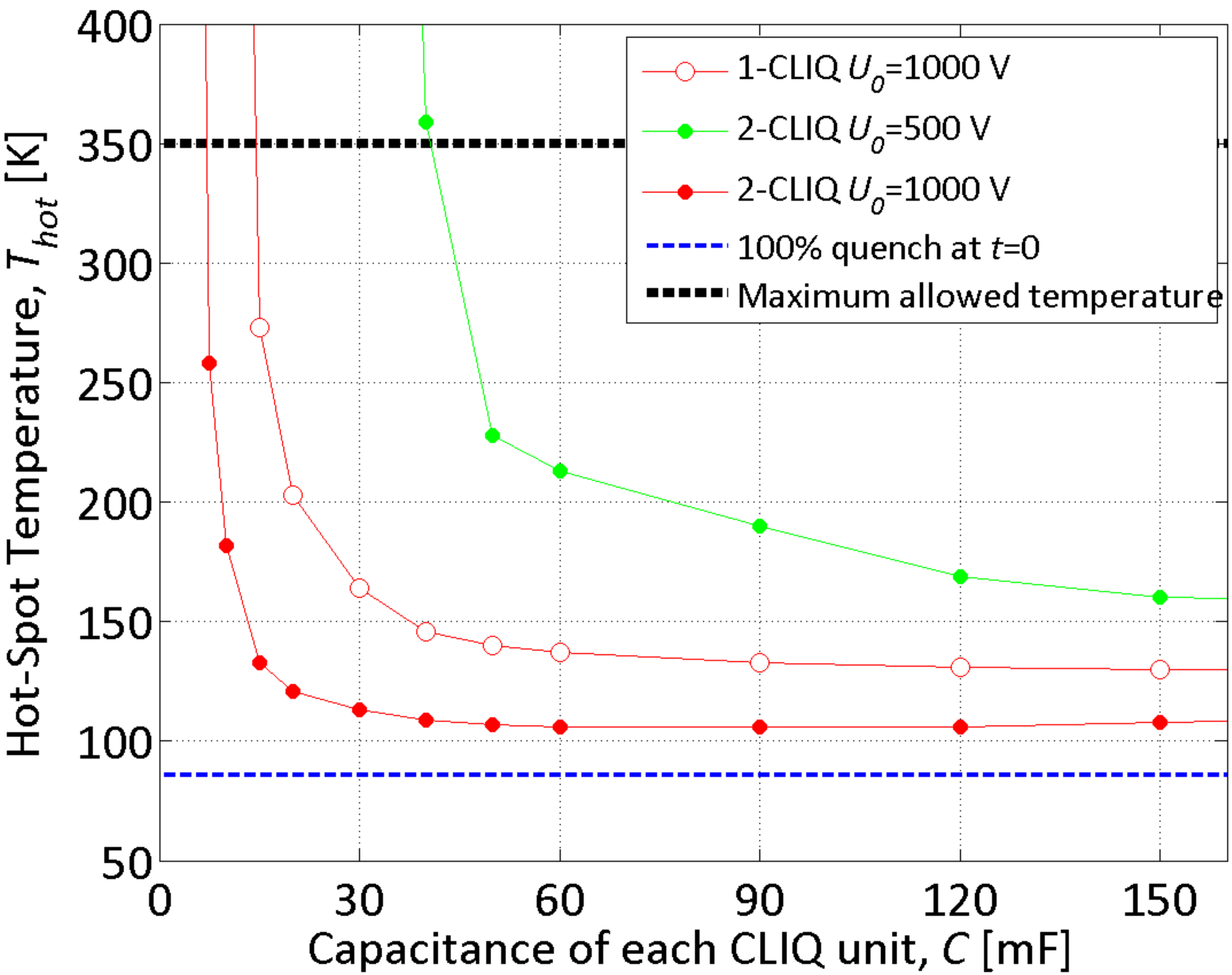
Quadrupole magnet for the **LHC high luminosity upgrade** (US-LARP collaboration)

For each studied configuration a minimum capacitance is needed to protect the magnet

As expected performance of 2-CLIQ-500 V similar to 1-CLIQ-1 kV

Assumptions: no QH; no EE; RRR=140; 10 ms detection time

Simulation results – I_0 = 9 kA (~50% I_{nom})



1-CLIQ-500 V
is not sufficient to protect the full-length magnet

Both 2-CLIQ-500 V and 1-CLIQ-1 kV are **valid protection solutions** for C>50 mF

Assumptions: no QH; no EE; RRR=140; 10 ms detection time

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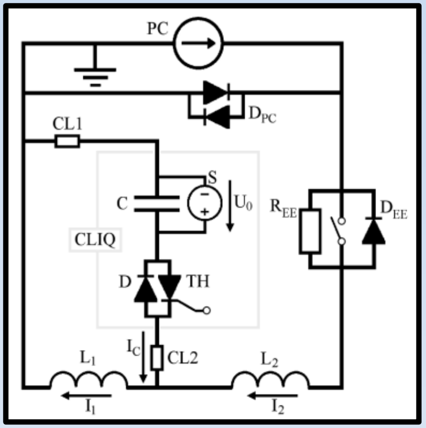
Protecting a Full-Scale Nb_3Sn Magnet with CLIQ -Conclusion

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

First CLIQ tests on the **Nb_3Sn** model magnet for the LHC high luminosity upgrade very successful

Optimization

Optimization strategy for **full-scale** magnets clearly outlined

1. Select **optimum** CLIQ **discharge circuit**

2a. Increase CLIQ **charging voltage**

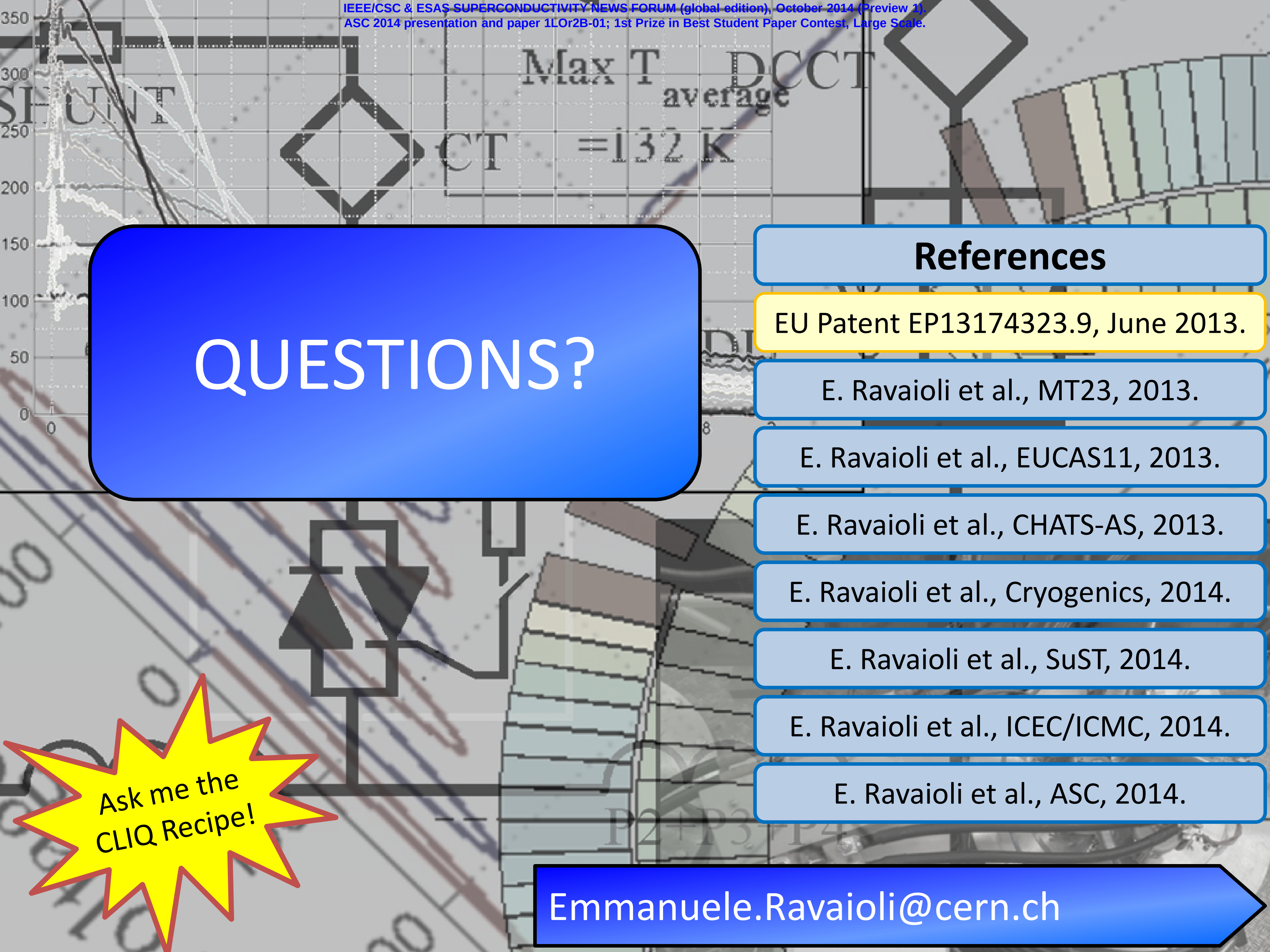
2b. **Multiple** CLIQ units (Multi-CLIQ)

3. Increase CLIQ **capacitance**

$$\frac{P_{IF}}{vol} \propto \left(\frac{dI}{dt}\right)^2 \propto \left(\frac{U_0}{l_m}\cdot\frac{N_C}{L_{1-CLIQ}}\right)^2$$

Simulations show that **CLIQ is a valid solution**
for the protection of the full-scale quadrupole magnet
for the LHC high luminosity upgrade (MQXF)

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



QUESTIONS?

Ask me the CLIQ Recipe!

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Development of a CLIQ-based protection system for the full-scale quadrupole magnet for the LHC high luminosity upgrade

Preliminary Analysis and Simulations

CLIQ tests on the model magnet (HQ02b)

Validation of the simulation tools and further CLIQ optimization

Simulation of CLIQ-based protection the full-scale magnet (MQXF)

TODAY

CLIQ tests on the model magnet (HQ03) with improved CLIQ config

Design of a CLIQ-based protection for MQXF (possible integration with Quench Heaters or Energy Extraction)

<u>Model magnet</u> (HQ02b)

Nb_3Sn Quadruopole Magnet

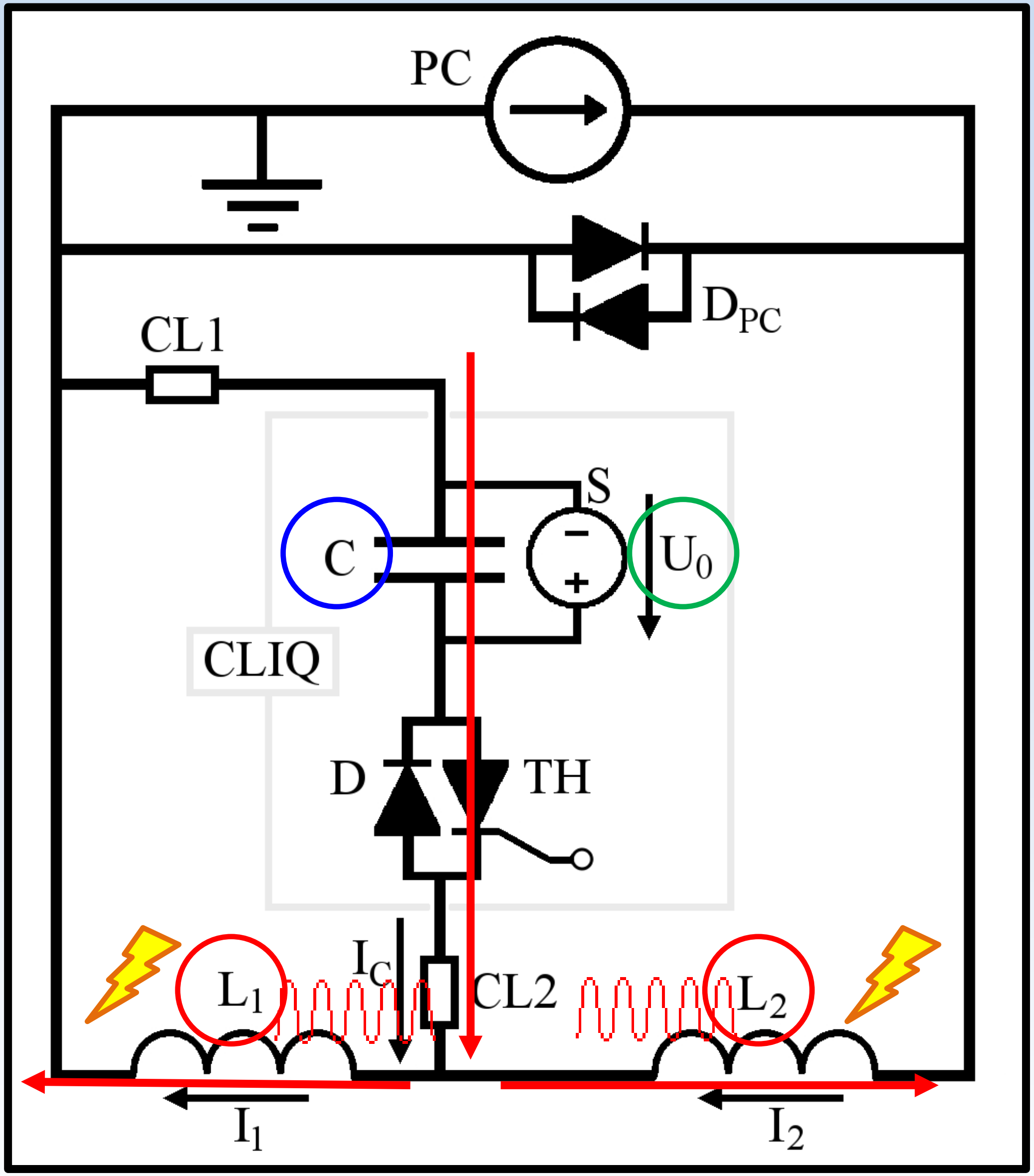
Magnetic Length	0.8 m
Self-inductance	6.4 mH
Nominal current	14.6 kA

<u>Full-length magnet</u> (MQXF)

Nb_3Sn Quadruopole Magnet

Magnetic Length	6.8 m
Self-inductance	70 mH
Nominal current	17.3 kA

CLIQ – Coupling-Loss Induced Quench



Current Change

Magnetic Field Change

Coupling-Losses (Heat)

Temperature Rise

QUENCH

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

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

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

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

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

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

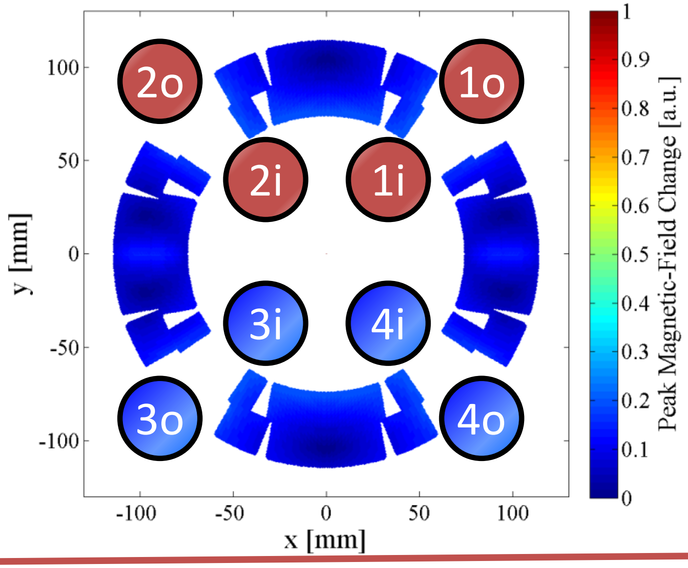
$$\beta_{IF} = \left(\frac{l_p}{2\pi}\right)^2\frac{1}{\rho_{eff}(B)}$$

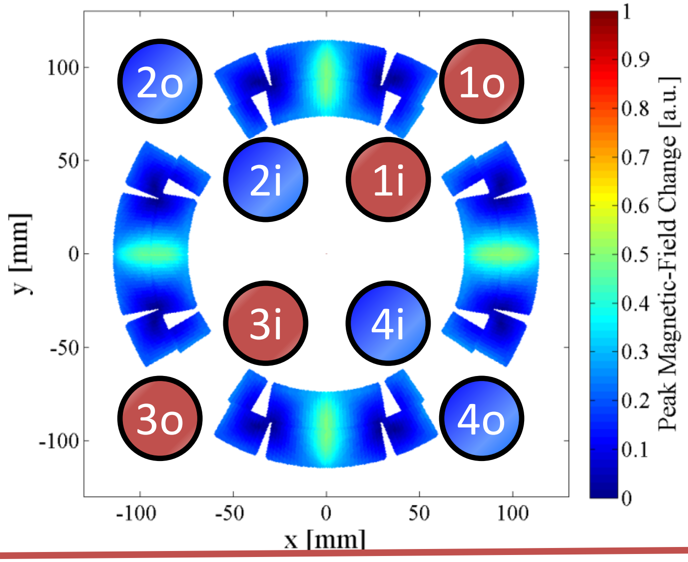
Principle: When subjected to a magnetic field change, **coupling losses** occur in superconducting wires and cables. These losses are **heat** generated directly in the superconductor to quench!

With CLIQ connections at the joint between inner/outer layers

Golden rule for optimizing any CLIQ discharge circuit

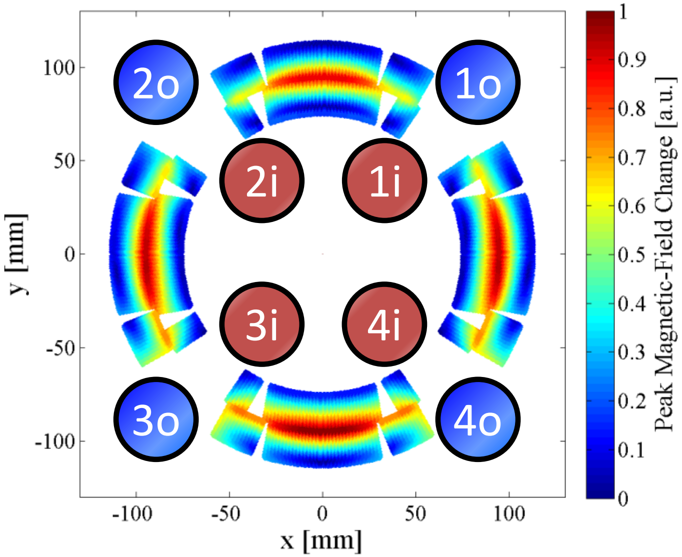
Introduce opposite current change in coils which are physically adjacent

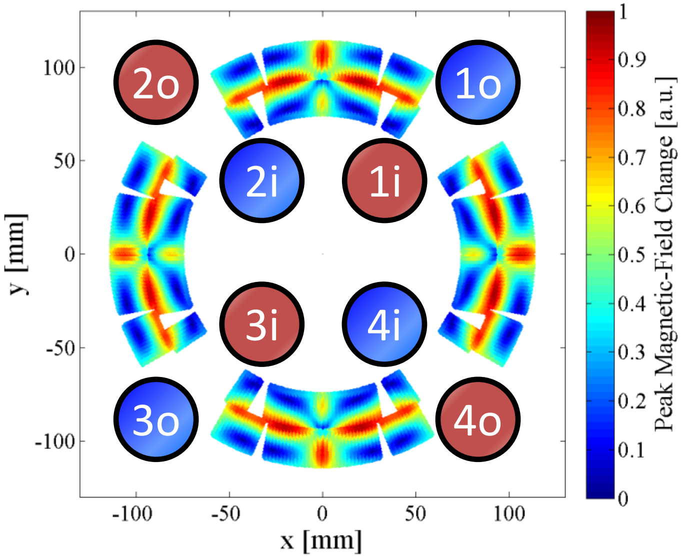




Existing magnets

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





Future magnets

With connections between **in/out layers**

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

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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

Optimum CLIQ discharge configuration – 1-CLIQ

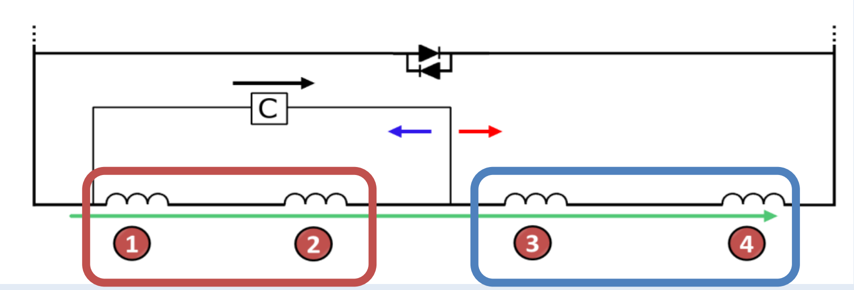
	P1	P2	P3	P4
P1	Ls	Mc	Mf	Mc
P2	Mc	Ls	Mc	Mf
P3	Mf	Mc	Ls	Mc
P4	Mc	Mf	Mc	Ls

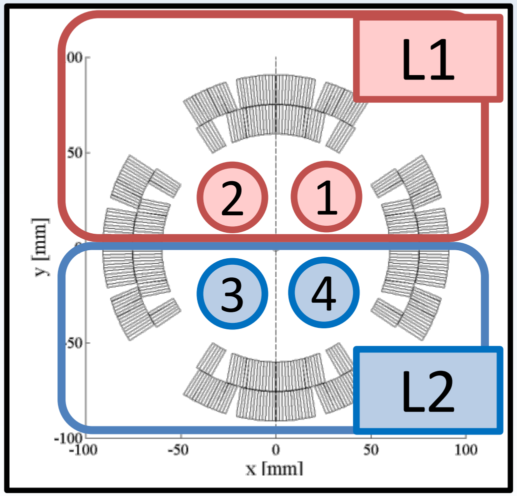
Self and Mutual inductance of the 4 poles of a quadrupole magnet

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

8.4 mH

		MQXC2
Ls Self inductance of one pole	Ls > Mc	+1.6 mH
Mc Mutual ind between close poles	Mc > 0	+0.4 mH
Mf Mutual ind between front poles	Mf < 0	-0.2 mH



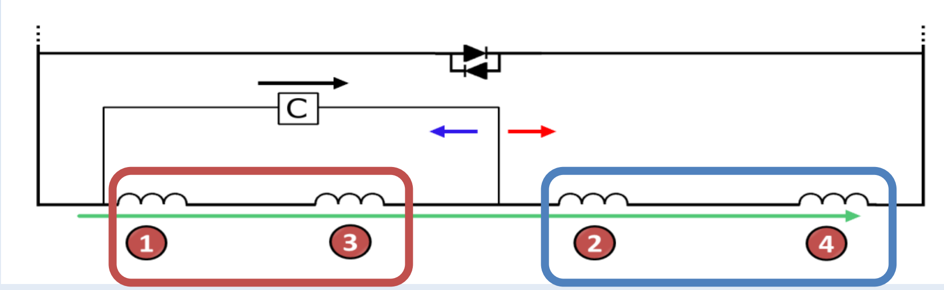


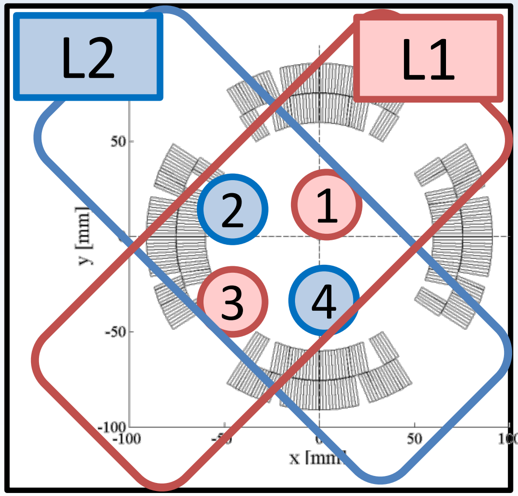
P12-P34

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

MQXC2

1.8 mH





P13-P24

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

MQXC2

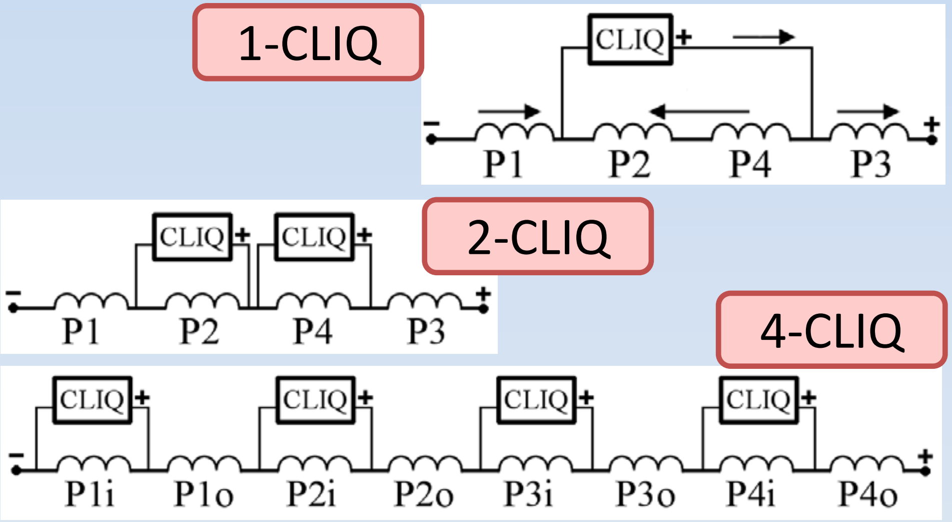
0.6 mH

3 times smaller

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

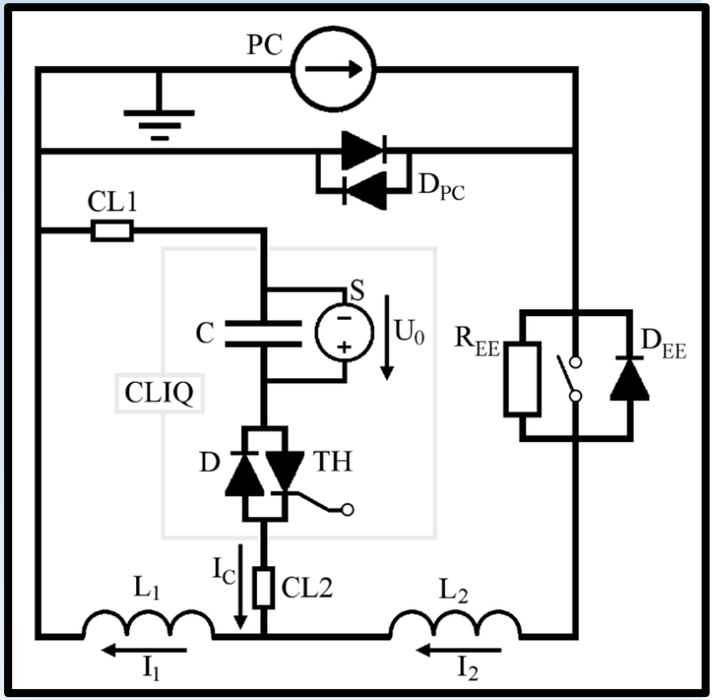
L_{eq} can be reduced by further subdividing the electrical circuit into N_E elements, effectively in parallel when CLIQ is triggered.
They can be **magnets** in a chain, **poles** of a magnet, or inner/outer **layers** of each pole.

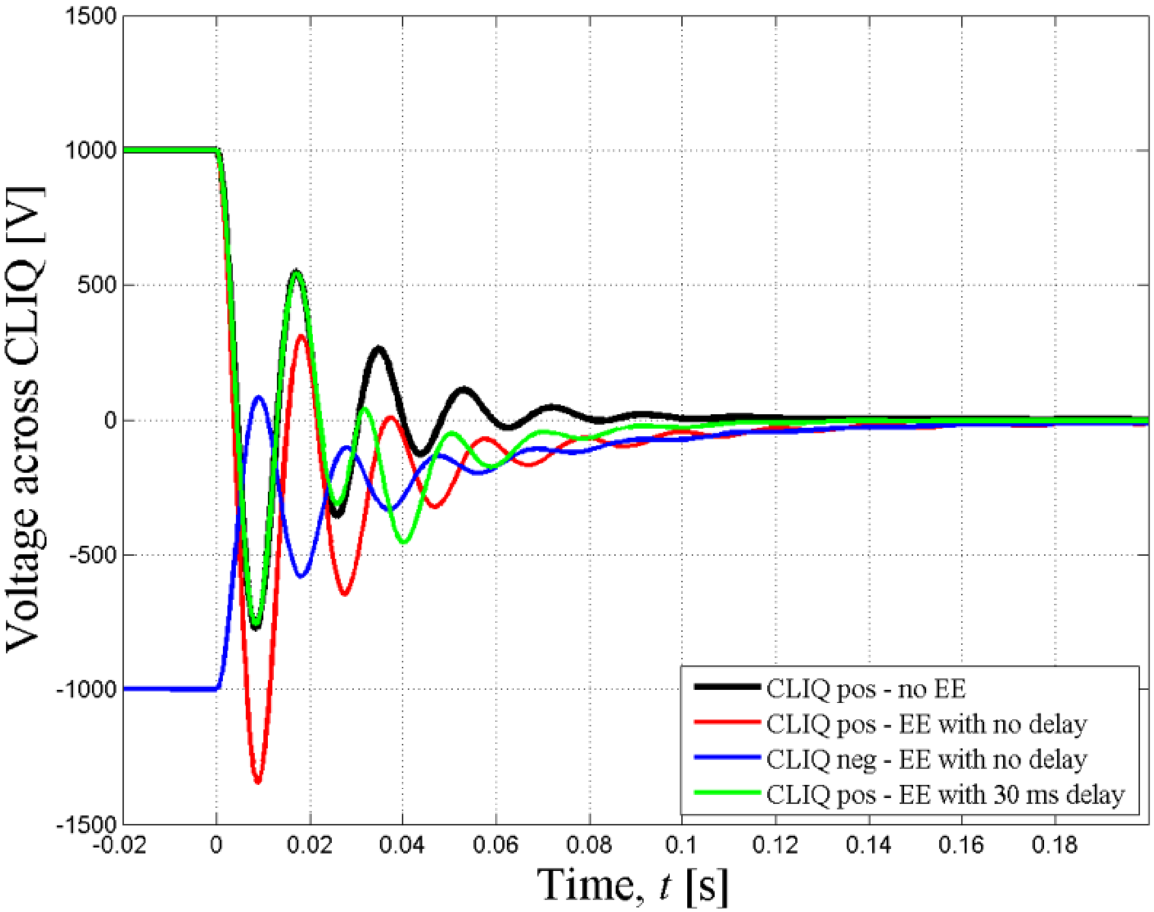
Peak power deposition proportional to N_C^2



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	$\div N_C^2$
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	$\infty(U_0/L_{eq}/N_E)$^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?





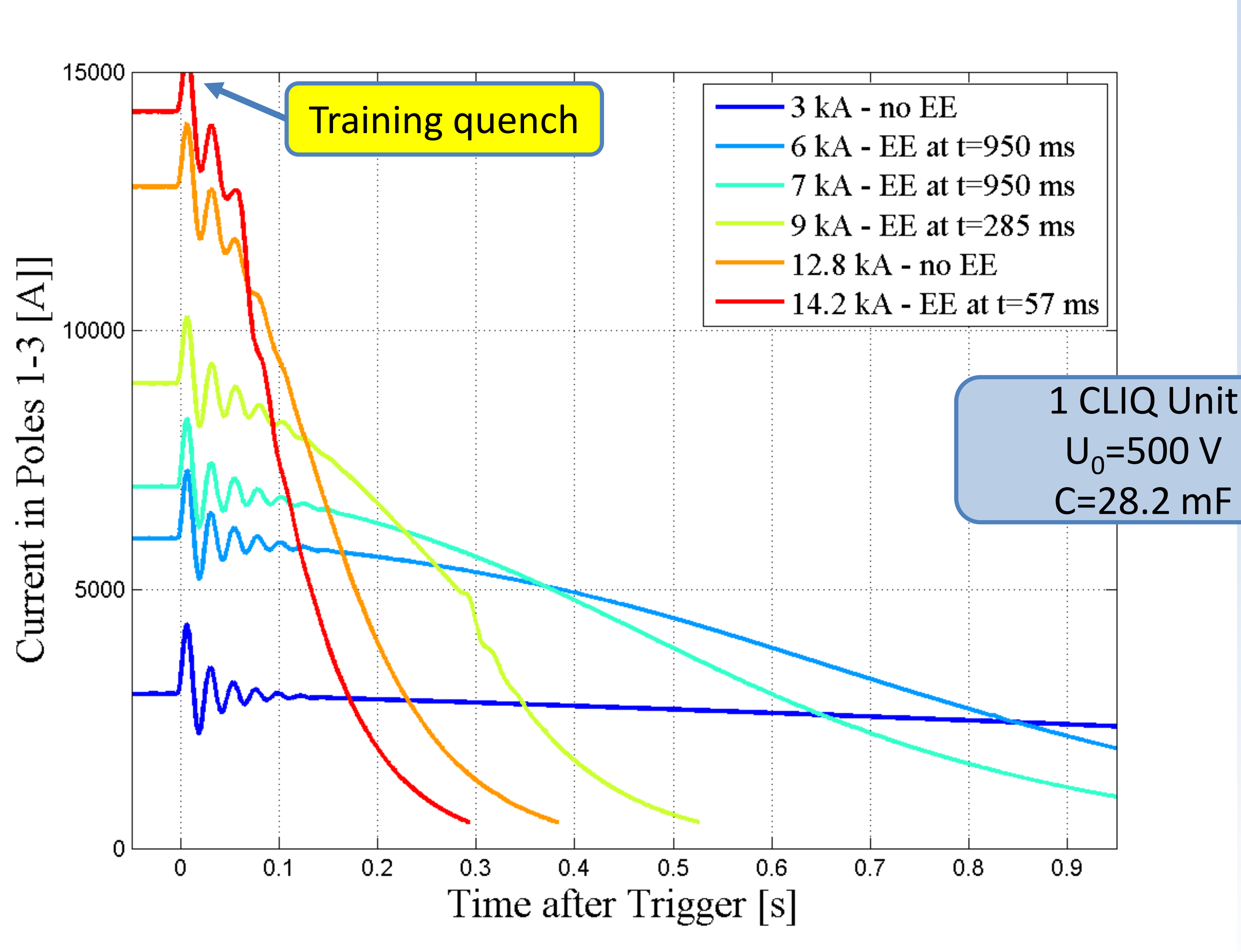
Avoid interference between CLIQ and EE system

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

IEEE/CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), October 2014 (Preview 1).
ASC 2014 presentation and paper 1LOr2B-01; 1st Prize in Best Student Paper Contest, Large Scale.

MQXC2

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



1 CLIQ Unit
U_0=500 V
C=28.2 mF