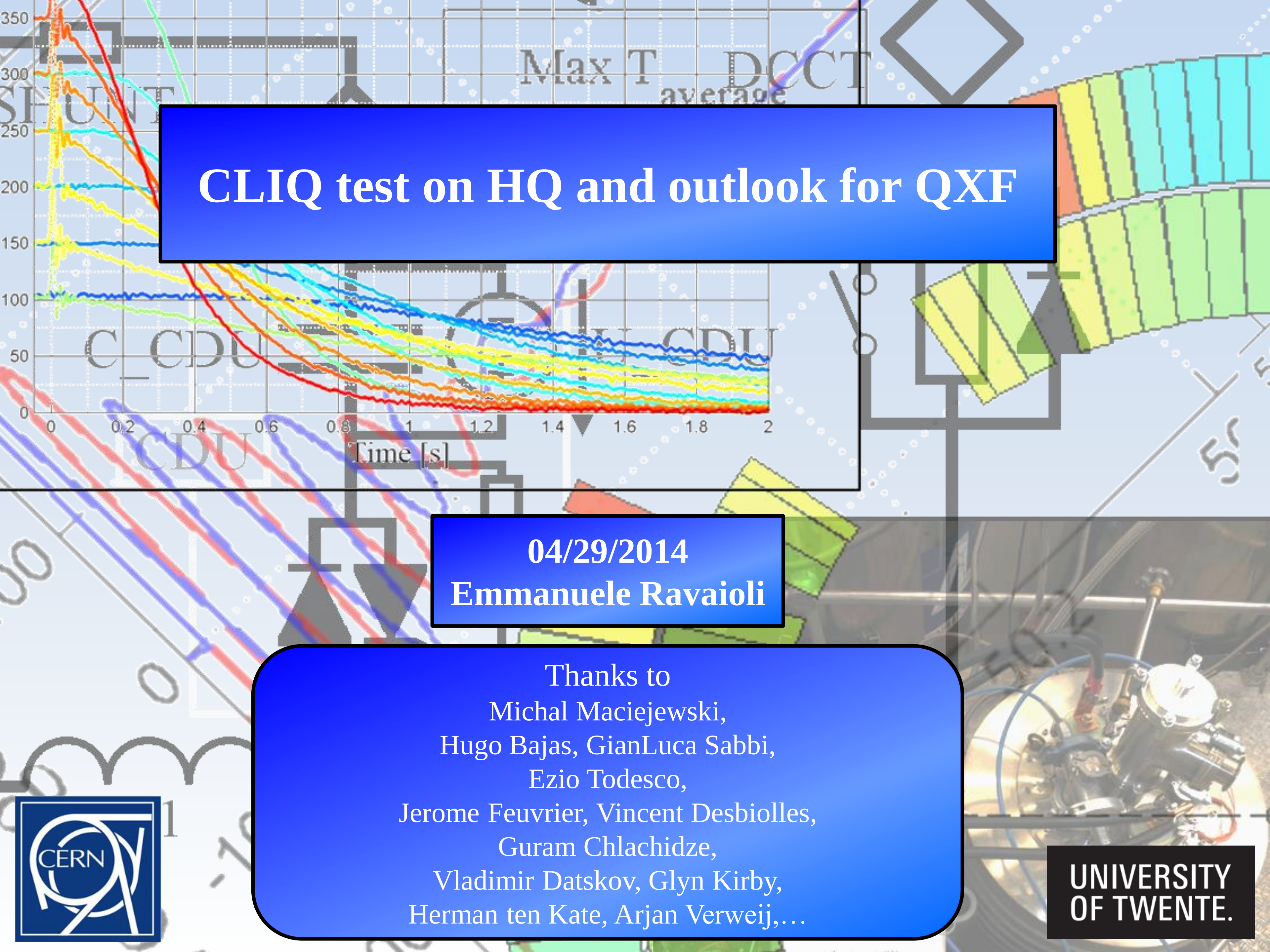

CLIQ test on HQ and outlook for QXF

04/29/2014
Emmanuele Ravaioli

Thanks to
Michal Maciejewski,
Hugo Bajas, GianLuca Sabbi,
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Vladimir Datskov, Glyn Kirby,
Herman ten Kate, Arjan Verweij,…

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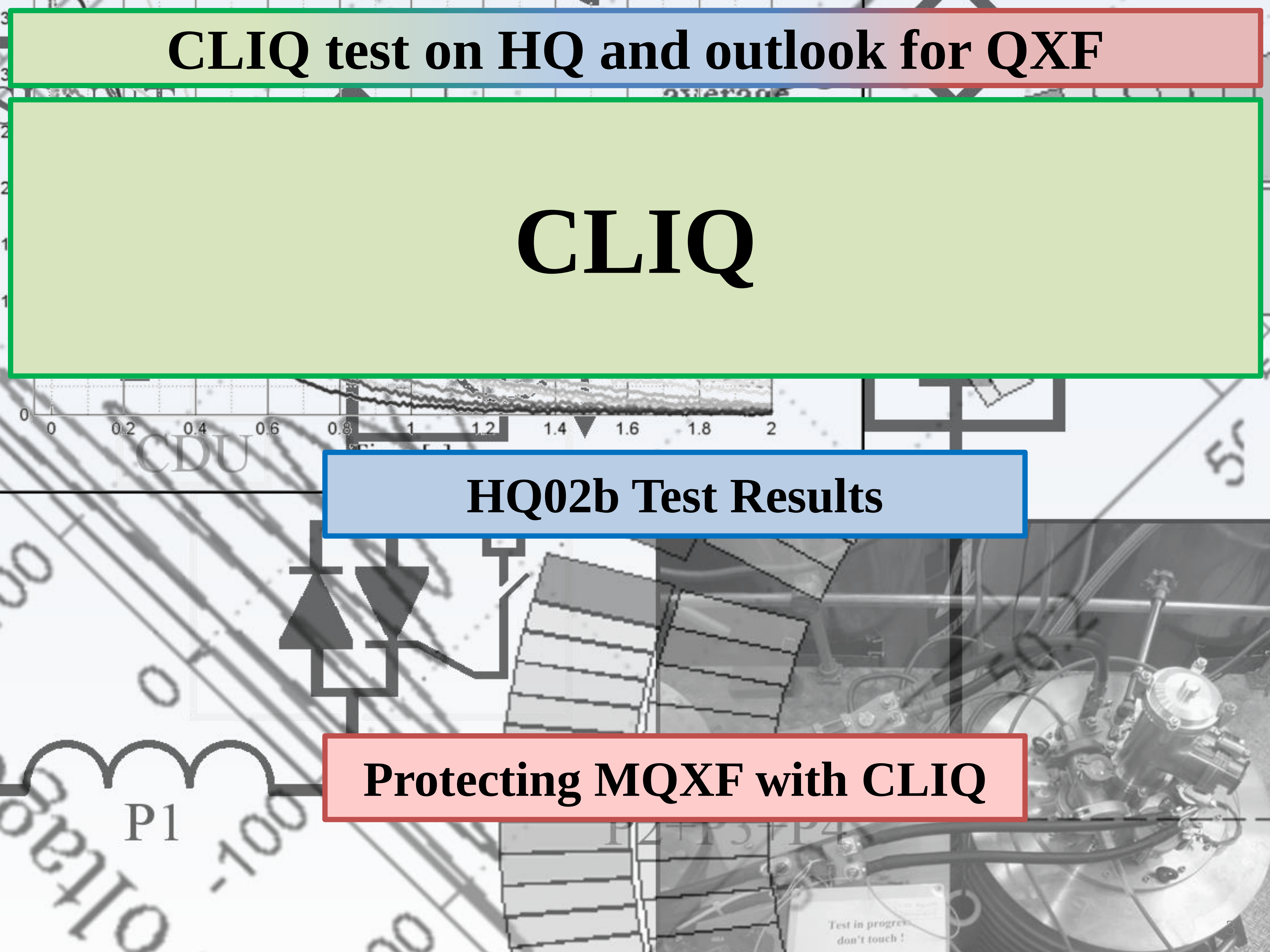
CLIQ test on HQ and outlook for QXF

CLIQ	Test Results	MQXF
Working principle	CLIQ tests on the HQ02 magnet	CLIQ Optimization
Key parameters	Importance of charging voltage	CLIQ tests on the HQ03 magnet
Governing equations	Comparison with Quench Heaters	Simulation of a CLIQ on the MQXF
Advantages & Drawbacks	Simulations & Model validation	Issues & Solutions

CLIQ test on HQ and outlook for QXF

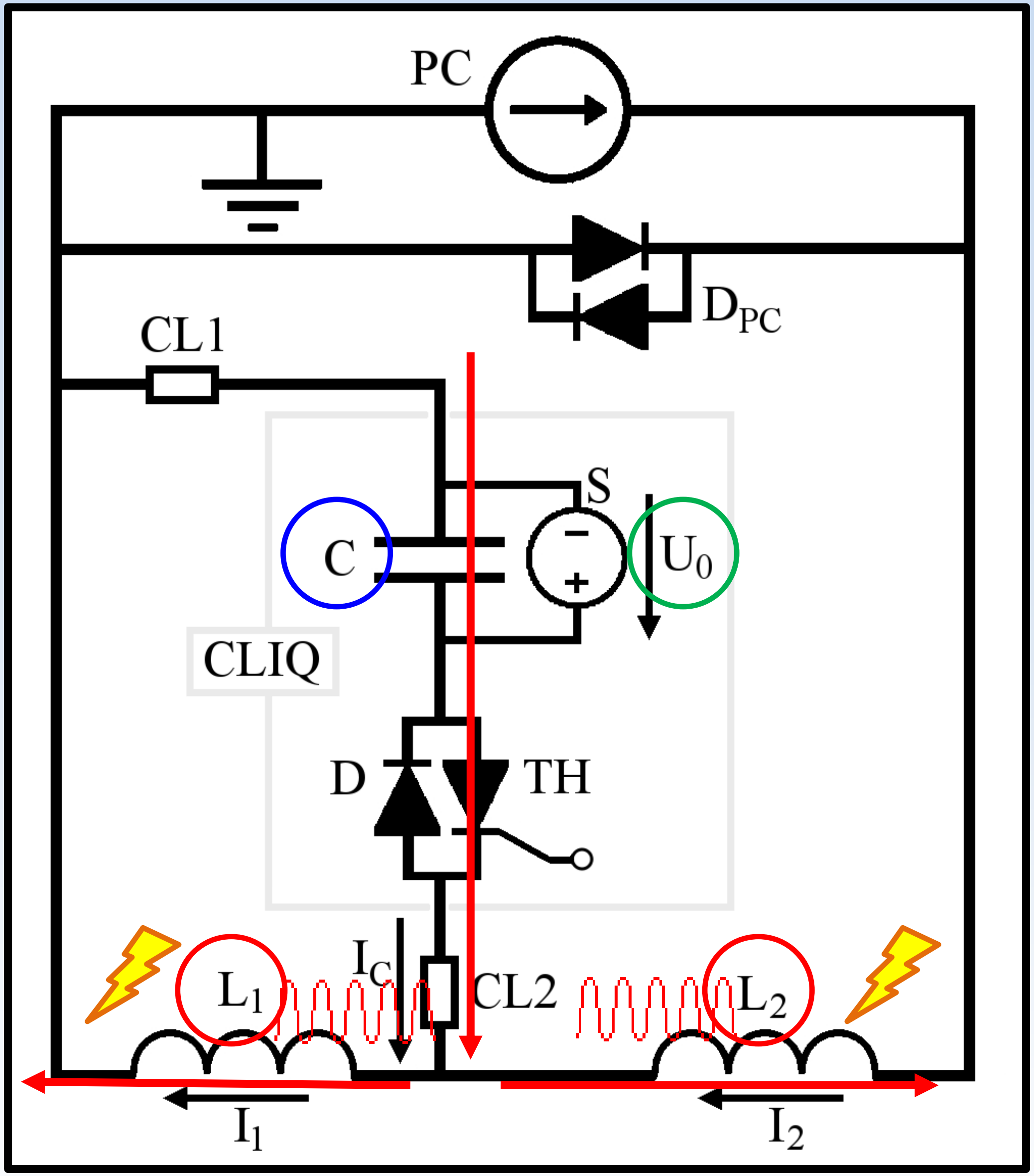


CLIQ

HQ02b Test Results

Protecting MQXF with CLIQ

CLIQ – Coupling-Loss Induced Quench



Current Change

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

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

Magnetic Field Change

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

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

Coupling-Losses (Heat)

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

Temperature Rise

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

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

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!

CLIQ – Key Parameters

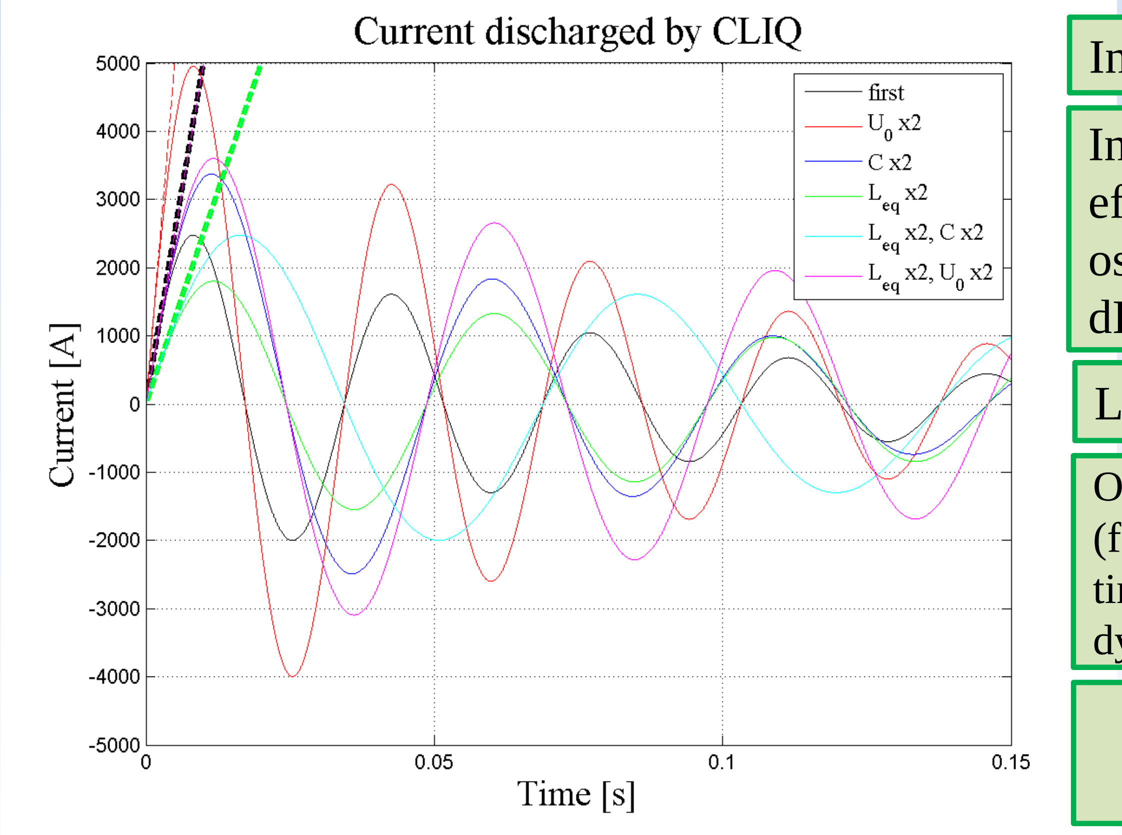
CLIQ performance is improved if

1. Current change is maximized U_0 L_{eq}
2. Peak current is maximized U_0 L_{eq} C
3. High current change is kept for a longer time L_{eq} C
4. Filament twist-pitch and Cu resistivity are optimized

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

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

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



Increasing U_0 increases dI/dt and I_{peak}

Increasing C increases I_{peak} but has no effect on the max dI/dt. Nevertheless, oscillation frequency decreases, so high dI/dt kept for a longer time

Larger L_{eq} decreases dI/dt and I_{peak}

Other parameters play a role, ignored here (filament twist-pitch, Cu resistivity (RRR), time constant of the coupling losses, dynamic effects, etc)

Main energy-deposition mechanism:
Inter-Filament Coupling Losses

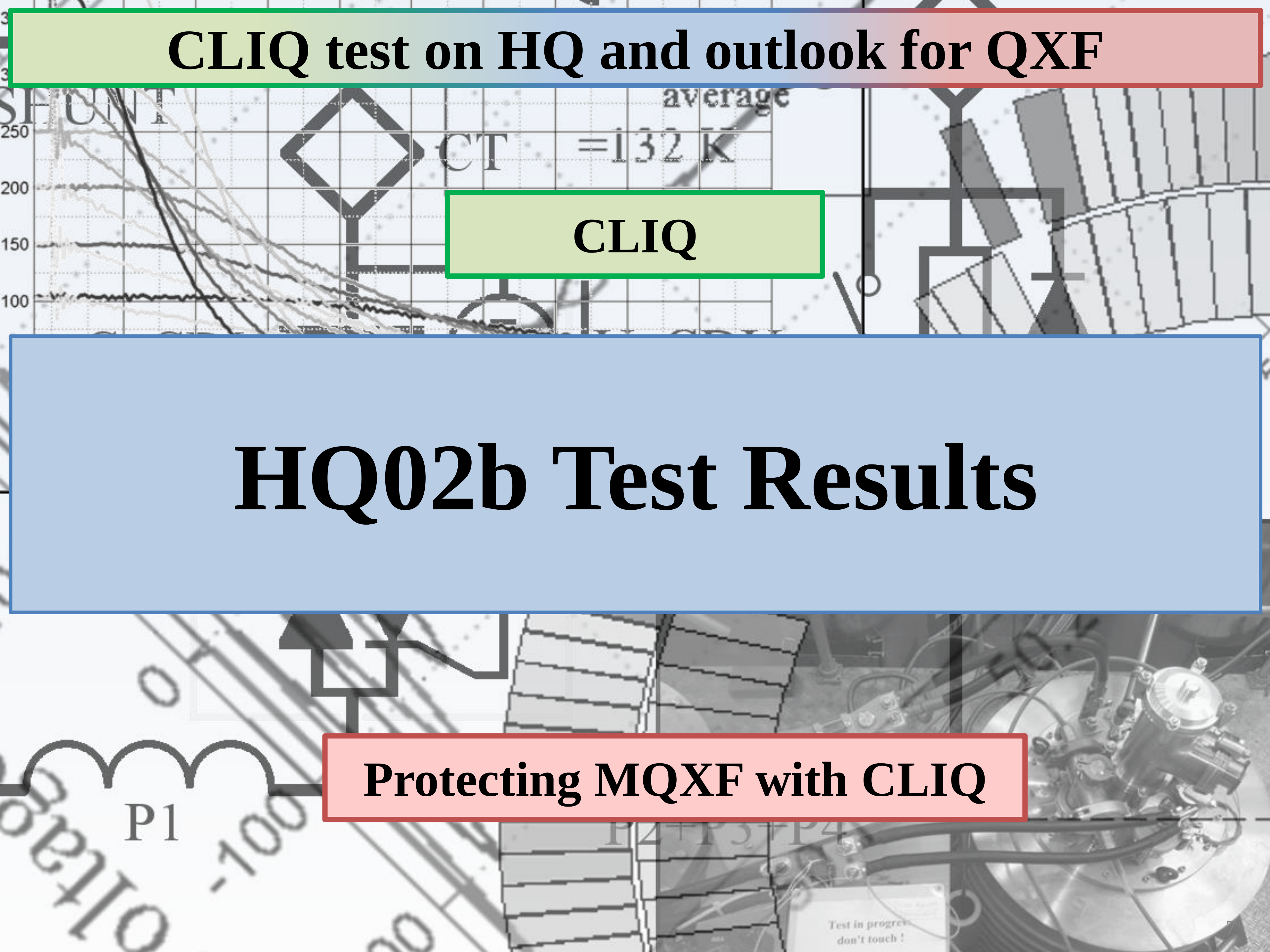
CLIQ – Advantages & Drawbacks (compared to Quench Heaters)

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



CLIQ test on HQ and outlook for QXF

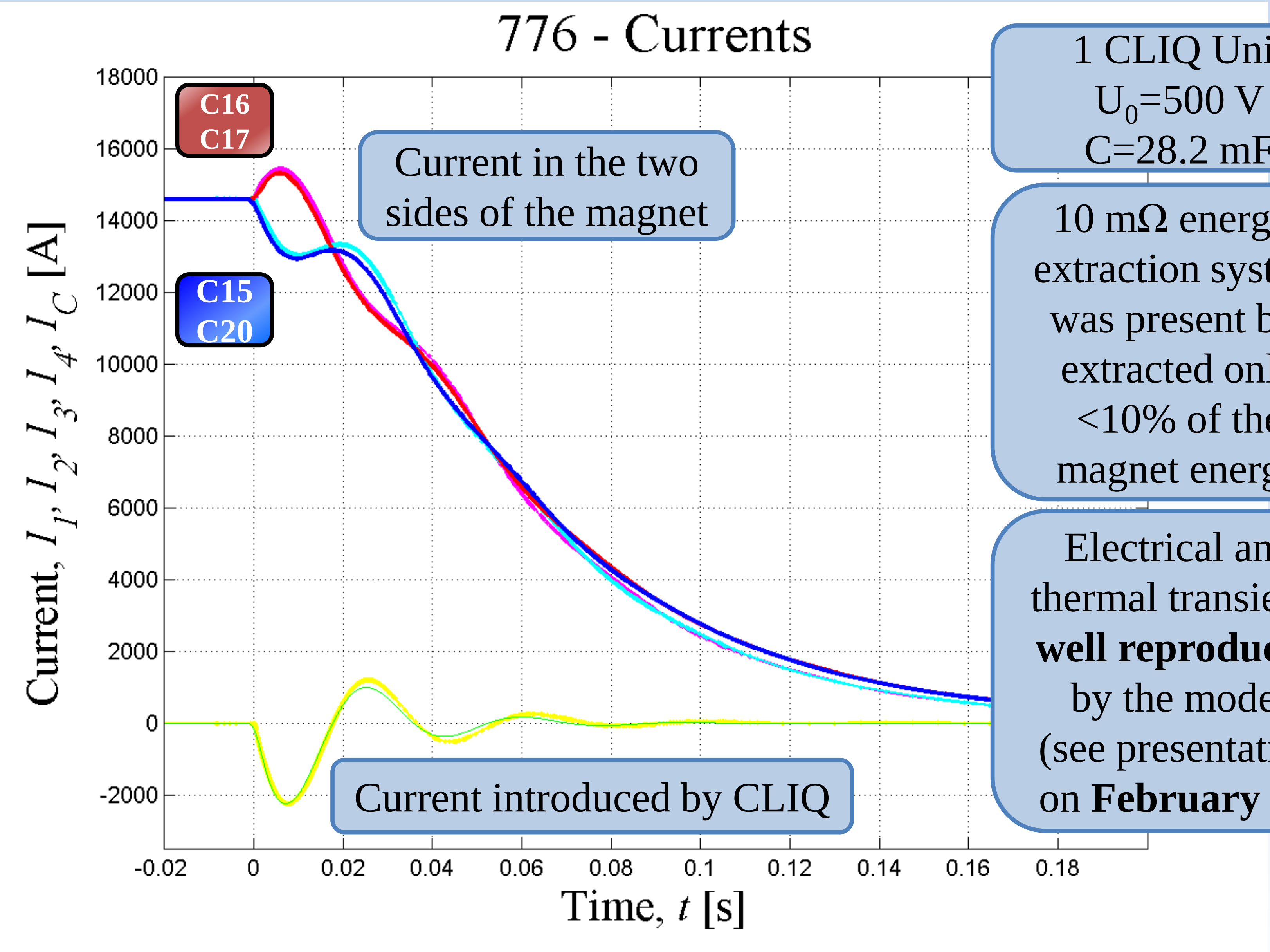
CLIQ

HQ02b Test Results

Protecting MQXF with CLIQ

HQ02b

Perfect agreement between **measurements** and **simulations**



Current in the two sides of the magnet

Current introduced by CLIQ

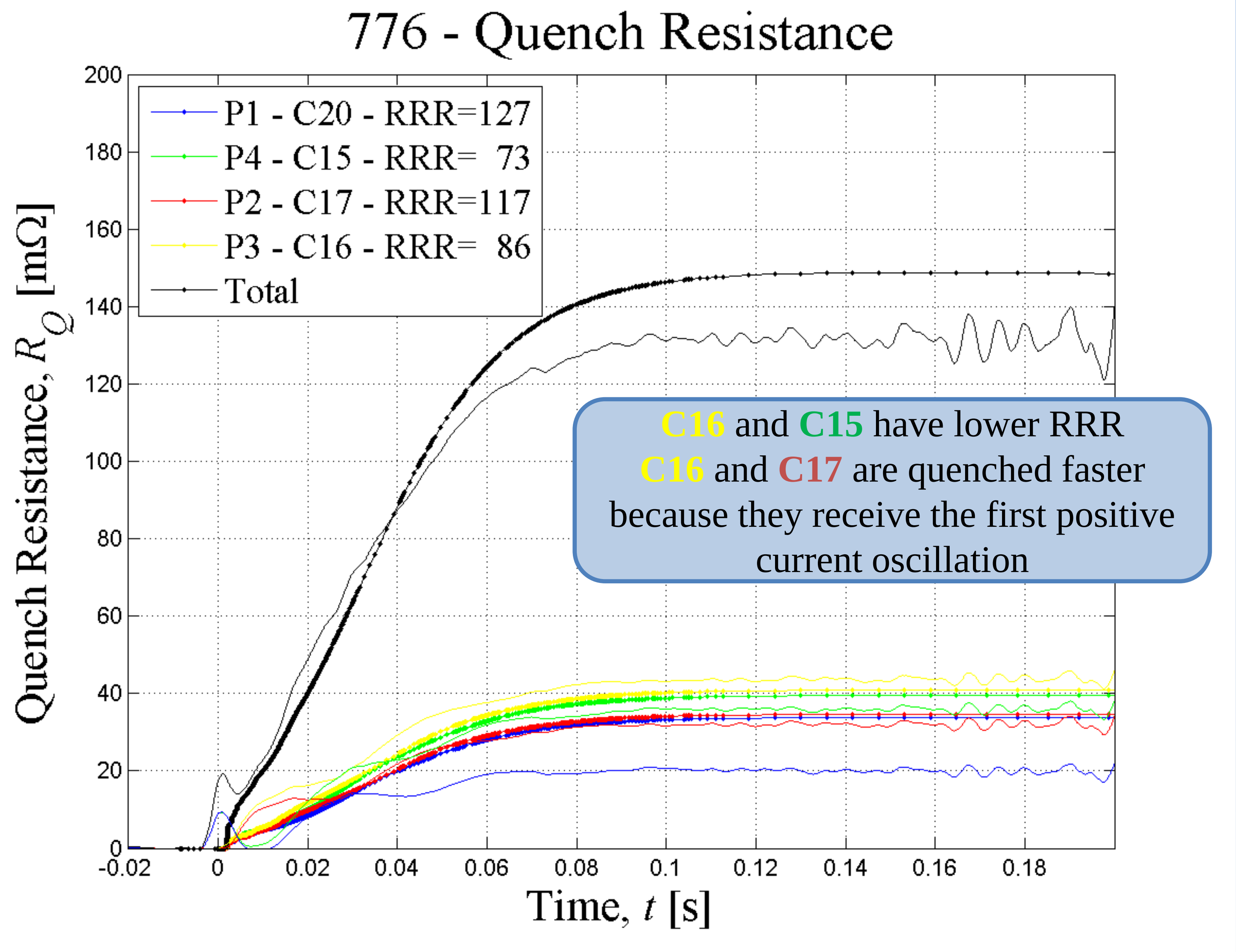
1 CLIQ Unit
U_0=500 V
C=28.2 mF

10 mΩ energy-extraction system was present but extracted only <10% of the magnet energy

Electrical and thermal transients **well reproduced** by the model (see presentation on **February 2**!)

HQ02b

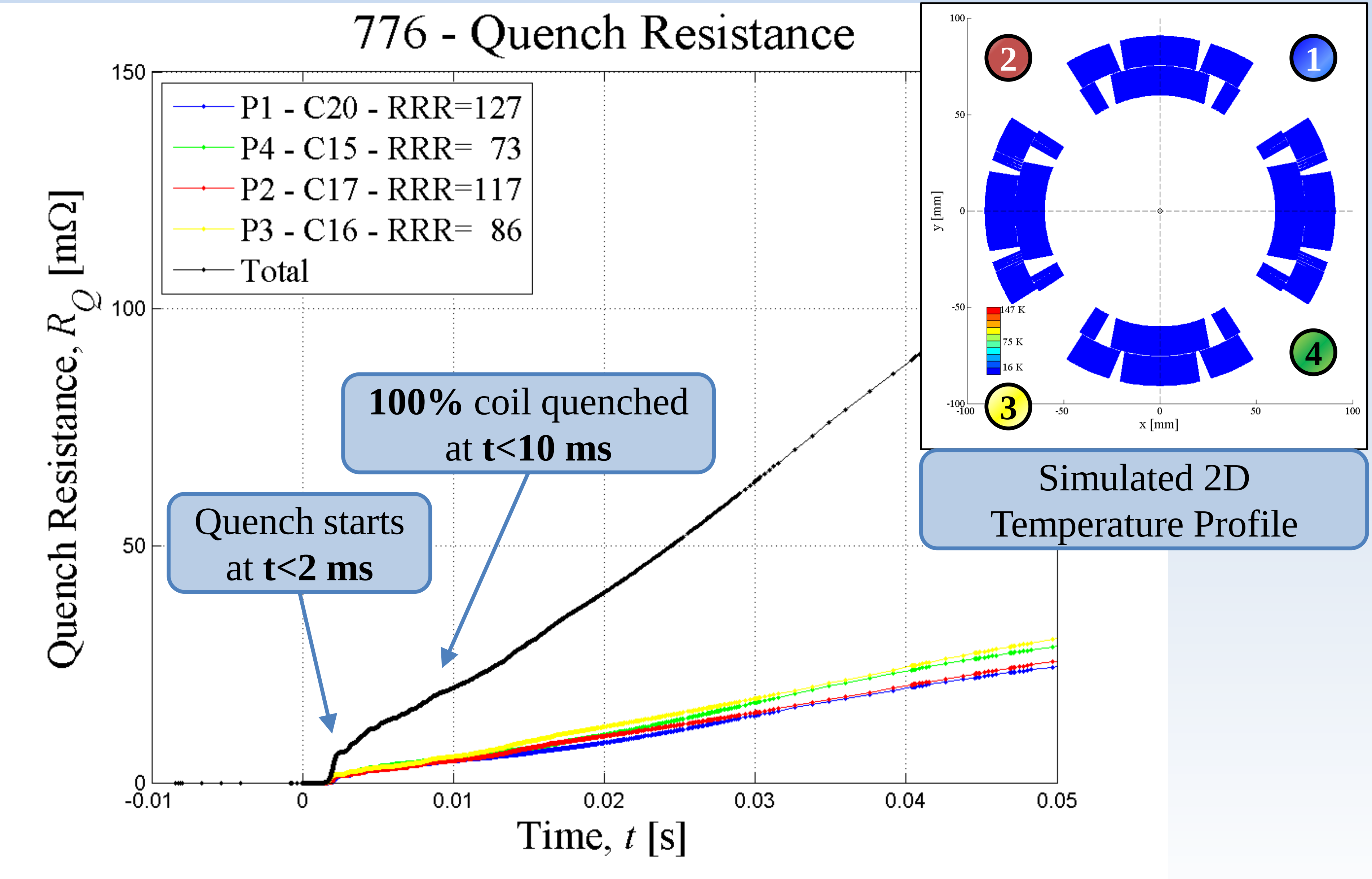
Perfect agreement between **measurements** and **simulations**



C16 and C15 have lower RRR
C16 and C17 are quenched faster because they receive the first positive current oscillation

HQ02b

Very fast quench initiation



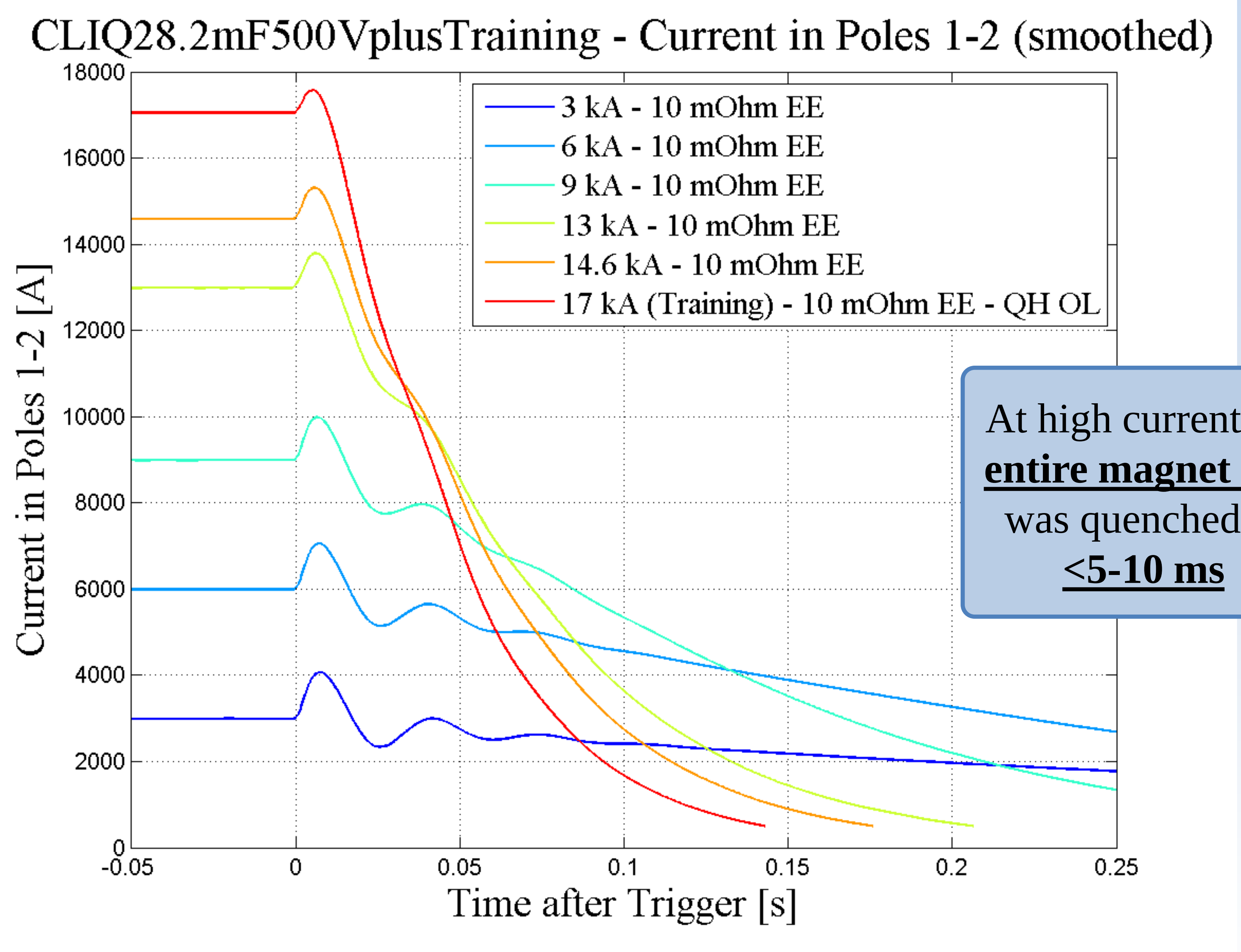
100% coil quenched
at **t<10 ms**

Quench starts
at **t<2 ms**

Simulated 2D
Temperature Profile

HQ02b

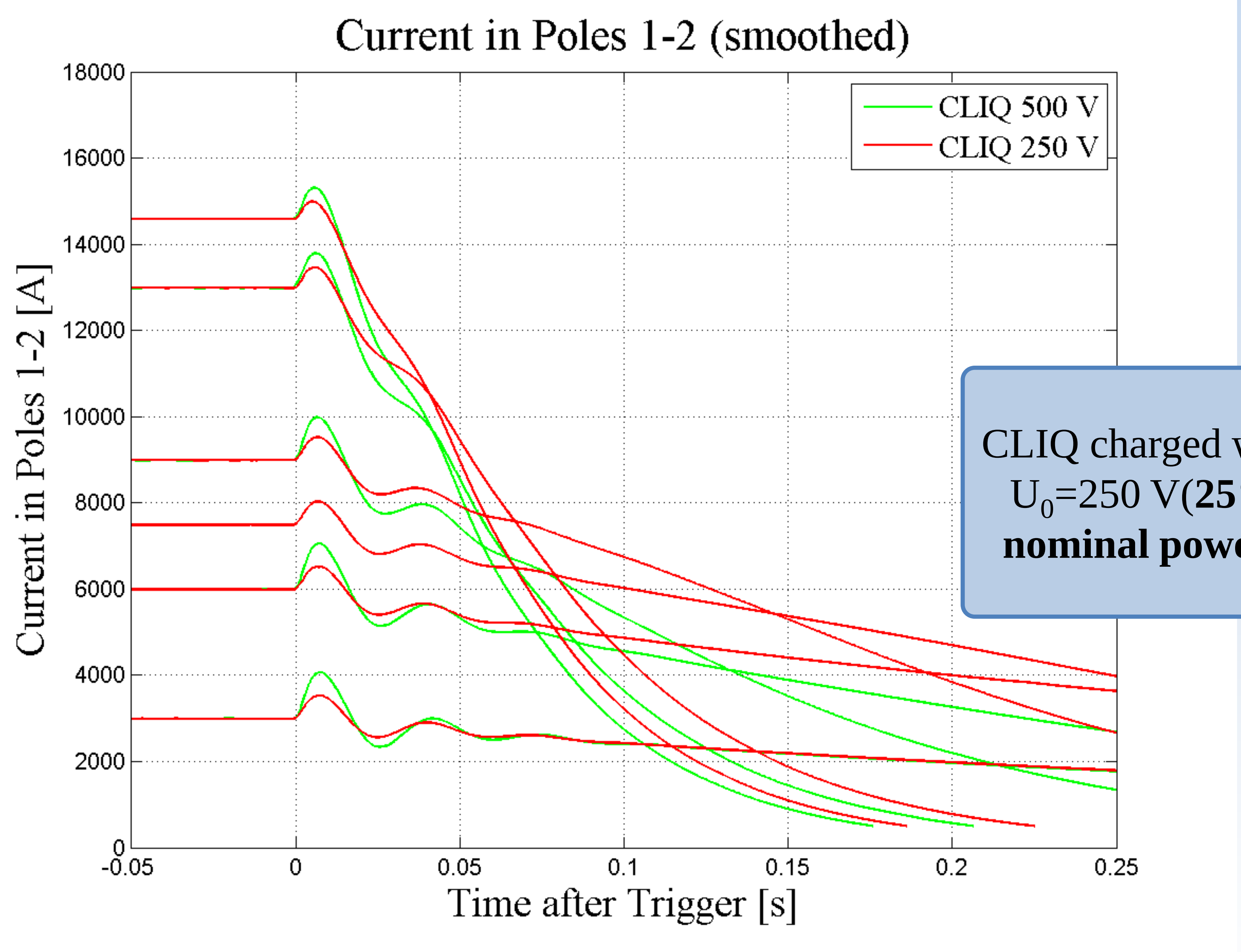
CLIQ protects the magnet **at any current level**



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

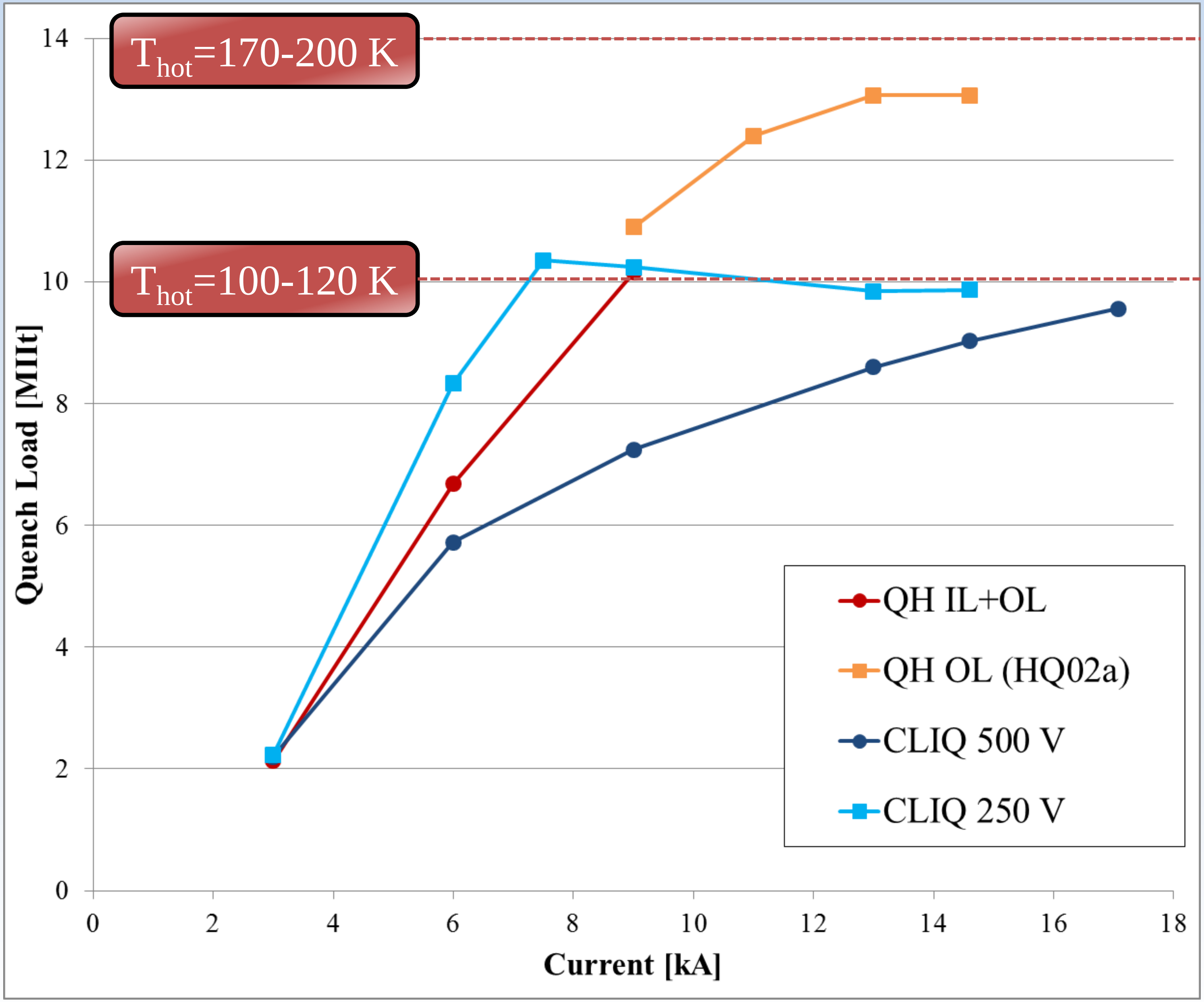
HQ02b

Very good performance even with **reduced voltage**



CLIQ charged with U_0=250 V(**25% nominal power**)

HQ02b Excellent CLIQ performance (**quench load reduced by 40%**)



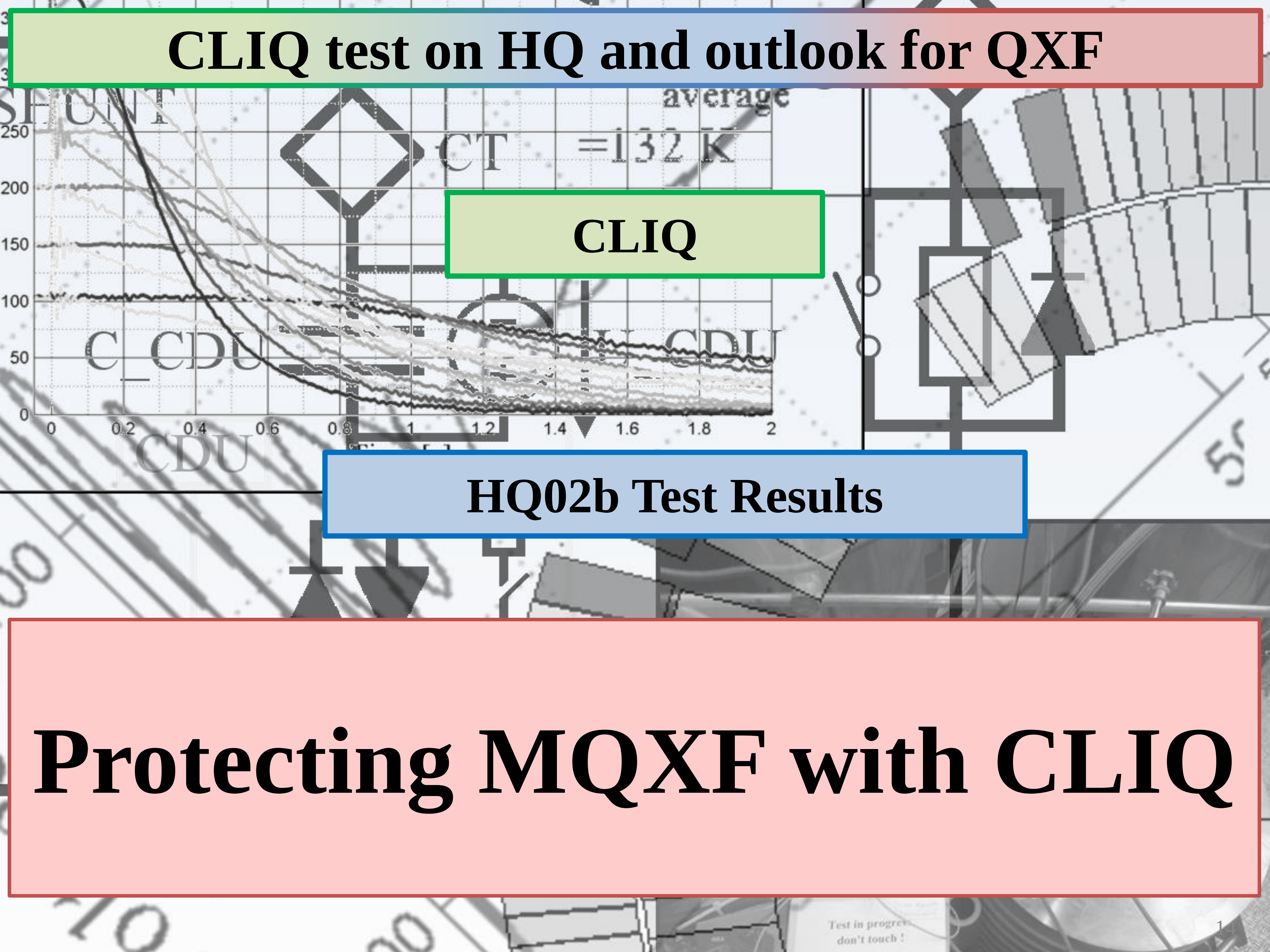
CLIQ charged with 500 V shows great performance!
QL<10 MIIt
T_{hot}<100-120 K

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!

CLIQ test on HQ and outlook for QXF



CLIQ

HQ02b Test Results

Protecting MQXF with CLIQ

Protecting MQXF with CLIQ – The challenge

Parameter	HQ02	LARP MQXF	CERN MQXF
Magnetic length [m]	0.84	4	6.8
Inductance per unit length [mH/m]	7.59	8.27	8.27
Inductance [mH]	6.4	**x5** 33	**x9** 56
Filament twist-pitch [mm]	14	19?	19?
RRR	80/140	140?	140?
IFCL per unit volume [a. u.]	1	**÷25** 1/25	**÷80** 1/80

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

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

The same CLIQ unit discharged on a magnet **9 times longer** will deposit **~80 times less inter-filament coupling loss**…

Strategy

Correct CLIQ discharge **configuration**

Increase charging **voltage U_0**

More than one CLIQ **units**

Optimize filament **twist pitch** and **RRR**

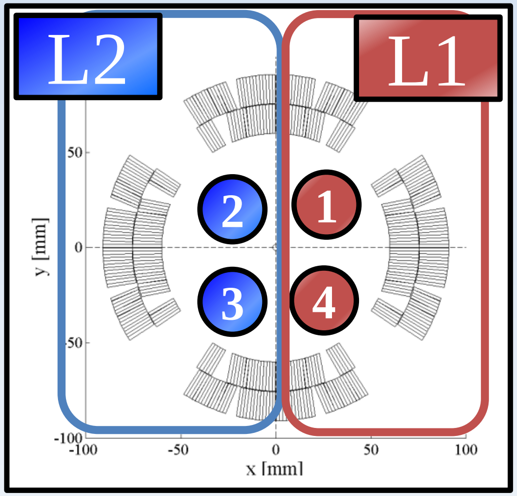
Correct CLIQ discharge configuration

L_{eq} reduced by a **factor 3**

The electrical order of the 4 poles does not change the magnet performance during DC operation

Nevertheless, this order has a large impact on the CLIQ performance. The **equivalent inductance L_{eq}** of the discharge circuit can be **reduced by 2.5-3 times** due to the increased coupling between L1 and L2

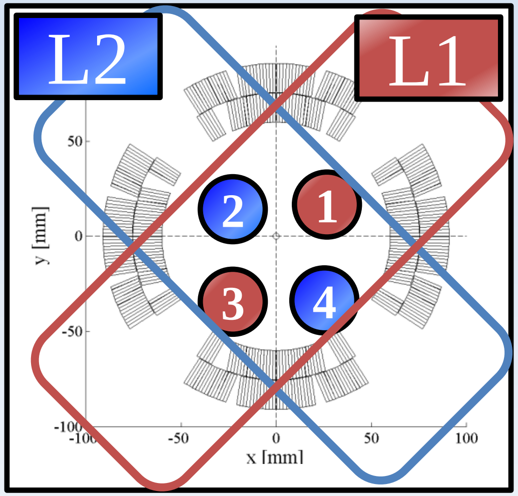
$$L_{eq} = \frac{L_1 \cdot L_2 - M_{12}^2}{L_{magnet}}$$



P14-P32

mH	L1	L2
L1	3.0	0.2
L2	0.2	3.0

L_{eq}=1.36 mH



P13-P42

mH	L1	L2
L1	2.1	1.1
L2	1.1	2.1

L_{eq}=0.47 mH

MQXC2 (P13-P42): DC inductance ~30% larger than HQ02 (P14-P32), but measured L_{eq} ~2.4 times smaller!

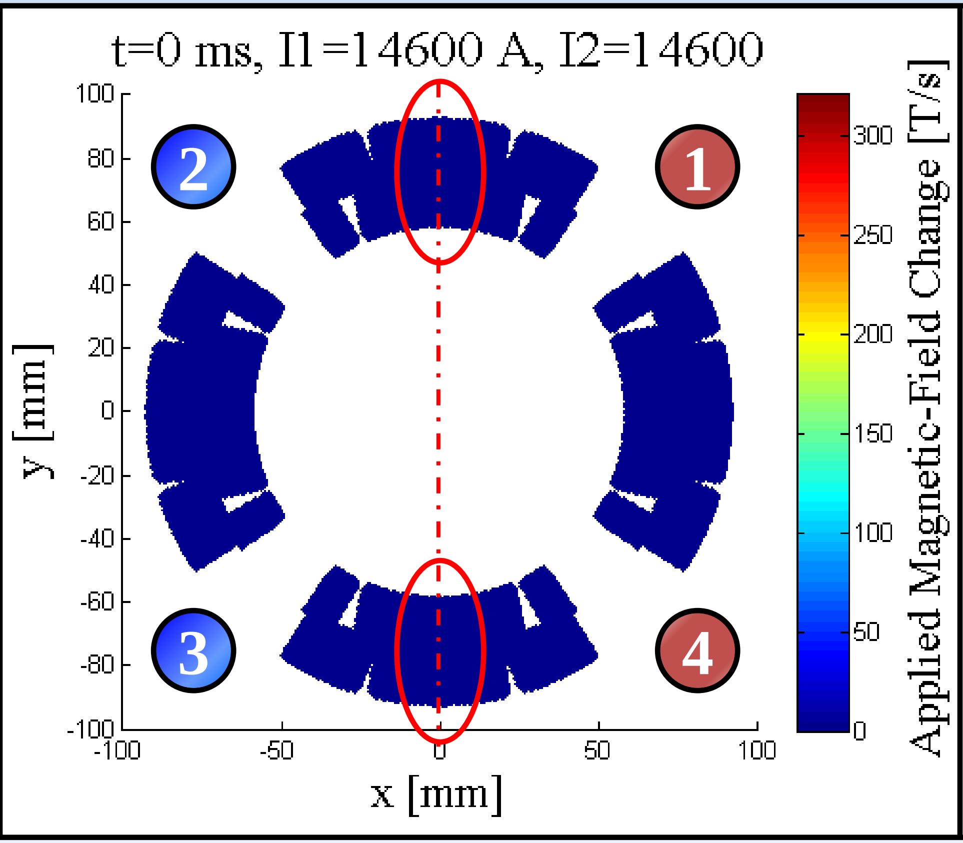
HQ03: Possible to test the **P13-P42** configuration (but 2 CLIQ current leads needed instead of 1). **L_{eq} reduced by a factor 2.5-3.**

No impact on magnet performance, and there is an additional advantage →

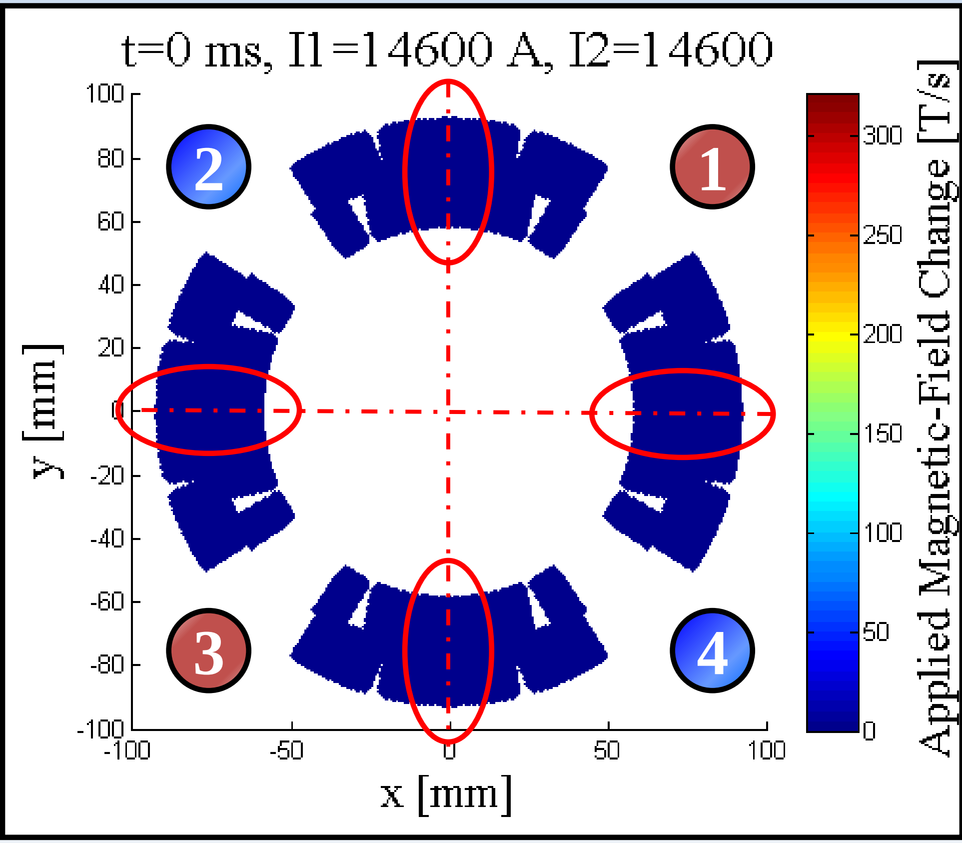
Correct CLIQ discharge configuration

Efficient magnetic-field change

P14-P32



P13-P42

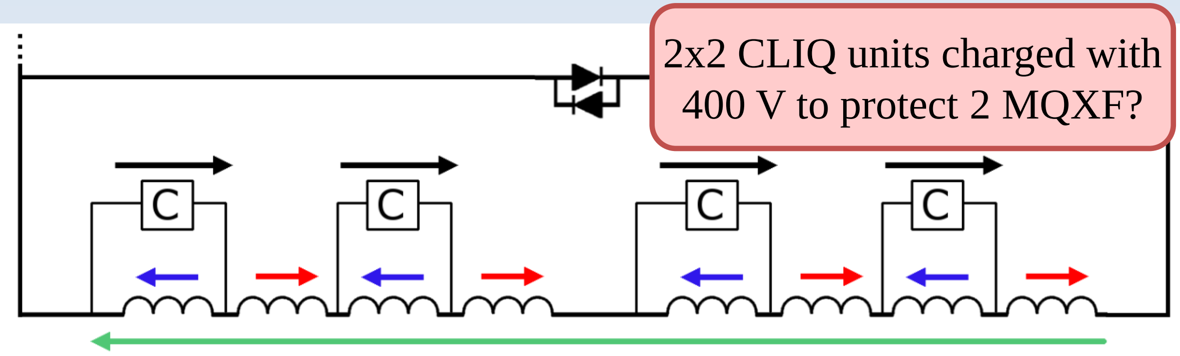


At the edges of two coils with opposite current change the magnetic-field change generated by the two coils superpose, thus creating a region with **very high local magnetic-field change**. Choosing configuration **P13-P42** creates **4 such regions** (instead of 2). This result, combined with the reduced equivalent inductance of the circuit, greatly enhances the CLIQ performance.

Protecting MQXF with CLIQ – Increase of U_0 or Multi-CLIQ

Parameter	HQ02	HQ03	MQXF 4 m	MQXF 6.8 m
Equivalent Inductance L_{eq} [mH]	1.36	÷3 0.47	x5/3 2.62	x3 4.45
CLIQ voltage to achieve the same performance of HQ02-500V [V]	*500*	÷3 170	x5/3 960	x3 1600
CLIQ voltage to achieve the same performance of HQ02-250V [V]	*250*	÷3 85	x5/3 480	x3 800

One can roughly estimate the CLIQ charging voltage U_0 required to protect a longer magnet simply scaling U_0 to achieve the same ratio $\mathbf{U_0/L_{eq}}$. **MQXF-CERN** (full-size, **6.8 m** long) can be protected with **1 CLIQ unit** charged with **800 V** (or 2 CLIQ units charged with 400 V)



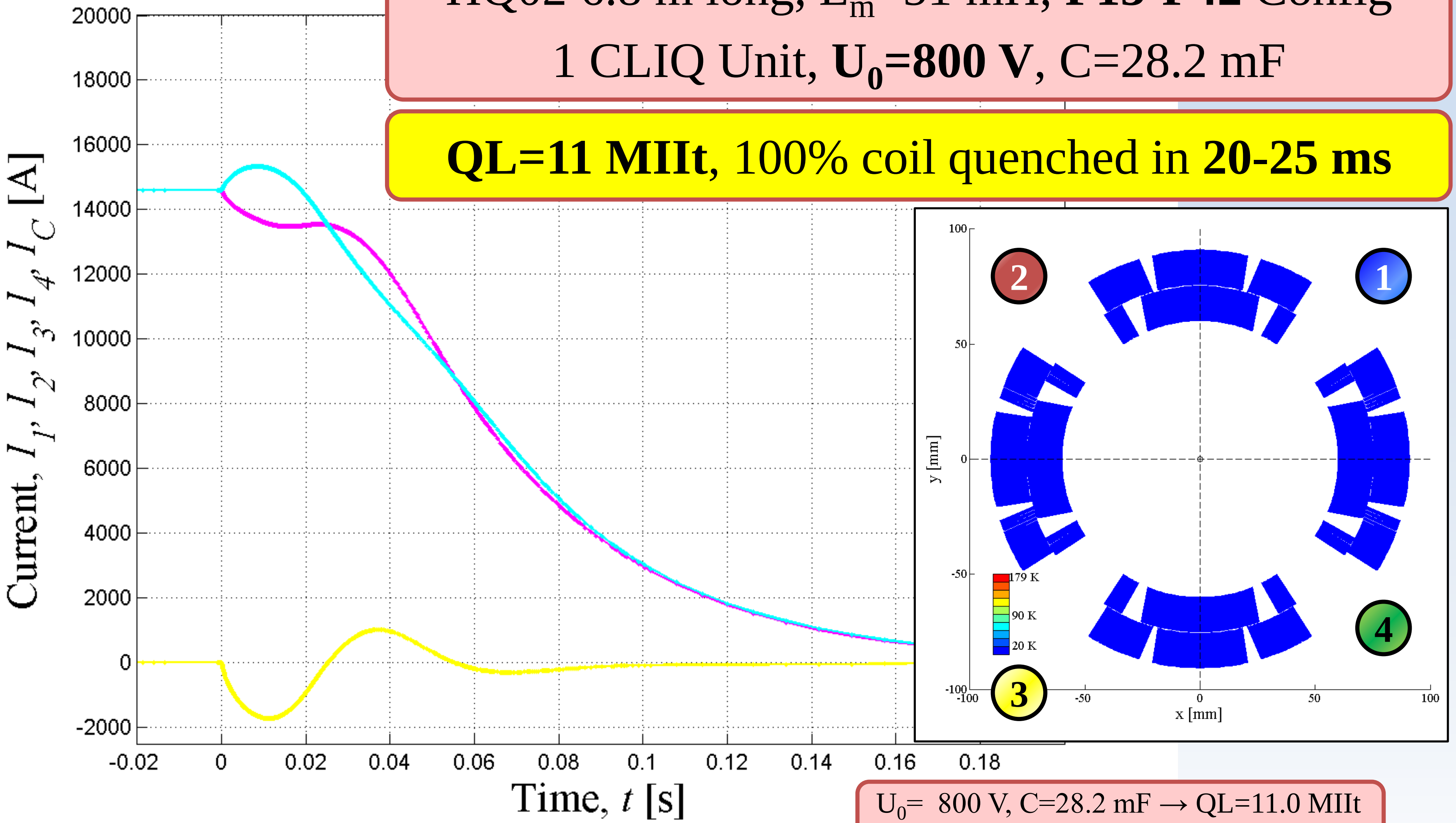
2x2 CLIQ units charged with 400 V to protect 2 MQXF?

Of course, this is only a rough estimation. **Complete simulations** are required in order to predict the complex electro-thermal transients following a CLIQ discharge.

Protecting MQXF with CLIQ – Preliminary Sim (HQ02 6.8 m long)

HQ02 6.8 m long, L_m=51 mH, **P13-P42** Config
1 CLIQ Unit, **U_0=800 V**, C=28.2 mF

QL=11 MIIt, 100% coil quenched in **20-25 ms**



U_0= 800 V, C=28.2 mF → QL=11.0 MIIt
U_0=1000 V, C=28.2 mF → QL=10.4 MIIt
U_0=1600 V, C=28.2 mF → QL= 9.7 MIIt

Cpr **800 V EE system: QL>20 MIIt**

Increasing the **filament twist pitch** and/or the **RRR** of the strands can further improve CLIQ performance

Protecting MQXF 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

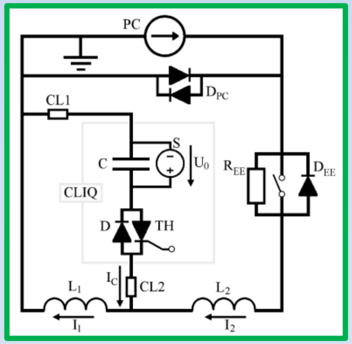
CLIQ test on HQ and outlook for QXF – Conclusion

CLIQ

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

The transients following a CLIQ discharge are well understood and are successfully reproduced with electro-thermal simulations

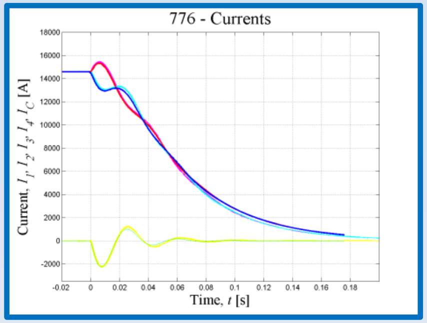
$$\frac{P_{IF}}{vol} \propto \left(\frac{U_0}{L_{eq}}\right)^2$$

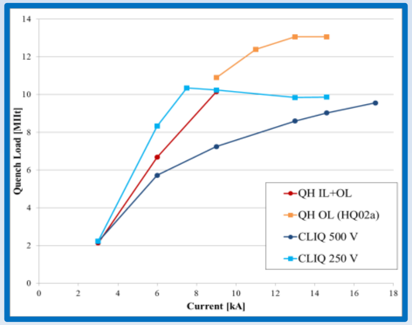


Test Results

HQ02b test campaign: quench load obtained using CLIQ is up to 40-50% smaller than using outer QH (with not optimized CLIQ)

No detraining was observed in HQ02 after CLIQ discharges



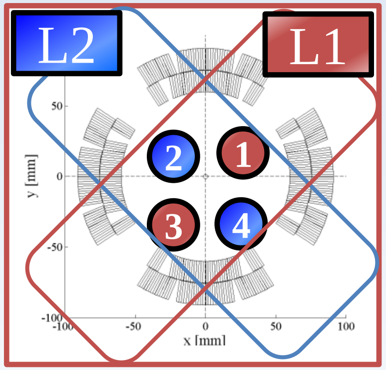


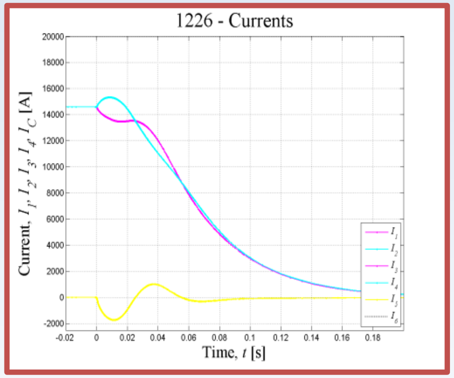
MQXF

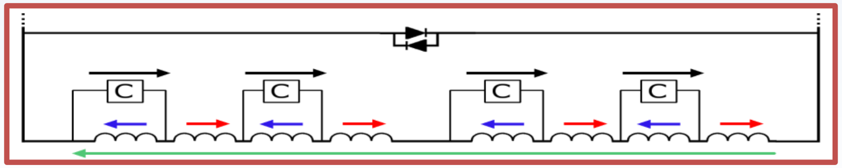
The electrical connection of the four poles has a significant impact on the CLIQ performance

It is possible to protect the full-size MQXF magnet using CLIQ charged with <1 kV with performance similar to HQ02

The developed electro-thermal model is used to asses the CLIQ performance and study new circuit configurations







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Ezio Todesco,
Christian Giloux, Jerome Feuvrier, Vincent Desbiolles,
Gerard Willering, Marta Bajko,
Francois-Olivier Picot,…

QUESTIONS?

Ask me the CLIQ Recipe!

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.

Emmanuele.Ravaioli@cern.ch

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

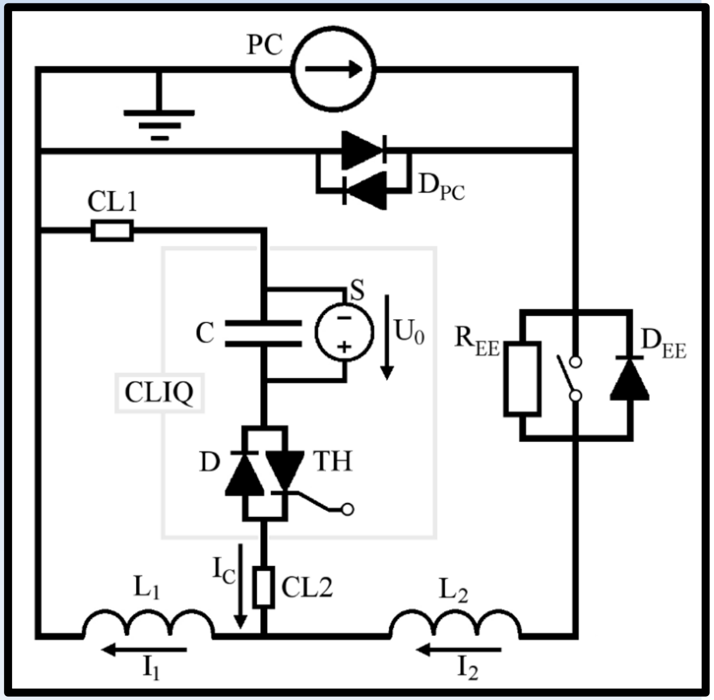
For typical strand twist-pitch and cross-contact resistance, time constant in the order of hundreds of ms / seconds
Limited energy deposition with CLIQ discharge

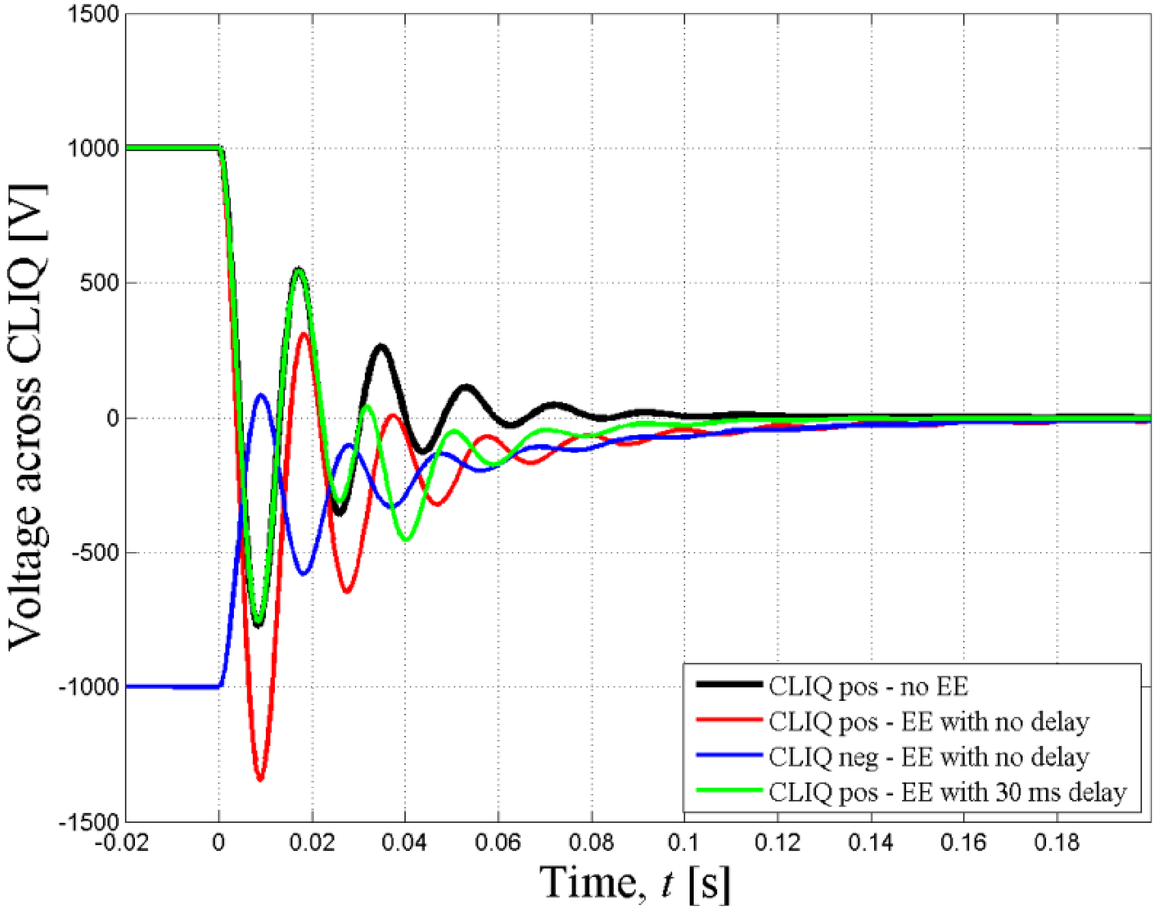
Magnetization Loss

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

Limited energy deposition with CLIQ discharge

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

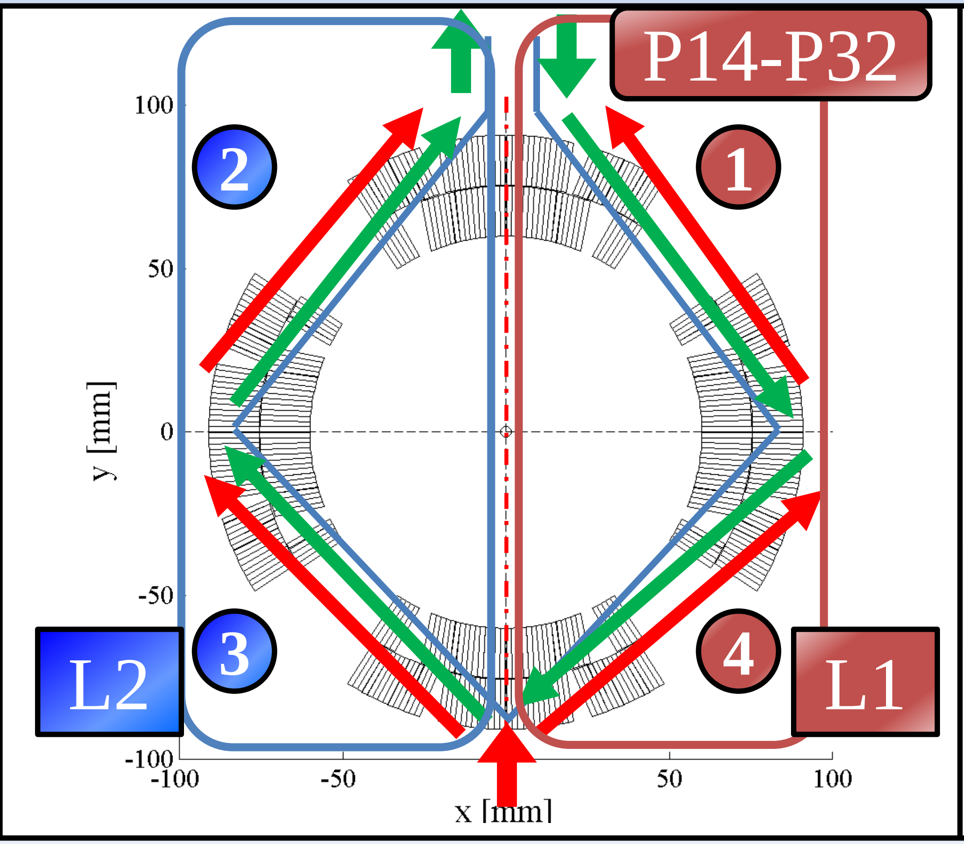


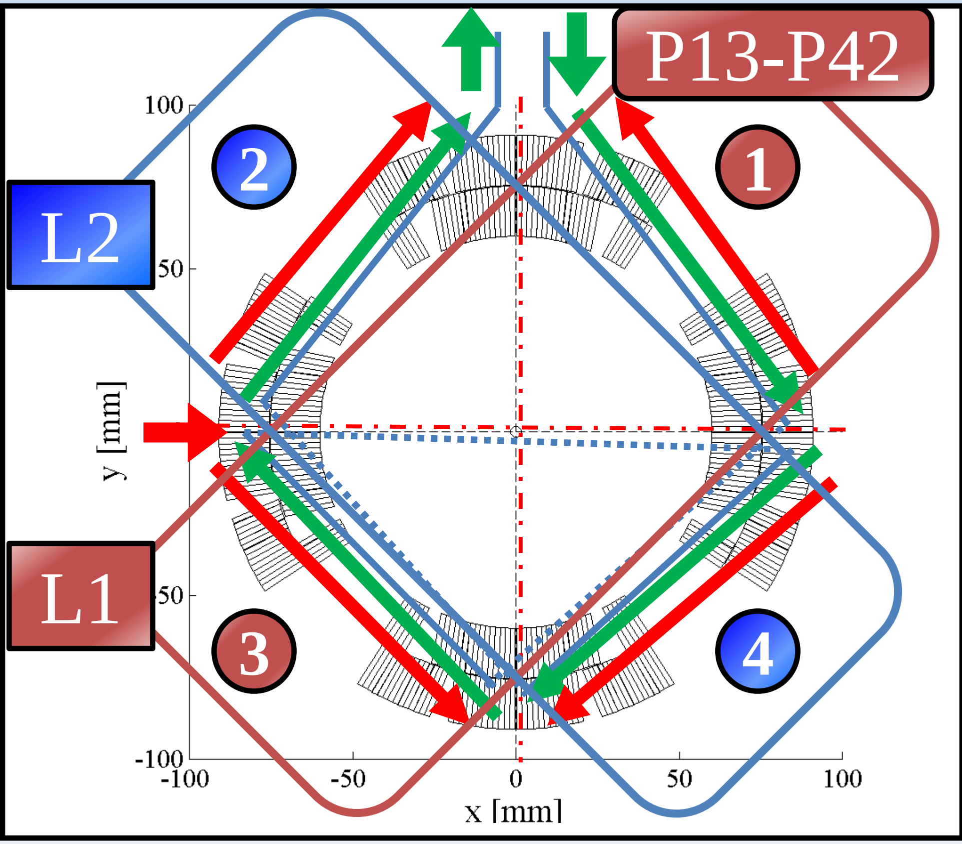


Avoid interference between CLIQ and EE system

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

Protecting MQXF with CLIQ – Optimization – Equivalent Inductance L_{eq}





The electrical order of the 4 poles does not change the magnet performance during DC operation

Nevertheless, this order has a large impact on the CLIQ performance. The **equivalent inductance** of the discharge circuit can be **reduced by 2.5-3 times** due to the increased coupling between L1 and L2

$$L_{eq} = \frac{L_1 \cdot L_2 - M_{12}^2}{L_1 + L_2 + 2M_{12}}$$

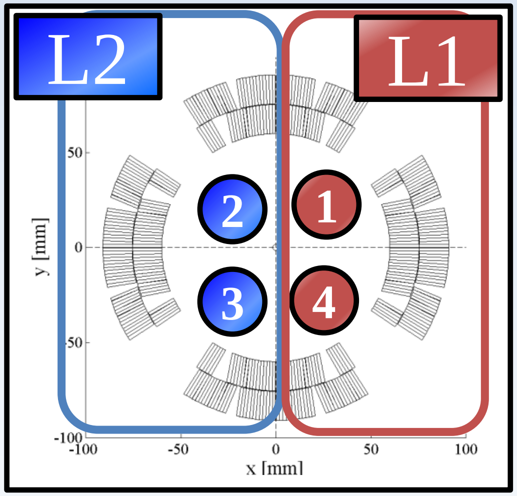
Equivalent Inductance L_{eq} of the CLIQ discharge circuit

HQ02 Quadrupole Magnet [mH]

	P1	P2	P3	P4
P1	1.19	0.28	-0.16	0.28
P2	0.28	1.19	0.28	-0.16
P3	-0.16	0.28	1.19	0.28
P4	0.28	-0.16	0.28	1.19

The total DC inductance of the magnet is 6.38 mH. The equivalent inductance L_{eq} of the CLIQ discharge circuit depends on the **electrical connection** of the four poles.

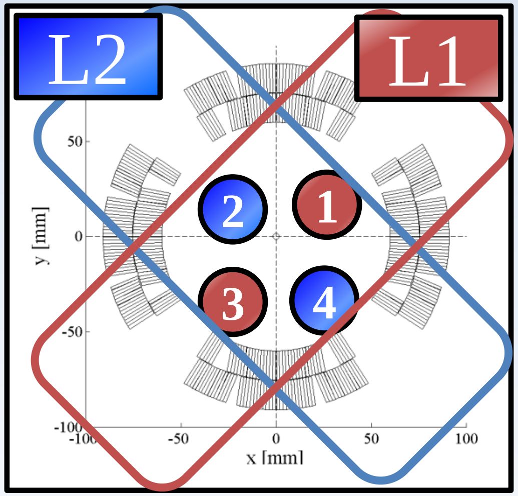
$$L_{eq} = \frac{L_1 \cdot L_2 - M_{12}^2}{L_1 + L_2 + 2M_{12}}$$



P14-P32

	L1	L2
L1	3.0	0.2
L2	0.2	3.0

L_{eq}=1.36 mH



P13-P42

	L1	L2
L1	2.1	1.1
L2	1.1	2.1

L_{eq}=0.47 mH

Changing the electrical order of the four poles, the **equivalent inductance L_{eq}** of the discharge circuit can be **reduced by 2.5-3 times** due to the increased coupling between L1 and L2

Protecting MQXF with CLIQ – Expected equivalent inductance L_{eq}

Parameter	MQXC2	HQ02	HQ03	LARP MQXF	CERN MQXF
CLIQ Configuration	**P13-P42**	**P14-P32**	**P13-P42**	**P13-P42**	**P13-P42**
Magnetic length [m]	1.655	0.84	0.84	4	6.8
Inductance per unit length [mH/m]	5.08	7.59	7.59	8.27	8.27
Inductance [mH]	8.4	6.4	6.4	x5 33	x9 56
Equivalent Inductance L_{eq} [mH]	**0.57**	**1.36**	÷3 **0.47**	x5 **2.62**	x9 **4.45**
Filament twist-pitch [mm]	15/18	14	14?	19?	19?
RRR	210-230	80/140	140?	140?	140?

The expected reduction in the equivalent inductance L_{eq} of the CLIQ discharge circuit was observed testing the **MQXC2 magnet**. Even if the DC inductance of this magnet is ~30% larger than HQ02, the measured L_{eq} was 2.4 times smaller than HQ02!

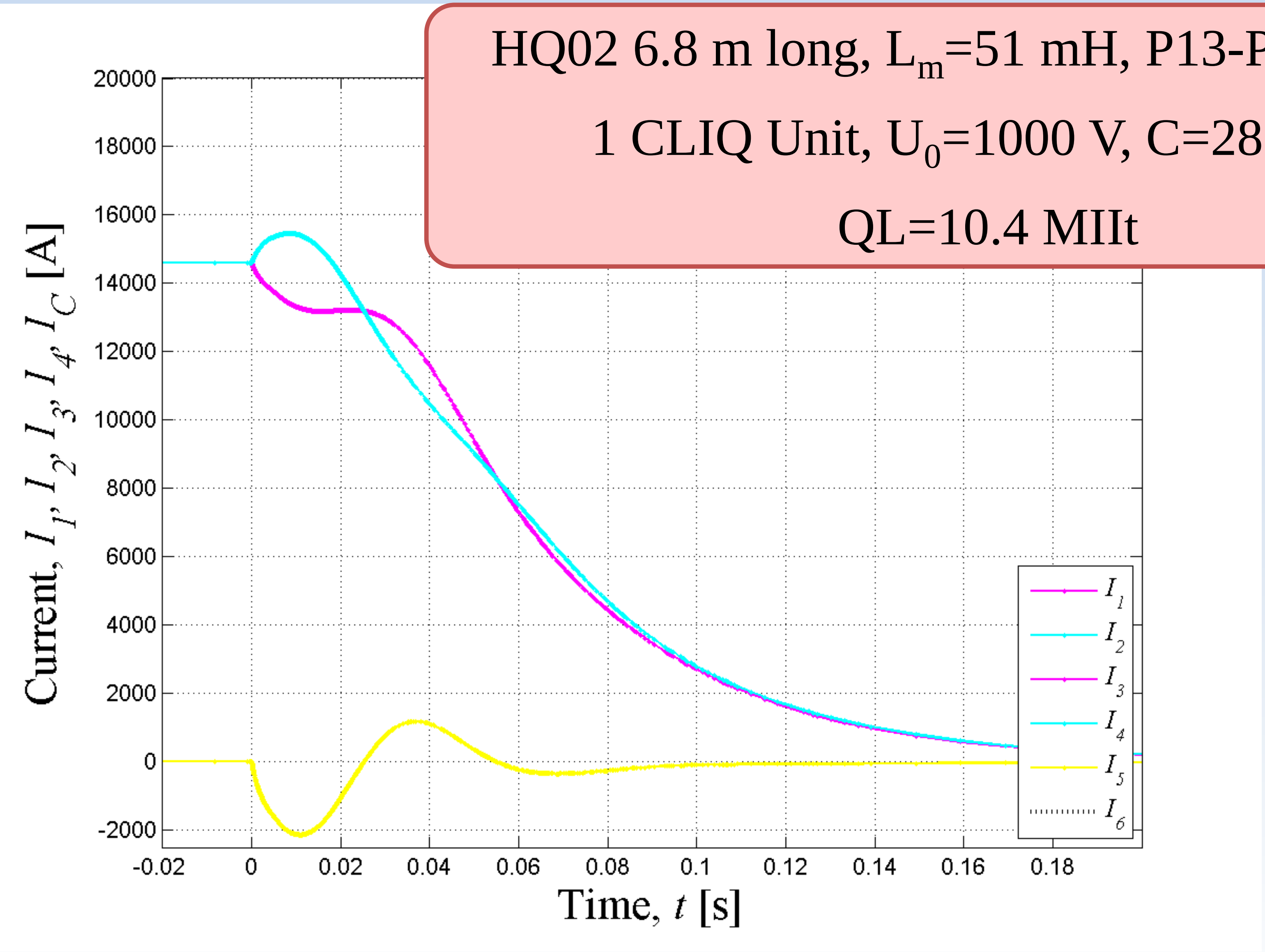
The reduction of L_{eq} can be verified by testing CLIQ on the **HQ03 magnet** in a **P13-P42** configuration (but 2 CLIQ current leads need to be connected to the magnet instead of 1). **A reduction of L_{eq} of a factor 2.5-3 is expected.**

Protecting MQXF with CLIQ – Preliminary Sim (HQ02 6.8 m long)

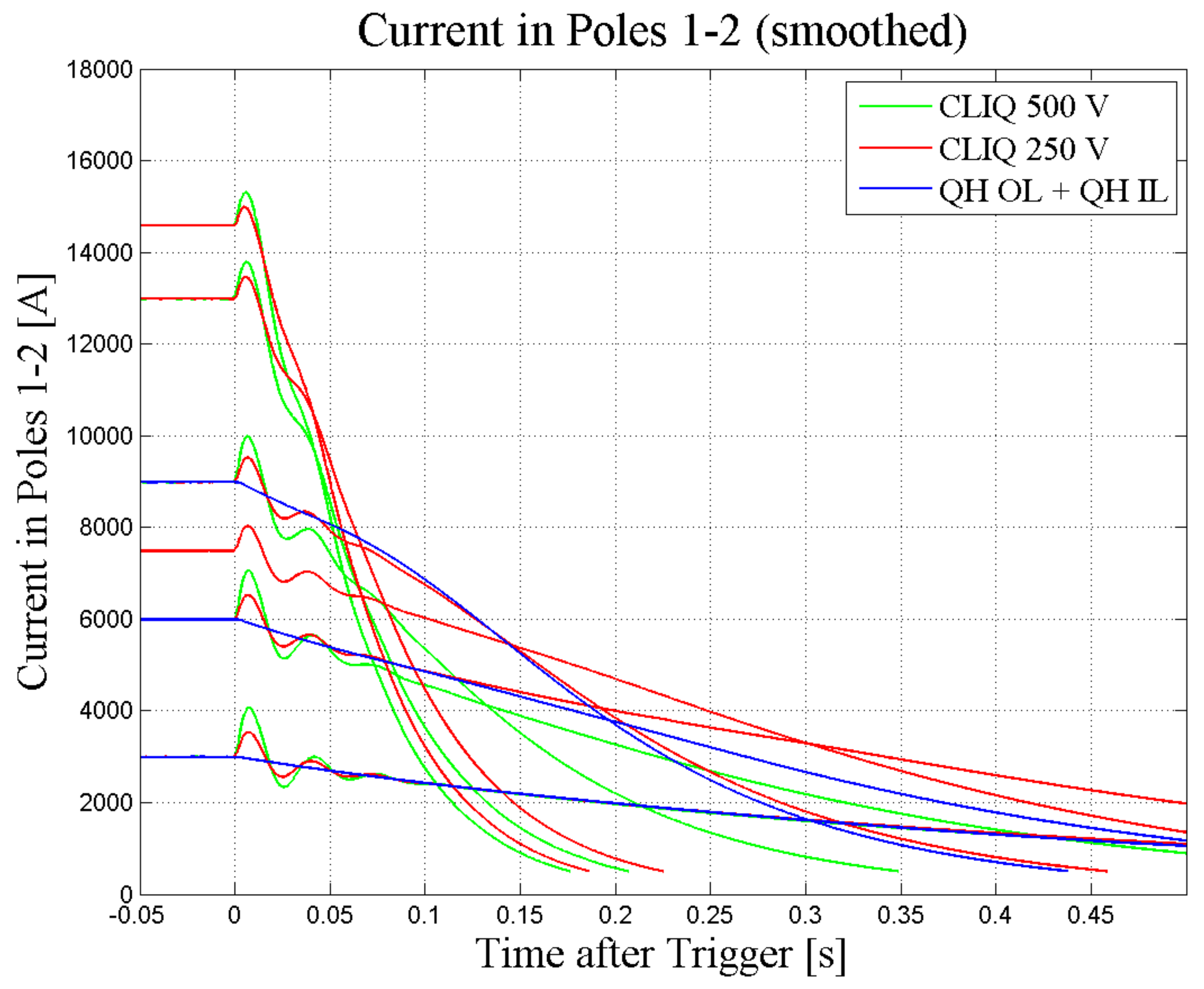
HQ02 6.8 m long, L_m=51 mH, P13-P42 Config

1 CLIQ Unit, U_0=1000 V, C=28.2 mF

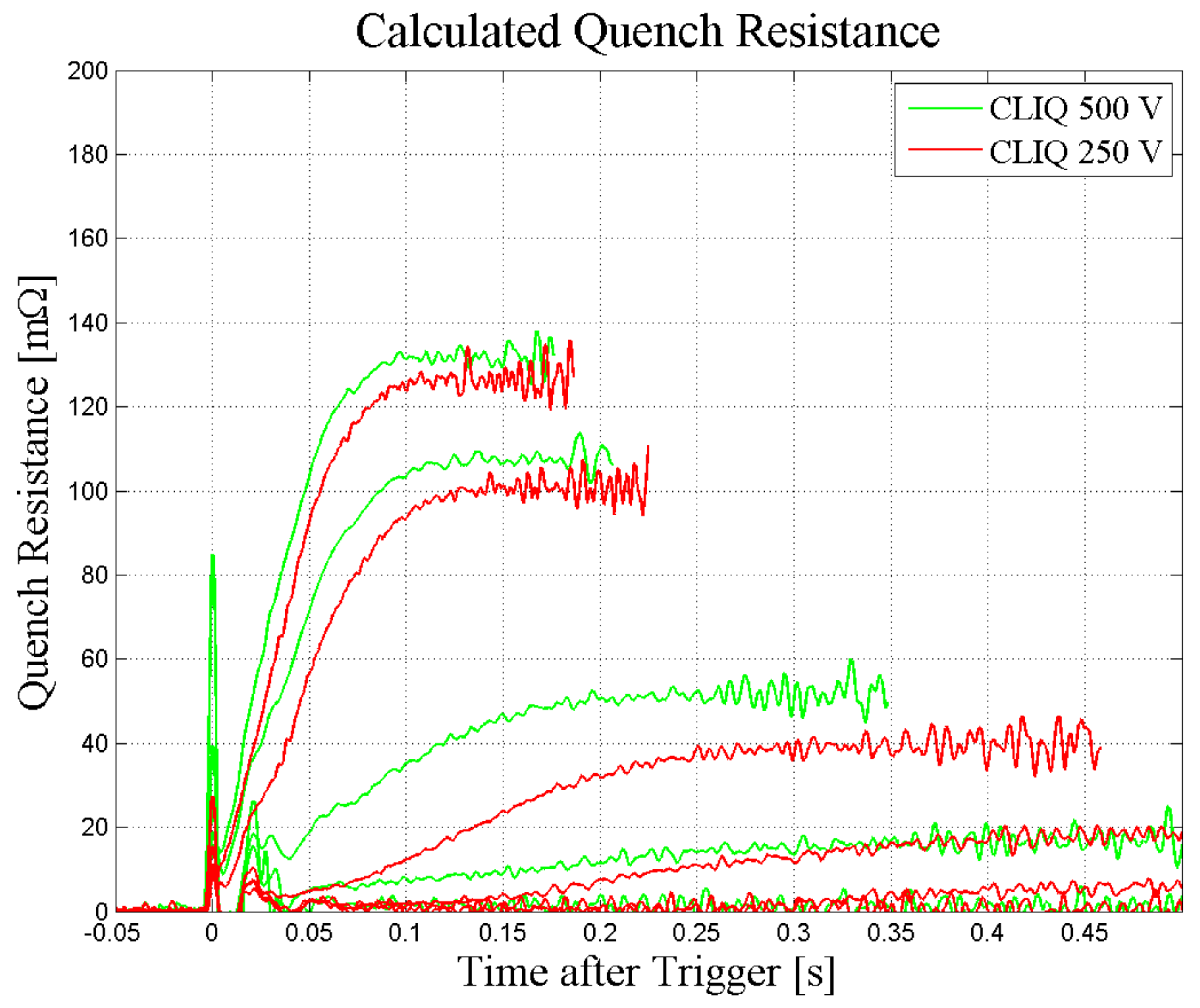
QL=10.4 MIIt



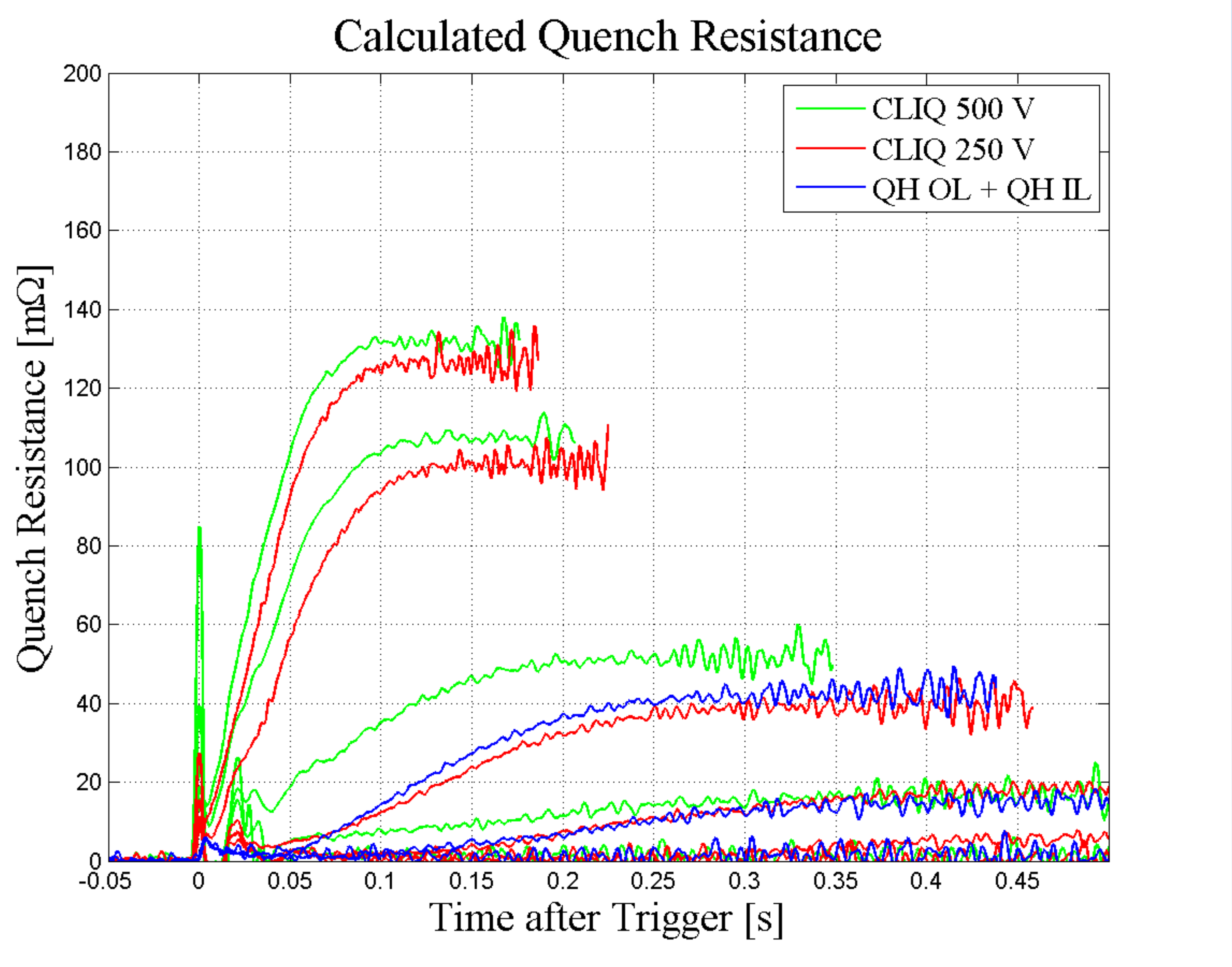
HQ02b Test Results – CLIQ 500 V cpr CLIQ 250 V cpr QH IL+OL



HQ02b Test Results – CLIQ 500 V cpr CLIQ 250 V



HQ02b Test Results – CLIQ 500 V cpr CLIQ 250 V cpr QH IL+OL



CLIQ Tests on the HQ2b – Main Goals

From 2 February 2014!

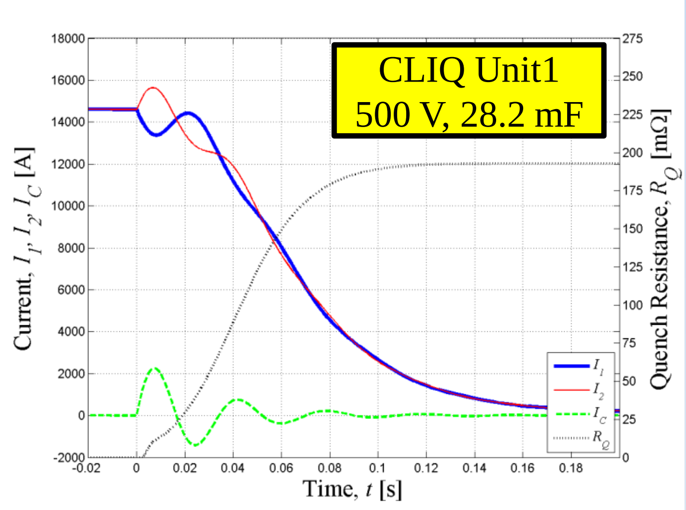
Test the CLIQ on a **Nb_3Sn** magnet for the first time (**higher energy density** to introduce to provoke and propagate a quench in the coil, more **fragile** coil)

Comparison with quench-heater performance: quench load (**MIIt's**), **hot-spot** temperature, development of **quench resistance**

Test of the **hybrid protection system** composed of CLIQ + Quench Heaters

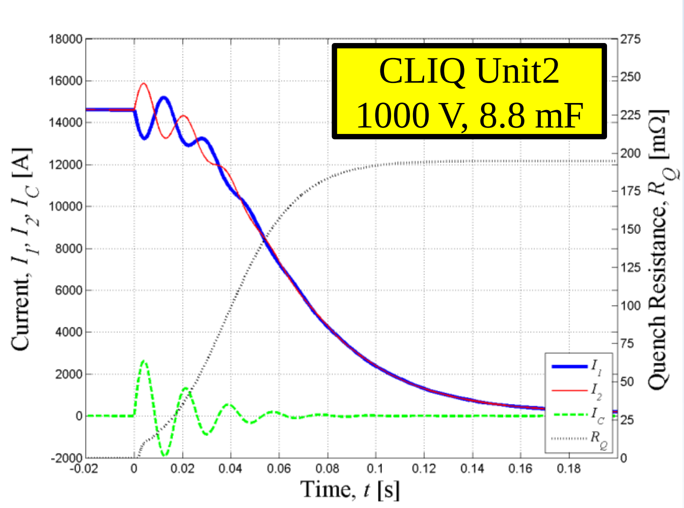
Test of **both CLIQ units** (500 V, 28.2 mF vs 1 kV, 8.8 mF) (different **frequency**, different **power**)

Information about the protection of larger coils (larger **inductance**, lower **dI/dt**, different **frequency**)



CLIQ Unit1
500 V, 28.2 mF

Preliminary!



CLIQ Unit2
1000 V, 8.8 mF

Preliminary!