First Experience with the New Coupling-Loss Induced Quench System

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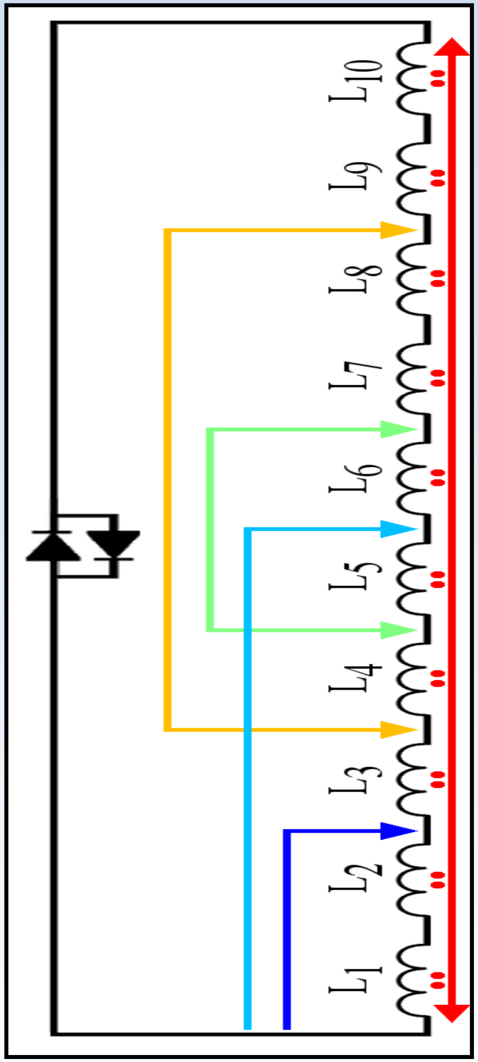
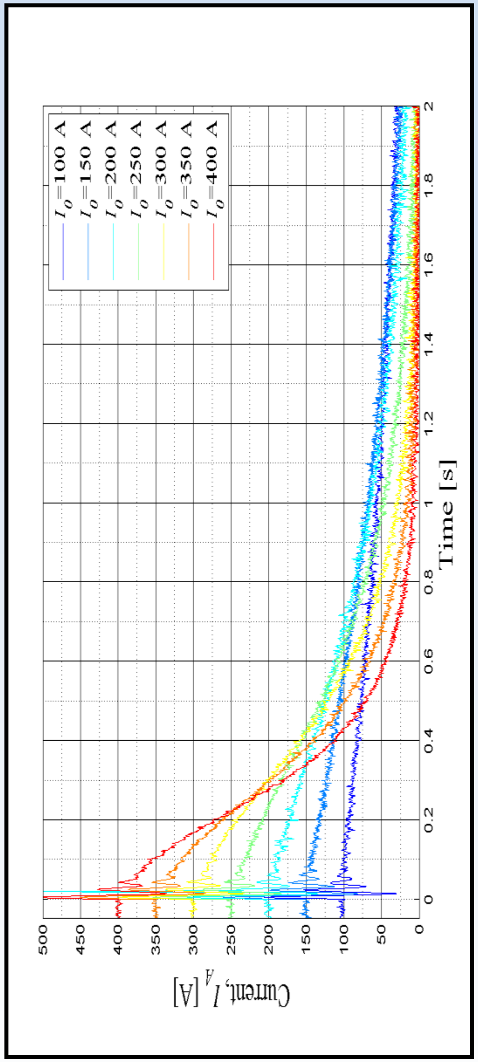
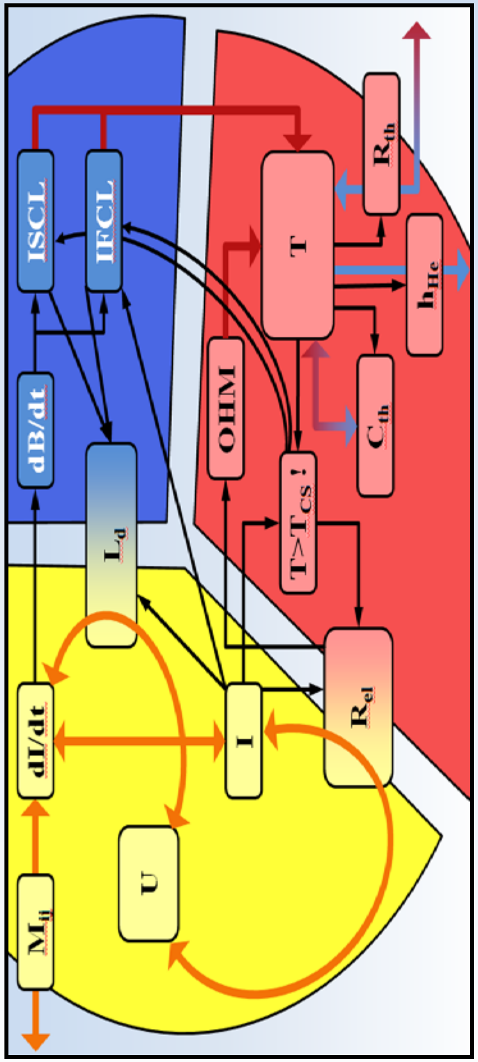
First Experience with the New Coupling-Loss Induced Quench System

Theory	Test Results	Modeling	Outlook







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Quench in a Superconducting Magnet

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

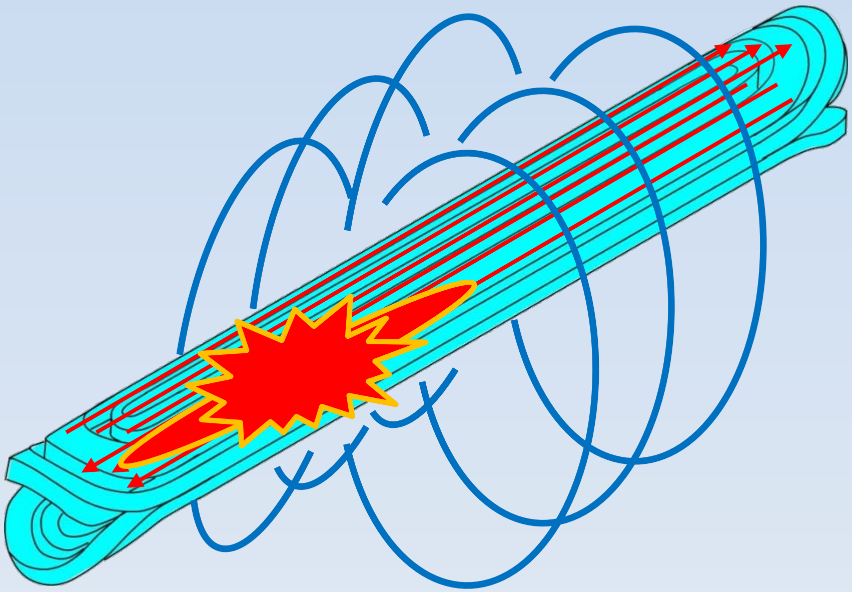
High Magnetic Field
B = 5-10 T (15 T?)

High Energy Density
$e = B^2/(2\mu_0) \approx 10\text{-}40\ MJ/m^3$

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

Quench Propagation
The heat mainly propagates through the Copper matrix around the sc filaments

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

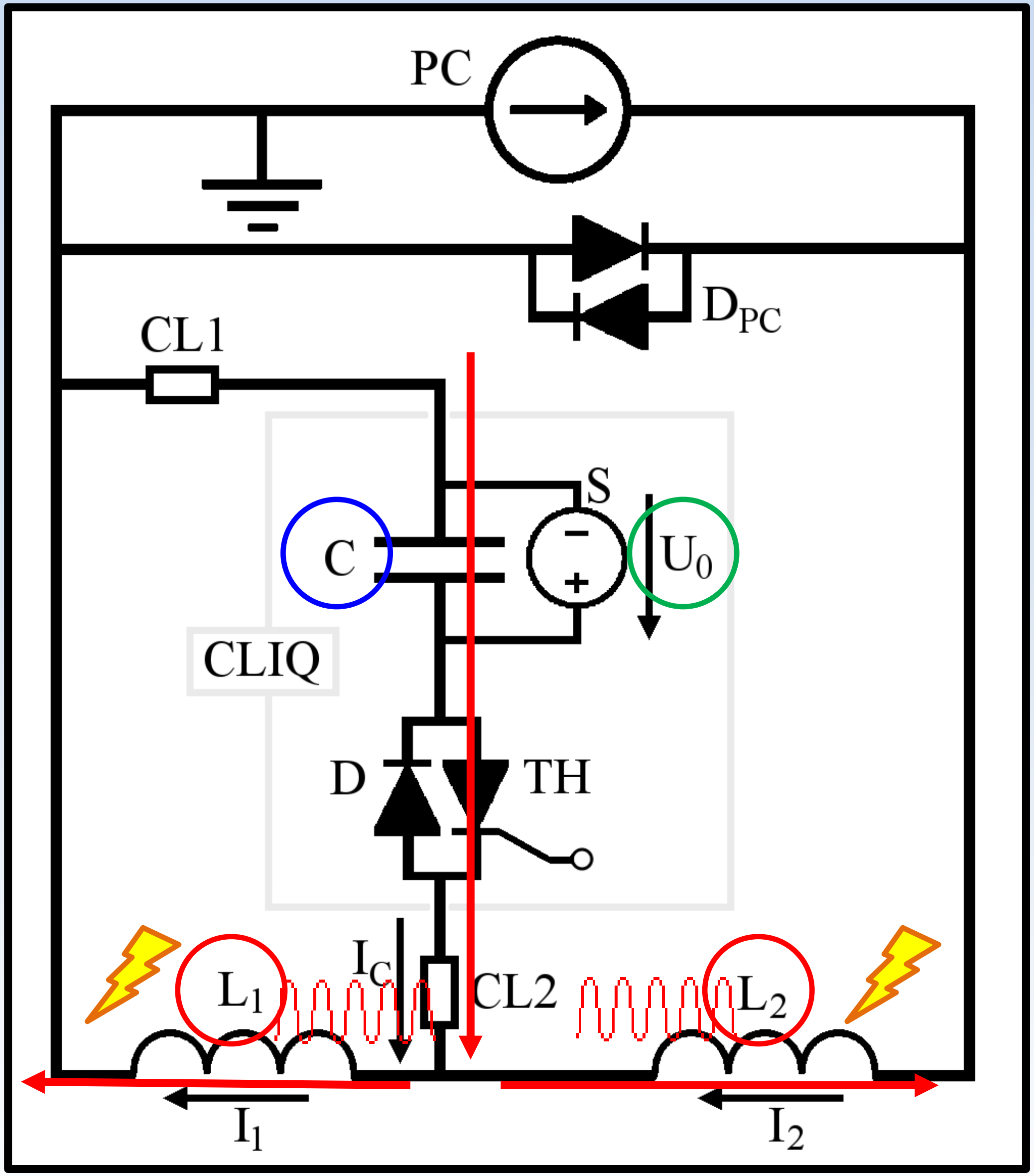


How to keep the hot-spot temperature low and protect the magnet?

Quick extraction of the energy (i.e. the current) stored in the magnet

Fast propagation of the quench to reduce the discharge time

Concept of CLIQ – Coupling-Loss Induced Quench



Current Change

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

$$\frac{dI_C(t)}{dt} \approx \frac{U_0}{L} \cdot \cos\left(\frac{t}{\sqrt{LC}}\right)$$

Magnetic Field Change

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

Coupling-Losses (Heat)

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

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

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

Temperature Rise

QUENCH

E. Ravaioli et al., MT23, 2013.

E. Ravaioli et al., EUCAS11, 2013.

EU Patent EP13174323.9, June 2013.

CLIQ – Main Advantages

Heat generated exactly where we need it: directly in the copper matrix of the strand, without relying on thermal diffusion

Very fast quench mechanism

Global quench initiation
→ More homogenous temperature distribution

Cheap and robust system

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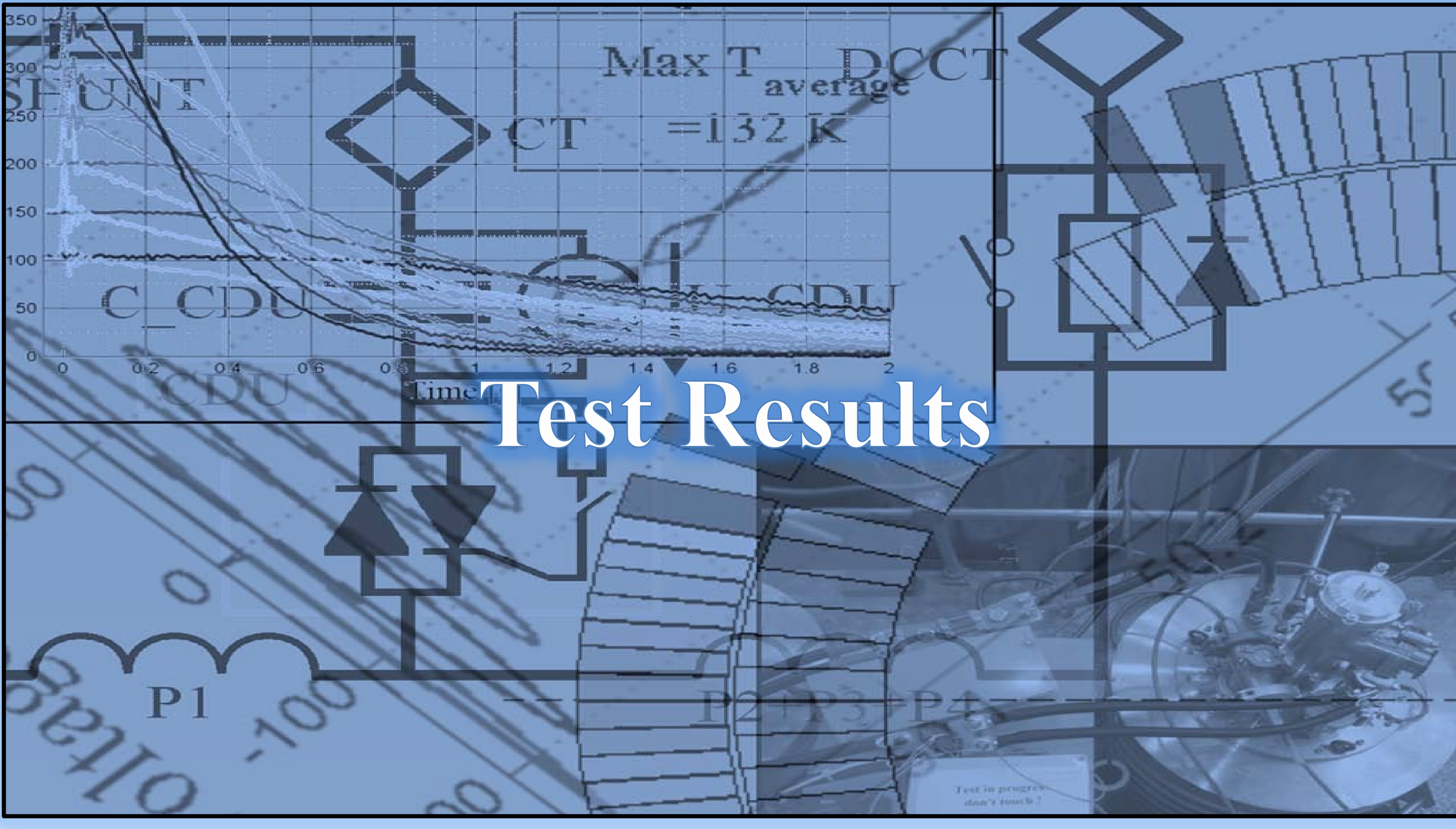
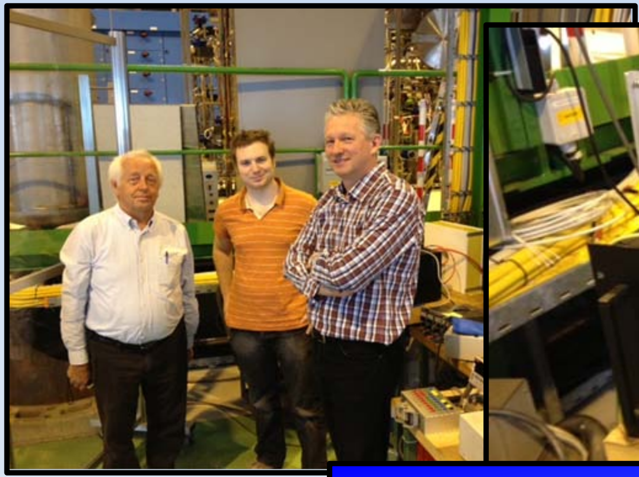
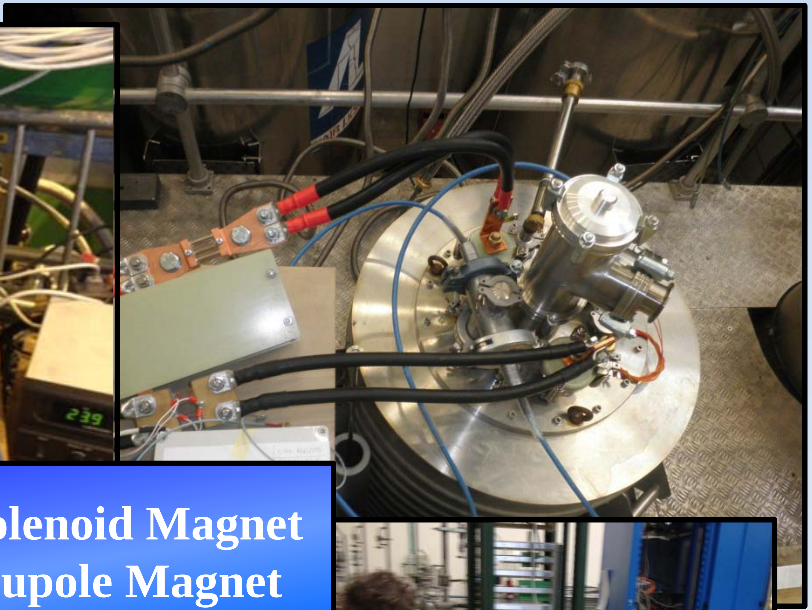


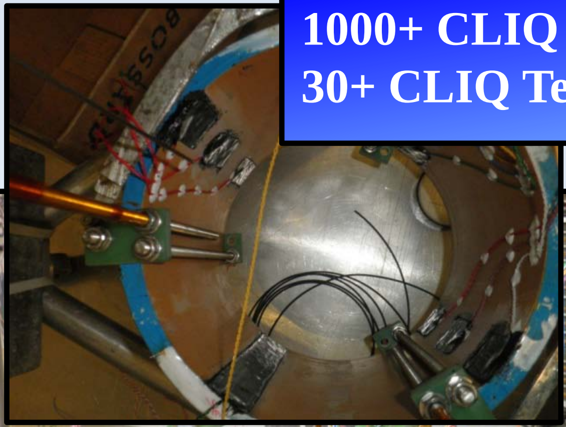
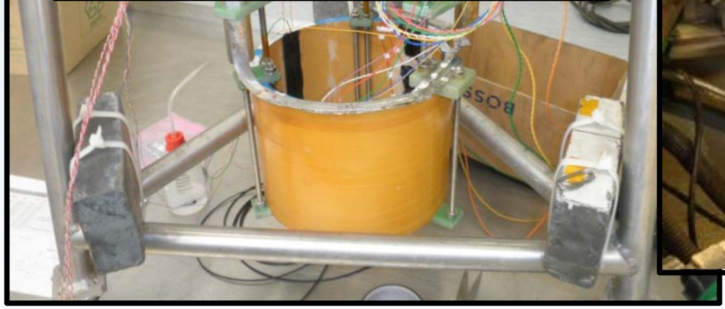
Test Results

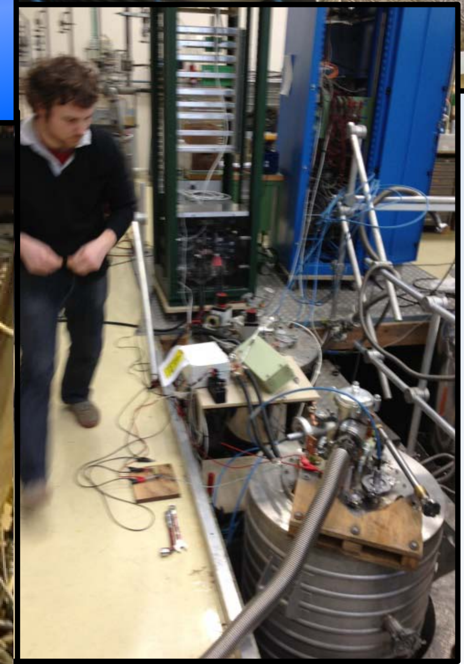
Test Setup – CERN Cryogenic Laboratory & Magnet Test Facility



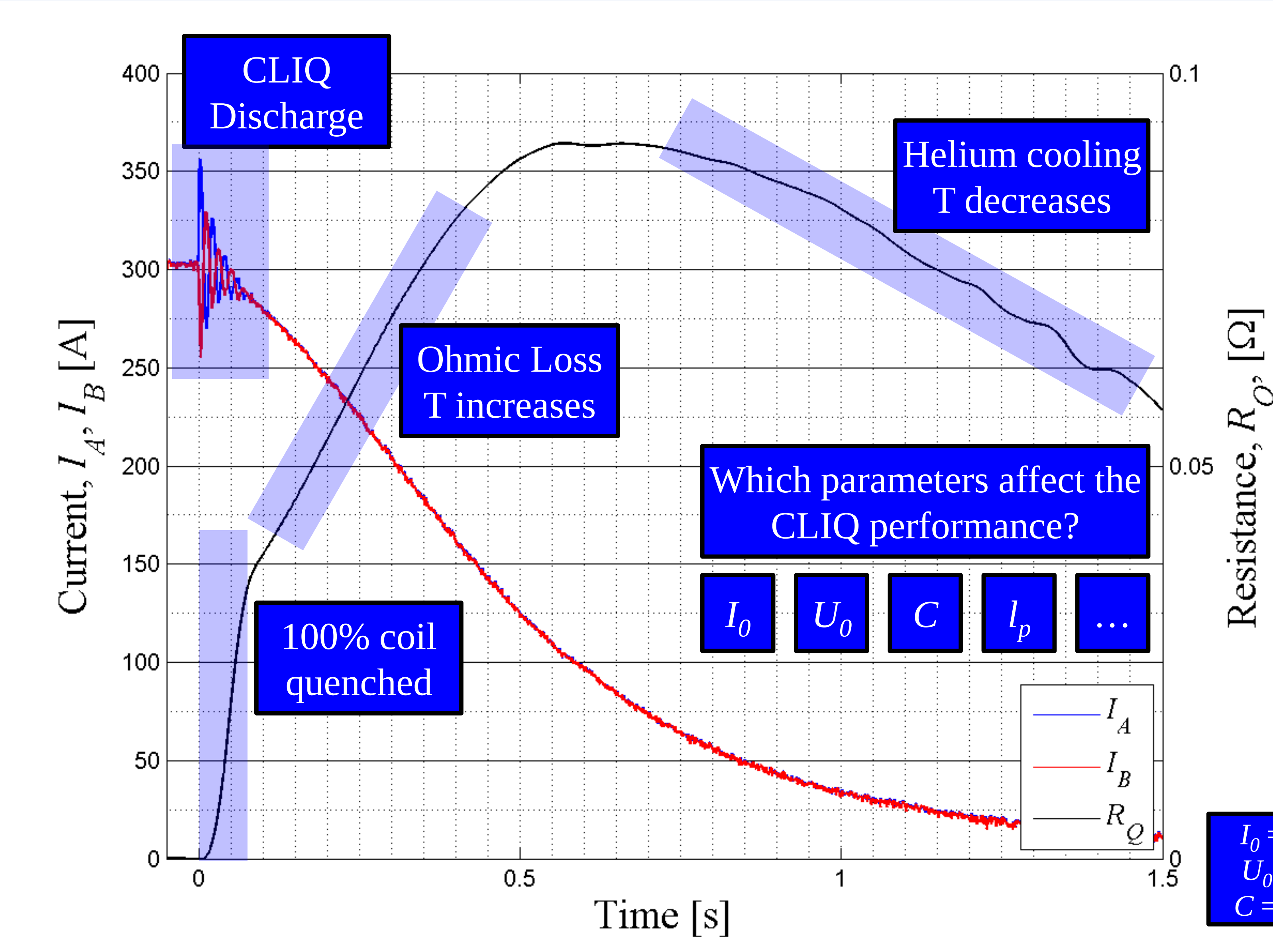


1000+ CLIQ Tests on a small-size Solenoid Magnet
30+ CLIQ Tests on a 2 meter Quadrupole Magnet

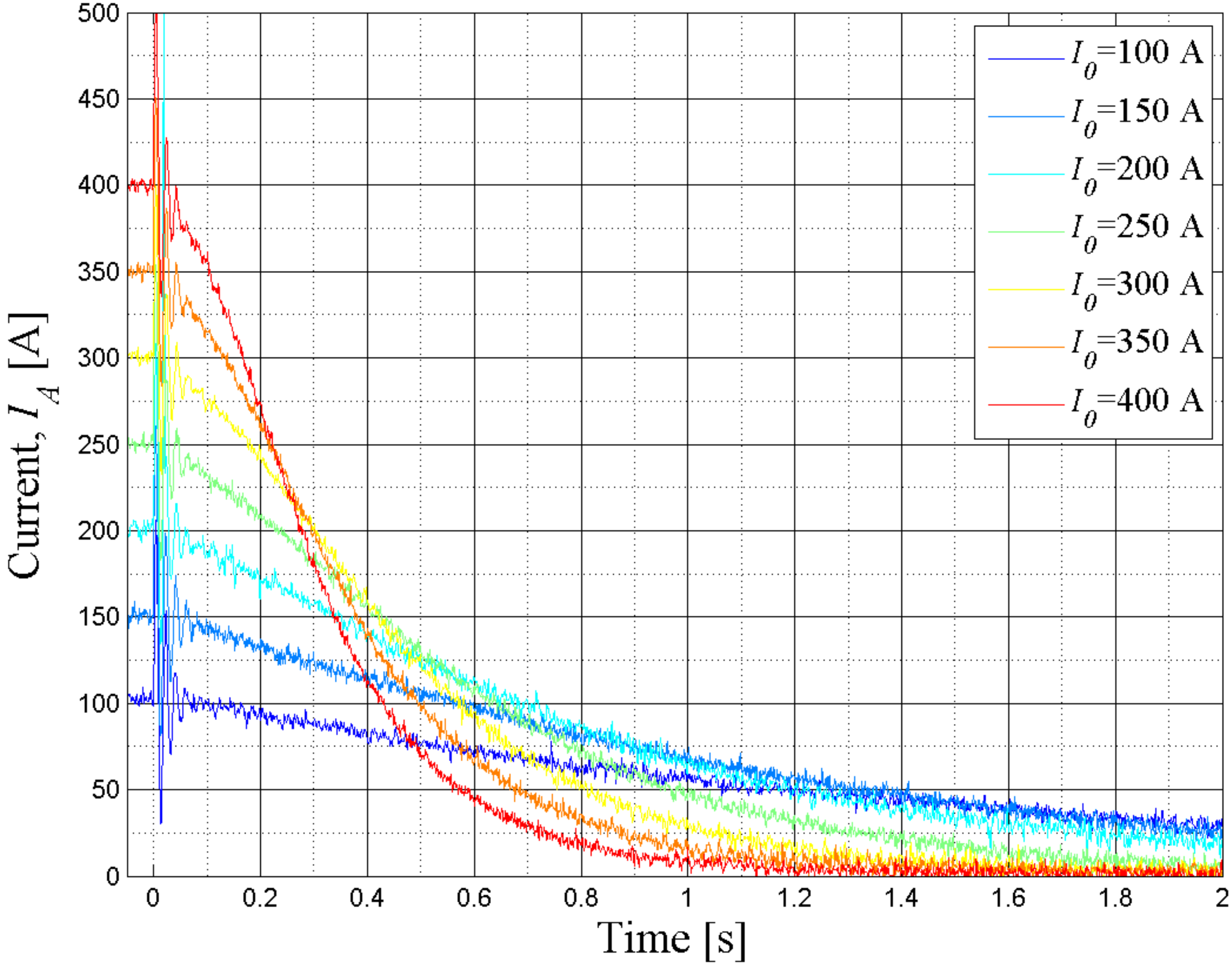


CLIQ – Coupling-Loss Induced Quench



I_0 = 300 A
U_0 = 75 V
C = 4.4 mF

CLIQ – Effect of the Initial Current I_0 – Magnet Current



$$\frac{dI}{dt} \neq f(I_0)$$

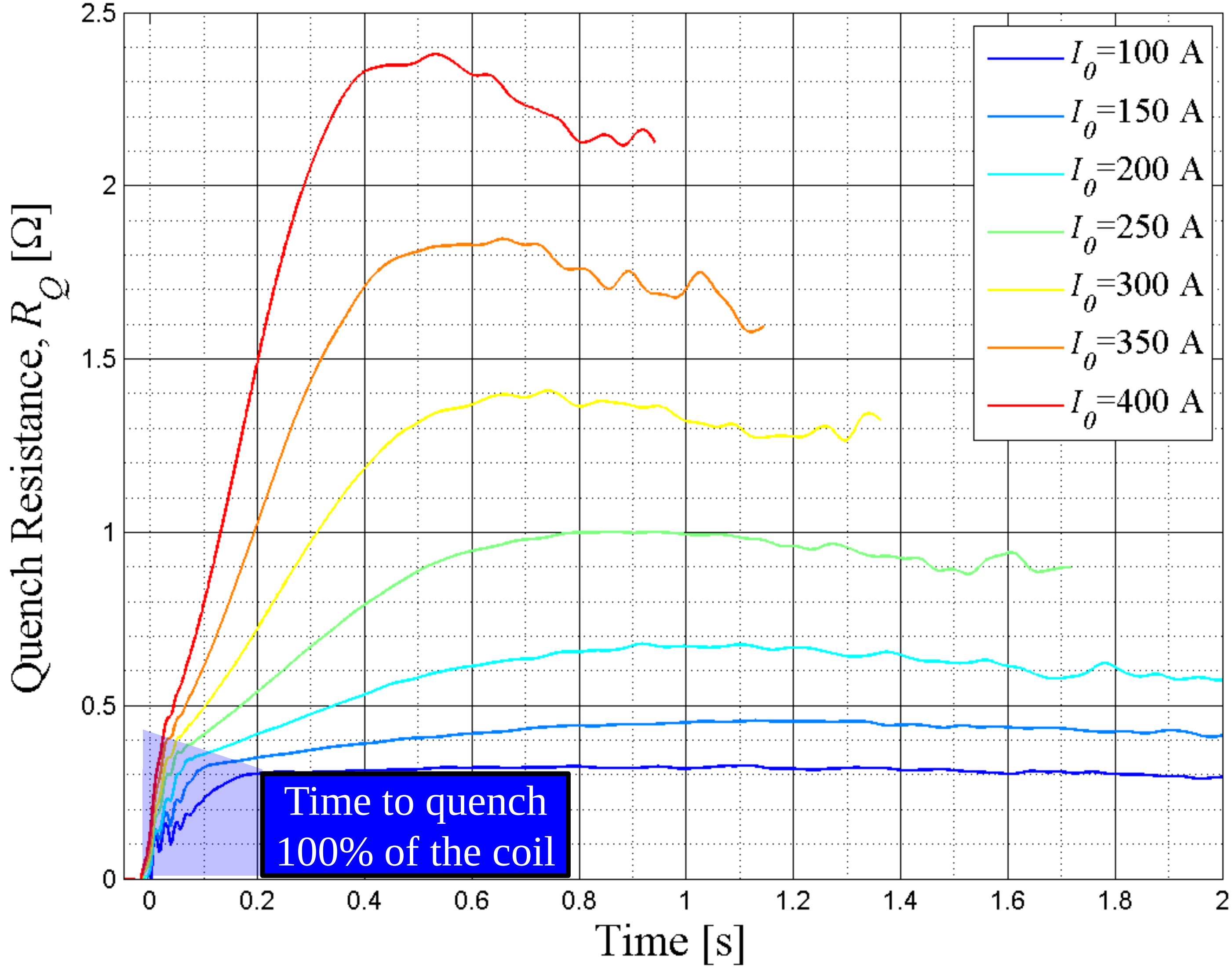
$$\frac{P_{IF}}{vol} \neq f(I_0)$$

$$T_{cs} = f(I_0)$$

$$P_{Ohm} \propto I_0^2$$

U_0 = 150 V
C = 4.7 mF

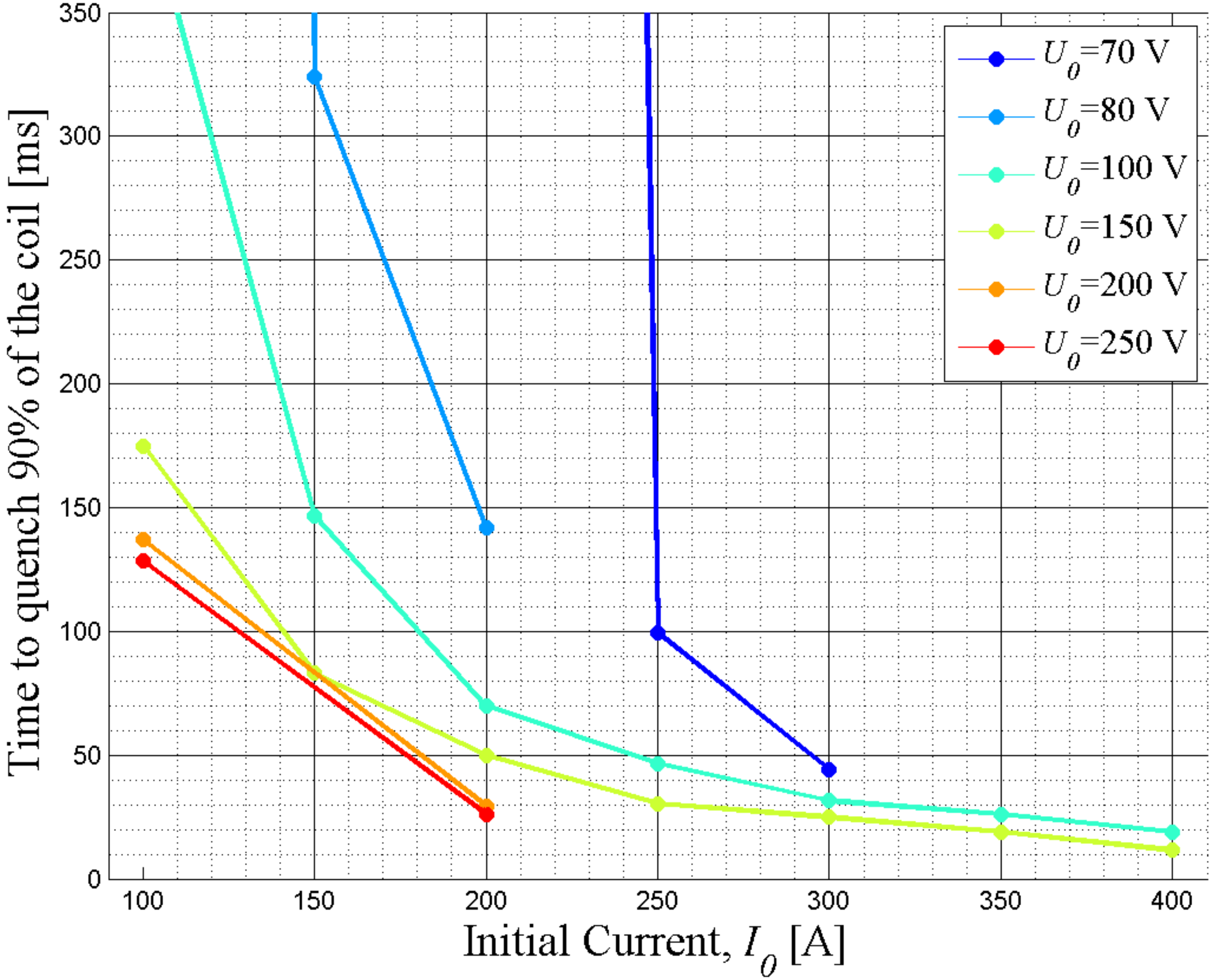
CLIQ – Effect of the Initial Current I_0 – Quench Resistance



$T_{cs} = f(I_0)$
$P_{Ohm} \propto I_0^2$

U_0 = 150 V
C = 4.7 mF

CLIQ – Effect of the Charging Voltage U_0 – Time to Quench

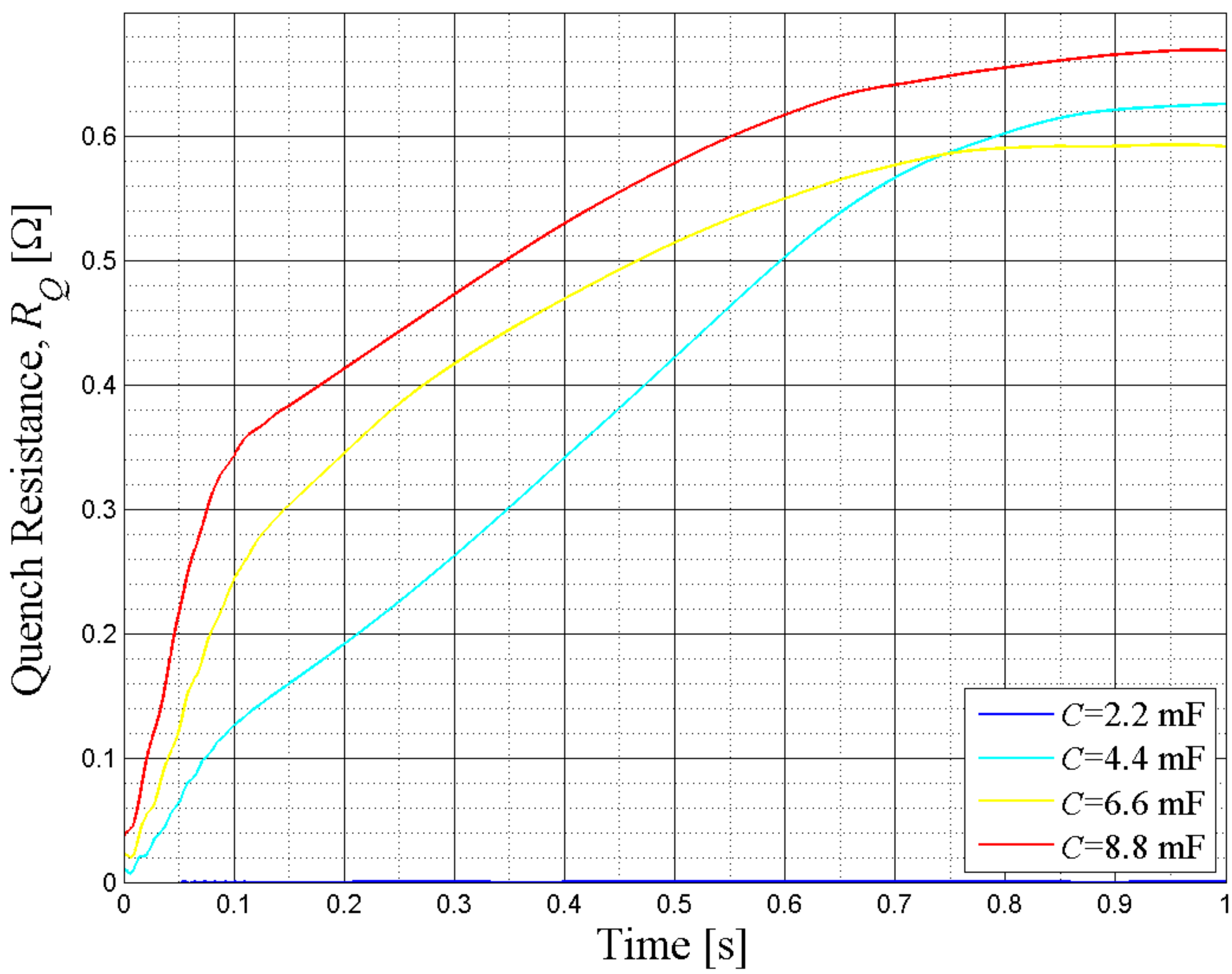


$$\frac{P_{IF}}{vol} \propto \left(\frac{U_0}{L}\right)^2$$

U_0 usually limited by safety limits

C = 4.7 mF

CLIQ – Effect of the Capacitance *C* – Quench Resistance



For the tested magnet the performance improves with larger *C*

I_0 = 200 A
U_0 = 75 V

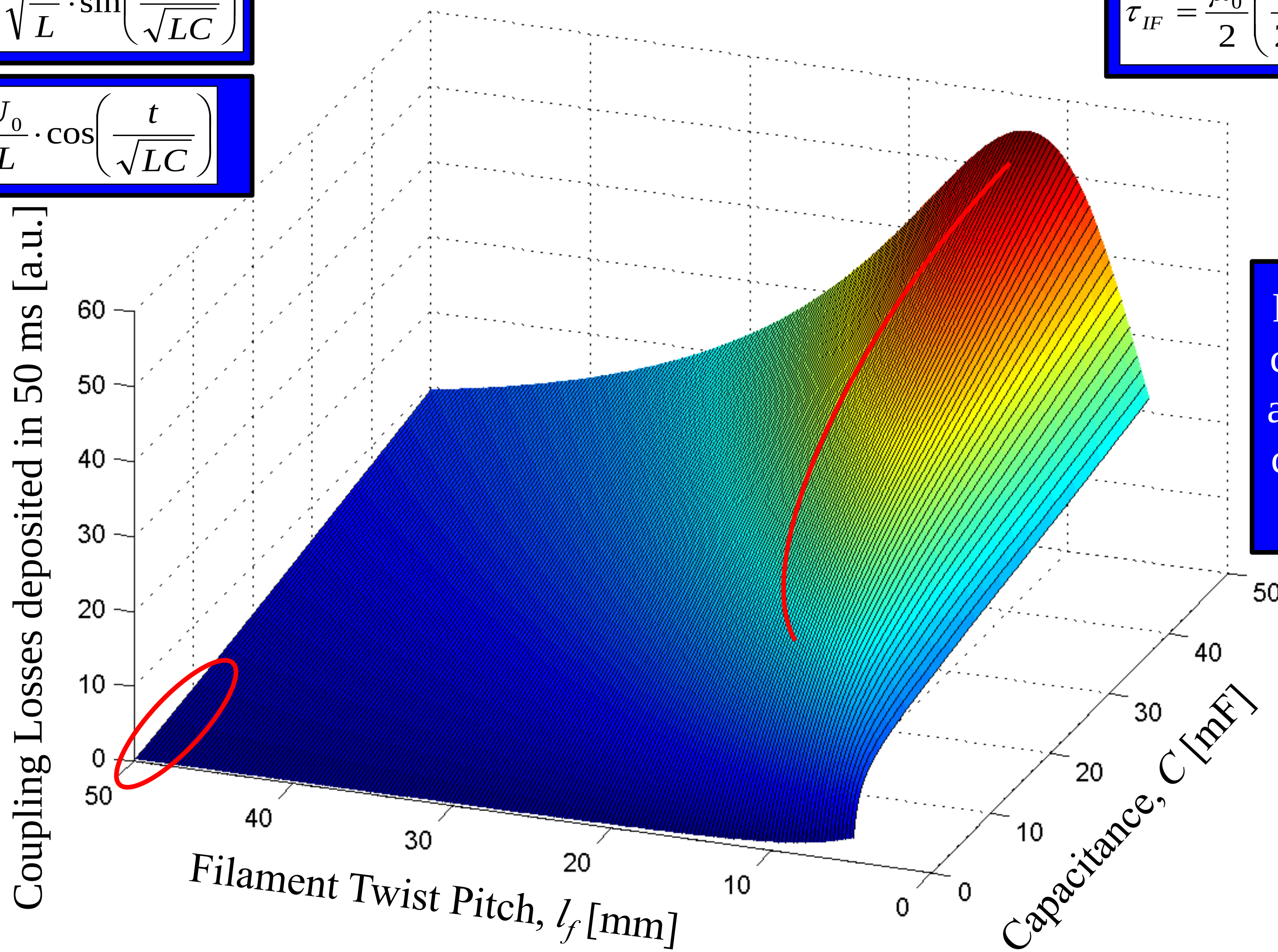
CLIQ – Effect of the Capacitance and of the Filament Twist Pitch

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

$$\frac{dI_C(t)}{dt} \approx \frac{U_0}{L} \cdot \cos\left(\frac{t}{\sqrt{LC}}\right)$$

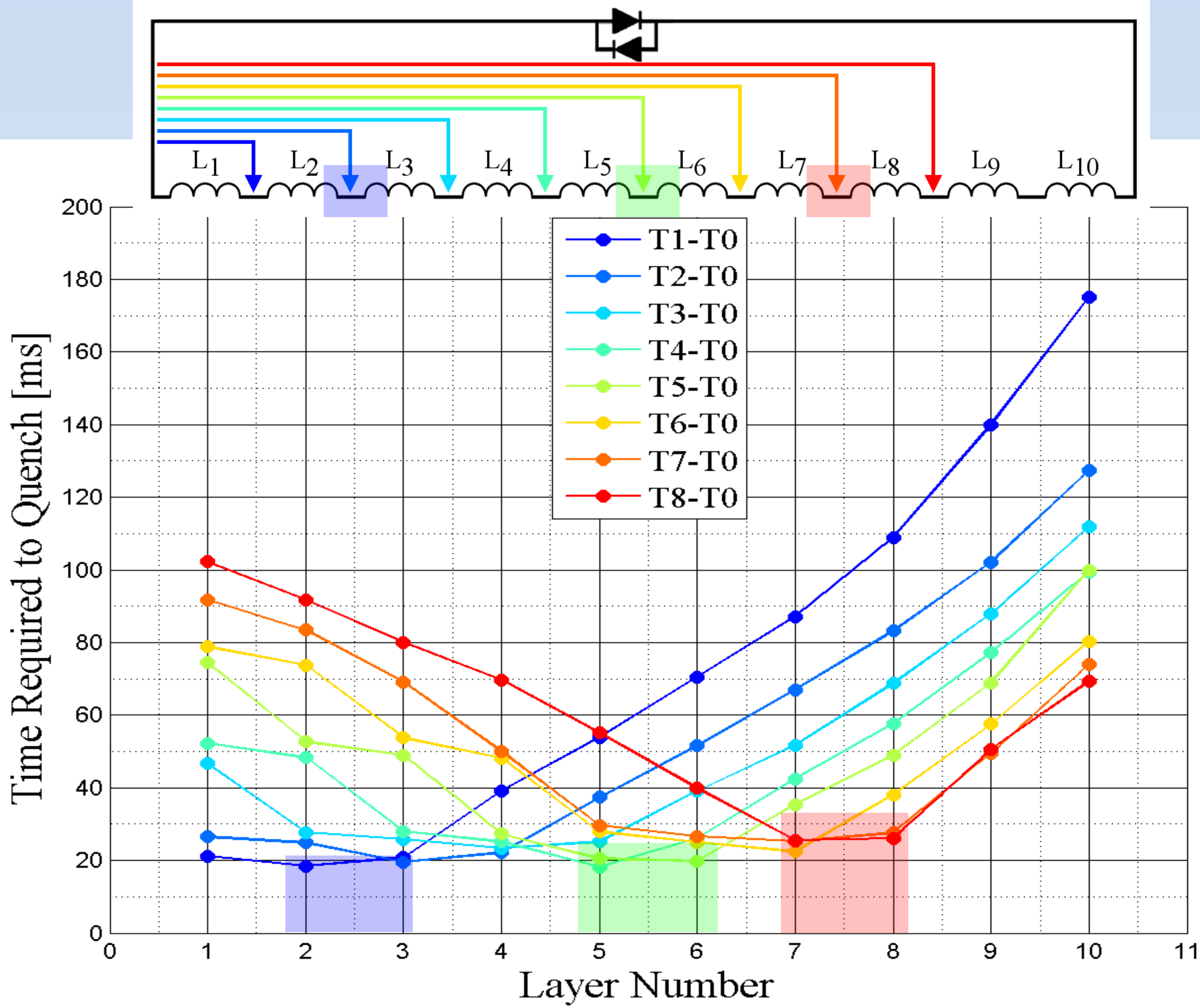
$$\tau_{IF} = \frac{\mu_0}{2}\left(\frac{l_p}{2\pi}\right)^2 \frac{1}{\rho_{eff}(B)}$$

$$\omega = \frac{1}{\sqrt{LC}}$$



For a given coil there is an optimum choice of C and l_f

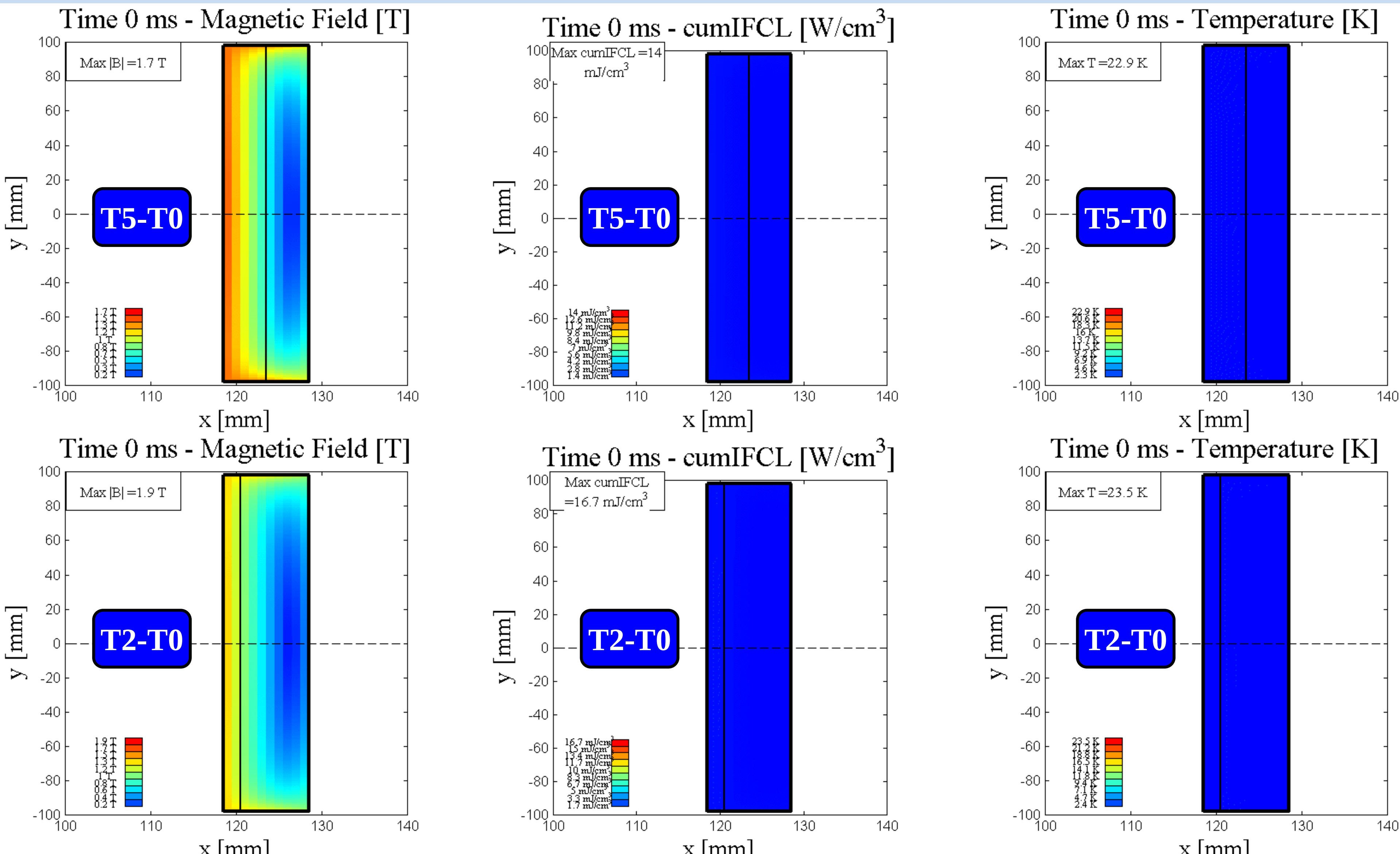
CLIQ – Effect of the Injection/Extraction Points – Time to Quench



CLIQ discharge in the central region spreads the quench faster

I_0 = 200 A
U_0 = 75 V
C = 8.8 mF

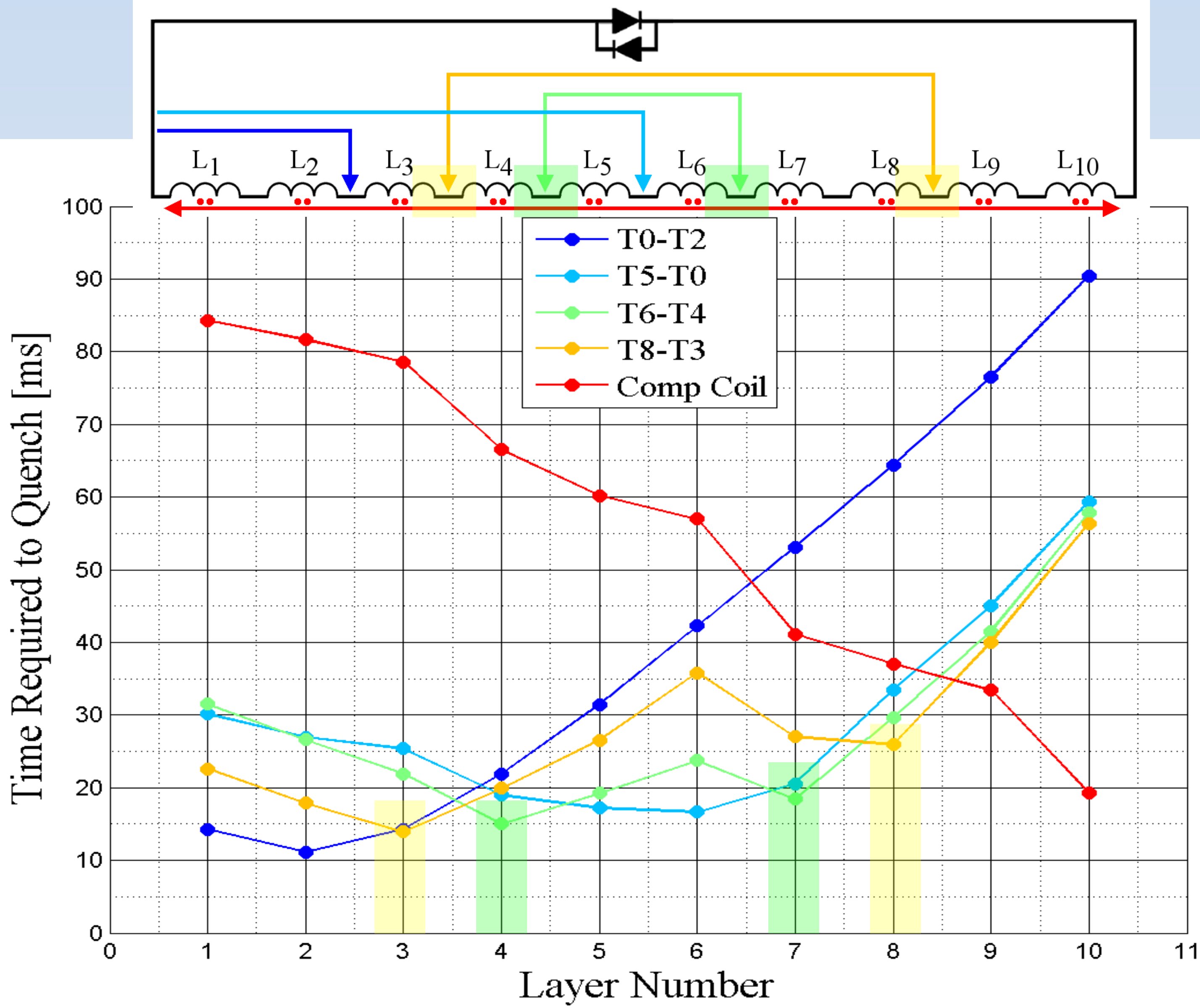
CLIQ – Effect of the Injection/Extraction Points – Simulation



Magnetic field calculated with Soleno, University of Twente

IFCL + Thermal Behavior with an in-house Matlab script

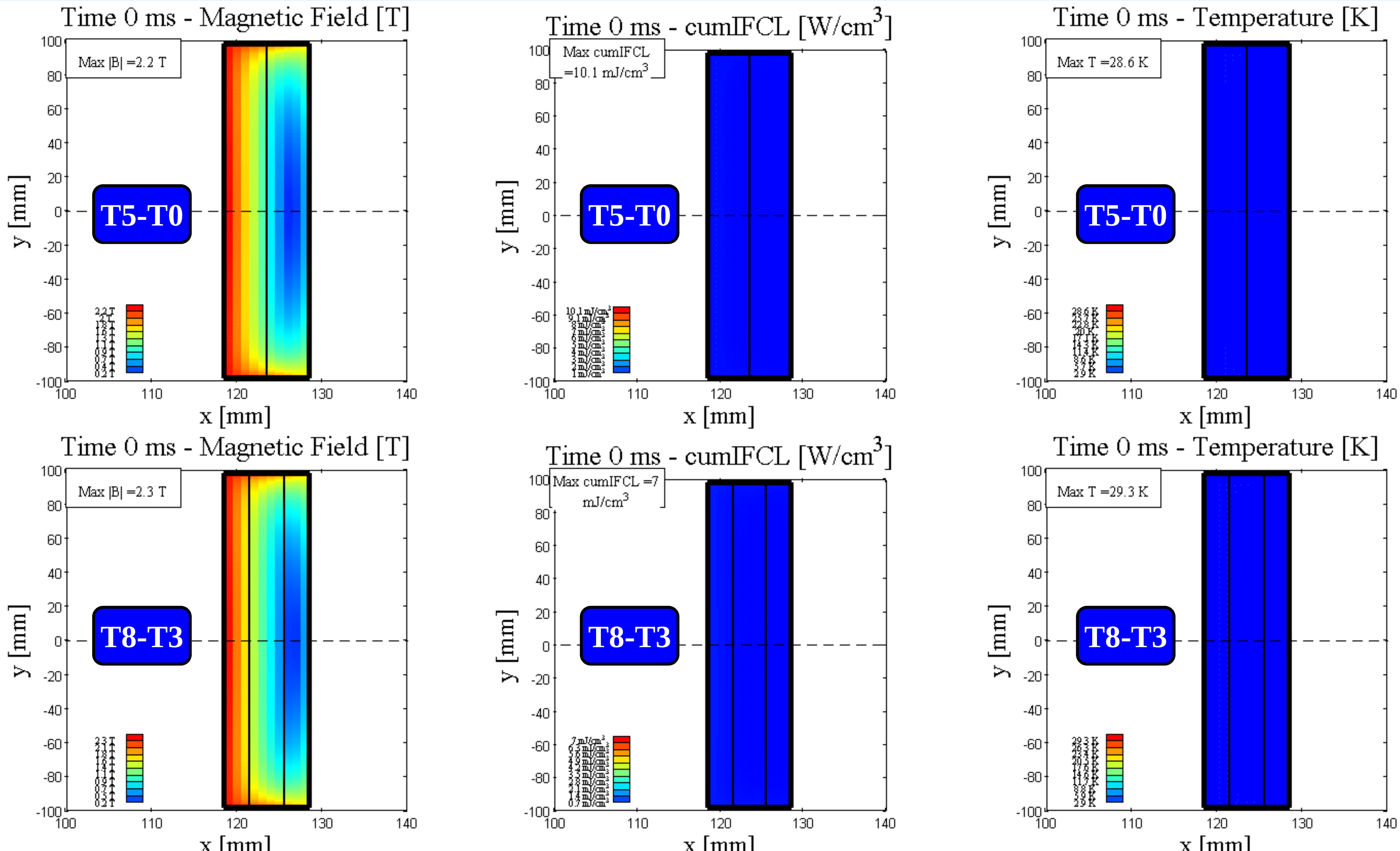
CLIQ – Effect of the Injection/Extraction Points – Time to Quench



Two separate quench areas can be created

I_0 = 300 A
U_0 = 75 V
C = 8.8 mF

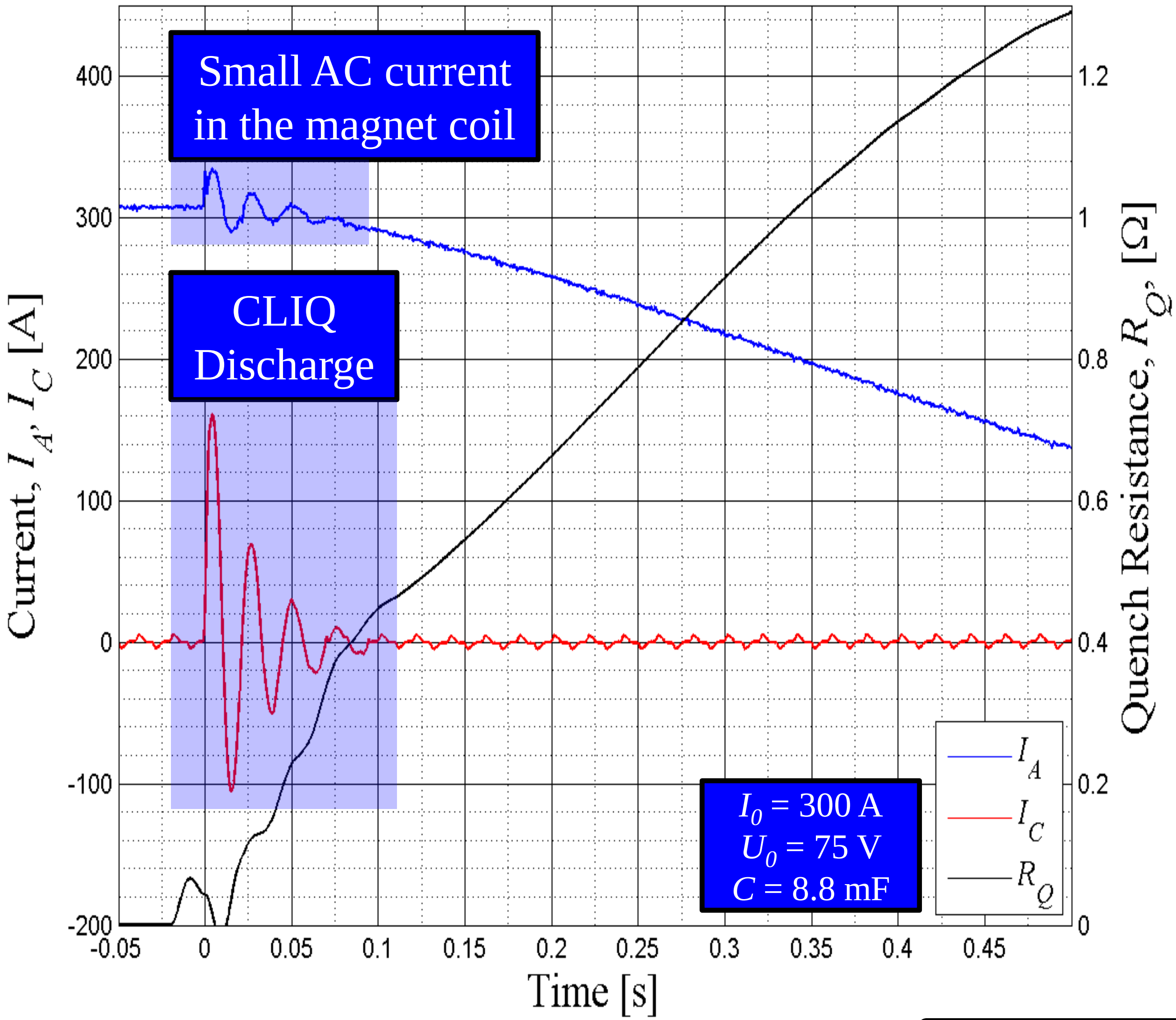
CLIQ – Effect of the Injection/Extraction Points – Simulation

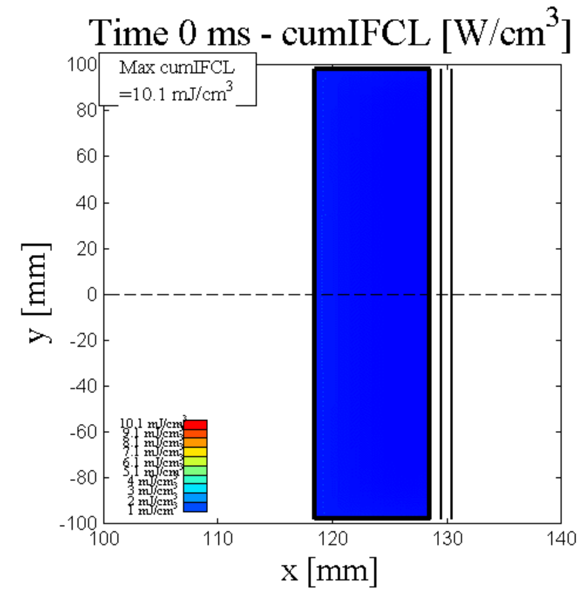


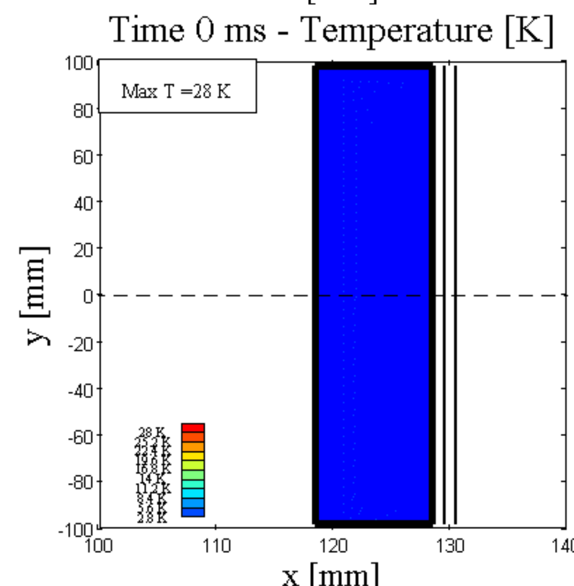
Magnetic field calculated with Soleno, University of Twente

IFCL + Thermal Behavior with an in-house Matlab script

CLIQ – Using the Compensation Coil – Measurements + Sims







Magnetic field calculated with Soleno, University of Twente

IFCL + Thermal Behavior with an in-house Matlab script

CLIQ – Using the Compensation Coil – Pros & Cons

Pros

- The CLIQ discharging circuit is **electrically insulated** from the magnet
- Increasing the **insulation thickness** of the compensation coil does not reduce the quench efficiency because CLIQ does not rely on thermal diffusion (**higher voltage** allowed)
- The **AC current** is not directly injected in the coil, thus the change in the magnet current is limited (little increase of Ohmic loss due to CLIQ)
- A purposefully-designed, **highly-insulated**, **robust** compensation coil can work at high voltage and AC current without a great impact on the **safety** in the system

Cons

- For a given coil and charging voltage, it is typically **less efficient** than a standard CLIQ discharge (if the compensation coil has **less turns** than the solenoid magnet)
- How to implement this on a **dipole/quadrupole magnet?...**

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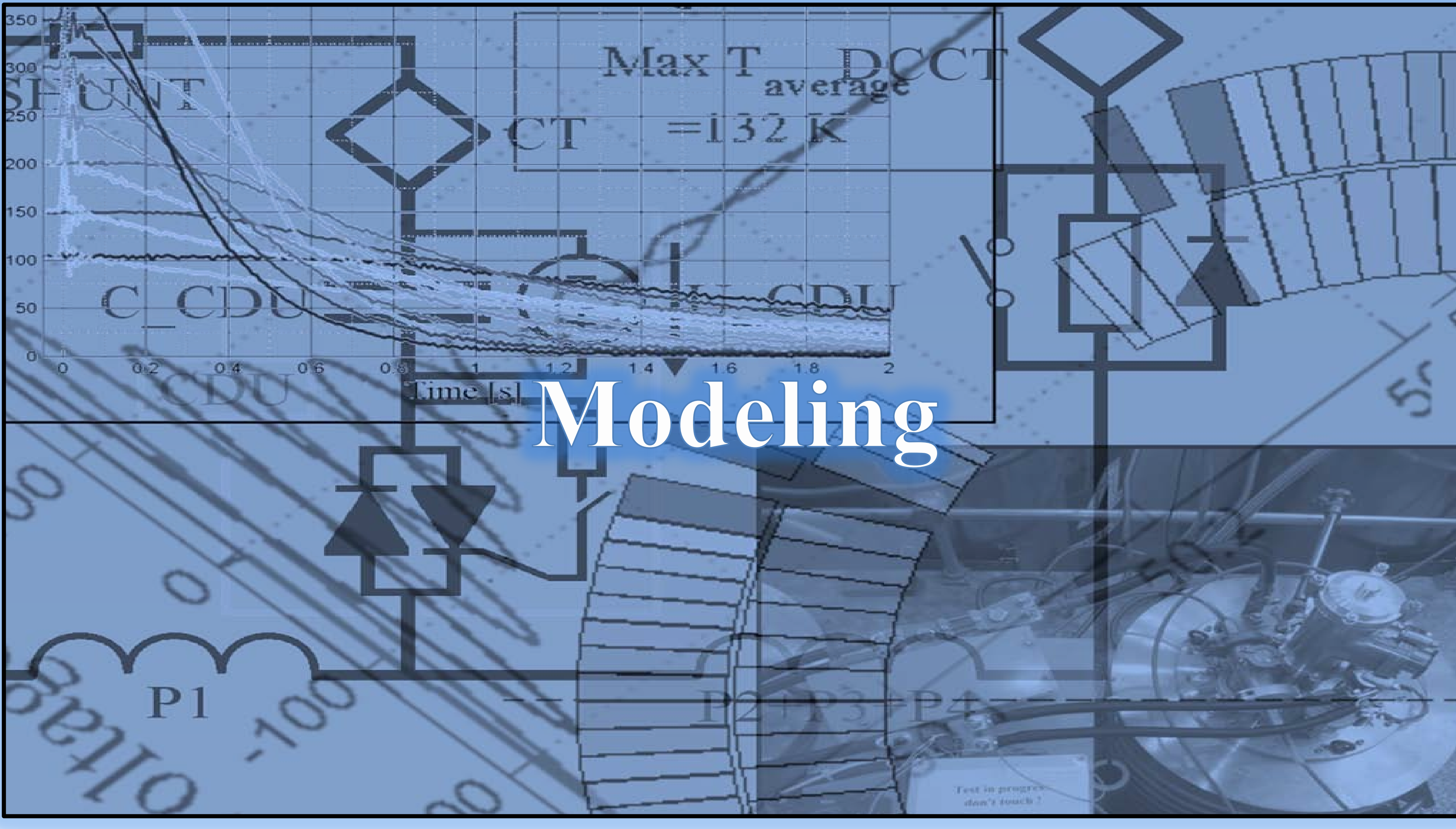


LEDET Lumped-Element Dynamic ElectroThermal model

2D model
No longitudinal direction

Superconducting magnet divided in blocks with homogeneous properties: magnetic field, temperature, heat capacity, resistivity, thermal conductance, etc

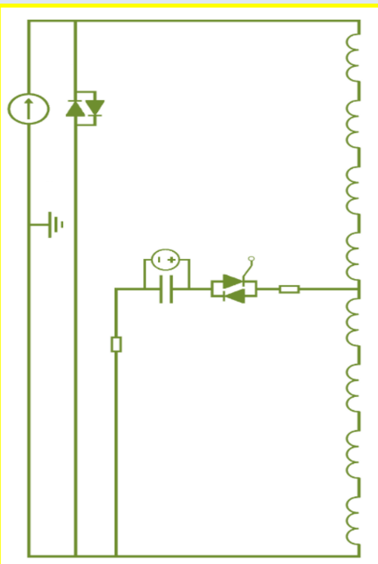
The electrical, thermal, and dynamic problems are described with networks of lumped-elements which are solved simultaneously with commercial software (PSpice, Simulink, Simplorer, etc)

Very fast simulations but a smart method for the choice of the lump-elements has to be found

Electrical - *Obvious*

U≡ΔT , I≡Q

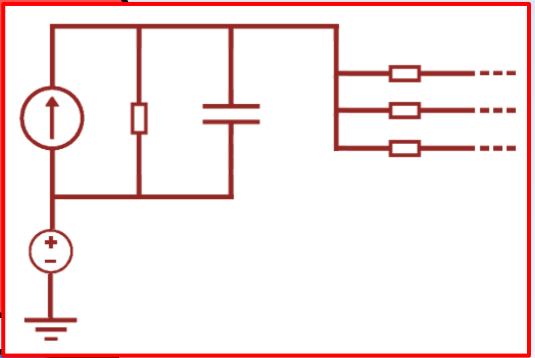
Thermal - *Easy*



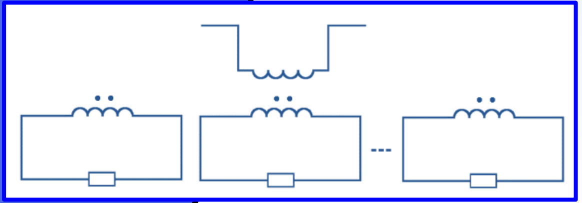
???

$$U_{source}, I_{source}$$
$$U_R = R_{EL} I$$
$$I_C = C\, dU_C / dt$$
$$U_L = L\, dI_L / dt$$

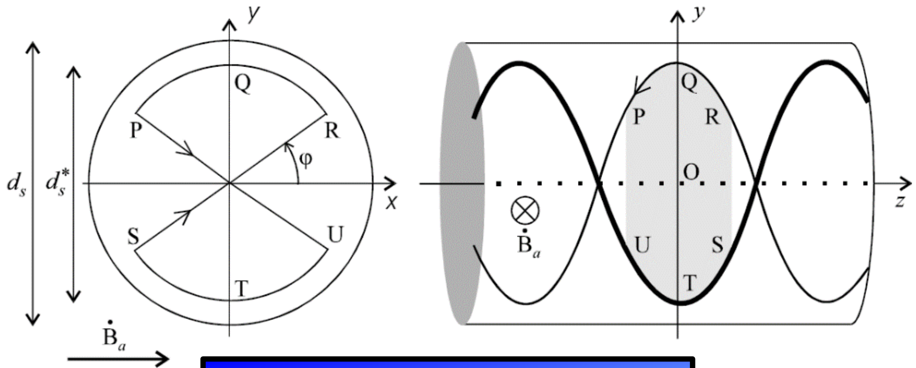
$$Q_{OHM} = R_{EL} I^2$$
$$\Delta T = R_{TH} Q_{ex}$$
$$Q_{TH} = C_{TH}\, dT/dt$$



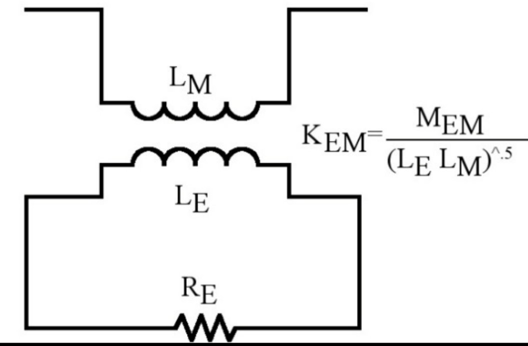
Dynamic - *Tricky*



Implementation of the Magnet Dynamic Behavior in the Model



$P_{IF} \equiv R_E I_E^2$
$I_{IF} \equiv I_E$
$\tau_{IF} \equiv L_E/R_E$



Physical Behavior

$$\begin{cases} P_{IF} = \beta V \dot{B}_t^2 \\ I_{IF} = \pm \frac{2 d_s^* \dot{B}_i}{\mu_0} = \pm \frac{2 d_s^* \tau \dot{B}_t}{\mu_0} = \pm \beta d_s^* \dot{B}_t \end{cases}$$

$$\begin{cases} \dot{B}_t = \dot{B}_a + \dot{B}_i \\ \dot{B}_t = \pm \frac{1}{\beta d_s^*} I_{IF} \\ \dot{B}_a = f_M \dot{I}_M \\ \dot{B}_i = \frac{\mu_0}{2 d_s^*} \dot{I}_{IF} \end{cases} \rightarrow \begin{matrix} \pm \frac{1}{\beta d_s^*} I_{IF} = f_M \dot{I}_M + \frac{\mu_0}{2 d_s^*} \dot{I}_{IF} \\ \pm \frac{V}{\beta d_s^{*2}} I_{IF} = \frac{f_M V}{d_s^*} \dot{I}_M + \frac{\mu_0 V}{2 d_s^{*2}} \dot{I}_{IF} \end{matrix}$$

Lumped-Element Equivalent Model

$$P_E = R_E I_E^2 \rightarrow R_E = \frac{P_E}{I_E^2} = \frac{V}{\beta d_s^{*2}}$$

For any coupling – loss loop

$$-R_E I_E = -M_{EM} \dot{I}_M + L_E \dot{I}_E$$

$$R_E = \frac{V}{\beta d_s^{*2}}, \quad M_{EM} = \frac{f_M V}{d_s^*}, \quad L_E = \frac{\mu_0 V}{2 d_s^{*2}}$$

A. Verweij, "Electrodynamics of Superconducting Cables in Accelerator Magnets," 1995.

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CLIQ – Conclusion… … and Future Steps

	CLIQ – Conclusion…	… and Future Steps
Design	• Heat deposited in the copper matrix • Not relying on thermal diffusion • Quick and global quench initiation • Robust system	• Multiple CLIQ Systems • Effect of a delay in the triggering • Redundancy
Tests	• 30+ tests on a 2 m long NbTi quadrupole magnet (MQXC2) • 1000+ tests on a small-size solenoid magnet • Key parameters studied and optimized • CLIQ with compensation coil	• CERN, NbTi quadrupole magnet (MQXC2) • FNAL, Nb3Sn quadrupole magnet (HQ2→MQXF) • Oxford Instruments, Nb3Sn solenoid magnet • CERN, NbTi Individually-Powered Quadrupole (IPQ) • CERN, NbTi solenoid magnet (Multi-CLIQ)
Modeling	• 2D • Lumped-Elements • Electro-Thermal • Dynamic behaviour	• Validation of the model on a wide variety of practical cases • More flexibility, modularity, GUI • Migration from PSpice to Simulink? 3D?

Thanks to

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QUESTIONS?

Ask me the CLIQ Recipe!

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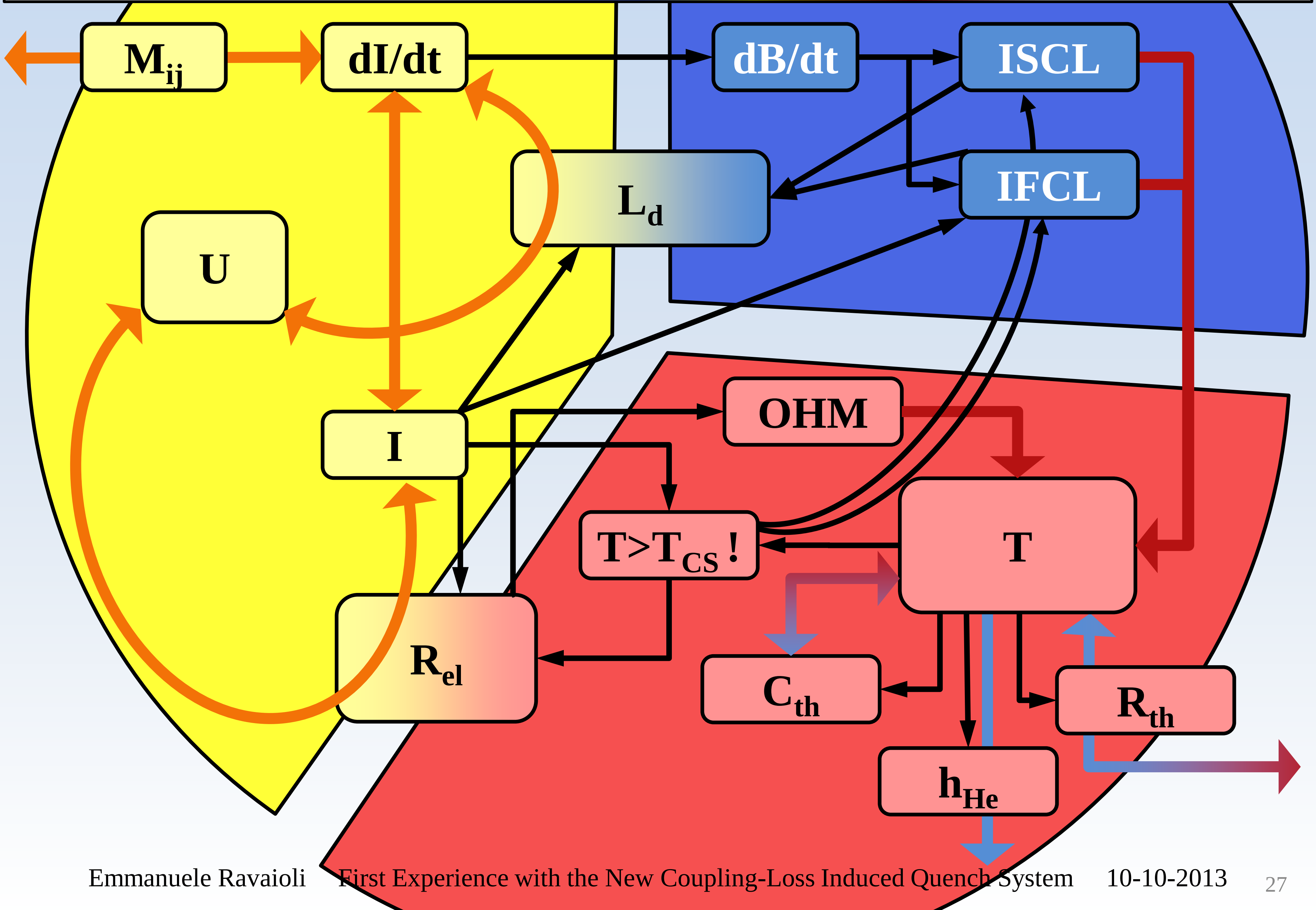
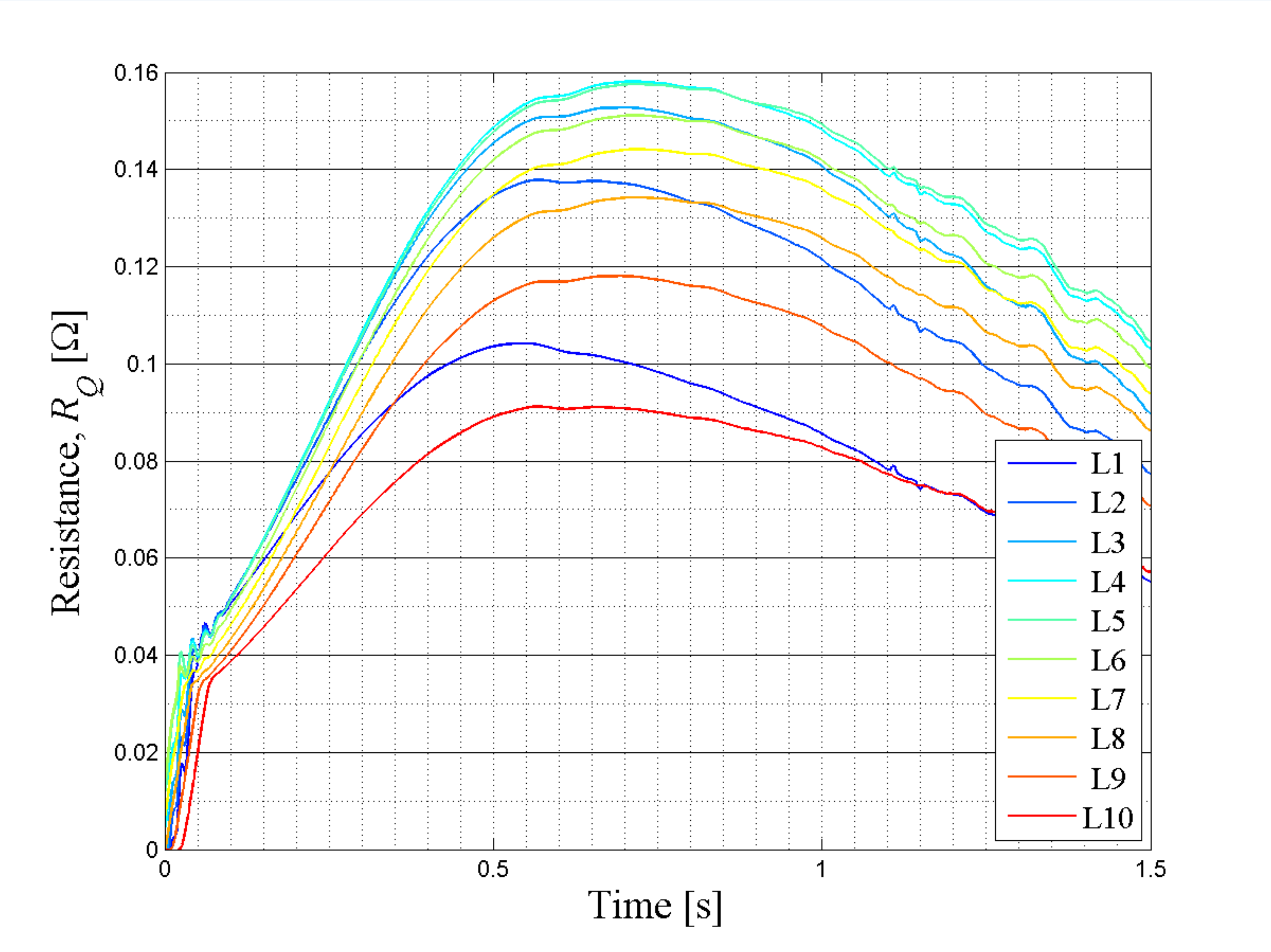
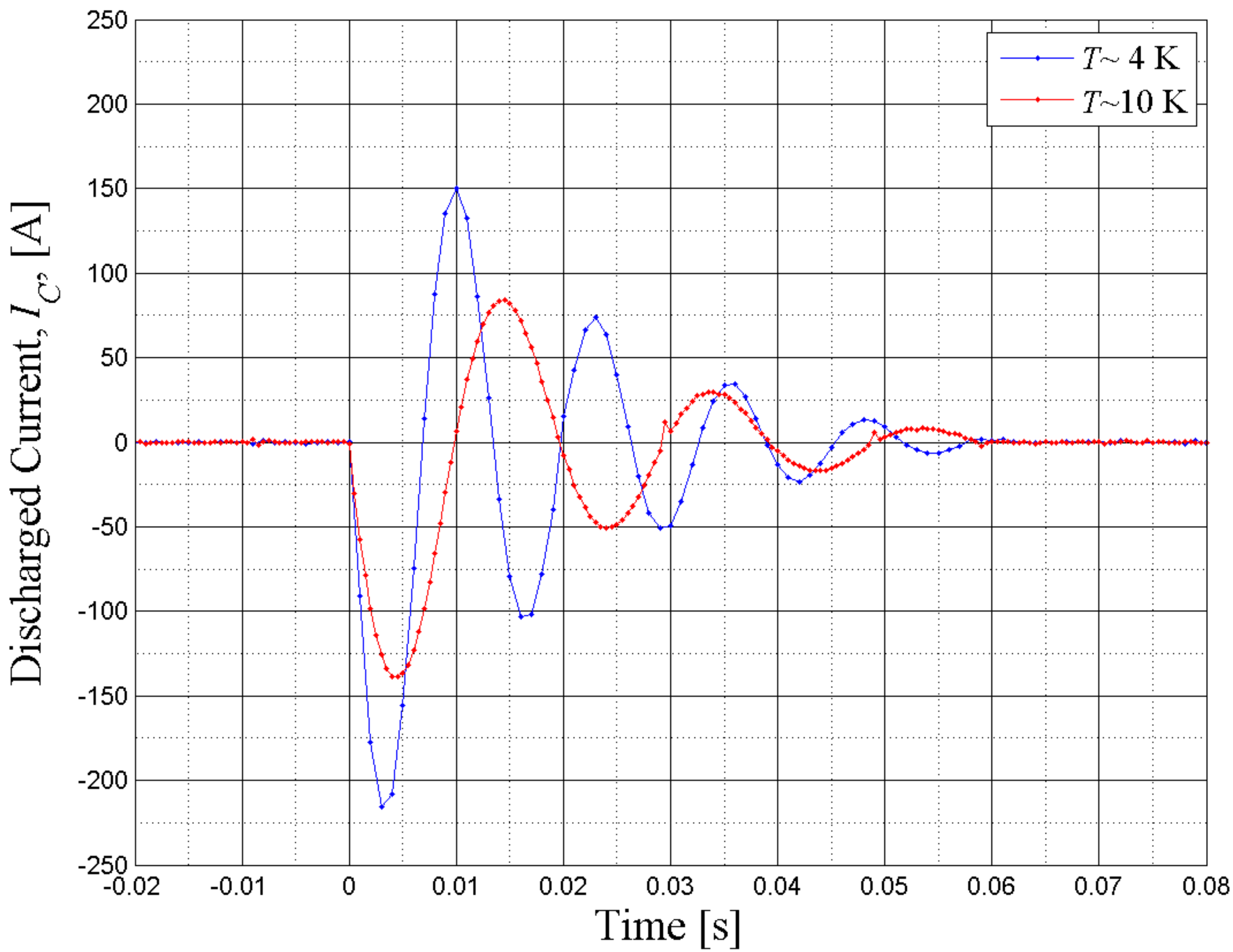
LEDET Lumped-Element Dynamic ElectroThermal model



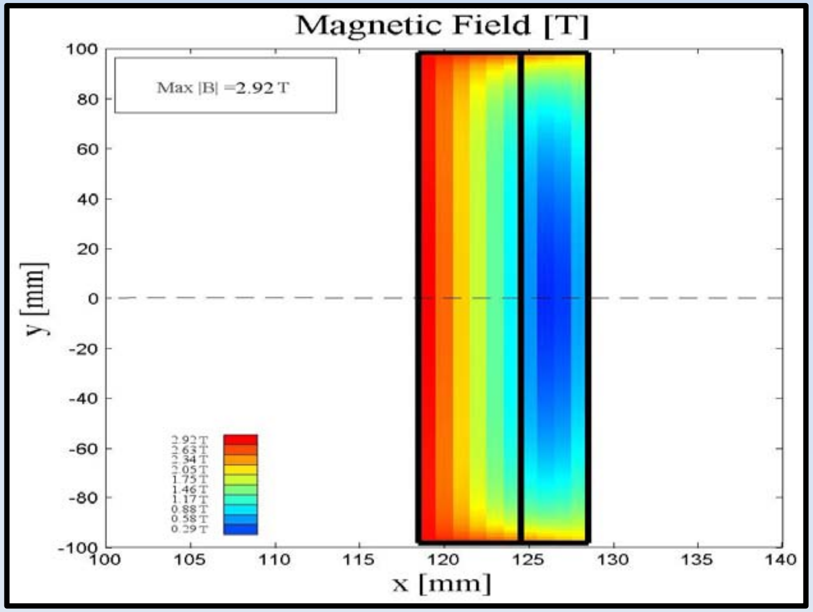
CLIQ – Coupling-Loss Induced Quench – Quench in the 10 Layers

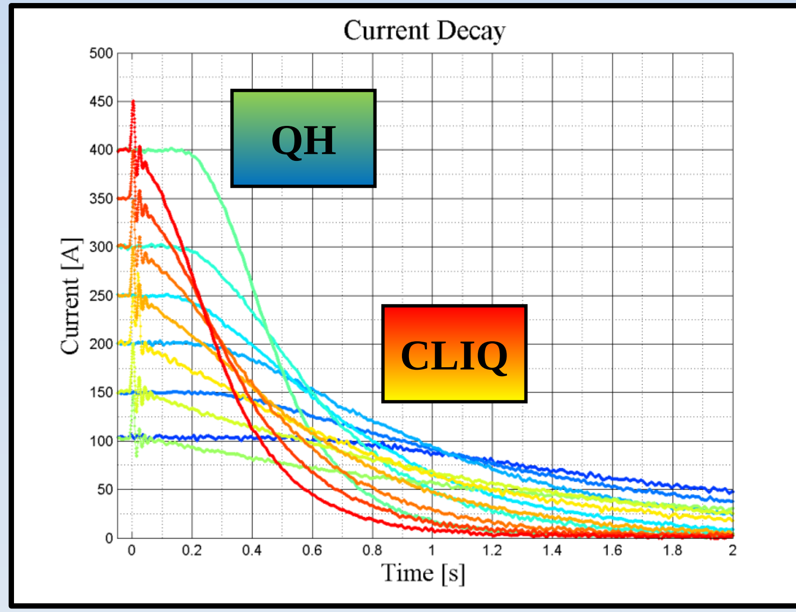


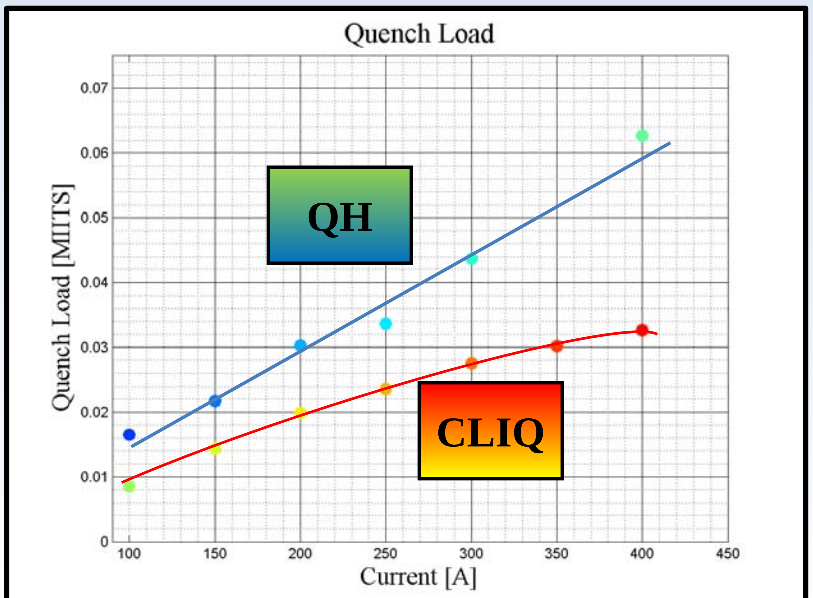
Dynamic Effects related to Inter-Filament Coupling Currents

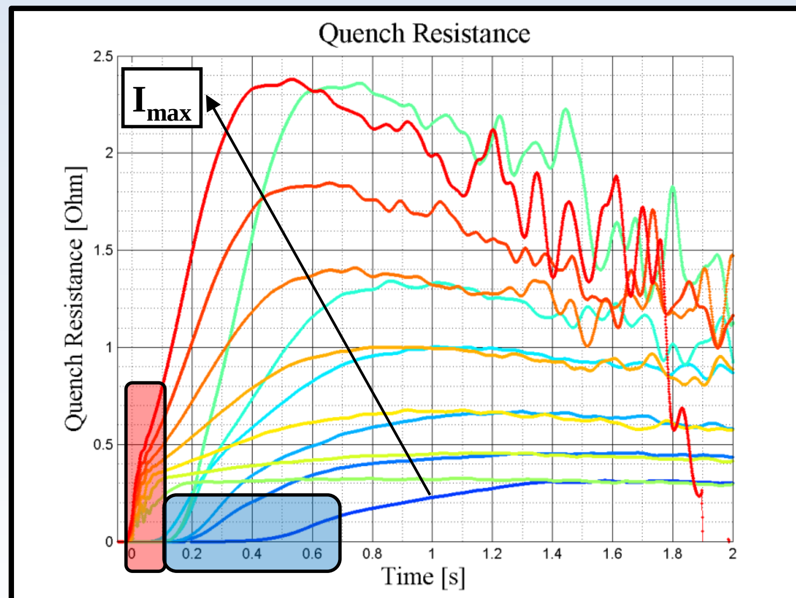


CLIQ Tests on a Superconducting Solenoid – CLIQ vs QH

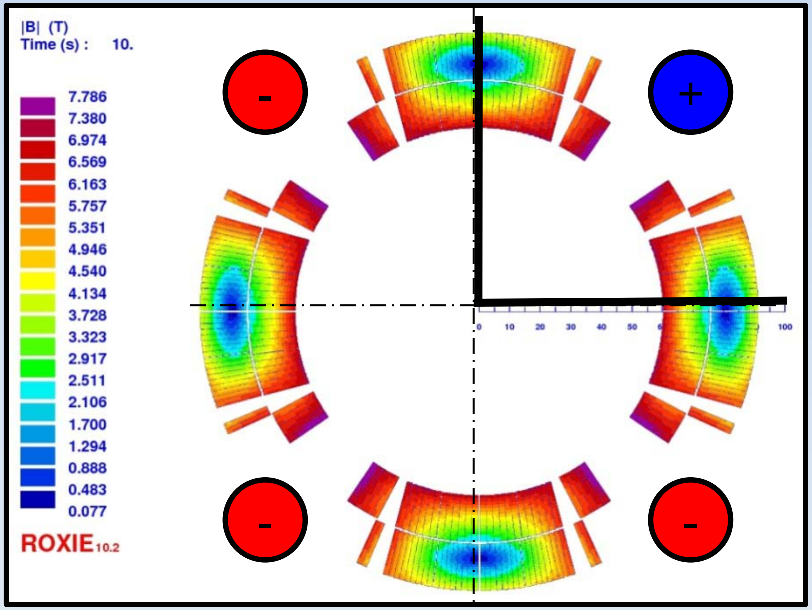


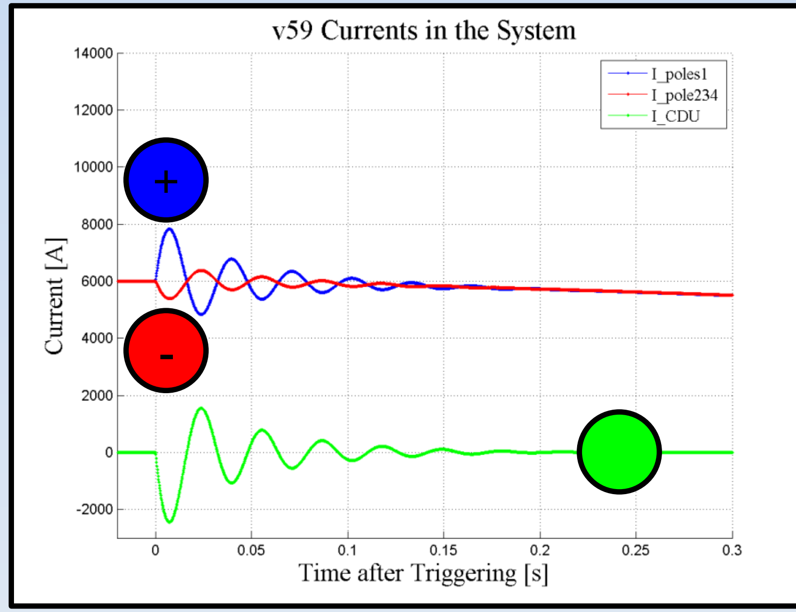


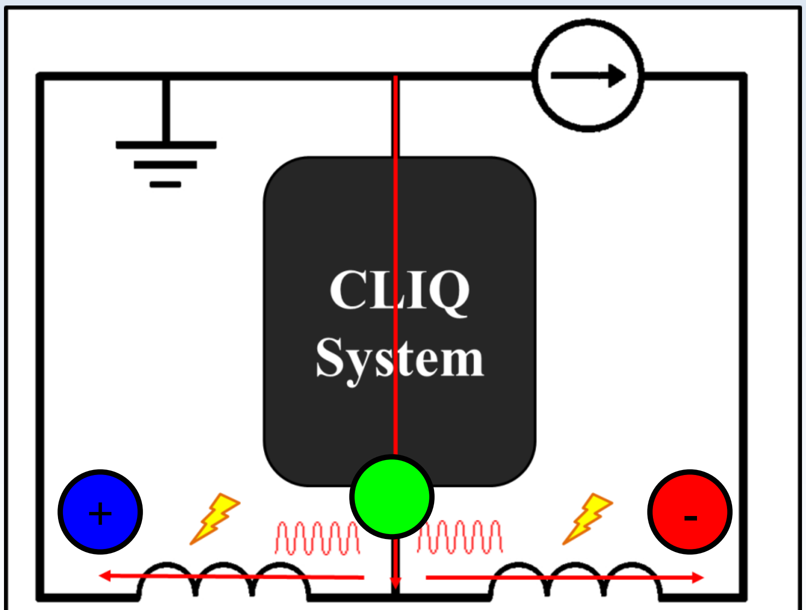


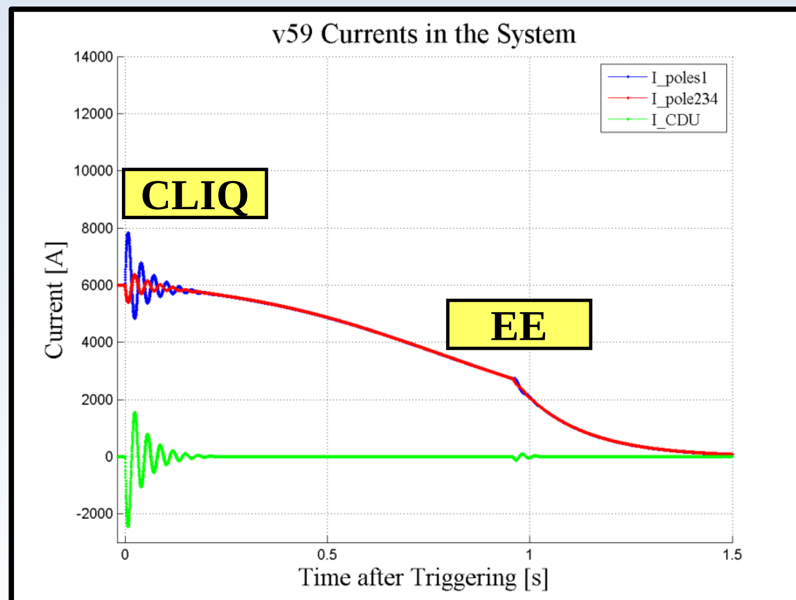


CLIQ Tests on a Superconducting Quadrupole Magnet – I=6 kA – d_EE=950 ms









CLIQ Tests on a Superconducting Quadrupole Magnet