# Lumped-Element Dynamic Electro-Thermal model of a superconducting magnet

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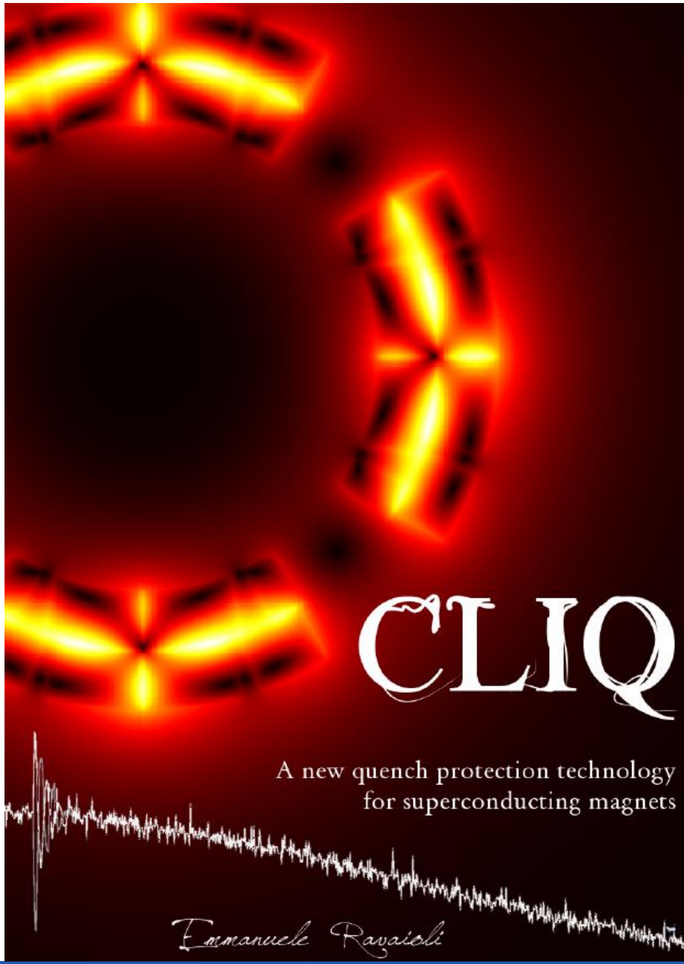
# Outline

1. Introduction to the Superconducting Magnets Modelling
2. LEDET model
3. TALES Simulation Framework
4. Simulation results
5. Summary



CLIQ

A new quench protection technology for superconducting magnets

Emmanuele Ravaioli

E. Ravaioli, CLIQ,
University of Twente, 2015.
http://doc.utwente.nl/96069/

# Superconducting Magnets Modelling: Challenges

- Different levels of detail
  - entire circuit→ magnet→ cable→ strand→ filament
- Different physical domains with nonlinearities
  - electrical, thermal, eddy-current effects
- Scalability and high flexibility needed
  - different magnet configurations, protection schemes
- Quick simulations
  - model development in 1-2 days, simulation runs < 1 hour

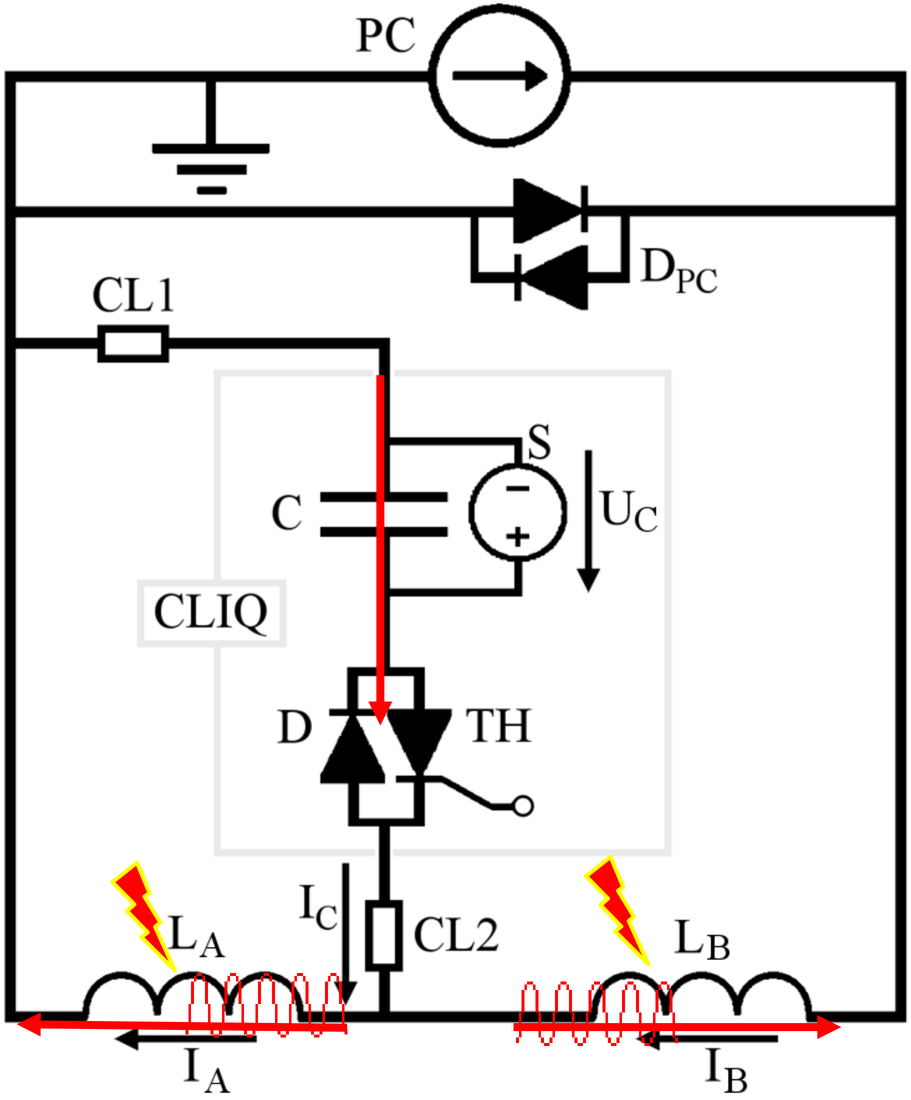
# Superconducting Magnets: Quench Protection

- To limit thermal load during quench one can employ
  - passive protection (parallel resistor, diode)
  - active protection (energy extraction, quench heaters, CLIQ)
- Simulations are mandatory to
  - optimize protection strategy and their parameters
  - study the impact of failures in the system
  - reproduce unusual events occuring in the machines

# Superconducting Magnets: Quench Protection

1. How does the differential inductance of a magnet change for high ramp rates?
2. When my magnet will quench due to quench back?
3. What is the effect of coupling currents on quench protection?
4. At which frequency will my magnet ring if I discharge a capacitor into it?

# Superconducting Magnets Protection: CLIQ



Current oscillations

Magnetic Field Change

Coupling-Losses (Heat)

Temperature Rise

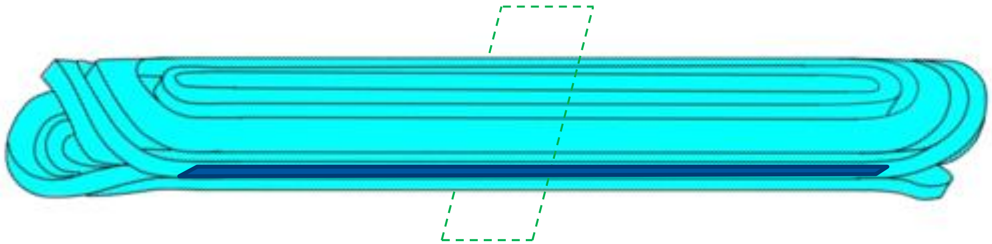
QUENCH

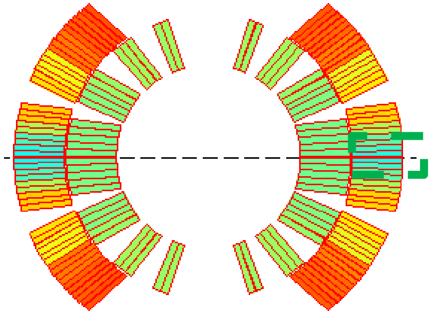
**Coupling**
**Loss**
**Induced**
**Quench**

E. Ravaioli, CLIQ, University of Twente, 2015. http://doc.utwente.nl/96069/

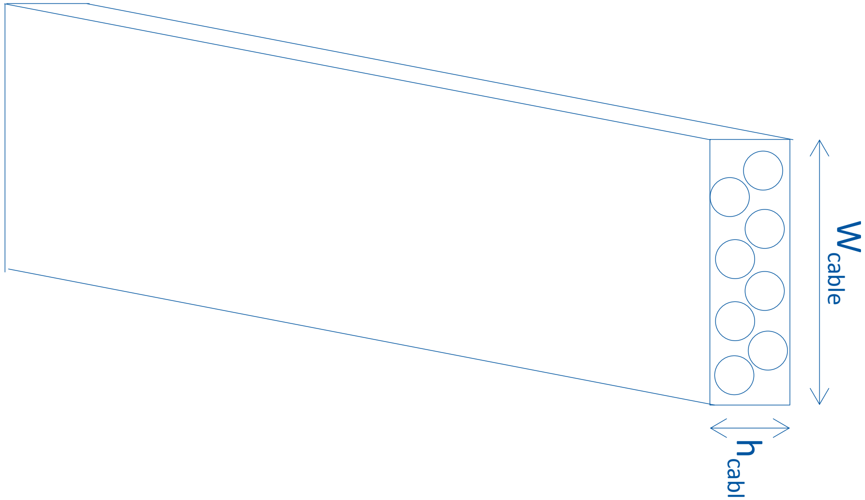
EU Patent EP13174323.9, June 2013.

# Introduction to LEDET model





We employ 2D Lumped-Element Dynamic Electro-Thermal Model

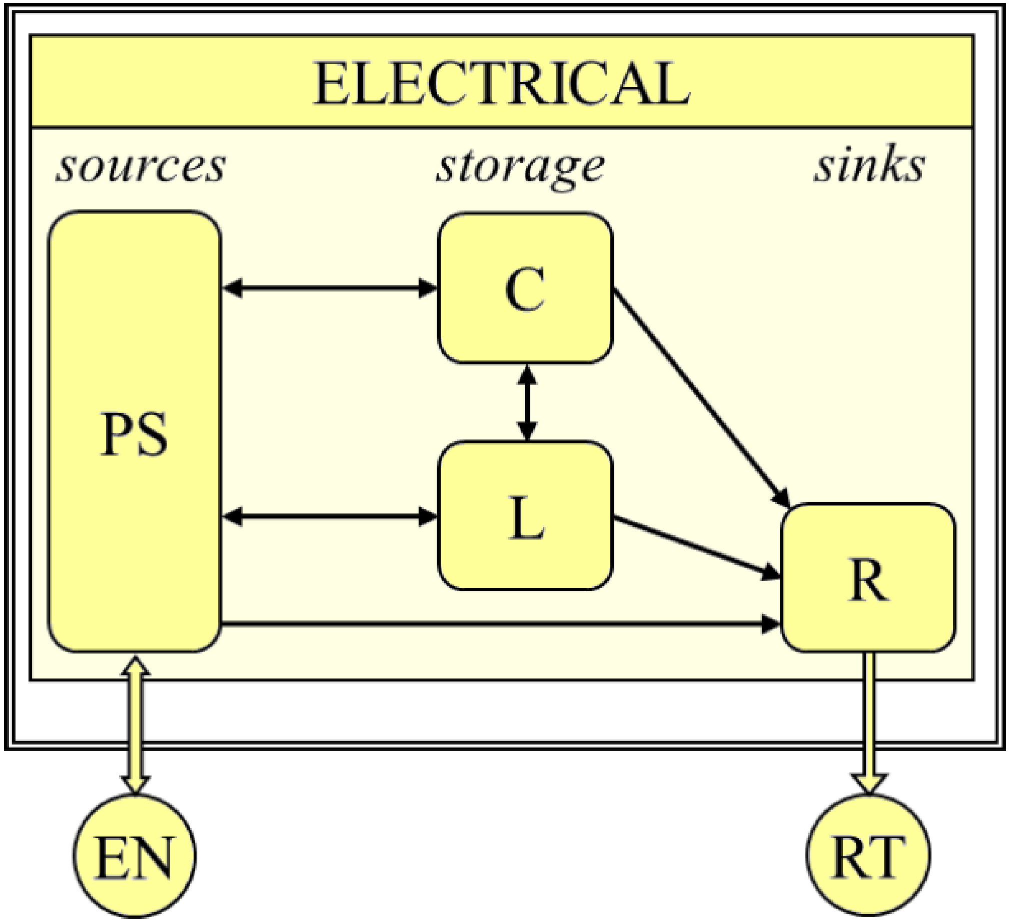


Electrical

Thermal

Coupling Loss

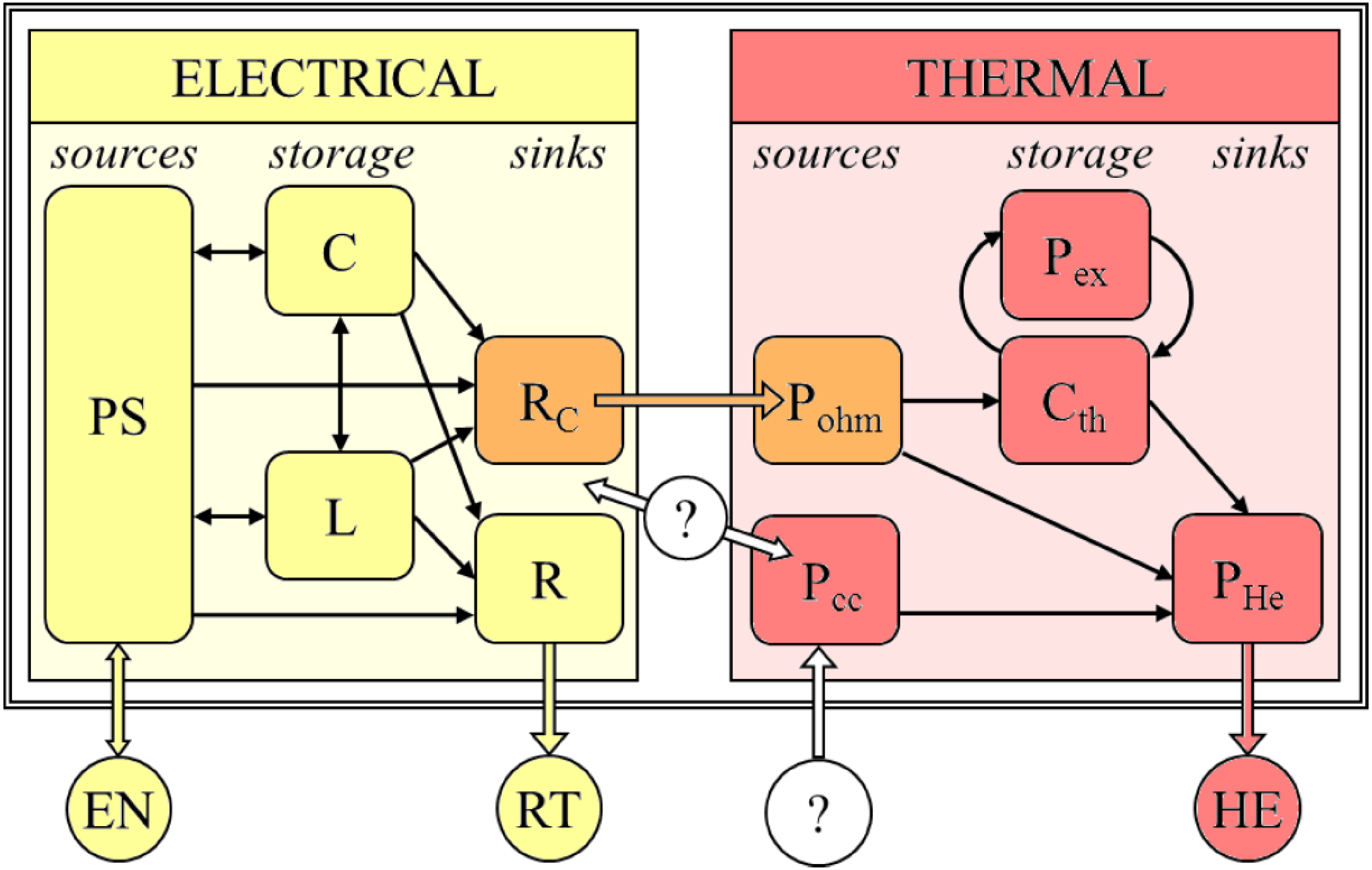
# Electrical Domain



EN – The main electric network

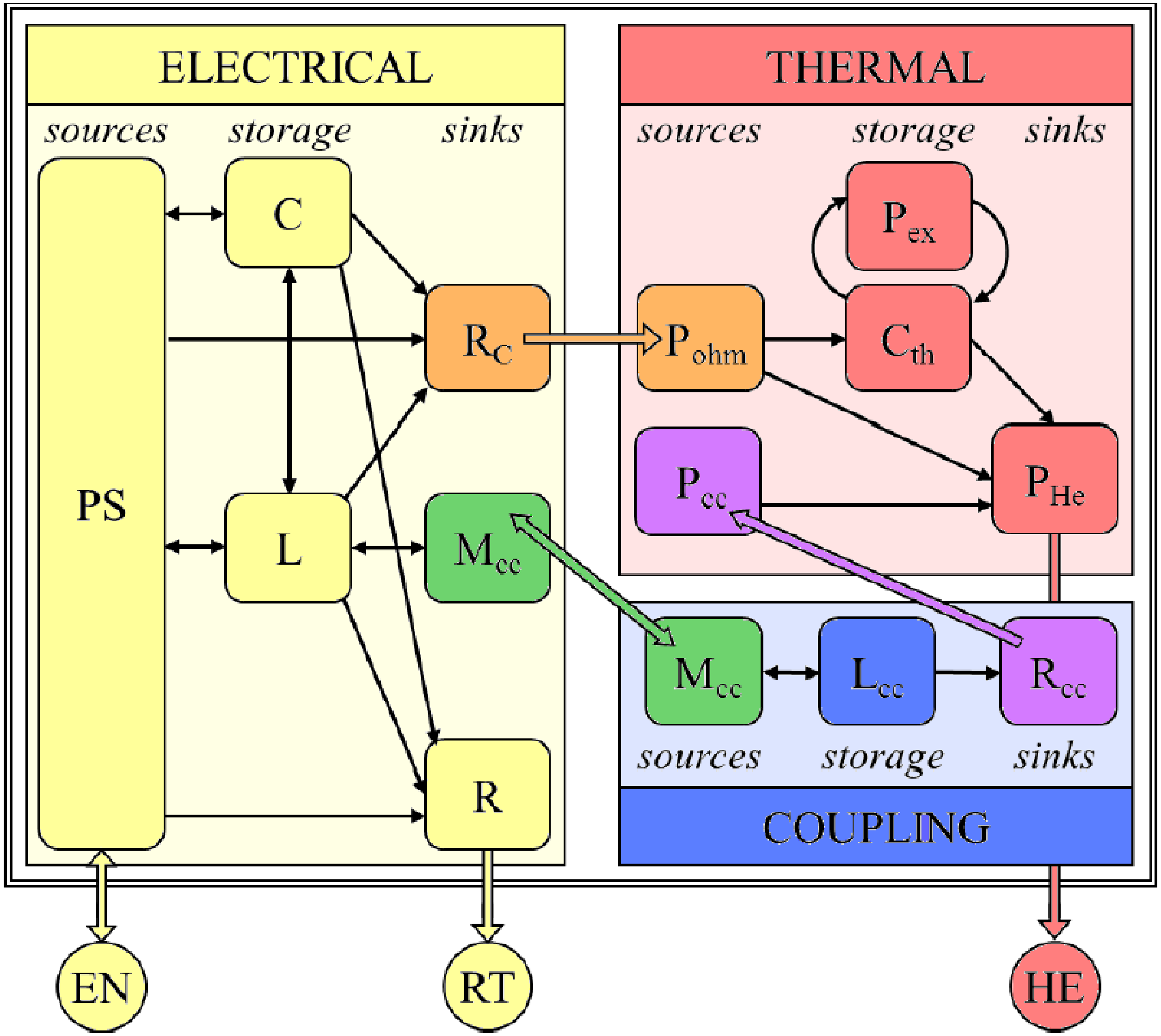
RT – Room-temperature environment

# Coupling between Electrical and Thermal Domains



HE – Helium Reservoir

# LEDET: Implementation of Interdependent Coupling Loss Mechanism



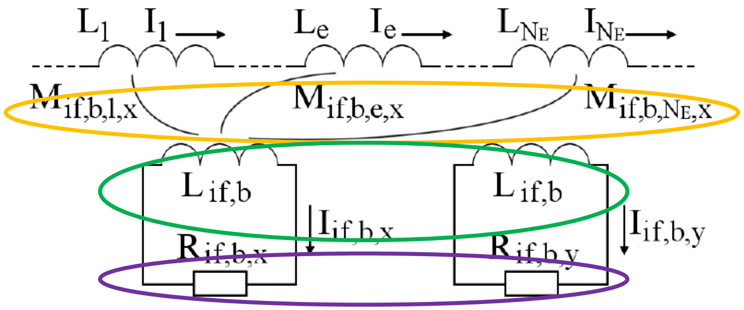
# LEDET: Inter-Filament Coupling Loss

The total magnetic-field change being the result of the applied magnetic-field change generated by a change in the local currents, and the magnetic-field induced in the strand (opposing to the change) reads

$$\frac{d\vec{B}_{\mathrm{t}}}{dt} = \frac{d\vec{B}_{\mathrm{a}}}{dt} + \frac{d\vec{B}_{\mathrm{if}}}{dt}. \qquad [\mathrm{Ts^{-1}}] \quad (24)$$

This set of equations describes the complex interaction between local IFCC and changes in the currents flowing in the main electrical circuit

$$\begin{cases} -R'_{\mathrm{if,x}} I_{\mathrm{if,x}} = \sum_{e=1}^{N_{\mathrm{E}}} M'_{\mathrm{if,e,x}} \frac{I_{\mathrm{e}}}{dt} + L'_{\mathrm{if,x}} \frac{I_{\mathrm{if,x}}}{dt} \\ -R'_{\mathrm{if,y}} I_{\mathrm{if,y}} = \sum_{e=1}^{N_{\mathrm{E}}} M'_{\mathrm{if,e,y}} \frac{I_{\mathrm{e}}}{dt} + L'_{\mathrm{if,y}} \frac{I_{\mathrm{if,y}}}{dt} \end{cases} \qquad [\mathrm{Vm^{-1}}] \quad (28)$$



E. Ravaioli, CLIQ, Chapter 4, University of Twente, 2015. http://doc.utwente.nl/96069/

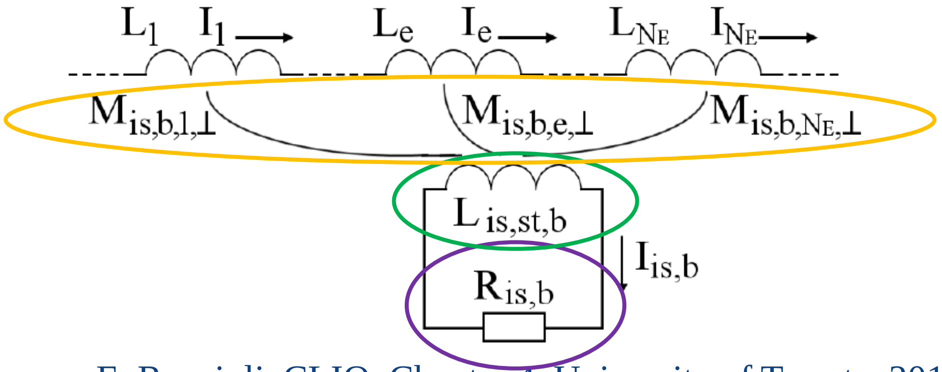
# LEDET: Inter-Strand Coupling Loss

The total magnetic-field change in the parallel direction to the cable broad face is a result of the applied magnetic-field change in the same direction and the magnetic-field change generated by a surface current flowing at the two sides of the cable

$$\frac{dB_{\mathrm{t},\perp}}{dt} = \frac{dB_{\mathrm{a},\perp}}{dt} + \frac{dB_{\mathrm{is}}}{dt}, \qquad [\mathrm{Ts}^{-1}] \qquad (51)$$

can be reformulated as follows

$$-R_{\mathrm{is,b}} I_{\mathrm{is,b}} = \sum_{e=1}^{N_{\mathrm{E}}} M_{\mathrm{is,b,e},\perp} \frac{dI_{\mathrm{e}}}{dt} + L_{\mathrm{is,st,b}} \frac{dI_{\mathrm{is,b}}}{dt}, \qquad [\mathrm{V}] \qquad (56)$$



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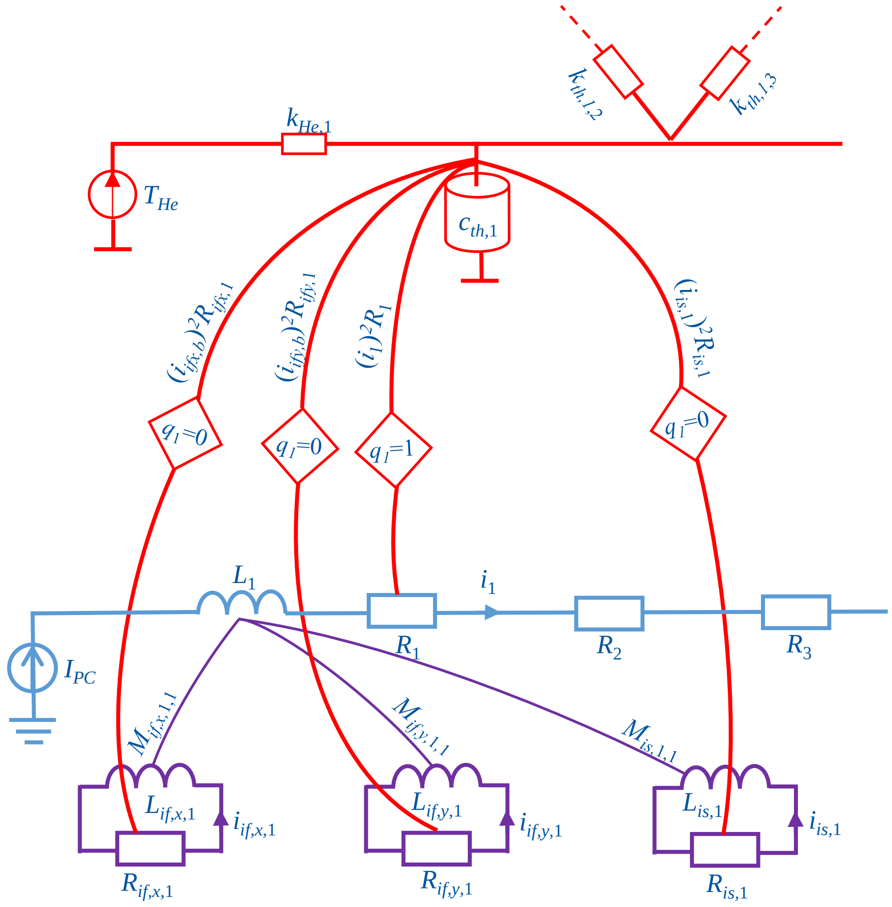
# LEDET model in a nutshell

## Single block level

## Magnet level



**Thermal Sub-system**

$$\mathbf{Q}_{CL}+\mathbf{Q}_{Ohm}+\mathbf{Q}_{ex}+\mathbf{Q}_{He}=\frac{d\left[\mathbf{C}(\mathbf{T})(\mathbf{T}-T_{He})\right]}{dt}$$

**Electrical Sub-system**

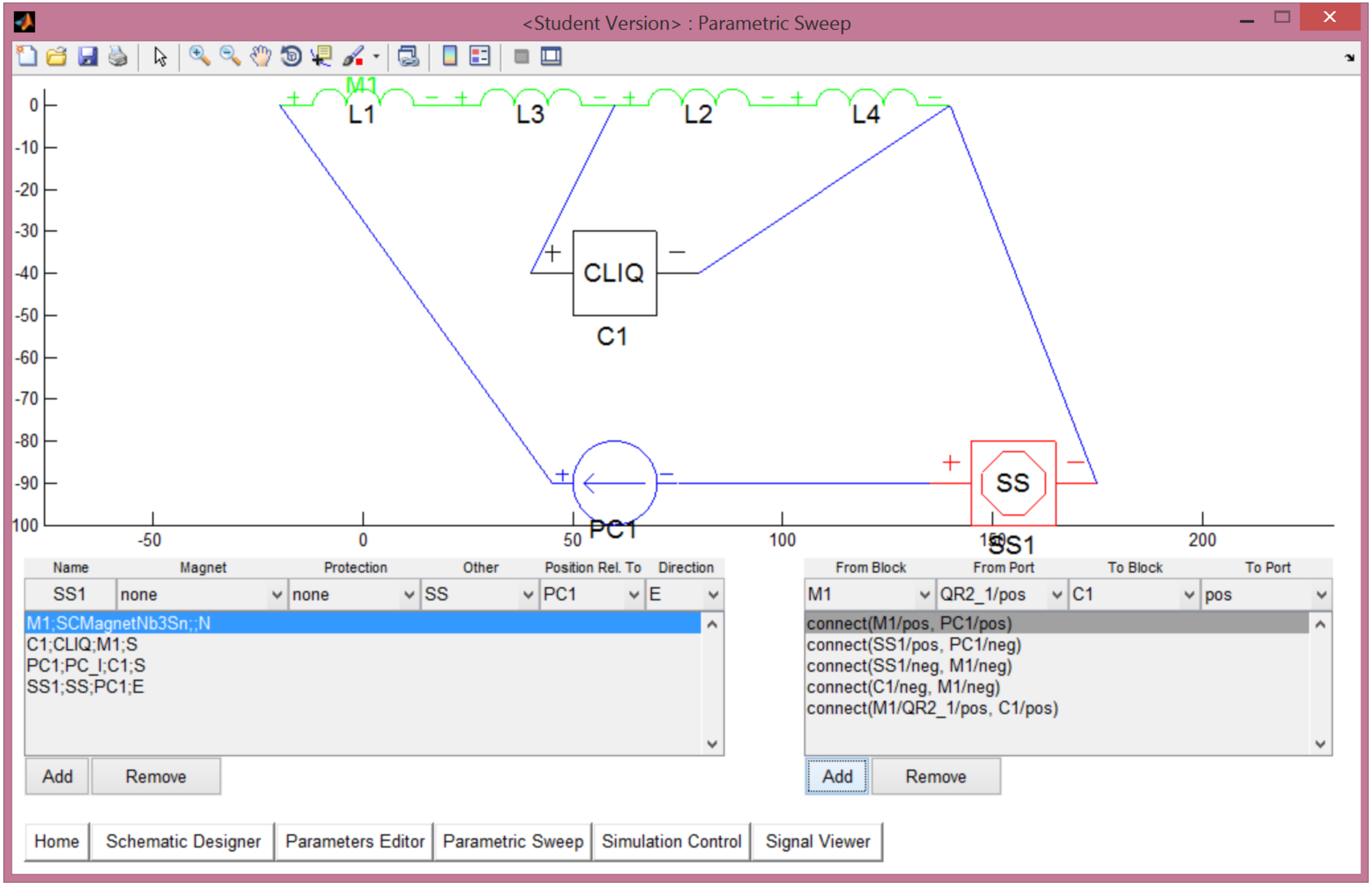
$$\mathbf{u}(t)=\mathbf{M}\cdot\frac{d\mathbf{i}(t)}{dt}+\mathbf{R}\cdot\mathbf{i}(t)$$

**Coupling Sub-system**

$$\mathbf{M}=\begin{bmatrix}\mathbf{M}_{el} & \mathbf{M}^T_{if,x} & \mathbf{M}^T_{if,y} & \mathbf{M}^T_{is}\\ \mathbf{M}_{if,x} & \mathbf{L}_{if,x} & \mathbf{0} & \mathbf{0}\\ \mathbf{M}_{if,y} & \mathbf{0} & \mathbf{L}_{if,x} & \mathbf{0}\\ \mathbf{M}_{is} & \mathbf{0} & \mathbf{0} & \mathbf{L}_{is}\end{bmatrix}$$

$$\mathbf{R}=diag\left(\mathbf{R}_{el},\mathbf{R}_{if,x},\mathbf{R}_{if,y},\mathbf{R}_{is}\right)$$

# Transient Analysis with Lumped-Elements of Superconductors (TALES)



| Name | Magnet | Protection | Other | Position Rel. To | Direction |
|---|---|---|---|---|---|
| SS1 | none | none | SS | PC1 | E |

M1;SCMagnetNb3Sn;;N
C1;CLIQ;M1;S
PC1;PC_I;C1;S
SS1;SS;PC1;E

| From Block | From Port | To Block | To Port |
|---|---|---|---|
| M1 | QR2_1/pos | C1 | pos |

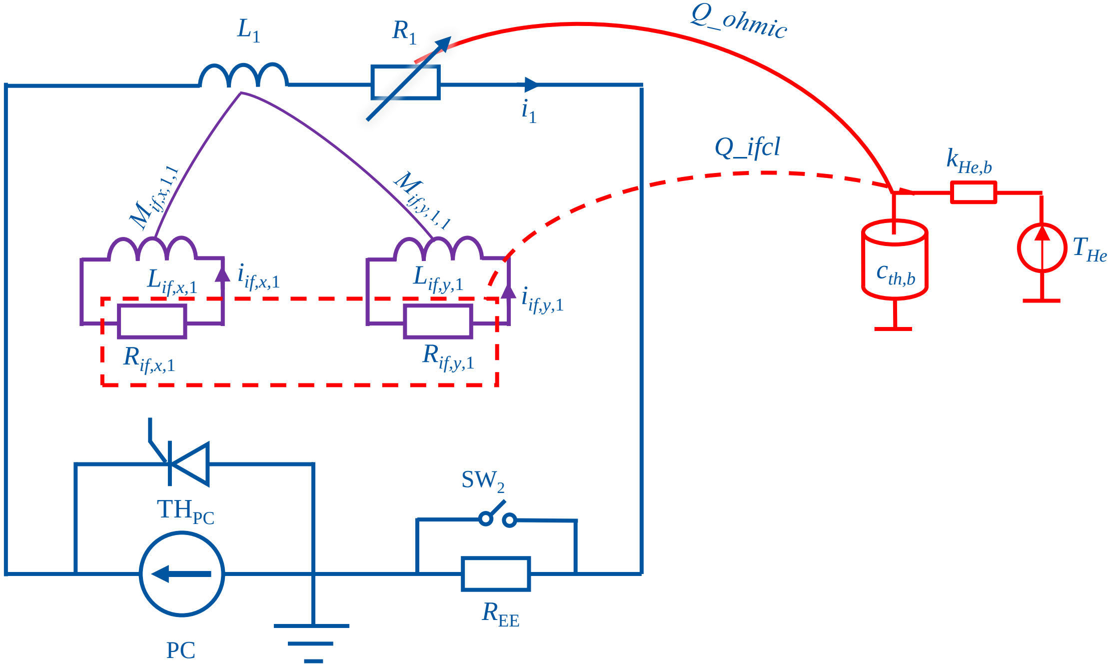
connect(M1/pos, PC1/pos)
connect(SS1/pos, PC1/neg)
connect(SS1/neg, M1/neg)
connect(C1/neg, M1/neg)
connect(M1/QR2_1/pos, C1/pos)

# TALES - Use cases

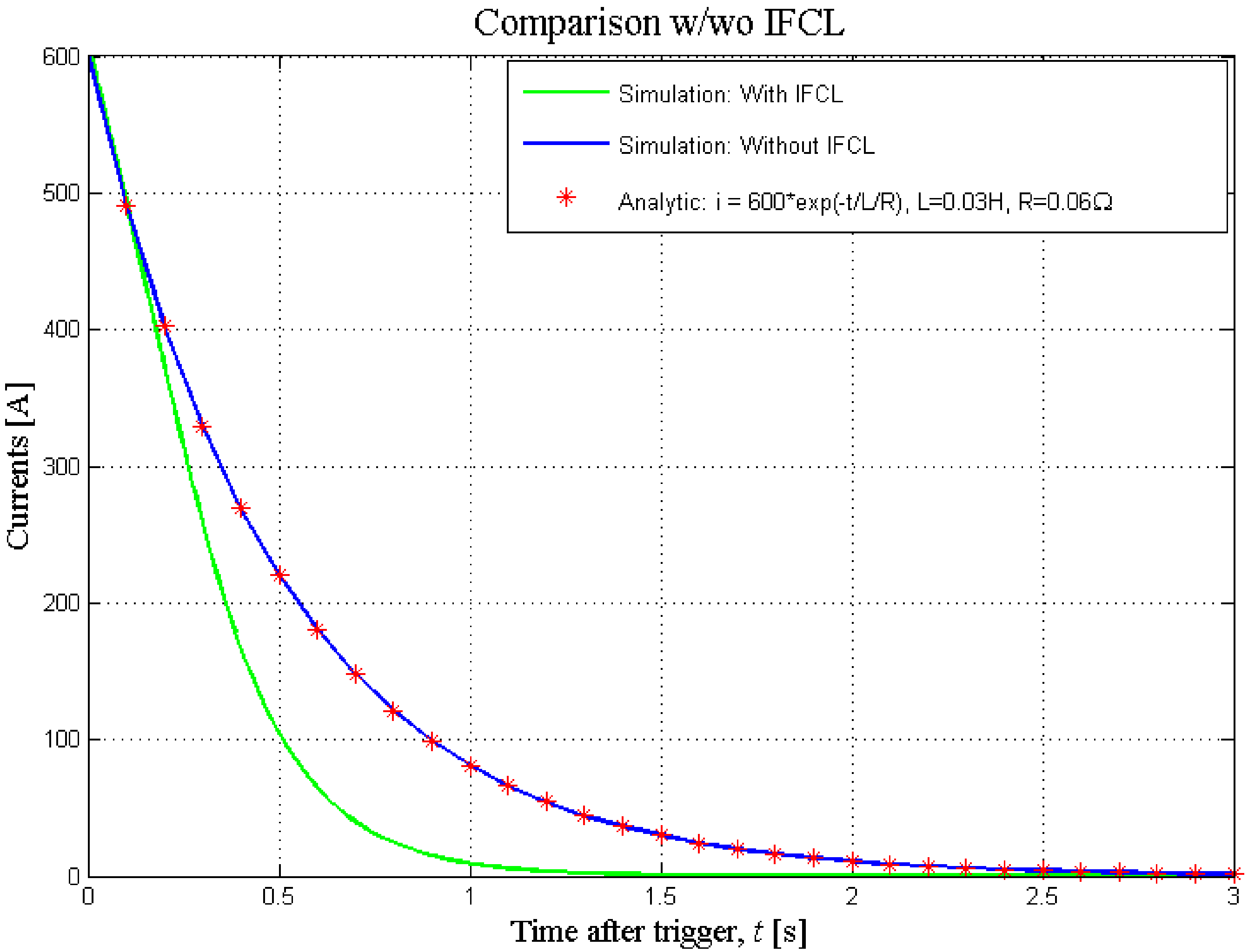
1. Quench-back in LHC corrector magnet
2. CLIQ protection of HQ02b magnet
3. CLIQ on an LHC main dipole magnet

# MQT cable: coupling effects on the inductance

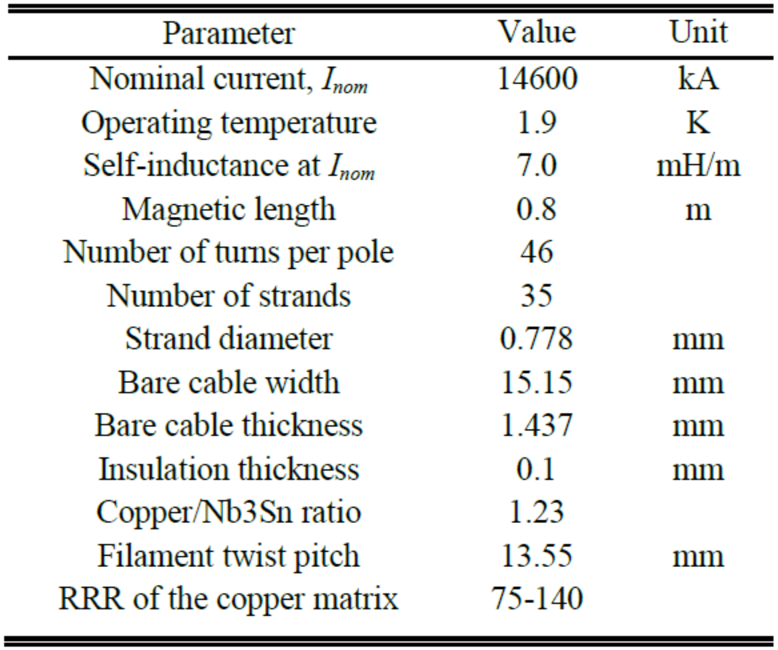
- 3.4 m long quadrupole magnet composed of single-wire superconductor
- Only IFCL are present
- Operating current 600 A
- Self-inductance $L_{eq}$=0.03H
- Energy Extraction $R_{EE}$=0.06Ω



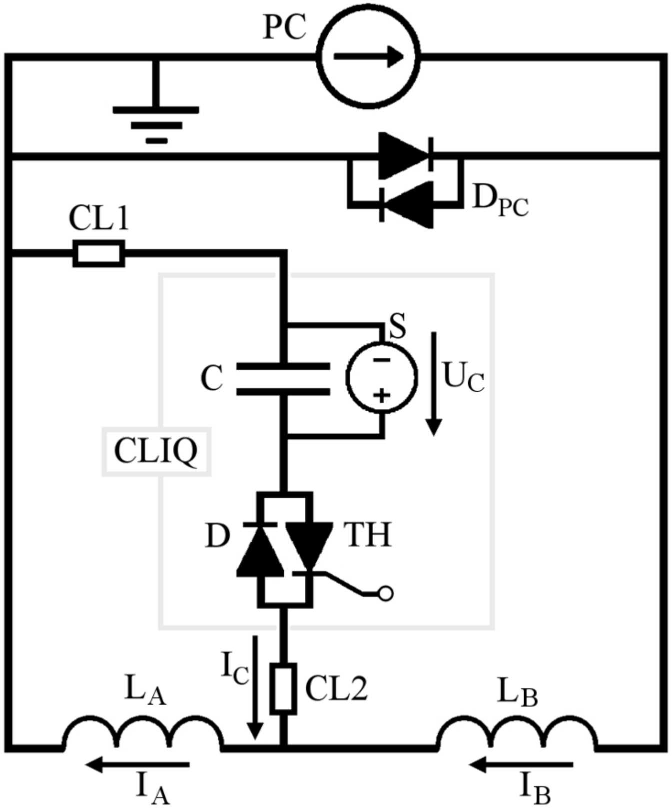
# MQT cable: coupling effects on the inductance



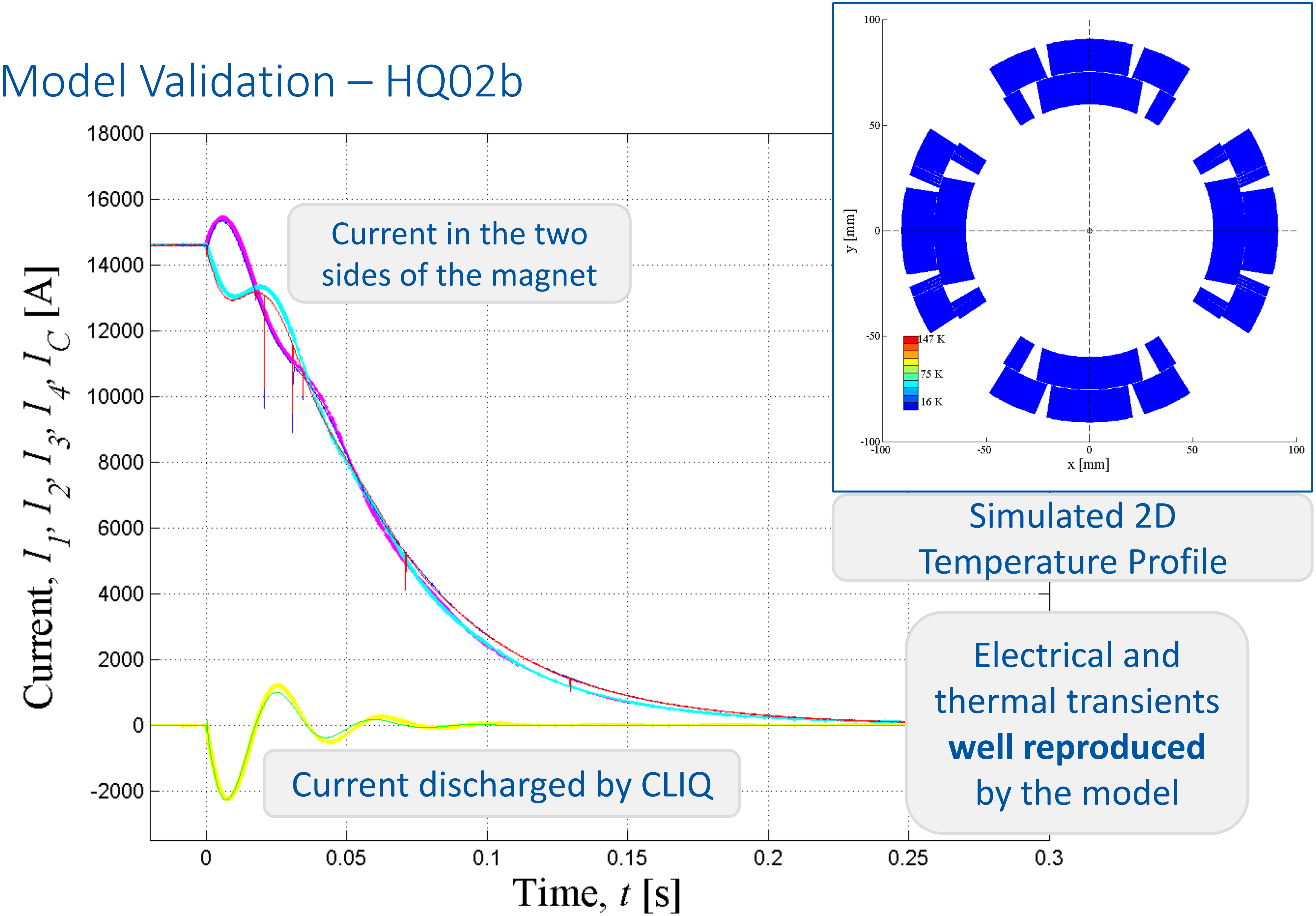
# Model Validation: Standalone prototype HQ02b Magnet



| Parameter | Value | Unit |
|---|---|---|
| Nominal current, $I_{nom}$ | 14600 | kA |
| Operating temperature | 1.9 | K |
| Self-inductance at $I_{nom}$ | 7.0 | mH/m |
| Magnetic length | 0.8 | m |
| Number of turns per pole | 46 | |
| Number of strands | 35 | |
| Strand diameter | 0.778 | mm |
| Bare cable width | 15.15 | mm |
| Bare cable thickness | 1.437 | mm |
| Insulation thickness | 0.1 | mm |
| Copper/Nb3Sn ratio | 1.23 | |
| Filament twist pitch | 13.55 | mm |
| RRR of the copper matrix | 75-140 | |



# Model Validation – HQ02b



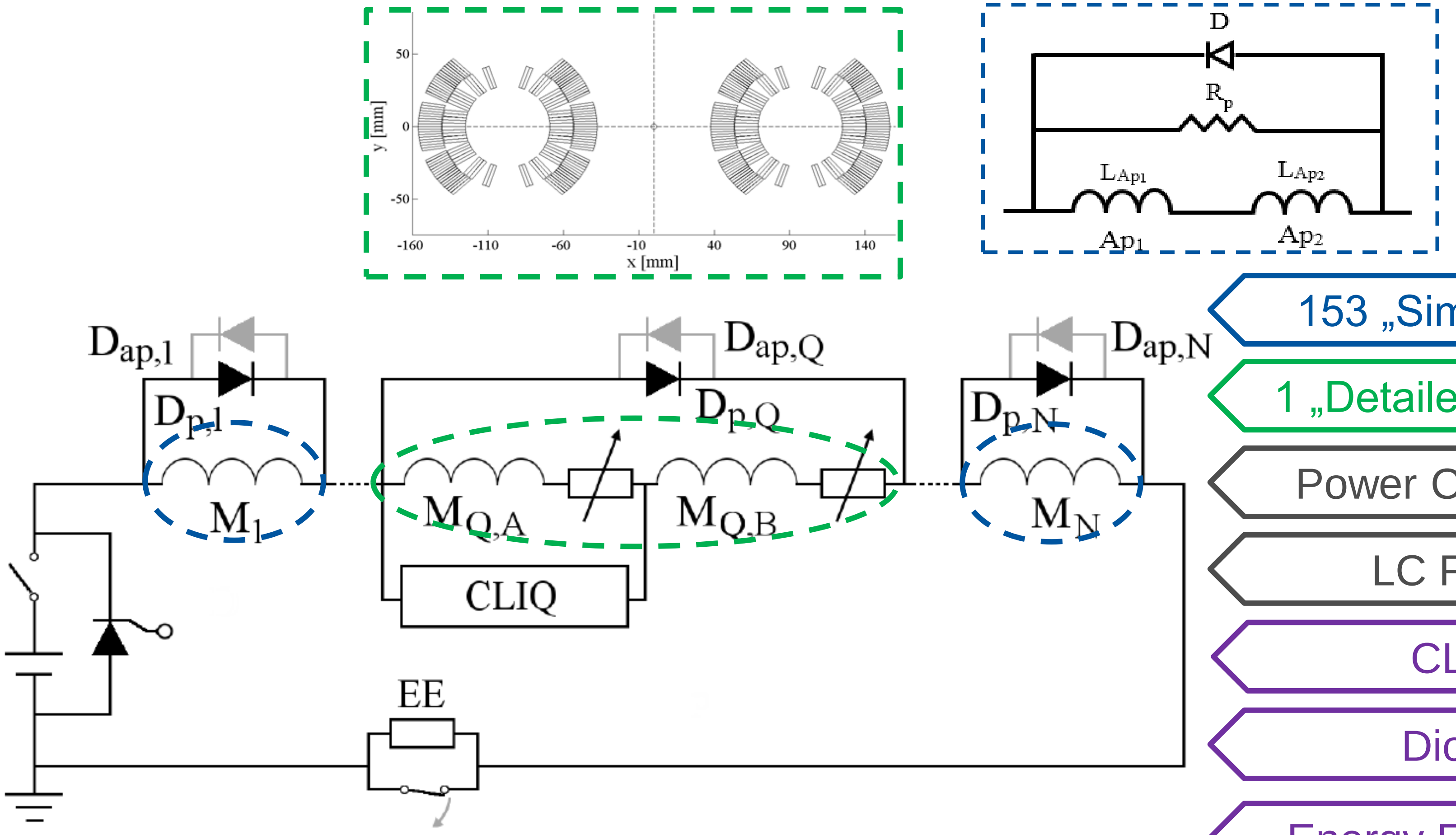
Current in the two sides of the magnet

Current discharged by CLIQ

Simulated 2D Temperature Profile

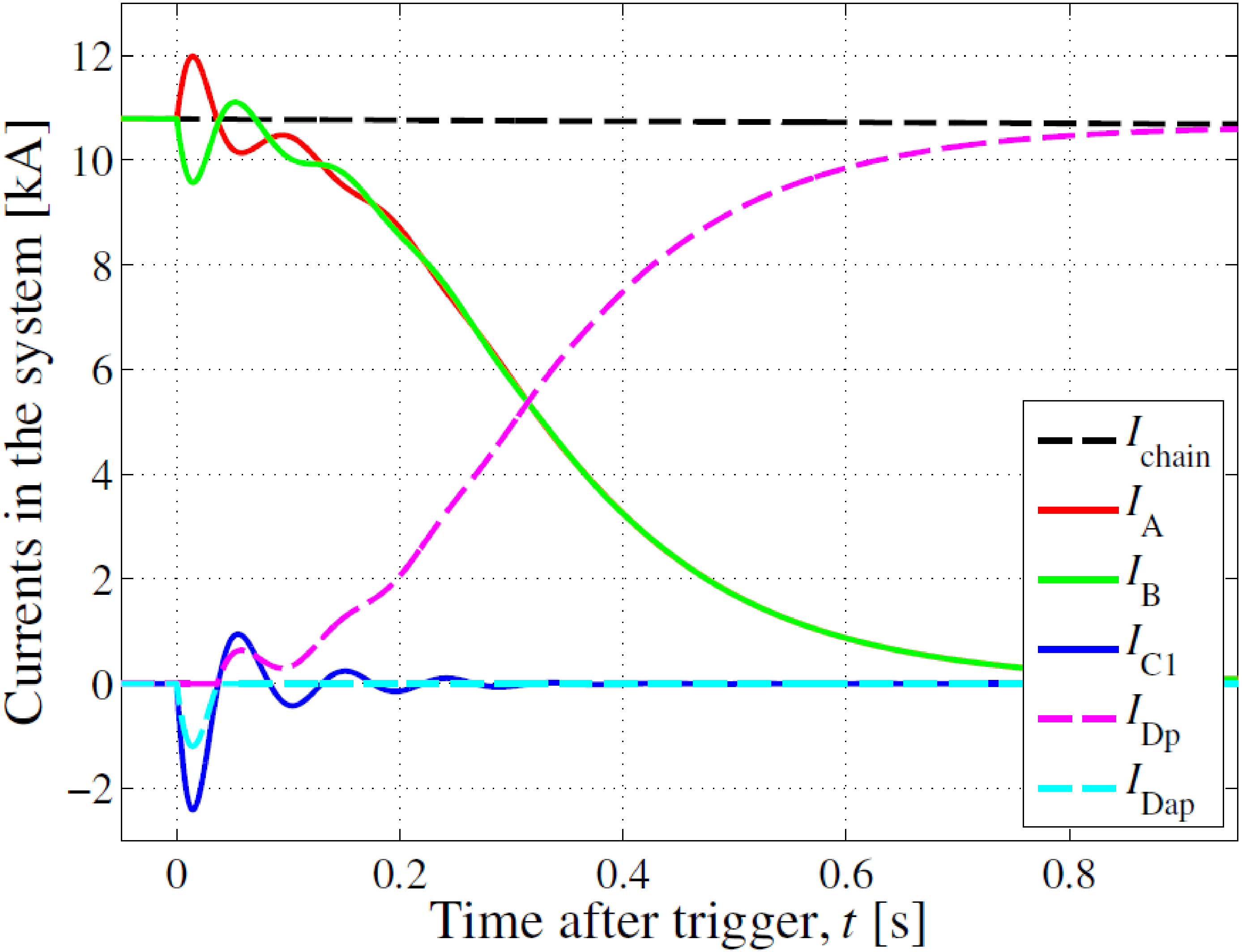
Electrical and thermal transients **well reproduced** by the model

# LHC  Main Dipole Circuit With CLIQ Protection



- 153 „Simple" MB
- 1 „Detailed 2D" MB
- Power Converter
- LC Fillter
- CLIQ
- Diode
- Energy Extraction
- Quench Heaters

# LHC Main dipole circuit with CLIQ protection



# Conclusions (1/2)

1. Quench protection is a key ingredient of superconducting magnet design
2. Developed model combines in a monolythic code various coupled physical domains with different spatial scales
3. Coupling effects can have a very significant impact on magnet protection
4. LEDET approach is capable of appropriately reproducing IFCC and ISCC and their effect on the magnet differential inductance

# Conclusions (2/2)

1. TALES has been extensively validated against experimental results for magnets of different types, superconducting materials, and sizes
2. TALES can model arbitrarily complex external circuits as well as multiple CLIQ-protected magnets in a circuit.
3. TALES allows automatically testing various configurations of superconducting circuits, combining magnet protection and circuit protection, analyzing failure-cases

# *Thank you for attention*

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