# Protection-related studies on HL-LHC $Nb_3Sn$–based magnets in SM18

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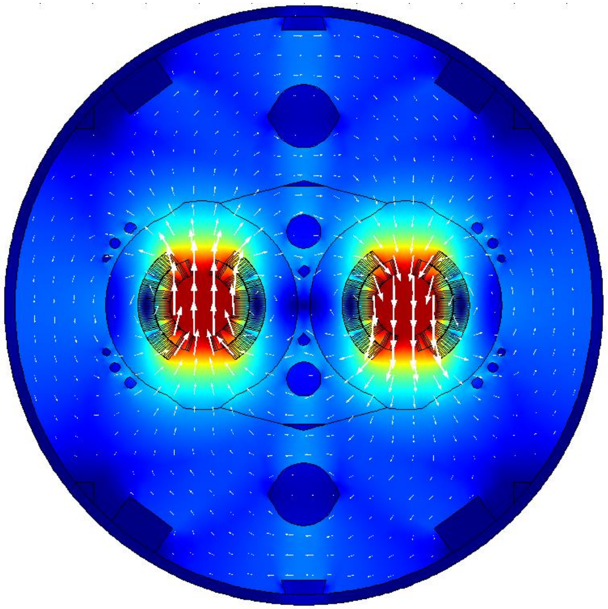
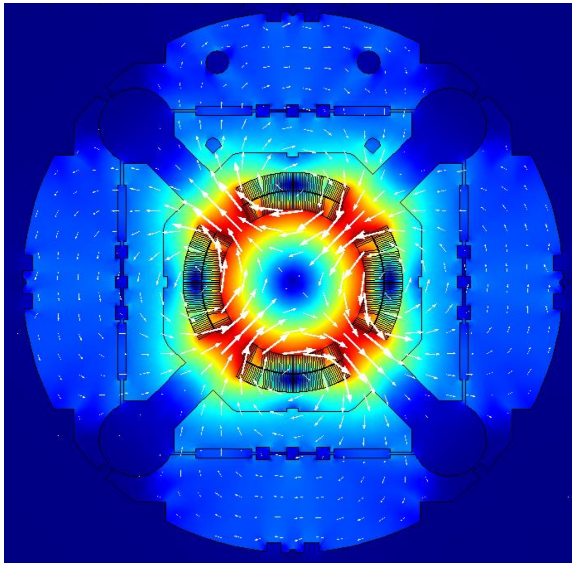
# HL-LHC $Nb_3Sn$ magnets





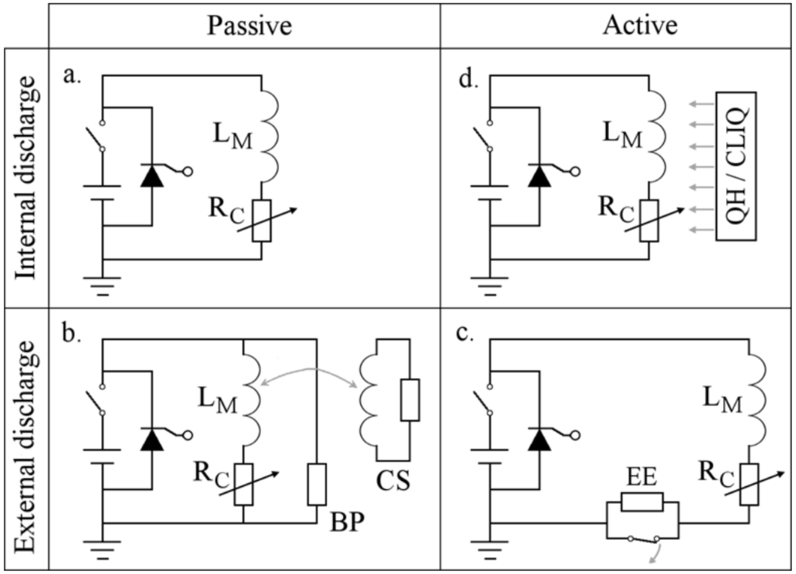
11 T dipole magnet

- To replace NbTi MB magnets in RB circuit (modified RB)
- Enhanced field strength, so same field integral is achieved with reduced length
  → Creates free space for collimator
- Nominal quench protection: Quench heaters
- SM18 tests: QHs + CLIQ

MQXF quadrupole magnet

- To replace LHC inner triplet with NbTi MQXA/MQXB magnets
- Enhanced field strength for enhanced focusing
- Nominal quench protection: Quench heaters + CLIQ
- SM18 tests: QHs + CLIQ

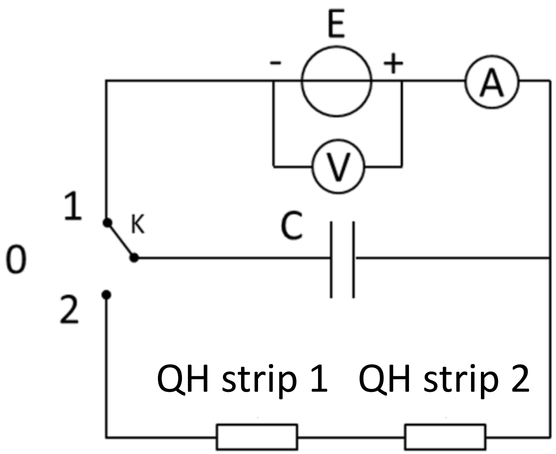
# What is quench protection?



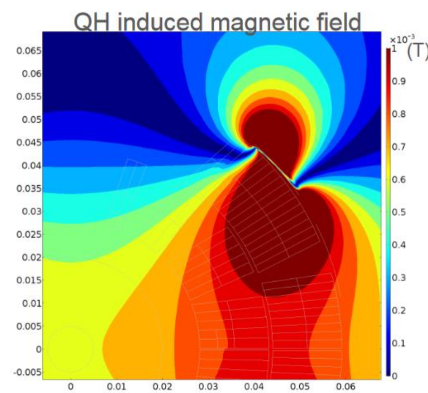

Quench protection is:

- Detection of a quench in a fast, reliable, and redundant manner
  - Traditional method: Voltage taps
  - Novel means: For instance stray capacitance monitoring, acoustic monitoring, quench antennas, fiber-optics
- Fast discharge of the magnet
  - Self-protection (relatively fast quench propagation → passive internal discharge)
  - External discharge (passive: coupled coil, active: external dump resistor)
  - Active quench initiation though heating (For instance quench heaters and / or CLIQ) → Used for HL-LHC $Nb_3Sn$-based magnets

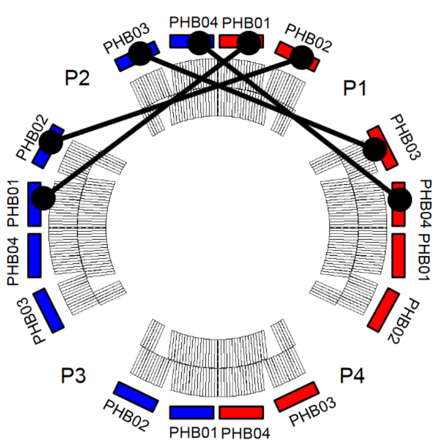
# Quench protection basics: Quench heaters



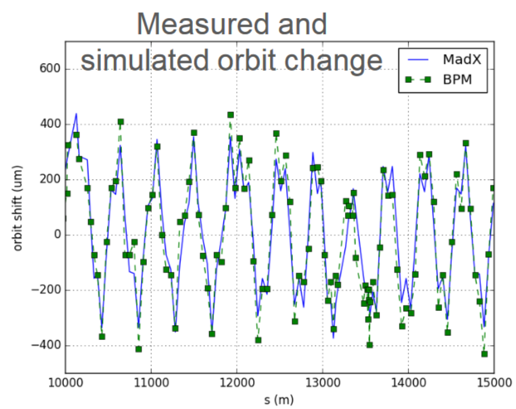

*Quench heater circuit*




*Fast magnetic field transient due to QH*




*MQXF heater scheme*




*QH impact on beam (MB magnet)*

Quench heaters (QHs)

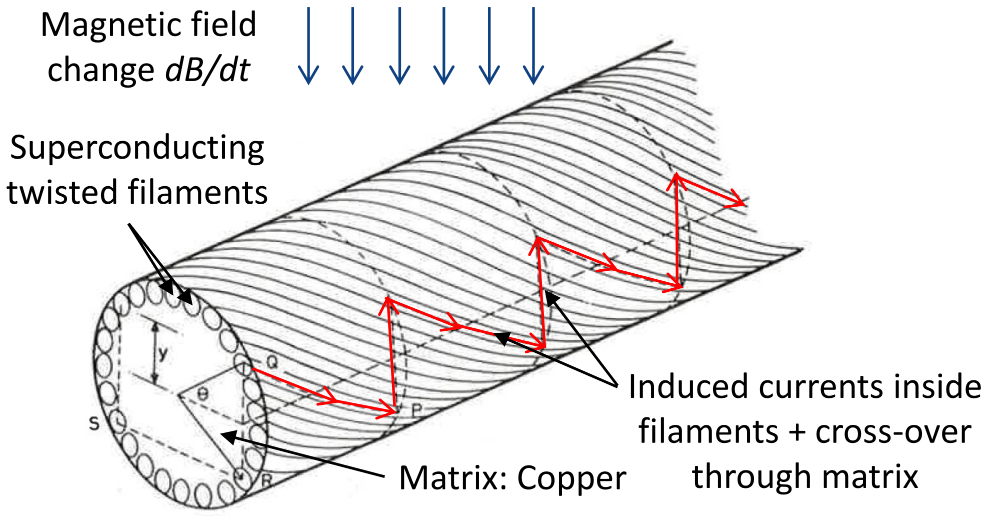
- Resistive heater strips in close thermal contact to the coil
- Powered by discharging a capacitor over two strips in series
- QH discharge → Magnet is heated to above current sharing temperature → Stored energy is discharged over magnet

Implications

- Good: Conceptually straight-forward
- Efficient for inducing a normal zone
- Challenge #1: Different electric potential versus coil, with minimal insulation layer in between → Increased potential for insulation issues
- Challenge #2: Delamination issues (MQXF inner layer heater)
- Challenge #3: Produces rapid *dB/dt* over bore at moment of discharge, which affects the beam [1]

[1]. Valette – Presented at 7$^{th}$ HL-LHC coll. Meeting (2017)

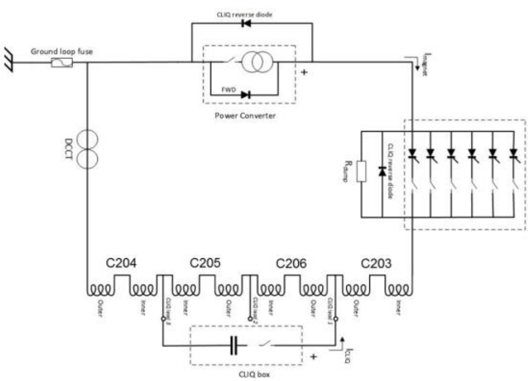
# Quench protection basics: CLIQ



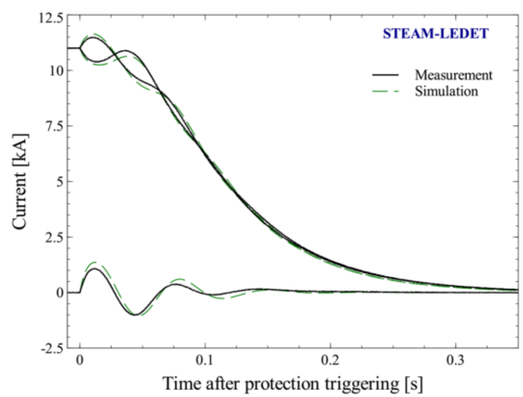

*Inter-filament coupling losses in superconducting strands*

Coupling-Loss Induced Quench system (CLIQ)

- Capacitor is discharged, parallel to part of a magnet
- Creates oscillating currents → Time varying magnet fields *dB/dt* over superconducting cables
- *dB/dt* → Inter-filament coupling losses (+ Inter-strand coupling losses) → Heating → Magnet is brought to normal state




*Circuit, CLIQ unit parallel to two of four coils*




*Currents after CLIQ discharge*

Implications

- Good: Magnet is very quickly brought to normal state
- Good: Robust
- Challenge #1: Relatively new technology and conceptually much harder to understand than quench heaters
- Challenge #2: Relatively complex modelling required

# Protection studies, overview

Protection studies in SM18 (In collaboration with TE-MSC), objectives:

- For finding potential problems in short magnet models and prototypes
- For ensuring that we understand the protection-related behavior of magnets
- For validating quench simulation tools which are then use to understand the behavior of magnets powered by circuits → Modified RB circuit, HL-LHC inner triplet

Procedure

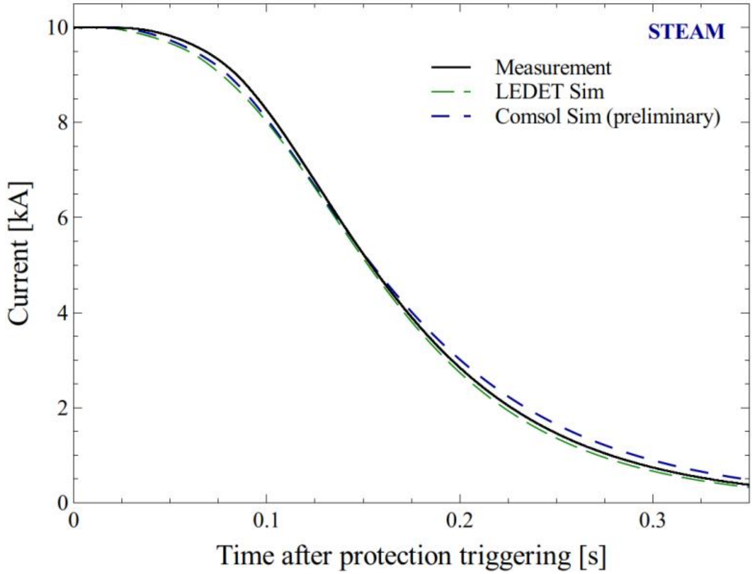
- Definition of test plan: Discharges using quench heaters, CLIQ, extraction, and combination of methods
- Preliminary calculation of expected behavior with simulation tools
- Execution of test plan
- Comparison of measured behavior versus expected behavior, and documentation

Simulation tools within our section

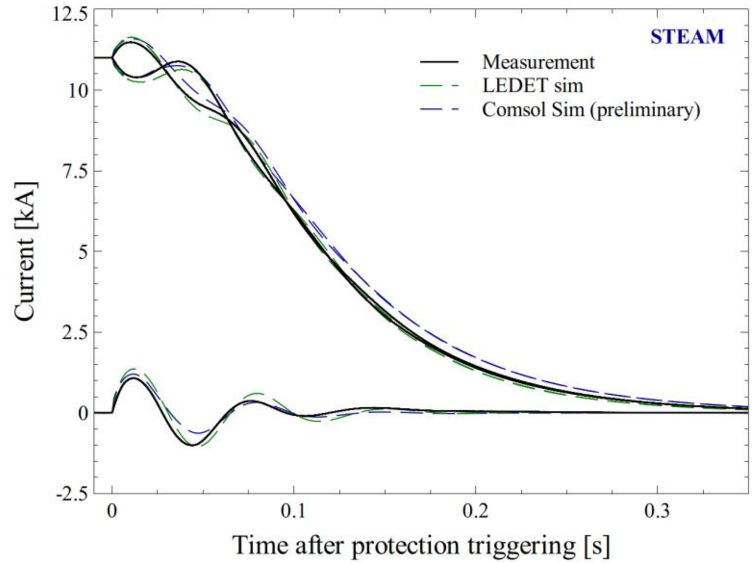
- Variety of tools, depending on magnet type and protection method
- For magnets with CLIQ:
    - LEDET [1]: Previously validated
    - Comsol [2]: Partially validated, currently being validated for new features
    - TALES [3]: No longer supported

[1]. Ravaioli et al., Cryog. 80, p 346 (2016).
[2]. Bortot et al, IEEE TAS 27, p. 4001305 (2017)
[3]. Maciejewski, Master thesis, (2014)

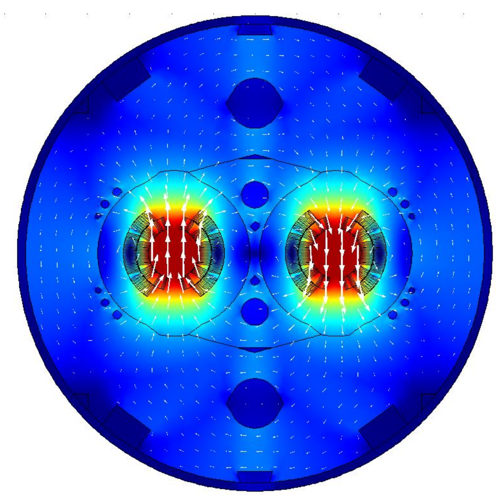
# 11T, MBHDP102 double-aperture short model




*Quench heater discharge*

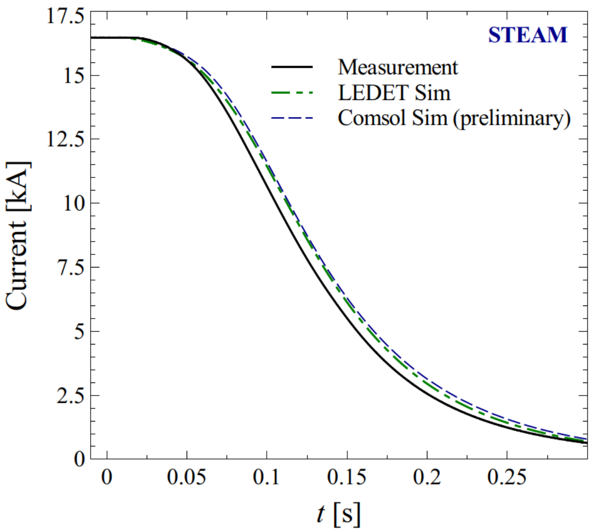



*CLIQ + QH discharge*

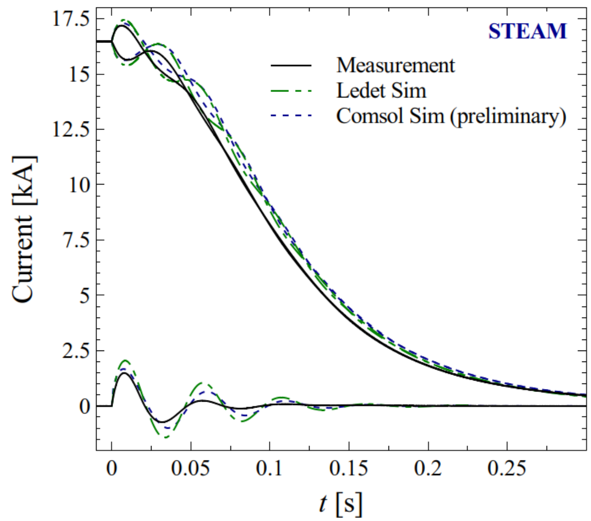


- Magnet could only be measured up to 11 kA (due to a conductor limitation)
- Particular to this magnet: Different conductor properties in both apertures (copper fraction, RRR) leading to energy transfer from one aperture to the other during quench, increased hot-spot temperature, increased voltage-to-ground at the electrical midpoint
- Sole free parameter: $f_{rho,eff}$ → Affects effectiveness of inter-filament coupling losses, but with modest impact on quench behavior
- With CLIQ, $I_{nom}$: Over 100 K reduction in hot-spot temperature
- Observed results are generally consistent with expectations

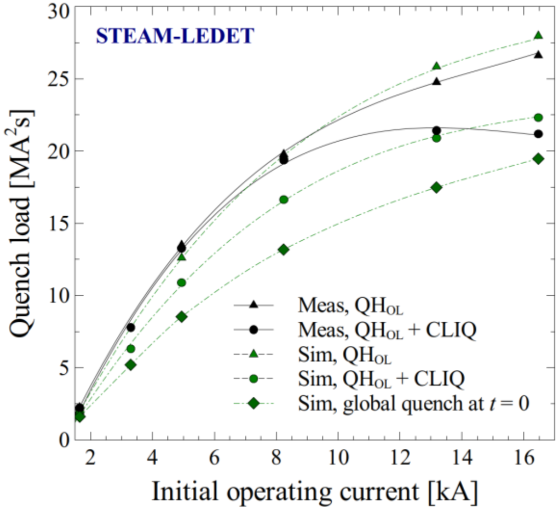
# MQXFs5, short model



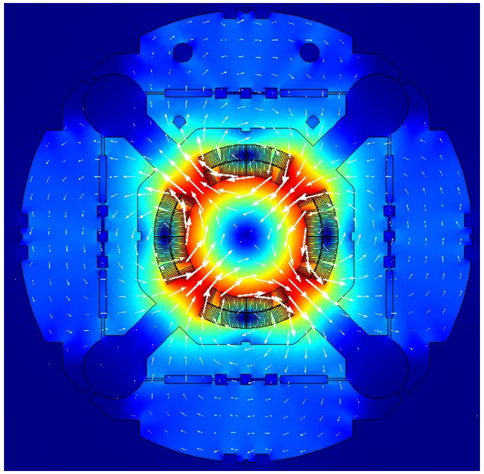

*Quench heater discharge*




*CLIQ + QH discharge*




*Quench load, simulation vs observation*



- Measured up to nominal current
- Sole free parameter: $f_{rho,eff}$ → Affects effectiveness of inter-filament coupling losses, but with modest impact on quench behavior
- Quench load: QL=$\int I^2 dt$ → Indicative of hotspot temperature
  - Higher quench load → Higher hotspot temperature
  - Measured Quench load higher than expected at lower currents, and somewhat lower than expected at higher currents
- For MQXF magnets, combination of CLIQ and QHs works very well at nominal current, more efficiently than expected → Subject of ongoing investigation

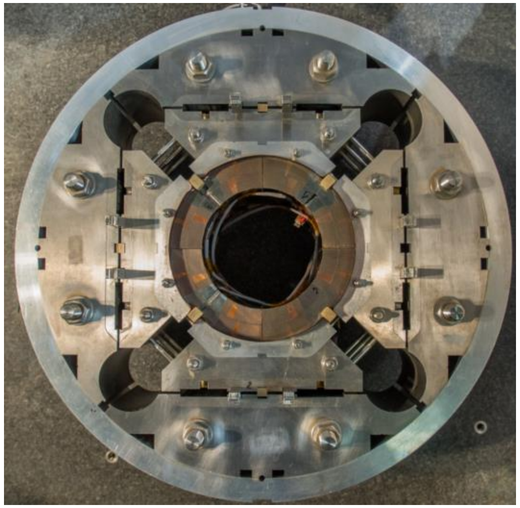
# Summary

Continuous measurement campaign in SM18, to understand behavior of HL-LHC short model magnets and prototypes

Measurements + simulations demonstrate that both $Nb_3Sn$ magnet types are protected at all current levels

STEAM effort to compare modelling results to experimental observations

- Continuous development and tweaking of simulation tools
- Measurements versus simulations: Protection-related behavior is generally well understood
- Simulation tools + validated models used to predict behavior of HL-LHC circuits, such as modified RB and HL-LHC inner triplet



*MQXF cross-section*

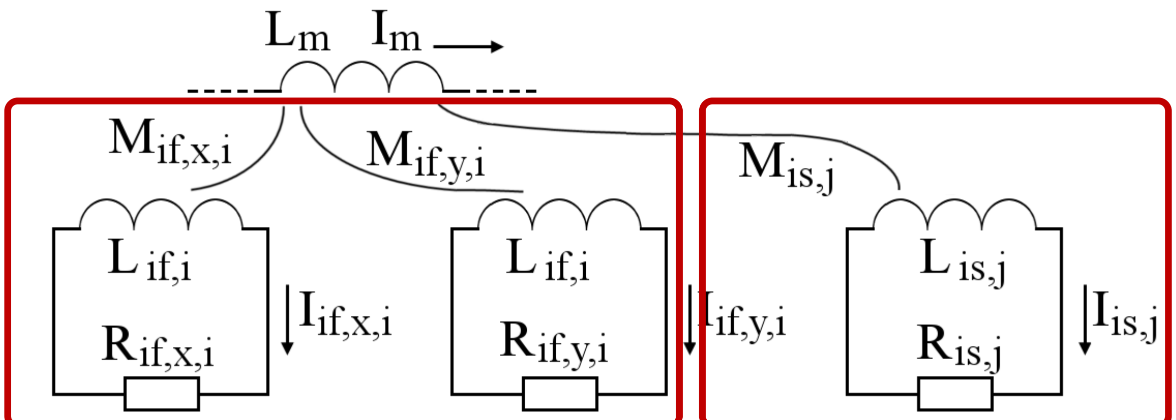
*11 T coils during production*

# LEDET model

**Runs in 3 minutes!**

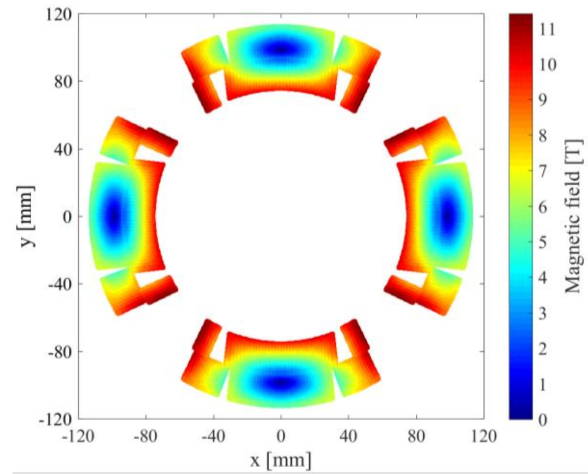
The **interaction** between the superconducting magnet and the local coupling currents is modeled with an array of **RL dissipative loops mutually coupled** with the magnet self-inductance

All simulations presented today are performed with the **LEDET** 2D model (Lumped-Element Dynamic Electro-Thermal)




Inter-filament coupling currents

Inter-strand coupling currents

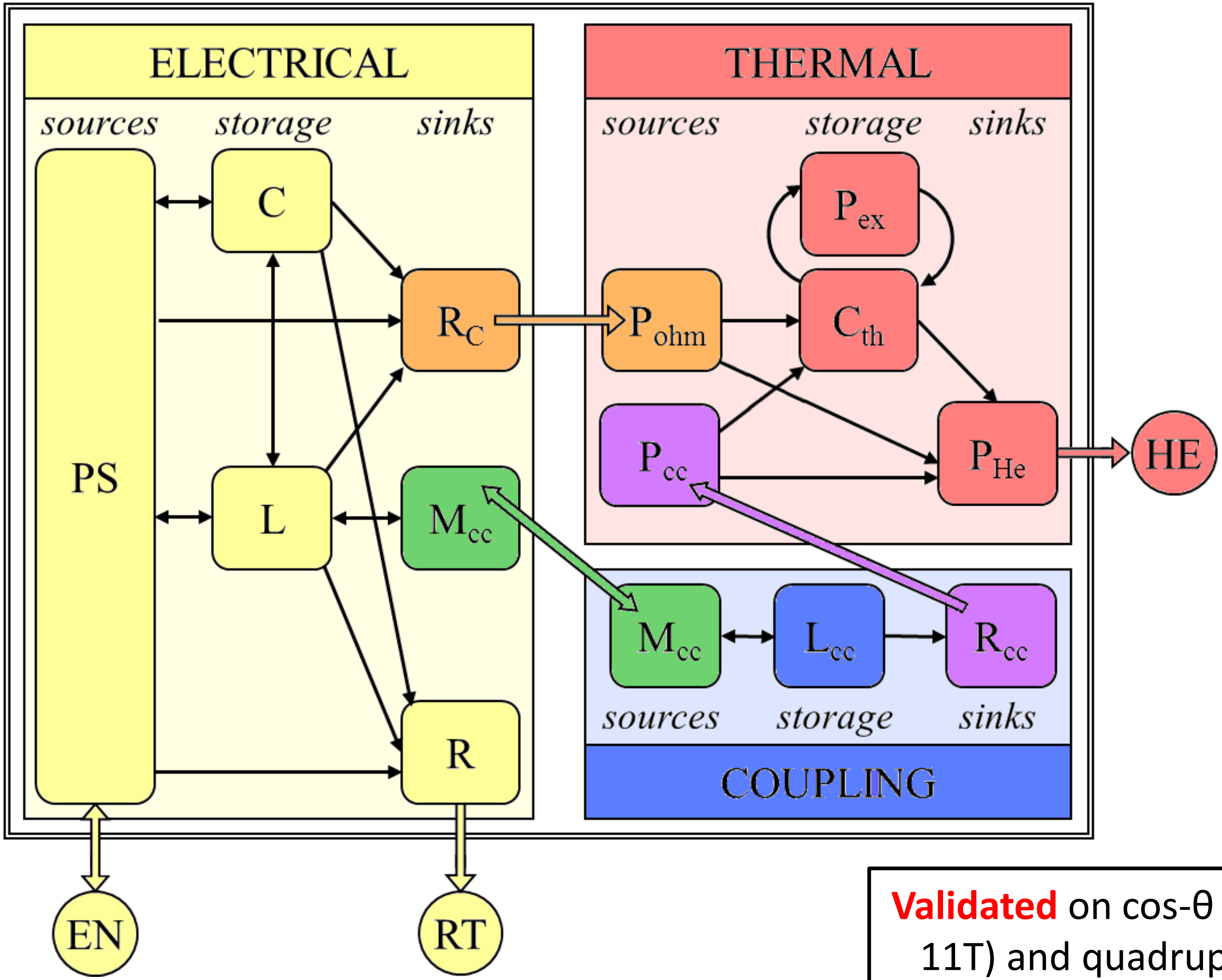



Example: HL-LHC 12 T $Nb_3Sn$ quadrupole magnet (MQXF)

- 2x 16000 IFCL loops
- 400 ISCL loops


*[1] E. Ravaioli, "CLIQ", PhD thesis, 2015*
*[2] E. Ravaioli et al., Cryogenics 2016*

# LEDET (Lumped-Element Dynamic Electro-Thermal)




**Validated** on cos-θ dipole (MB, 11T) and quadrupole (MQY, MQXC, HQ, MQXF) magnets