Quench protection performance measurements in the first MQXF magnet models

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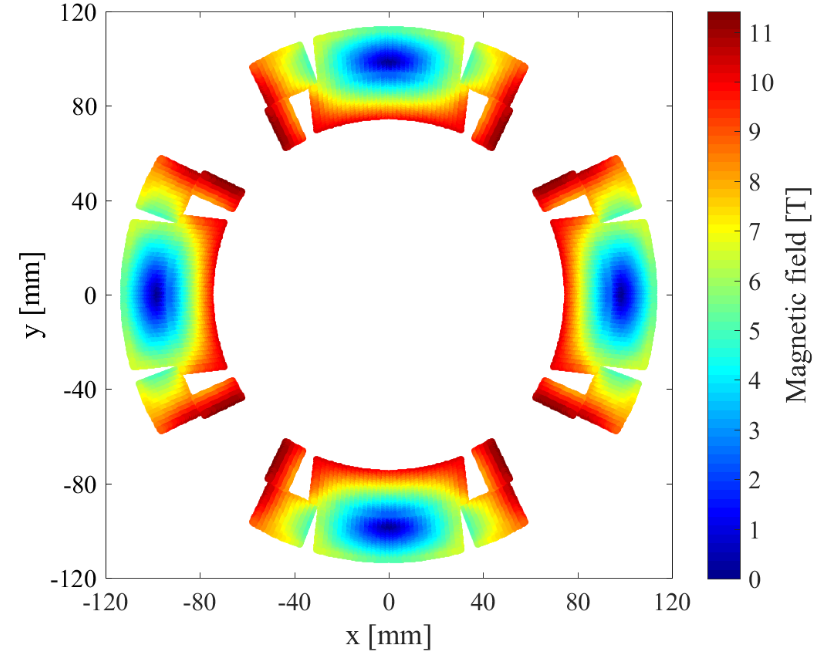
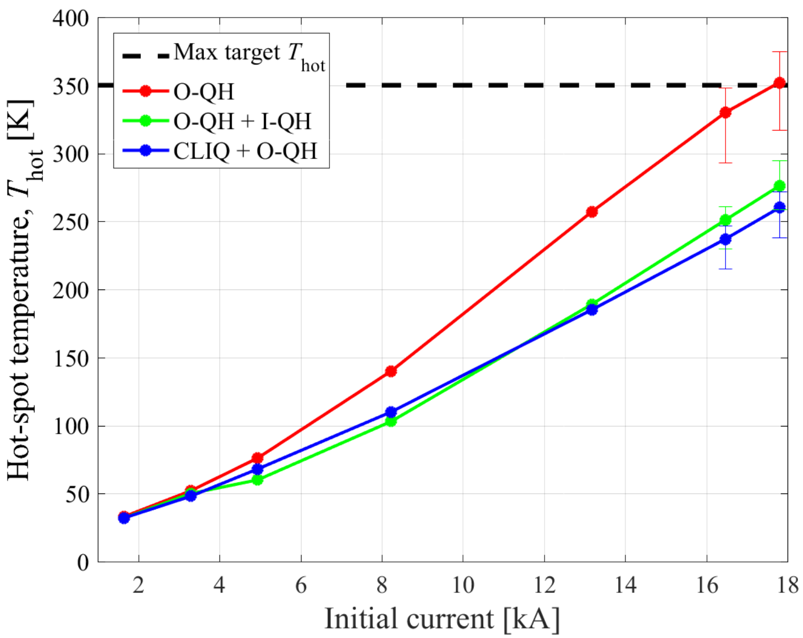
MQXF powering and protection strategy

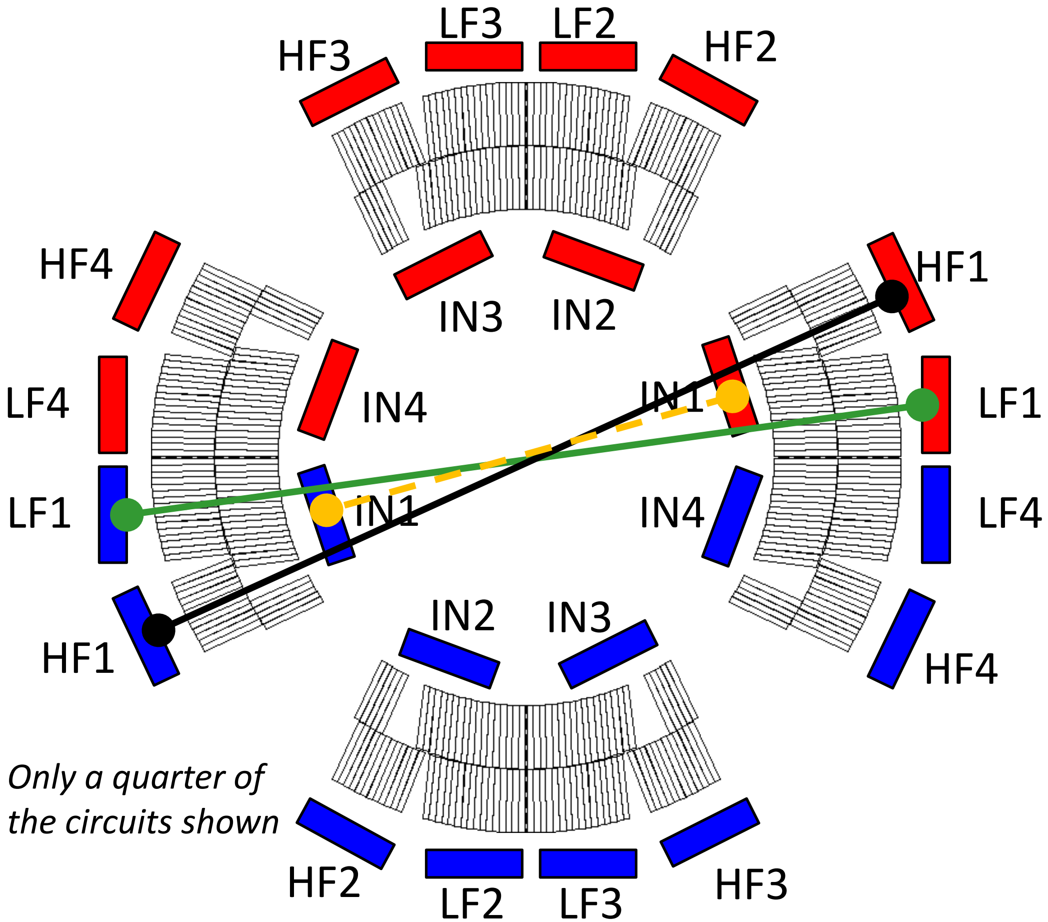
- → High Luminosity LHC inner triplets
- → 132.6 T/m gradient, 4.2/7.1 m long
- → 16.5 kA, ~12 T in the conductor
- → Nb_3Sn superconductor
- → Quench protection is challenging





Quench protection system includes heaters and CLIQ to improve **redundancy** and **effectiveness**

Heaters



Only a quarter of the circuits shown

Strip heating

Heat transfer to coil

Temperature increase

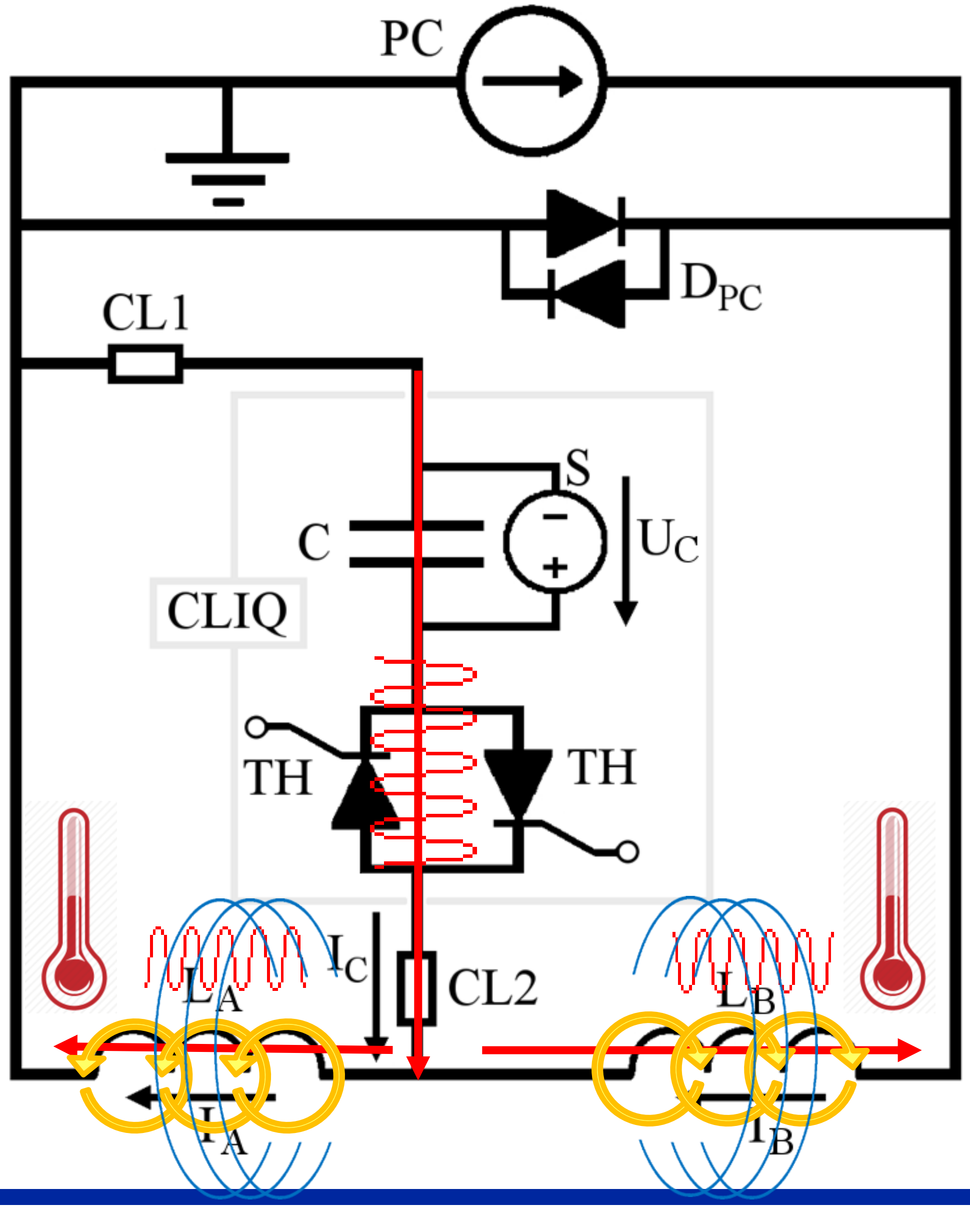
QUENCH

Outer layer heater strips

Inner layer heater strips

CLIQ (Coupling-Loss Induced Quench)

Patent EP13174323.9



Current change

Magnetic field change

Coupling losses (Heat)

Temperature rise

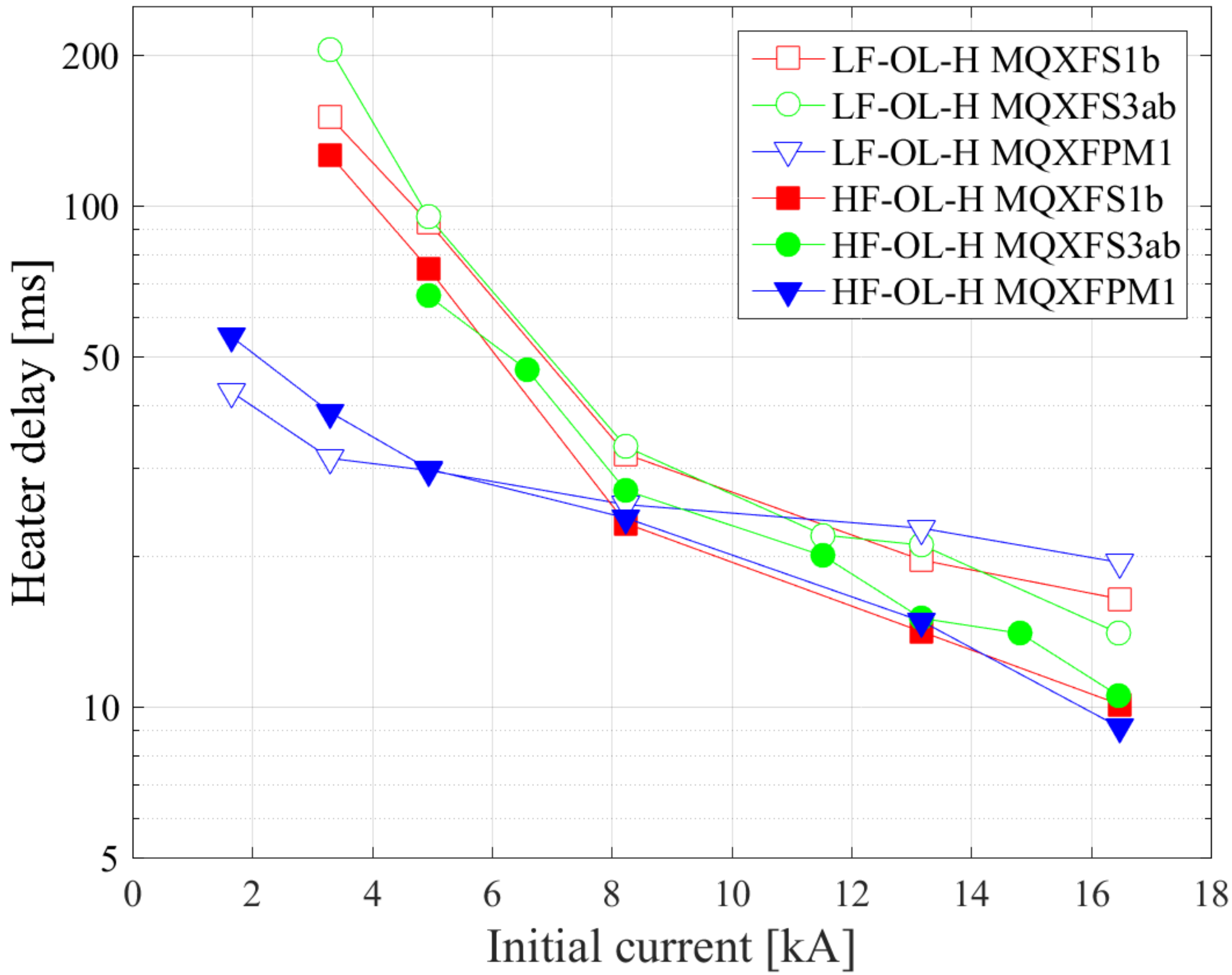
QUENCH

MQXF quench protection studies

Studies	MQXFS1a-b-c (1.2 m short model)	MQXFS3a-b (1.2 m short model)	MQXFPM1 (4.0 m mirror)
Quench integral – oQH	√	√	
Quench integral – oQH+iQH	~	√	
Quench integral – oQH+CLIQ	√		
QH delays	√	√	√
QH min energy to quench	√		√
CLIQ studies	√		
EE discharge (quench-back)	√		

<u>Goal</u>: Verify that the baseline quench protection system parameters are suitable for quench protection performance

Outer layer heater delays



High-field OL heaters
9-11 ms at I_{nom}

Low-field OL heaters
14-19 ms at I_{nom}

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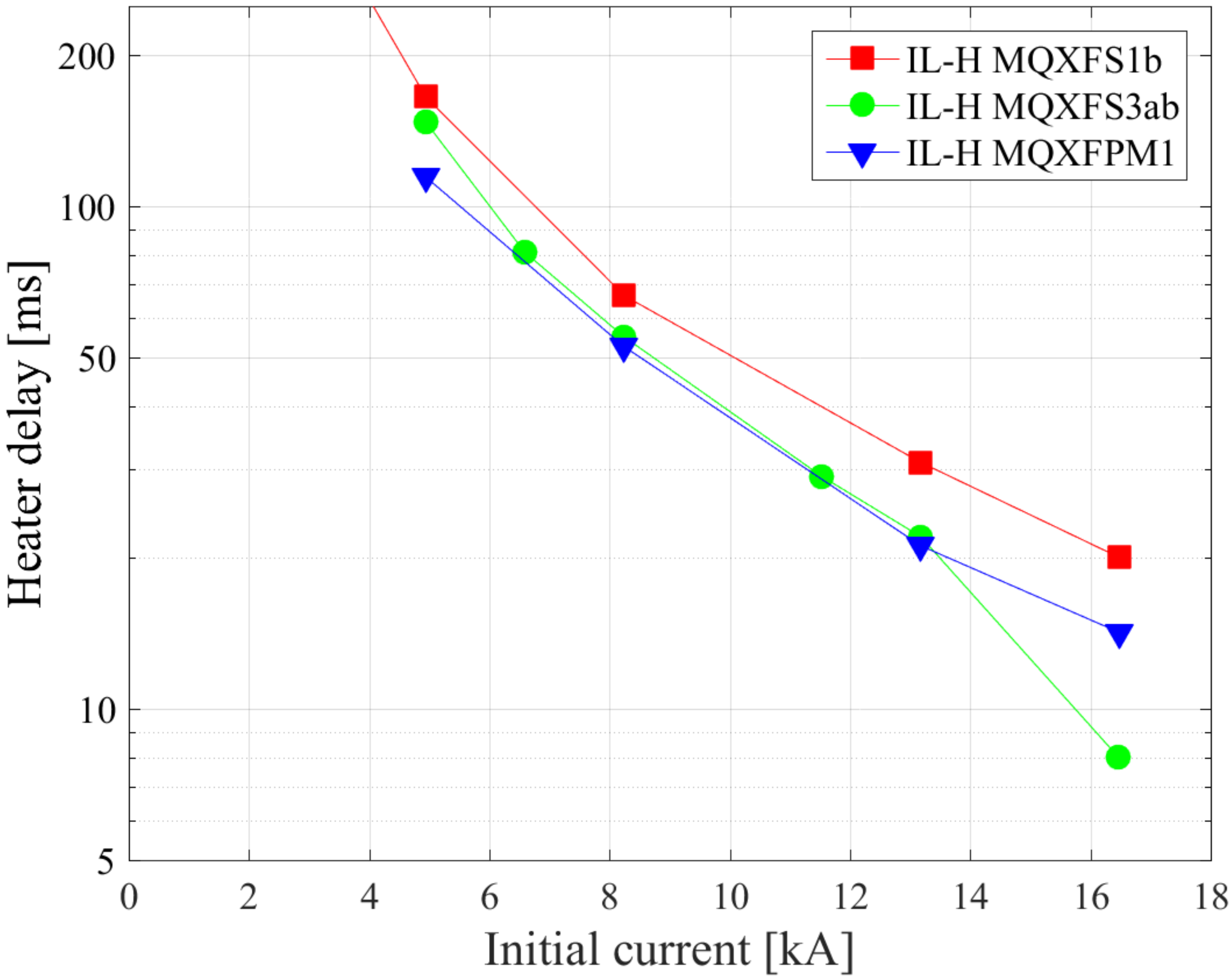
Inner layer heater delays

Long-term reliability not yet demonstrated



IL heaters
8-20 ms at I_{nom}

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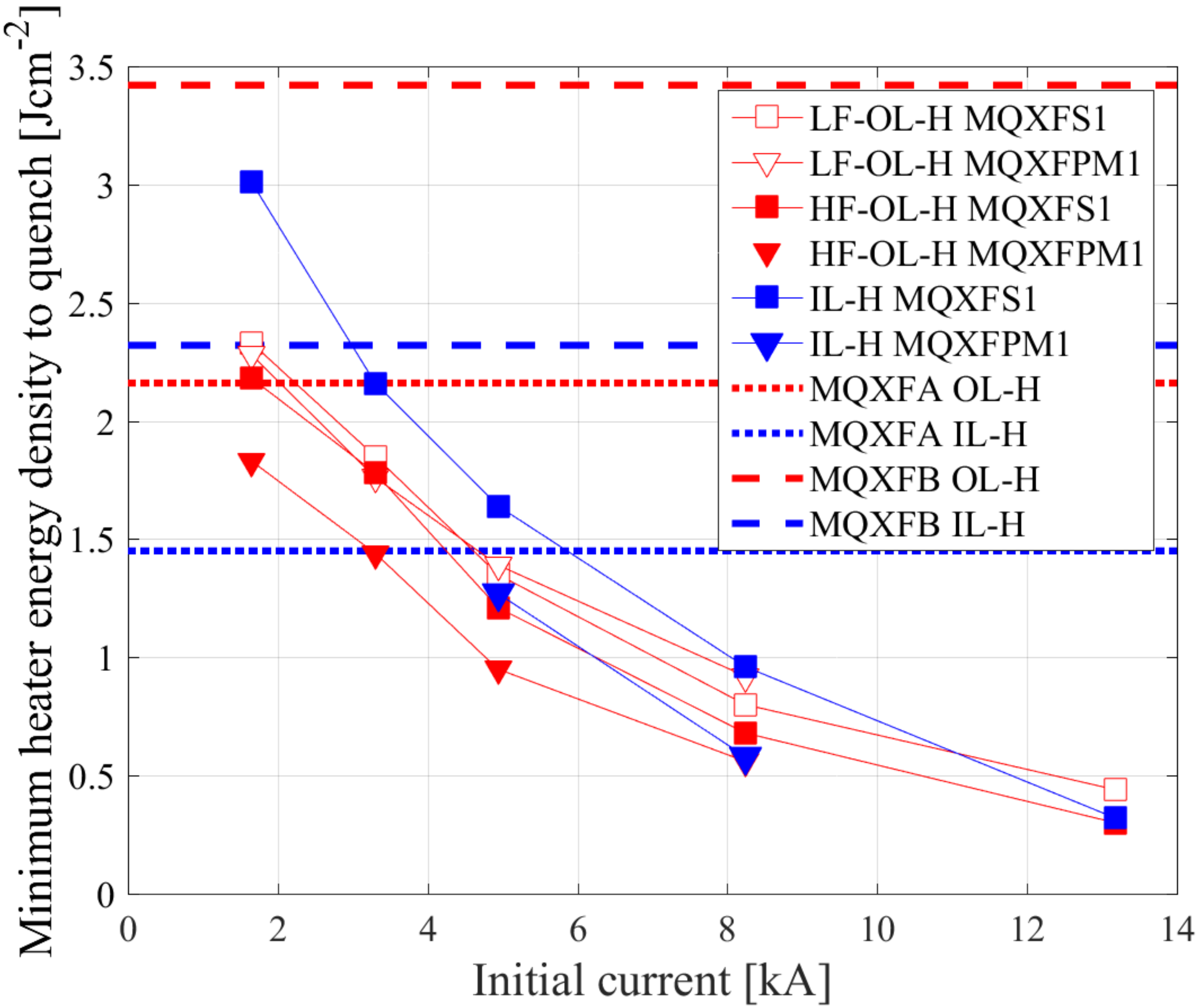
Heater minimum energy density to quench



OL heaters deposit enough energy to quench at current ≥1.5 kA

IL heaters deposit enough energy to quench at current >3-5 kA

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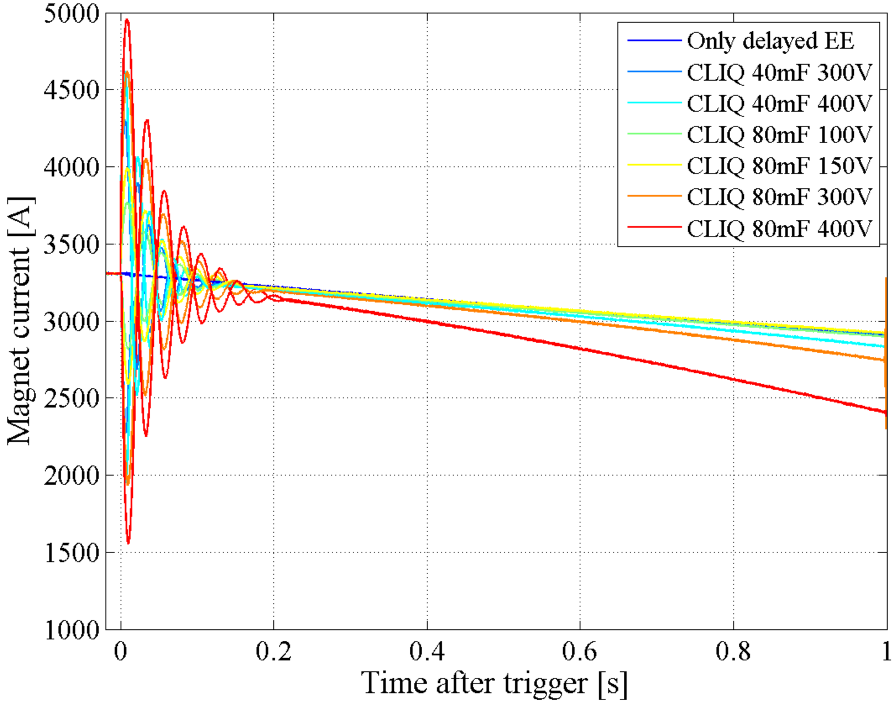
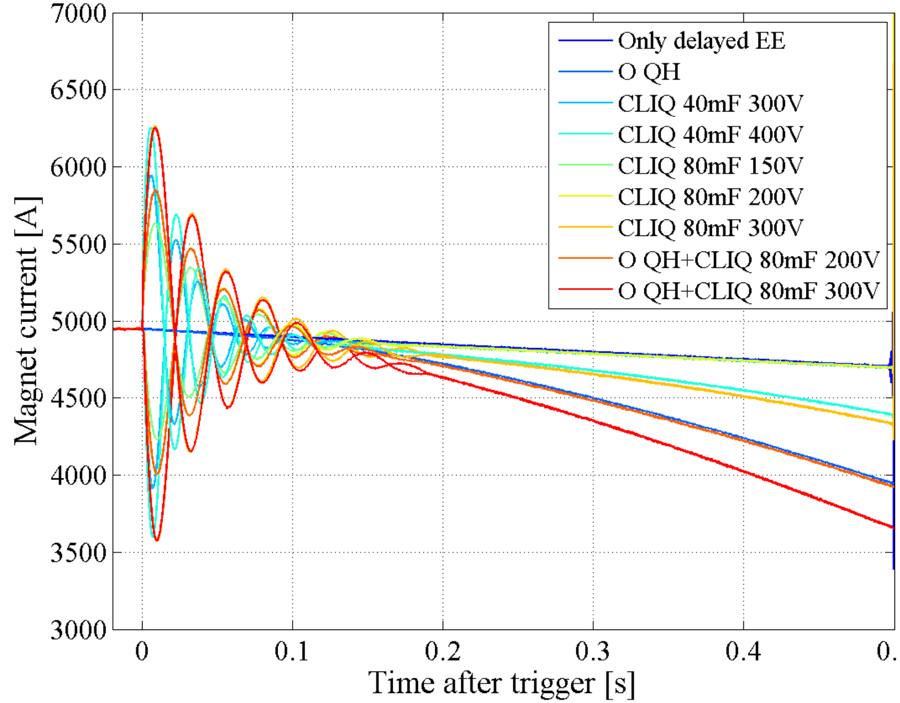
CLIQ studies – Energy to quench





Initial current	CLIQ capacitance [mF]	CLIQ charging voltage [V]	CLIQ stored energy [kJ]	CLIQ stored energy per unit length wrt 7m baseline	Quench
3.3 kA	40	300	1.8	54%	
	40	400	3.2	96%	X
	80	100	0.4	12%	
	80	150	0.9	27%	
	80	300	3.6	108%	X
	80	400	6.4	192%	X
4.9 kA	40	300	1.8	54%	
	40	400	3.2	96%	X
	80	200	1.6	48%	
	80	300	3.6	108%	X

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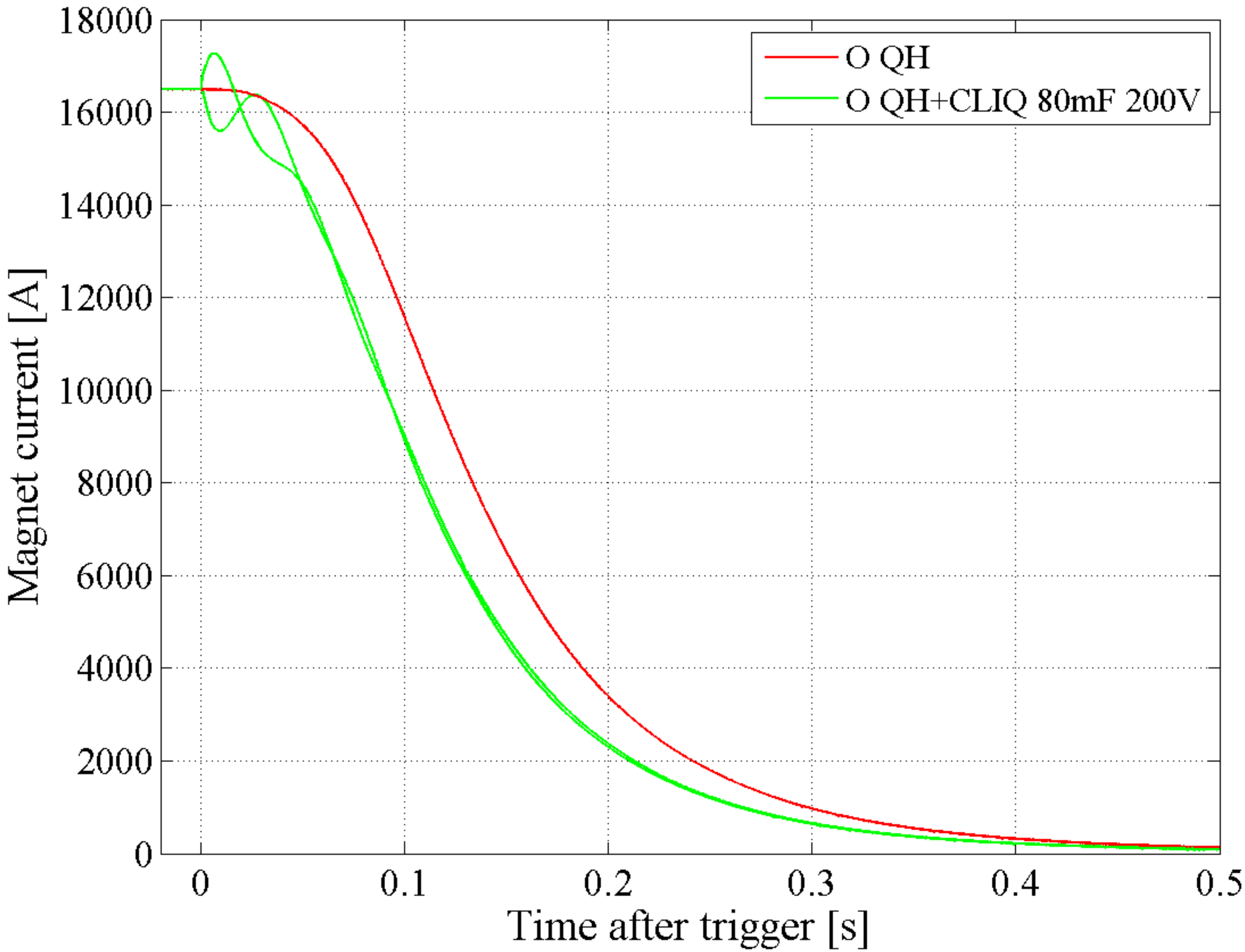
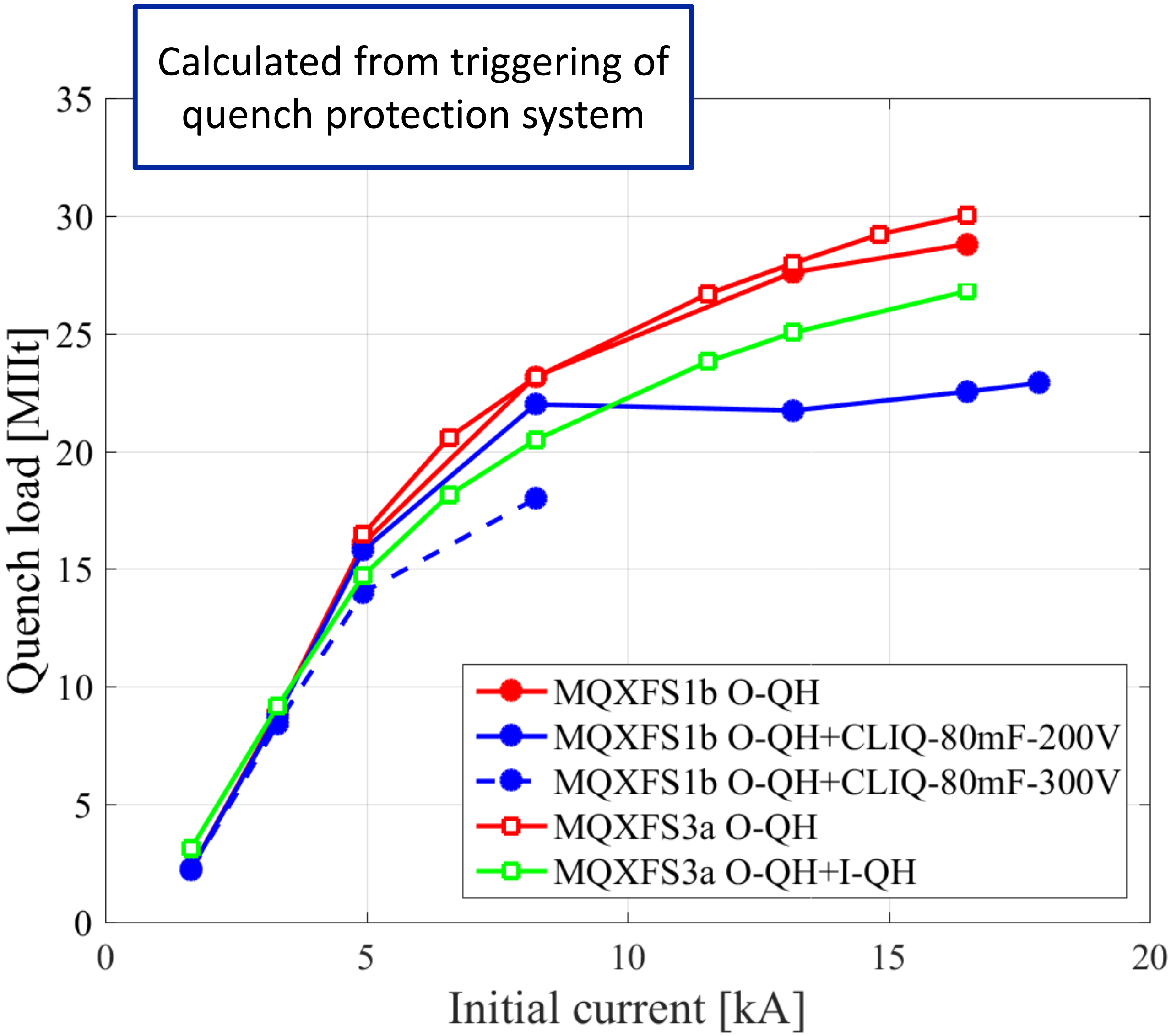
MQXFS1b – Two discharges at nominal current



Quench protection performance



Note!
Heater performance are poorer than baseline
- Unavailability of some I-QH strips (4oo8)
- Hardware limitations limited power density

Quench load due to detection + validation time to be added
At nominal current ~4 MIIt

RRR
MQXFS1ab: 250, 105, 255, 135
MQXFS3ab: 140, 140, 140, 170

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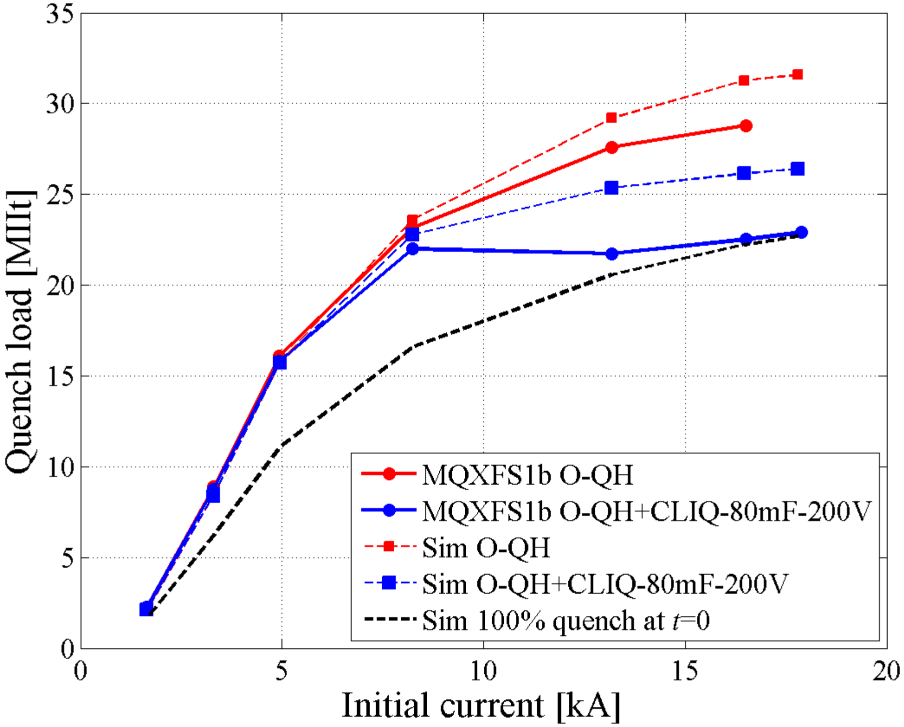
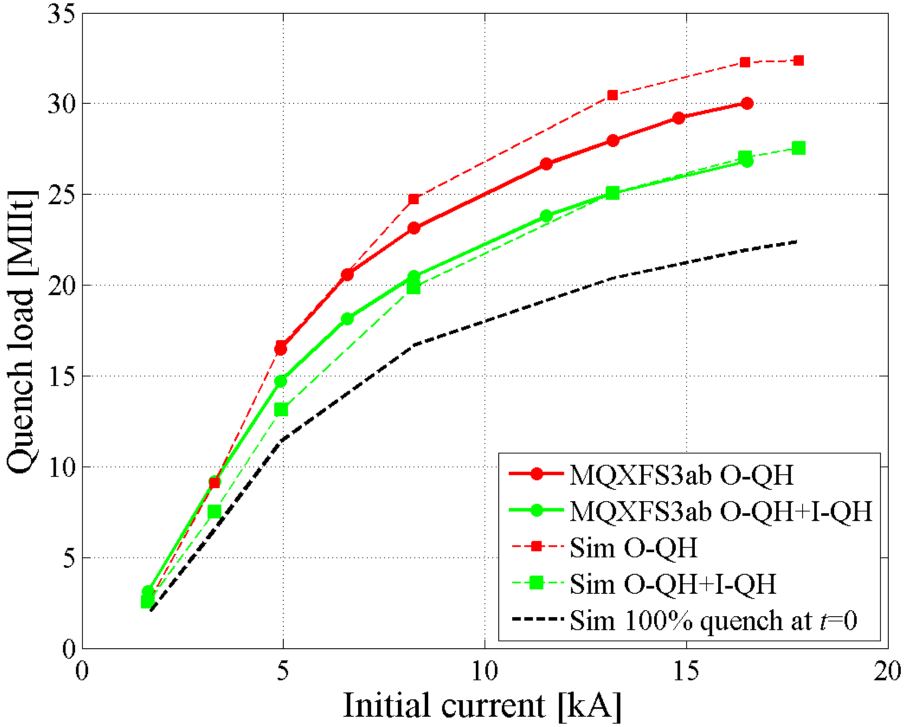
Comparison to LEDET simulation results

MQXFS1a-b



MQXFS3a-b



Possible causes for the faster experimental discharges

- strain-dependency of the Nb_3Sn critical current
- effect of the strand twist-pitch on the ohmic loss per unit length
- superconductor hysteretic loss (magnetization)
- temperature gradient within the conductor's metal, epoxy, and insulation

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Conclusion & next steps

Latest MQXF quench protection studies

Two 1.2 m short model and one 4.0 m mirror magnets tested at FNAL, CERN, BNL.

With baseline quench protection parameters:

- HF O-QH: 9-11 ms delays at nominal current. Energy density sufficient to quench at 1.6 kA
- LF O-QH: 14-19 ms delays at nominal current. Energy density sufficient to quench at 1.6 kA
- I-QH: 8-20 ms delays at nominal current. Energy density sufficient to quench at ≥3-5 kA
- CLIQ: quench in <5 ms. Energy density sufficient to quench at ≥3 kA

→ Quench protection up to ultimate current successfully demonstrated

→ Baseline parameters offer satisfactory quench protection performance (fast quench initiation, redundancy, scalability, reproducibility)

→Long-term reliability of inner QH not yet demonstrated (failures, detachment)

Next MQXF quench protection studies

New 1.2 m short models and 4.0 m prototype magnet to be tested at BNL, CERN, FNAL.

Goal: Define the baseline for the quench protection system after quench protection studies on the first 4 m prototype magnet

Electro-magnetic and thermal modeling

→ LEDET model needs to be refined to reproduce faster than expected CLIQ discharge

Goal: Implement the identified potential sources of inaccuracy and validate the new model

QUESTIONS?

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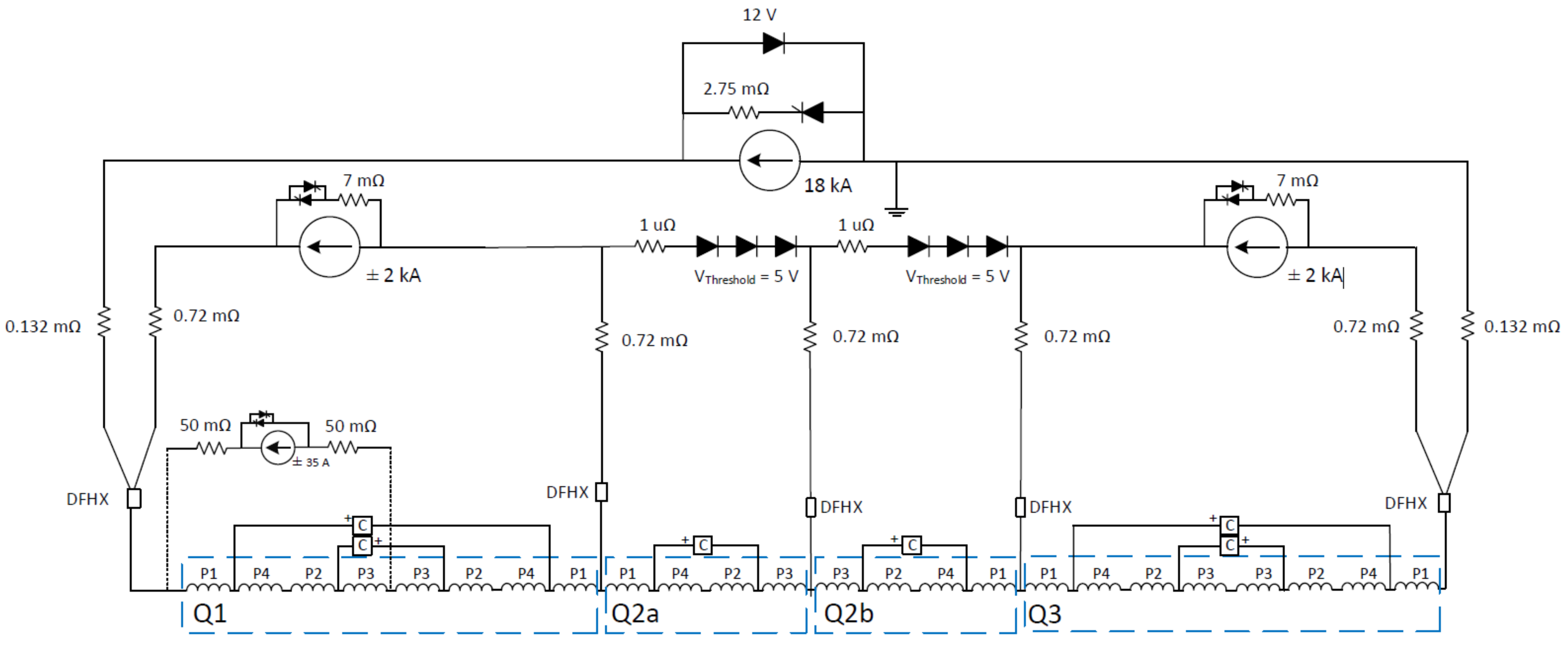
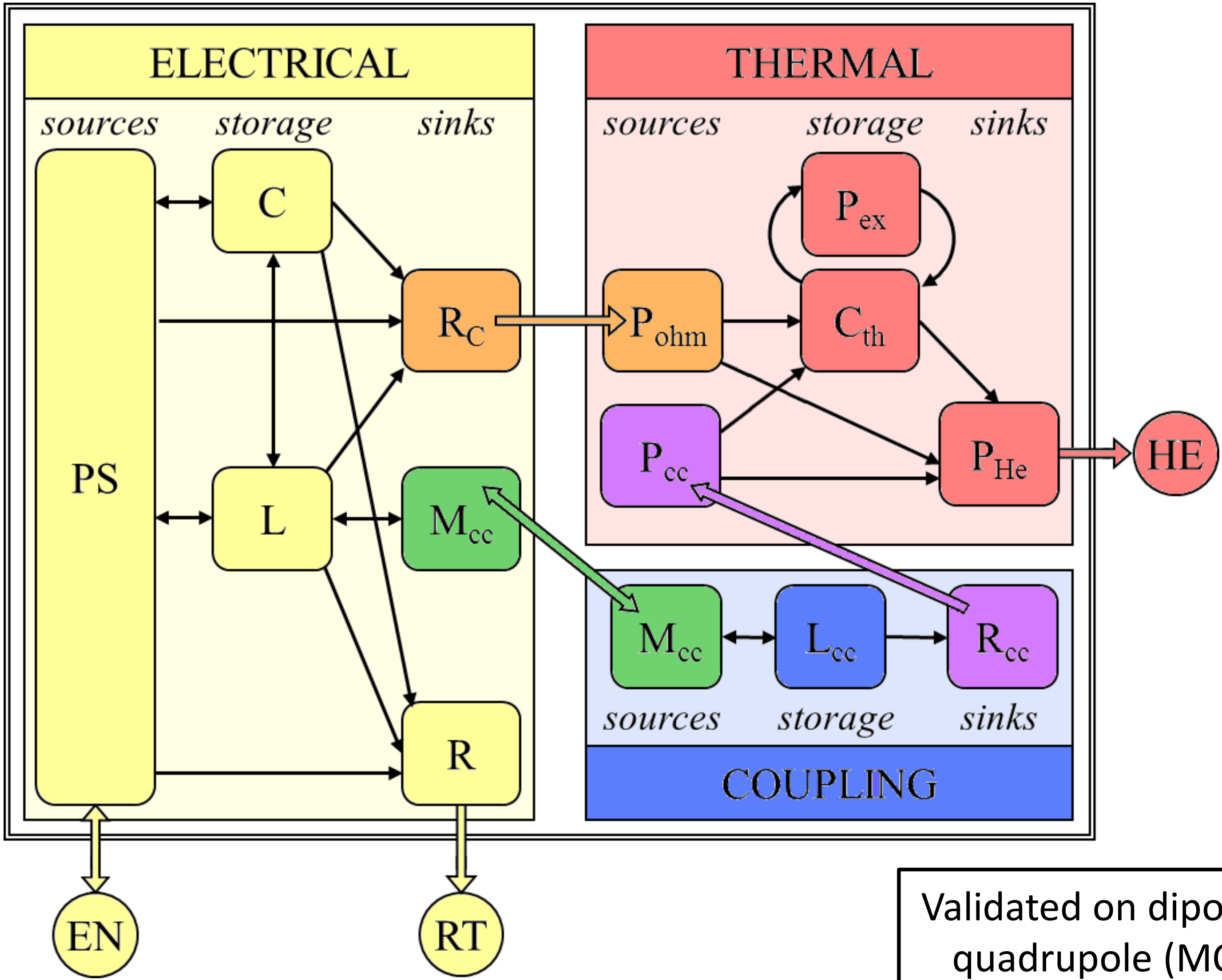
MQXF powering and protection circuit



LEDET (Lumped-Element Dynamic Electro-Thermal)



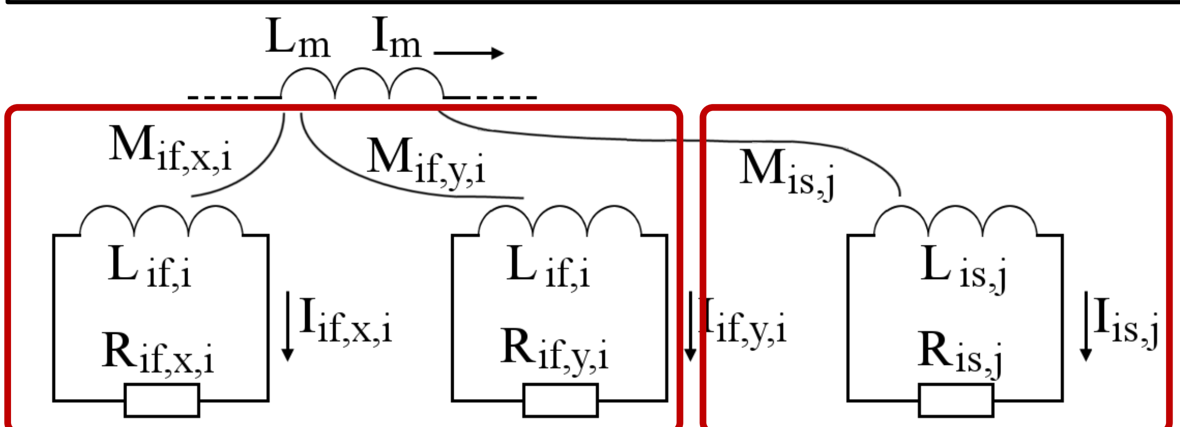
Validated on dipole (MB) and quadrupole (MQY, MQXC, HQ, MQXF) magnets

LEDET model

Runs in 3 minutes!

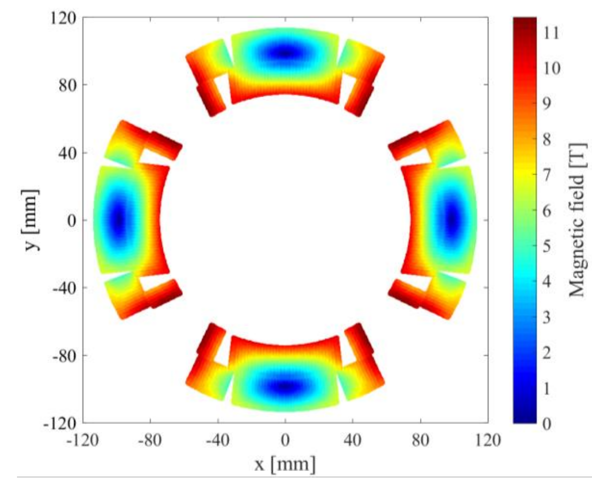
The **interaction** between the superconducting magnet and the local coupling currents is modeled with an array of **RL dissipative loops mutually coupled** with the magnet self-inductance

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