Quench protection of the 16 T Nb_3Sn ERMC and RMM dipole magnets

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26 September 2019

The eRMC and RMM program at CERN

eRMC

Enhanced Racetrack Model Coil

16 T mid-plane field

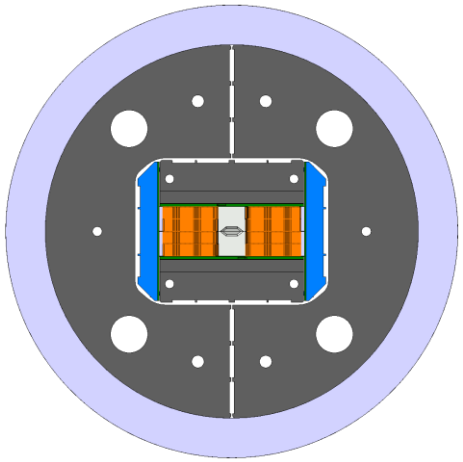
- Demonstrate field on the conductor
- Coil technology development

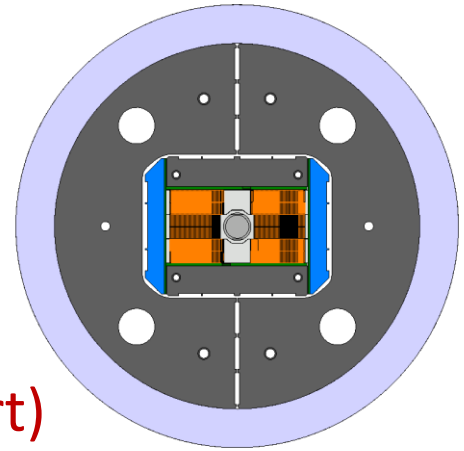
RMM

Racetrack Model Magnet

16 T in a 50 mm cavity

- Demonstrate field on the aperture
- Mechanics (including inner coil support)



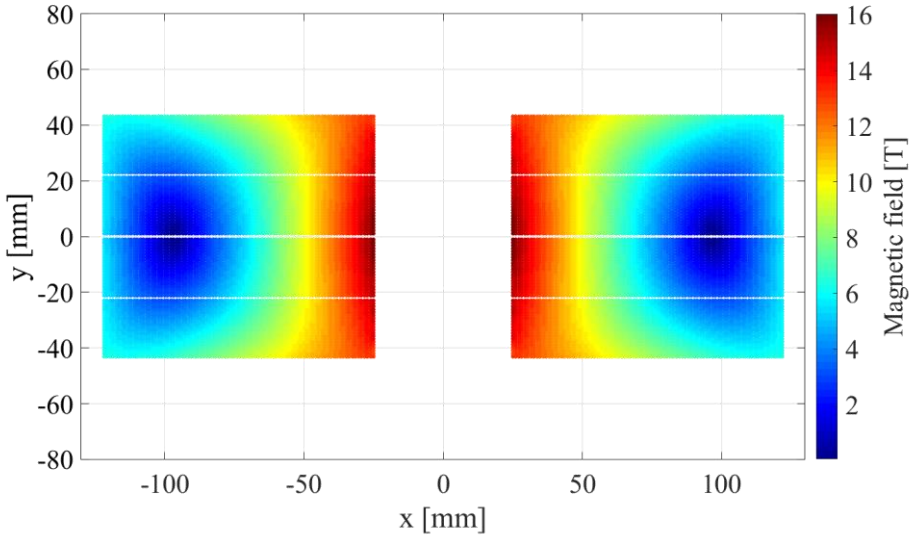


Base for the development of the technology needed for the 16 T dipole program

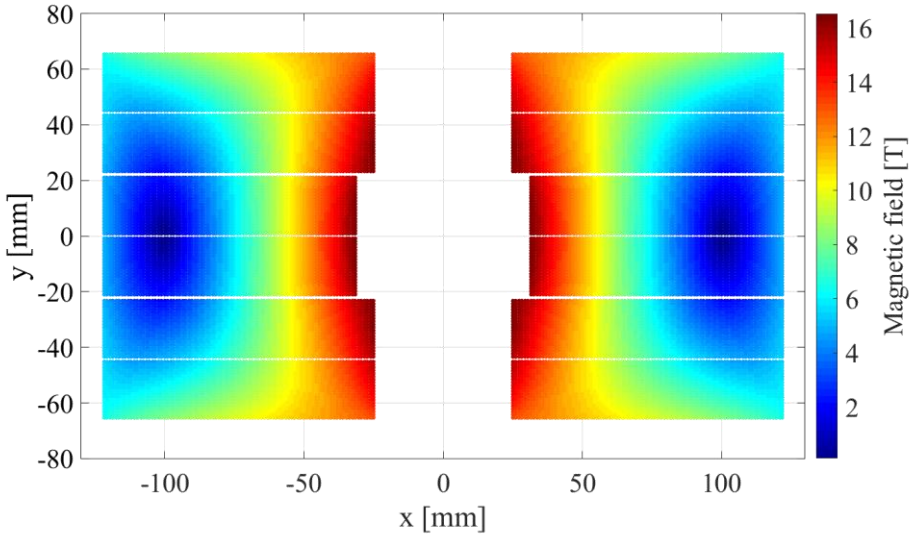
Slide courtesy of S. Izquierdo Bermudez

[1] S. Izquierdo Bermudez
[2] E. Rochepault

eRMC and RMM magnets



eRMC



RMM

TABLE I
2-D MAGNET PARAMETERS

Parameter	Unit	ERMC	RMM
Closed aperture diameter	mm	8	50
Aluminum shell thickness	mm	70	70
Magnet outer diameter	mm	800	800
Number of turns per quadrant	–	90	132
Nominal current I_{nom}	kA	13.13	11.40
Insulated cond. current density at I_{nom}	A/mm^2	282	245
Nominal bore field B_{nom}	T	15.7	16.0
Coil peak field at I_{nom}	T	16.00	16.15
Short sample current I_{ss} at 4.2 K	kA	14.38	12.66
Coil peak field at 4.2 K I_{ss}	T	17.28	17.72
Short sample current I_{ss} at 1.9 K	kA	15.91	14.05
Coil peak field at 1.9 K I_{ss}	T	18.90	19.39
Stored energy per unit length at I_{nom}	MJ/m	1.5	2.1
Inductance per unit length at I_{nom}	mH/m	16.6	31.1
F_x per quadrant at I_{nom}	MN/m	5.86	8.03
F_y per quadrant at I_{nom}	MN/m	−3.34	−4.05

Magnetic field maps calculated using ROXIE

[1] S. Izquierdo Bermudez
[2] E. Rochepault

Focus of today's presentation

Design of the **quench protection systems** for **full-scale** [**14.3 m**] eRMC and RMM magnets

Main features:

→ **CLIQ** technology

→ **Multi-physics** analysis with STEAM-LEDET

→ Analysis of transients at **all current levels**

Quench protection of the 16 T Nb_3Sn ERMC and RMM dipole magnets

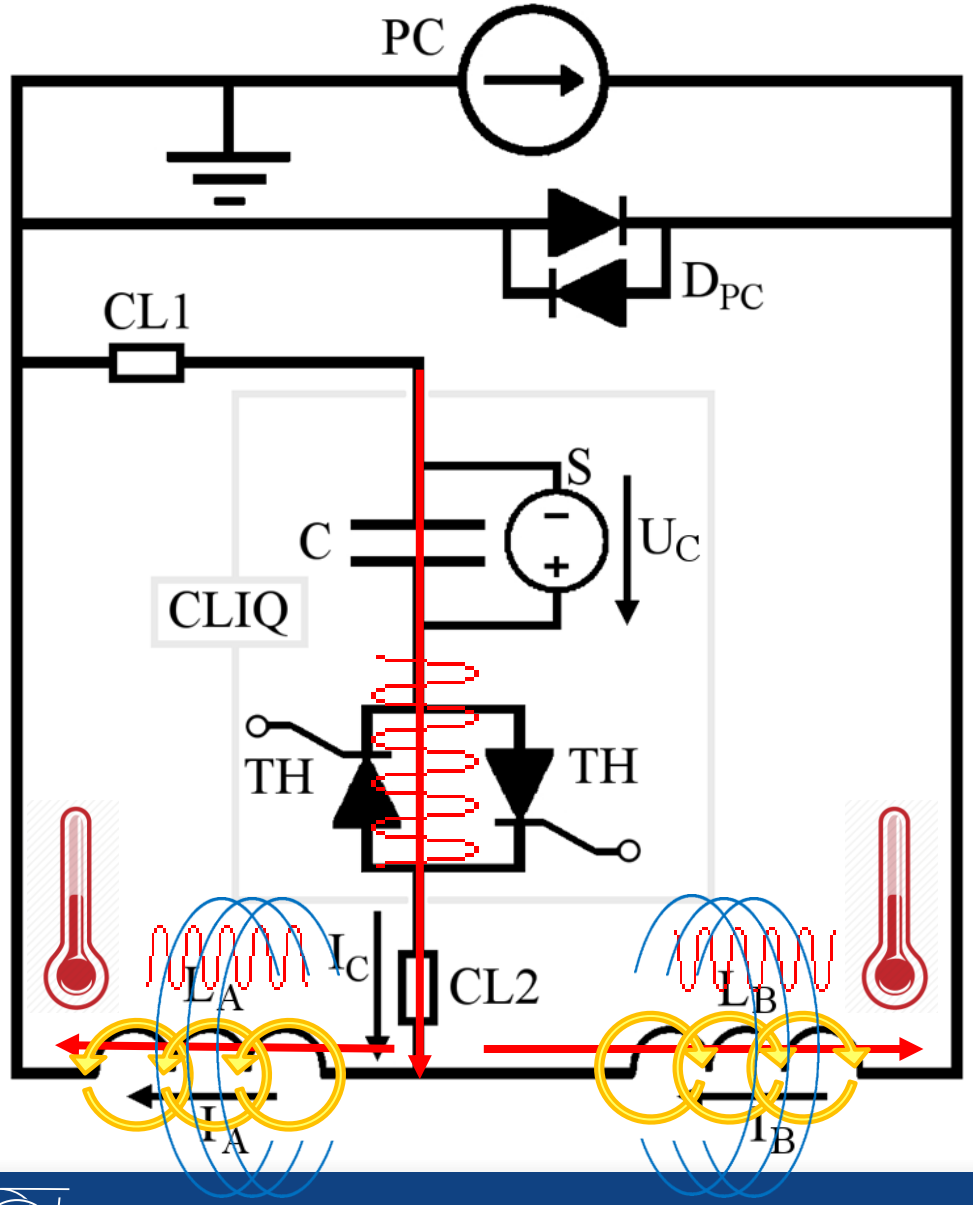
Quench protection based on CLIQ

Modelling with STEAM-LEDET

eRMC magnet quench protection

RMM magnet quench protection

CLIQ (**C**oupling-**L**oss **I**nduced **Q**uench) technology



Current change

Magnetic field change

Coupling losses (Heat)

Temperature rise

Coil SC→resistive

Magnet current discharged

Reduced hot-spot temperature

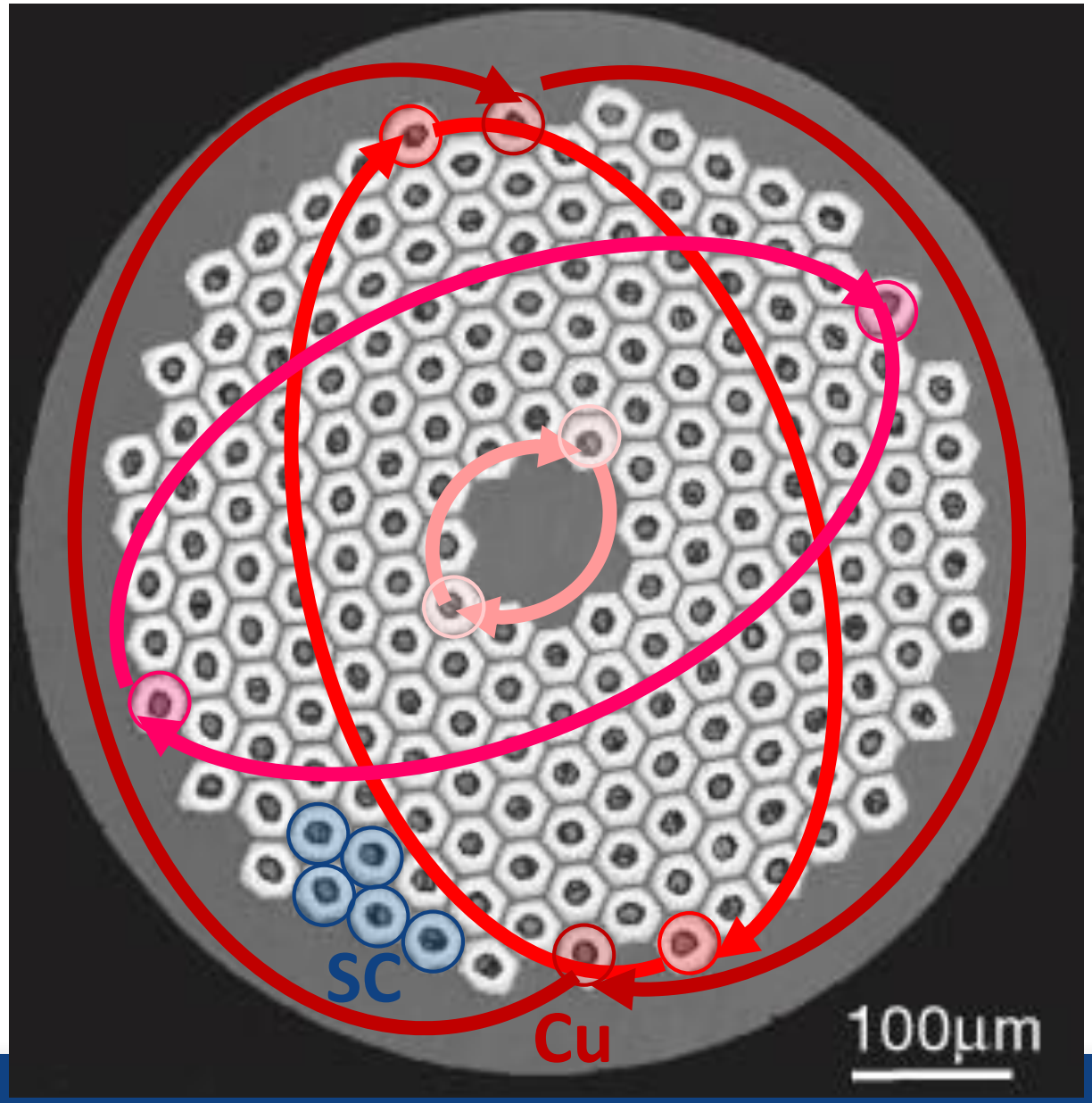
Main CLIQ ingredients

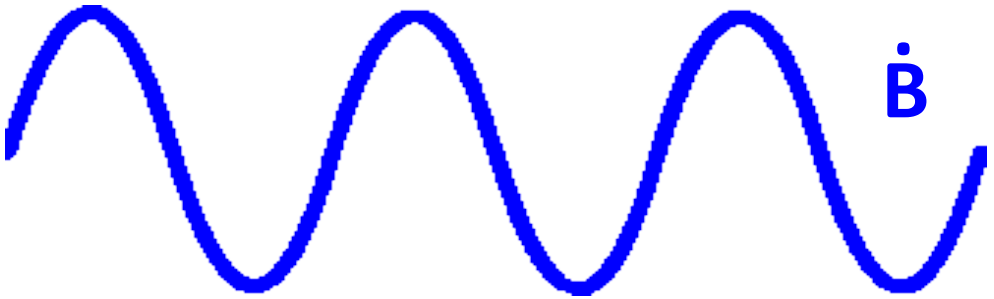
- **Connection** scheme
- Capacitance **C**
- Charging voltage $\mathbf{U_0}$

[1] G. Kirby, V. Datskov, E. Ravaioli, Patent EP13174323.9, 2013

[2] E. Ravaioli, "CLIQ", PhD thesis, 2015

Inter-filament coupling loss





"Fast" loss:
Characteristic time constant in the order of **ms** or **tens of ms**

Deposited **power** density roughly proportional to **$(dB/dt)^2$**

CLIQ advantages & disadvantages with respect to conventional technology

- More **effective** energy deposition
- **Faster** and more **homogeneous** quench initiation

- **More robust** electrical design
- **Easier** to implement and repair
- Lower expected **failure rate**

- **Integration** in the magnet circuit to be studied

- Internal **voltage distribution** to be carefully analyzed

- **Redundancy** of the system

CLIQ technology tests

Name	Where	Year	Geometry	Superconductor	Stored energy [MJ]
Small-scale solenoid	CERN	2013	Solenoid	Nb-Ti	0.04
Solenoid system	Private	2014	Solenoid	Nb_3Sn	-
MQXC2	CERN	2014	Quadrupole	Nb-Ti	1.10
HQ	CERN	2014	Quadrupole	Nb_3Sn	0.60
MQY	CERN	2015	Twin-aperture quadrupole	Nb-Ti	0.96
MB	CERN	2015	Twin-aperture dipole	Nb-Ti	6.88
MQXF	FNAL	2016-2019	Quadrupole	Nb_3Sn	1.46
→Baseline for HL-LHC inner triplet magnets	CERN	2017-2019	Quadrupole	Nb_3Sn	1.46
	BNL	2018-2019	Quadrupole	Nb_3Sn	4.91
11T dipole	CERN	2017	Twin-aperture dipole	Nb3Sn	1.94
PUP4	NHMFL	2017	Solenoid	Bi-2212	0.3E-3

…and more in the pipeline

CLIQ was tested in 7 different test facilities on more than 15 magnets with different superconductor types (Nb-Ti, Nb_3Sn, Bi-2212), geometries, and magnet sizes

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eRMC magnet quench protection

RMM magnet quench protection

LEDET in a nutshell

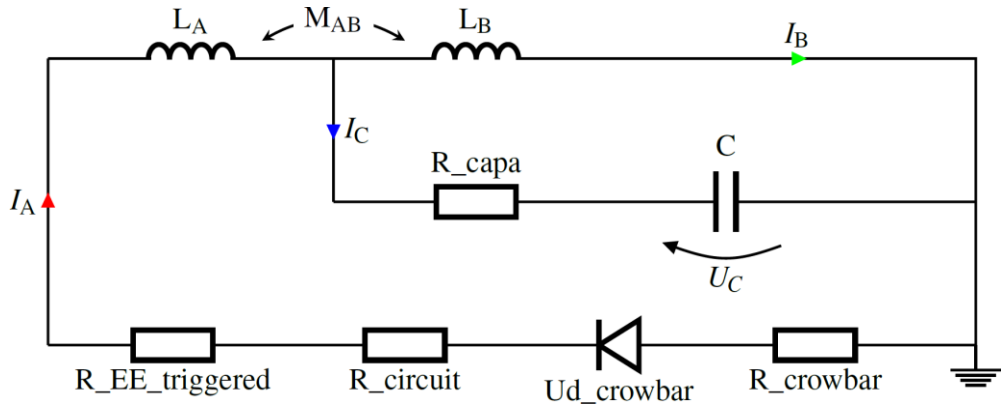
Tool to simulate electro-magnetic and thermal transients in superconducting magnets.

https://cern.ch/steam

- 2D magnet model + simplified electrical circuit
- Magnetic field maps and inductance dependence on iron yoke saturation calculated externally (usually with ROXIE)
- **Inter-filament and inter-strand coupling currents included**
- Turn-to-turn heat exchange, simplified helium cooling included
- Energy-extraction, quench heaters, CLIQ transients simulated
- Comes as a .exe file. A typical simulation runs in ~2 minutes.

Key feature for CLIQ simulations

Framework to simulate transient effects in superconducting magnets and circuits



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

Application and tutorial freely available!
→More info: https://cern.ch/steam/ledet

LEDET validation and current studies

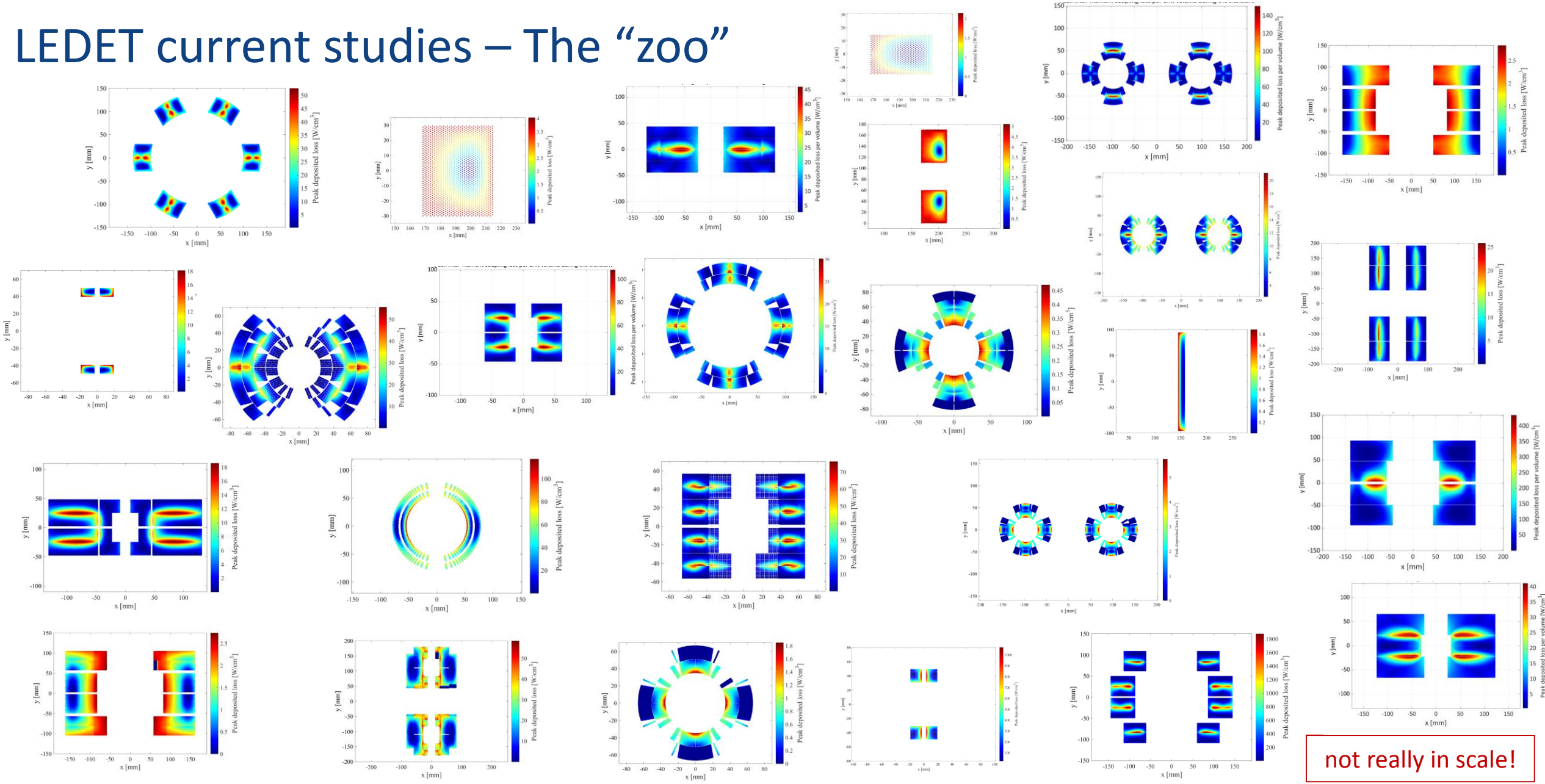
Project	Magnet	Notes	Validation
LHC	MQXA	Helium, Heaters	Partial
LHC	MQXB	Helium, Heaters	Partial
LHC	MQ	Helium, Heaters, initial hot-spot	Yes
LHC	MQY	Helium, Heaters, initial hot-spot	Started
LHC	MCBY	Helium, Self-protection	Started
HL-LHC	MQXF	Quench protection design	Yes
HL-LHC	11 T dipole		Yes
FCC	Cos-θ	Quench protection design	No data available
FCC	Block-coil	Quench protection design	No data available
FCC	Common-coil	Quench protection design	No data available

Project	Magnet	Notes	Validation
Other	FECR sextupole	Sextupole	No data available
Other	FECR solenoids	Solenoids	No data available
Other	**eRMC / RMM**		**No data available**
Other	HEPdipo	Block-coil	No data available
Other	HD3	Block-coil	No data available
Other	16T common-coil	Insert/Outsert	No data available
Other	PYPUP magnets	Bi-2212, Solenoids	No data available
Other	RC series	Bi-2212, Current-sharing	Partial
Other	LBL common-coil	Bi-2212, Current-sharing	No data available
Other	15 T dipole		No data available
Other	***	New quench protection ideas	No data available

LEDET was used to simulate transients in more than 25 magnets with different superconductor types, geometries, quench protection systems

At MT26:
Mon-Mo-Po1.03-07
Mon-Af-Po1.16-04
Thu-Mo-Po4.02-03
Wed-Af-Or13-03

LEDET current studies – The “zoo”



not really in scale!

LEDET simulations workflow

Magnetic model (ROXIE)

Semi-automatic model generation

Input file is an excel file + .exe file

Simulations are run in a batch

Output as txt files, figures, animated GIFs, pdf report,…

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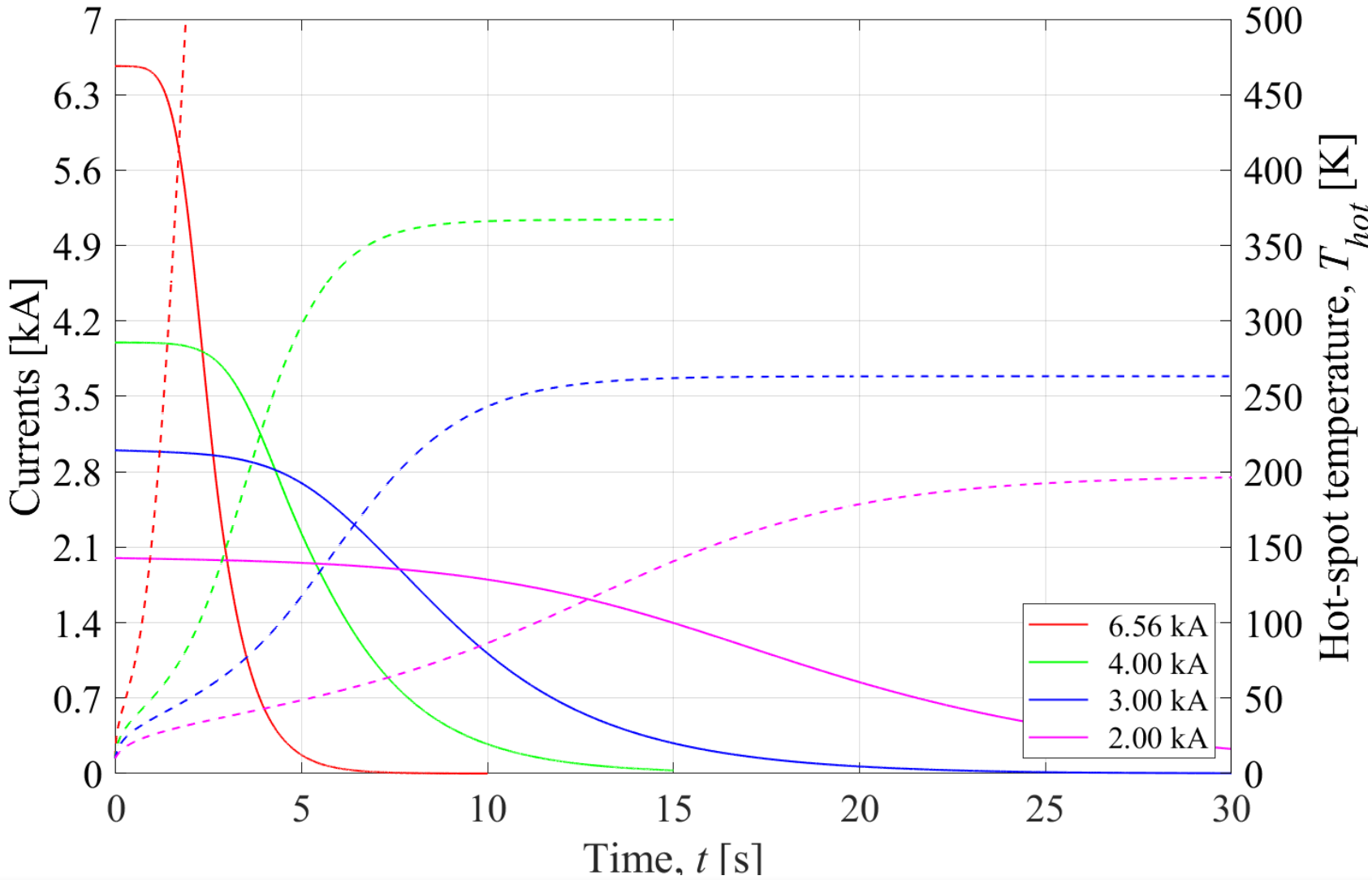
Modelling with STEAM-LEDET

eRMC magnet quench protection

RMM magnet quench protection

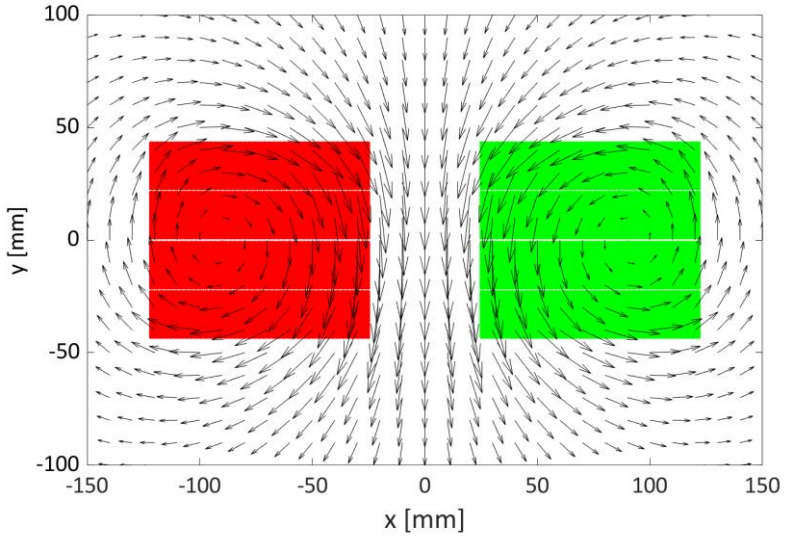
eRMC – Self-protectability



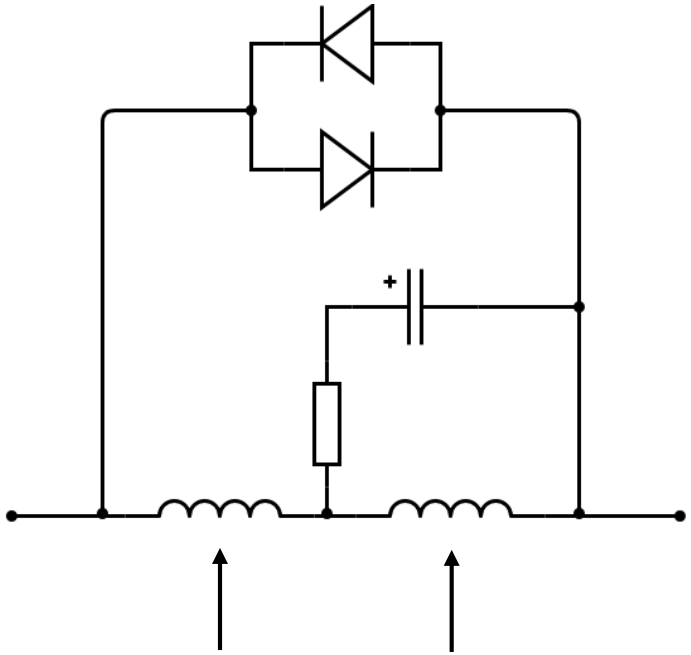
Magnet self-protected for currents ≤3 kA
Assumed v_Q=2.5 m/s

Above ~20% of nominal current, **active protection is needed**

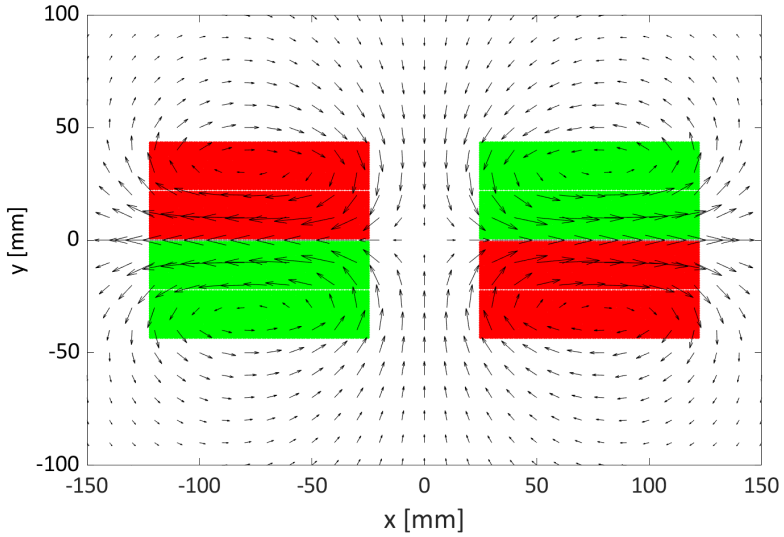
eRMC – CLIQ connection scheme (per aperture)



Normal operation DC
current polarities and magnetic field

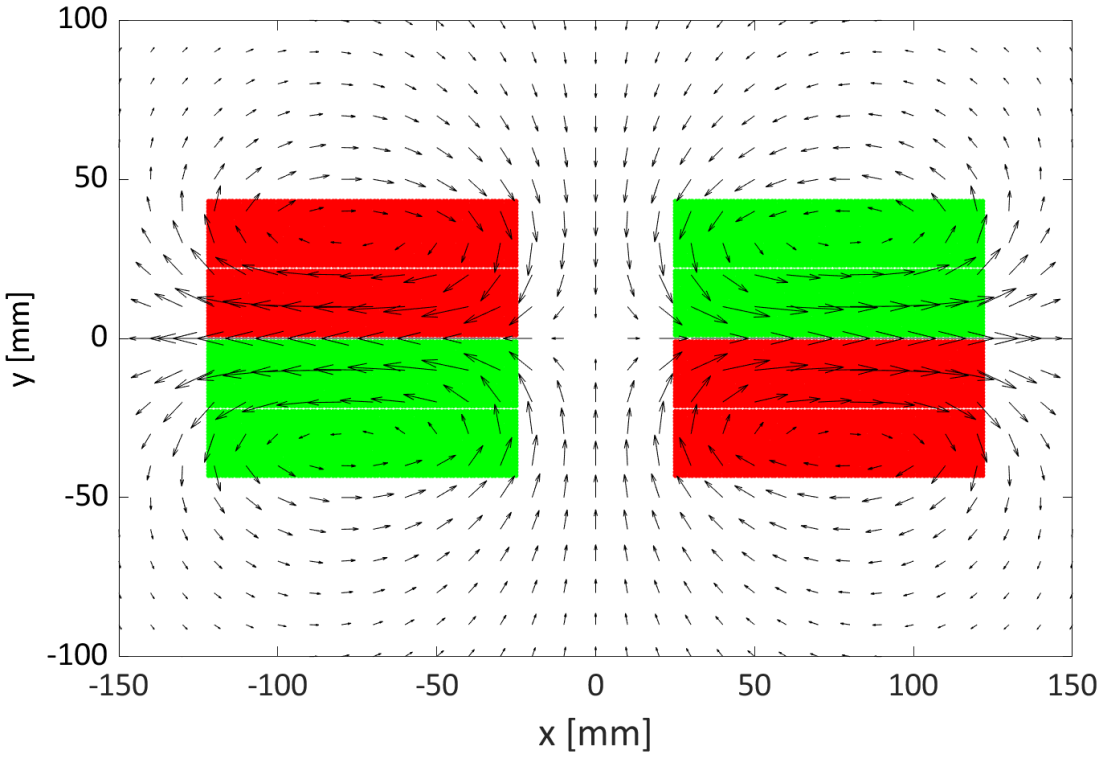


Simplified CLIQ circuit

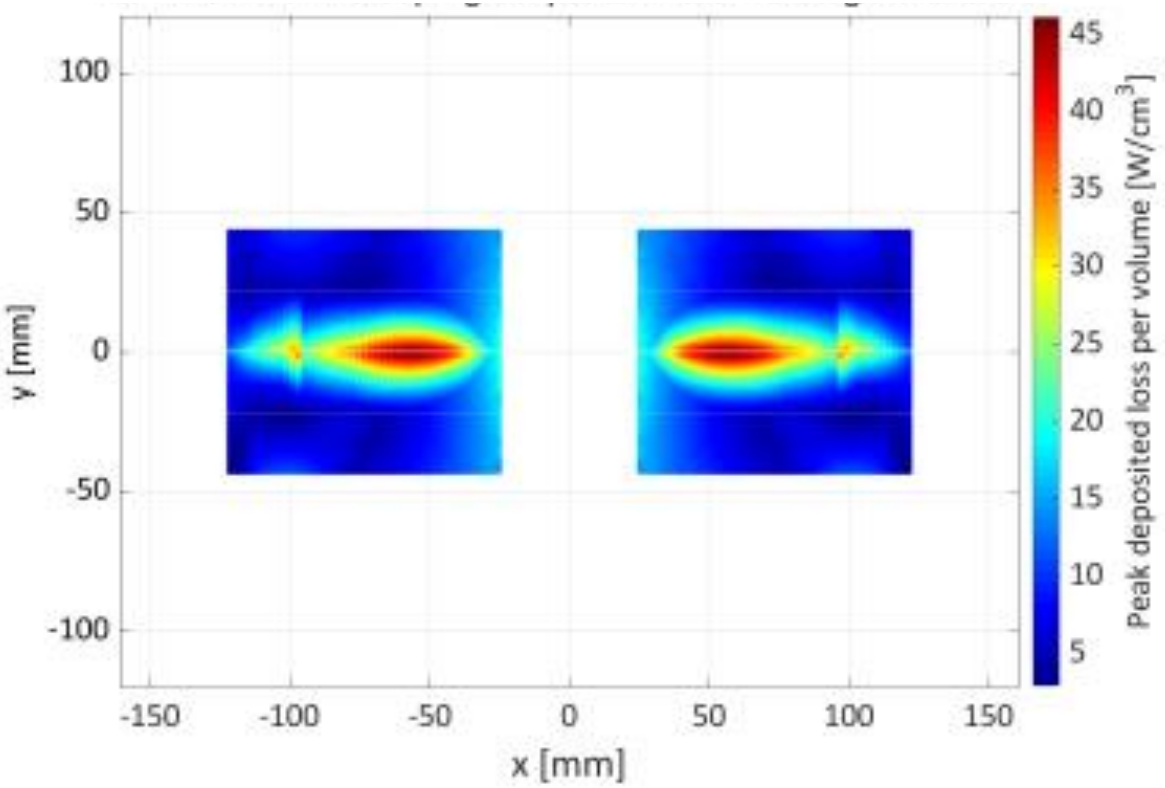


CLIQ-induced oscillating
current polarities and magnetic field

eRMC – Generation of inter-filament coupling loss

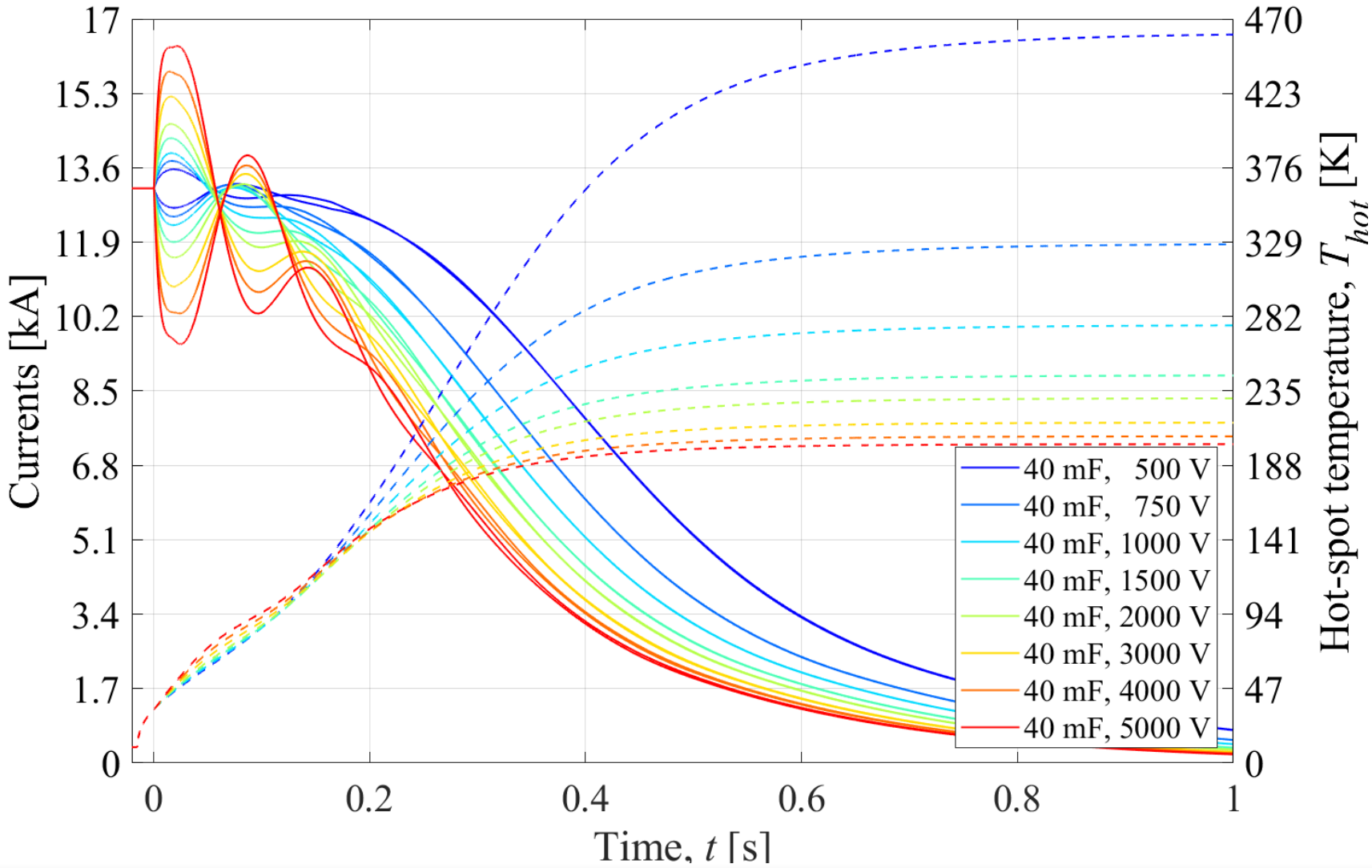


Oscillating current polarities and **magnetic field**



Peak inter-filament coupling loss (**heat**)

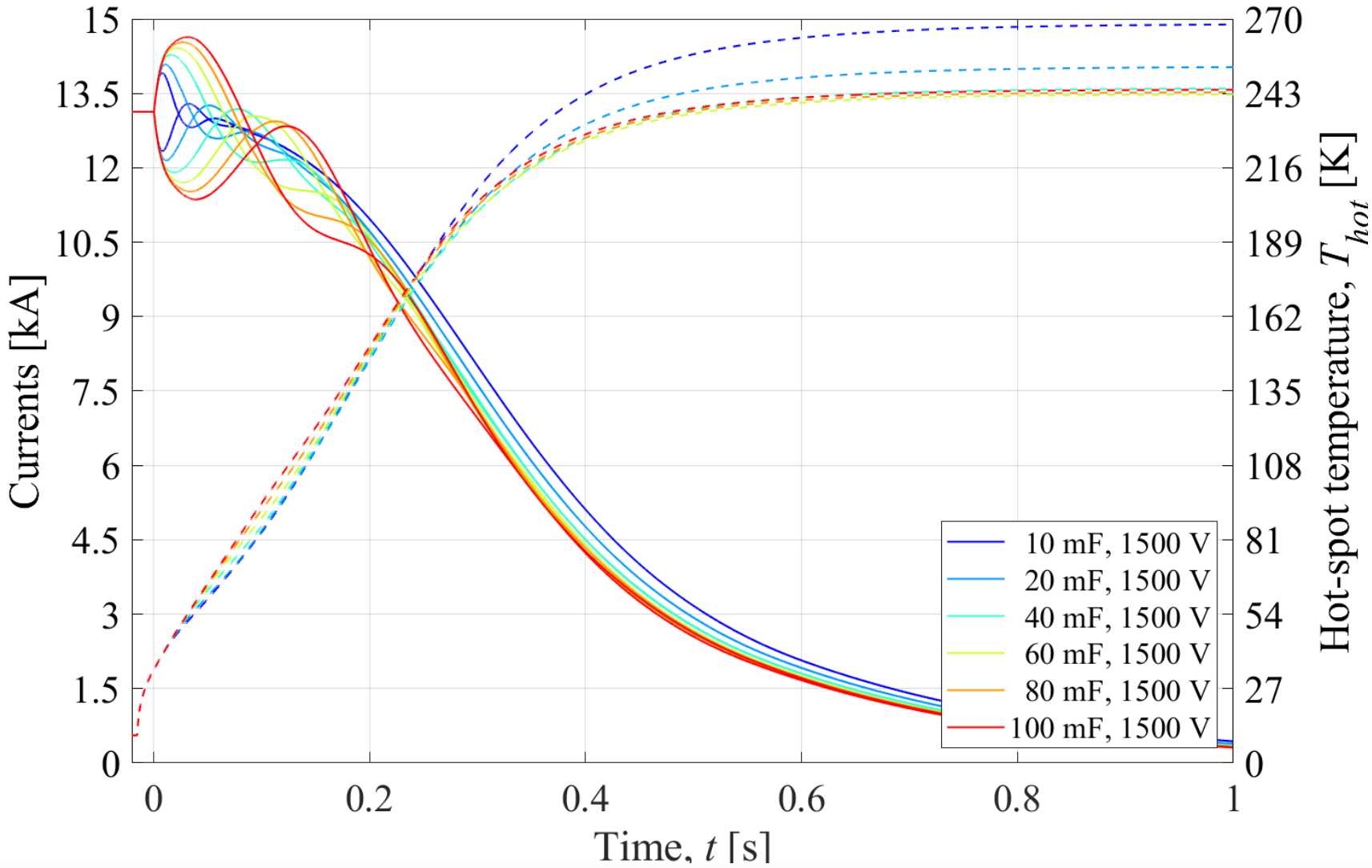
eRMC – Quench protection at I_{nom} – Effect of CLIQ voltage U_0



In first approximation:

Peak current	$\propto U_0$
Current rate	$\propto U_0$
Power	$\propto U_0^2$
Energy	$\propto U_0^2$
Frequency	~

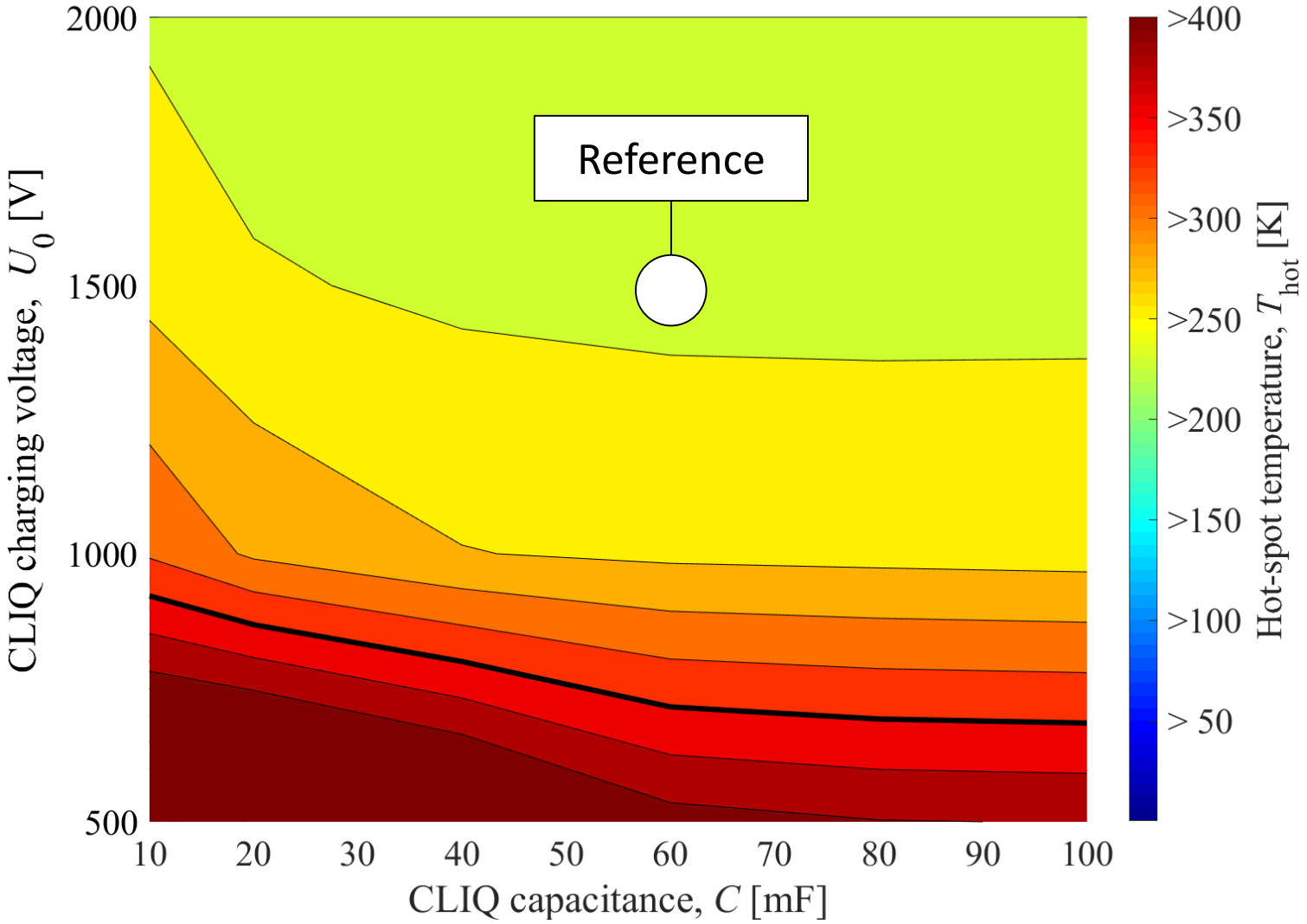
eRMC – Quench protection at I_{nom} – Effect of CLIQ capacitance **C**



In first approximation:

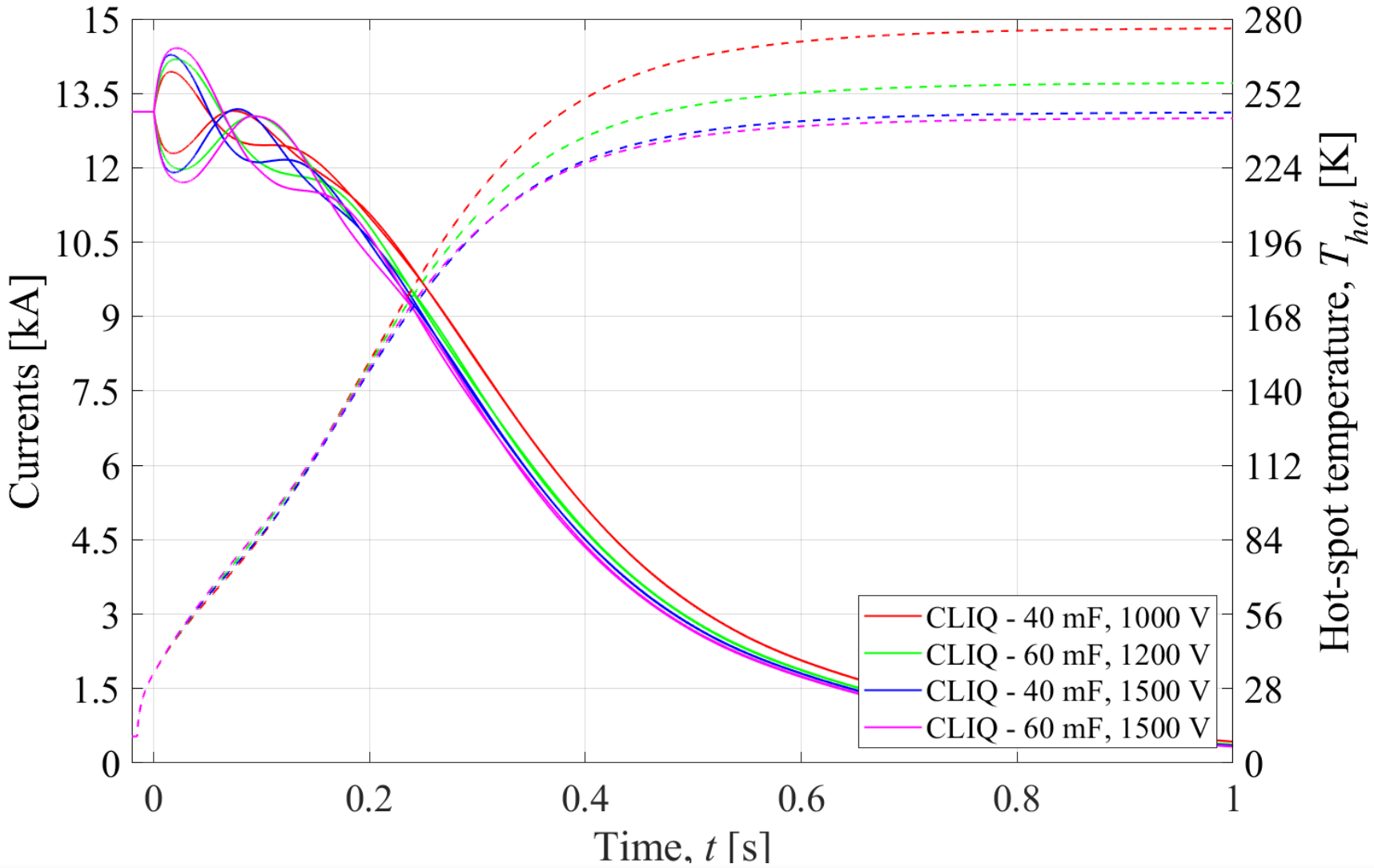
Peak current	$\propto C^{0.5}$
Current rate	~
Power	~
Energy	$\propto C$
Frequency	$\propto 1/C^{0.5}$

eRMC – Quench protection at I_{nom} – Effect of U_0 and C



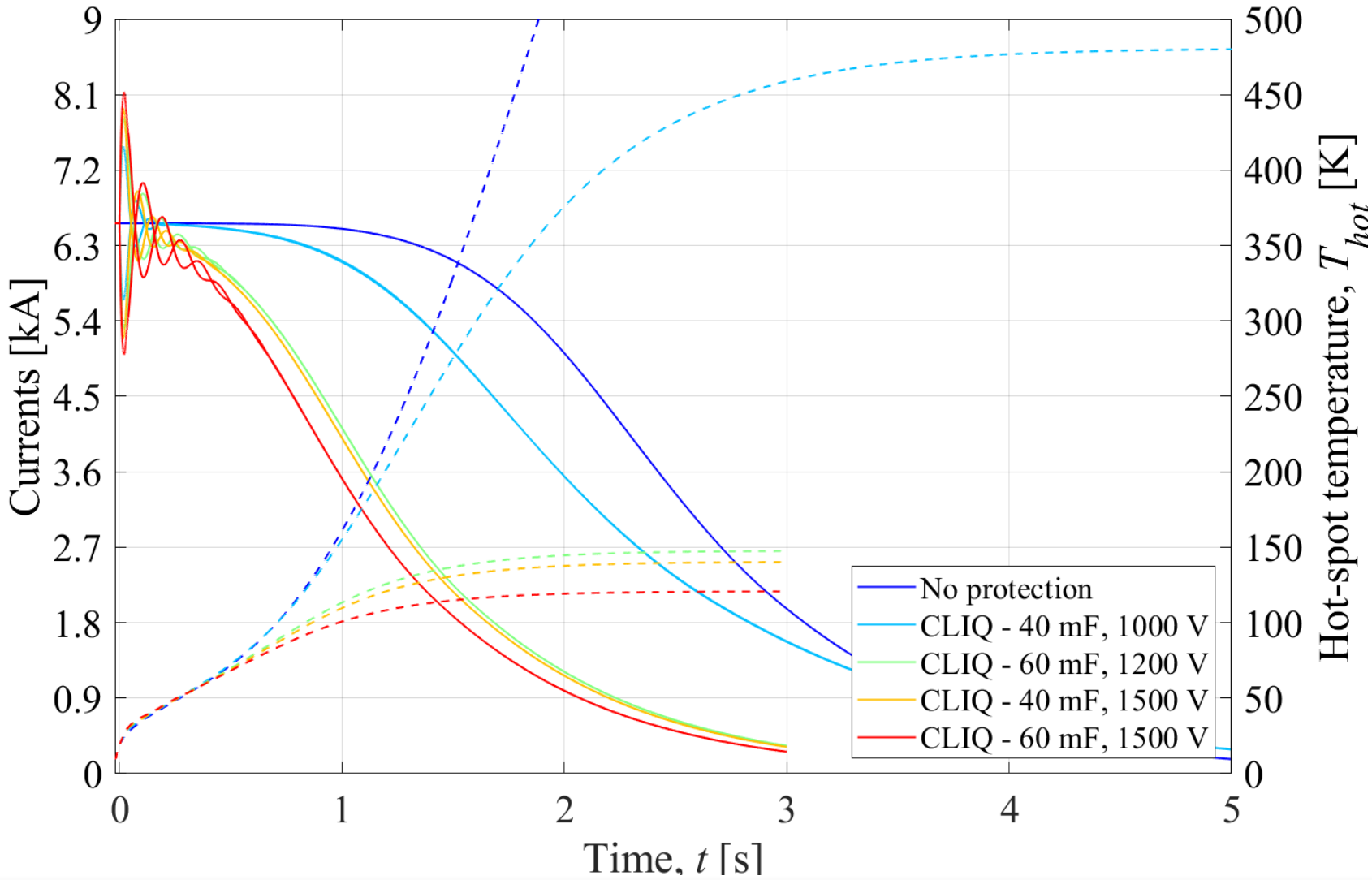
Selected configuration
C=60 mF U_0=1.5 kV

eRMC – Quench protection at $I=I_{nom}=13.13$ kA



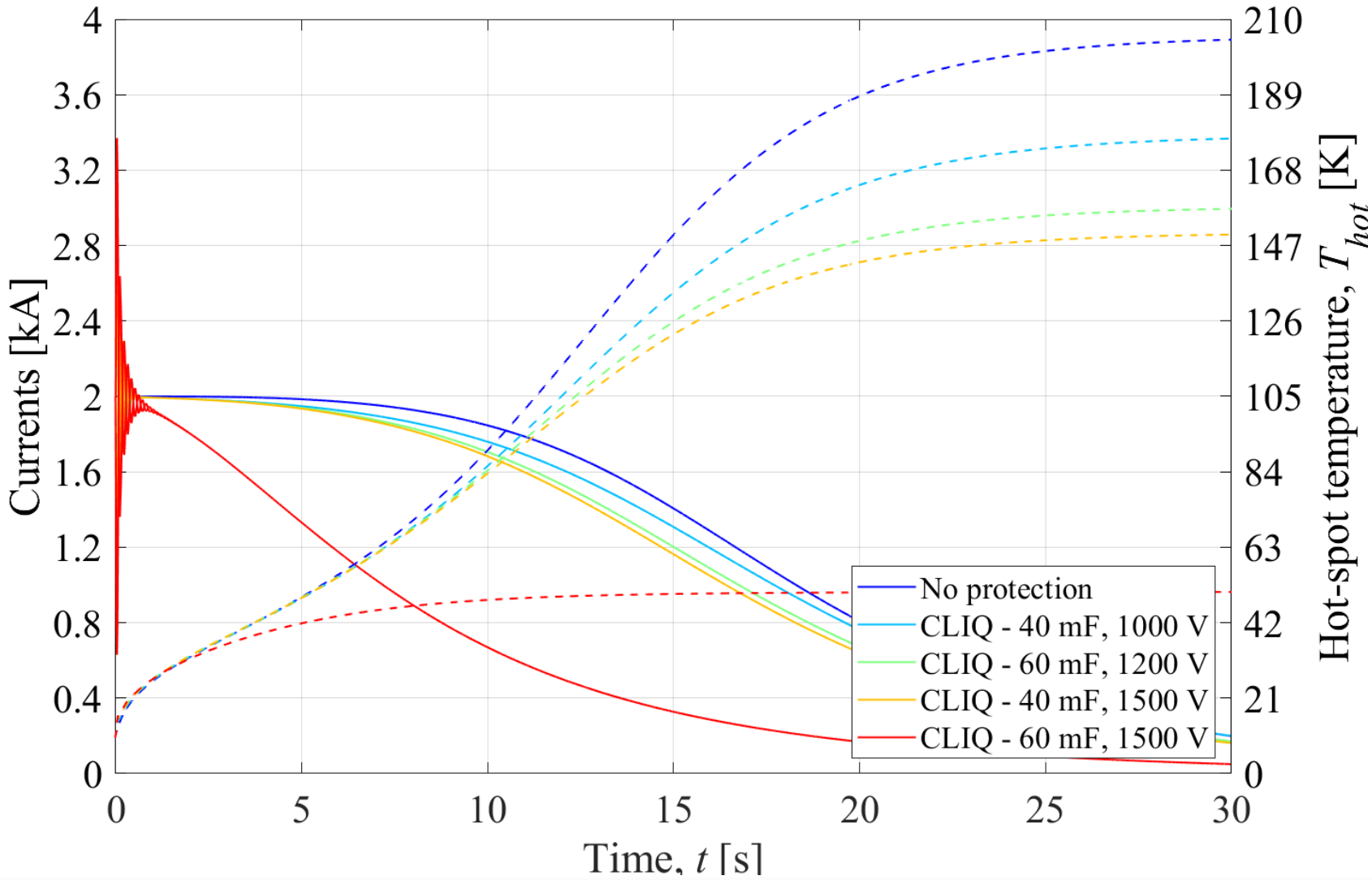
At nominal current, hot-spot temperature maintained in a comfortable range of **250 to 300 K**

eRMC – Quench protection at I=50% I_{nom}=6.56 kA



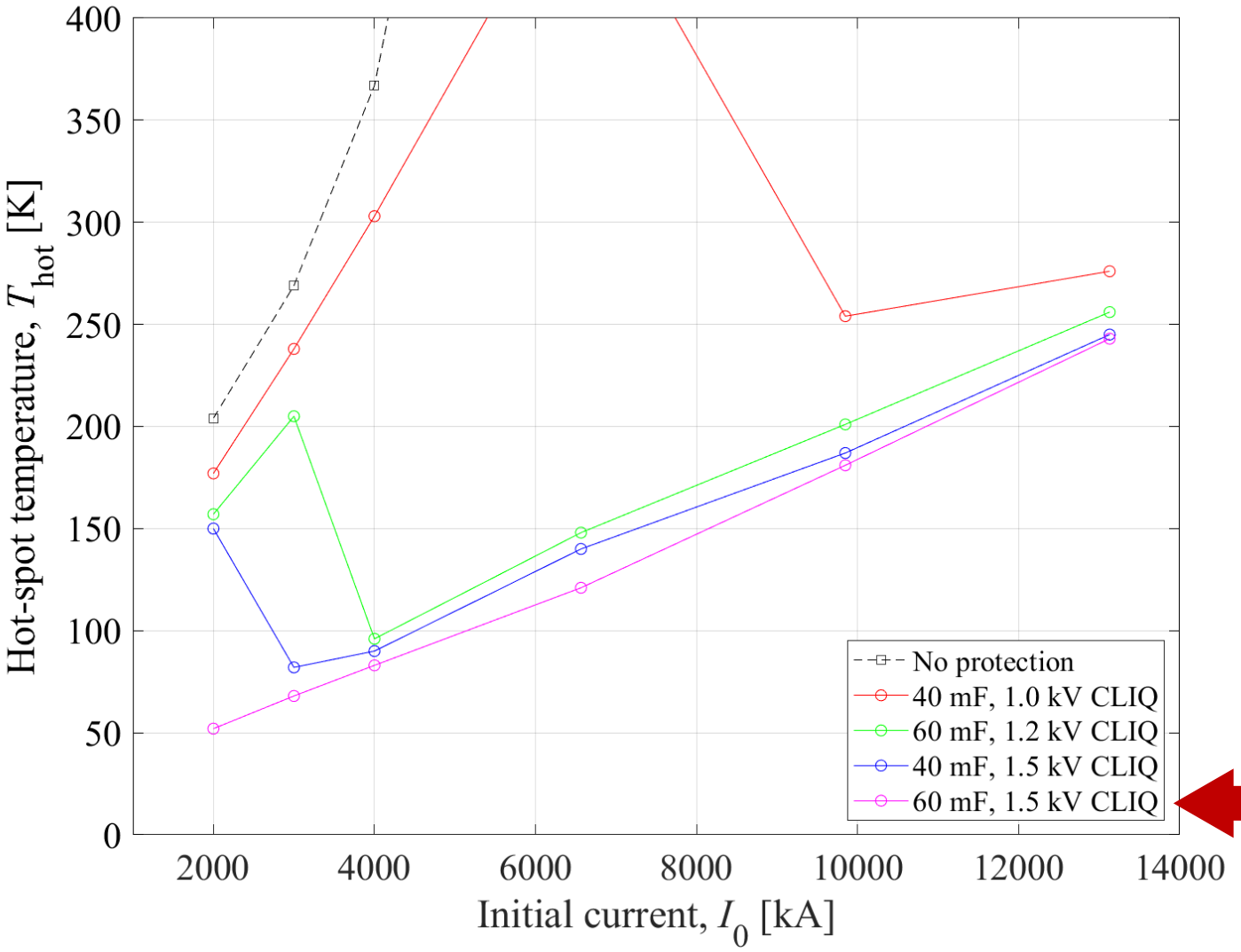
At mid-range current, **sufficient energy to quench** large coil sections must be provided (**C↑**)

eRMC – Quench protection at I=2 kA



At low current,
even more energy
must be provided (**C↑**)

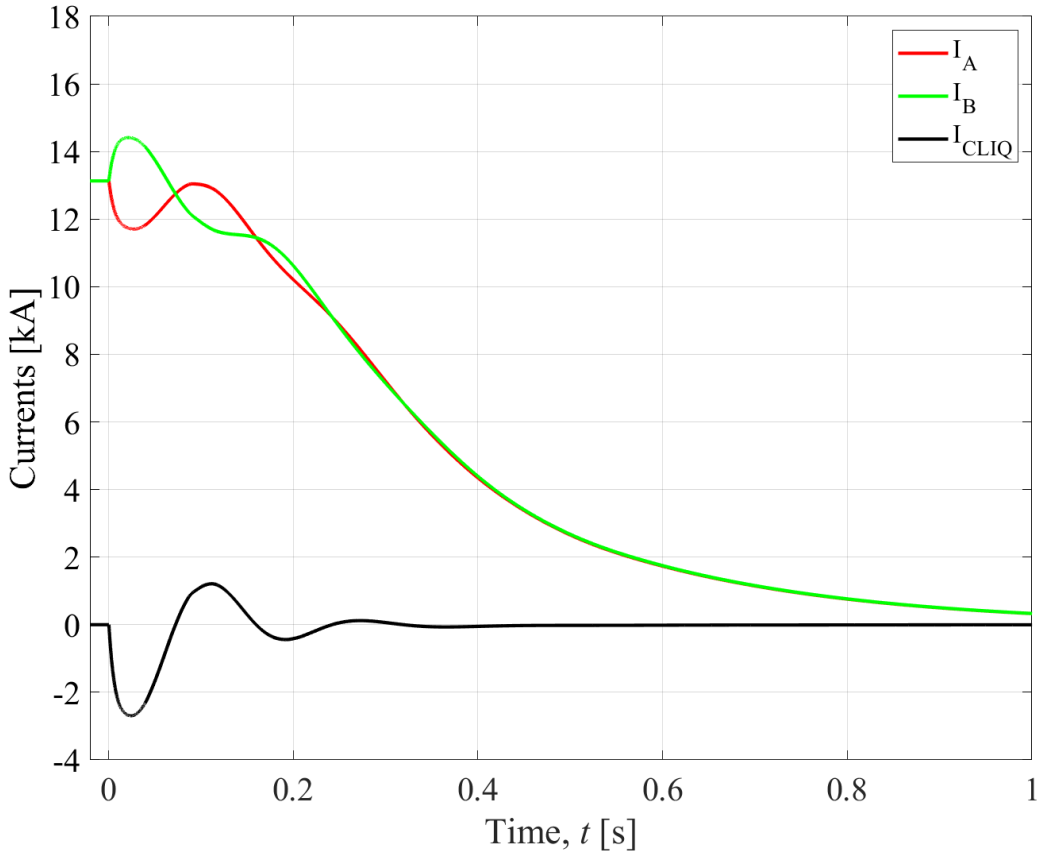
eRMC – Quench protection summary



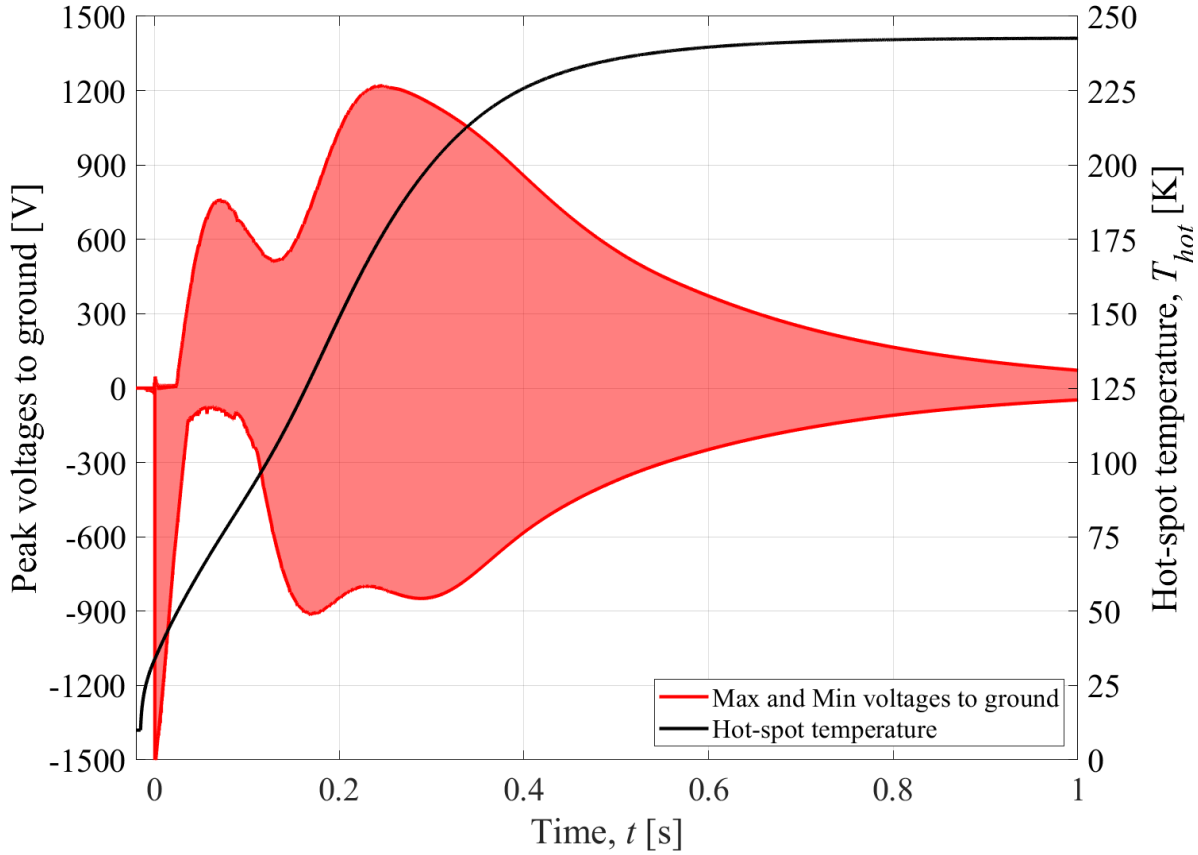
Selected configuration
C=60 mF U_0=1.5 kV

Induces quench
at all current levels

eRMC – Quench protection at I_{nom} – Reference quench protection

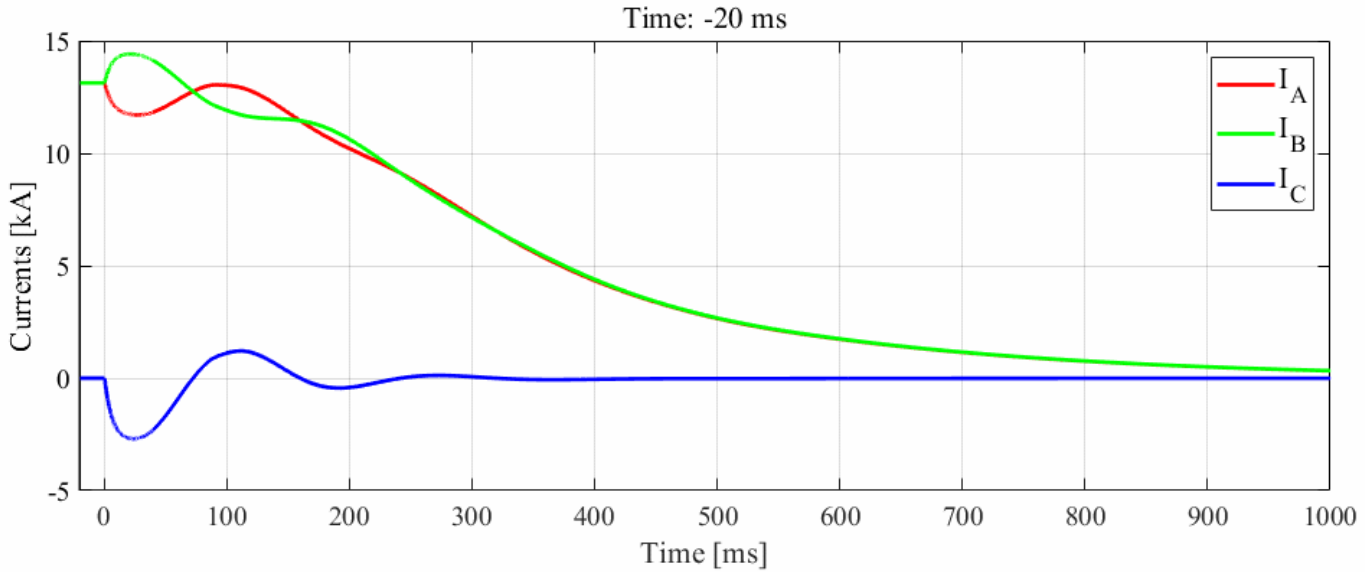


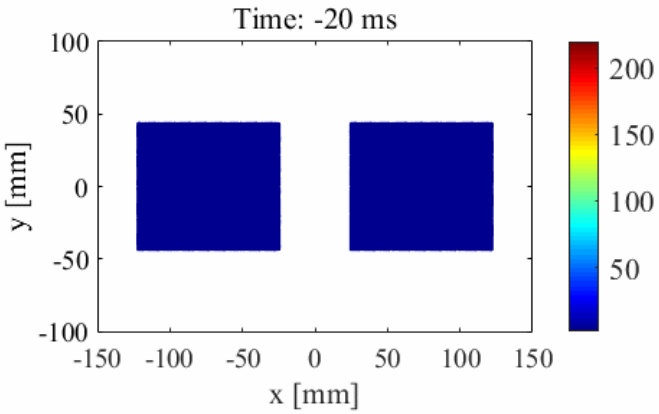
Currents in the system

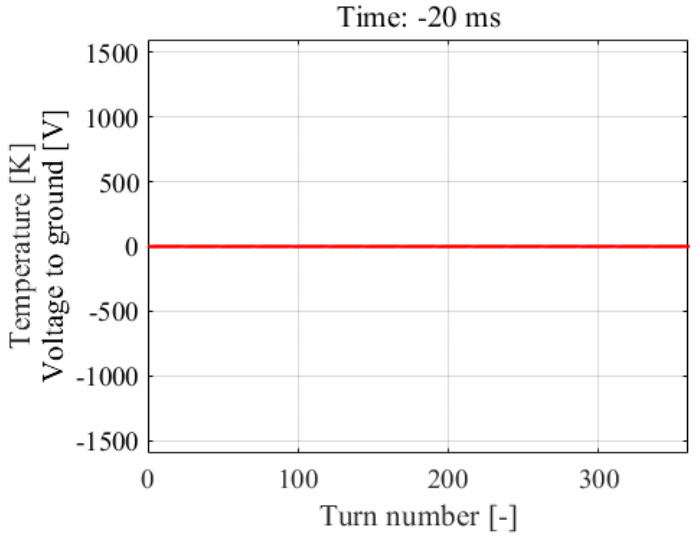


Voltage to ground distribution and hot-spot temperature

eRMC – Quench protection at I_{nom} – Reference quench protection







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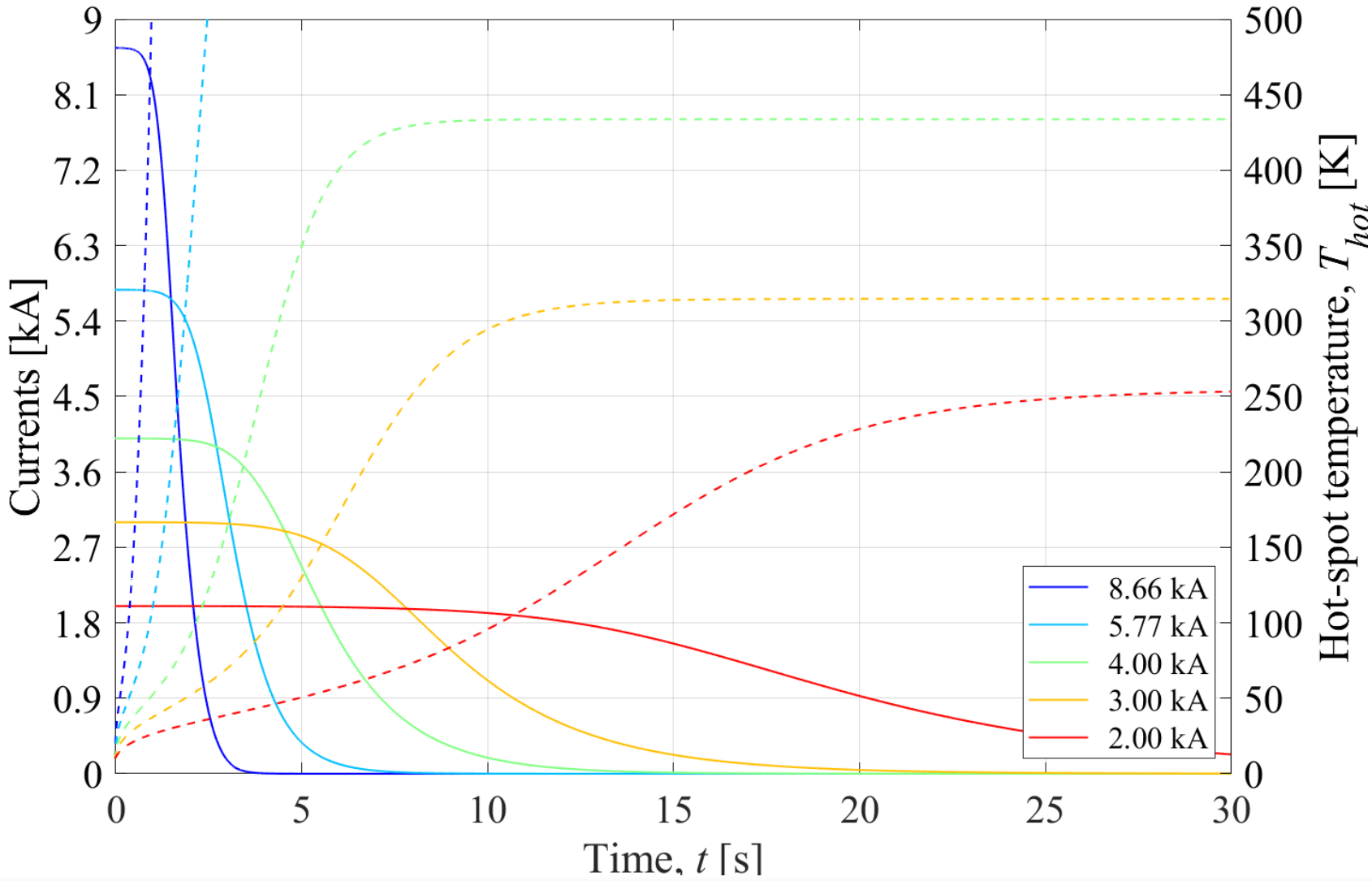
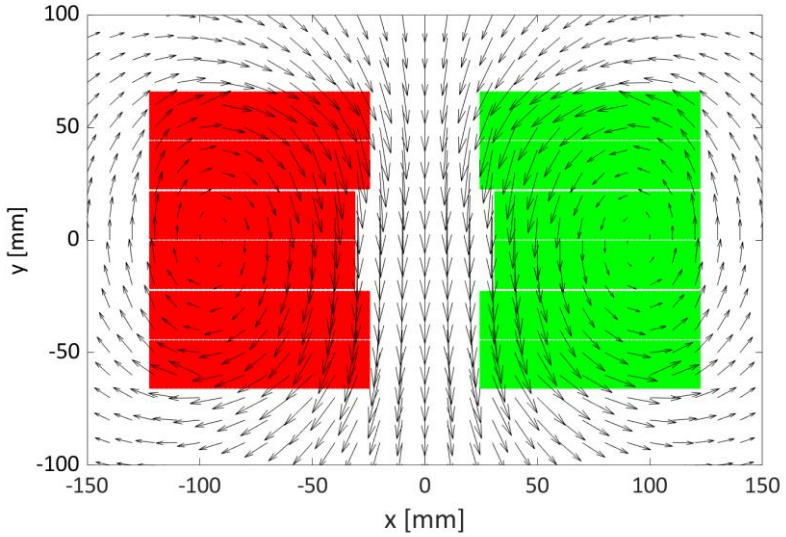
RMM – Self-protectability

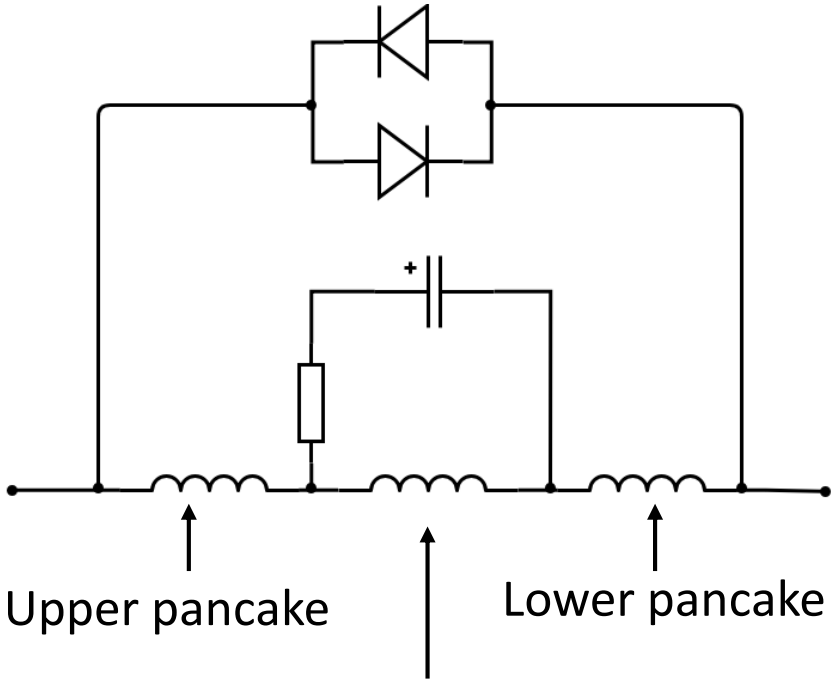


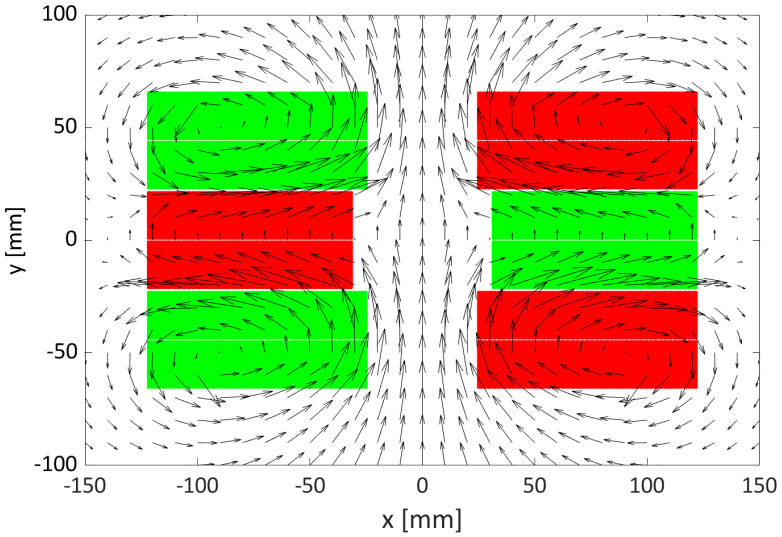
Magnet self-protected for currents ≤3 kA
Assumed v_Q=2.5 m/s

Above ~20% of nominal current, **active protection is needed**

RMM – CLIQ connection scheme (per aperture)





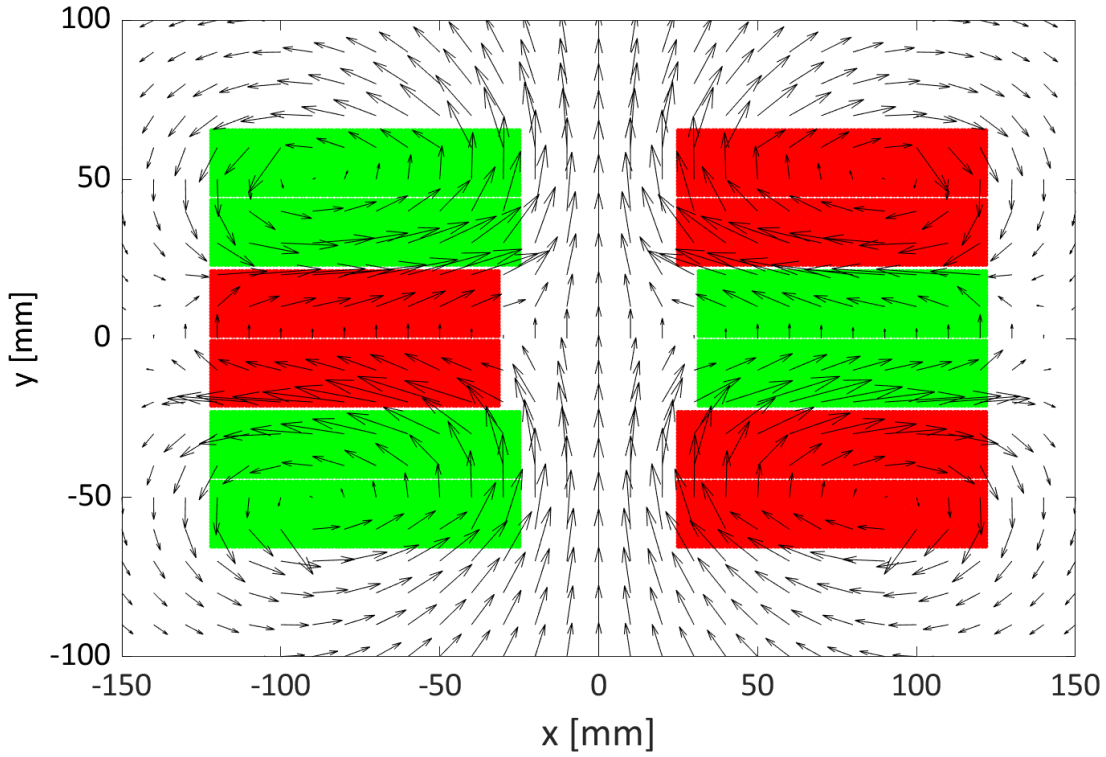


Normal operation DC
current polarities and magnetic field

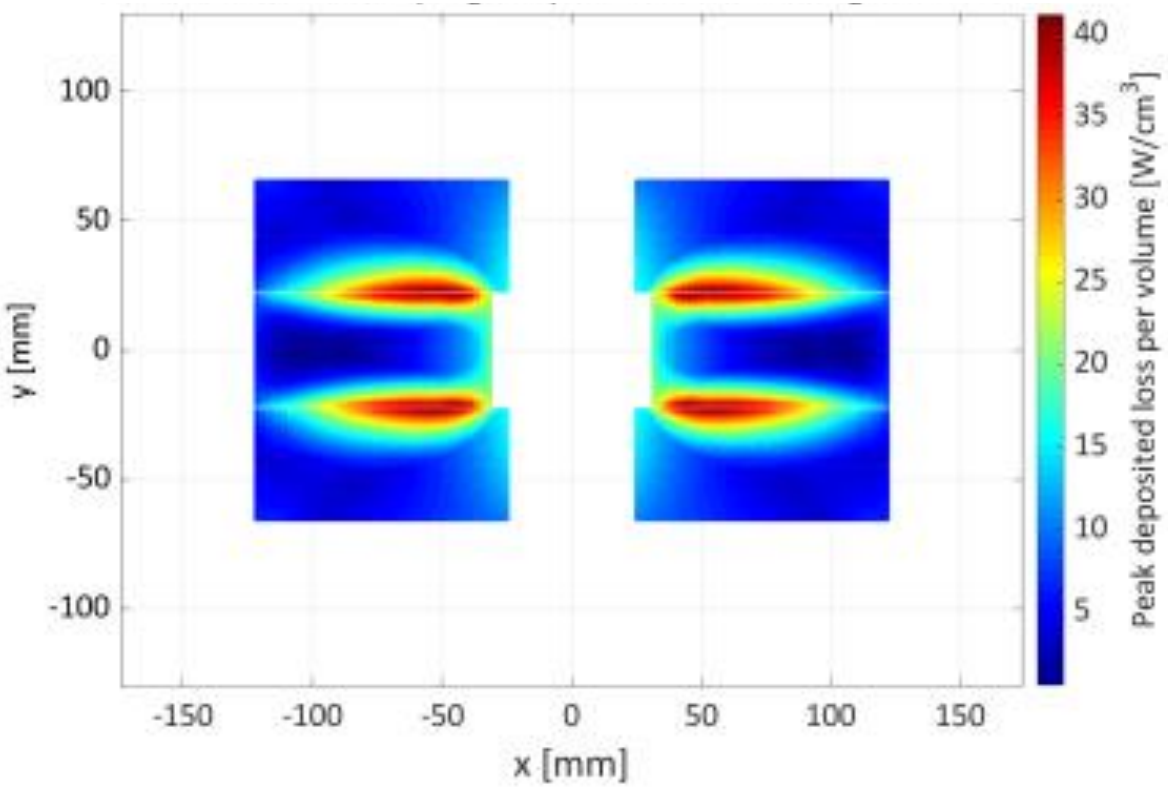
Simplified CLIQ circuit

CLIQ-induced oscillating
current polarities and magnetic field

RMM – Generation of inter-filament coupling loss

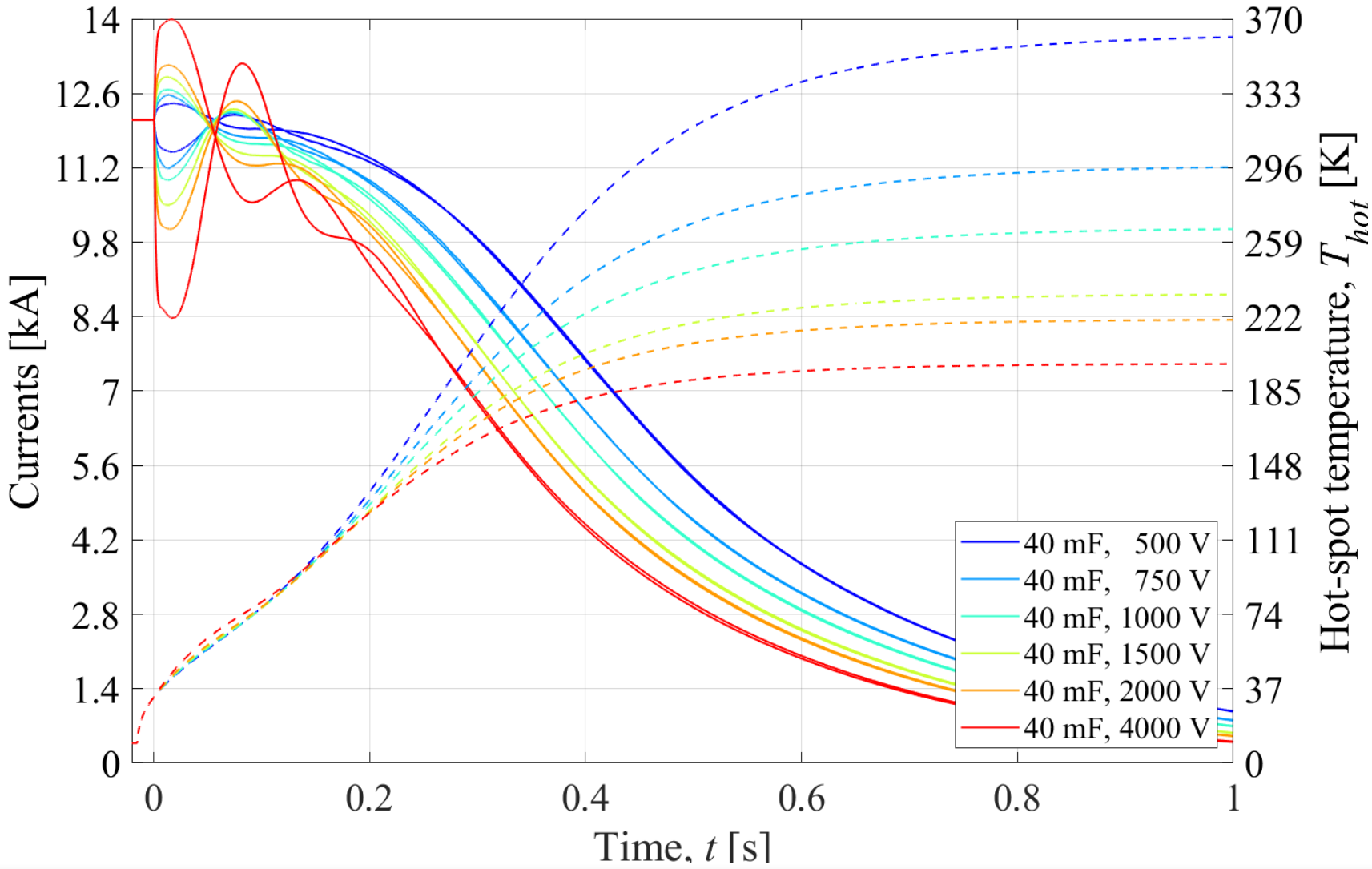


Oscillating current polarities and **magnetic field**



Peak inter-filament coupling loss (**heat**)

RMM – Quench protection at I_{nom} – Effect of CLIQ voltage U_0



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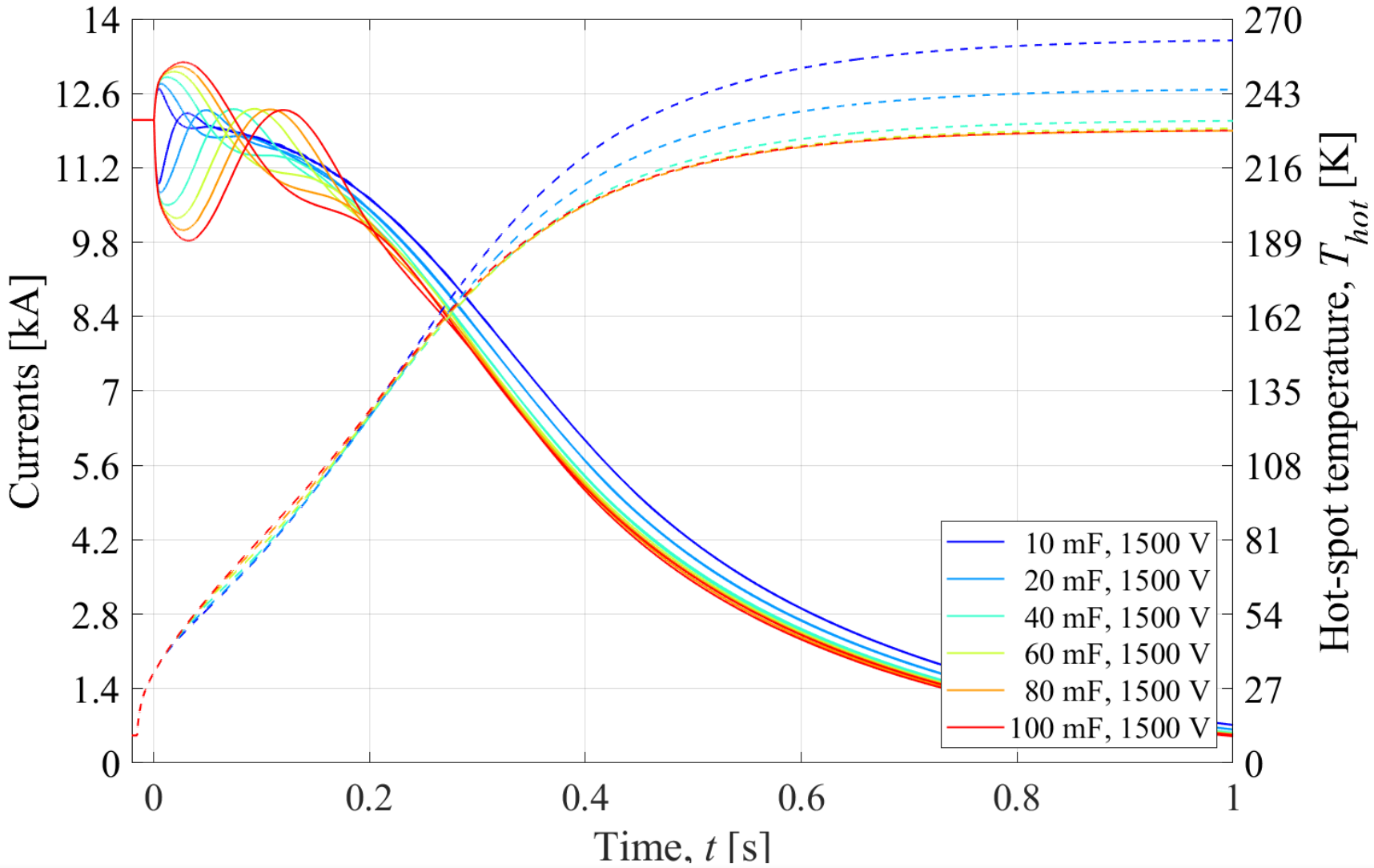
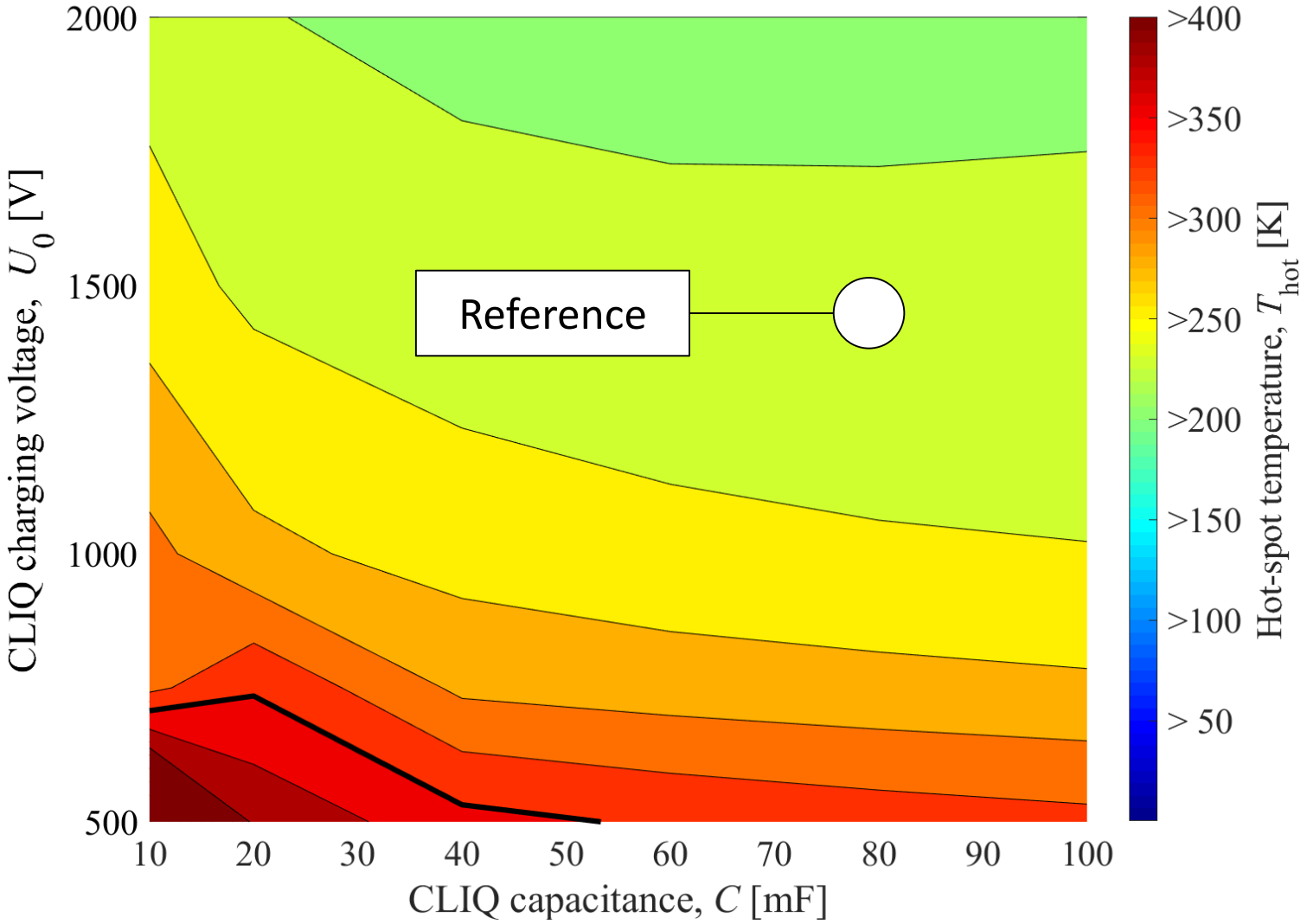


In first approximation:

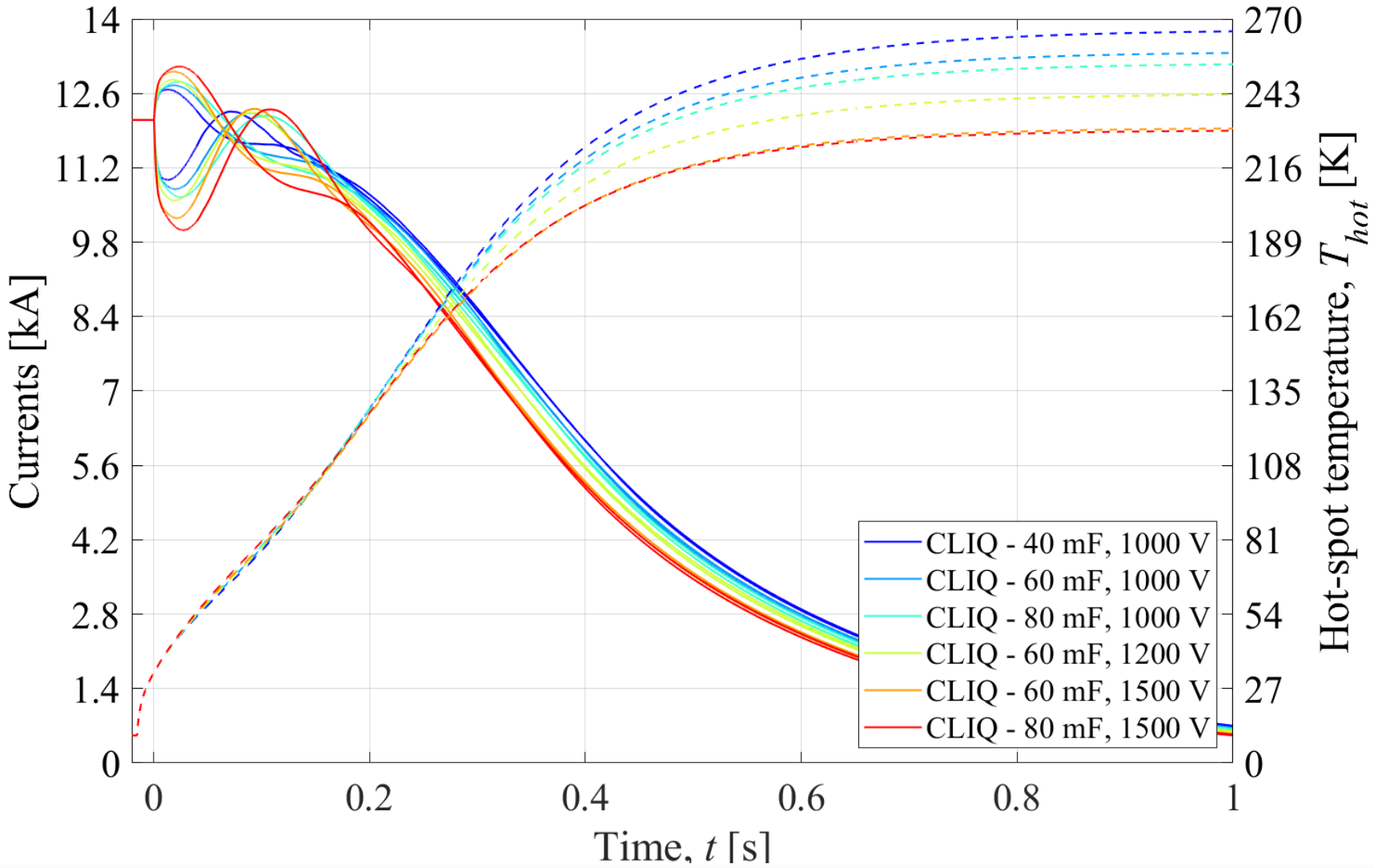
Peak current	$\propto C^{0.5}$
Current rate	~
Power	~
Energy	$\propto C$
Frequency	$\propto 1/C^{0.5}$

RMM – Quench protection at I_{nom} – Effect of U_0 and C



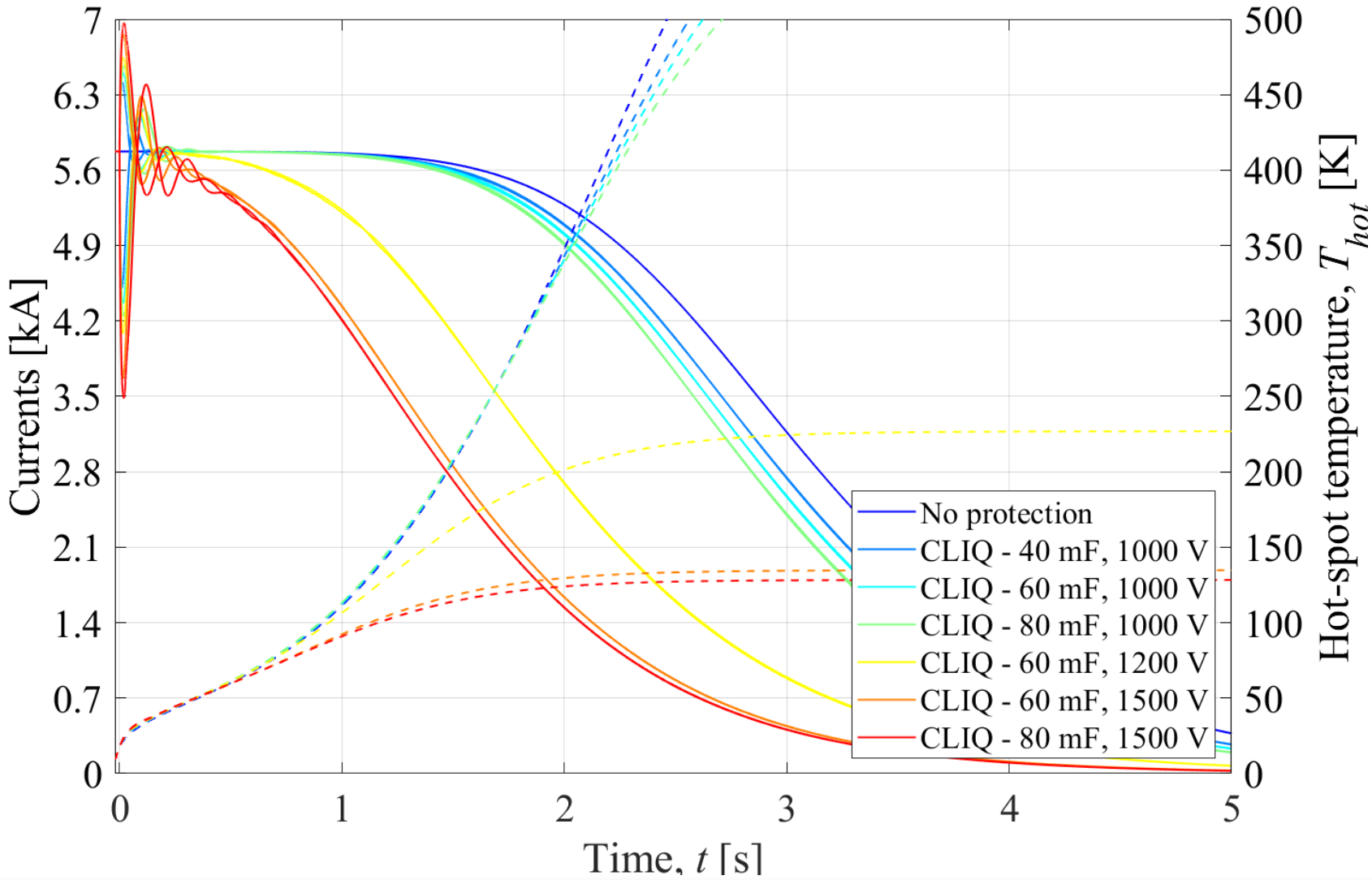
Selected configuration
C=80 mF U_0=1.5 kV

RMM – Quench protection at $I=I_{nom}=12.1$ kA



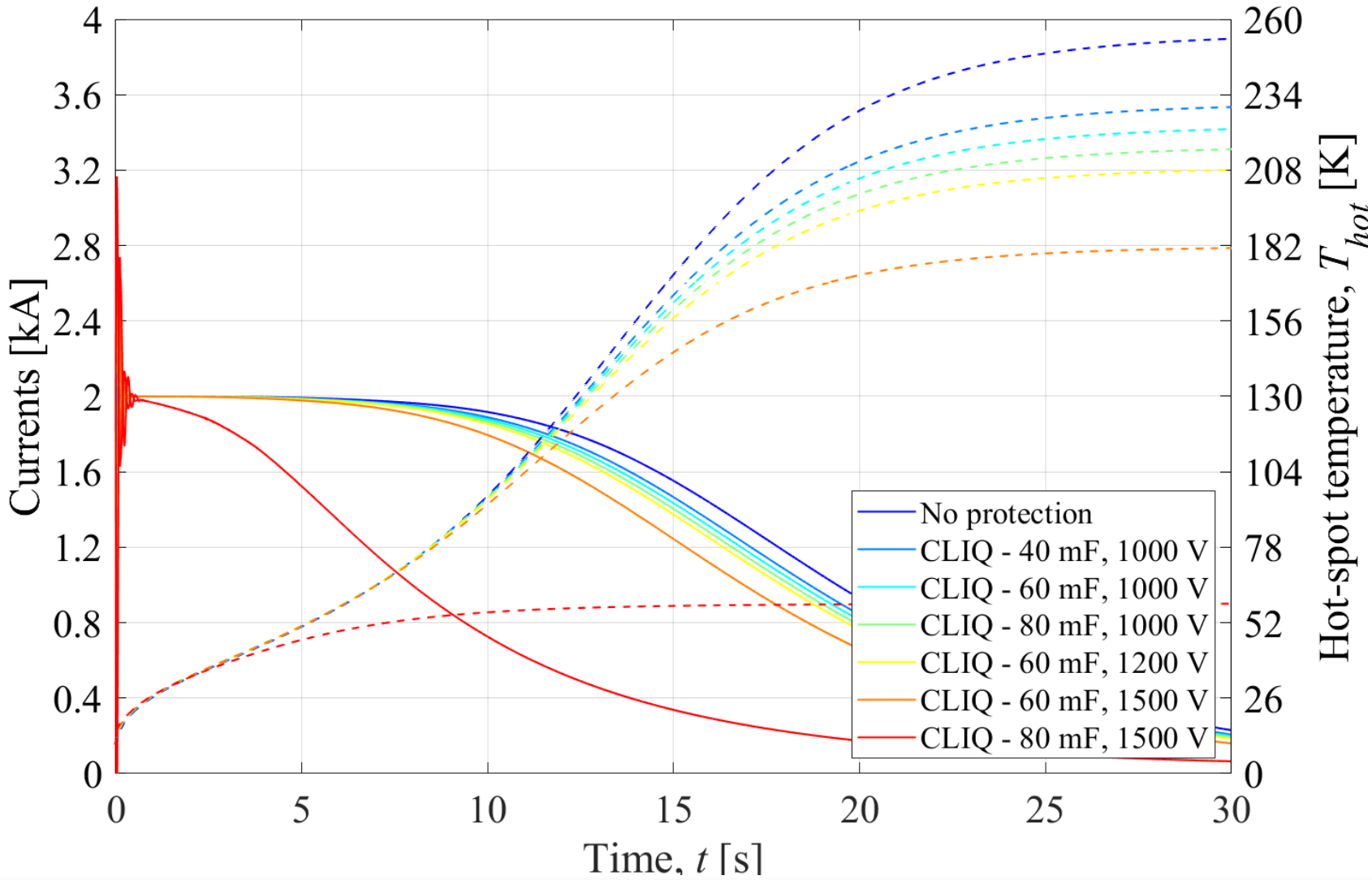
At nominal current, hot-spot temperature maintained in a comfortable range of **250 to 300 K**

RMM – Quench protection at I=50% I_{nom}=5.77 kA



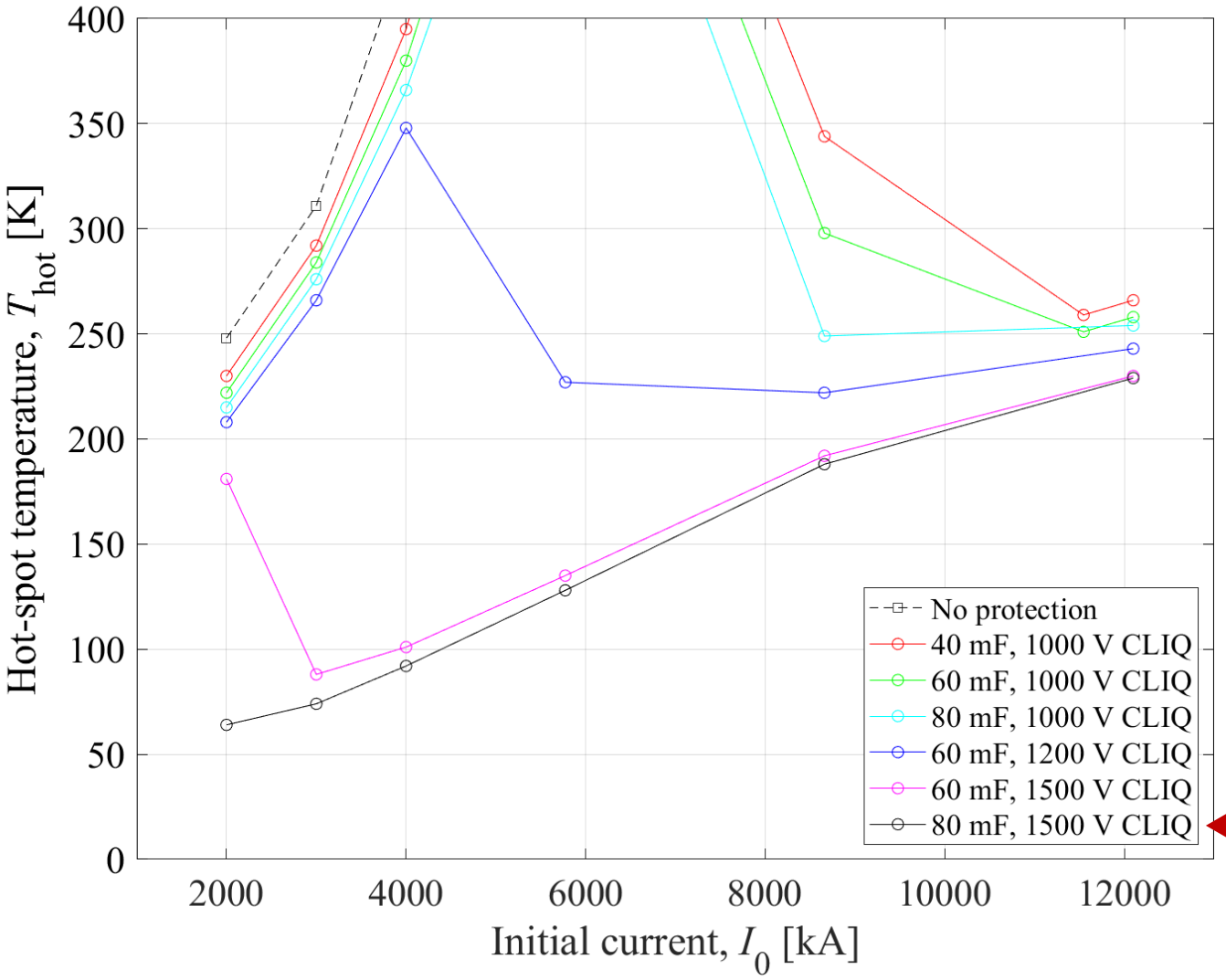
At mid-range current, **sufficient energy to quench** large coil sections must be provided (**C↑**)

RMM – Quench protection at I=2 kA



At low current,
even more energy
must be provided (**C↑**)

RMM – Quench protection summary



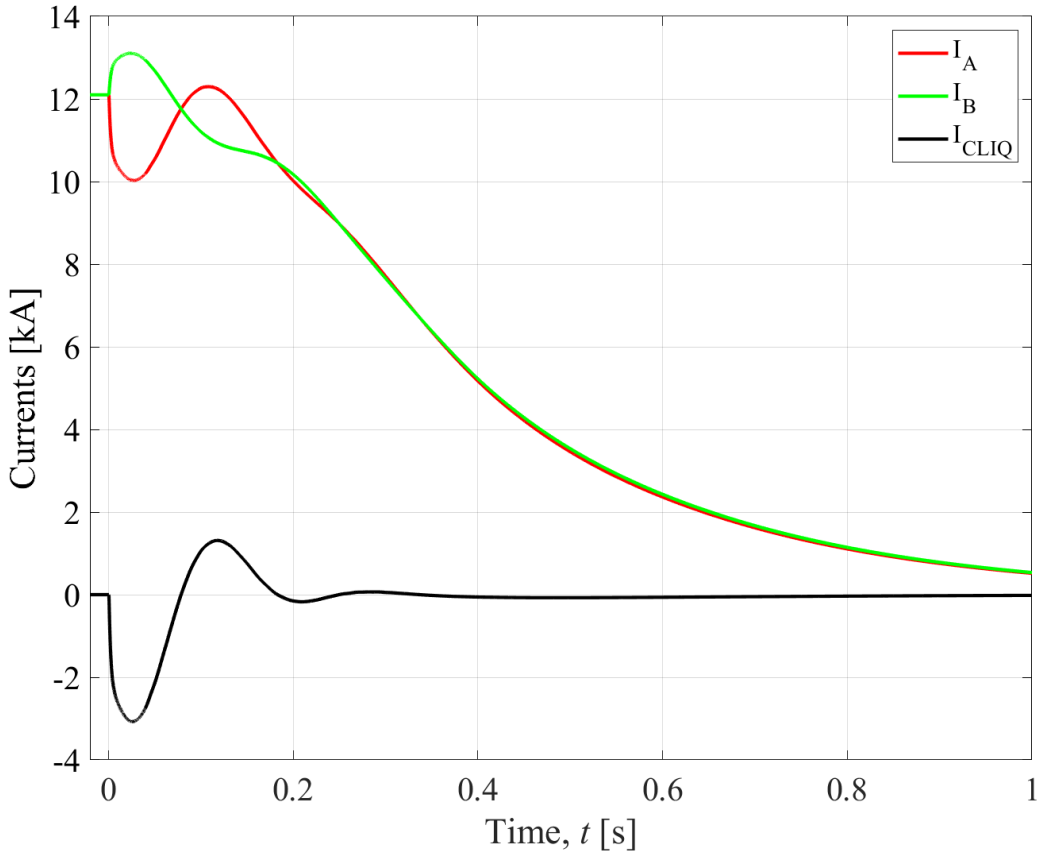
Selected configuration

C=80 mF U_0=1.5 kV

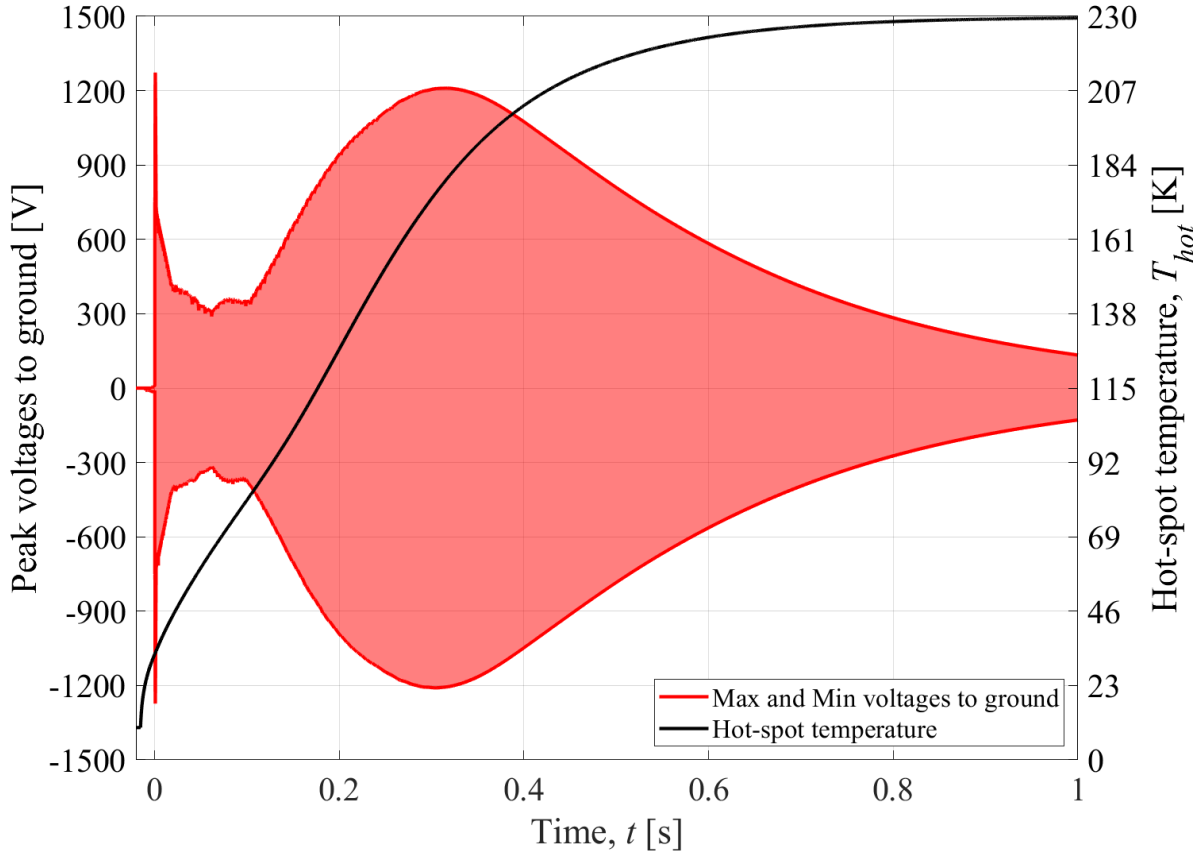
Induces quench

at all current levels

RMM – Quench protection at I_{nom} – Reference

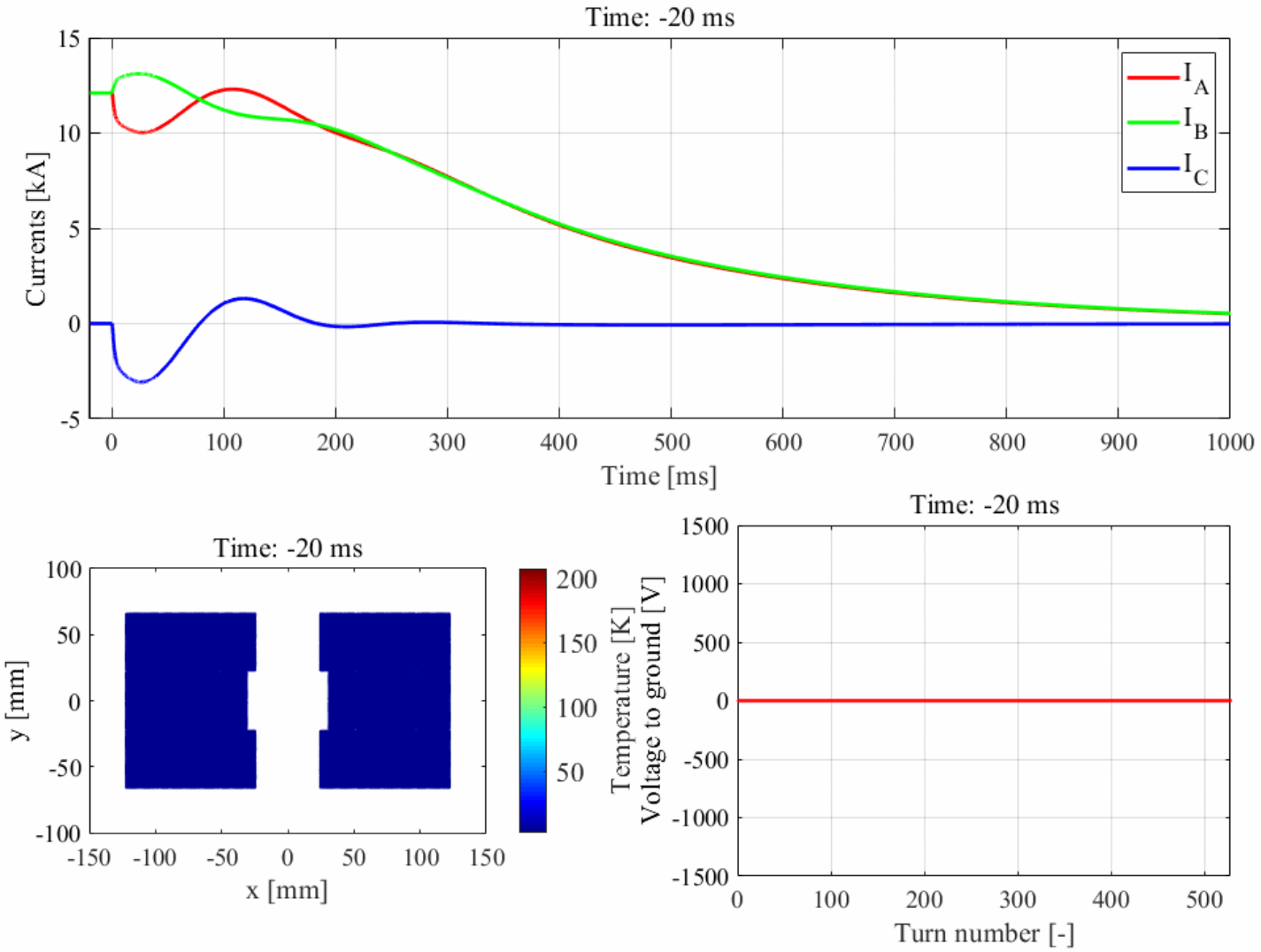


Currents in the system



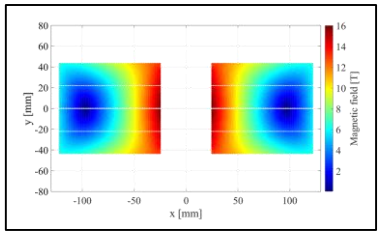
Voltage to ground distribution and hot-spot temperature

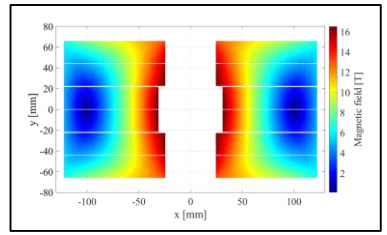
RMM – Quench protection at I_{nom} – Reference

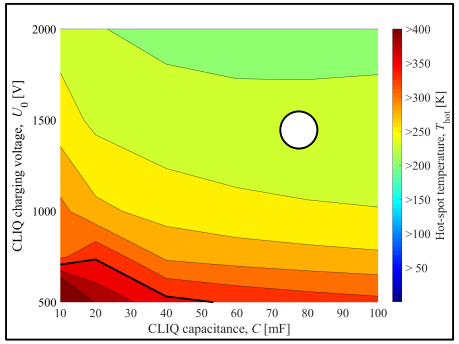


Conclusion

Quench protection of two **16 T Nb_3Sn** dipole magnets analyzed
→ All simulations performed with **STEAM-LEDET**

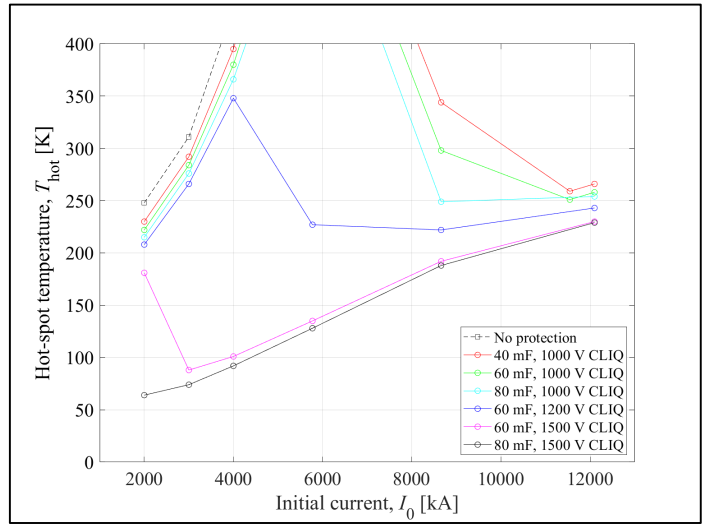






Proposed solution is based on **CLIQ** (Coupling-Loss Induced Quench)
→ CLIQ **connection optimized** for both magnets
→ CLIQ **unit capacitance** and **charging voltage** selected for both magnets
→ Solution will be **tested** in the coming month on a short magnet

With the proposed quench protection system
→ Hot-spot temperature **<250 K** at nominal current
→ Peak voltage to ground **<1500 V** at nominal current
→ Magnets protected **at all current levels**, with margin



Don't forget to analyze the mid-current range!...

https://cern.ch/steam

QUESTIONS?

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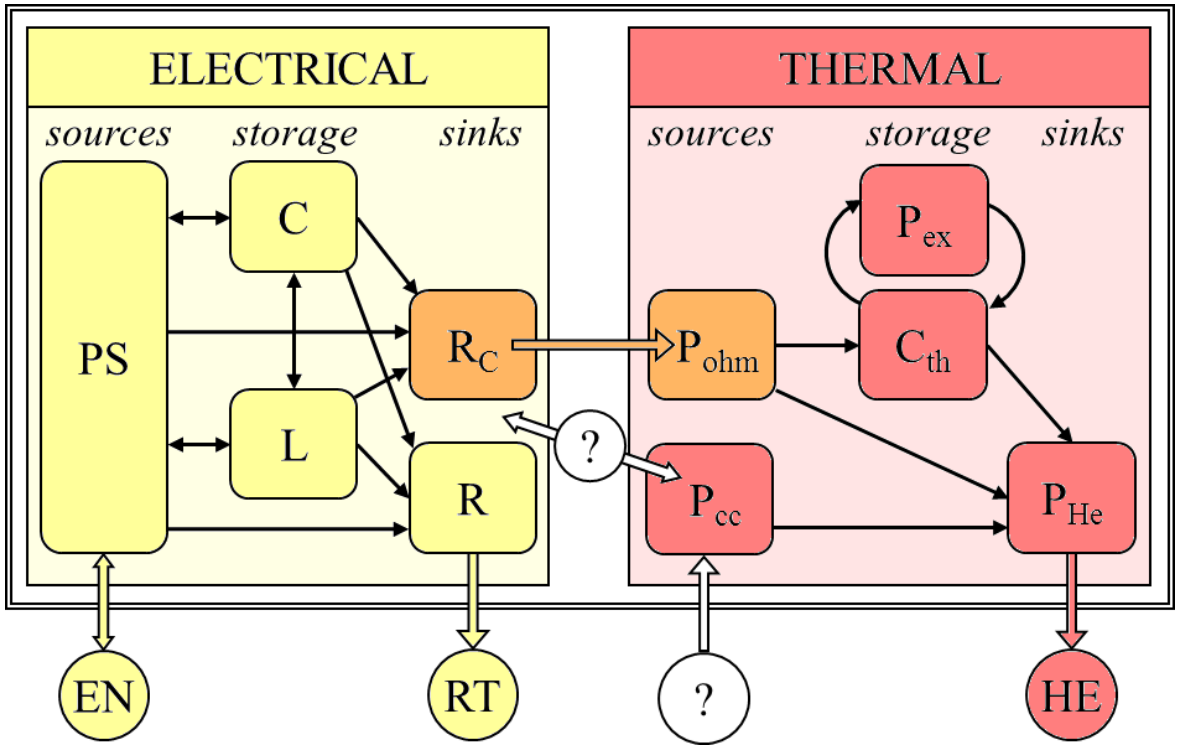
N. Bourcey, A. Carlon Zurita, R. De Paz Ludena, C. Fernandes, P. Ferracin,
S. Ferradas Troitino, M. F. Garcia Perez, J. Massard, D. Martins Araujo,
G. Maury, J. Mazet, J. Osieleniec, P. Moyret, C. Petrone (CERN)

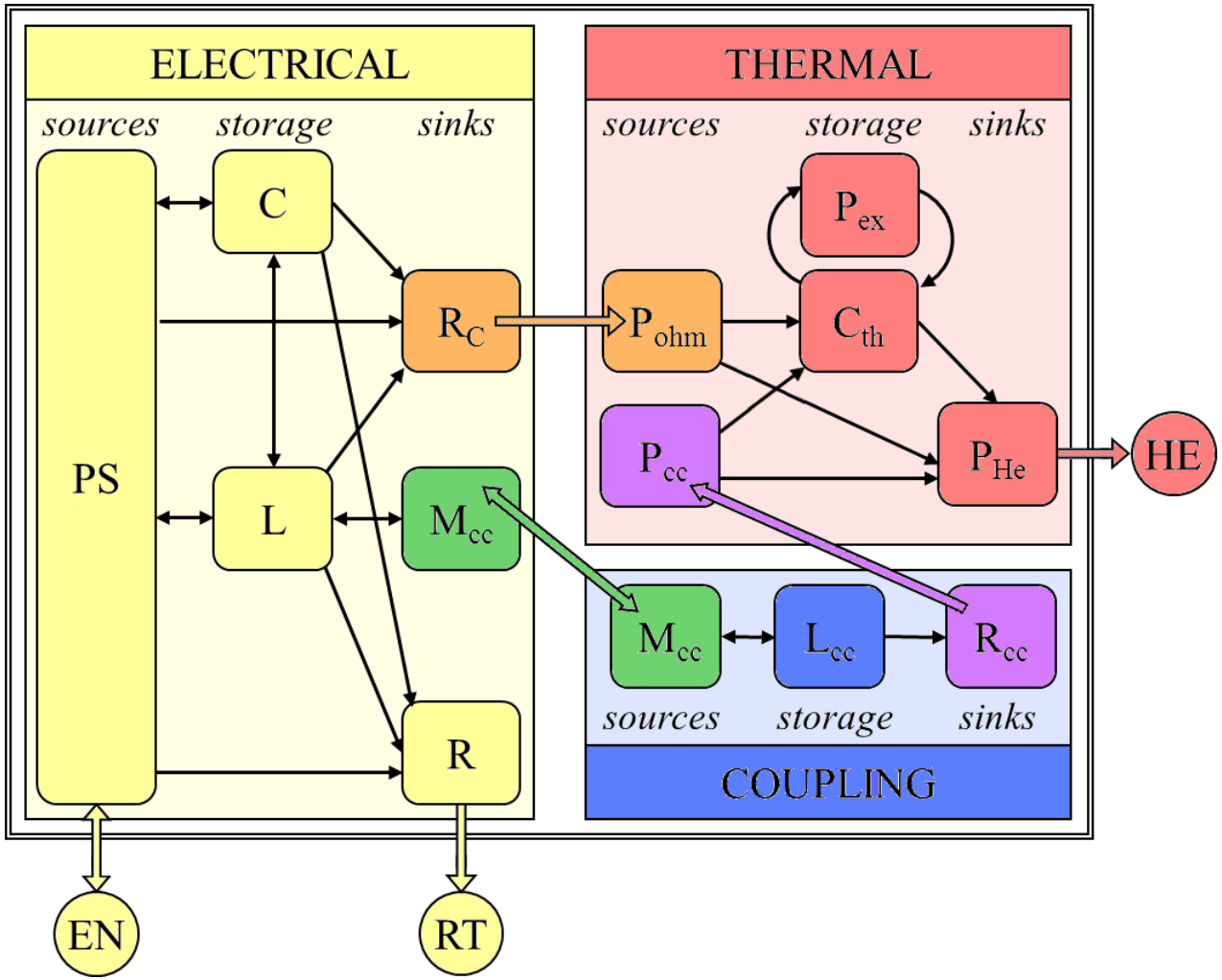
Annex

Energy exchanges in multiphisics models

Electro-thermal models



LEDET



eRMC magnet

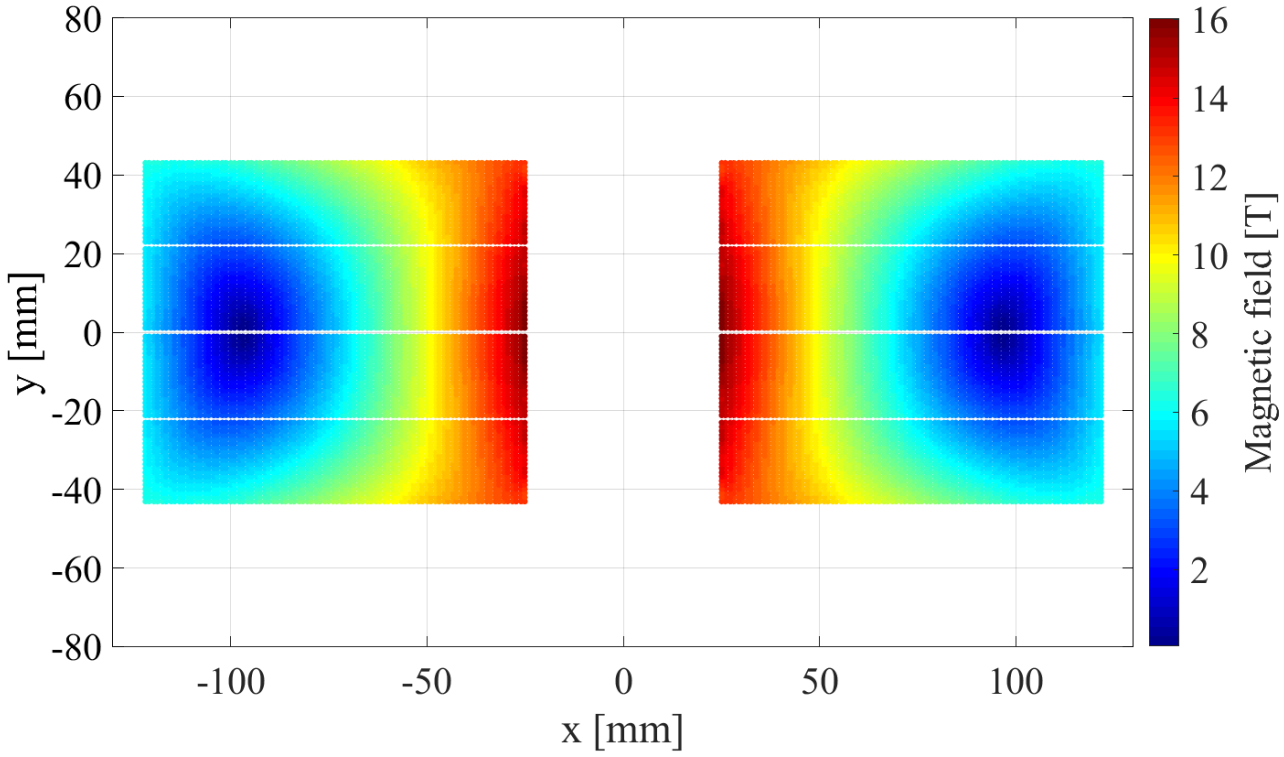


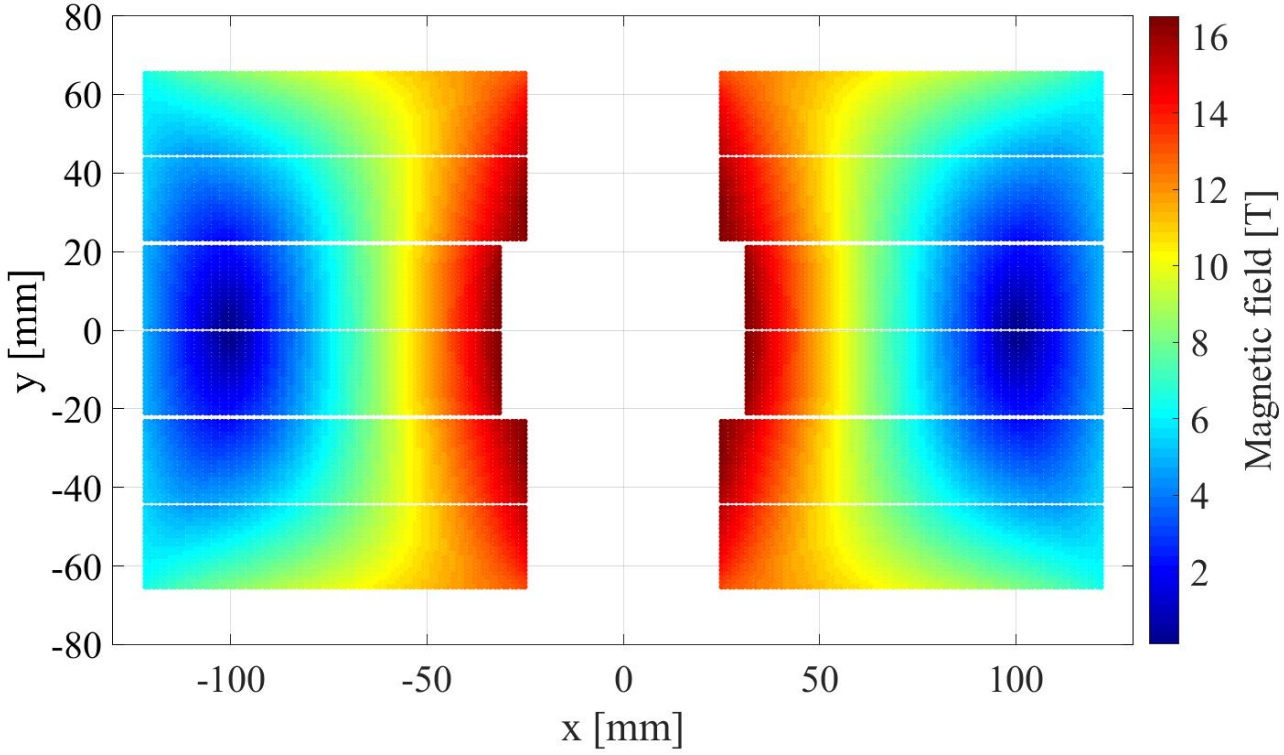
TABLE I
2-D MAGNET PARAMETERS

Parameter	Unit	ERMC	RMM
Closed aperture diameter	mm	8	50
Aluminum shell thickness	mm	70	70
Magnet outer diameter	mm	800	800
Number of turns per quadrant	–	90	132
Nominal current I_{nom}	kA	13.13	11.40
Insulated cond. current density at I_{nom}	A/mm^2	282	245
Nominal bore field B_{nom}	T	15.7	16.0
Coil peak field at I_{nom}	T	16.00	16.15
Short sample current I_{ss} at 4.2 K	kA	14.38	12.66
Coil peak field at 4.2 K I_{ss}	T	17.28	17.72
Short sample current I_{ss} at 1.9 K	kA	15.91	14.05
Coil peak field at 1.9 K I_{ss}	T	18.90	19.39
Stored energy per unit length at I_{nom}	MJ/m	1.5	2.1
Inductance per unit length at I_{nom}	mH/m	16.6	31.1
F_x per quadrant at I_{nom}	MN/m	5.86	8.03
F_y per quadrant at I_{nom}	MN/m	−3.34	−4.05

In this analysis: I_{nom}=13.13 kA

[1] S. Izquierdo Bermudez
[2] E. Rochepault

RMM magnet



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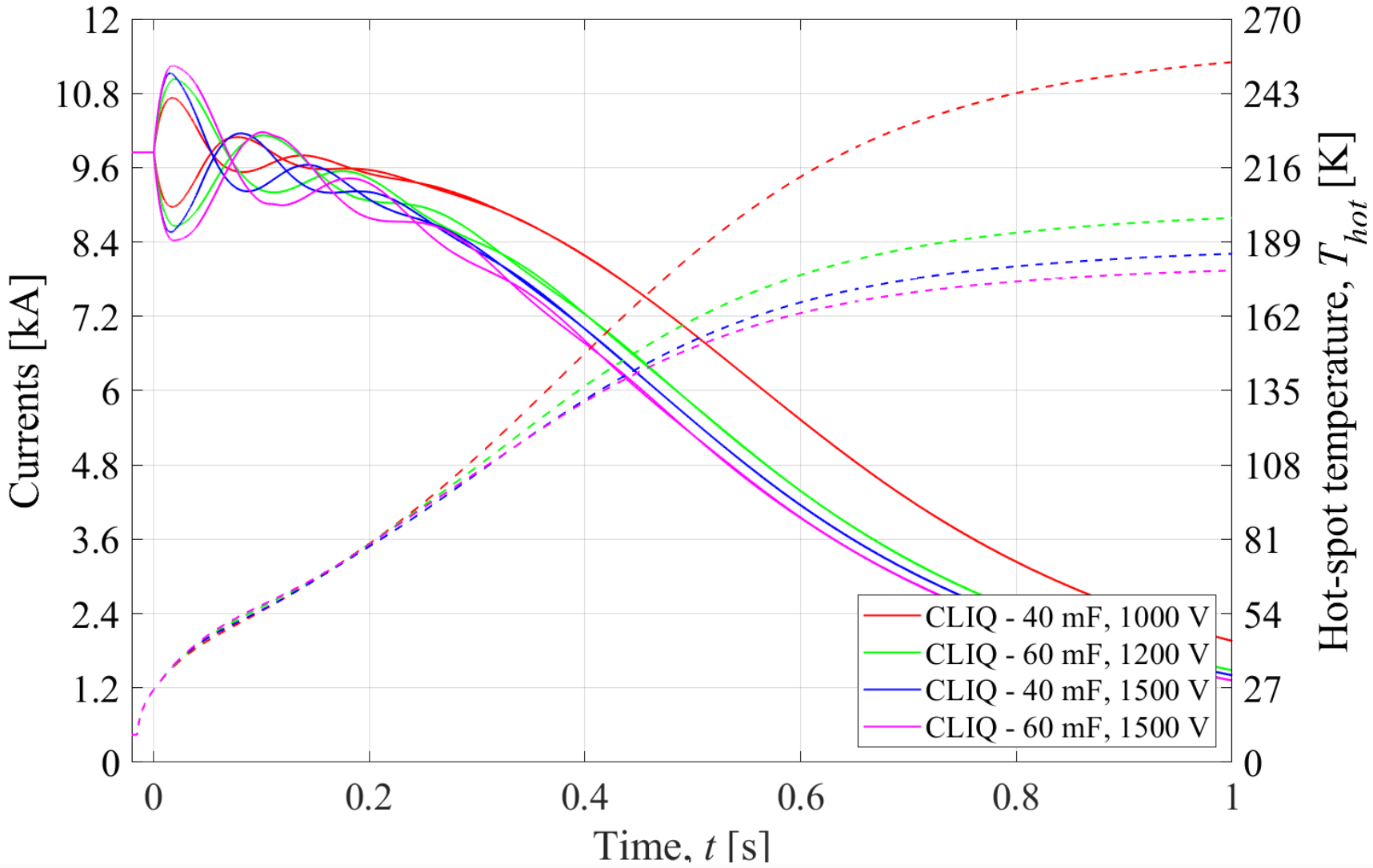
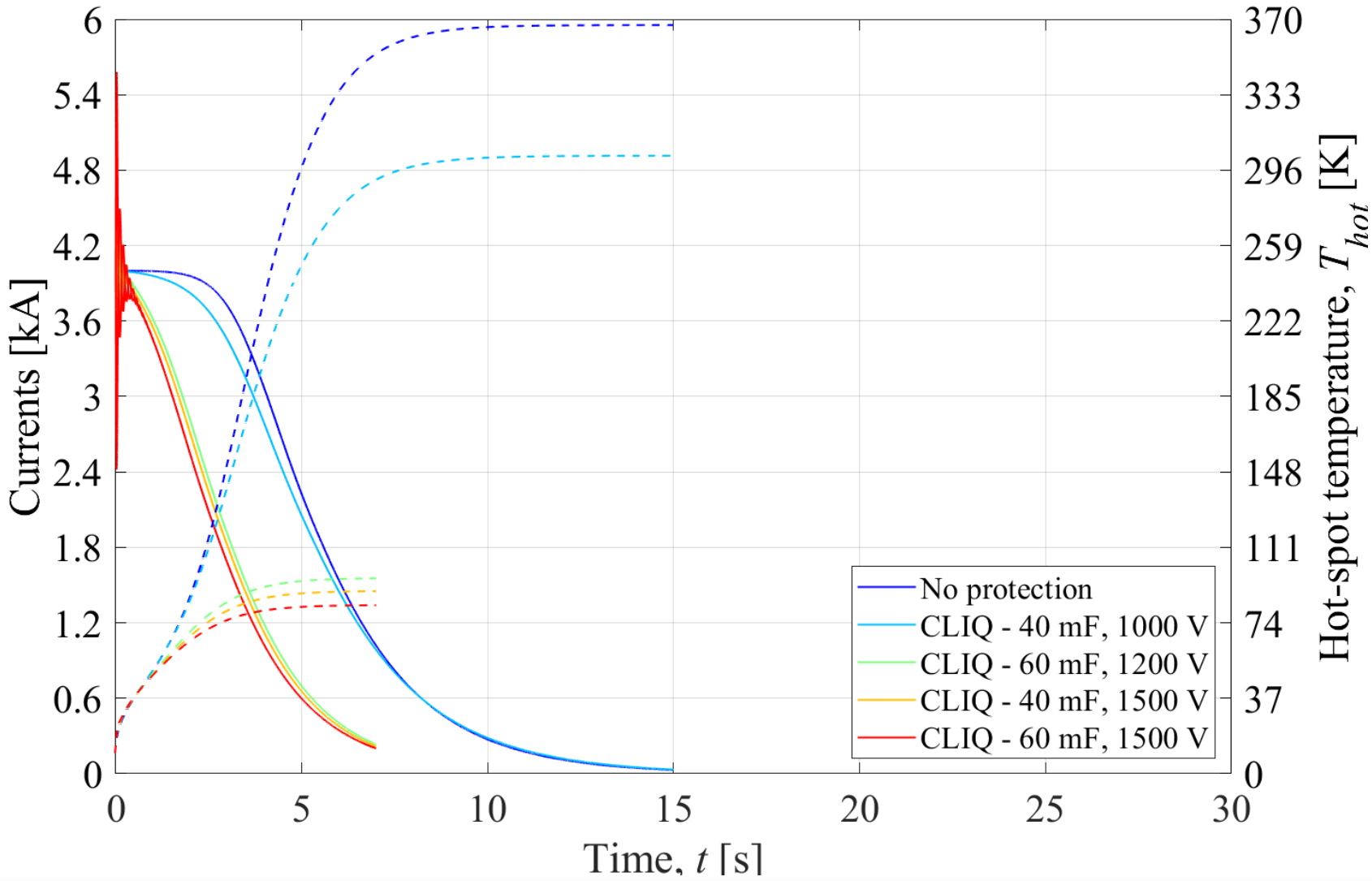
In this analysis: I_{nom}=12.10 kA

[1] S. Izquierdo Bermudez
[2] E. Rochepault

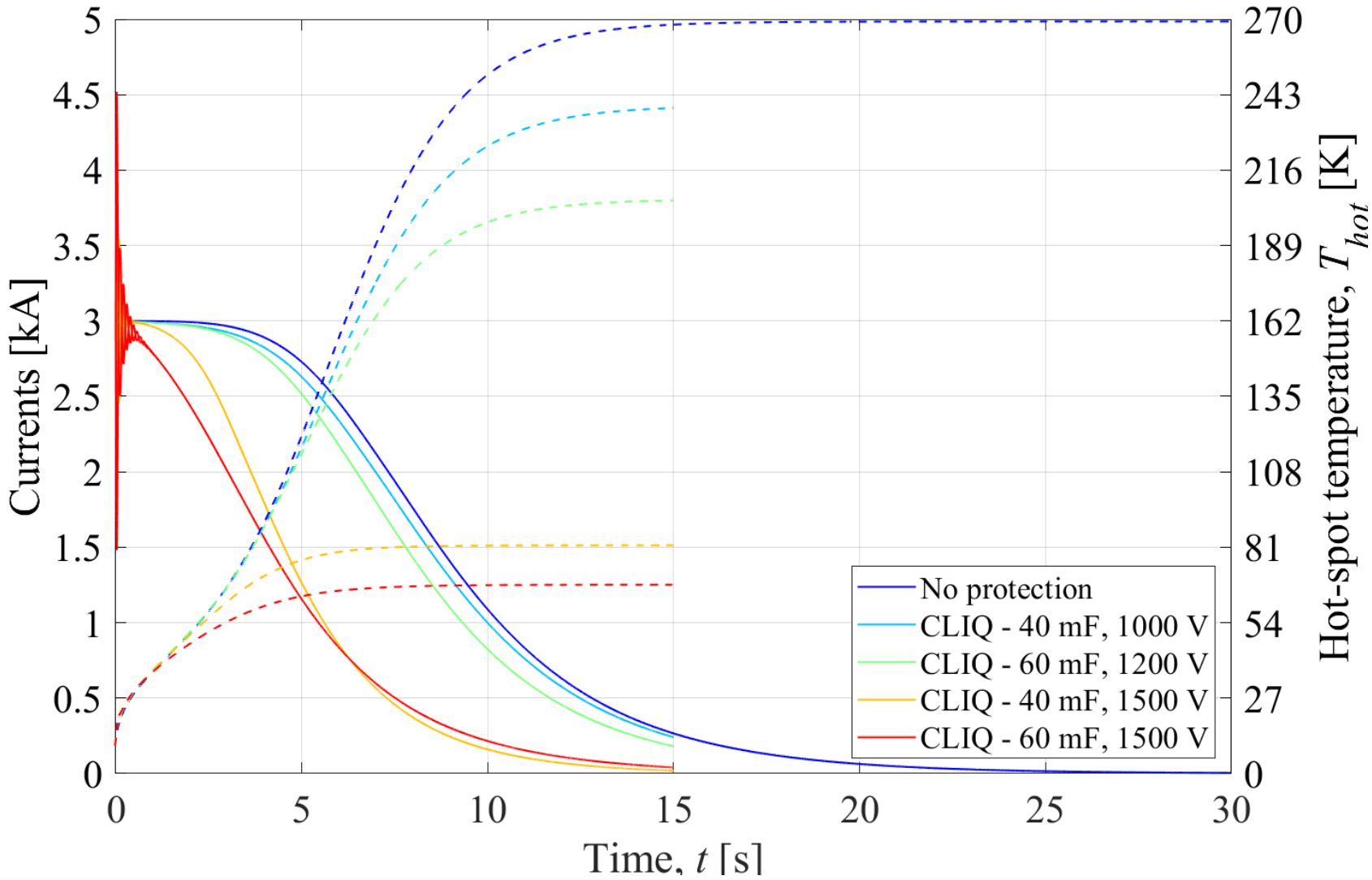
eRMC – Quench protection at I=75% I_{nom}=9.85 kA



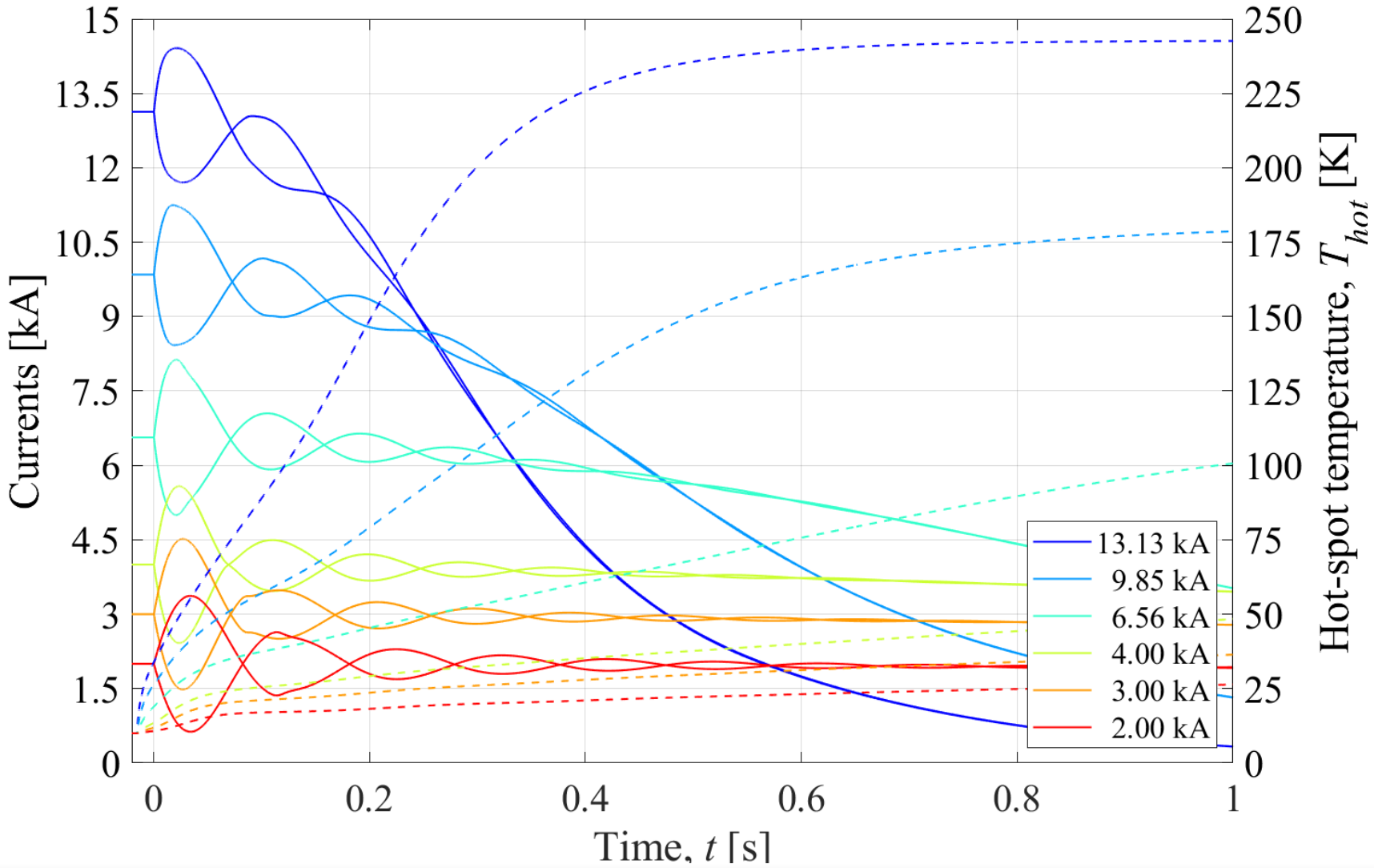
eRMC – Quench protection at I=4 kA



eRMC – Quench protection at I=3 kA

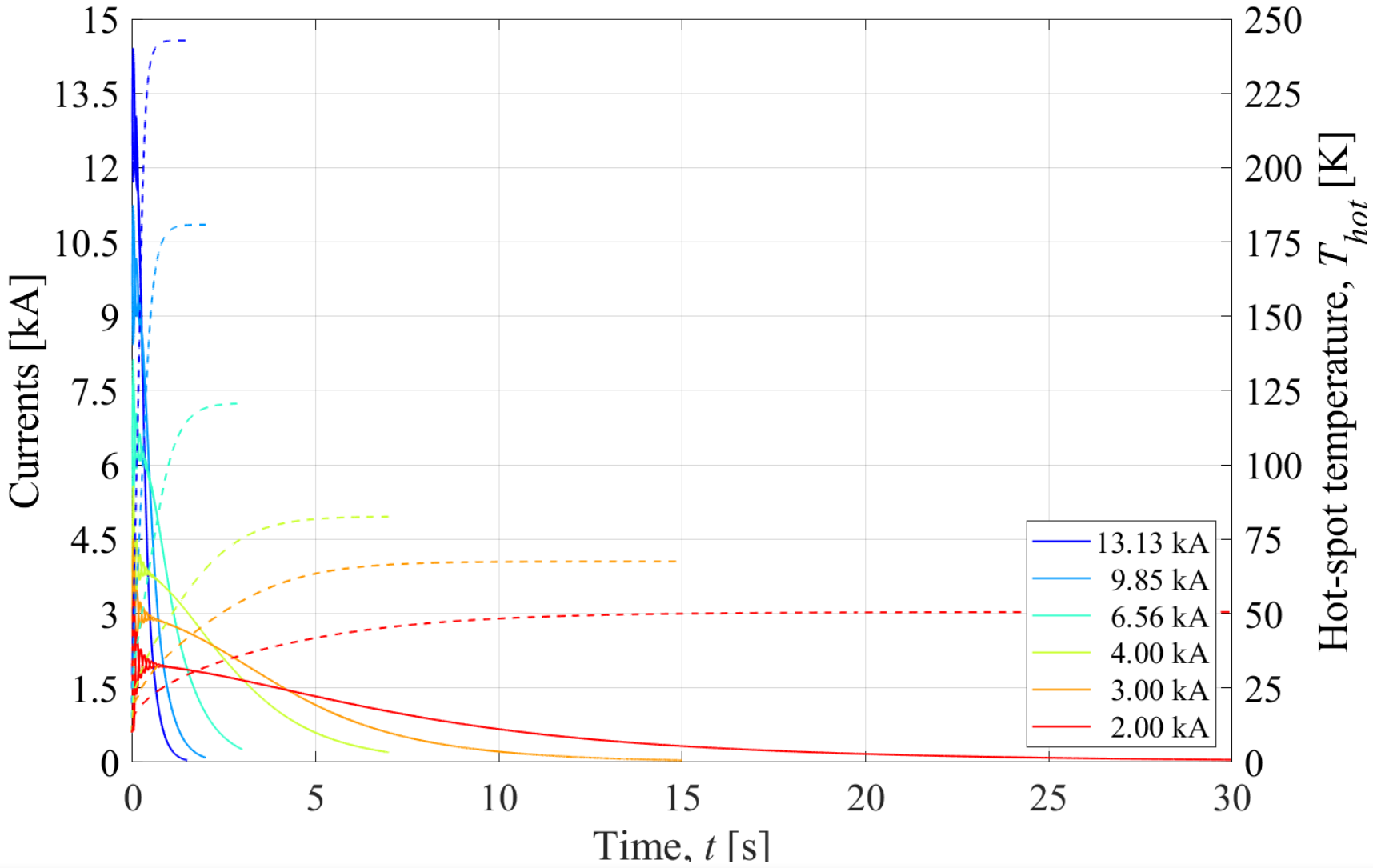


eRMC – Reference quench protection system – C=60 mF, U_0=1.5 kV



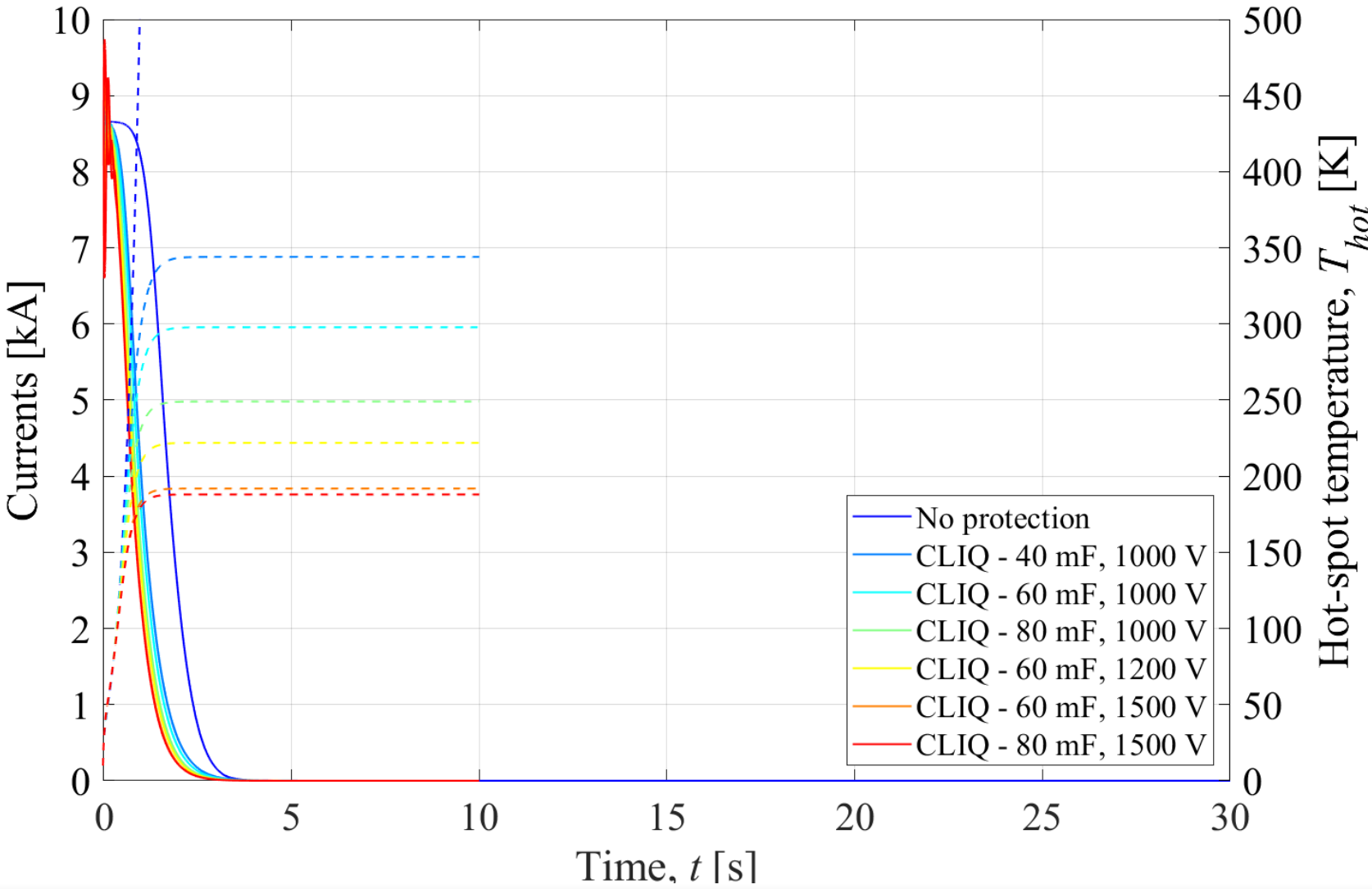
C=60 mF, U_0=1.5 kV

eRMC – Reference quench protection system – Zoom out

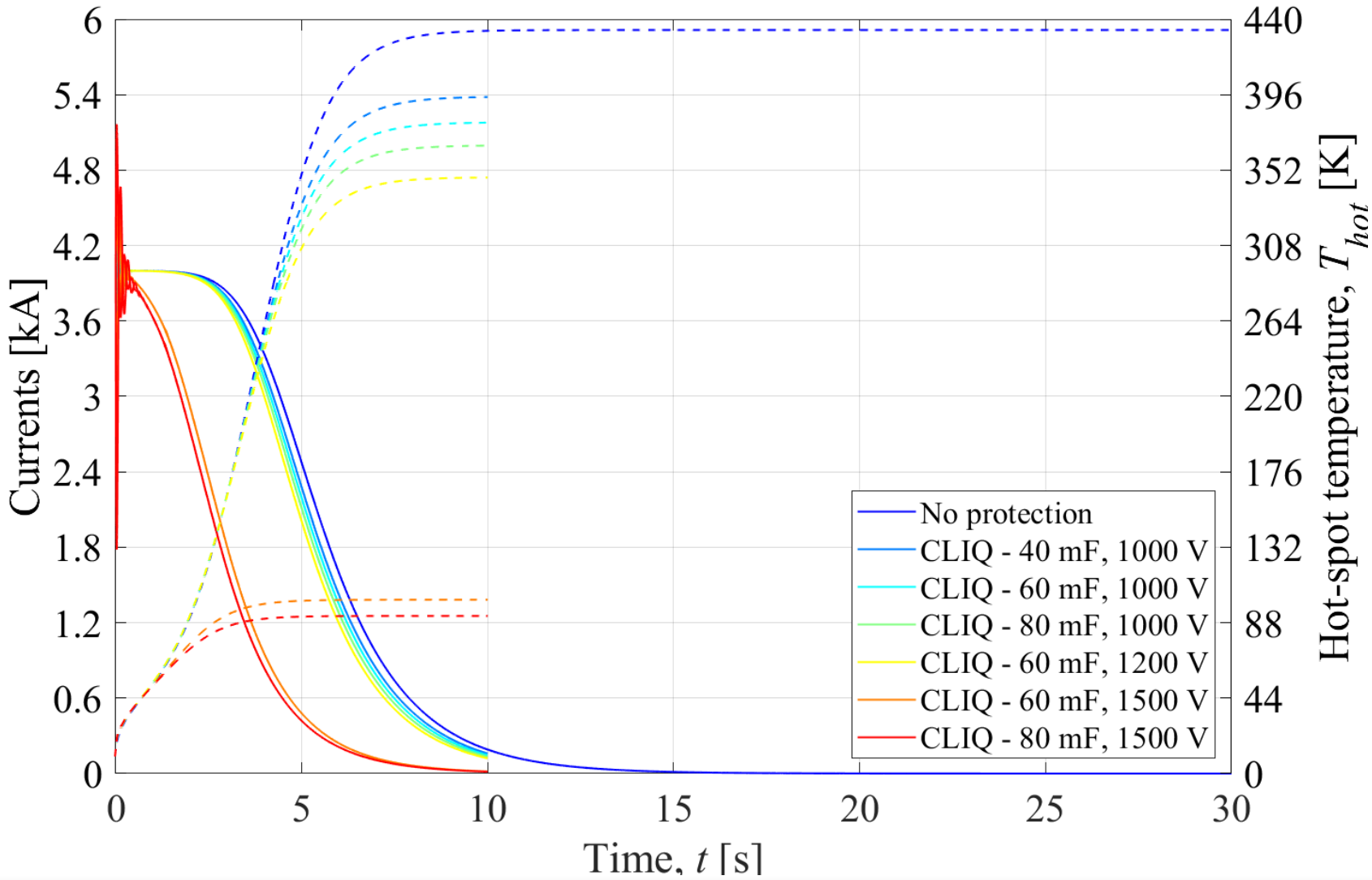


C=60 mF, U_0=1.5 kV

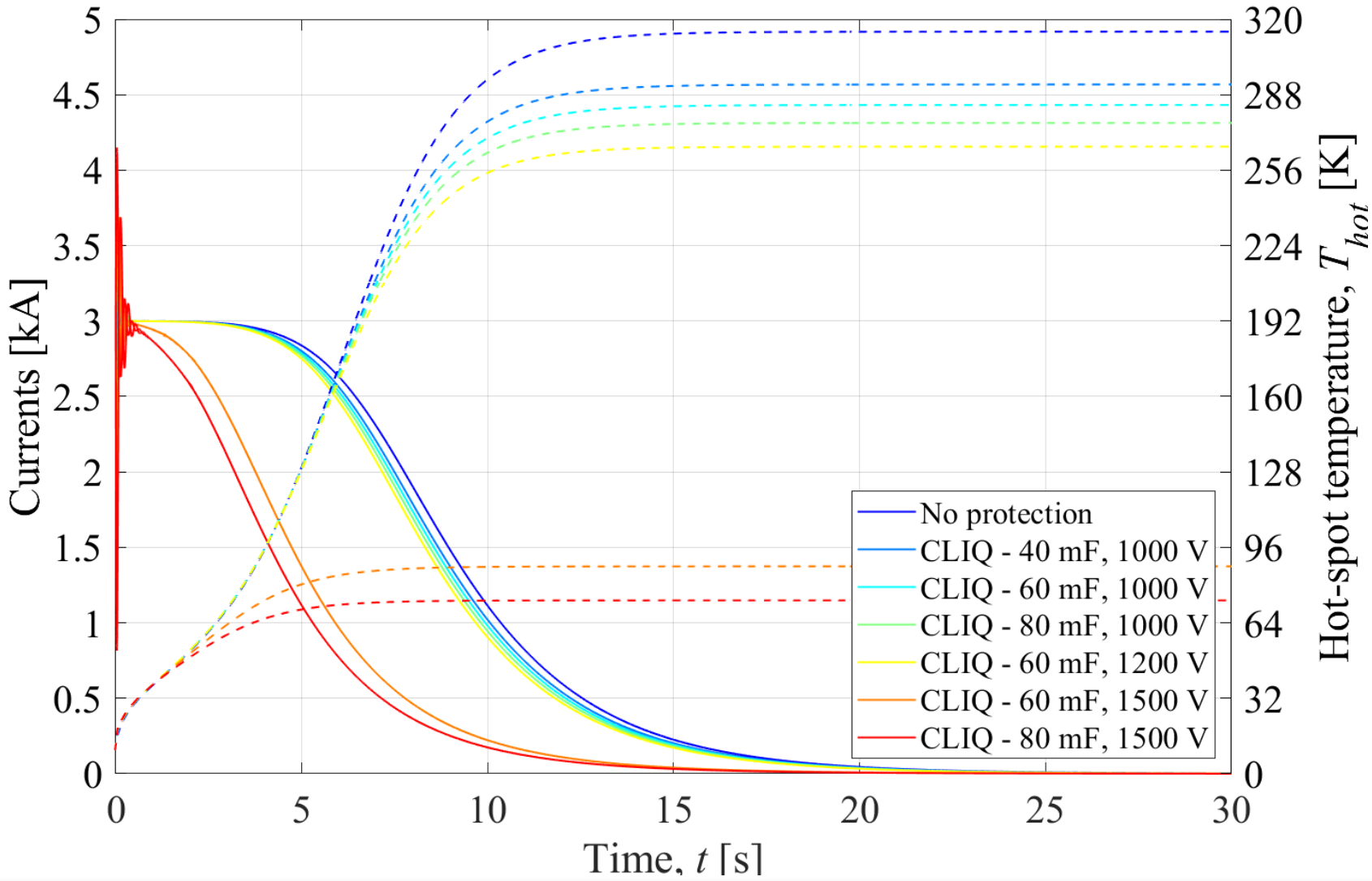
RMM – Quench protection at I=75% I_{nom}=8.66 kA



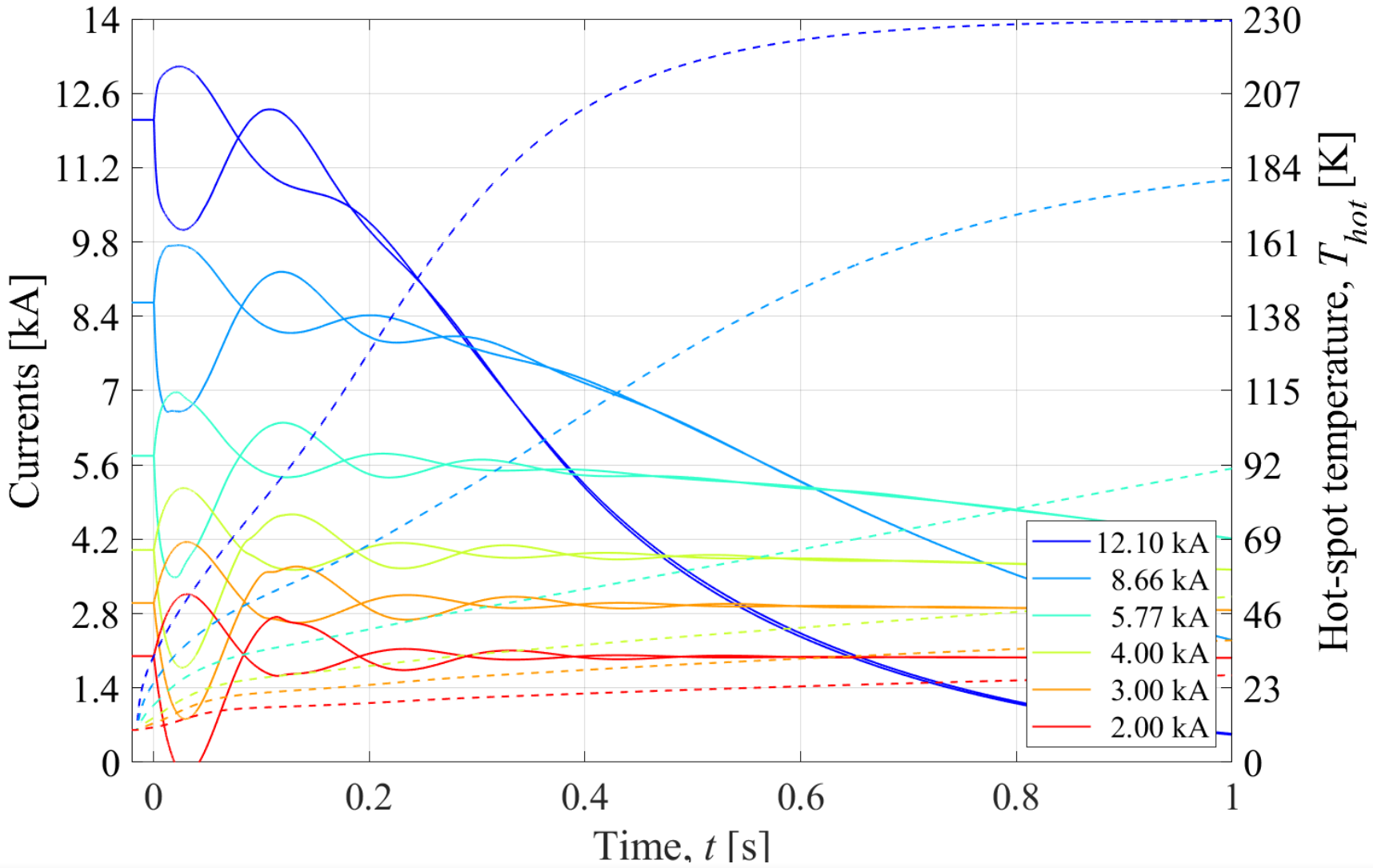
RMM – Quench protection at I=4 kA



RMM – Quench protection at I=3 kA

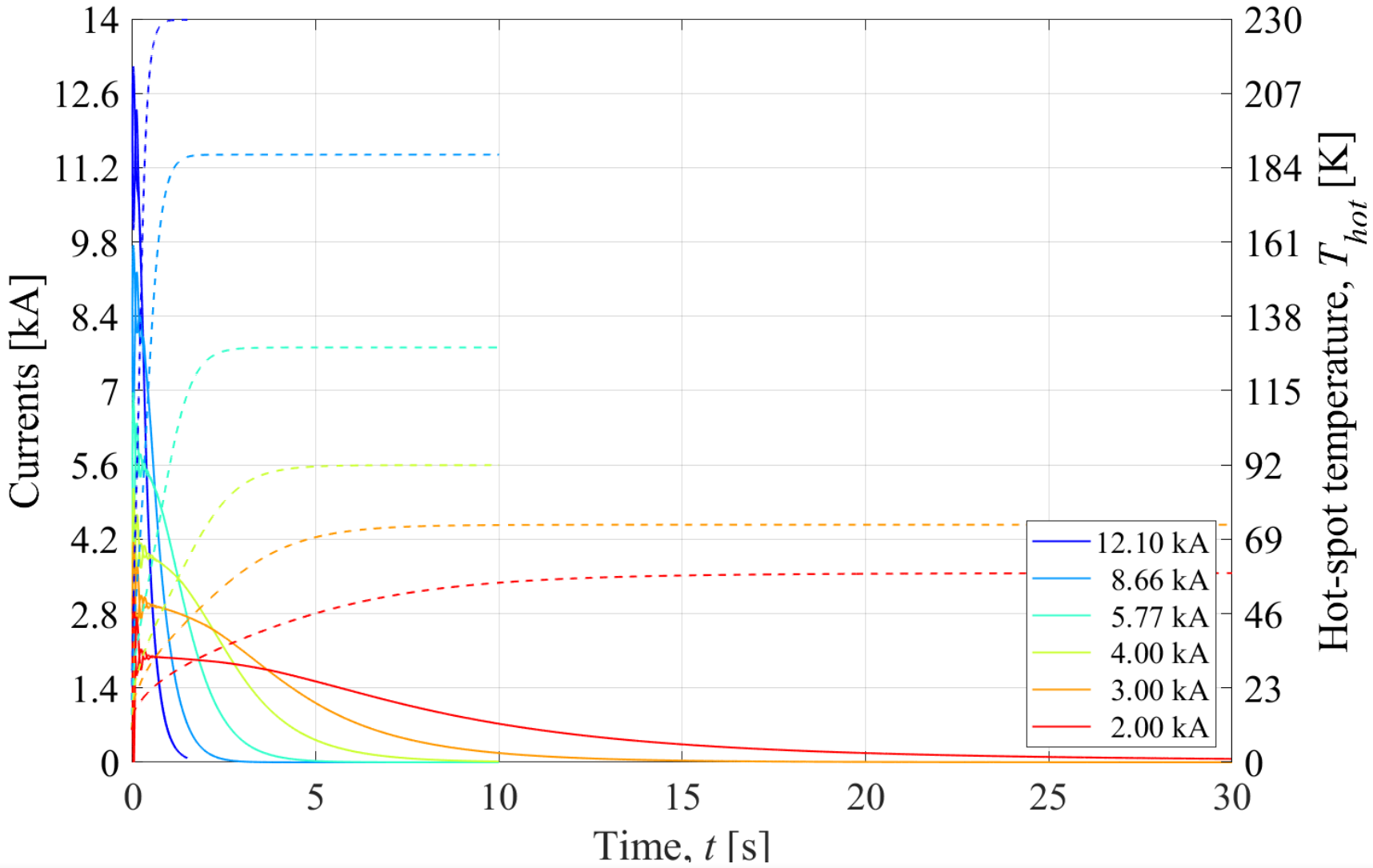


RMM – Ref quench protection system – C=80 mF, U_0=1.5 kV



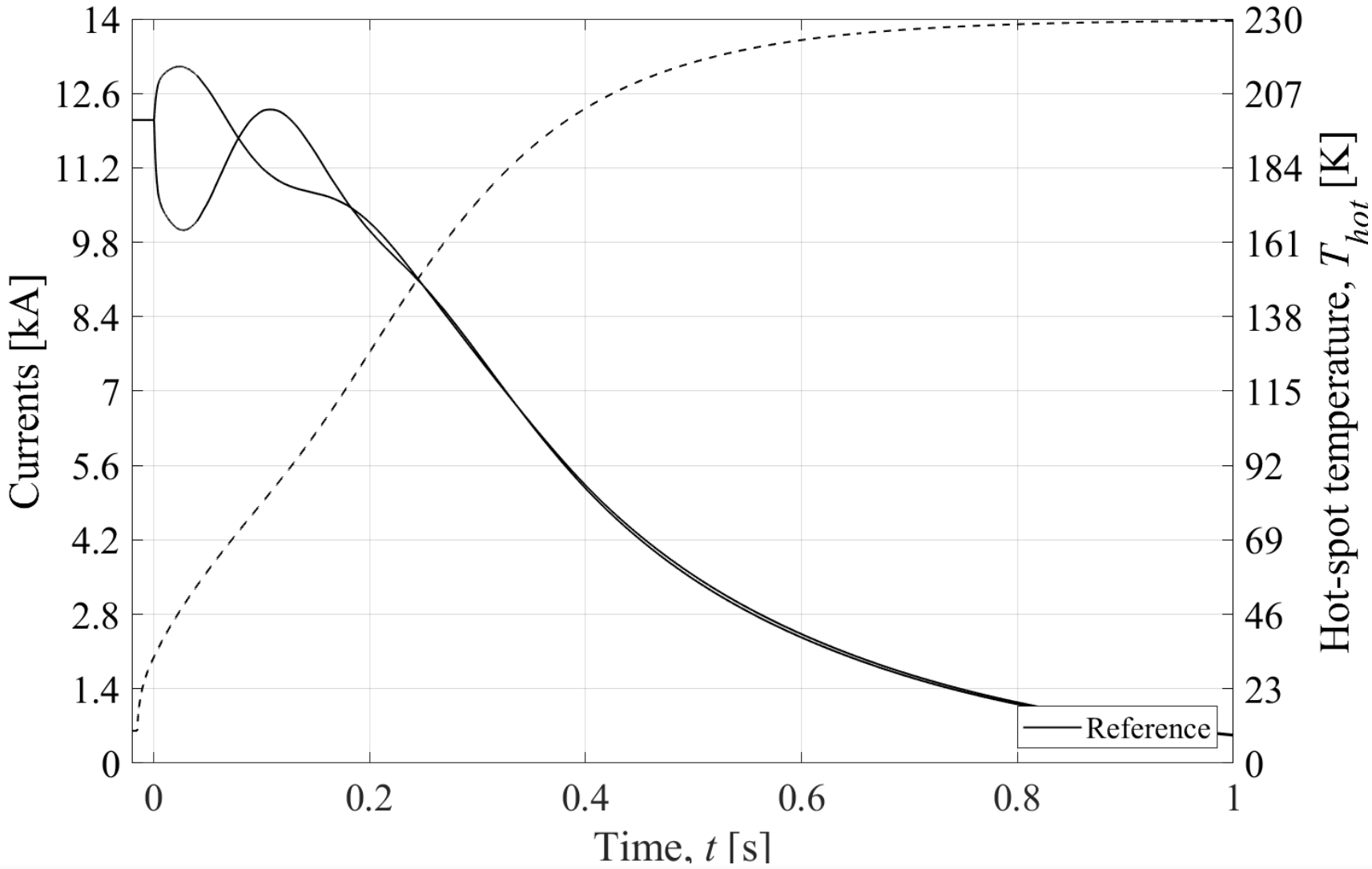
C=80 mF, U_0=1.5 kV

RMM – Reference quench protection system – Zoom out

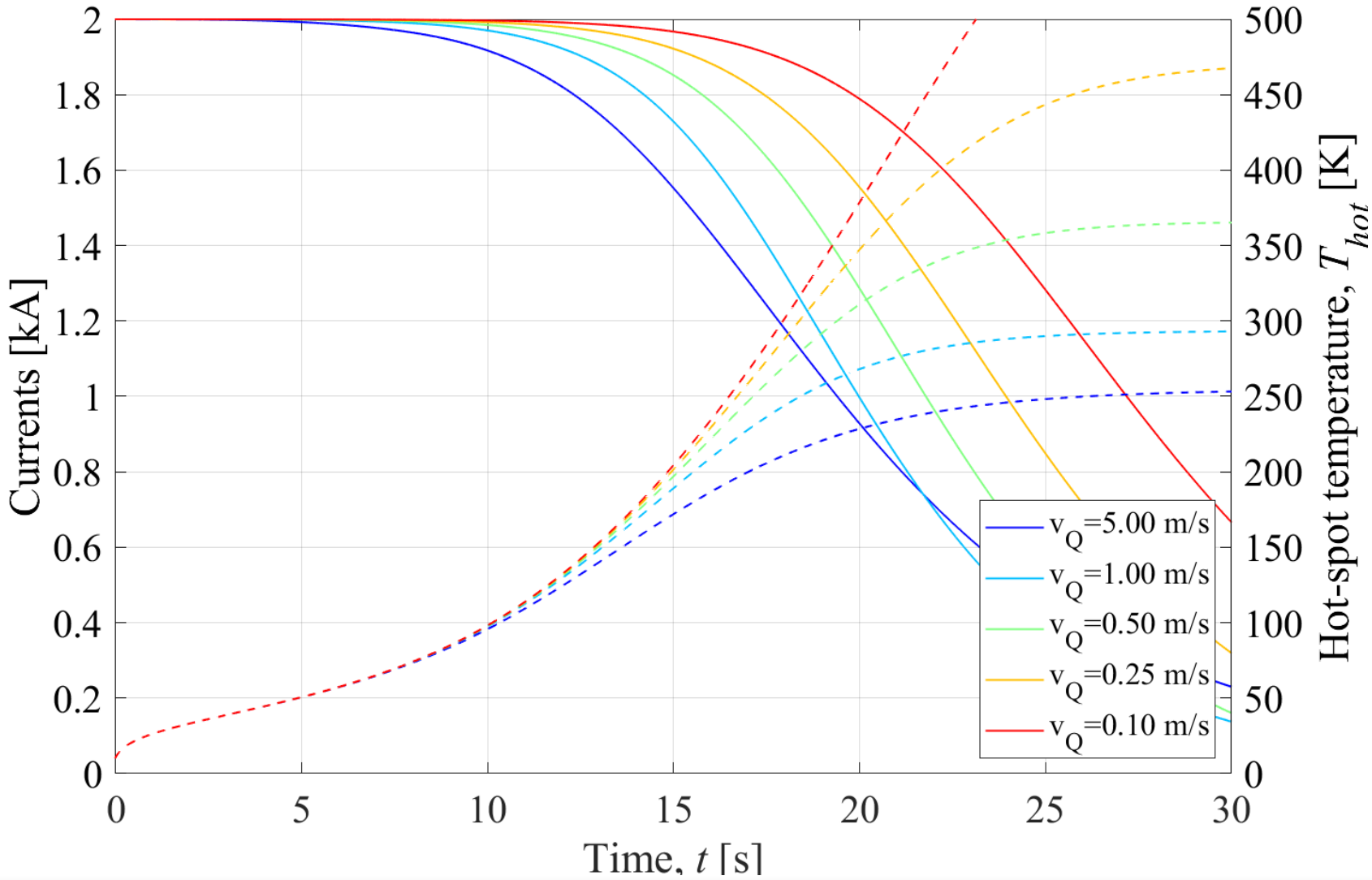
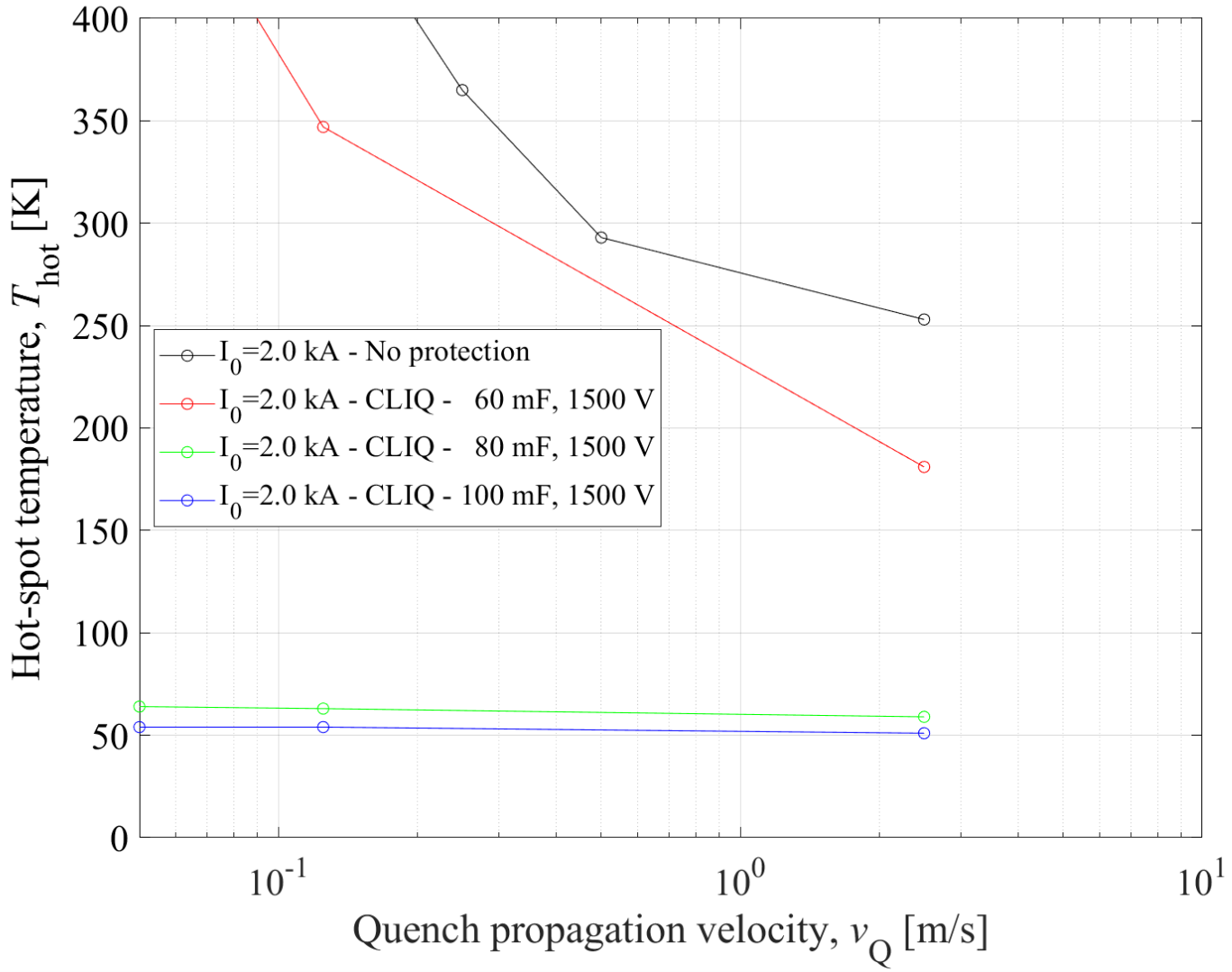


C=80 mF, U_0=1.5 kV

RMM – Quench protection at I_{nom} – Reference



RMM – Self-protectability – I=2 kA



RMM – Effect of quench propagation velocity – I=2 kA