Optimizing the quench protection of a 13 T Nb_3Sn common-coil magnet

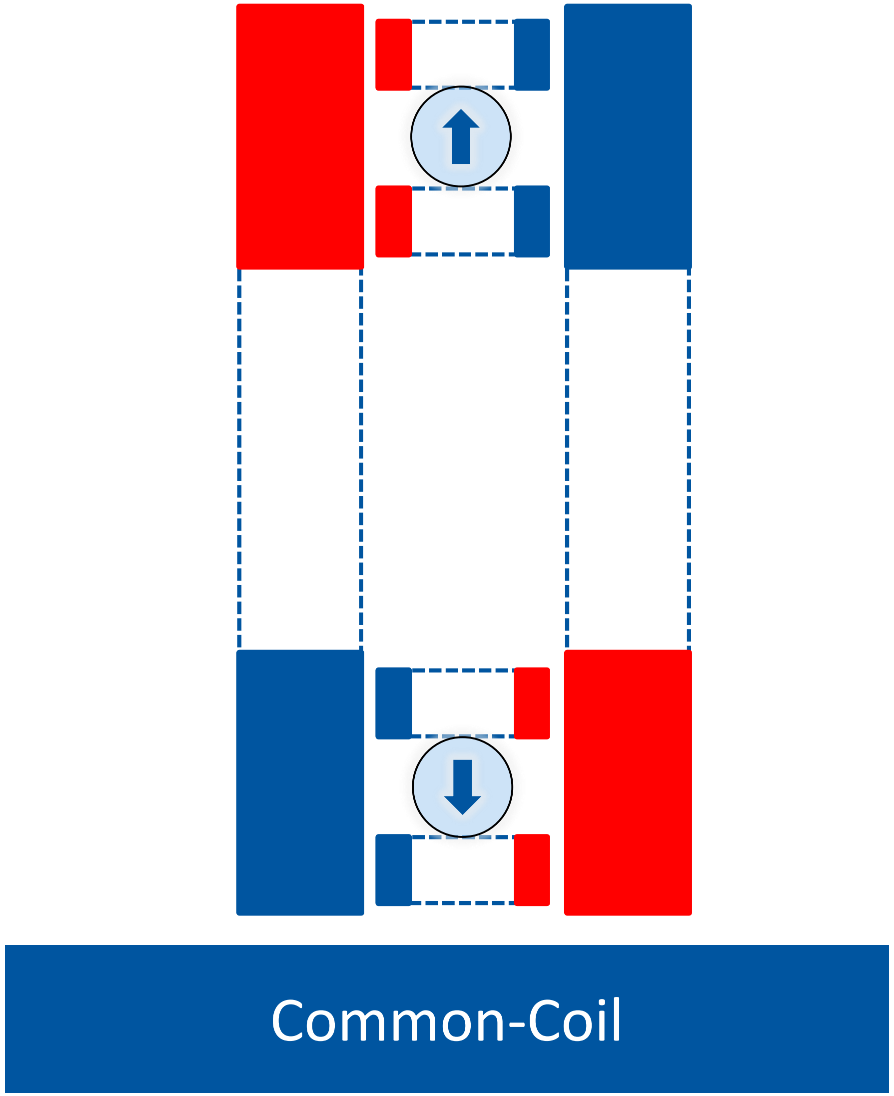
Emmanuele Ravaioli (CERN)

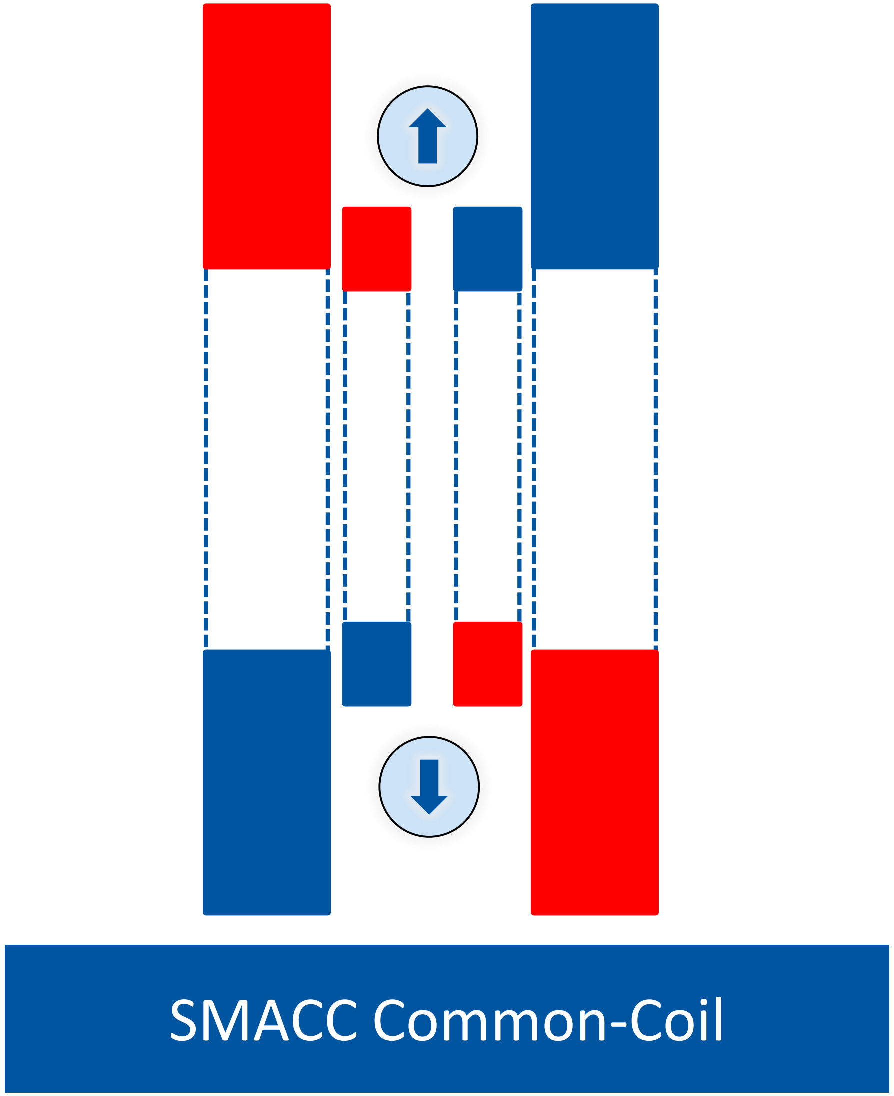
D. Araujo (PSI), B. Auchmann (PSI), A. Verweij (CERN), M. Wozniak (CERN)

2024.09.06

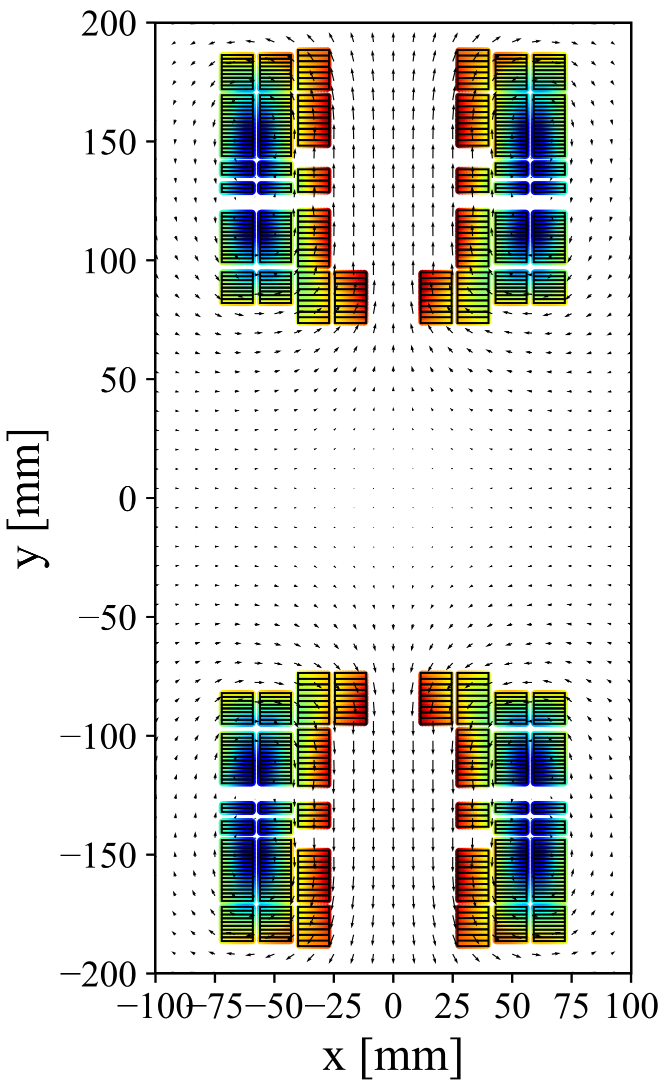
New common-coil concept by Douglas Araujo at PSI

with acknowledgment to a similar design proposed in LBNL, which did not focus on field quality [S. Gurlay et al., 1995]





SMACC magnet by Douglas Araujo at PSI



SMACC
Stress-Managed
Asymmetric
Common-Coil

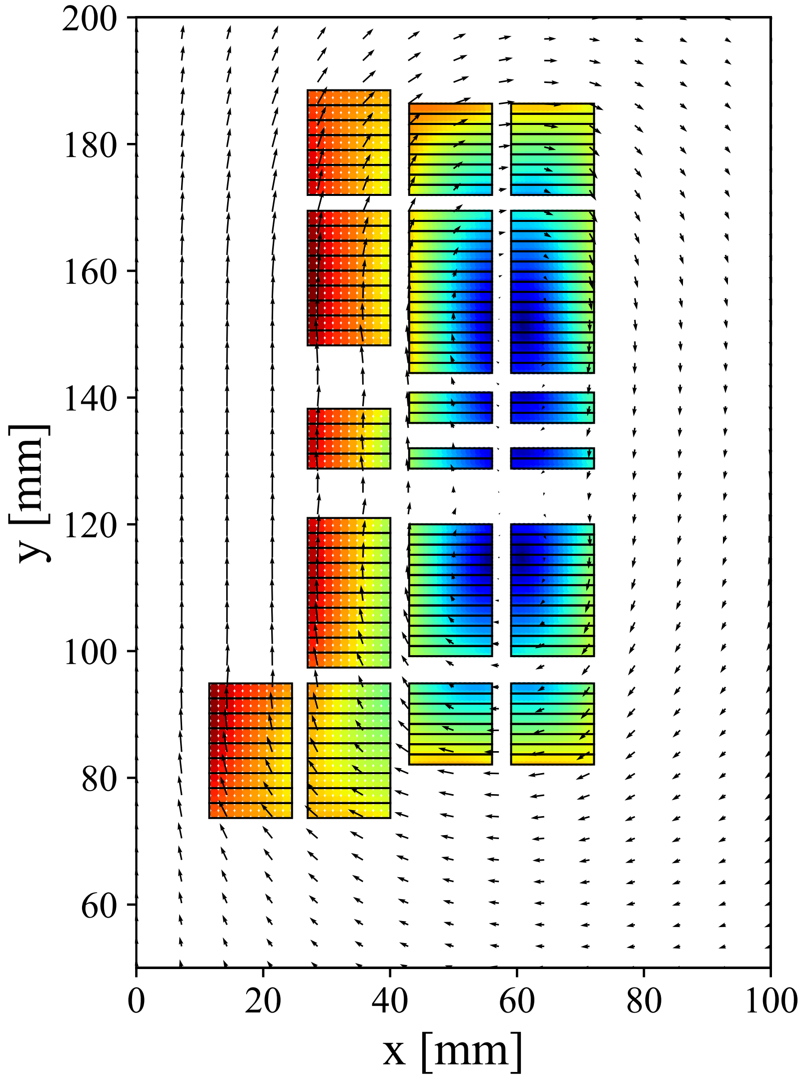
No racetrack coils around the pole

Large bending radius for all turns

Congratulations to Douglas!
This is a major development
for the common-coil technology!

1LPo1G-06 D. Araujo (PSI)

SMACC magnet by Douglas Araujo at PSI



First demonstrator will be built at PSI

- ✓ 13 T bore field with 10% margin at T=4.2 K
- ✓ Circular bore with 50 mm diameter
- ✓ 250 mm intra-beam distance
- ✓ Utilizing two already-existing Nb_3Sn cables

No flexibility in the choice of conductor grading

Quench protection is much more challenging
(<u>one conductor heats up twice more quickly!</u>)

Analyzed quench protection options

ACTIVELY
EXTRACT ENERGY

Energy extraction system

ACTIVELY
SPREAD ENERGY

Active heating system

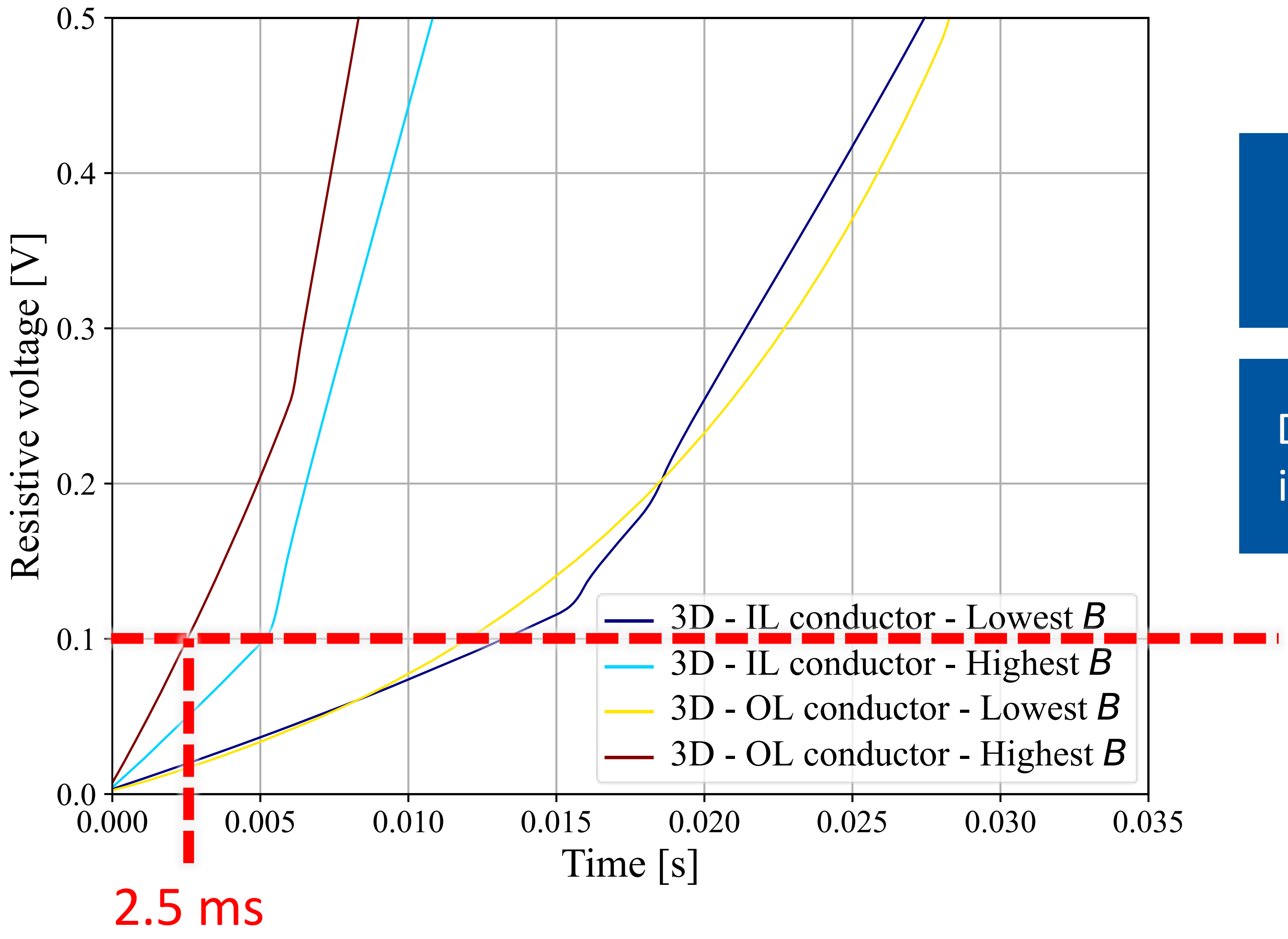
Energy extraction with constant resistor

Energy extraction with varistor

CLIQ
(Coupling-Loss Induced Quench system)

Energy Extraction + CLIQ

Quench detection based on differential voltage monitoring



Resistive voltage build-up simulated for different quench locations

Detection threshold of 100 mV is reached in 2.5 ms after quench in a high-field turn

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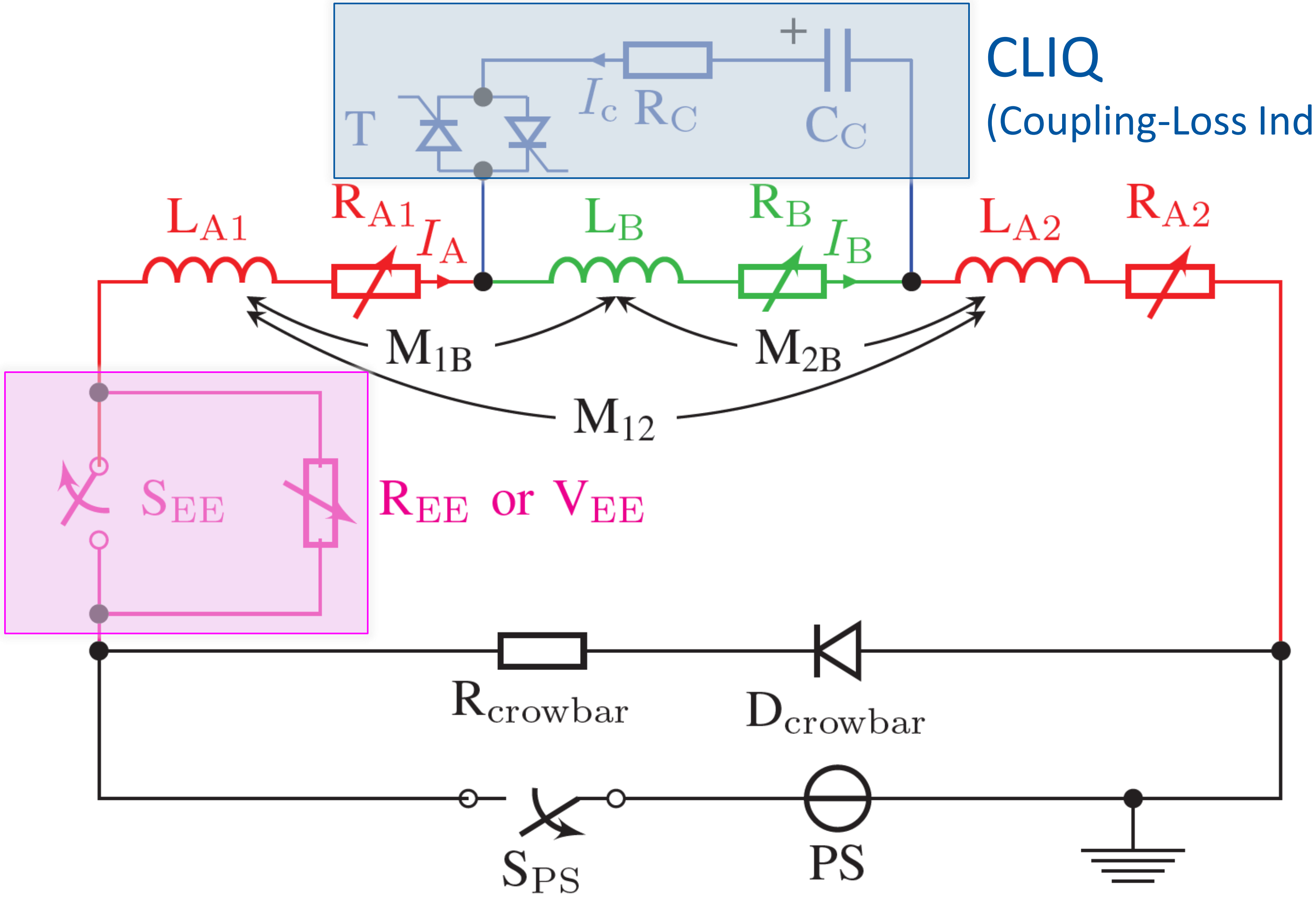
Total reaction time t_R

Quench detection time	+	Discrimination time	+	Triggering time	=	Total reaction time t_R
2.5 ms for a quench in the worst-case turn		5 ms assumption based on experience with similar magnets		3.2 ms for energy extraction mechanical switch	≈	11 ms for energy extraction
				0.5 ms for CLIQ unit		8 ms for CLIQ

Of course these values are not general, but they are valid for the test facility where the tests will be performed

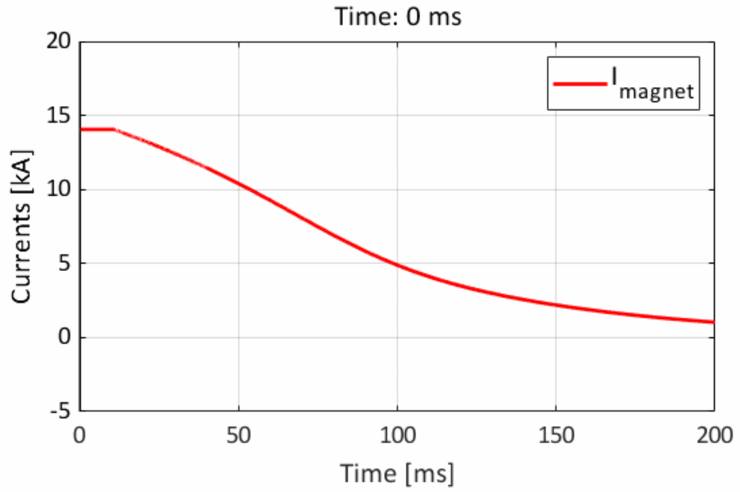
Quench protection options

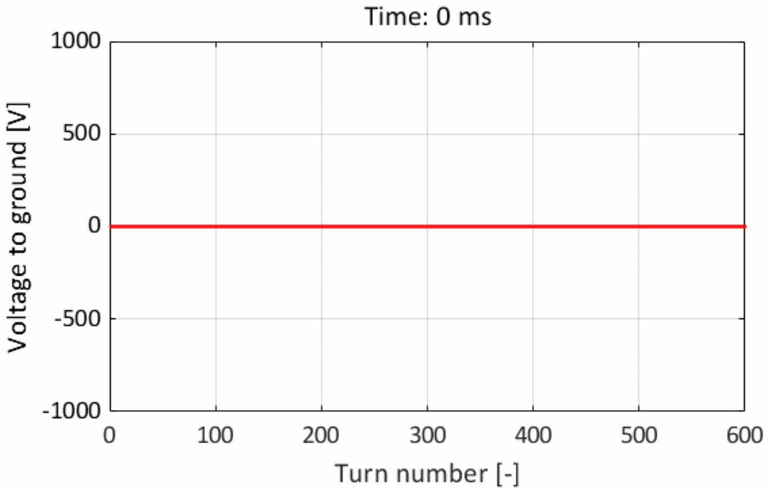


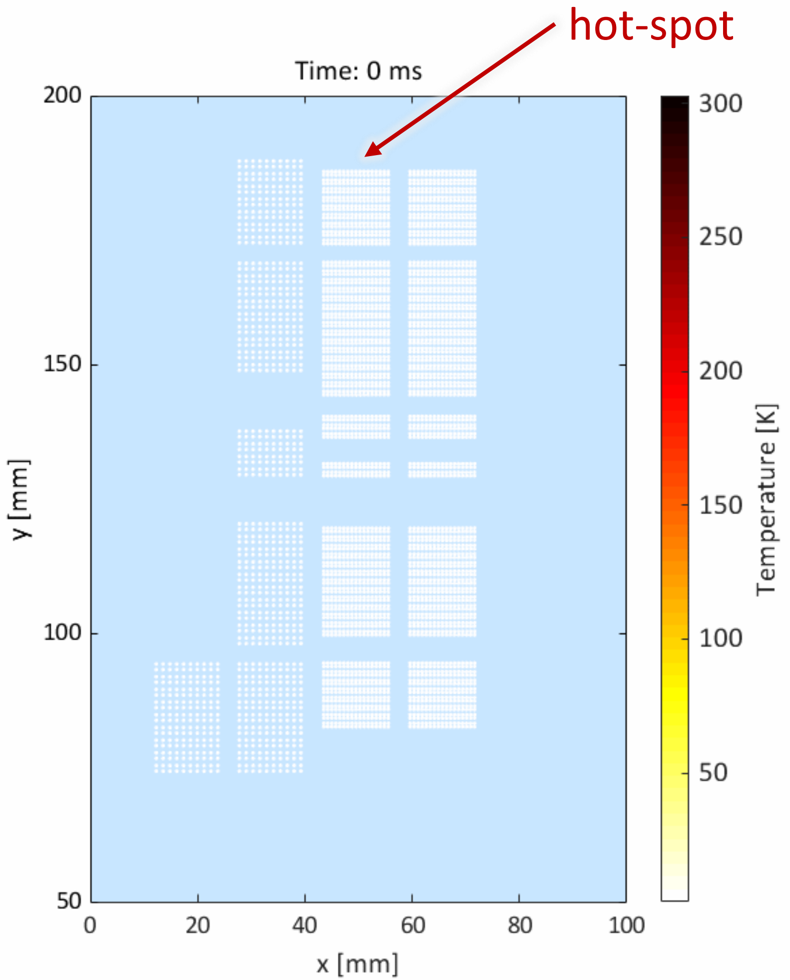
CLIQ
(Coupling-Loss Induced Quench system)

EE
(Energy extraction)

Quench protection with 1 kV energy extraction with constant resistor







The presence of quench-back influences significantly the transient

→ Reduction of differential inductance
→ Quench-back (coil resistance increase due to transient losses)

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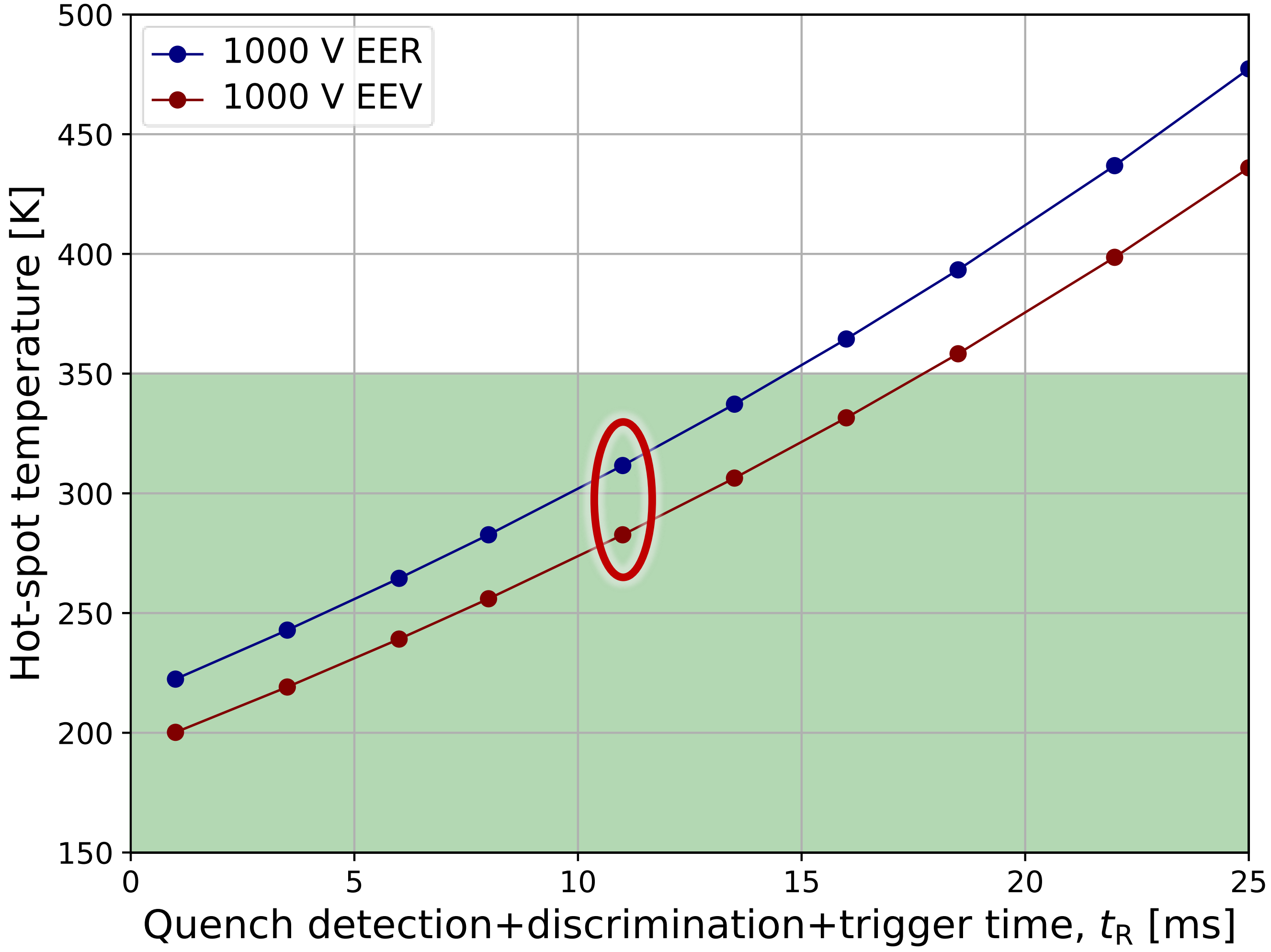
Hot-spot temperature as a function of total reaction time

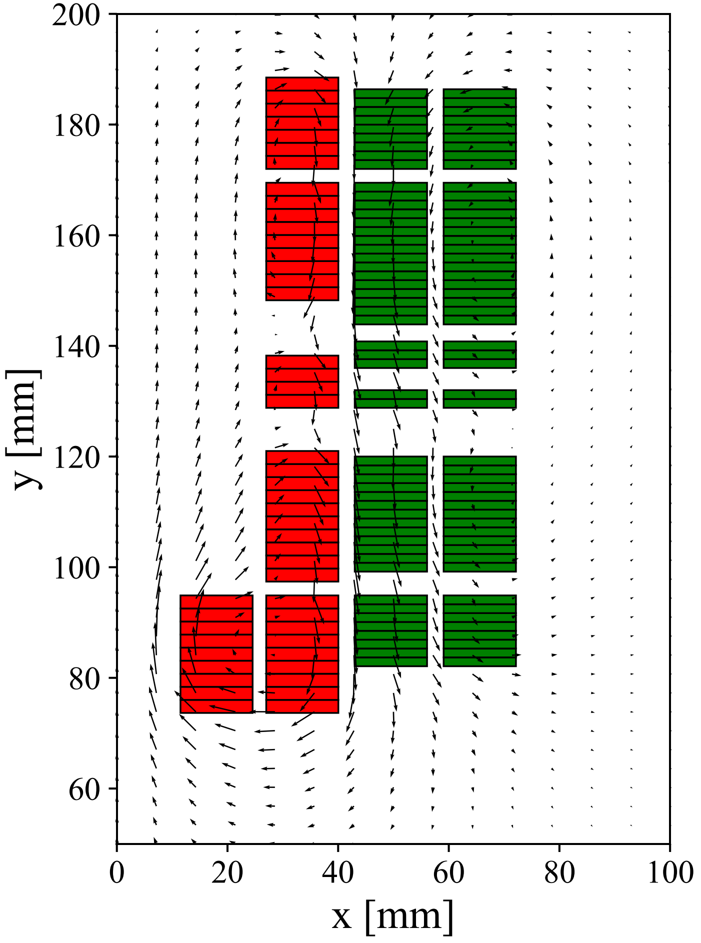


Varistor (EEV) marginally improves quench protection (20-40 K temperature reduction)

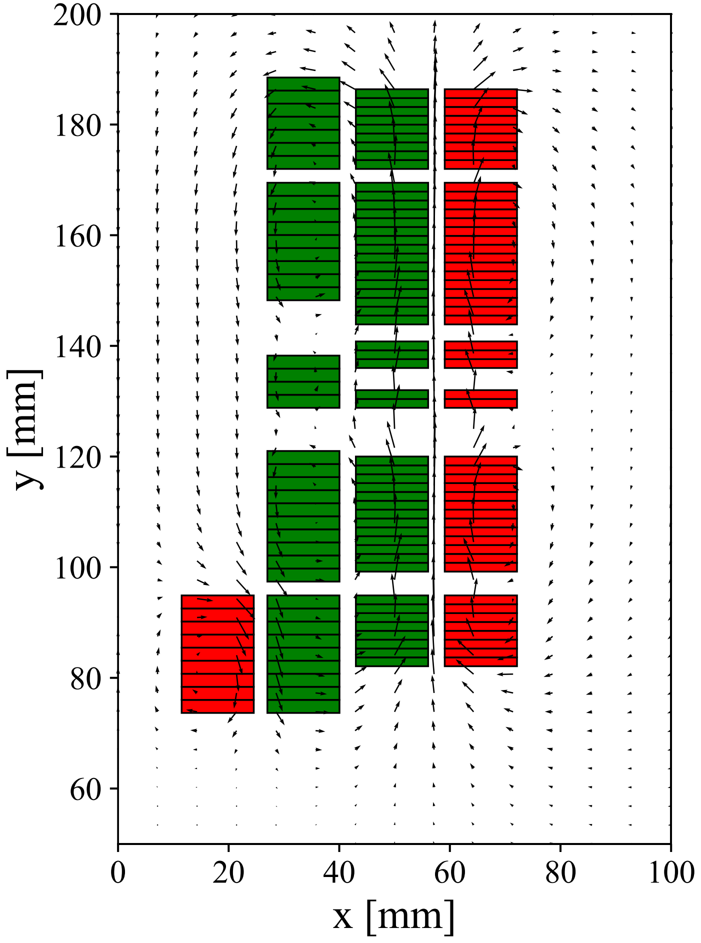
Quench protection possible (T_{hot}<350 K) if t_R<14 ms (for EER) or t_R<18 ms (for EEV)

CLIQ optimization

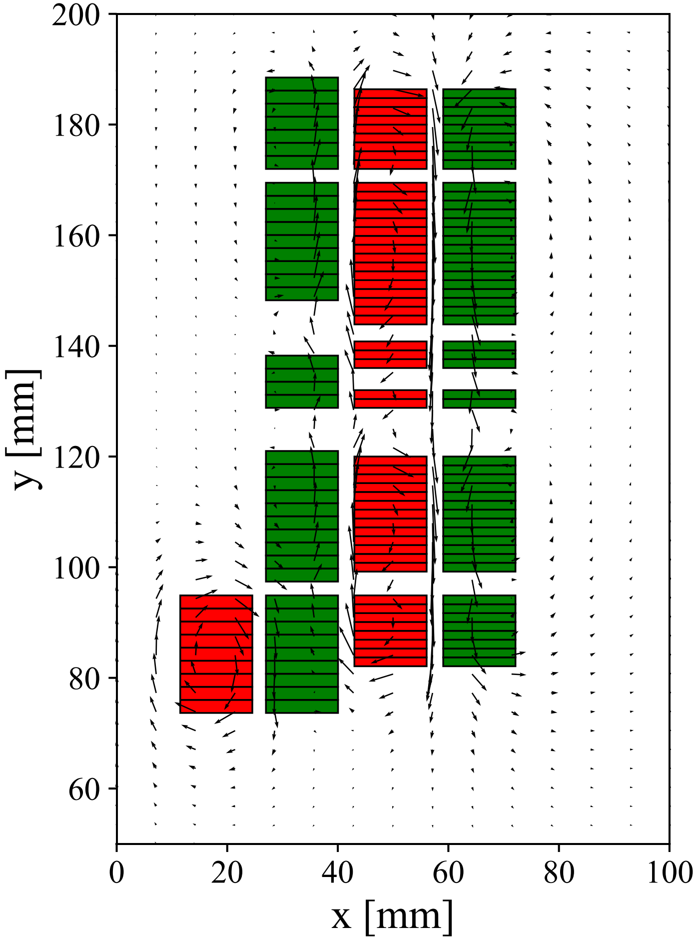
CLIQ-C1



CLIQ-C2



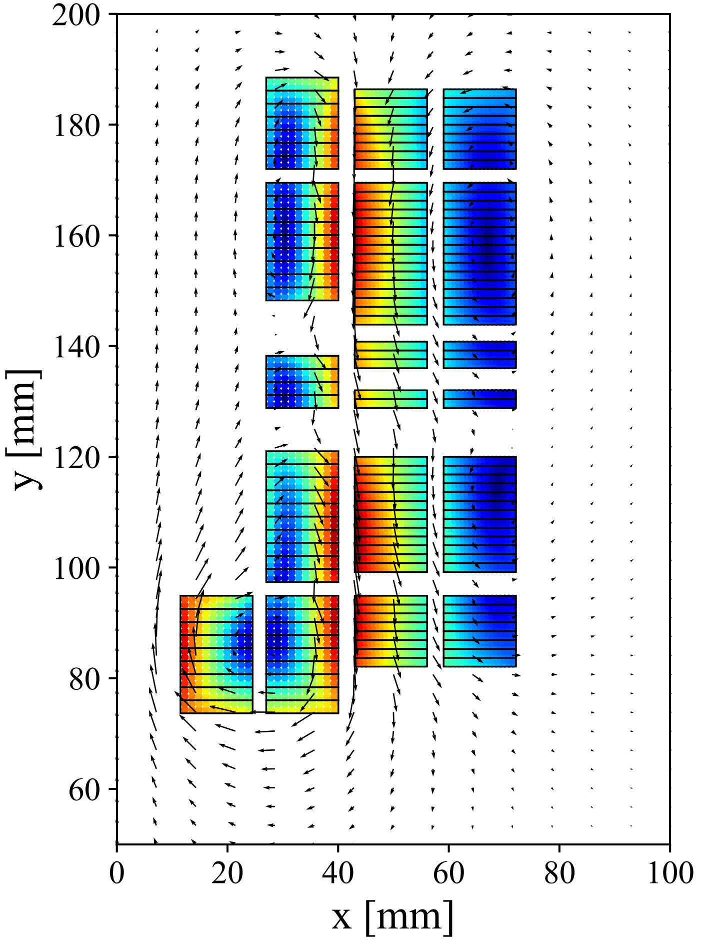
CLIQ-C3



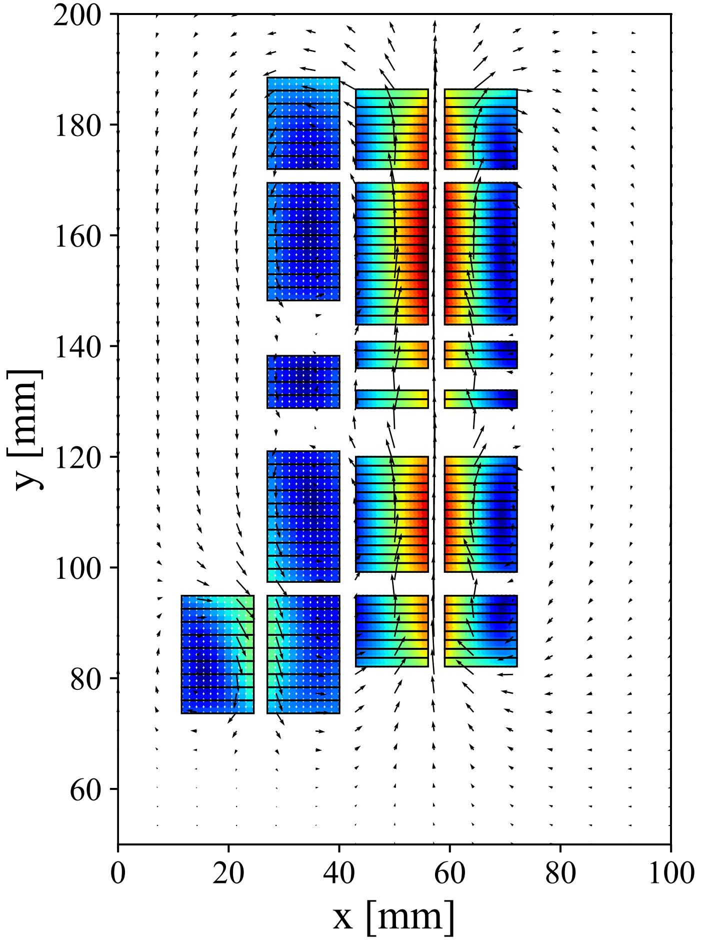
CLIQ PERFORMANCE CAN BE GREATLY ENHANCED BY SELECTING THE OPTIMUM CONFIGURATION

CLIQ optimization

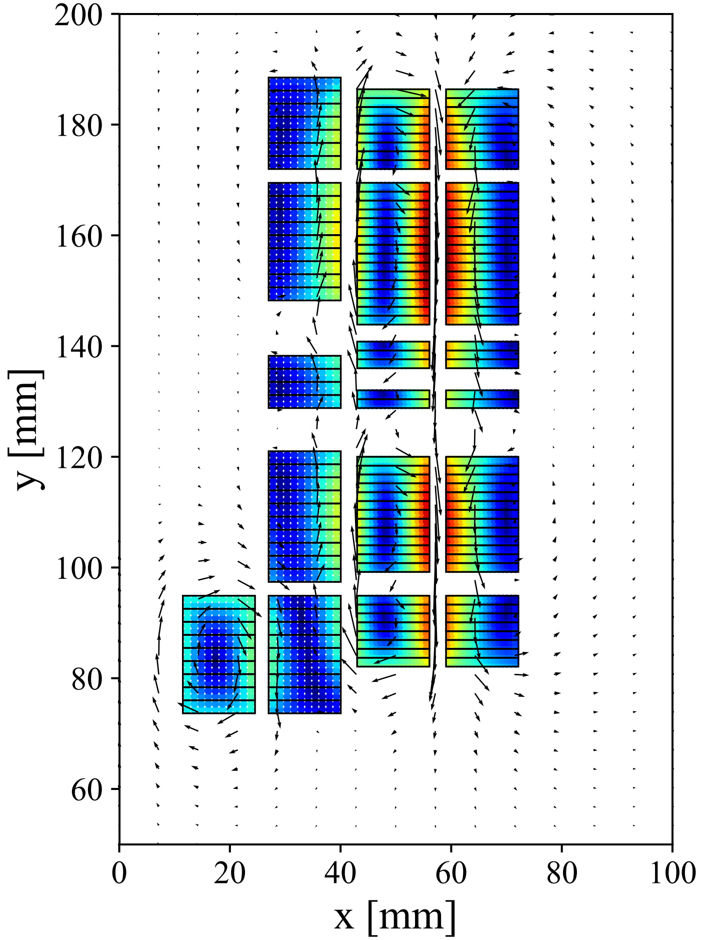
CLIQ-C1



CLIQ-C2

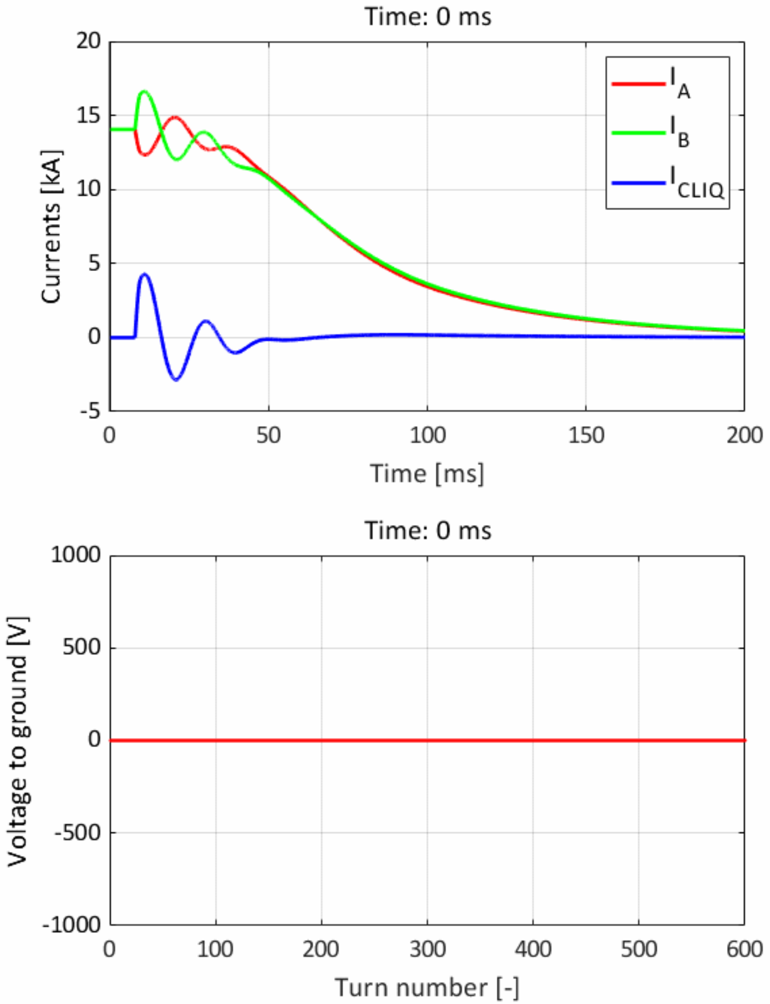


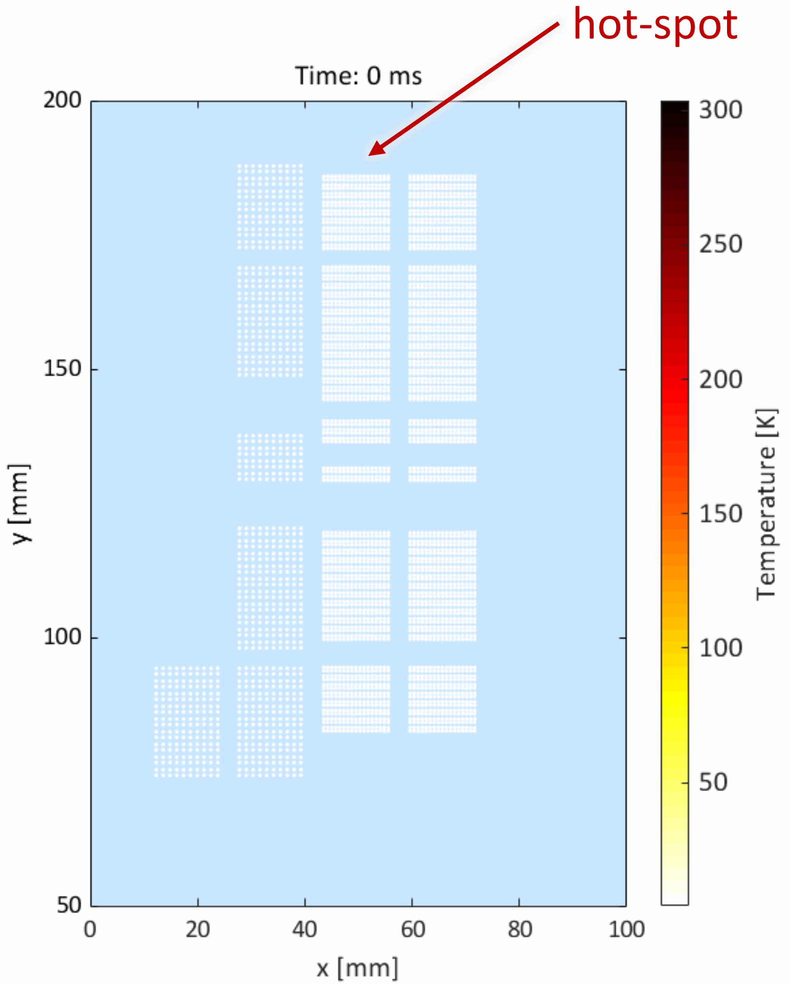
CLIQ-C3



CLIQ PERFORMANCE CAN BE GREATLY ENHANCED BY SELECTING THE OPTIMUM CONFIGURATION

Quench protection with 50 mF, 300 V CLIQ-C3 system





Very fast quench
(most turns quenched in <5 ms)

Hot-spot temperature ~310 K
Peak voltage to ground <200 V

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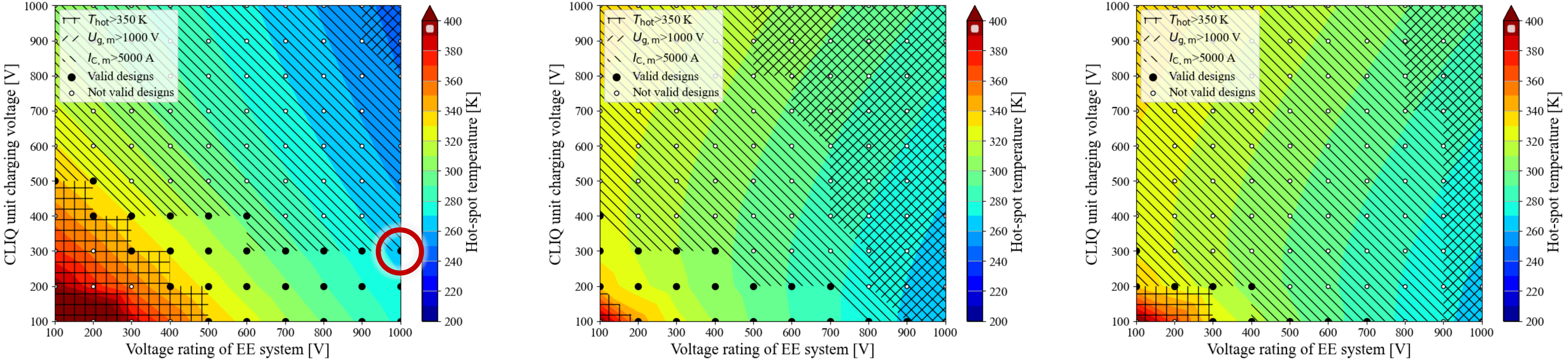
Energy extraction + CLIQ optimization

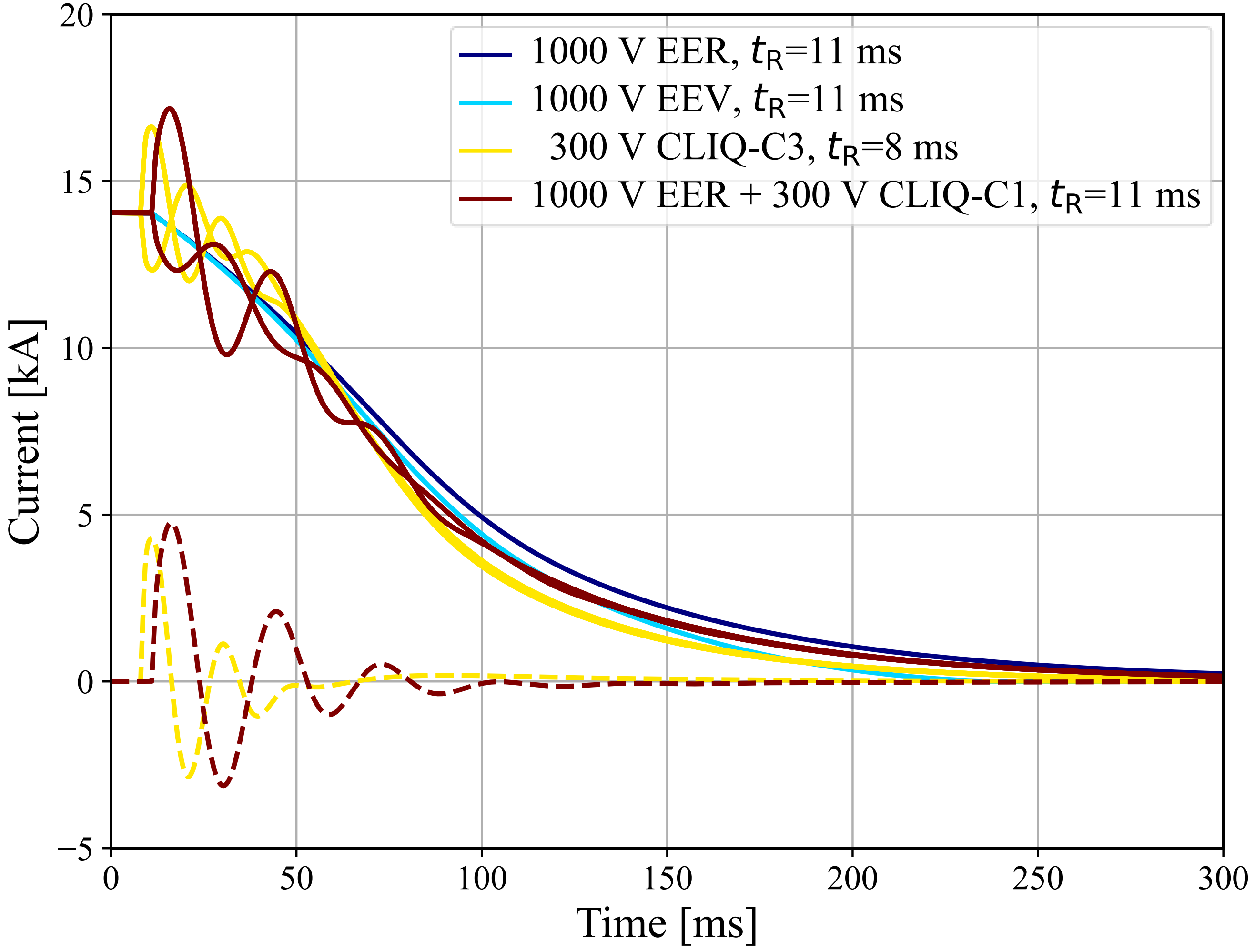
EE + CLIQ-C1	EE + CLIQ-C2	EE + CLIQ-C3



Parametric study to identify the combinations of CLIQ configuration, CLIQ charging voltage, and EE voltage rating that satisfy all requirements in terms of hot-spot temperature (T_{hot}<350 K), peak voltage to ground ($U_{g,m}$<1000 V), and peak CLIQ current ($I_{C,m}$<5 kA)

Recommendation: CLIQ "Configuration 1", 300 V CLIQ + 1 kV EE
Low hot-spot temperature. Redundancy. Easiest to implement CLIQ configuration.

Currents versus time for the different quench protection options



All options can protect the magnet if the total reaction time is <11 ms

CLIQ charged to low-medium voltage achieves sufficiently low temperature with 4-5 times lower voltage to ground

Energy extraction plus CLIQ achieves the lowest hot-spot temperature overall

Recommendation: CLIQ "Configuration 1", 300 V CLIQ + 1 kV EE

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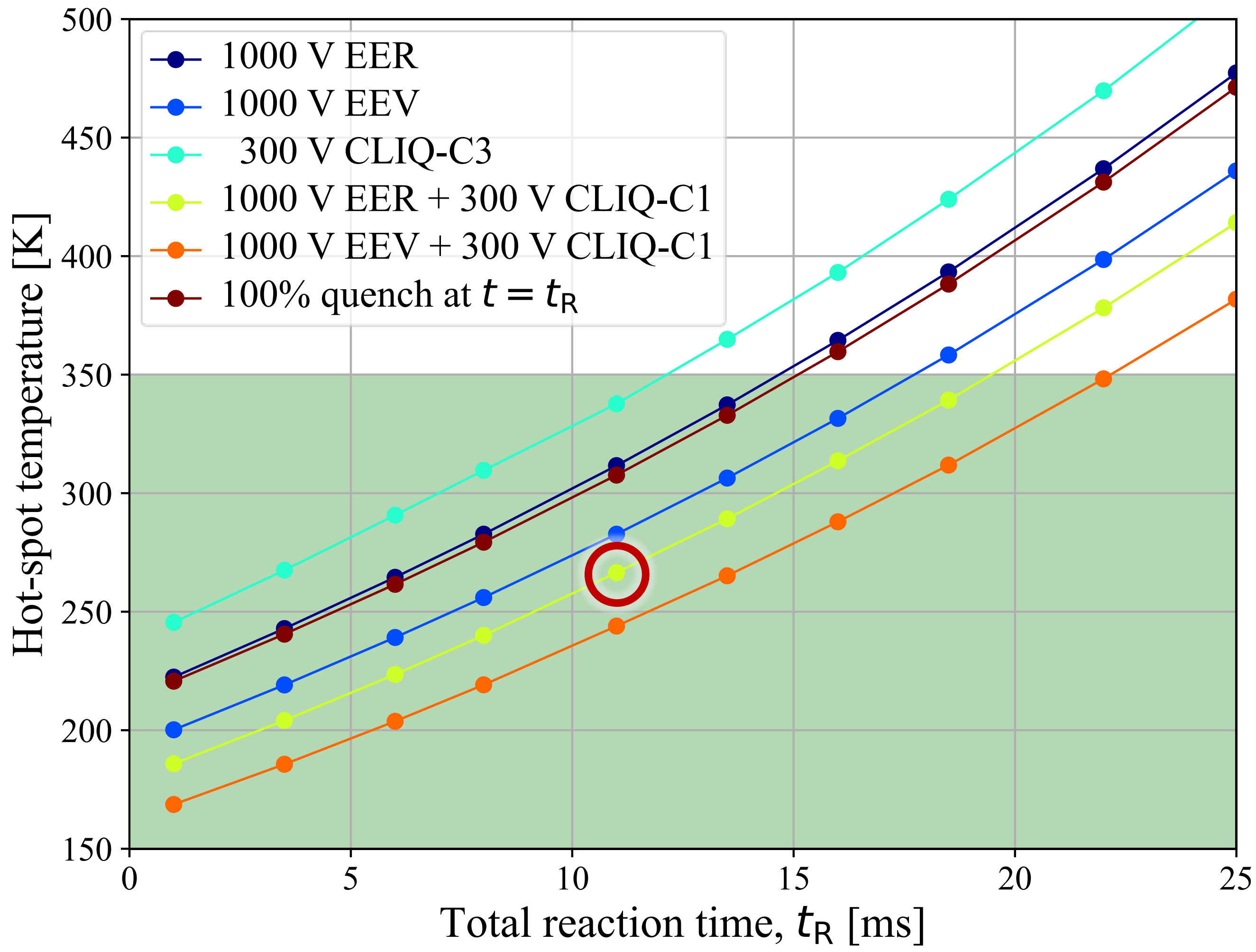
Hot-spot temperature as a function of total reaction time



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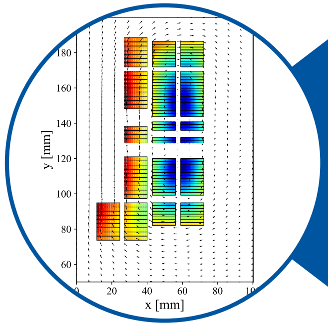
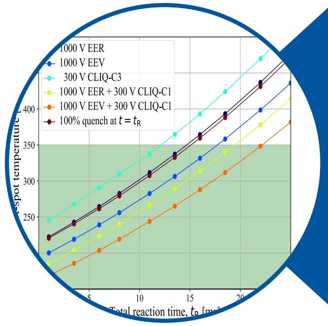
Conclusion

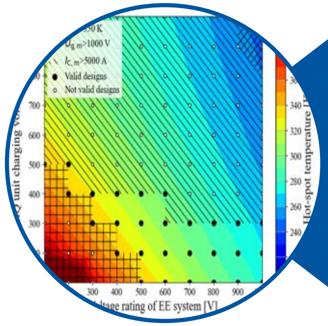


Quench protection of 13 T common-coil SMACC magnet (PSI)



Five quench protection strategies are analyzed and compared

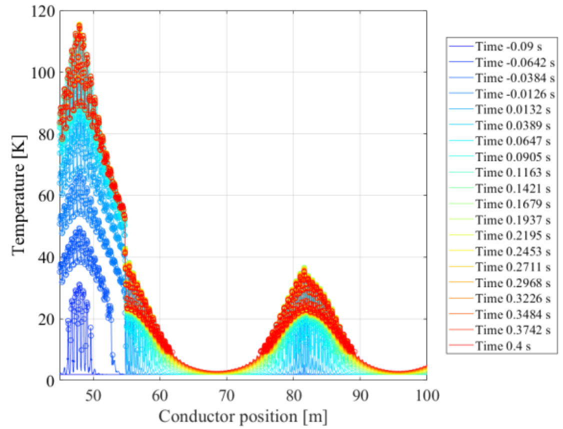
- Energy extraction with constant resistor
- Energy extraction with varistor
- CLIQ
- Energy extraction with constant resistor + CLIQ
- Energy extraction with varistor + CLIQ

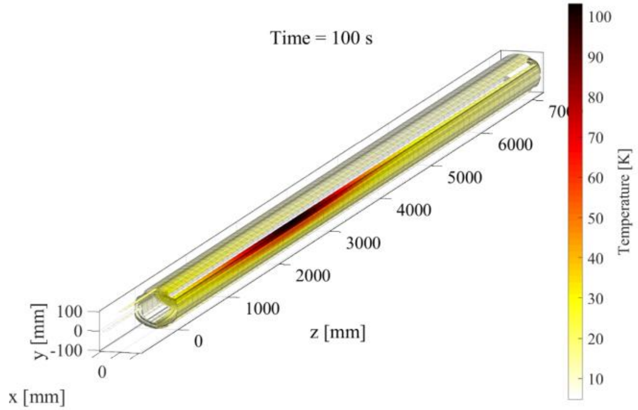


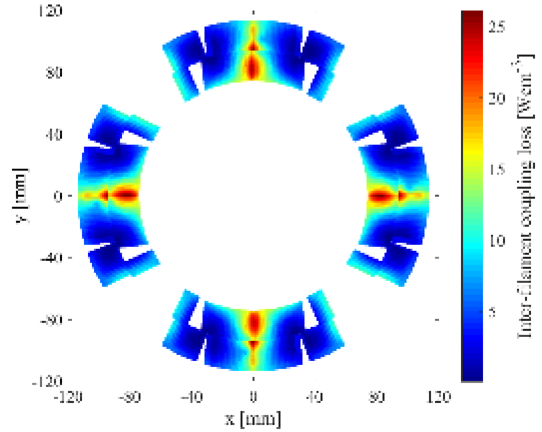
Optimized CLIQ connection configuration, CLIQ voltage, EE voltage rating

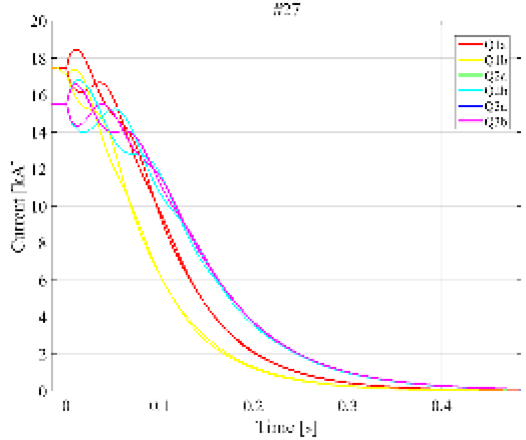
Recommendation: CLIQ "Configuration 1", 300 V CLIQ + 1 kV EE

→Low hot-spot temperature. Redundancy. Easiest to implement CLIQ config.





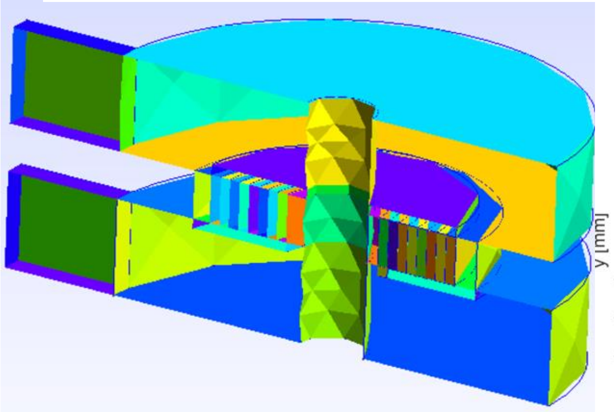


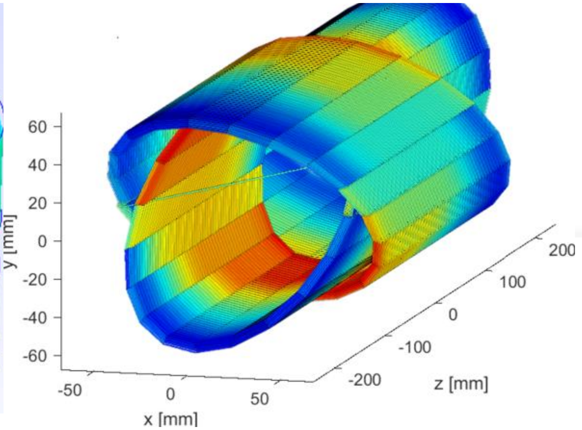


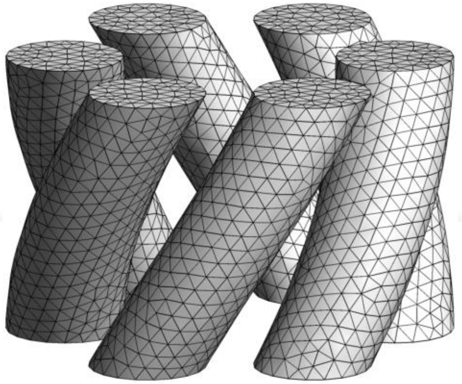
All simulations presented today were performed with LEDET, a program that is part of the STEAM framework developed at CERN

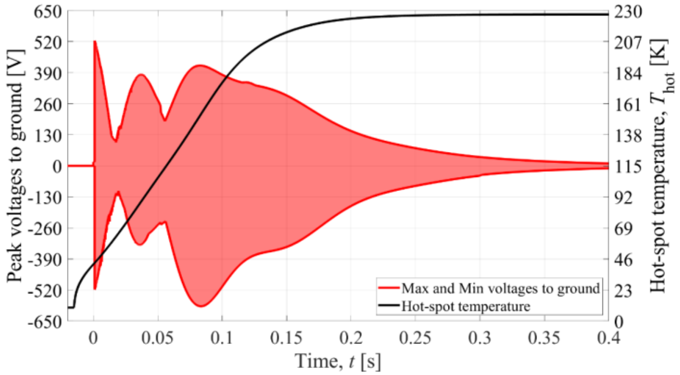
All STEAM programs are available free of charge for the community

Interested? Visit us → https://espace.cern.ch/steam or Contact us → steam-team@cern.ch







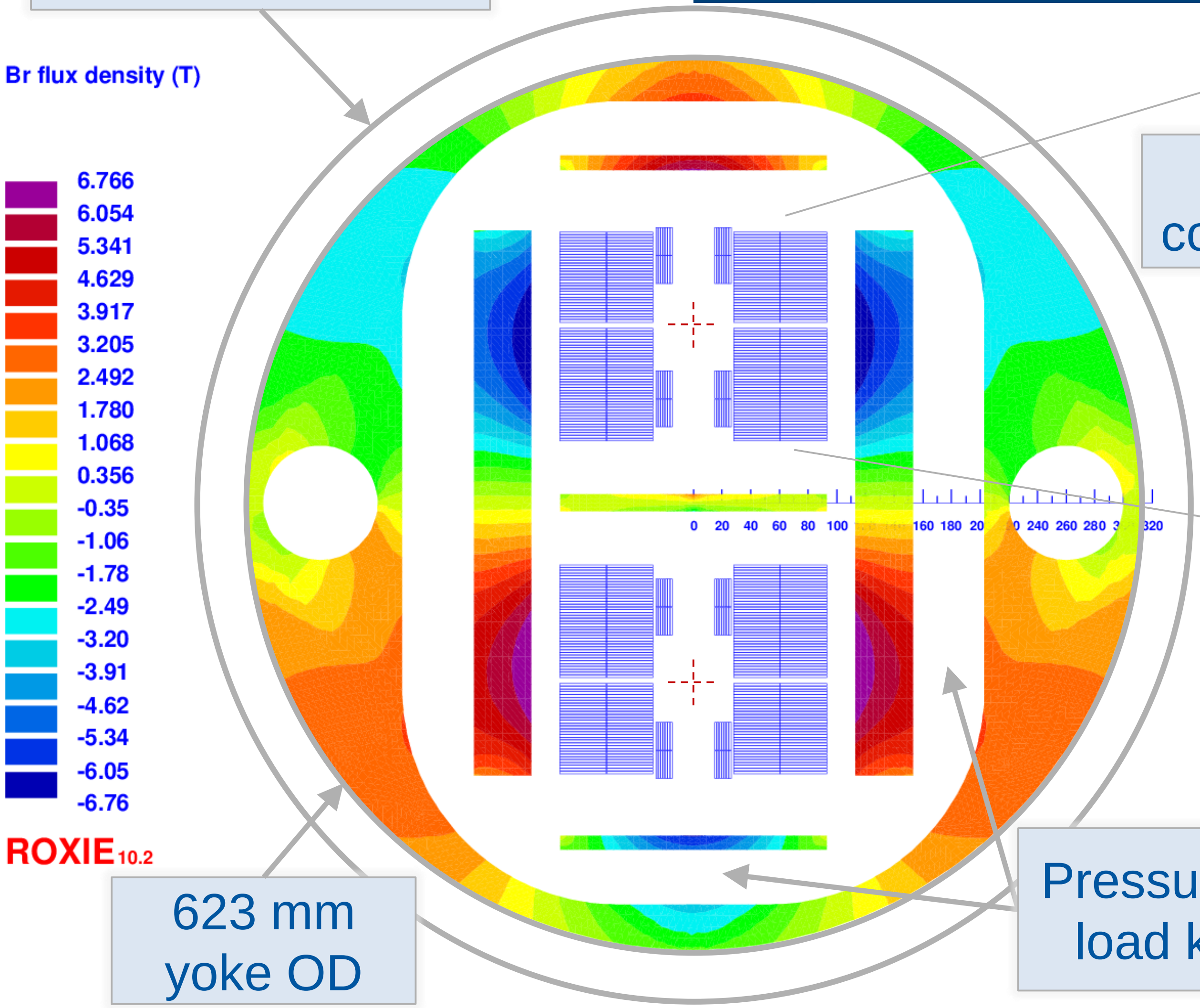


Annex

Asymmetric common-coil by GL. Sabbi and E. Ravaioli (LBNL)

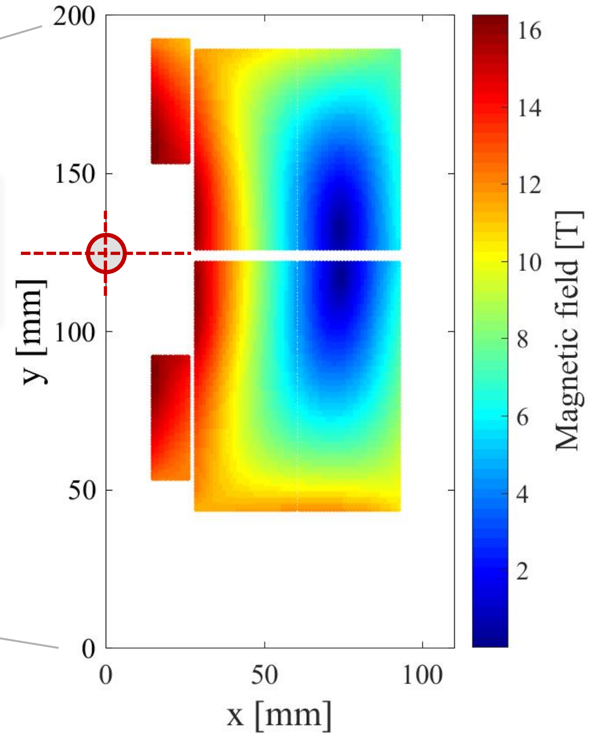
Magnet cross-section

4 cm thick Al shell



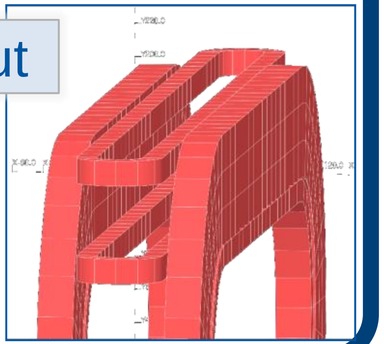
623 mm yoke OD

Top-bottom coil asymmetry



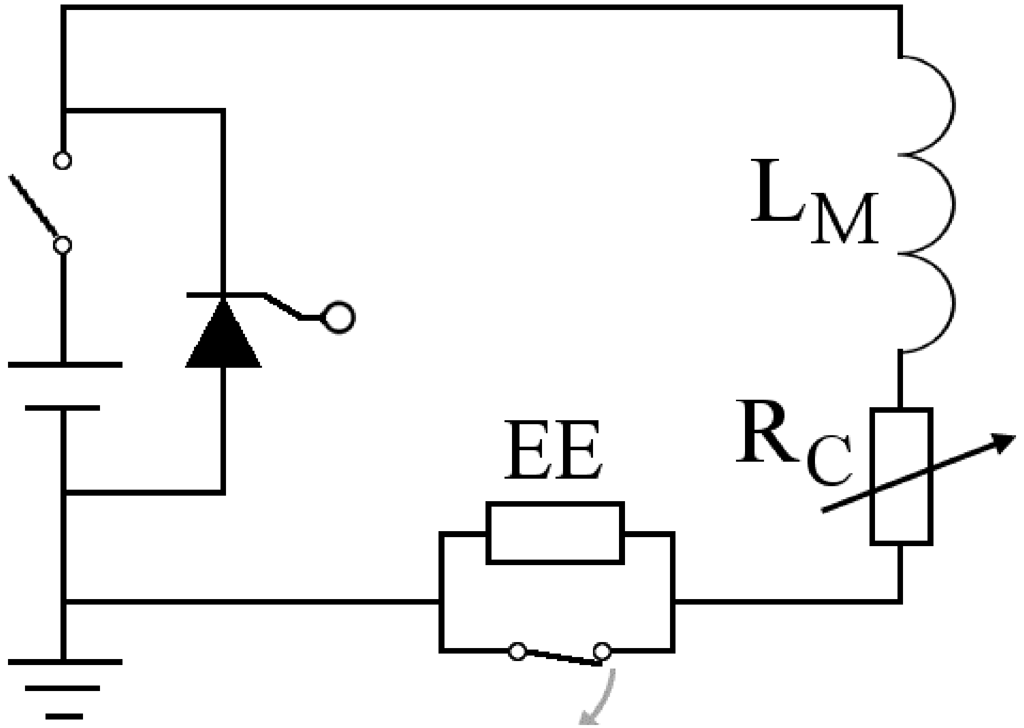
Pressured bladders and load keys for preload

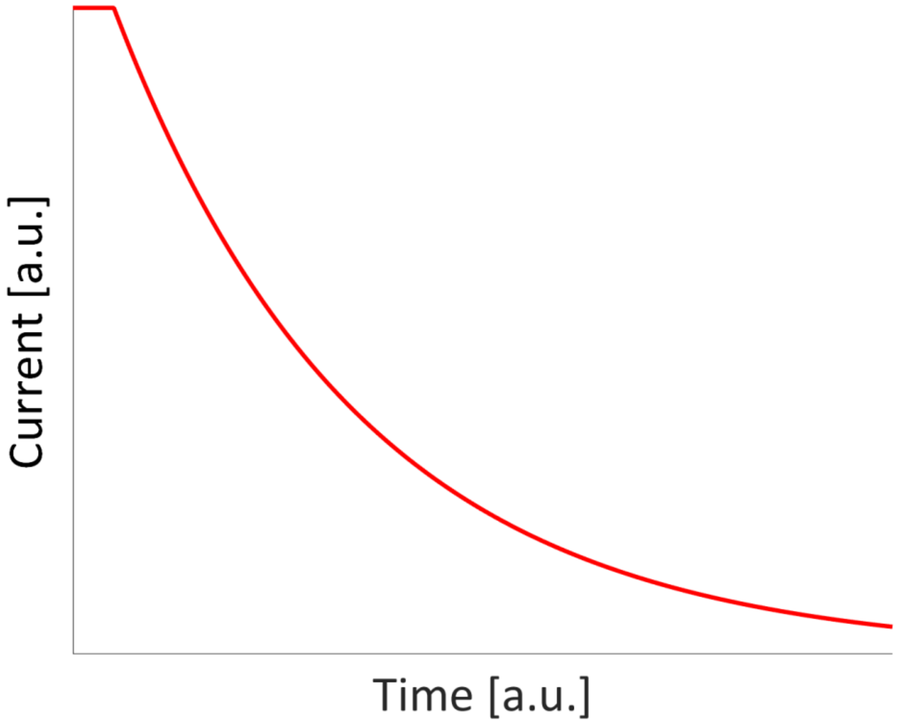
3D end layout



From FCC Week 2017

Energy extraction system (EE)



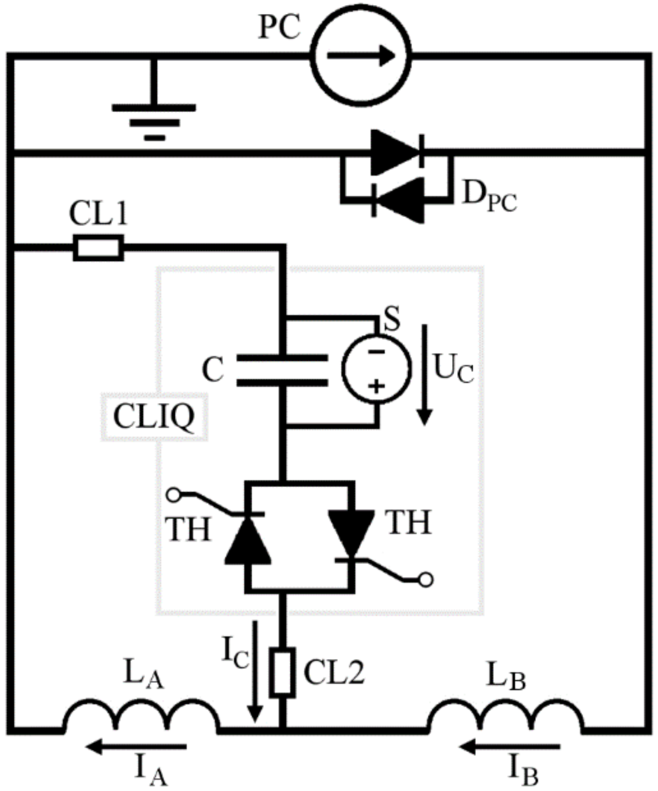


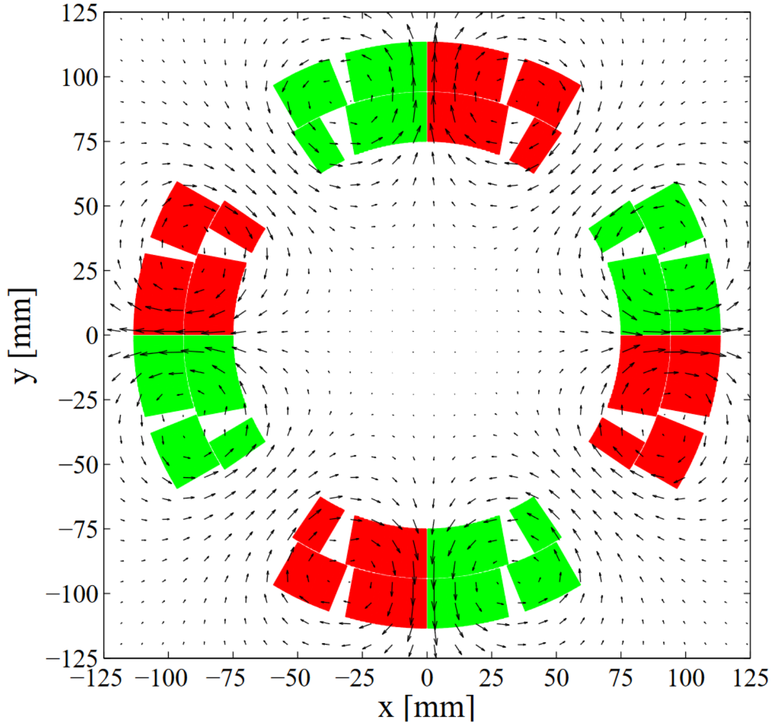
Advantages
- Straightforward design and implementation
- Extracts energy from the cryostat

Disadvantages
- Can be large and expensive for high current magnets
- Impractically high voltage needed for high current density magnets
- **Can't be applied to a chain of high-field magnets**

Note: EE of LHC main dipole circuits doesn't protect magnets

Coupling-Loss Induced Quench (CLIQ)





Current change

Field change

Transient losses

Temperature increase

Coil SC→resistive

Magnet energy discharged

Reduced hot-spot temperature

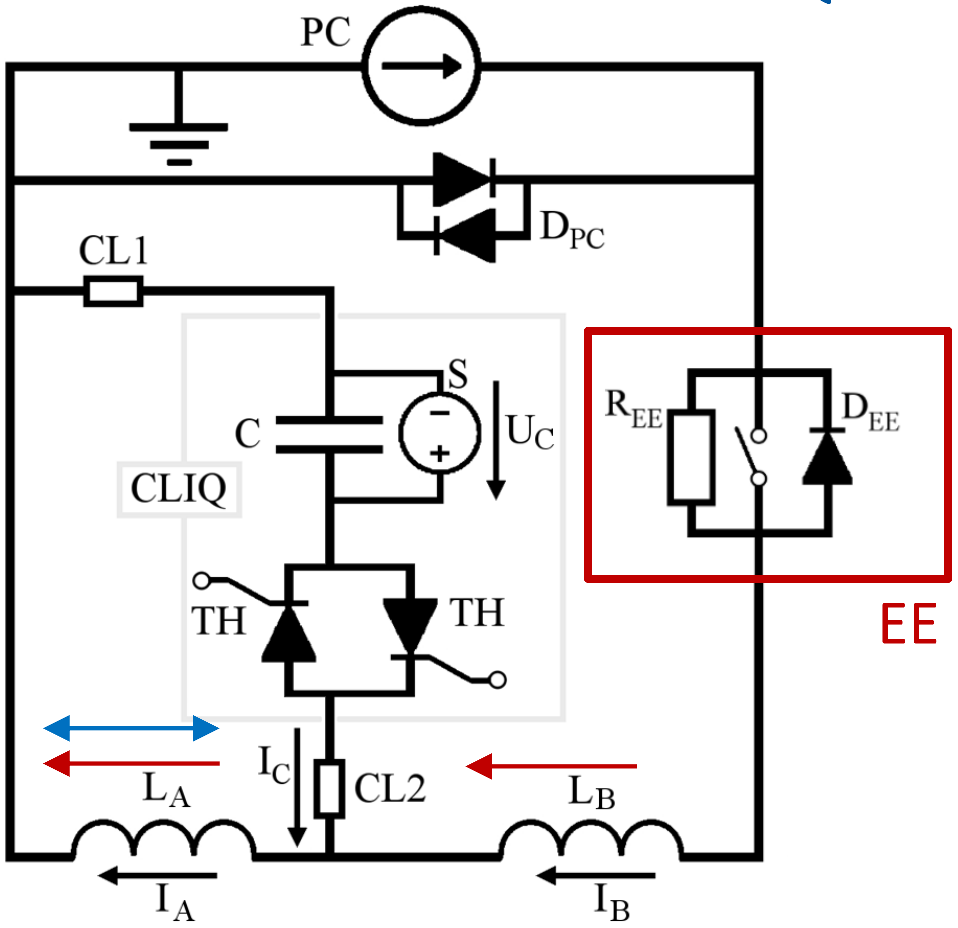
Advantages

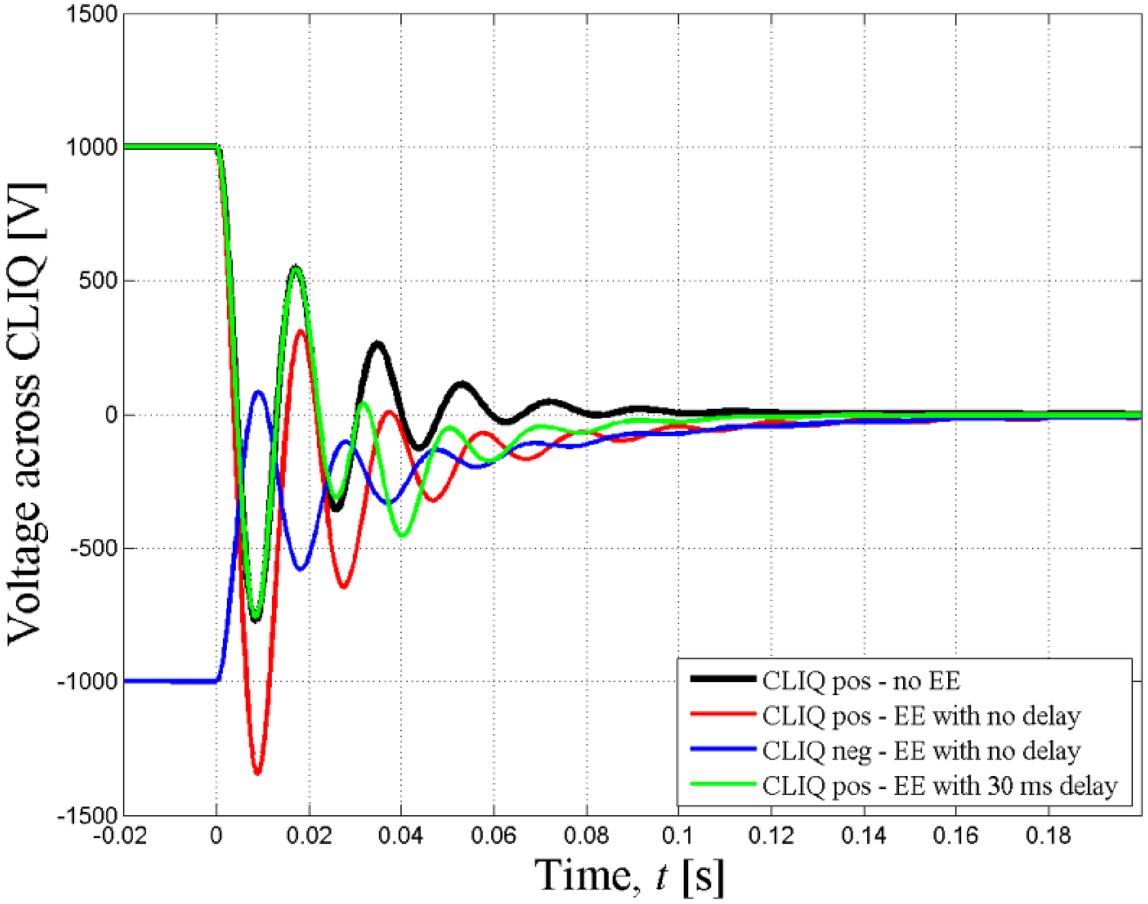
- Fast and effective heat deposition
- Heat deposited simultaneously in most of the coil volume
- Electrically robust system

Disadvantages

- Direct electrical connection to the magnet circuit
- Challenging to make it redundant
- Additional asymmetric forces on the magnet coils

Interaction between CLIQ and energy extraction (EE) system





Discussion

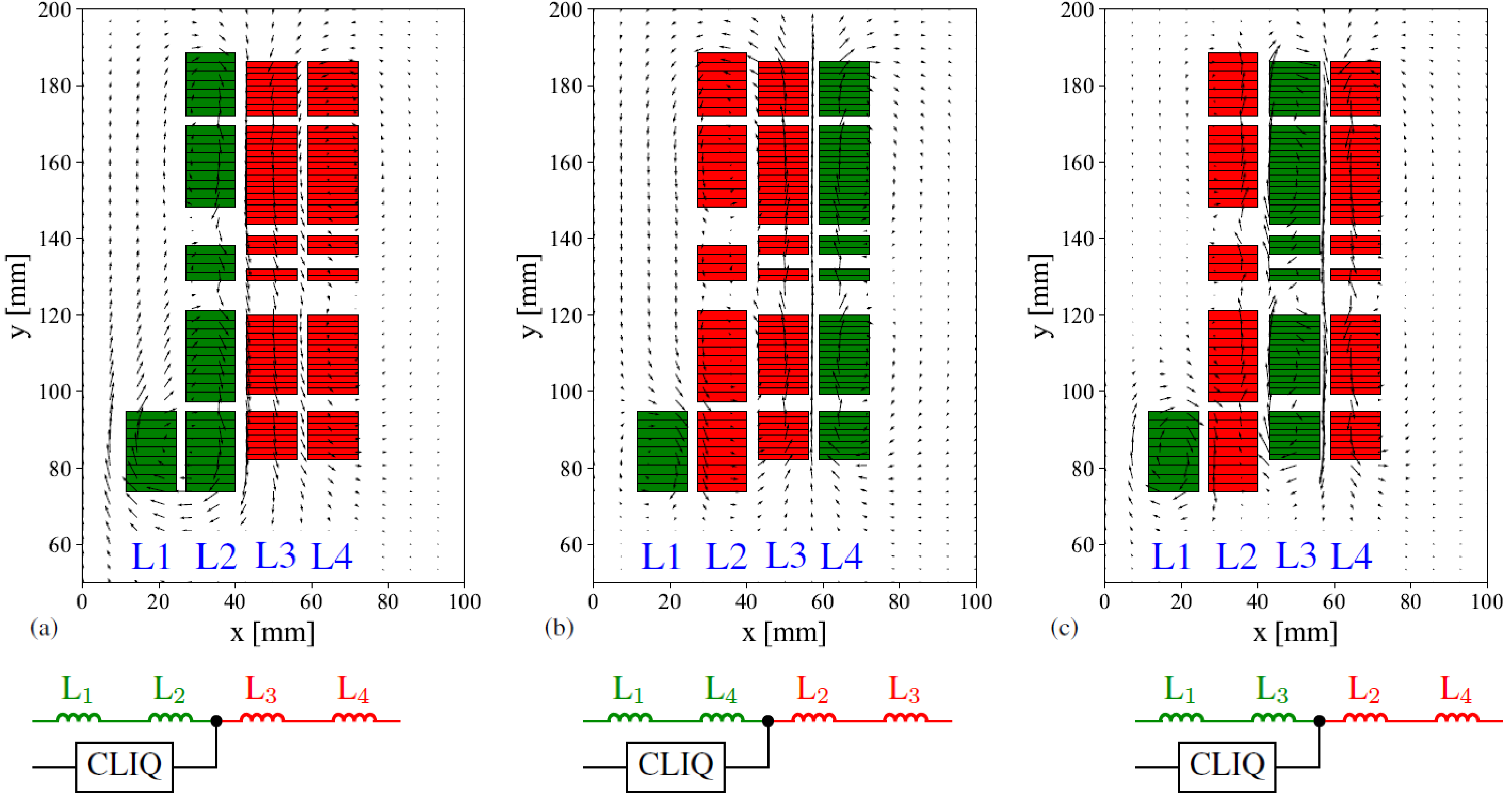
- Is it possible/recommended to test and EE system together?
- positive polarity → Superposition of voltage across CLIQ and across EE causes higher voltage to ground
- negative polarity → Subtraction of voltage across CLIQ and across EE reduces CLIQ performance

Summary of quench protection results

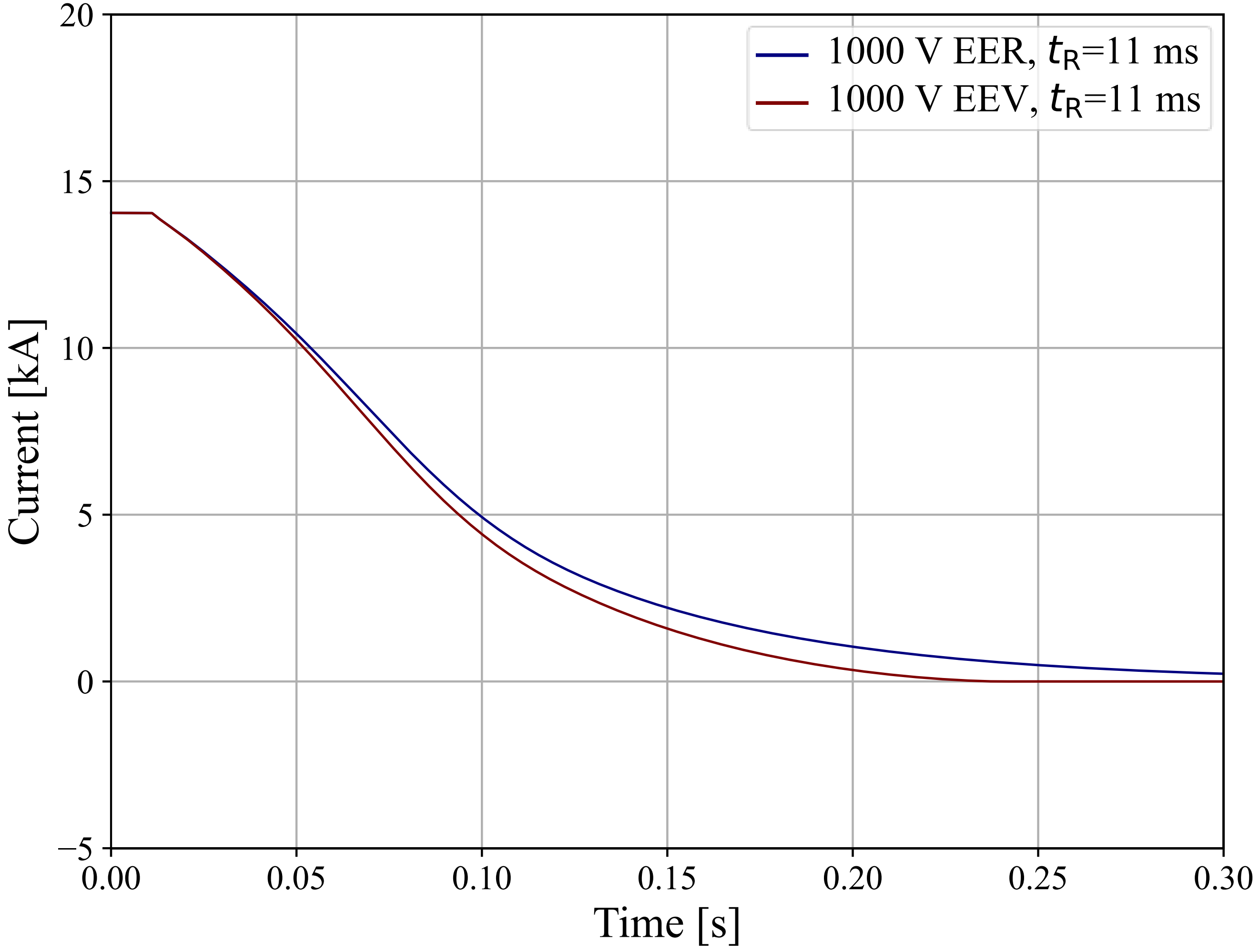
TABLE III
MAIN QUENCH PROTECTION RESULTS AT NOMINAL CURRENT

Protection system	t_R [ms]	T_{hot} [K]	$U_{g,m}$ [V]	$I_{C,m}$ [kA]
1000 V EER	11	312	1000	-
1000 V EEV	11	283	1000	-
500 V CLIQ-C1	8	321	250	4.5
400 V CLIQ-C2	8	305	199	4.4
300 V CLIQ-C3	8	310	184	4.3
1000 V EER +300 V CLIQ-C1	11	266	1000	4.8
900 V EER +100 V CLIQ-C2	11	268	958	4.7
700 V EER +100 V CLIQ-C3	11	285	711	4.9
1000 V EEV +300 V CLIQ-C1	11	244	1000	4.9
900 V EEV +100 V CLIQ-C2	11	254	958	4.9
600 V EEV +100 V CLIQ-C3	11	283	605	4.7
Ideal 100% quench	8	279	396	-

Electrical connections of CLIQ configurations

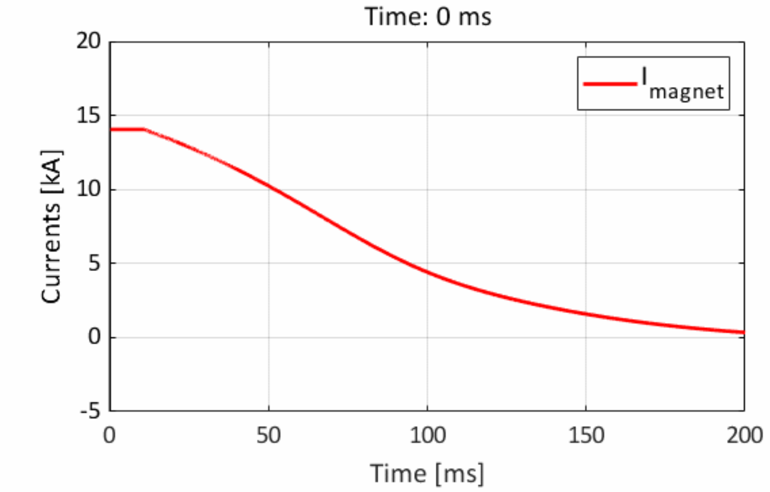


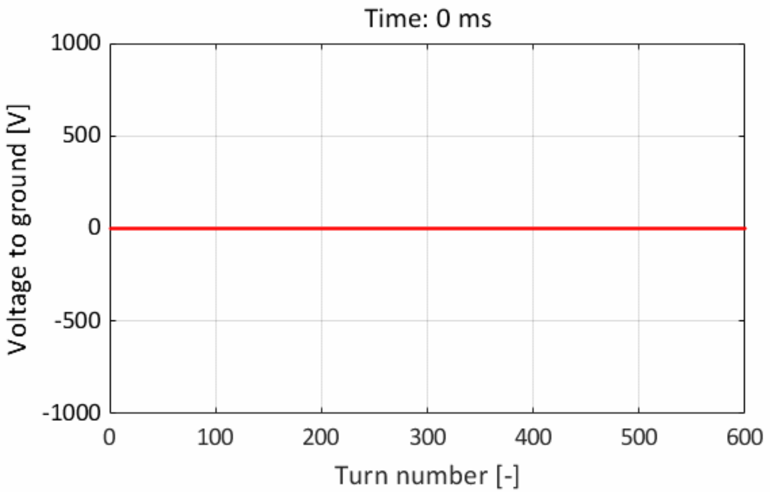
Currents versus time for the different EE protection options

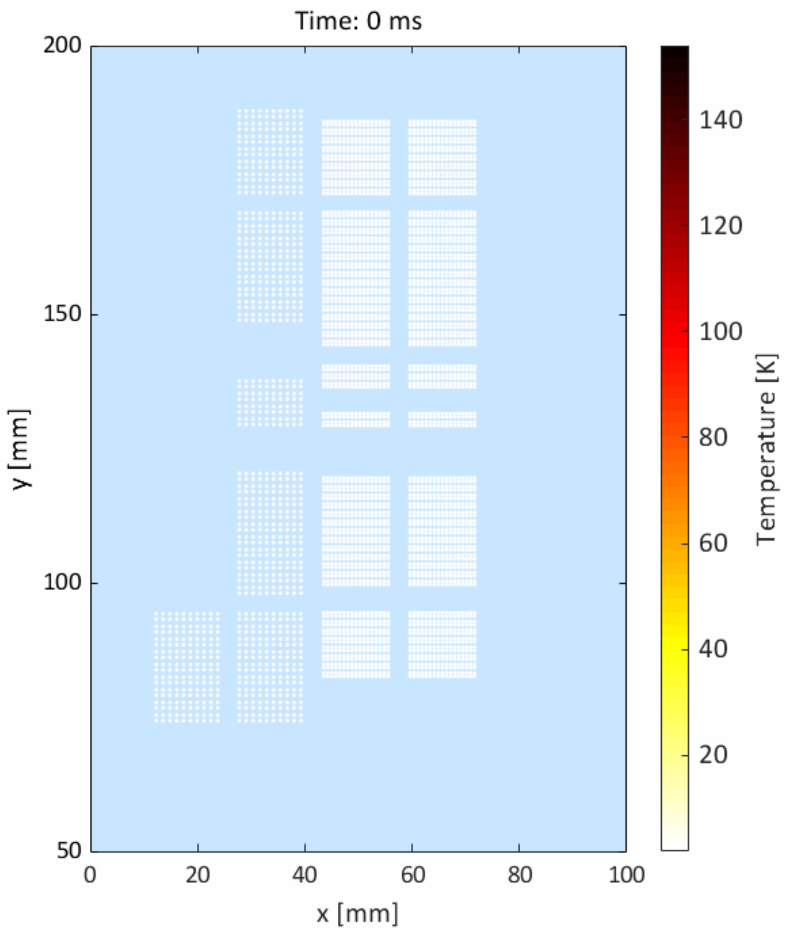


Varistor (EEV) marginally improves quench protection (20-40 K temperature reduction)

Quench protection with 1 kV energy extraction with varistor







The presence of quench-back influences significantly the transient

→ Reduction of differential inductance
→ Quench-back (coil resistance increase due to transient losses)

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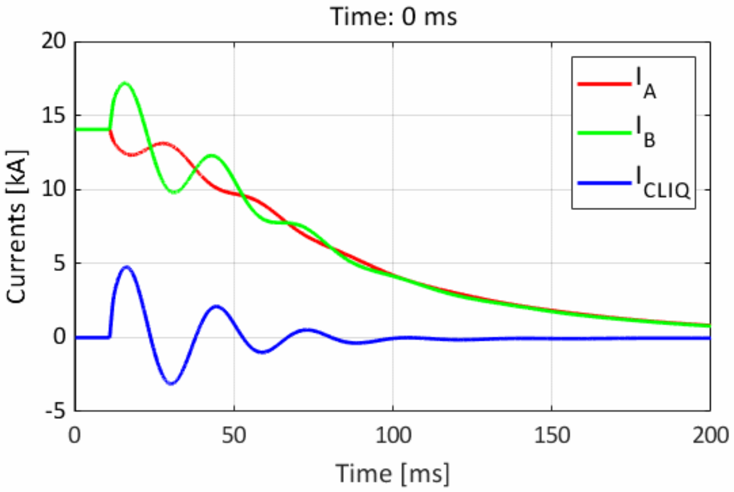
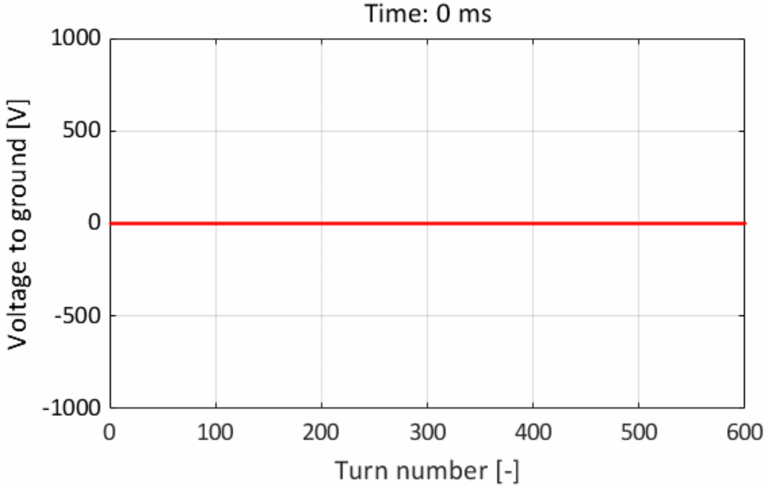
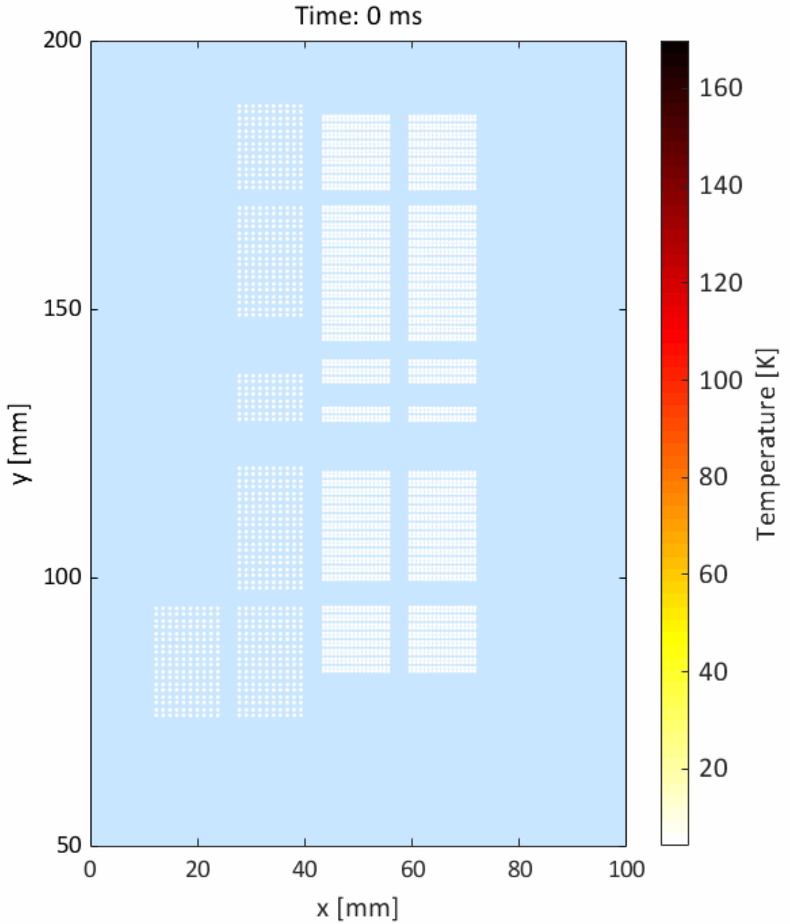
Quench protection with 1 kV EE + 50 mF, 300 V CLIQ-C1 system







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