Quench protection of the PSI Subscale Stress-managed common-coil magnet

E. Ravaioli (CERN)

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Meeting on the PSI Subscale Stress-managed common-coil test campaign

14 December 2023

Quench protection of the PSI subscale common-coil magnet

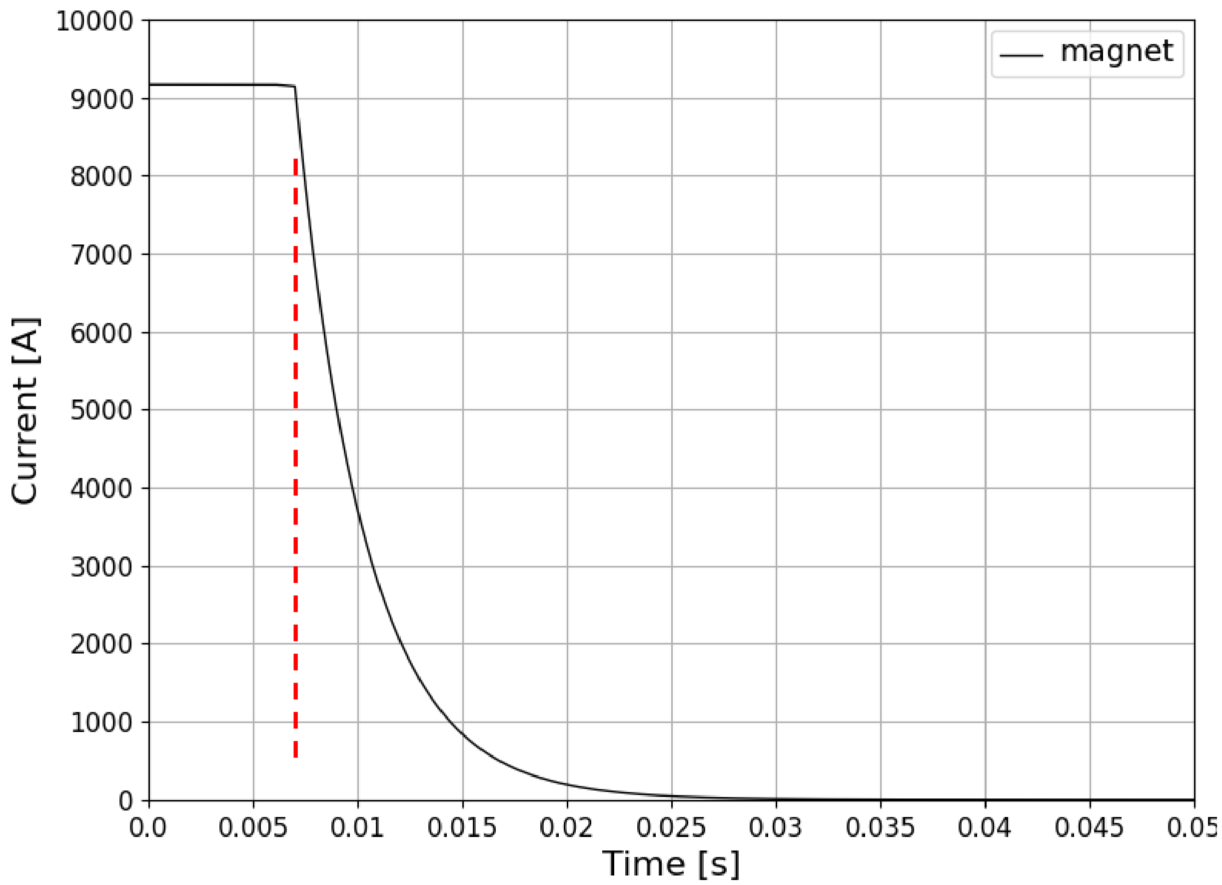
Quench protection based on EE

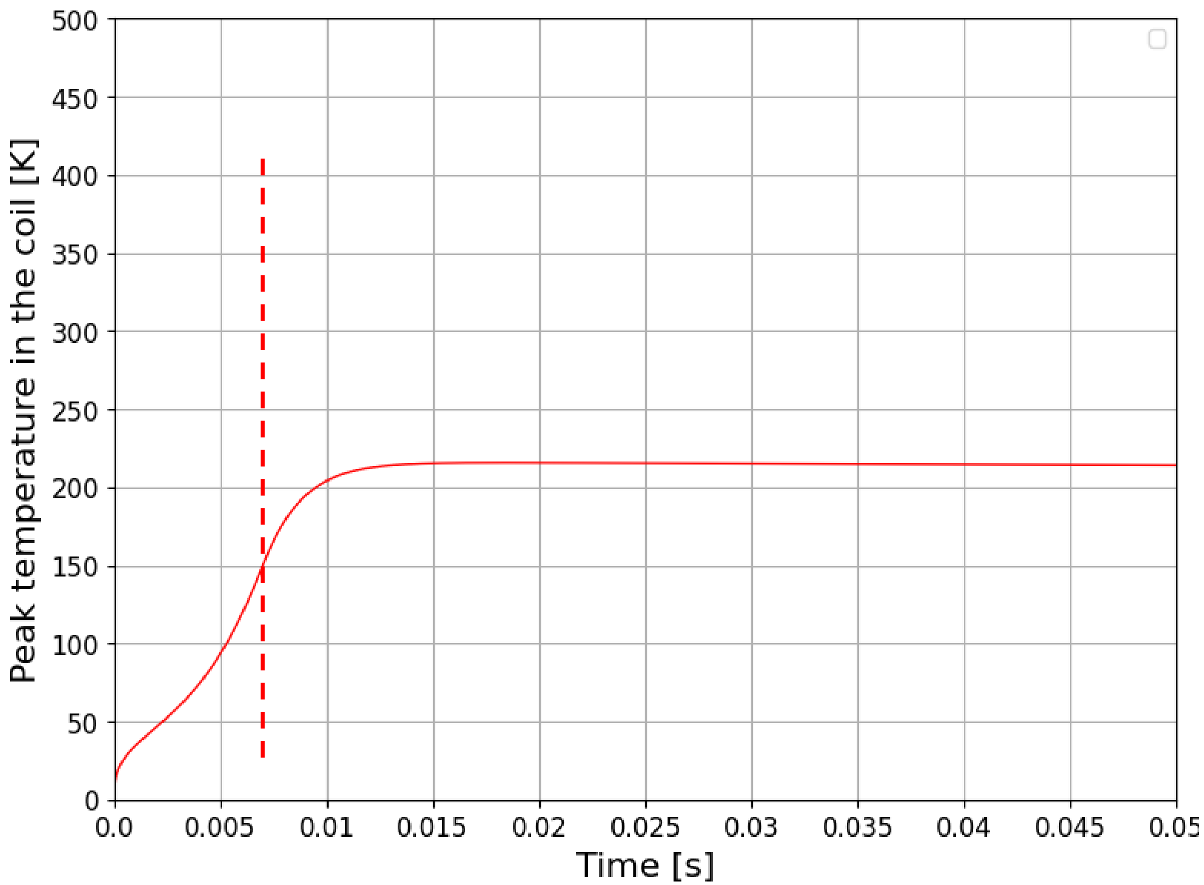
- *Baseline – used for most tests*
- *Goal: Assure the safe magnet protection while testing magnet performance*

Quench protection based on ESC

- *Preliminary results*
- *Goal: Test the ESC method performance (of course without destroying the coil)*

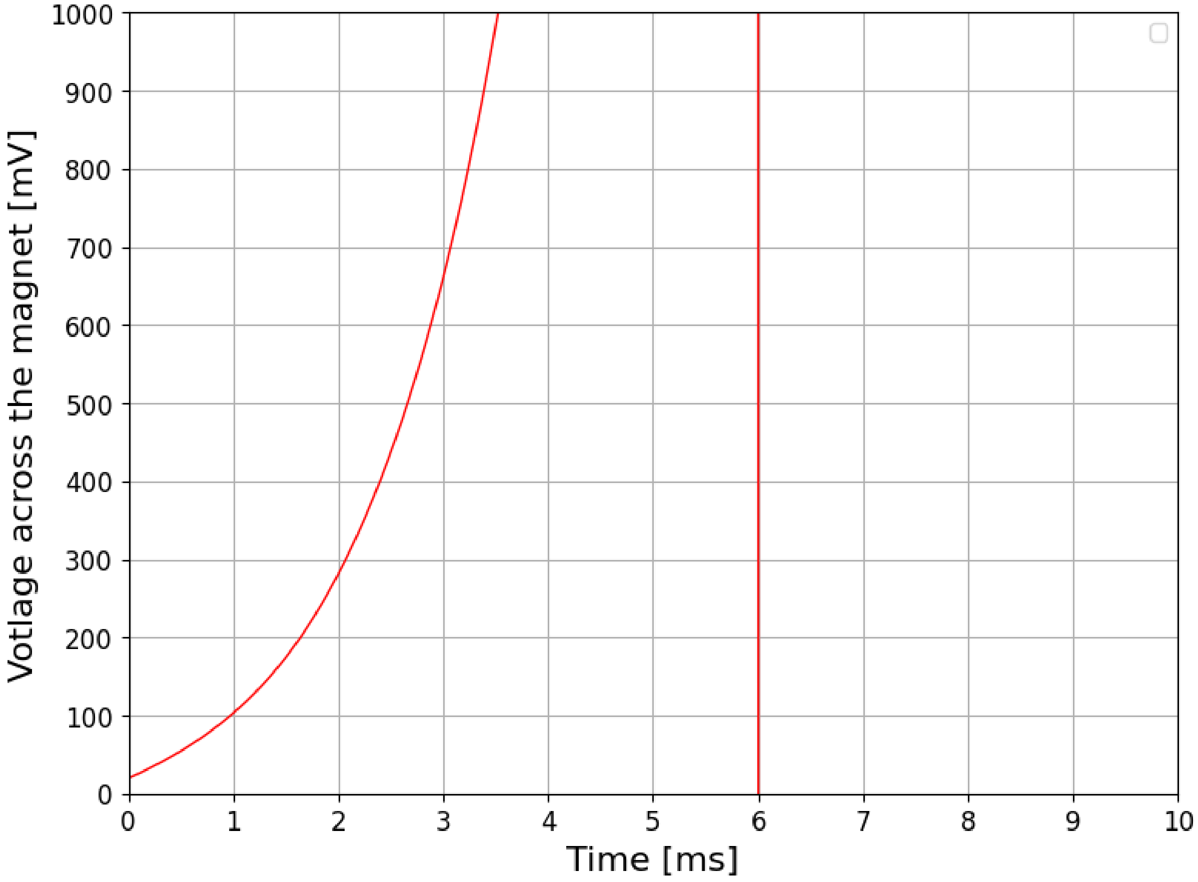
Quench protection based on energy extraction (EE)





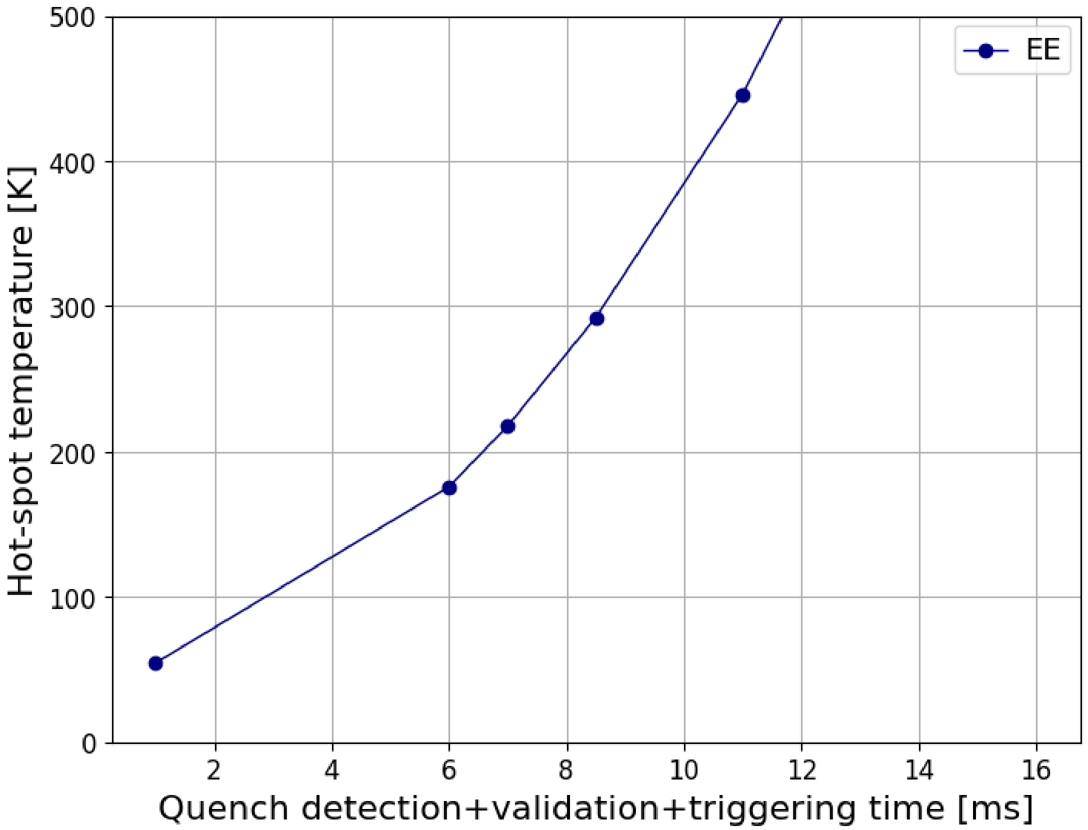
For R_EE=110 mΩ (i.e. peak voltage across the magnet of 1 kV) and quench detection+validation+trigger time of 7 ms

Quench detection

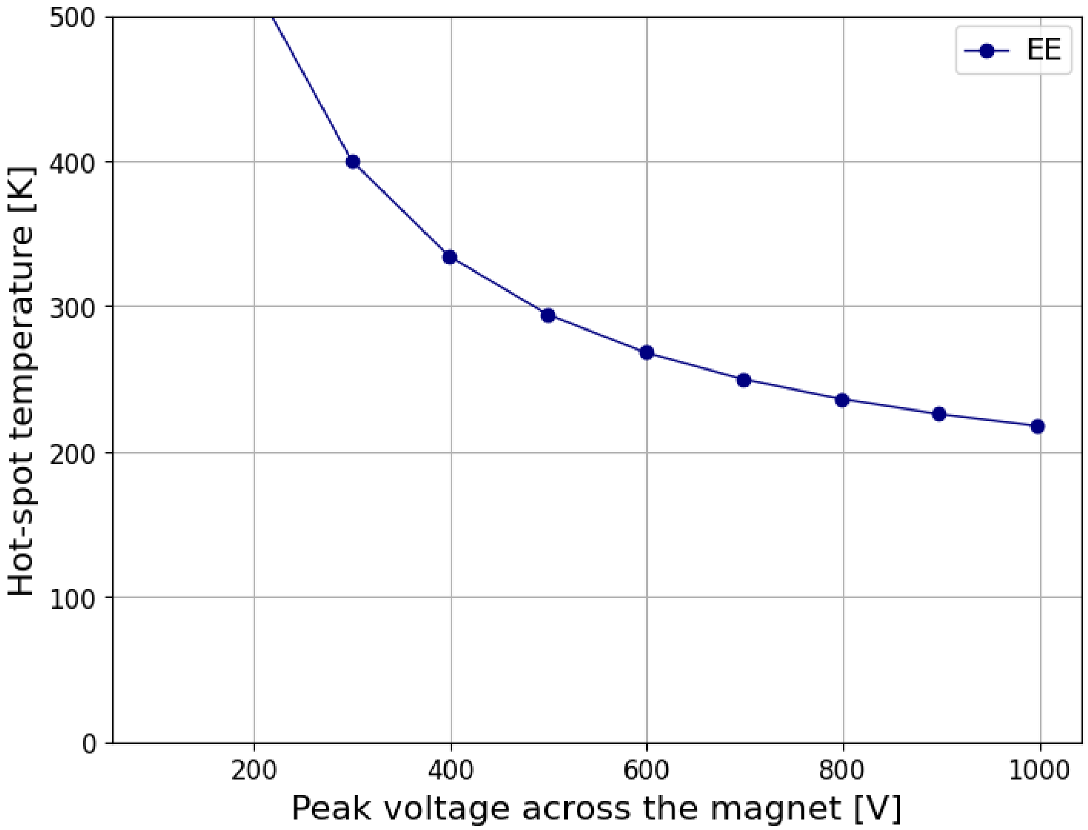


At I_{max}=9166 A, quench in the high field turn: 100 mV reached in 1 ms. 5 ms validation time seems achievable.

The challenge: Quench detection

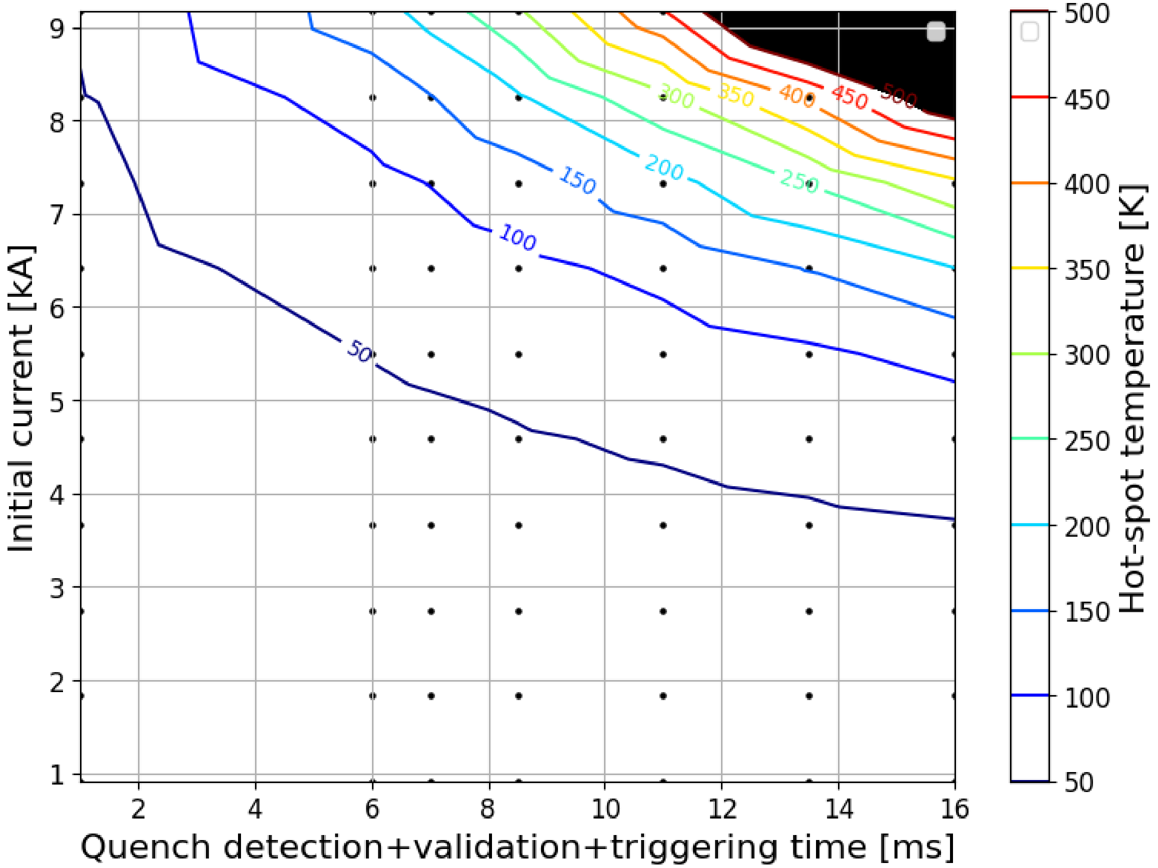


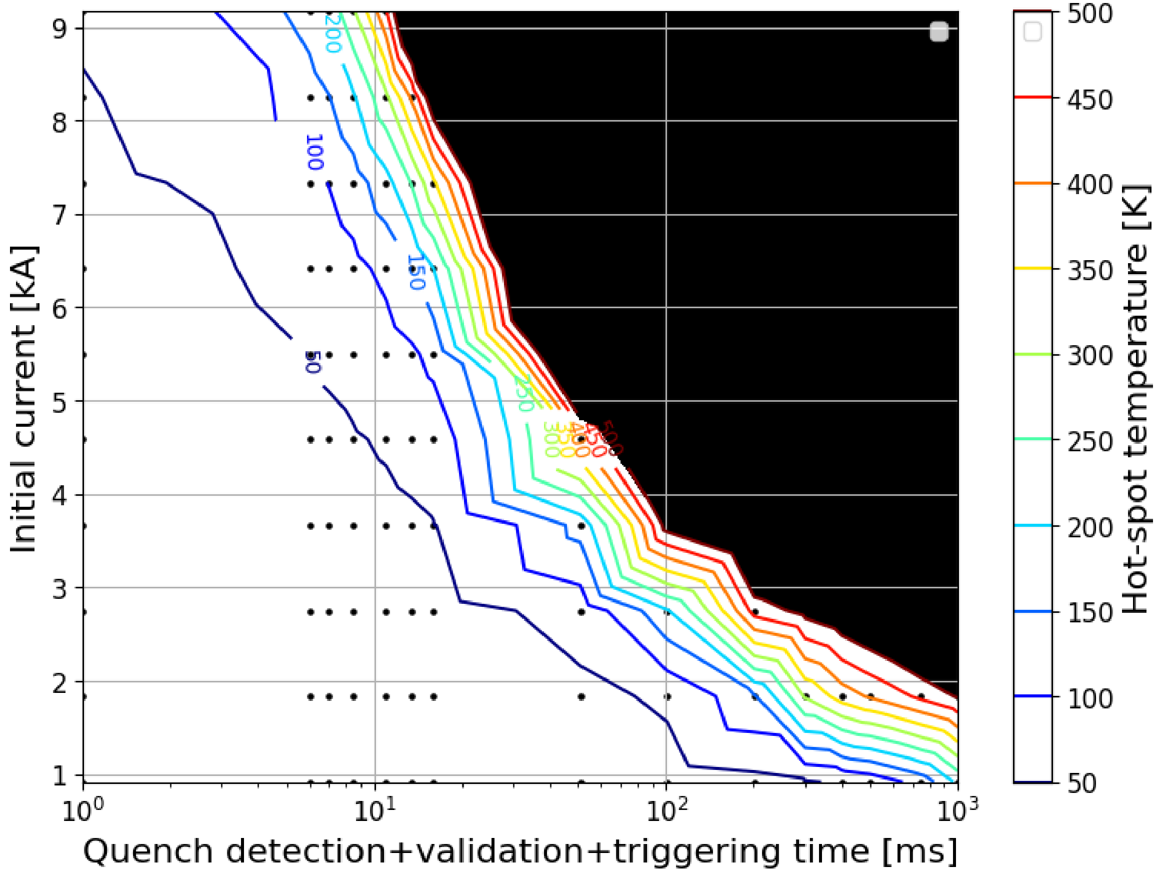
For peak voltage across the magnet of 1 kV



For quench detection+validation+trigger time of 7 ms

Quench protection at different current levels





Quench protection based on EE – Conclusions

- This magnet is actually quite challenging to protect
- Quench detection and protection seem tight but feasible with 1 kV energy extraction
- Quench detection will be the key
  - At maximum current, proposed targets are 1 ms + 5 ms + 1 ms for quench detection + validation + trigger
  - At lower and medium current levels, increased threshold to avoid spurious triggering because of flux jumps will result in longer quench detection → **input needed in order to estimate how critical it is**

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Quench protection based on ESC
- *Preliminary results*
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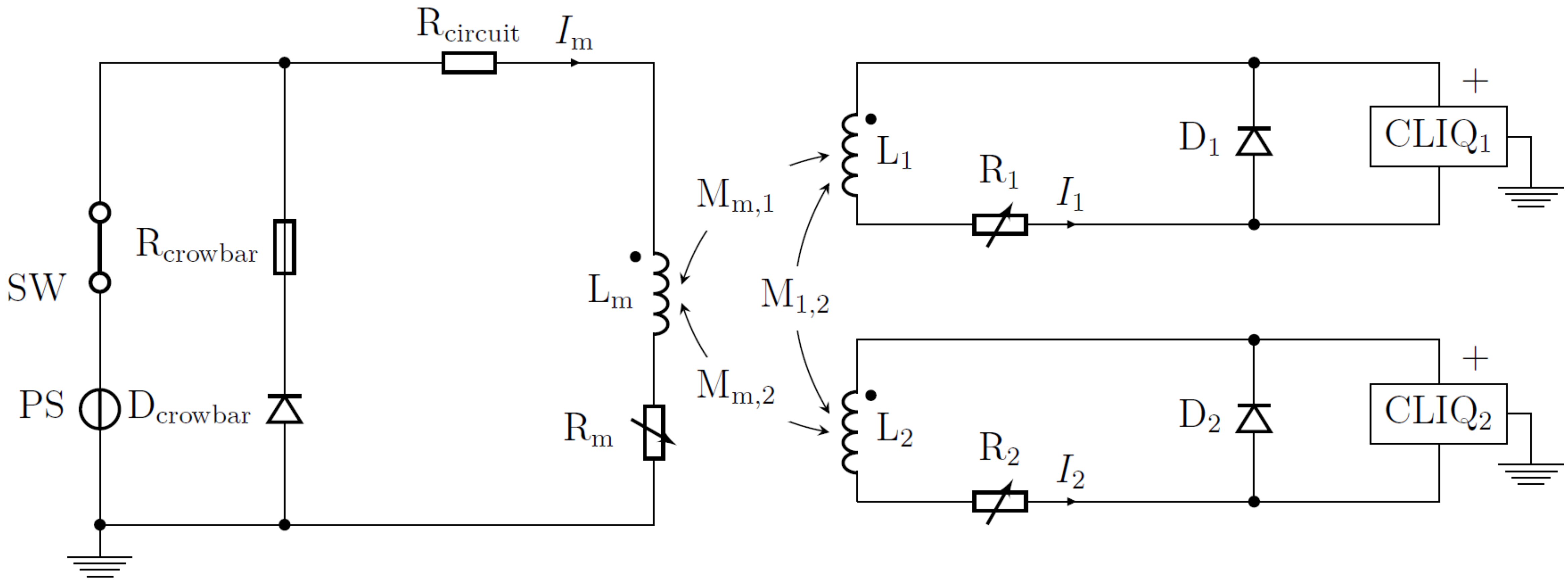
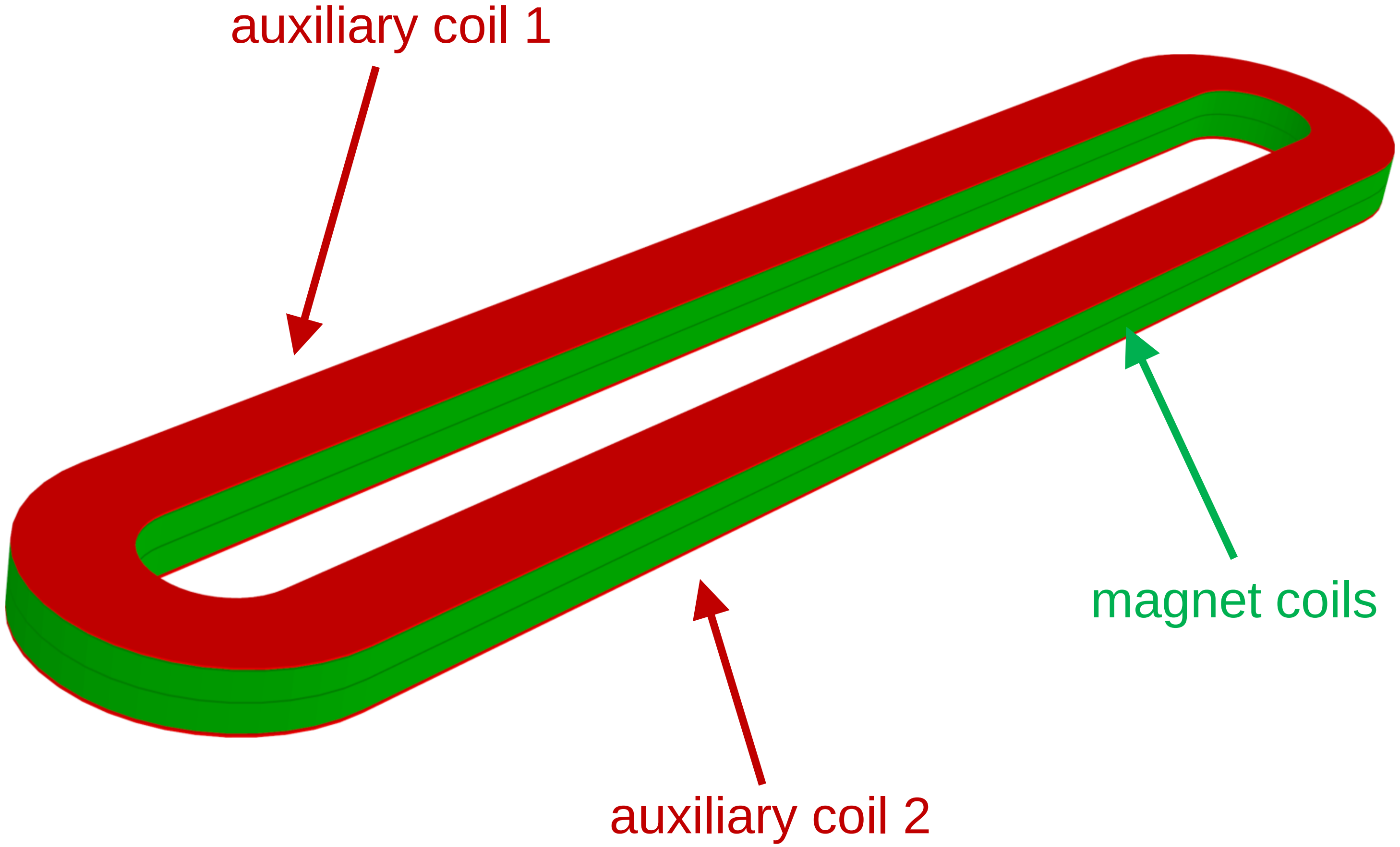
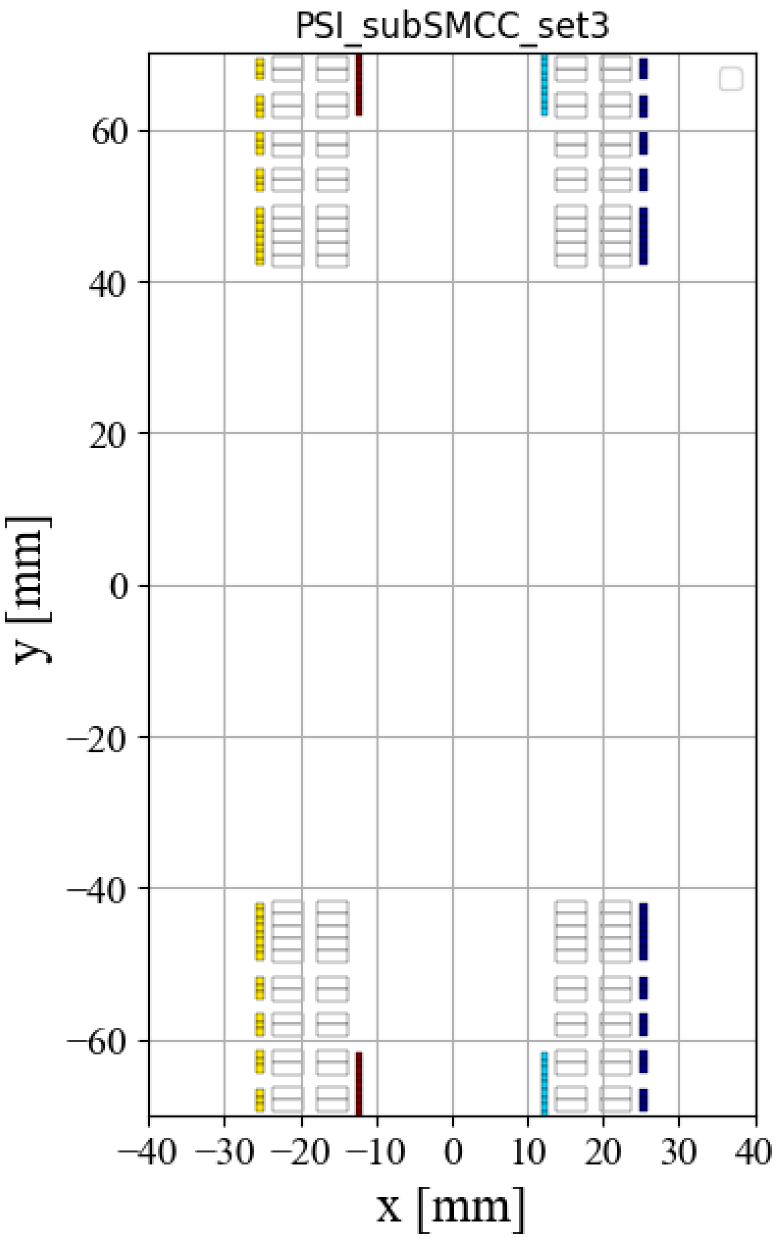
Quench protection based on Energy Shift with Coupling (ESC)



ESC auxiliary coils





ESC working principle

1	2	3
Immediate reduction of the transport current	Very high dB/dt (~1E2-1E3 T/s)	Energy shift from magnet coils to auxiliary coils
reduces ohmic loss and magneto-resistance	transfers most/all turns to the normal state	induced by CLIQ unit and coil resistance increase

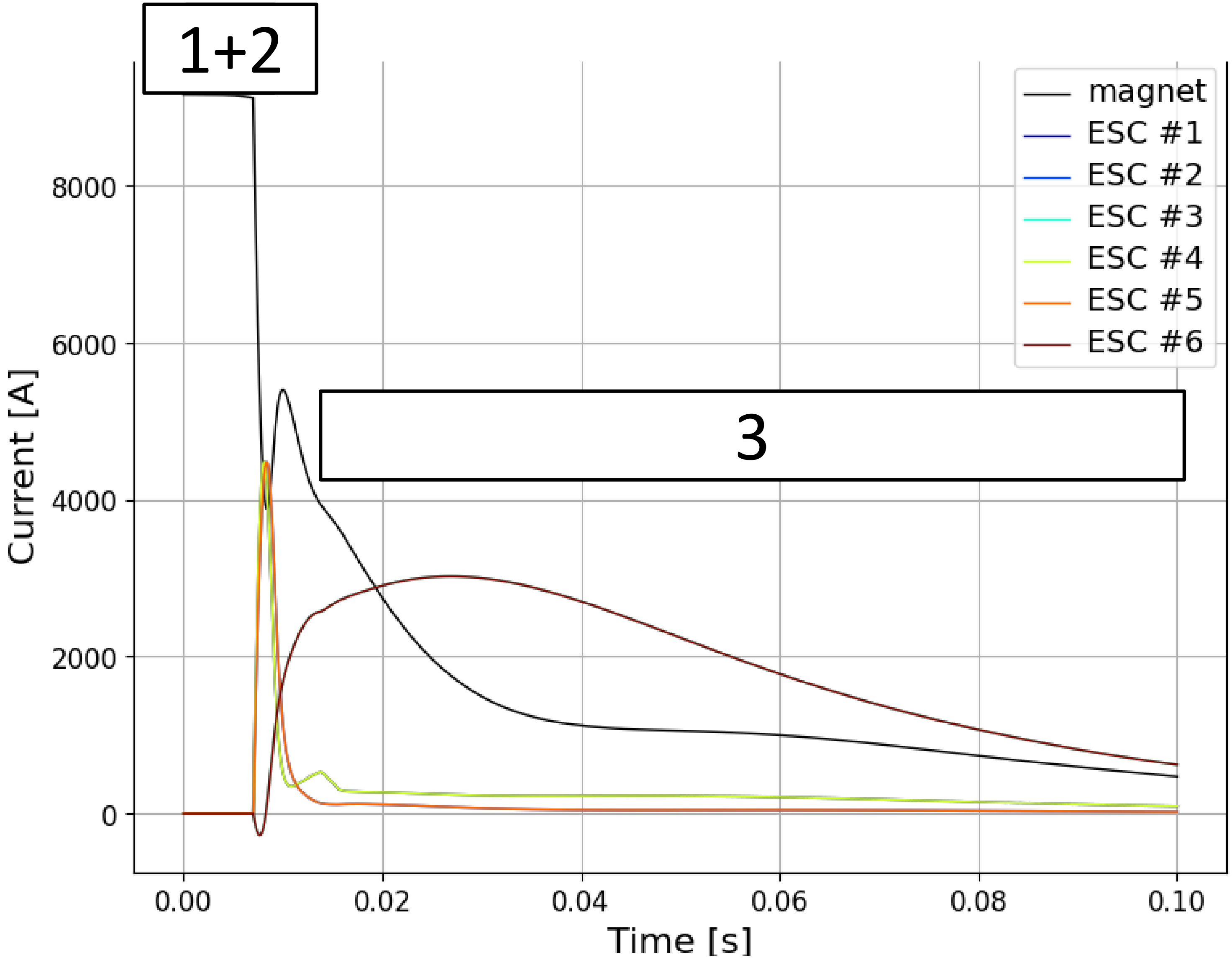
Very low hot-spot temperature and voltages to ground

ESC typical transient – Currents

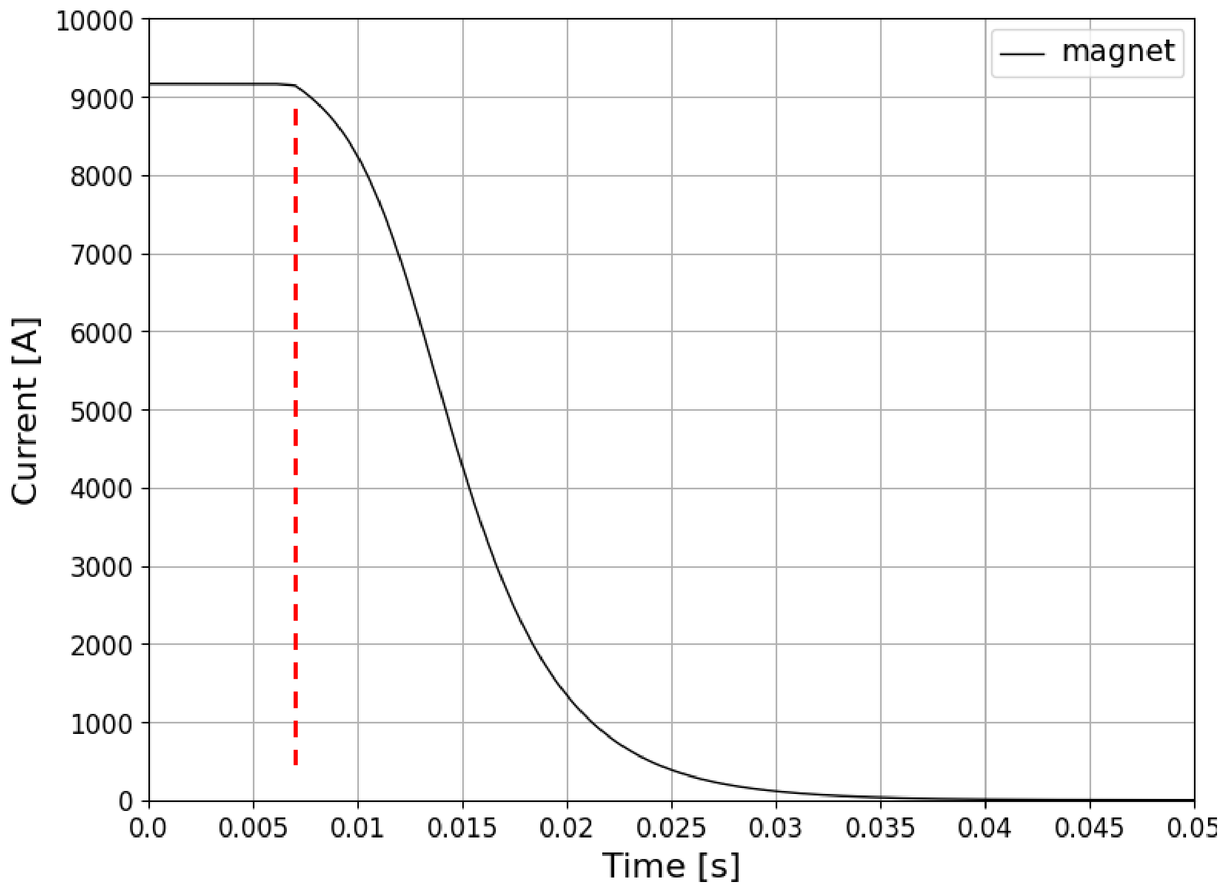
1
Fast current drop
Lower ohmic loss

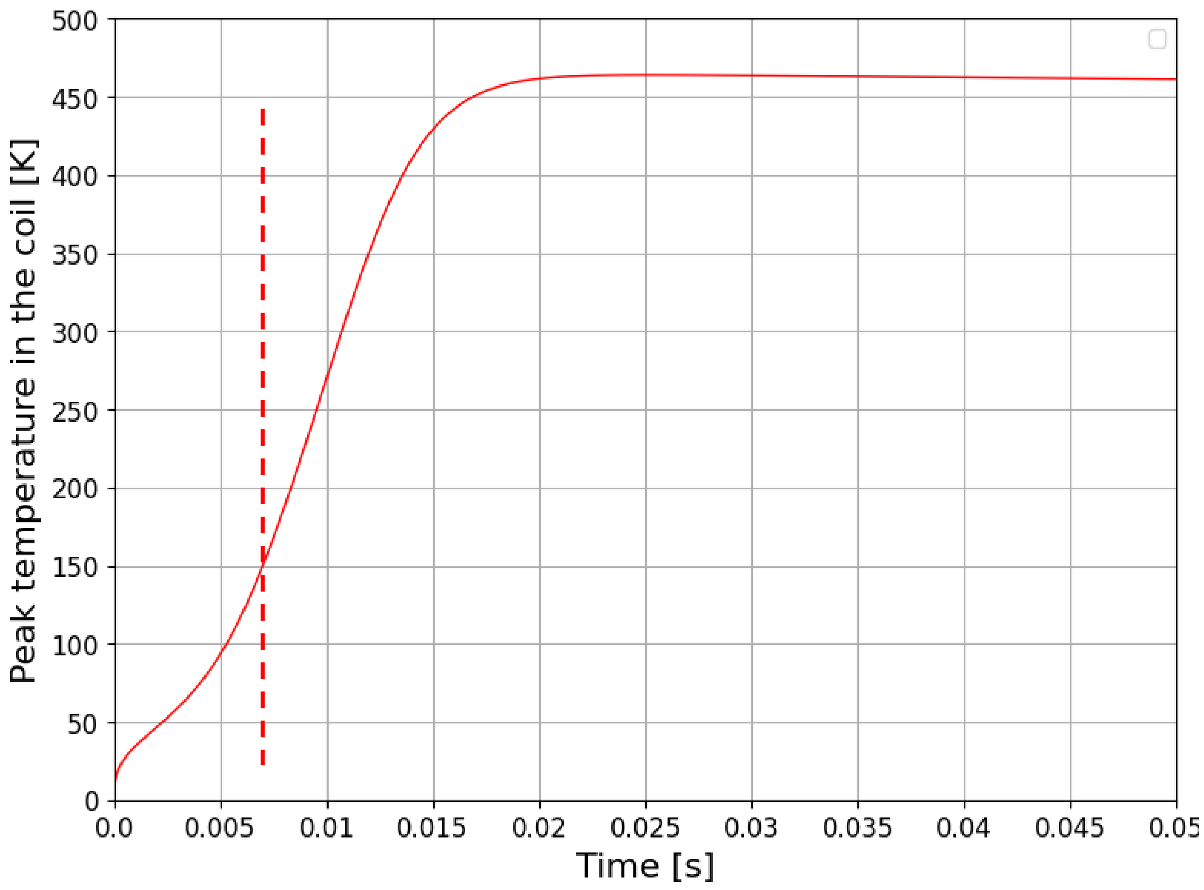
2
High dI/dt
High dB/dt
Fast quench

3
Energy extraction



PSI subscale: “Magic” quench of 100% of the coil at t=1+5+1=7 ms

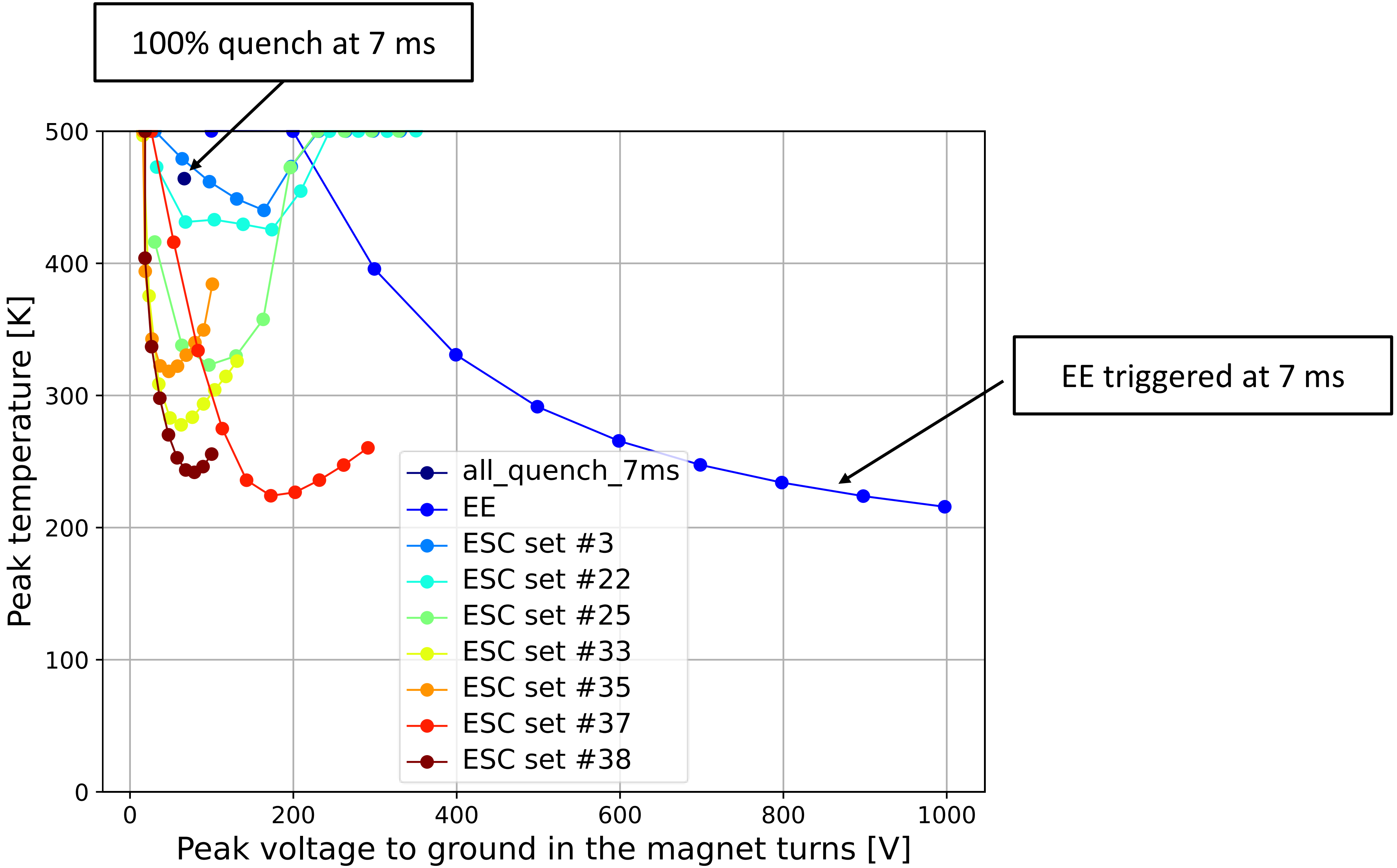




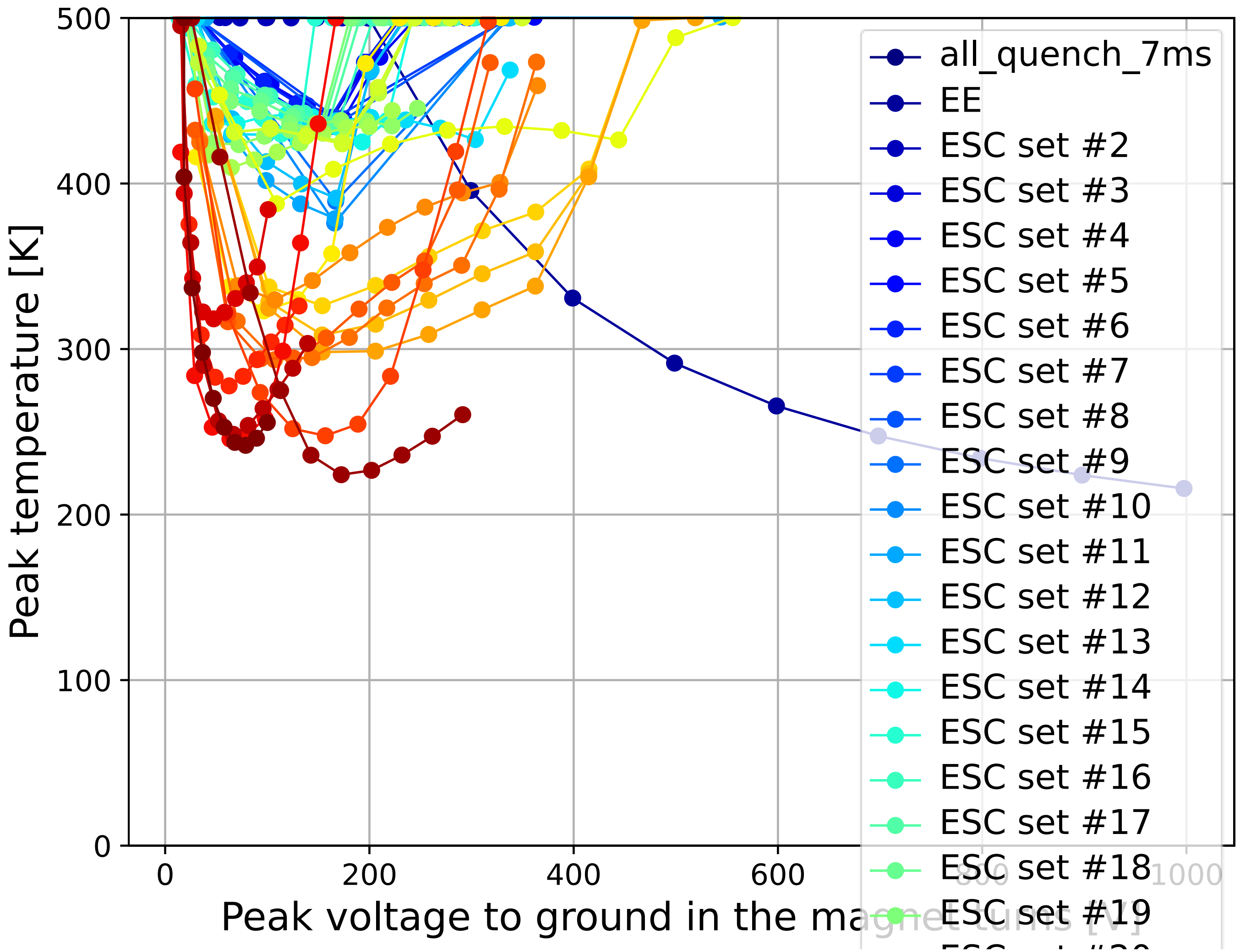
Even an ideal system quenching 100% of the magnet coil in no time is not enough to protect the magnet

ESC coil designs

ESC results

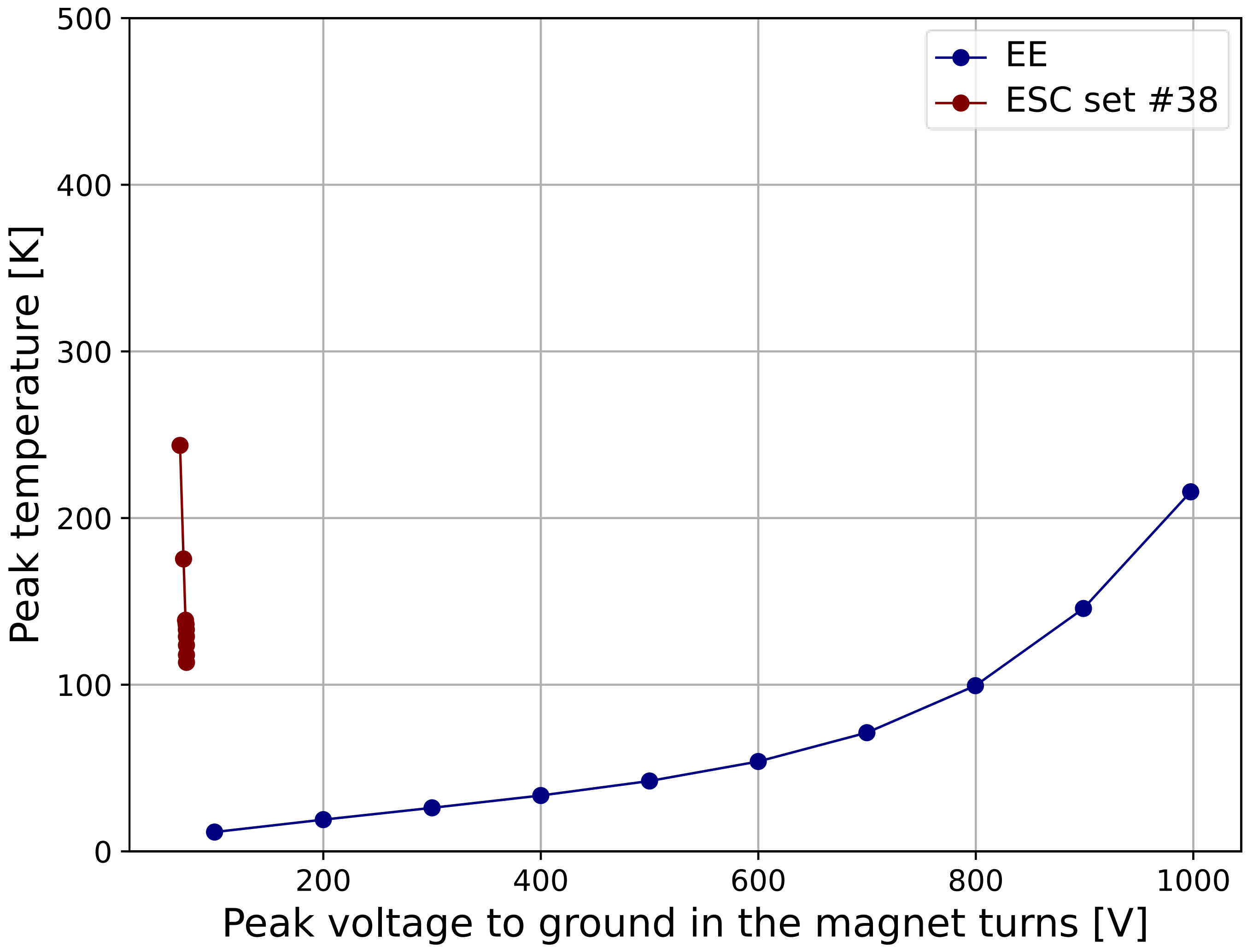

100% quench at 7 ms
EE triggered at 7 ms
Peak temperature [K]
Peak voltage to ground in the magnet turns [V]
0
100
200
300
400
500
0
200
400
600
800
1000
all_quench_7ms
EE
ESC set #3
ESC set #22
ESC set #25
ESC set #33
ESC set #35
ESC set #37
ESC set #38

ESC results

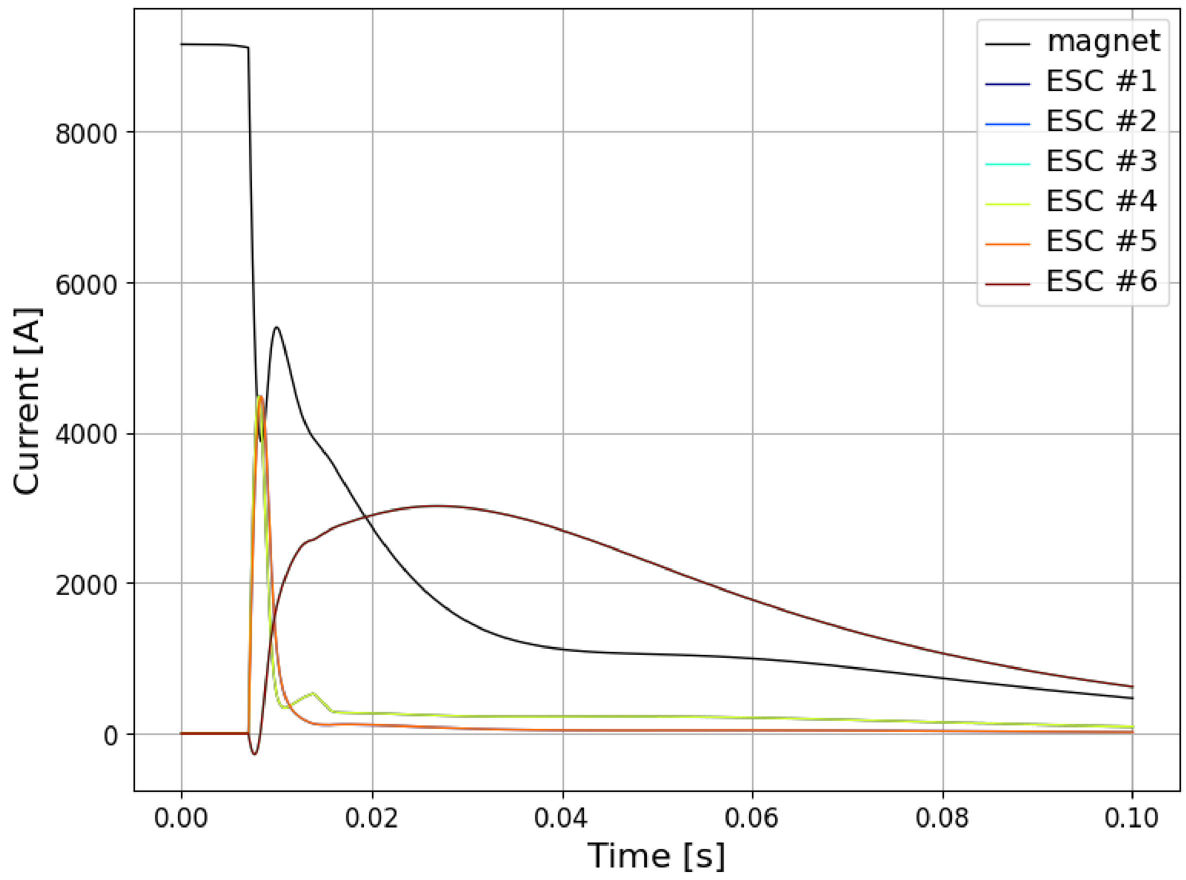


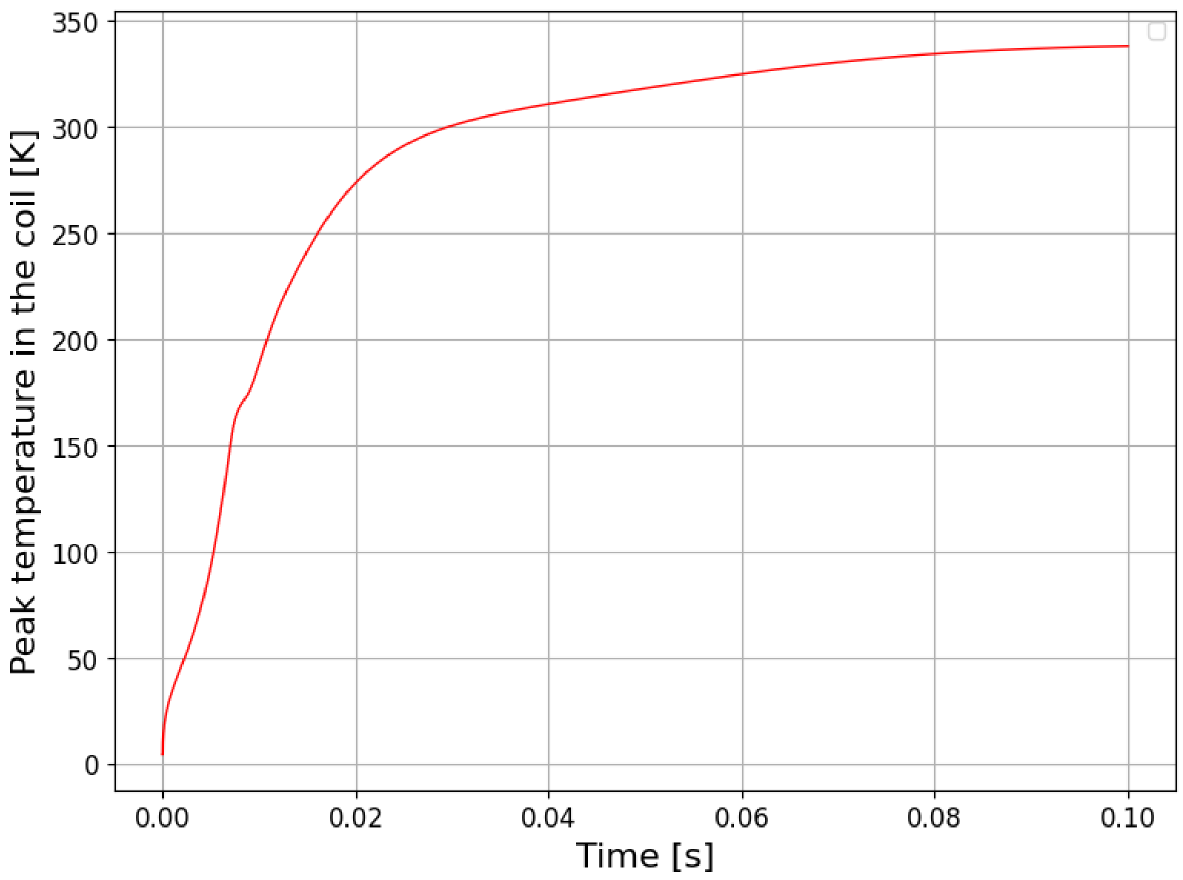
Peak temperature [K]
Peak voltage to ground in the magnet turns [V]
0
100
200
300
400
500
0
200
400
600
800
1000
all_quench_7ms
EE
ESC set #2
ESC set #3
ESC set #4
ESC set #5
ESC set #6
ESC set #7
ESC set #8
ESC set #9
ESC set #10
ESC set #11
ESC set #12
ESC set #13
ESC set #14
ESC set #15
ESC set #16
ESC set #17
ESC set #18
ESC set #19

Quench protection at different current levels



Example of an ESC transient





Quench protection based on ESC – Conclusions

- It seems possible to safely test the ESC method on the PSI subscale model
- Possible solutions to limit worst-case hot-spot temperature
  - Design and build voluminous ESC auxiliary coils (~5 times larger than the magnet coils) that can extract 80-90% of the magnet stored energy
  - Accept shorter validation time for these tests (possibly causing more spurious trips)
  - Accept to test only at low-medium current
  - Accept the risk of reaching ~400 K if a training quench occurs right before the test

Annex

Magnet parameters

PSI subscale stress-managed common coil magnet parameters	
Maximum current, I_{max}	9166 A
Peak field on the conductor at I_{max}	5.84 T
Operating temperature	4.5 K
Differential inductance per unit length at I_{max}	0.00126 H/m
Magnetic length	0.310 m
Superconductor	Nb_3Sn
Number of strands	11
Strand diameter	0.6 mm
Cu/no-Cu ratio	1.17
Insulation thickness	0.15 mm
RRR (assumed)	100