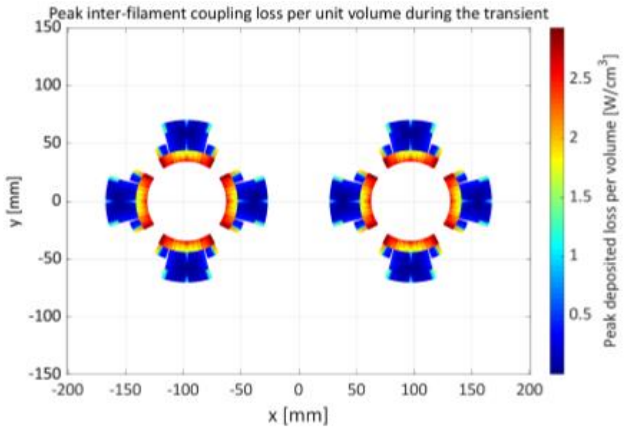
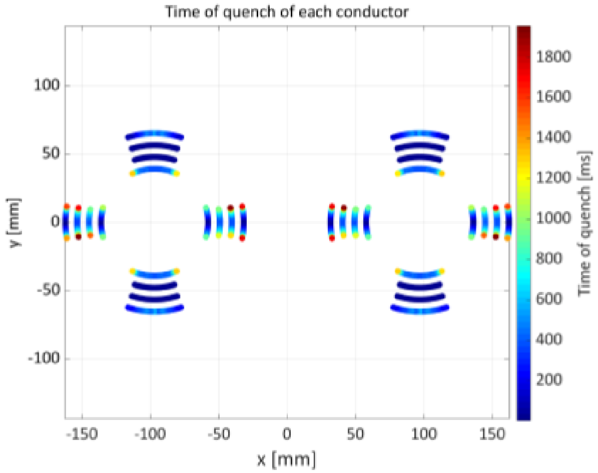
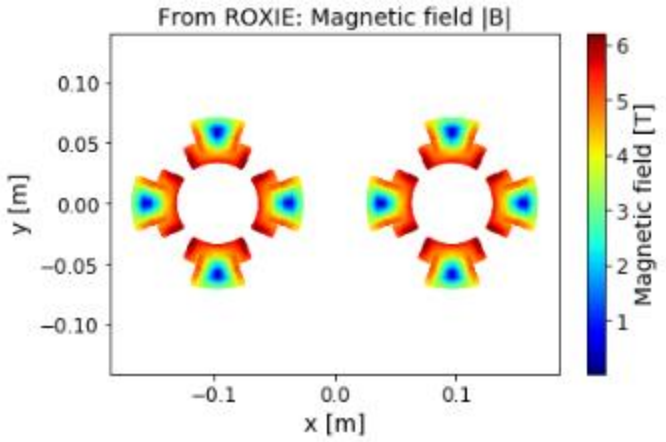
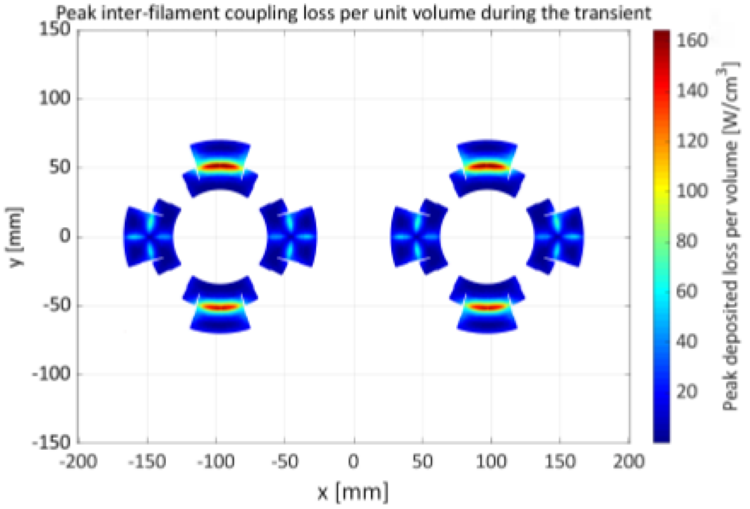




Generation and validation of the electro-thermal model of the MQY magnet using LEDET



Federica Murgia
STEAM team
7/11/2019

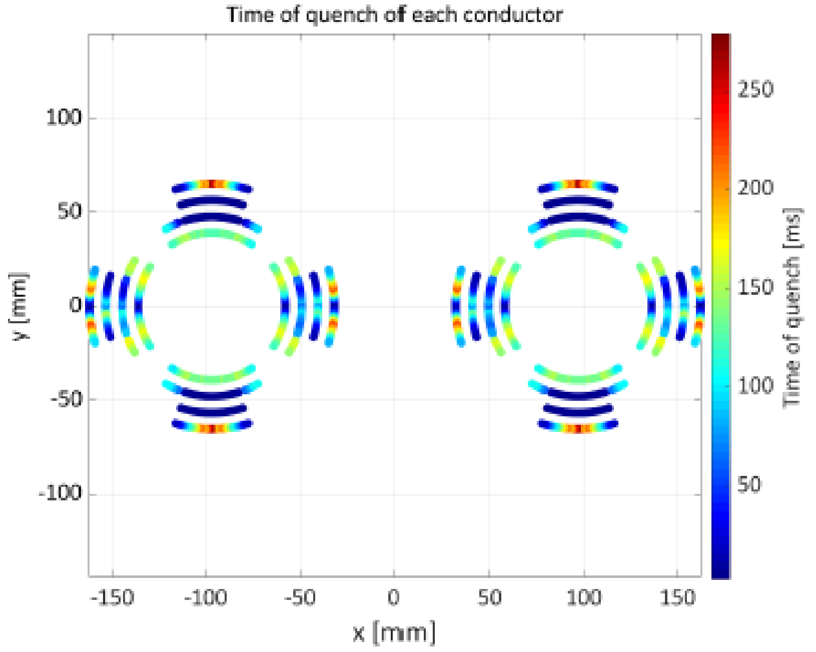


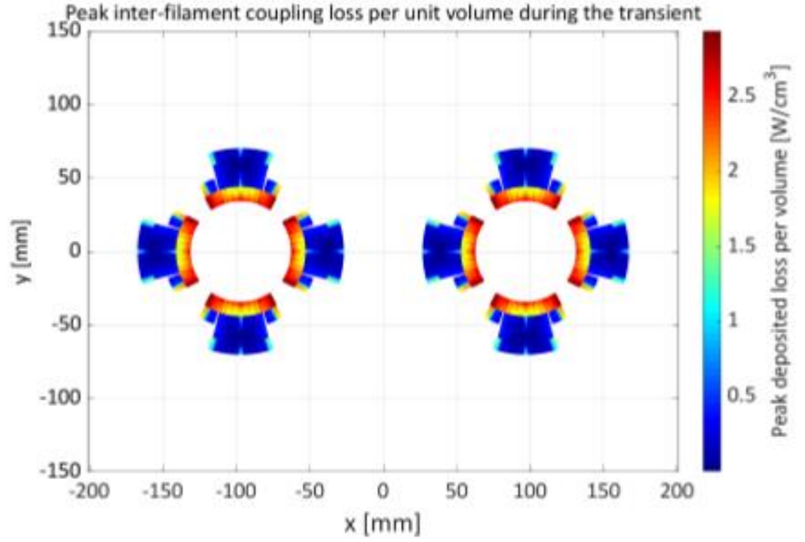
Special thanks to Emmanuele Ravaioli

cern.ch/STEAM

Outline:

- My Tasks
- STEAM
- LEDET
- SWAN
- MQY protection system
  - Energy Extraction
  - Quench Heaters
  - CLIQ
- MQY validation with LEDET
  - Fraction of helium in the cable cross section
  - New LEDET features (2D+1D model and quench velocity propagation)
  - Interfilament coupling current
- Unknown parameters
- Conclusion
- Future work





My Tasks

My tasks are:

- Work on the **LHC superconducting** magnets **circuit library**
- Develop an **electro-thermal model** of the **LHC superconducting magnets**
  - **Fresca 2**
  - **MQY**
  - …
- **Assist real time simulation** at CERN magnet test facility

For each **LHC circuit** the following will be generated

- **Magnet model** in **LEDET**
- **Electrical circuit** in **PSPICE** netlist
- **Co-simulation** of circuit and magnet models using **COSIM** (usually PSPICE+LEDET)

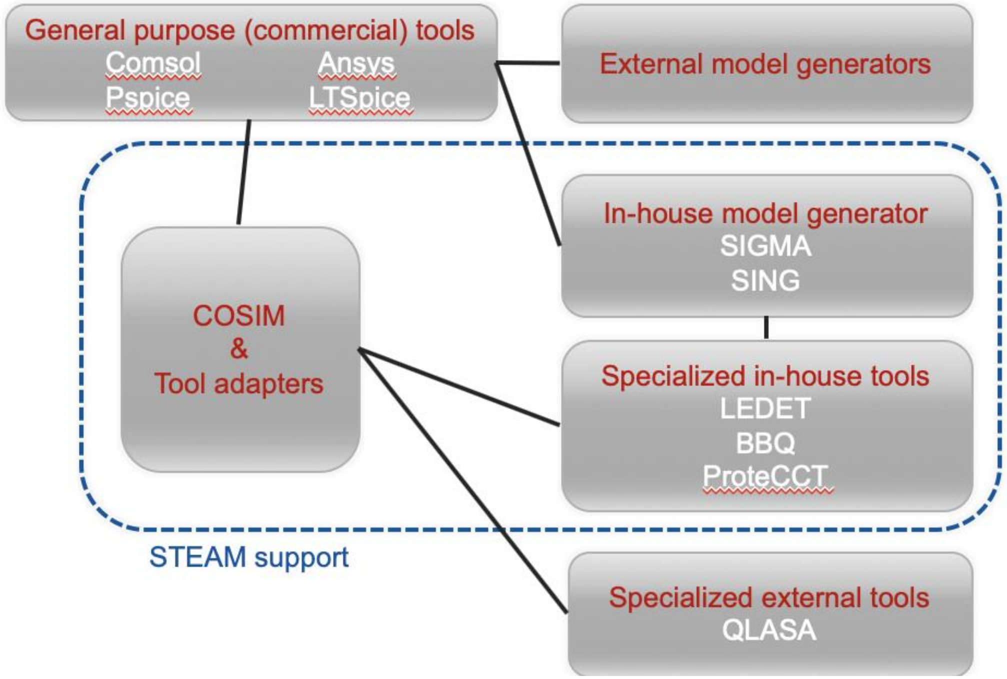
Framework to simulate *transient effects in the superconducting circuit and magnet*

cern.ch/STEAM

- Quench (training, beam-induced, triggered by QH/CLIQ, quench back)
- Fast Power Abort (converter switch-off and EE activation, voltage waves)
- Shorts (coil-to-ground, coil-to-heater, inter-turn, double short, arcing)
- ELQA tests (FTM, HiPotting, diode tests)
- Quench Detection

How is it composed?

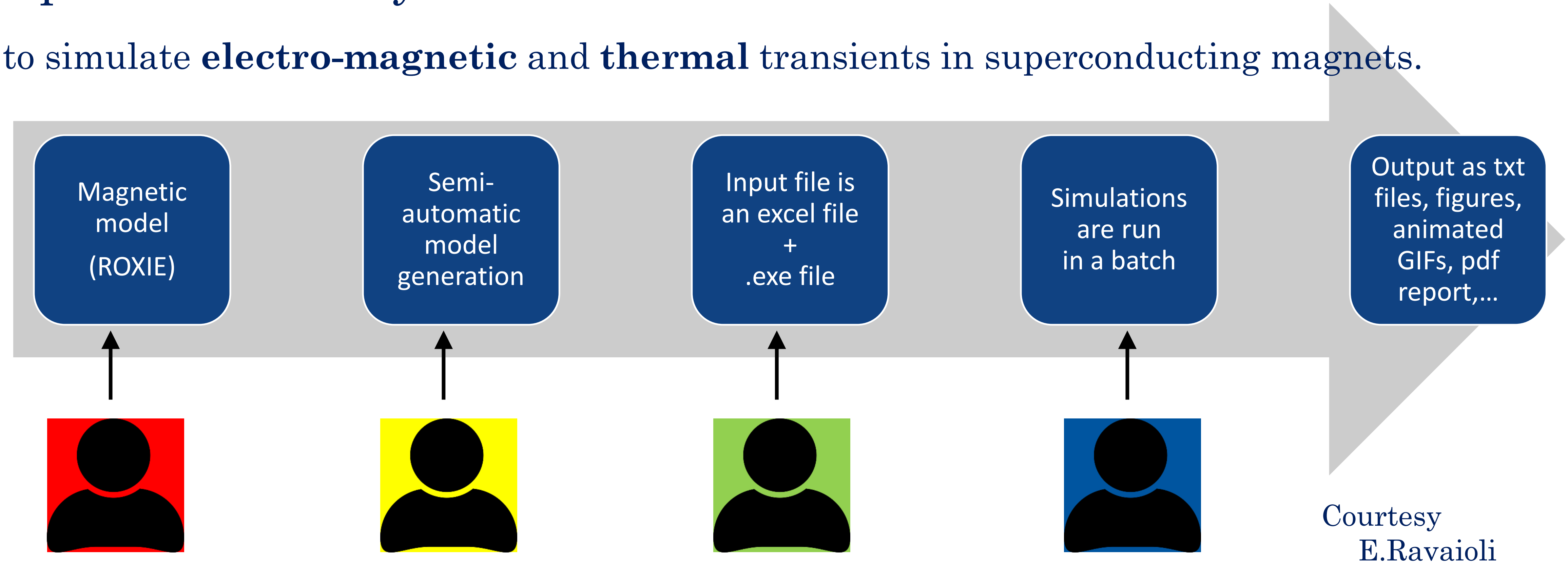
- Variety of tools (both commercial and in-house), each with its own features and advantages.
  - Attractive possibility to co-simulate two or more tools.
  - Tested, cross-checked, and validated.



What is LEDET?

Lumped-Element Dynamic Electro-Thermal

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

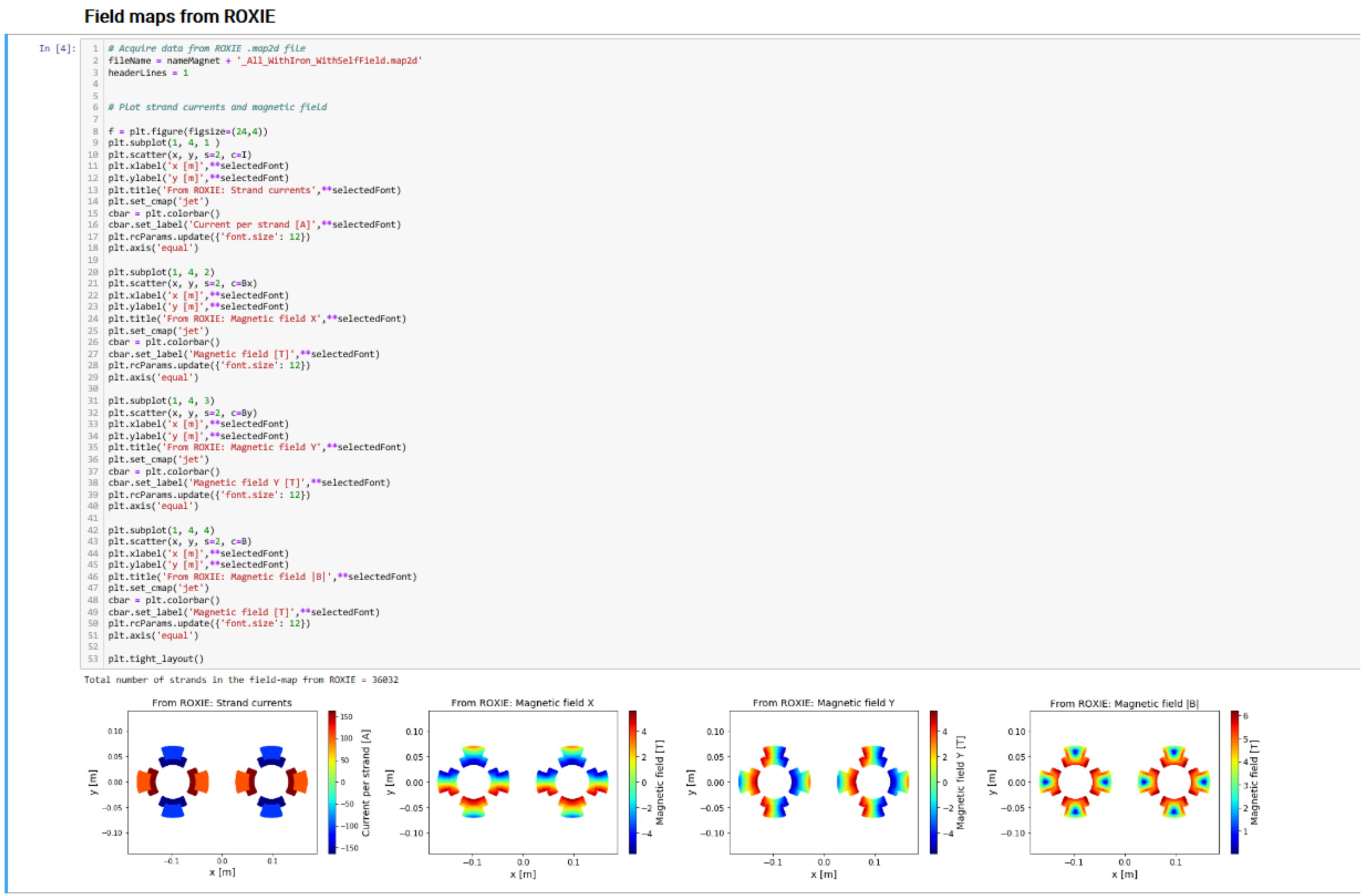


Courtesy
E.Ravaioli

https://cern.ch/STEAM/LEDET

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

What is the frontend?



generating PSPICE and COSIM models

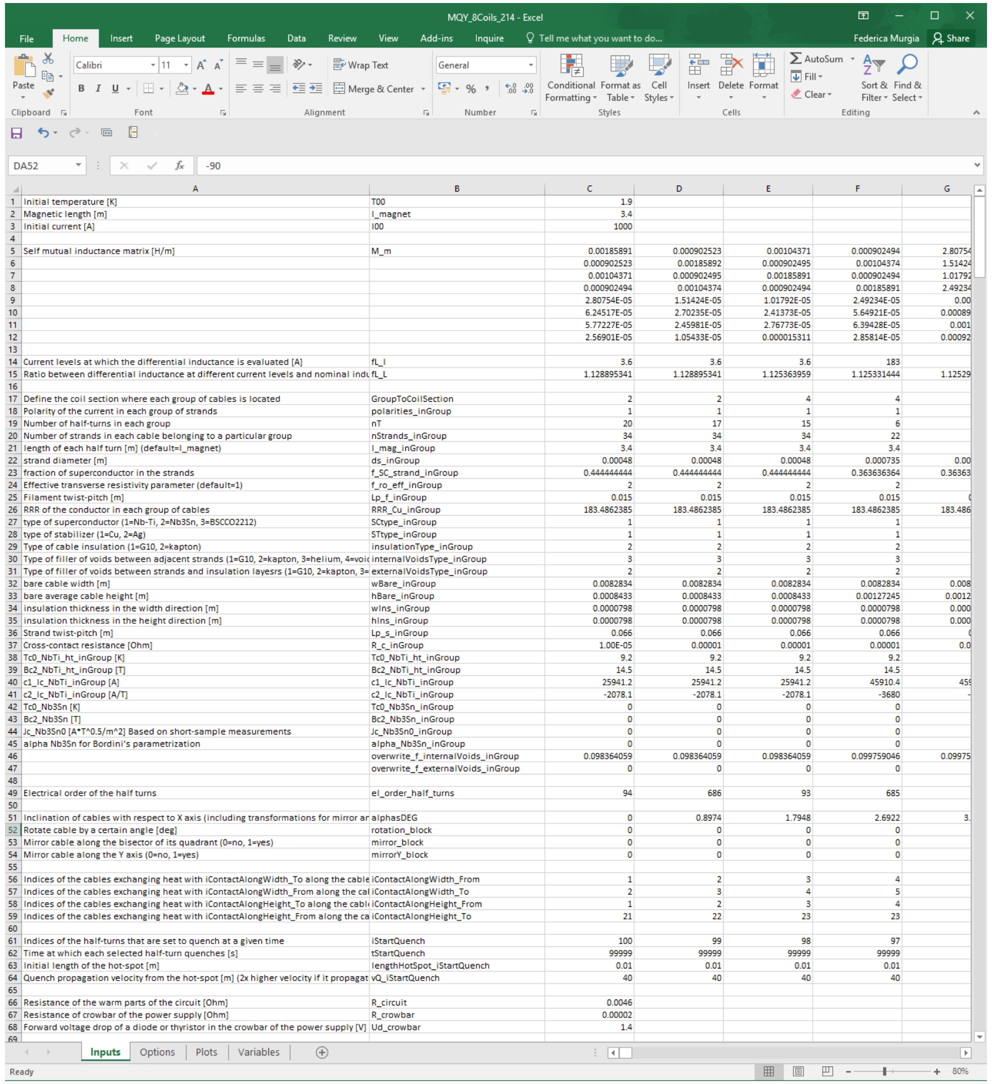
LHC signal monitoring

https://indico.cern.ch/event/834069/contributions/3585134/

How is the LEDET input file composed?

Four main sheets

- ❑ INPUT
- ❑ OPTION
- ❑ PLOTS
- ❑ VARIABLES



MQY, superconducting quadrupole magnet

MQY are quadrupoles that in Nb-Ti operate in LHC at 4.5 K, and will be used in HL-LHC at 1.9 K.

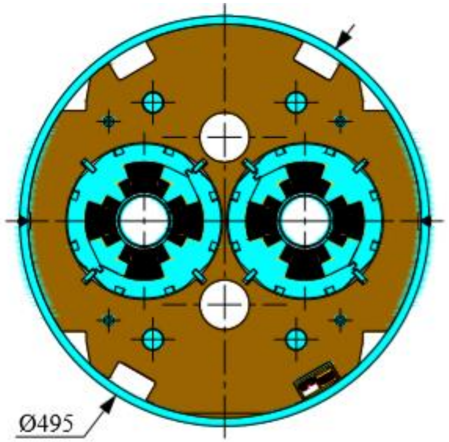
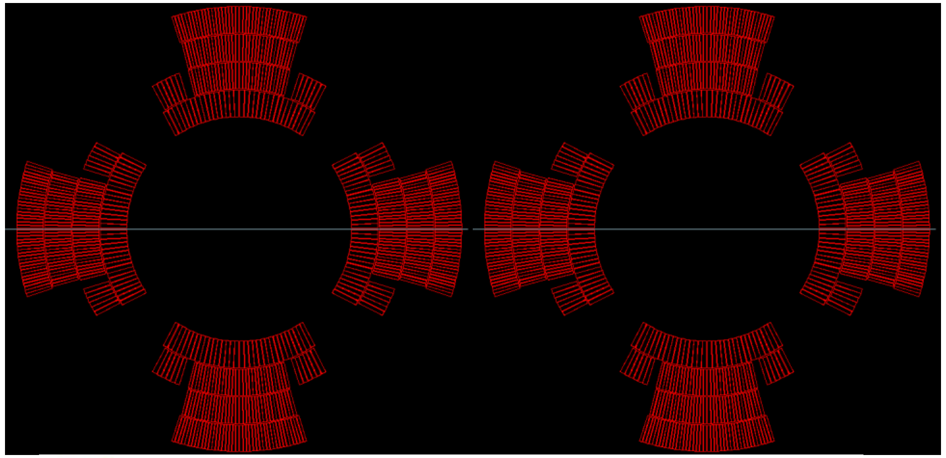
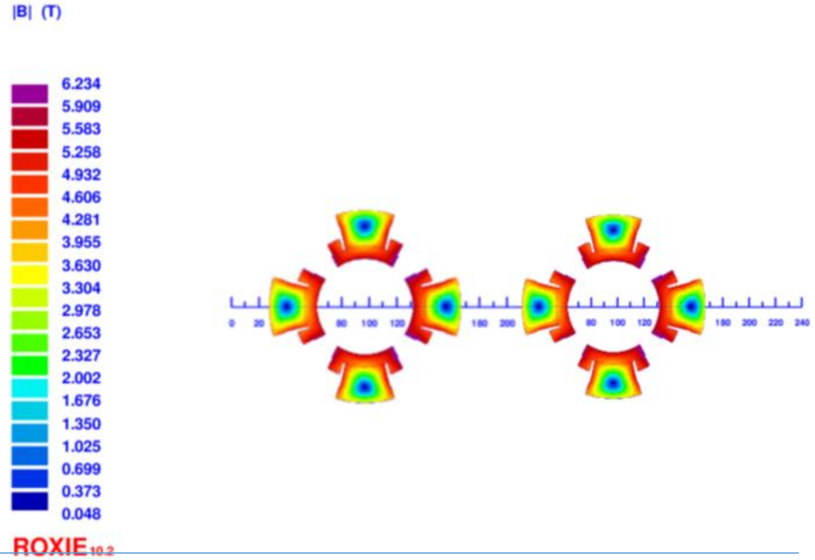


Table 8.4: Main parameters of the MQY matching quadrupole

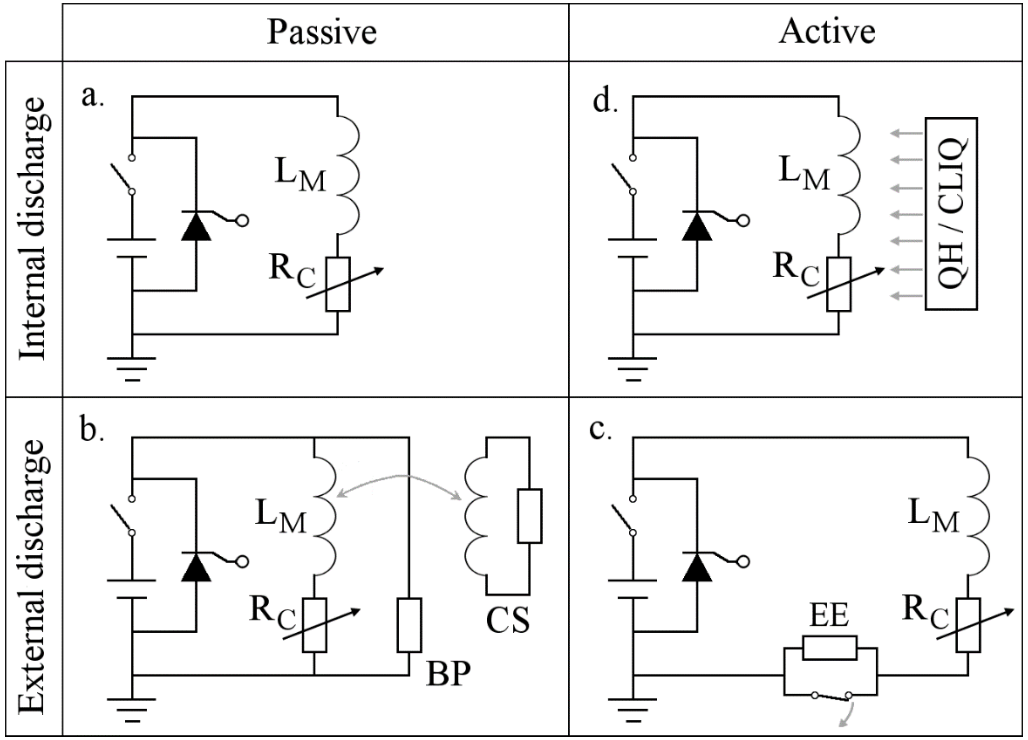
Coil inner diameter	70 mm
Magnetic length	3.4 m
Operating temperature	4.5 K
Nominal gradient	160 T/m
Nominal current	3610 A
Cold bore diameter OD/ID	66.5/62.9 mm
Peak field in coil	6.1 T
Quench field	7.5 T
Stored energy	479 kJ
Inductance	73.8 mH
Quench protection	Quench heaters, two independent circuits
Cable width, cable 1/2	8.3/8.3 mm
Mid-thickness, cable 1/2	1.285/0.845 mm
Keystone angle, cable 1/2	2.16/1.05 deg.
No of strands, cable 1/2	22/34
Strand diameter, cable ½	0.735/0.475 mm
Cu/SC Ratio, cable 1/2	1.25/1.75
Filament diameter, cable 1/2	6/6 μm
j_c, cable 1/2, (4.2 K and 5 T)	2670/2800 A/mm^2
Mass	4400 kg





Why is quench protection needed?

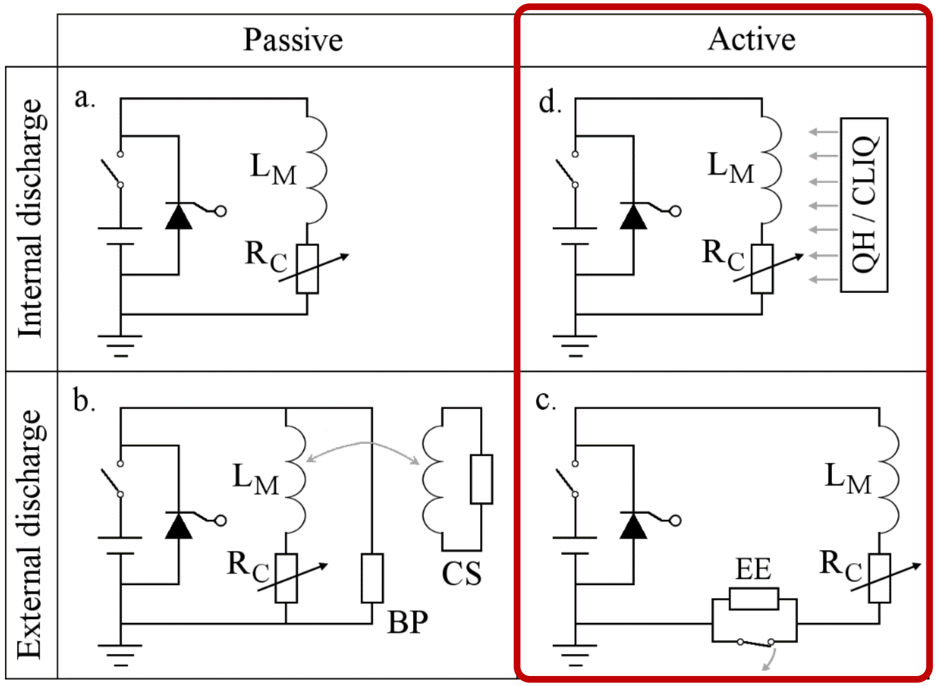
After a quench in a superconducting coil, the magnet current has to be discharged to avoid damage



- **Lower** hot-spot temperature
- **Lower** peak voltage to ground

Why is quench protection needed?

Active protection are usually required for **high energy density** magnets



CLIQ

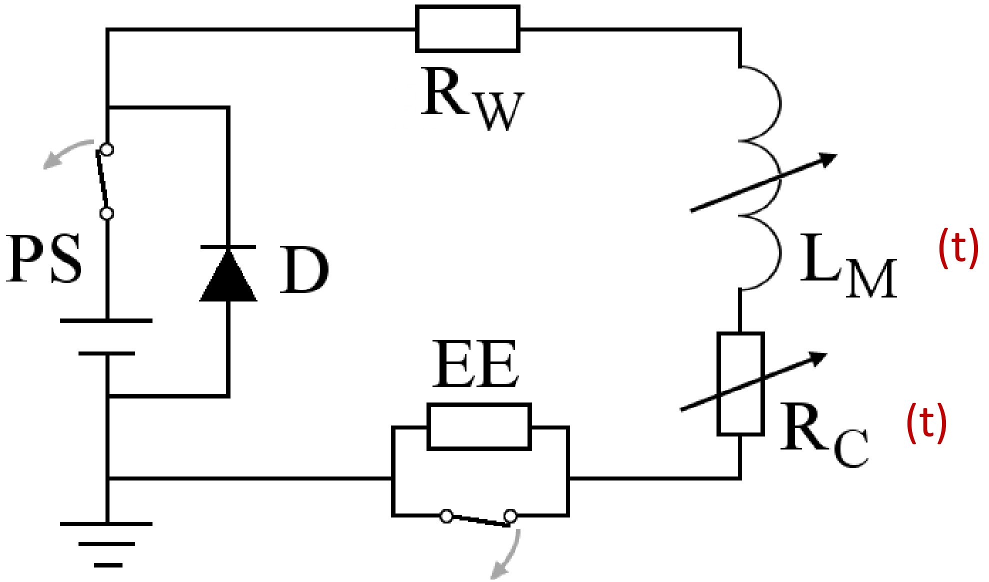
Quench Heaters

Energy Extraction

Energy Extraction

Quench Heaters

CLIQ



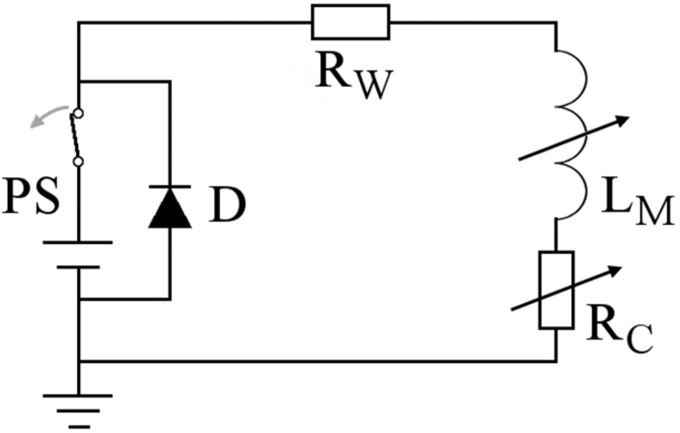
The **magnet differential inductance** and the **coil resistance** change in time.

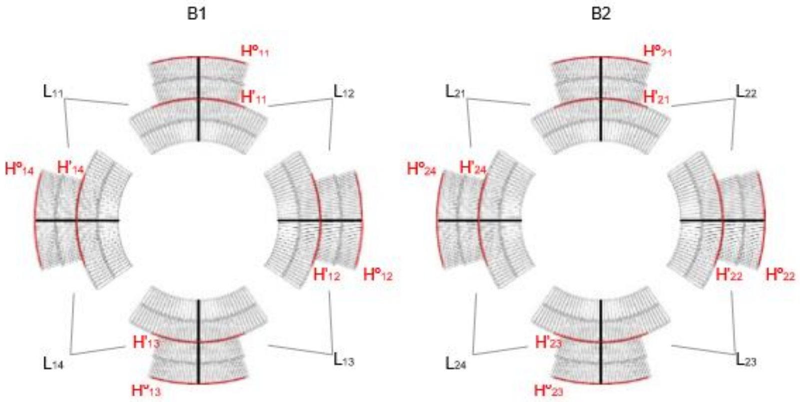
Courtesy E.Ravaioli

Energy Extraction

Quench Heaters

CLIQ





Quench heaters are μm-thin strips glued to the coil, which heat the turns by **thermal diffusion**

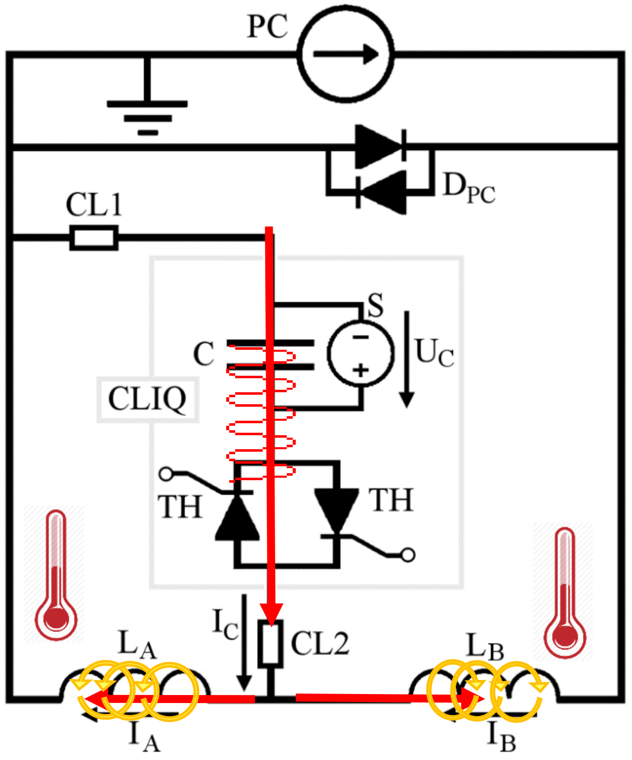
Courtesy E.Ravaioli

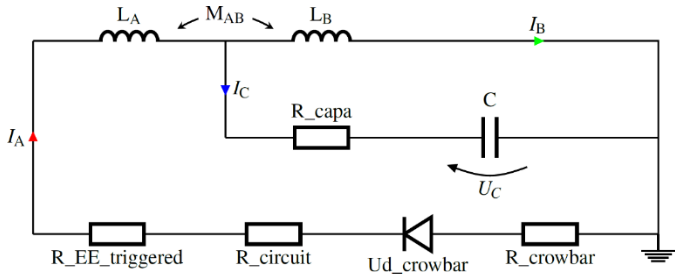
Energy Extraction

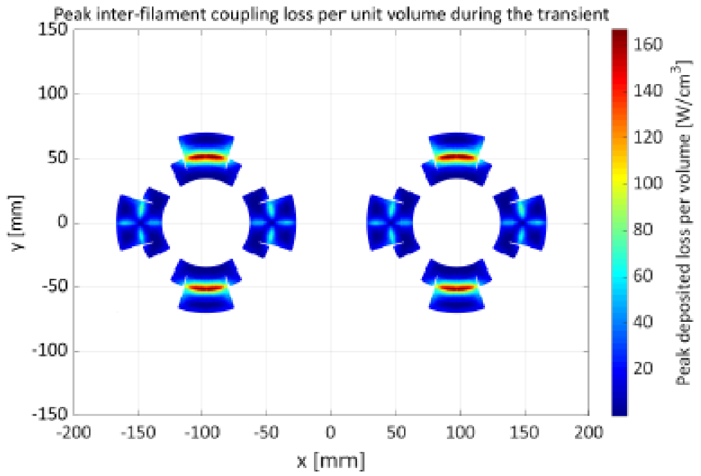
Quench Heaters

CLIQ

Coupling-Loss Induced Quench







Due to CLIQ's **faster** quench initiation,
lower hot-spot temperature and **more homogeneous** temperature distribution

The **oscillating current** introduced by CLIQ rapidly change the **local magnetic field.**

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

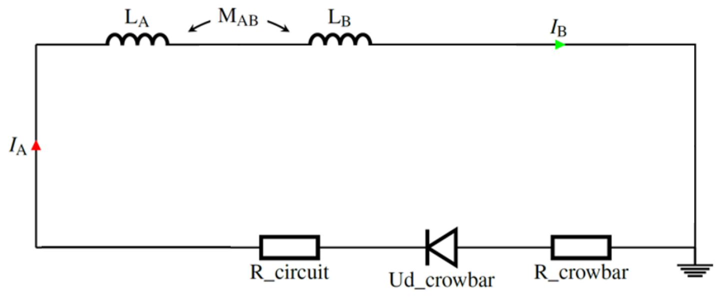
Validation of MQY→Tests overview

SM18 Ref	Test	T[K]	I[A]	EE (Delay)	CLIQ	QH
	Only EE					
1	1	1.9	1000	✓ (0.004s)	-	-
	QH+ EE					
14	2	1.9	3000	✓ (0.054s)	-	✓ (0.004s)
13	3	1.9	2000	✓ (0.254s)	-	✓ (0.004s)
4	4	1.9	1500	✓ (0.504s)	-	✓ (0.004s)
12	5	1.9	1000	✓ (0.504s)	-	✓ (0.004s)
	CLIQ+EE					
15	6	1.9	3000	✓ (0.054s)	✓ (0.0005s) CLIQ unit1 (650V;8.8mF)	-
9	7	1.9	2000	✓ (0.254s)	✓ (0.0005s) CLIQ unit1 (650V;8.8mF)	-
8	8	1.9	1500	✓ (0.504s)	✓ (0.0005s) CLIQ unit1 (650V;8.8mF)	-
7	9	1.9	1000	✓ (0.504s)	✓ (0.0005s) CLIQ unit1 (650V;8.8mF)	-
3	10	1.9	1500	✓ (0.504s)	✓ (0.0005s) CLIQ unit2 (500V;56.4mF)	-
2	11	1.9	1000	✓ (0.504s)	✓ (0.0005s) CLIQ unit2 (500V;56.4mF)	-
10	12	1.9	1000	✓ (0.504s)	✓ (0.0005s) CLIQ unit1 (500V;8.8mF)	-
11	13	1.9	1000	✓ (0.504s)	✓ (0.0005s) CLIQ unit1 (400V;8.8mF)	-

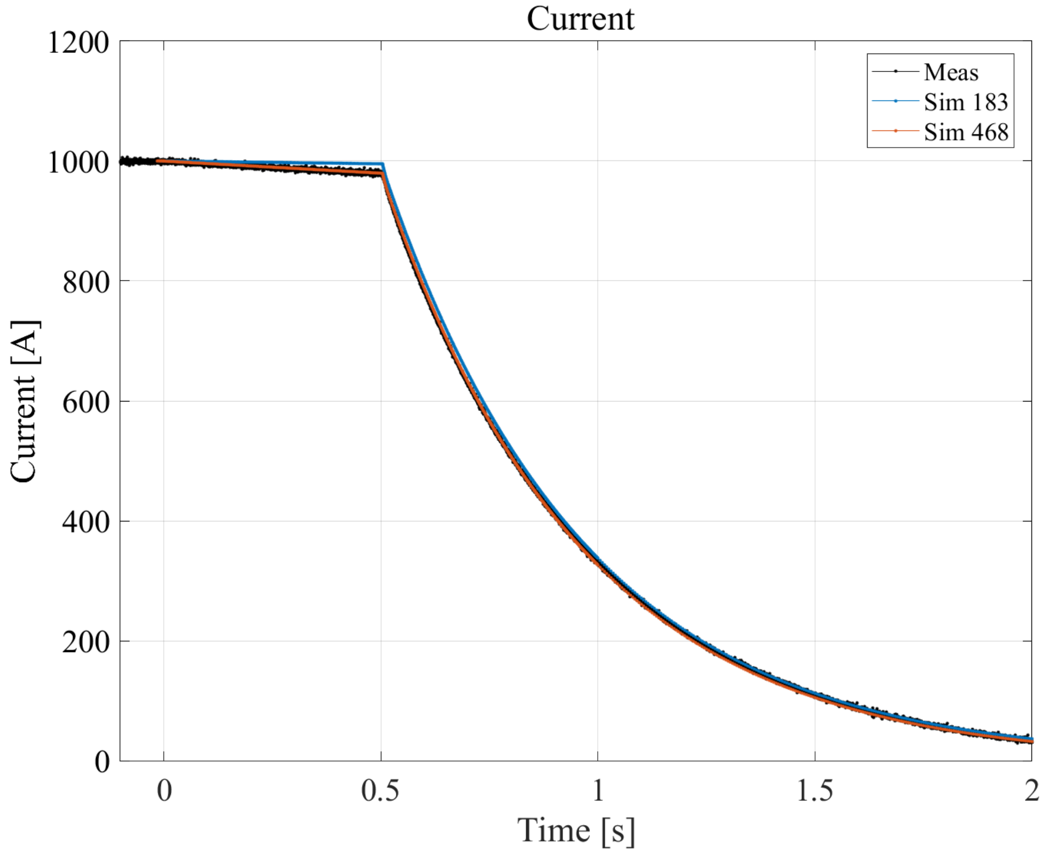
Warm circuit resistance

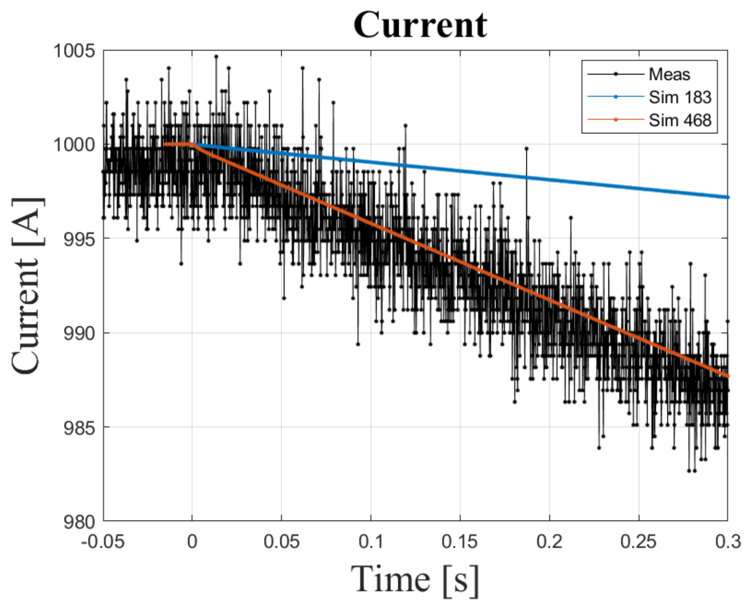
Test 1 (Only delay Energy Extraction)

I [A]	EE[s]
1000	0.504



R_circuit+R_crowbar=0.0023 Ohm and **Ud_crowbar** =0.7V





Tests overview

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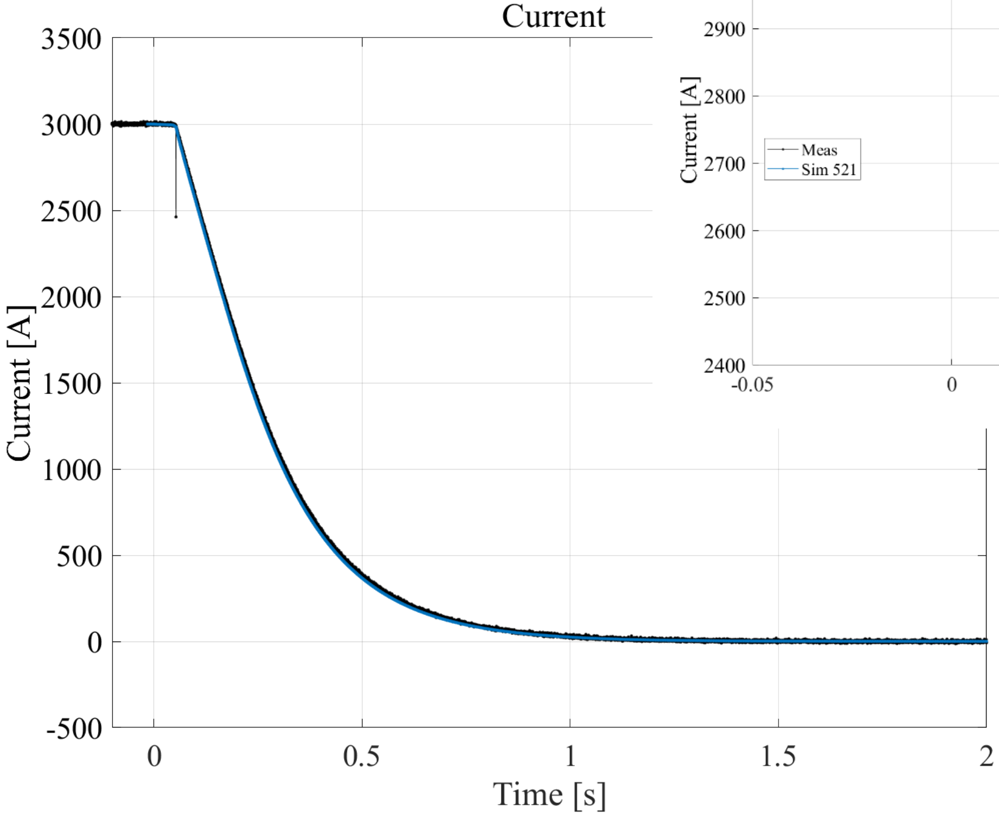
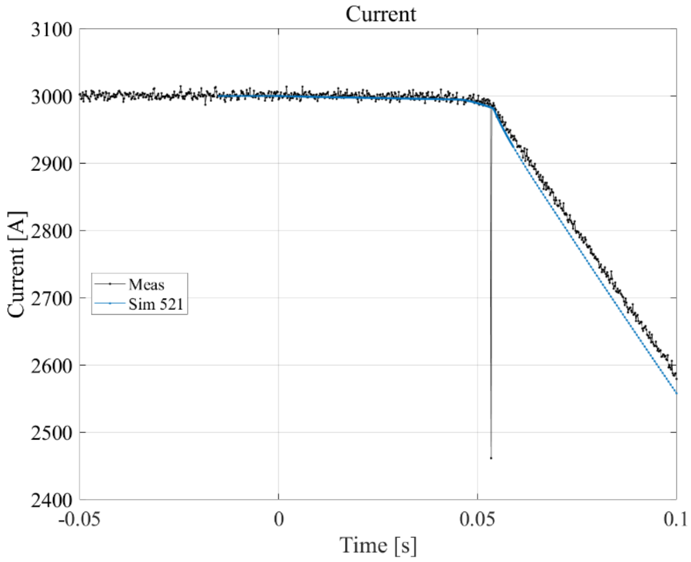
	Only EE					
1	1	1.9	1000	✓ (0.004s)	-	-
	QH+ EE					
14	2	1.9	3000	✓ (0.054s)	-	✓ (0.004s)
13	3	1.9	2000	✓ (0.254s)	-	✓ (0.004s)
4	4	1.9	1500	✓ (0.504s)	-	✓ (0.004s)
12	5	1.9	1000	✓ (0.504s)	-	✓ (0.004s)
	CLIQ+EE					
15	6	1.9	3000	✓ (0.054s)	✓ (0.0005s) CLIQ unit1 (650V;8.8mF)	-
9	7	1.9	2000	✓ (0.254s)	✓ (0.0005s) CLIQ unit1 (650V;8.8mF)	-
8	8	1.9	1500	✓ (0.504s)	✓ (0.0005s) CLIQ unit1 (650V;8.8mF)	-
7	9	1.9	1000	✓ (0.504s)	✓ (0.0005s) CLIQ unit1 (650V;8.8mF)	-
3	10	1.9	1500	✓ (0.504s)	✓ (0.0005s) CLIQ unit2 (500V;56.4mF)	-
2	11	1.9	1000	✓ (0.504s)	✓ (0.0005s) CLIQ unit2 (500V;56.4mF)	-
10	12	1.9	1000	✓ (0.504s)	✓ (0.0005s) CLIQ unit1 (500V;8.8mF)	-
11	13	1.9	1000	✓ (0.504s)	✓ (0.0005s) CLIQ unit1 (400V;8.8mF)	-

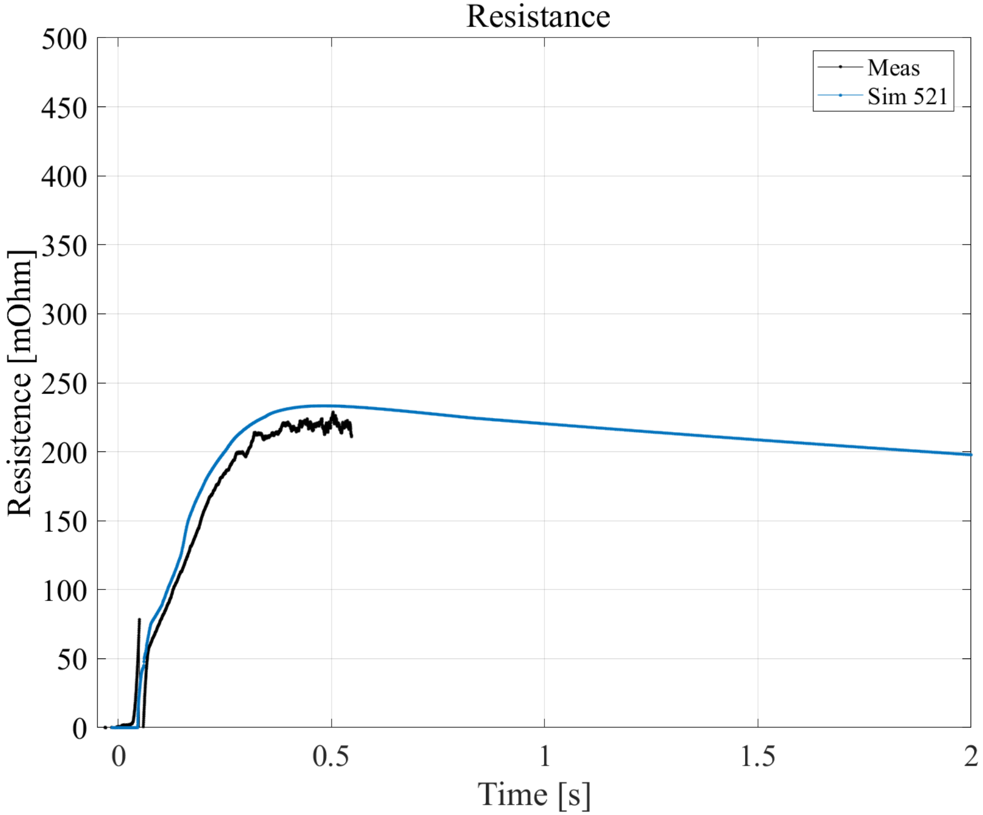
Test 2 (Quench Heaters + delay Energy Extraction)

I [A]	EE[s]	QH [s]	QH[V]	QH[mF]
3000	0.054	0.004	900	4*7.05





$$R = \frac{U_{res}}{I_m} = \frac{U_{mag} - L\frac{dI}{dt}}{I_m}$$



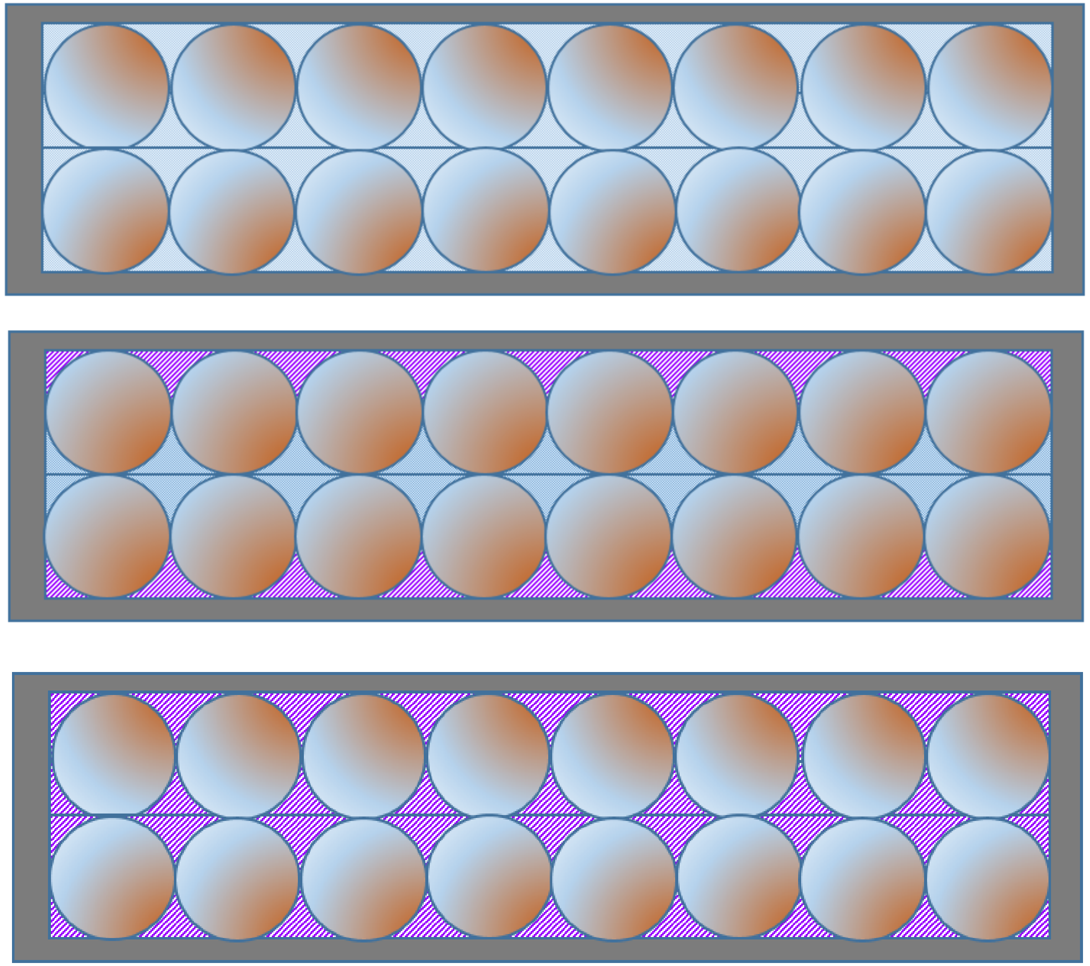
Helium fraction in cable cross section

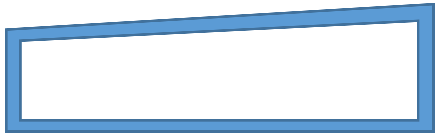
Test 2 (Quench Heaters + delay Energy Extraction)

I [A]	EE[s]	QH [s]	QH[V]	QH[mF]
3000	0.054	0.004	900	4*7.05

Quantity of infiltrated helium ~9.8% of the total

Sim	He_Int	He_Ext
522	0.098	0
523	0.045	0.054
524	0	0.098





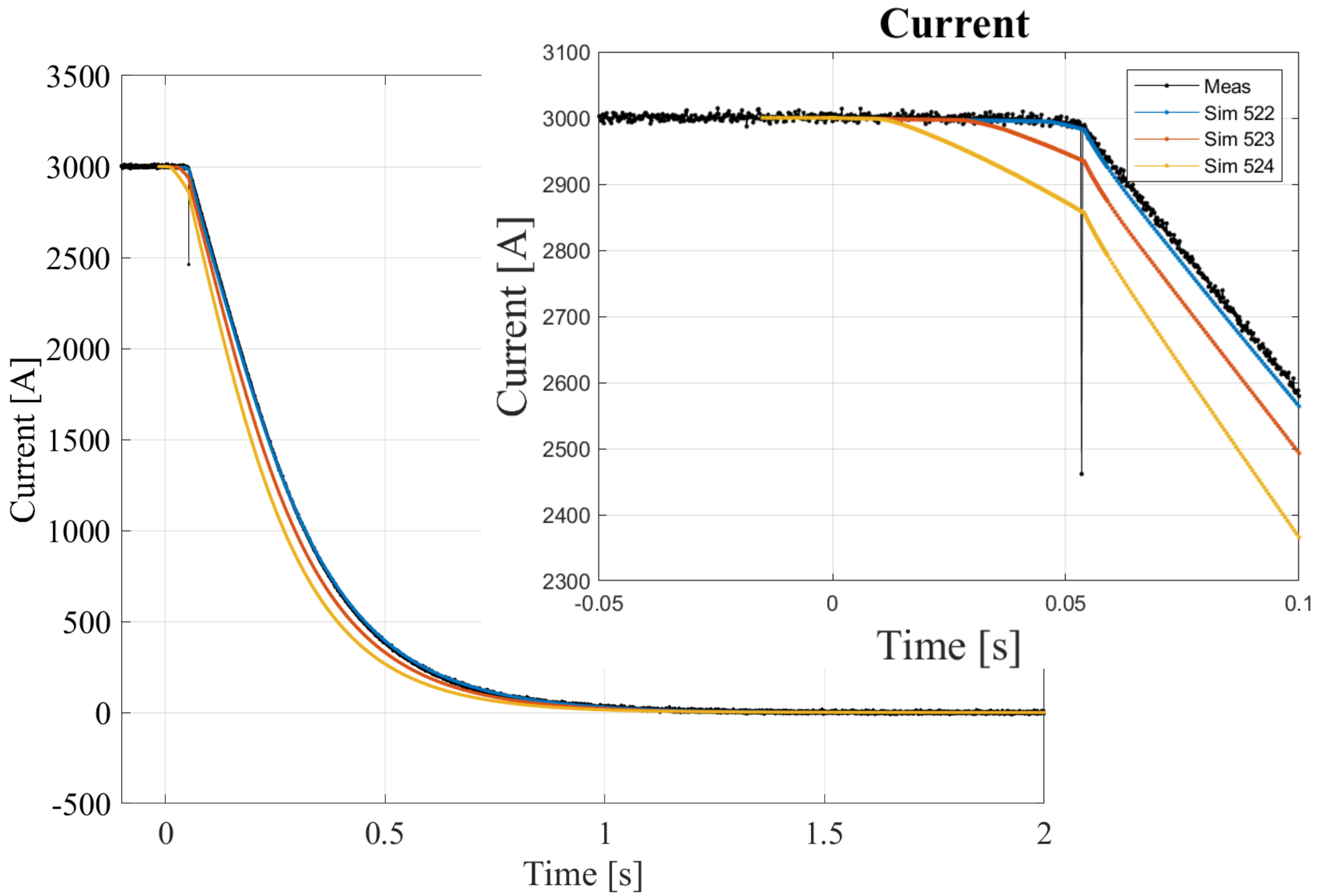
72% strand
17% insulation

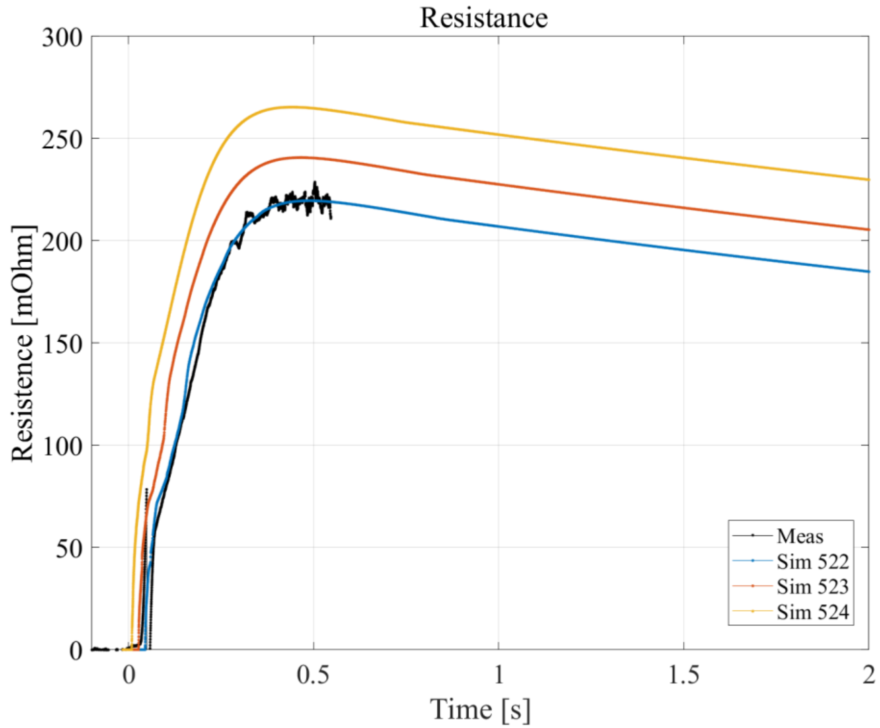
Helium fraction in cable cross section

Test 2 (Quench Heaters + delay Energy Extraction)

I [A]	EE[s]	QH [s]	QH[V]	QH[mF]
3000	0.054	0.004	900	4*7.05

Sim	He_Int	He_Ext
522	0.098	0
523	0.045	0.054
524	0	0.098

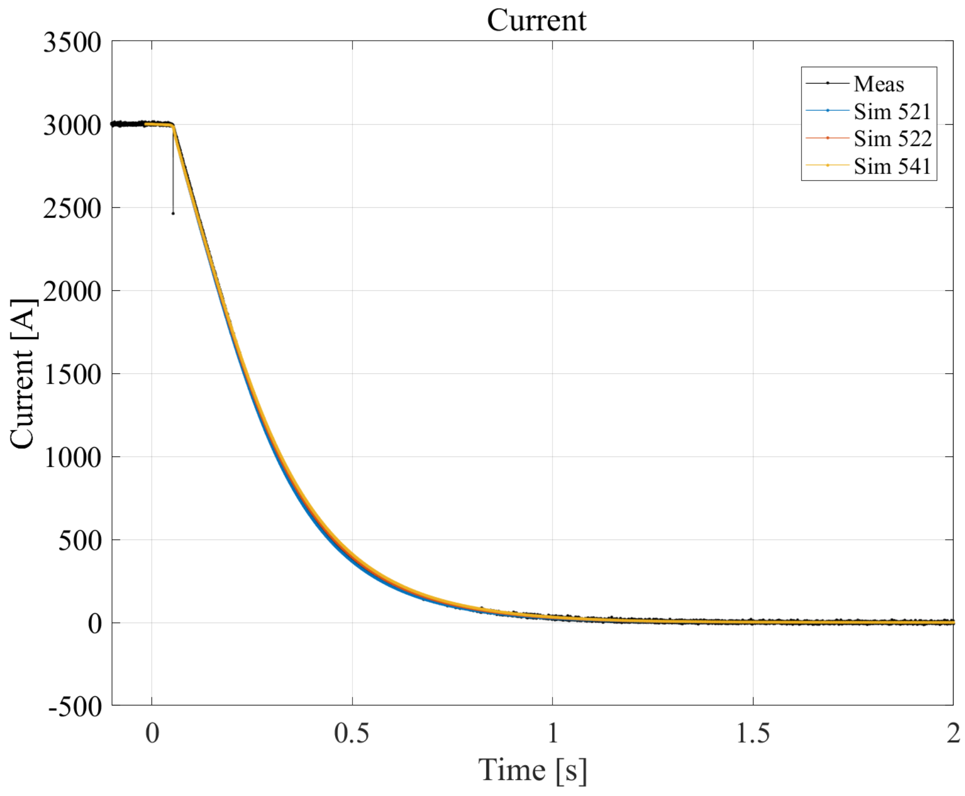


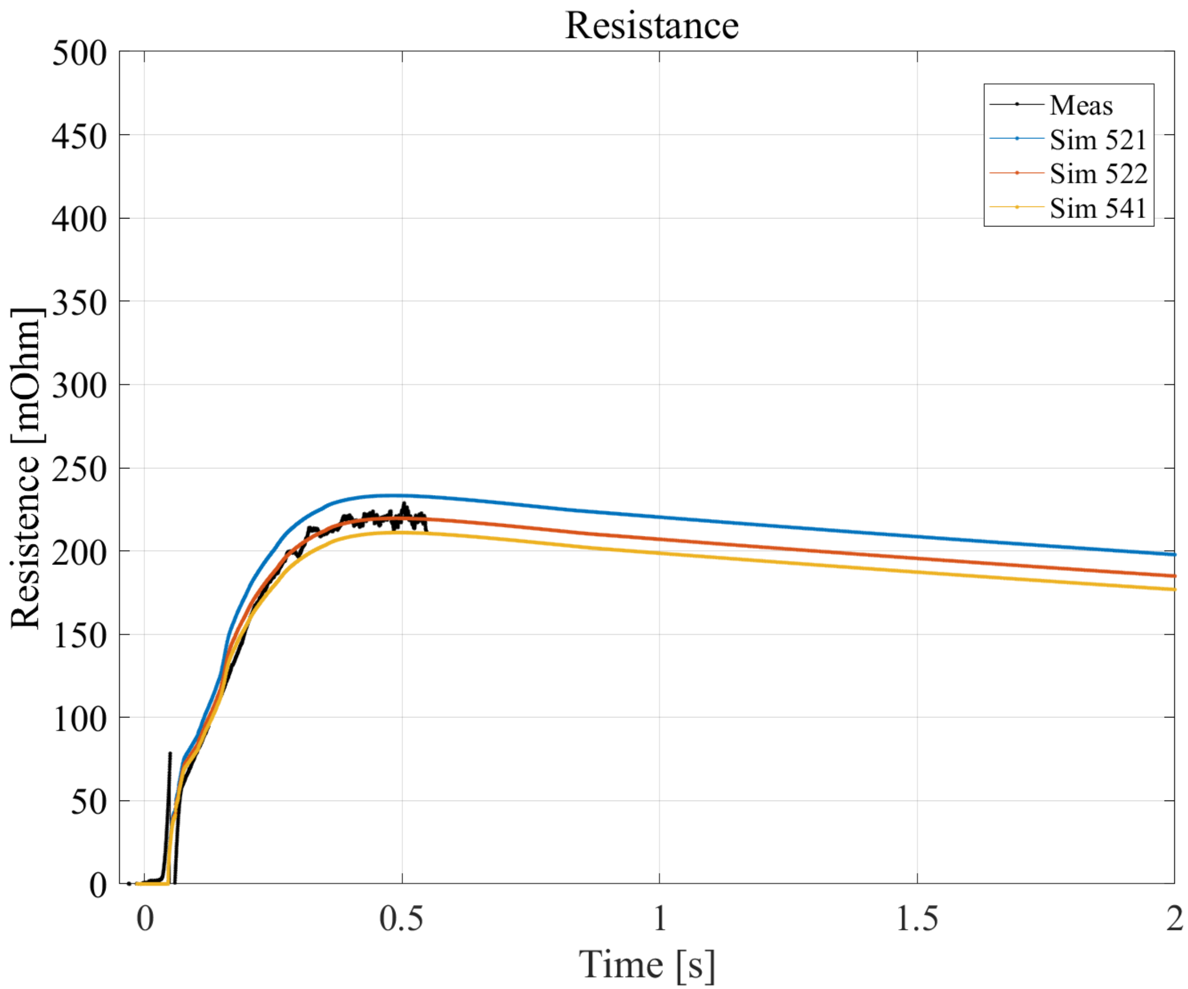


Residual Resistivity Ratio

Test 2 (Quench Heaters + delay Energy Extraction)

I [A]	EE[s]	QH [s]	QH[V]	QH[mF]
3000	0.054	0.004	900	4*7.05

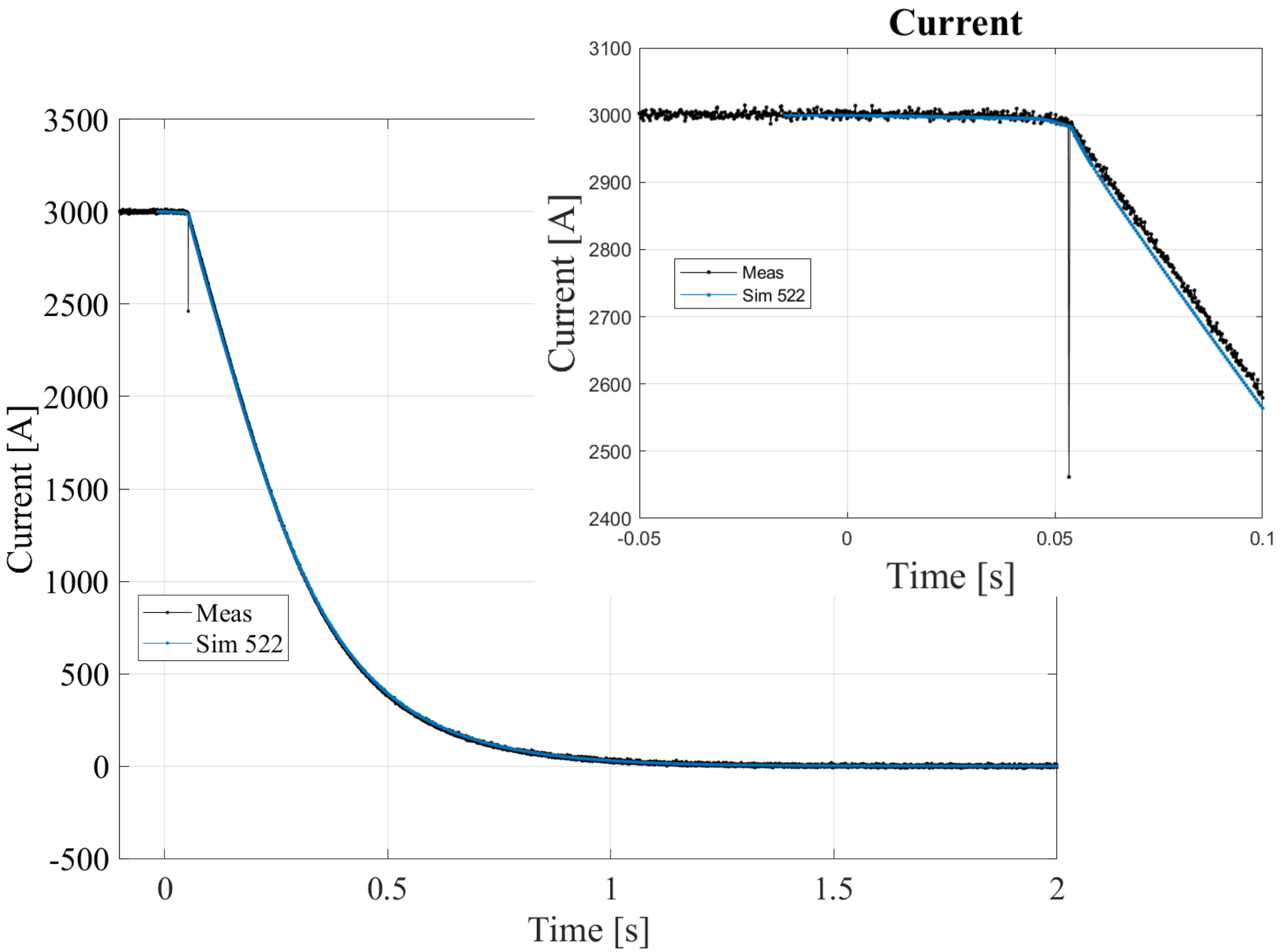


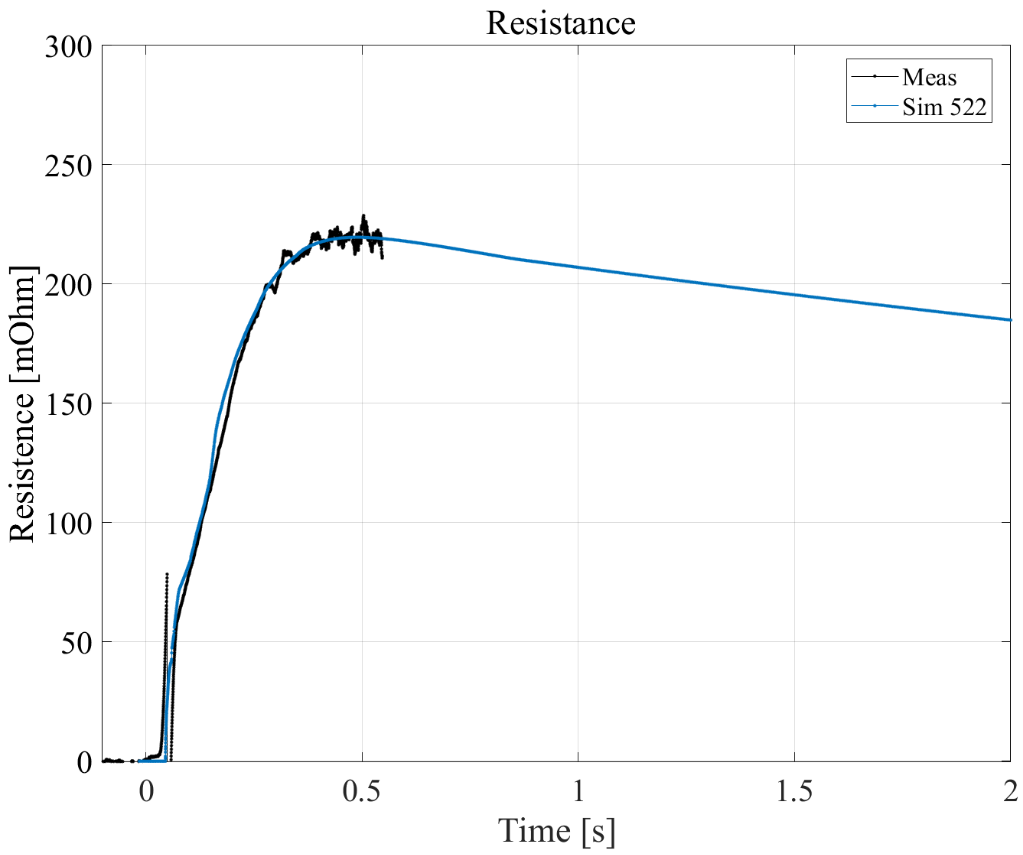


Sim	RRR
521	200
522	225
541	250

Test 2 (Quench Heaters + delay Energy Extraction)

I [A]	EE[s]	QH [s]	QH[V]	QH[mF]	RRR
3000	0.054	0.004	900	4*7.05	225





…New LEDET's features…

- **Model 2D+1D**
- **Quench velocity propagation**

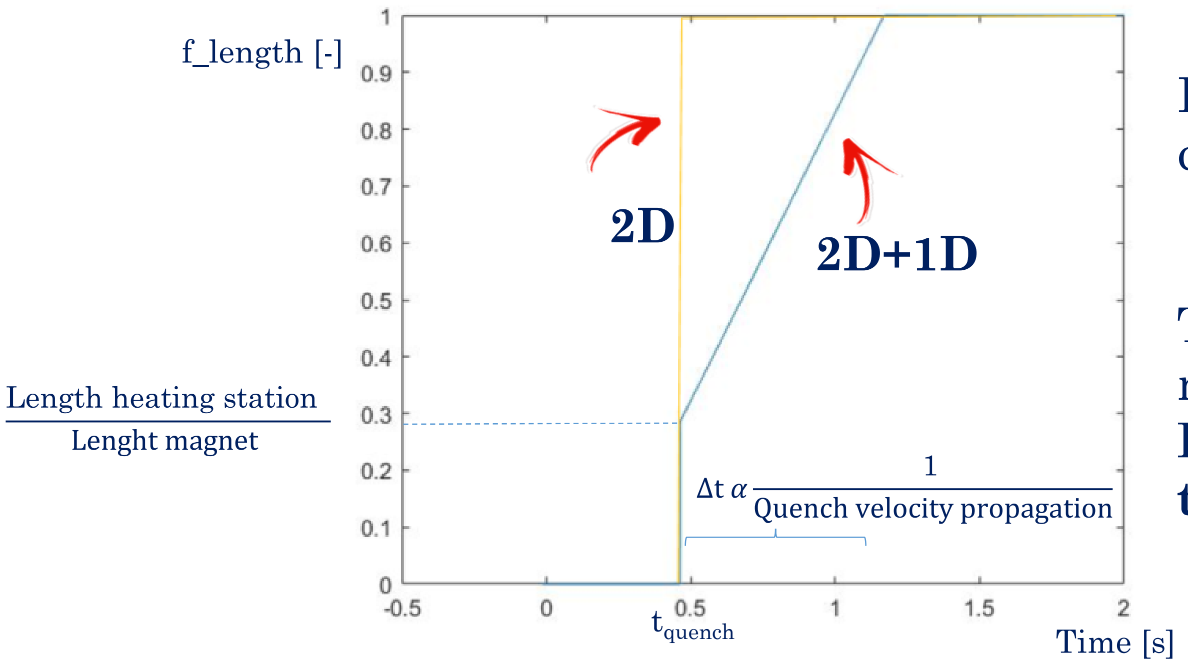
Thanks
Emmanuele

New LEDET's features

2D → 2D+1D

3.4m → Entire length of the magnet

0.97m → Length covered by the heating stations!
It is the initial longitudinal fraction of quenched conductor[m]; from here the heat starts to spread with a certain quench velocity propagation.



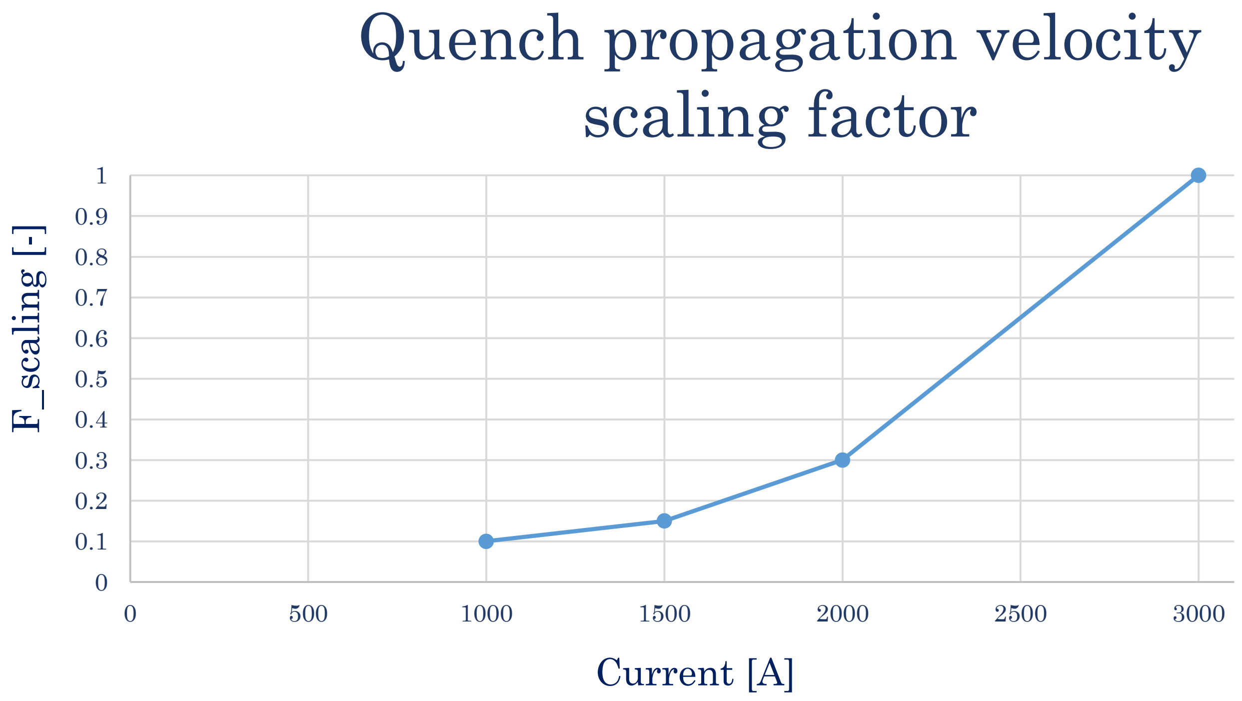
For each half-turn, f_length(t) is the fraction of quenched conductor in the longitudinal direction

The quench velocity propagation depends on the magnetic field and the current.
LEDET defines the quench velocity propagation **turns by turns.**

Quench velocity propagation

Quench propagation velocity scaling factor due to cooling effect

LEDET defines the quench velocity propagation **turns by turns.** It depends on the **magnetic field**, the **magnet current** and the **scaling factor,** that depends on the cooling effect.

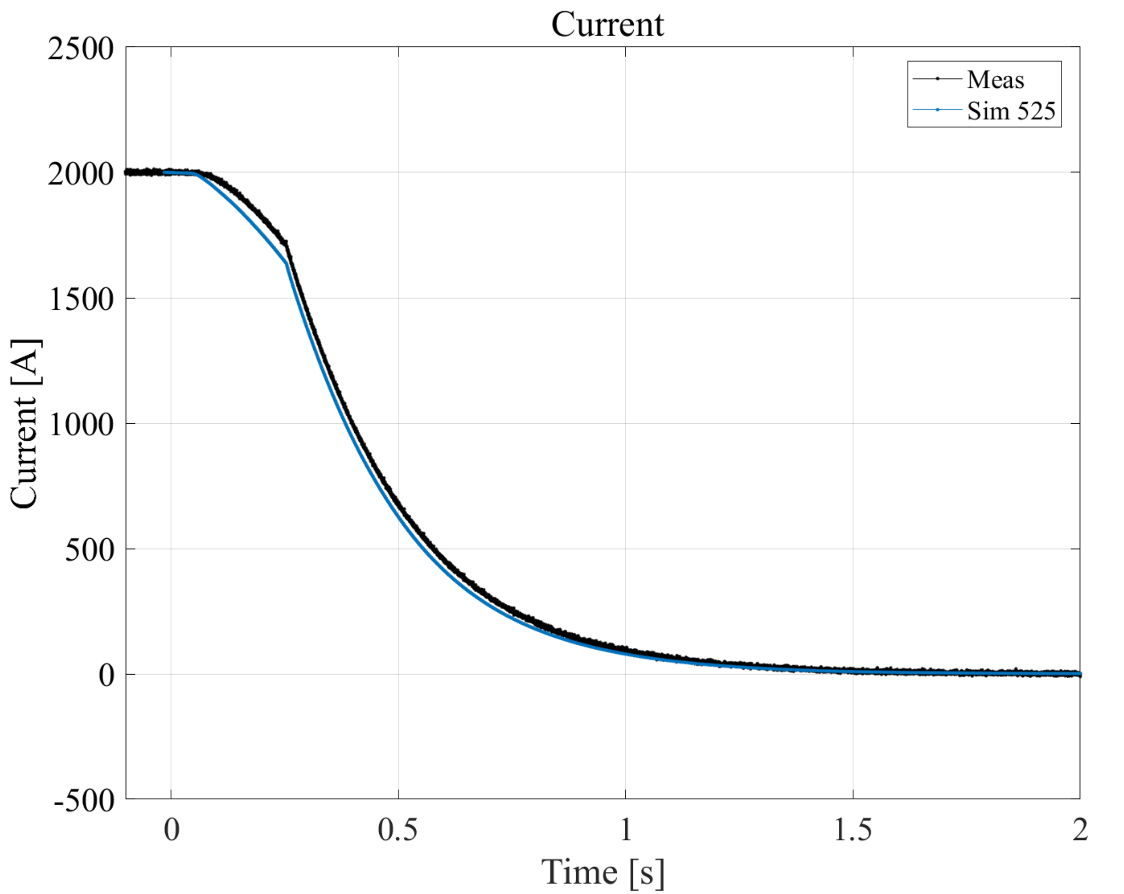


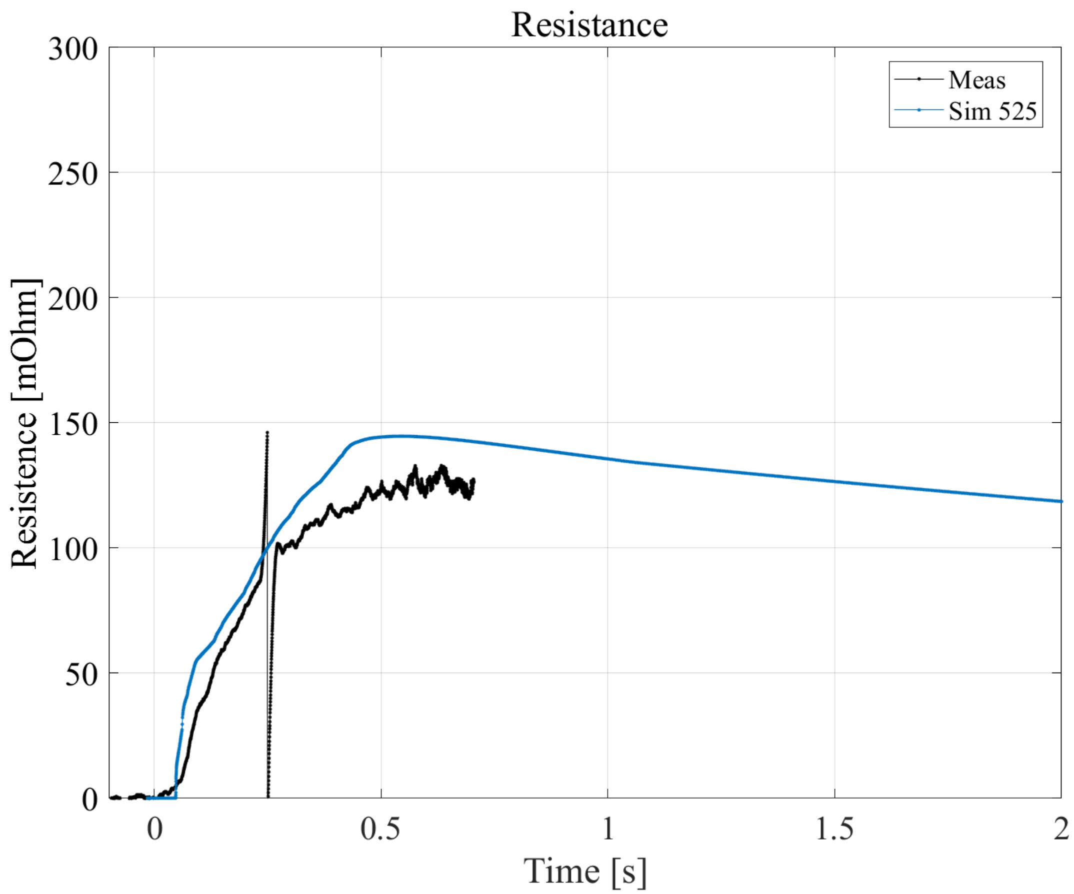
[3] Herman Ten Kate,Superconducting magnet quench propagation and protection, 2013

Test 3 (Quench Heaters + delay Energy Extraction)

I [A]	EE[s]	QH [s]	QH[V]	QH[mF]	RRR
2000	0.254	0.004	900	4*7.05	225

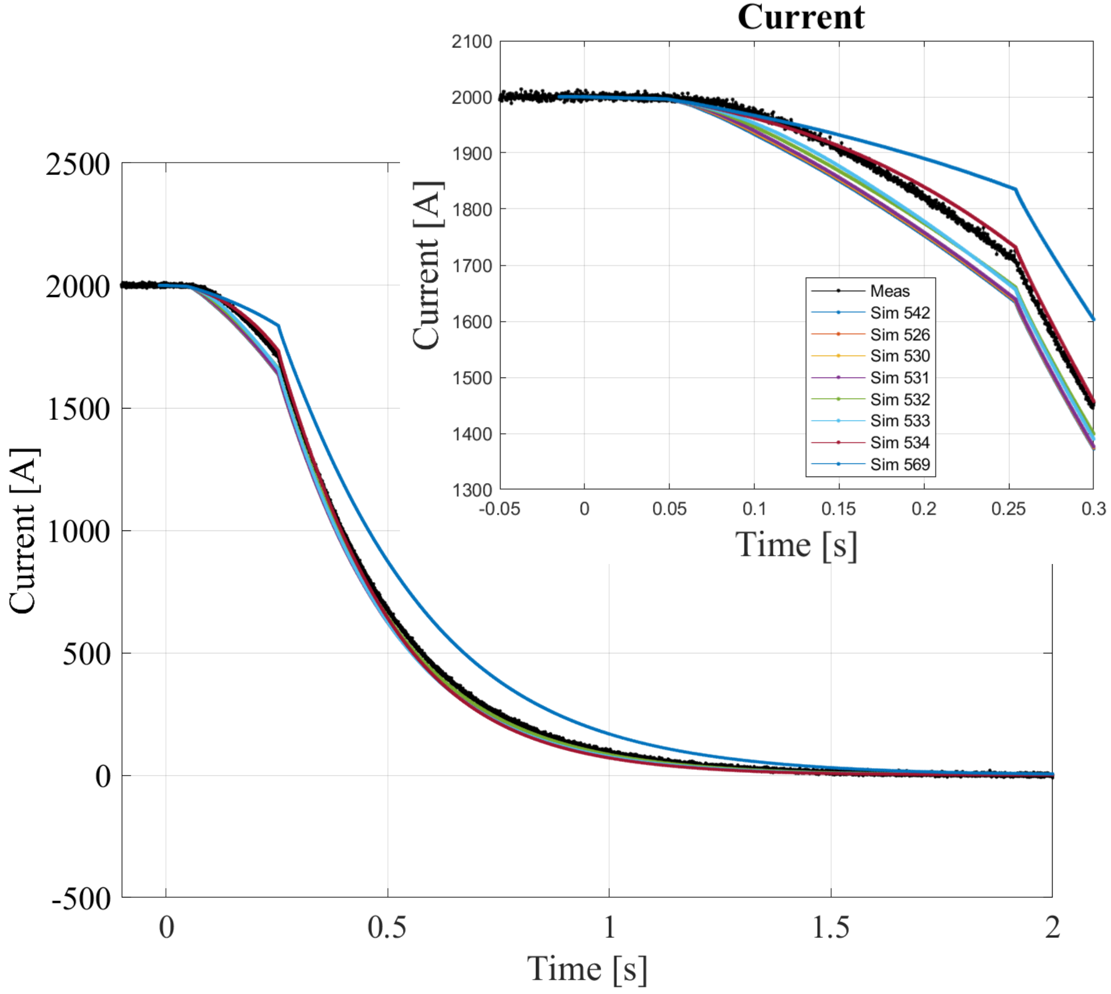
purely 2D model

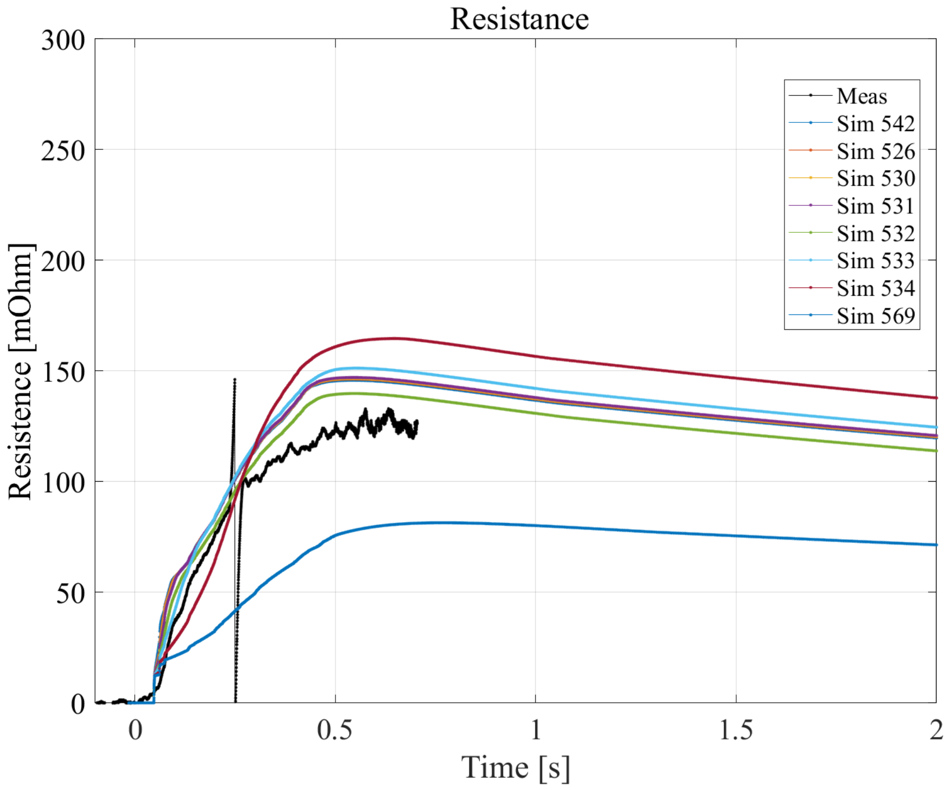




Test 3 (Quench Heaters + delay Energy Extraction)

I [A]	EE[s]	QH [s]	QH[V]	QH[mF]	RRR
2000	0.254	0.004	900	4*7.05	225

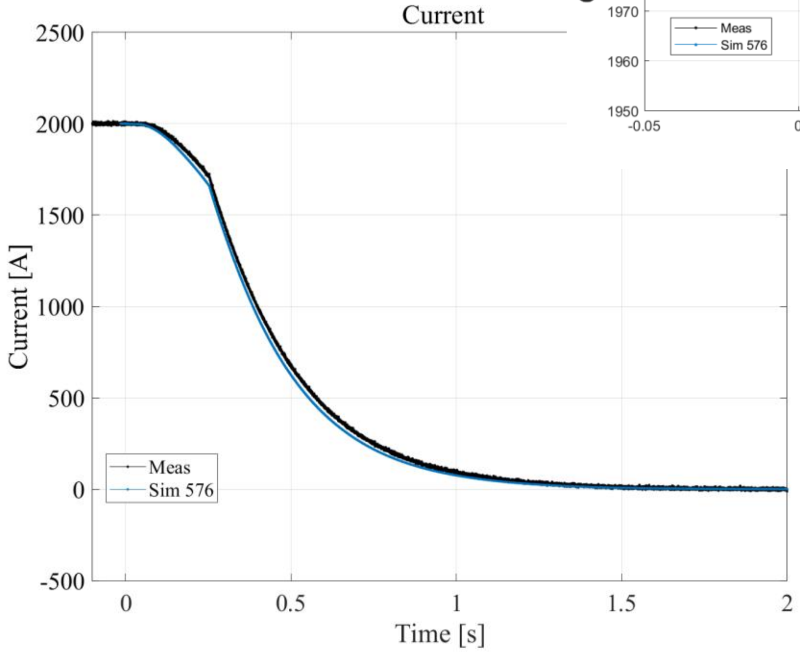


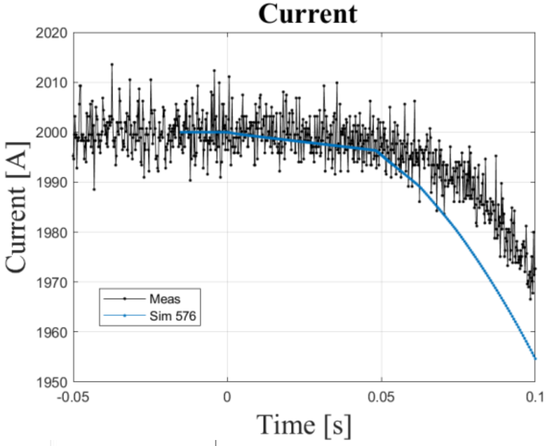


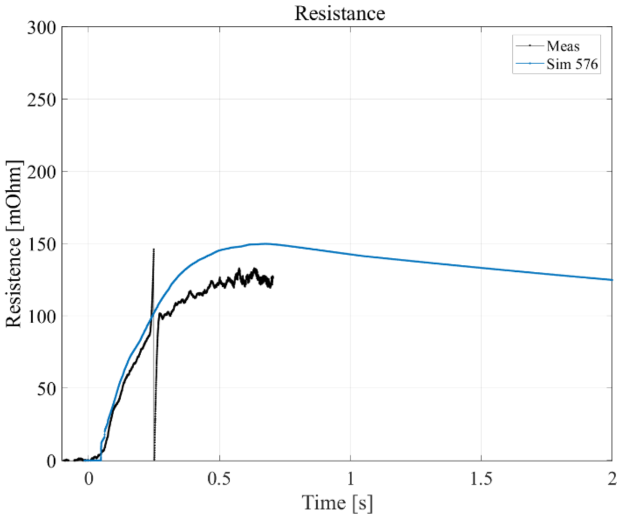
Sim	F_scaling vQ
542	1
526	0.9
530	0.8
531	0.7
532	0.5
533	0.3
534	0.1
569	0

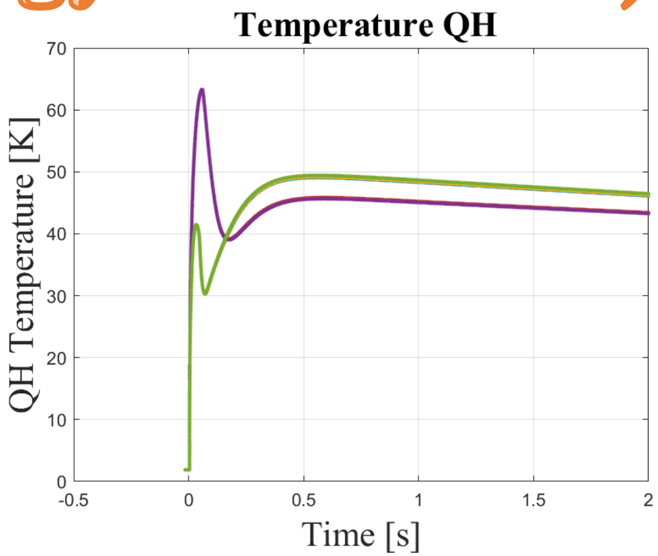
Test 3 (Quench Heaters + delay Energy Extraction)

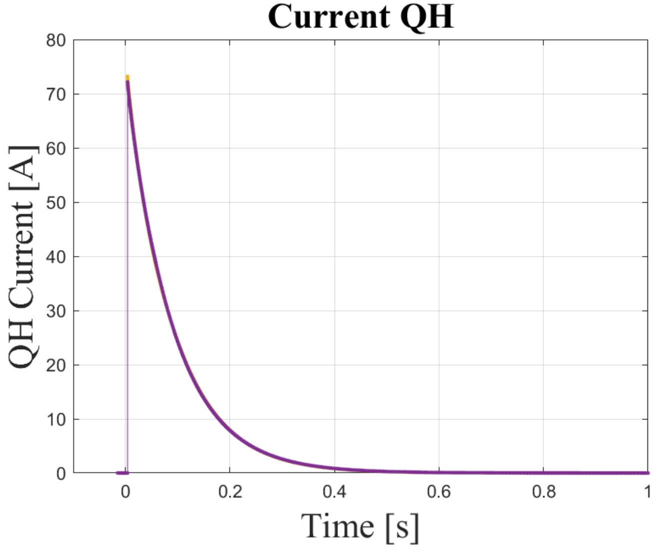
I [A]	EE[s]	QH [s]	QH[V]	QH[mF]	RRR	F_scaling vQ
2000	0.254	0.004	900	4*7.05	225	0.3







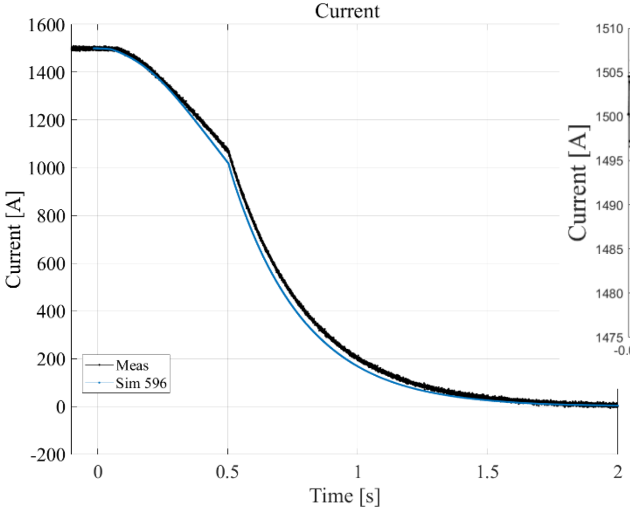


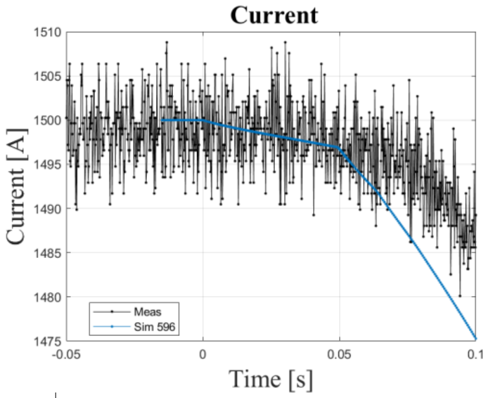


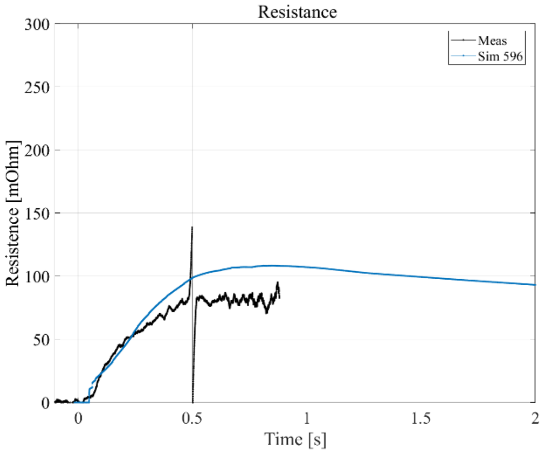
Quench velocity propagation

Test 4/5 (Quench Heaters + delay Energy Extraction)

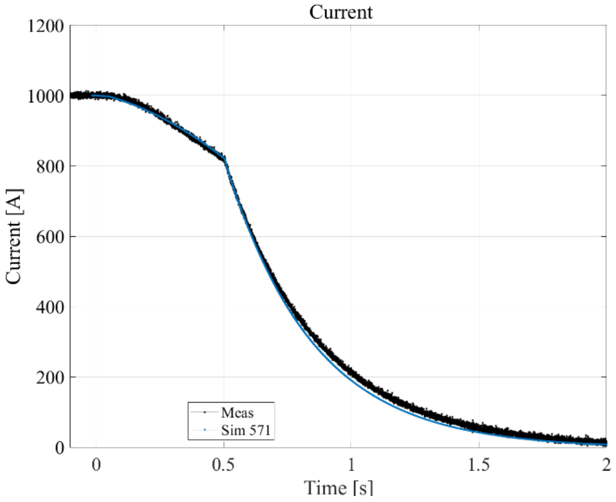
I [A]	EE[s]	QH [s]	QH[V]	QH[mF]	RRR	F_scaling vQ
1500	0.504	0.004	900	4*7.05	225	0.15

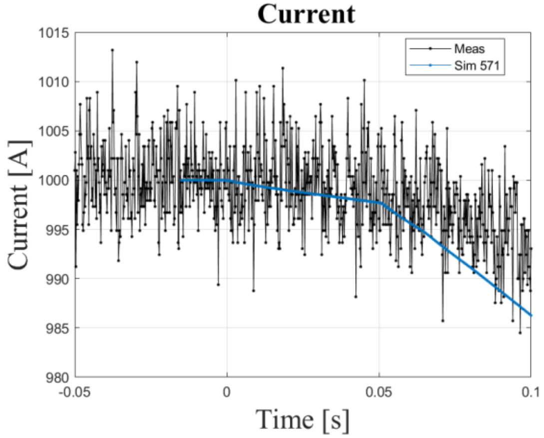


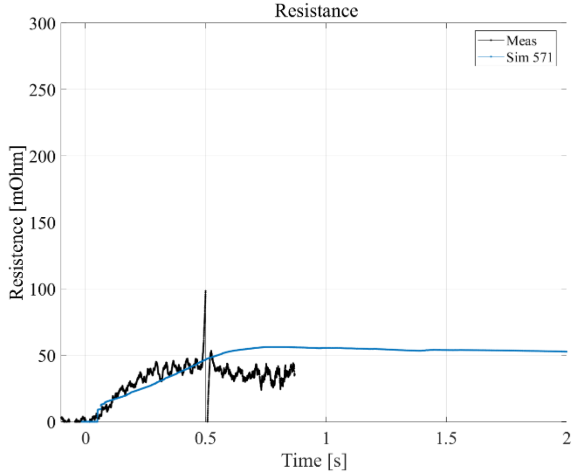




I [A]	EE[s]	QH [s]	QH[V]	QH[mF]	RRR	F_scaling vQ
1000	0.504	0.004	900	4*7.05	225	0.1







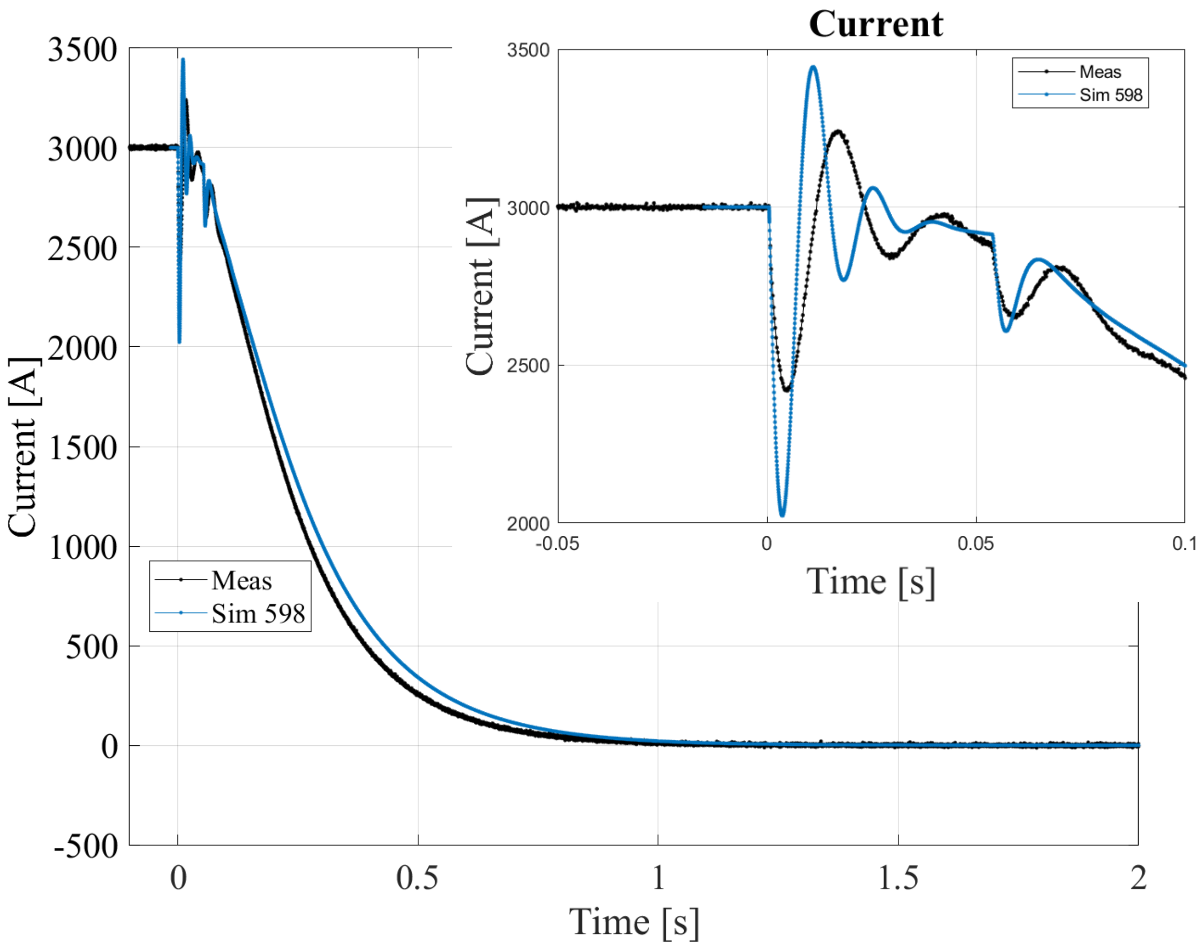
Tests overview

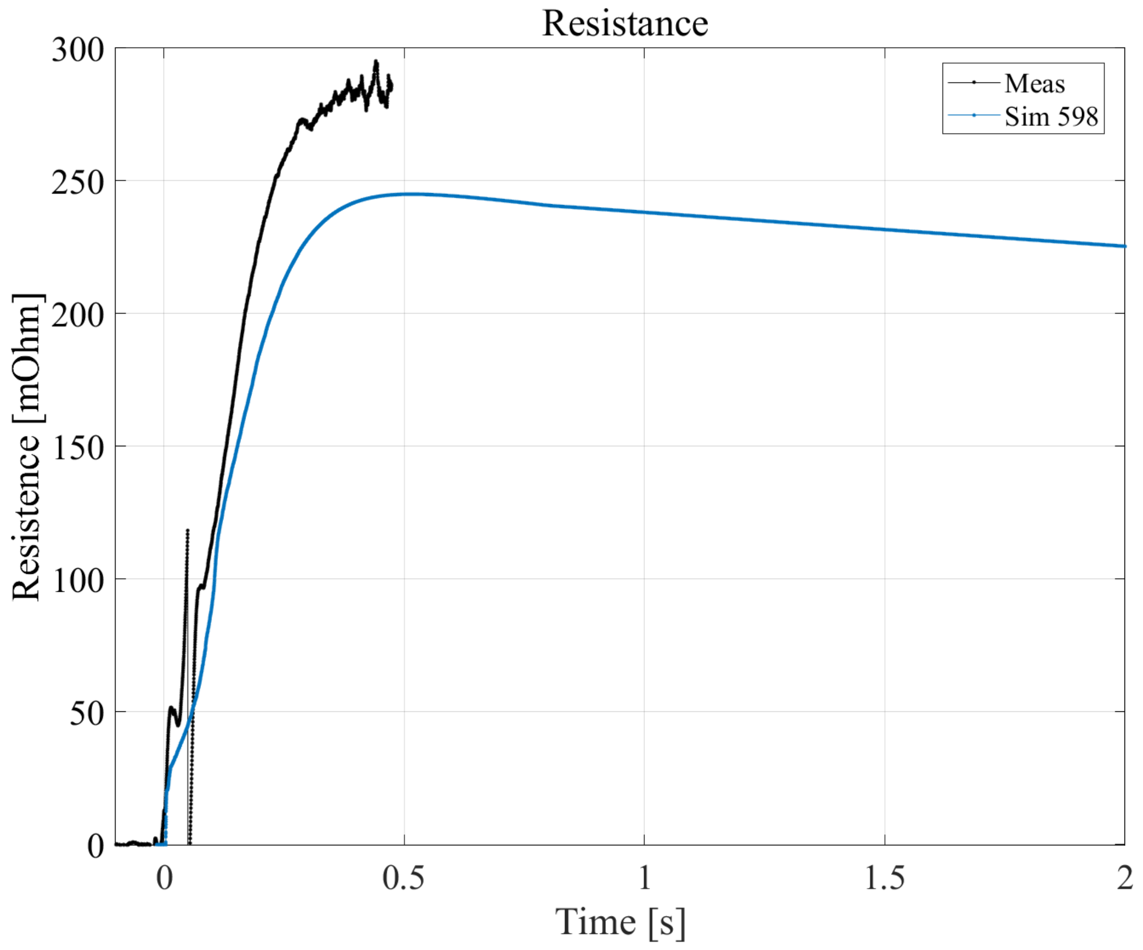
SM18 Ref	Test	T[K]	I[A]	EE (Delay)	CLIQ	QH
	Only EE					
1	1	1.9	1000	✓ (0.004s)	-	-
	QH+ EE					
14	2	1.9	3000	✓ (0.054s)	-	✓ (0.004s)
13	3	1.9	2000	✓ (0.254s)	-	✓ (0.004s)
4	4	1.9	1500	✓ (0.504s)	-	✓ (0.004s)
12	5	1.9	1000	✓ (0.504s)	-	✓ (0.004s)
	CLIQ+EE					
15	6	1.9	3000	✓ (0.054s)	✓ (0.0005s) CLIQ unit1 (650V;8.8mF)	-
9	7	1.9	2000	✓ (0.254s)	✓ (0.0005s) CLIQ unit1 (650V;8.8mF)	-
8	8	1.9	1500	✓ (0.504s)	✓ (0.0005s) CLIQ unit1 (650V;8.8mF)	-
7	9	1.9	1000	✓ (0.504s)	✓ (0.0005s) CLIQ unit1 (650V;8.8mF)	-
3	10	1.9	1500	✓ (0.504s)	✓ (0.0005s) CLIQ unit2 (500V;56.4mF)	-
2	11	1.9	1000	✓ (0.504s)	✓ (0.0005s) CLIQ unit2 (500V;56.4mF)	-
10	12	1.9	1000	✓ (0.504s)	✓ (0.0005s) CLIQ unit1 (500V;8.8mF)	-
11	13	1.9	1000	✓ (0.504s)	✓ (0.0005s) CLIQ unit1 (400V;8.8mF)	-

Test 6 (CLIQ+ delay Energy Extraction)

I [A]	EE[s]	CLIQ[s]	CLIQ[V]	CLIQ[mF]	RRR
3000	0.054	0.0005	650	8.8	225

simulation with first guess parameters





Interfilament coupling current

When a superconducting strand is subject to a changing magnetic field perpendicular to the transport current, **coupling currents are generated** between the superconducting filaments.The currents paths are closed across the normal conducting matrix and develop ohmic loss.
The interfilament coupling current develop with a characteristic **time constant**.

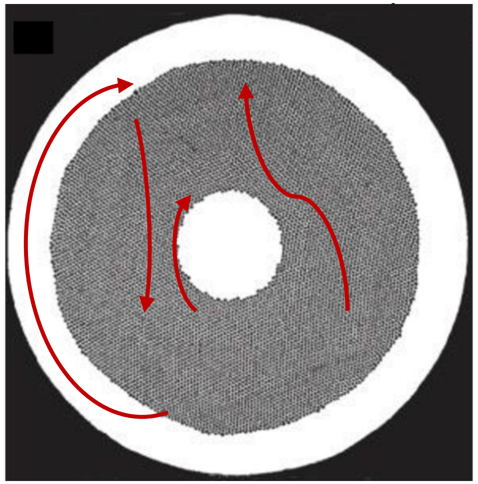
$$\tau_{IFCC} = \frac{\mu_0}{2}\left(\frac{l_f}{2\pi}\right)^2 \frac{1}{\rho_m(T,B) feff}$$

l_f is the intefilament twist peach$[m]$

ρ_m is the matrix resistivity $[\Omega m]$

μ_0 the magnetic permeability of vacuum$[TmA^{-1}]$

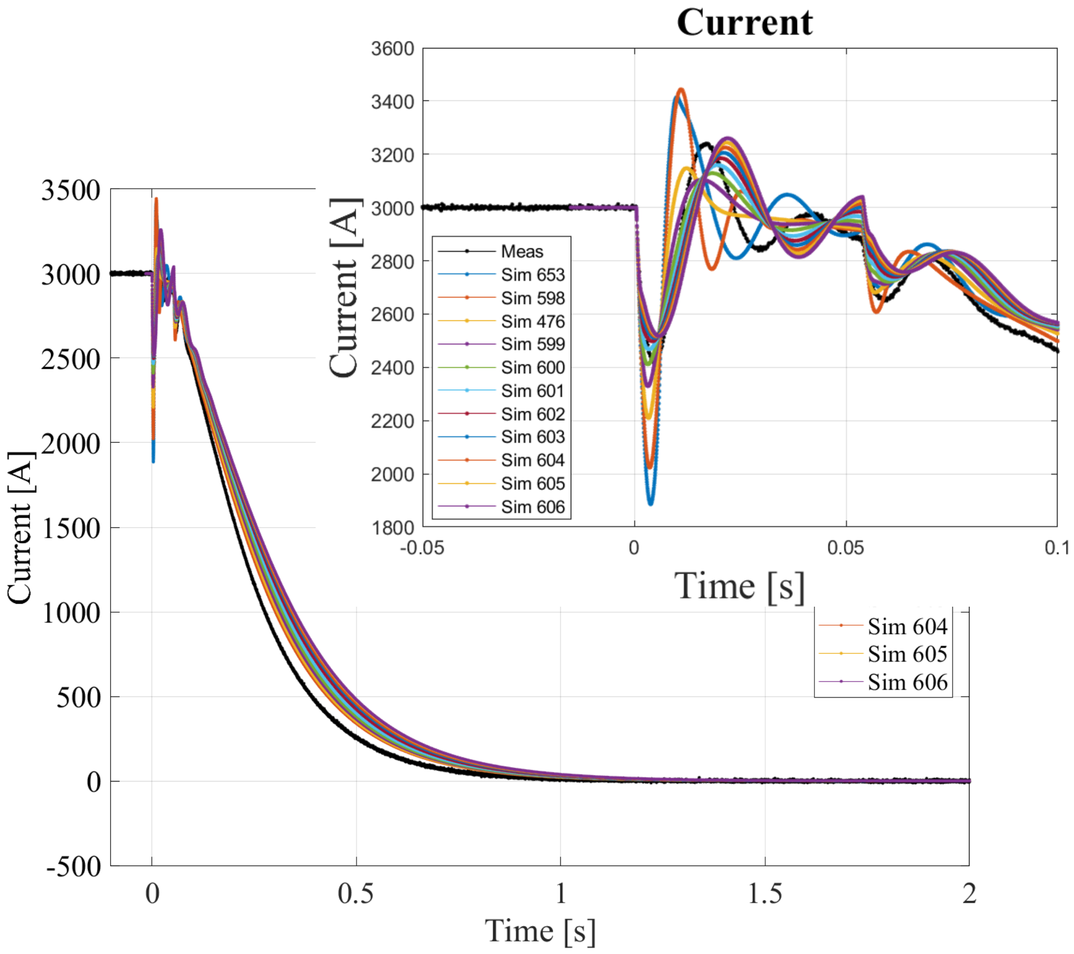
$\mathbf{f_{eff}}$ represents the **effective transverse resistivity parameter.** It depends on the superconductor fraction in the matrix, on the interface resistance between the filaments and the matrix, and the position of the filaments in the wire cross

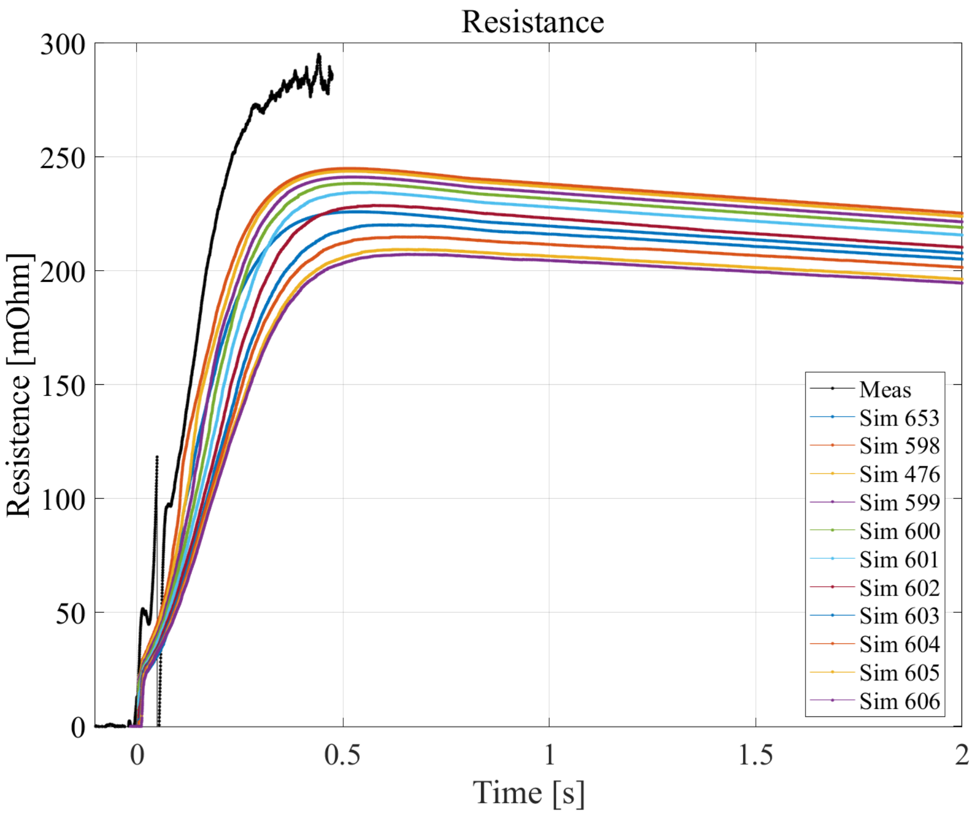


Effective transverse resistivity parameter

Test 6 (CLIQ+ delay Energy Extraction)

I [A]	EE[s]	CLIQ[s]	CLIQ[V]	CLIQ[mF]	RRR
3000	0.054	0.0005	650	8.8	225

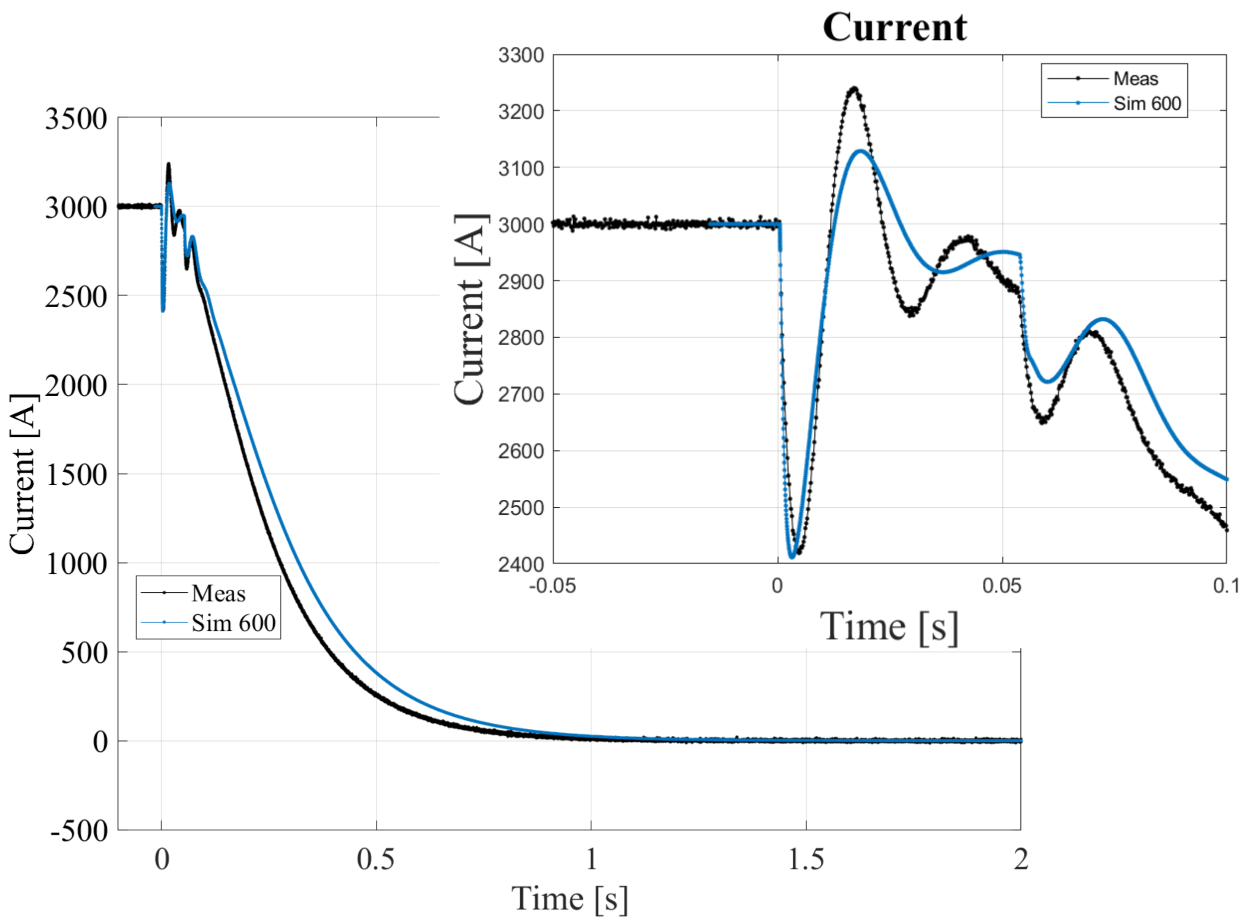


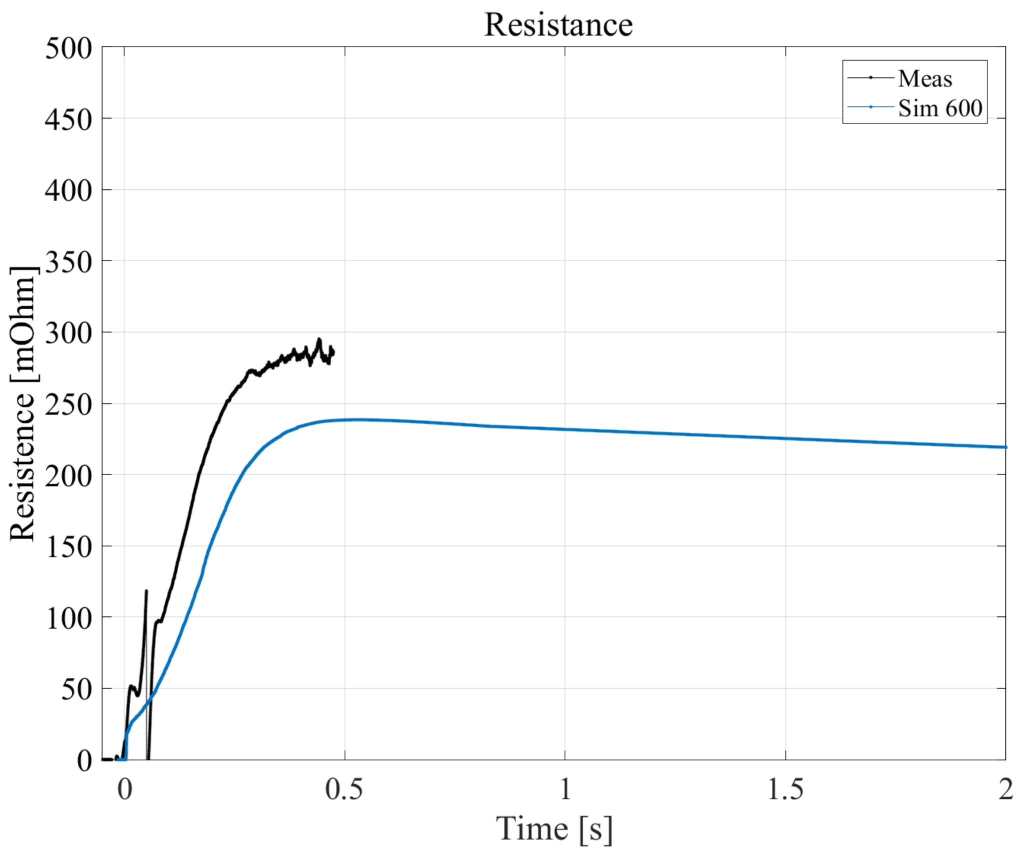


Sim	F_ro_eff
653	0.5
598	1
476	2
599	3
600	4
601	5
602	6
603	7
604	8
605	9
606	10

Test 6 (CLIQ+ delay Energy Extraction)

I [A]	EE[s]	CLIQ[s]	CLIQ[V]	CLIQ[mF]	RRR	f_ro_eff
3000	0.054	0.0005	650	8.8	225	4



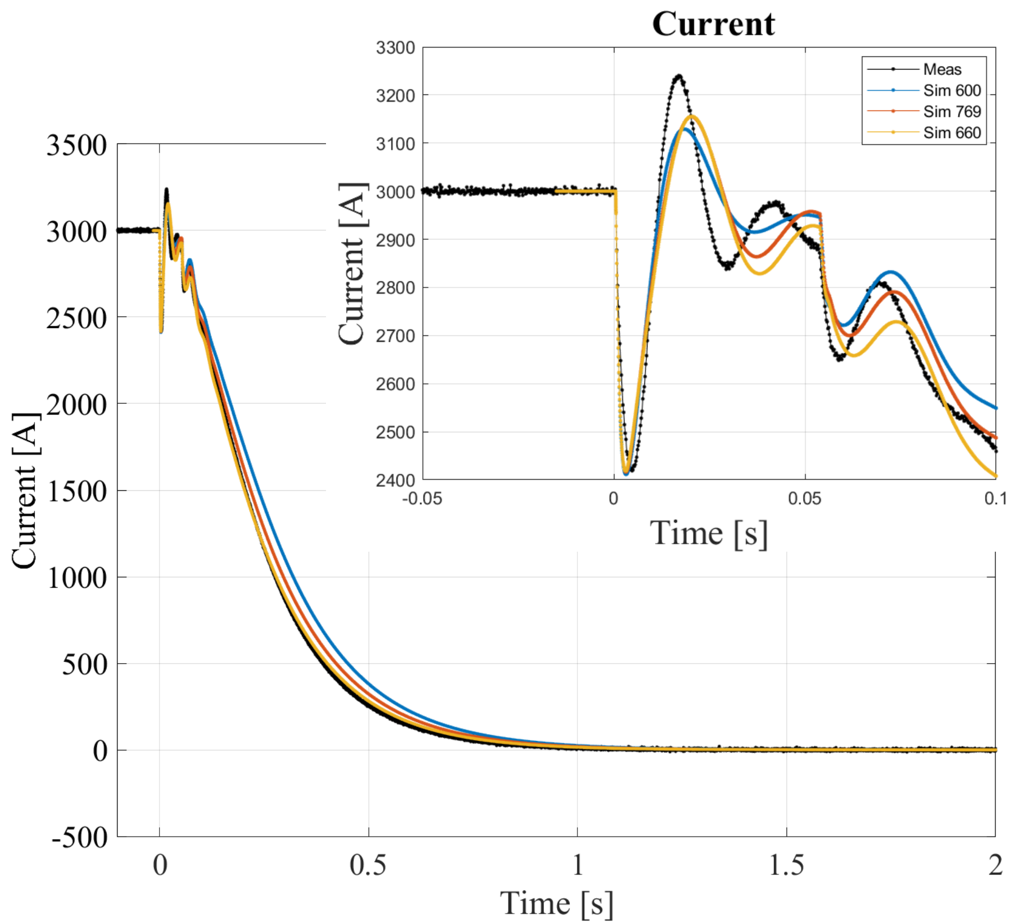


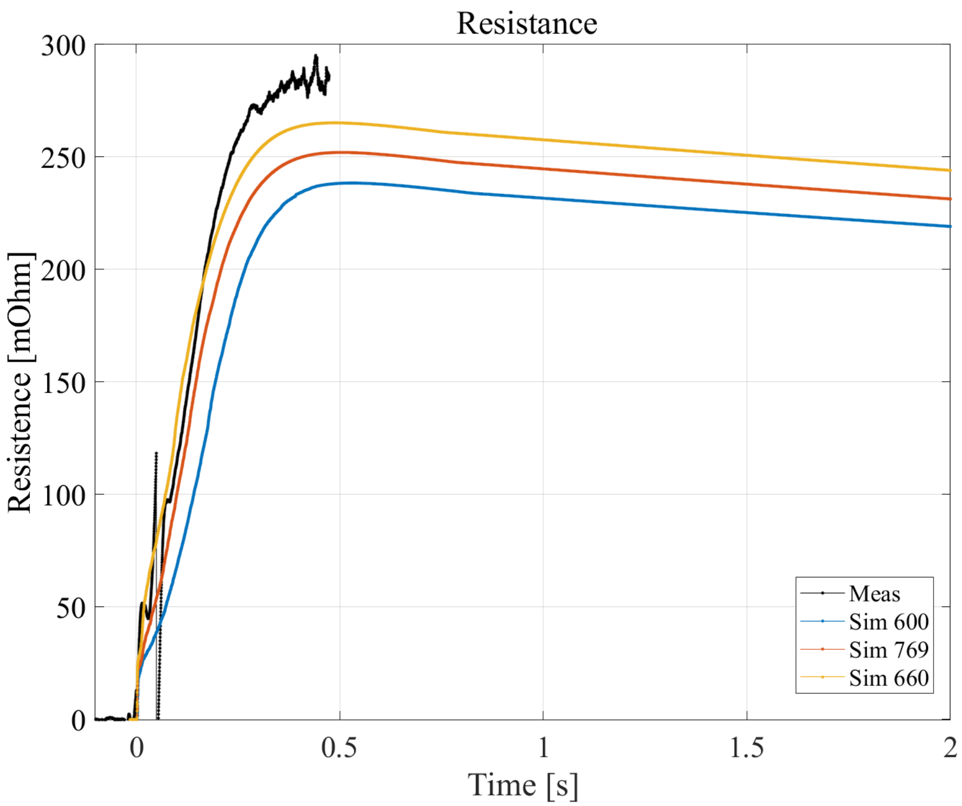
Helium fraction in cable cross section

Test 6 (CLIQ+ delay Energy Extraction)

I [A]	EE[s]	CLIQ[s]	CLIQ[V]	CLIQ[mF]	RRR	f_ro_eff
3000	0.054	0.0005	650	8.8	225	4

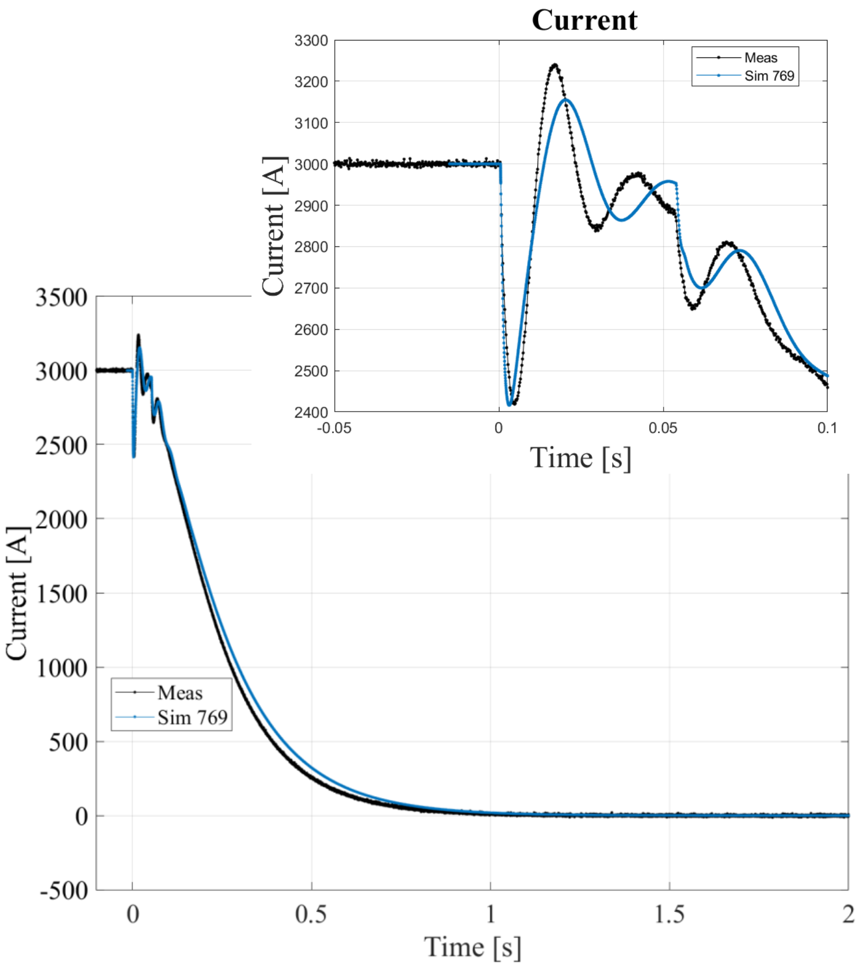
Sim	He_Int	He_Ext
600	0.098	0
769	0.07	0.028
660	0.045	0.054

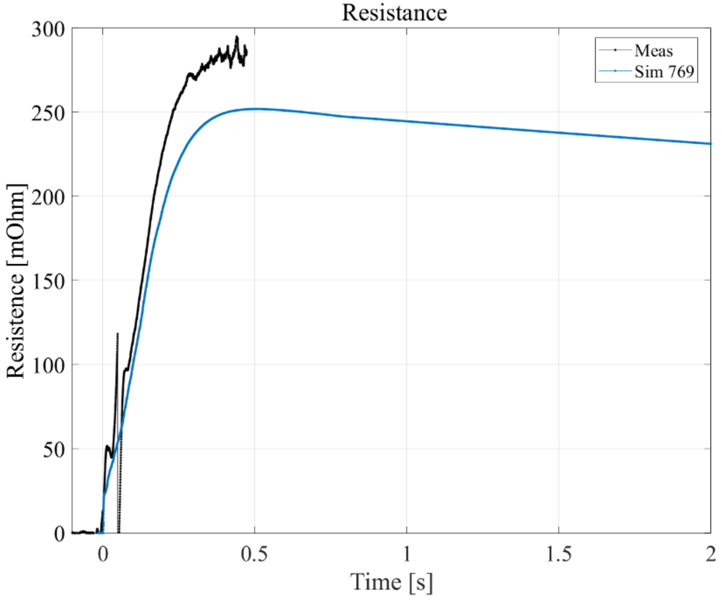


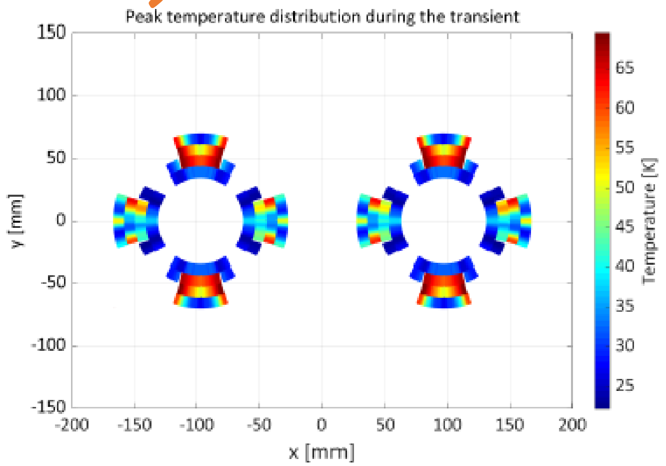


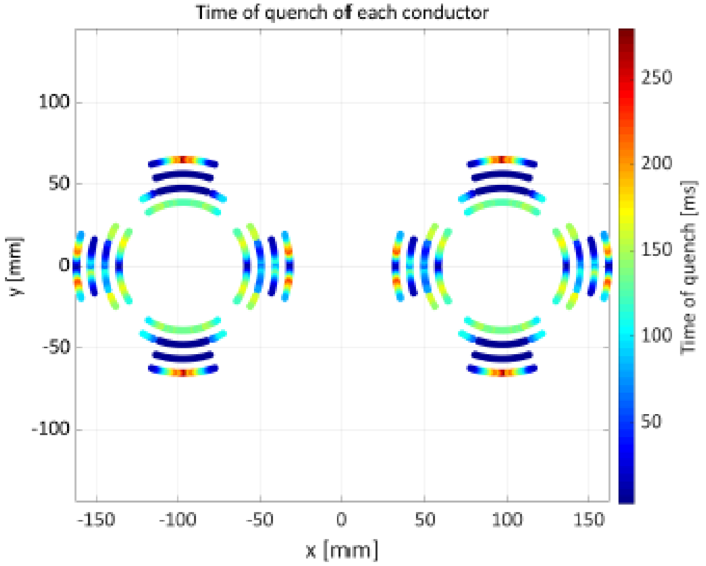
Test 6 (CLIQ+ delay Energy Extraction)

I [A]	EE[s]	CLIQ[s]	CLIQ[V]	CLIQ[mF]	RRR	f_ro_eff	He_int	He_ext
3000	0.054	0.0005	650	8.8	225	4	0.07	0.028







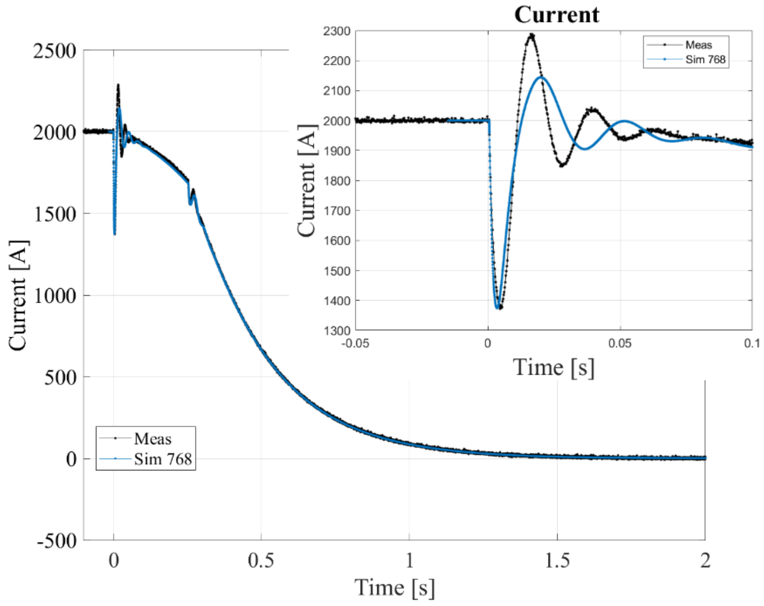


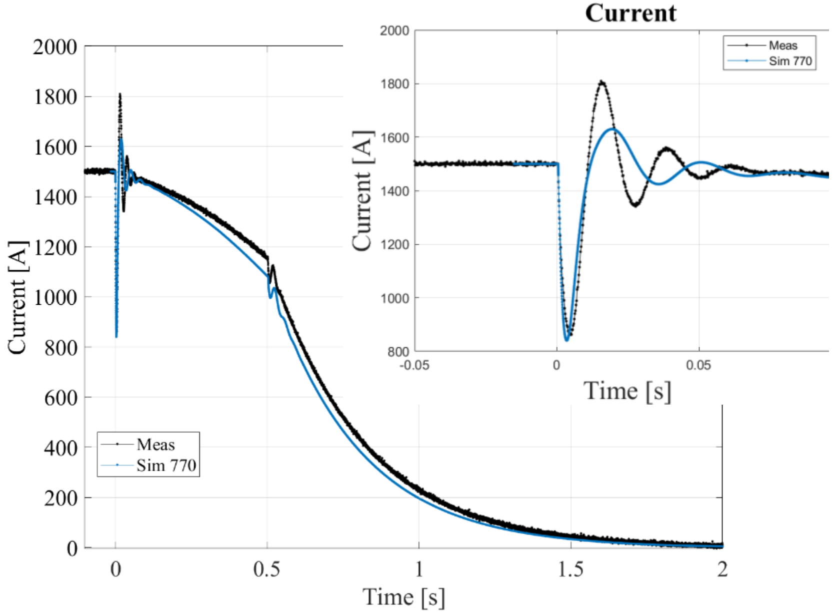
Test 7/8/9 (CLIQ+ delay Energy Extraction)

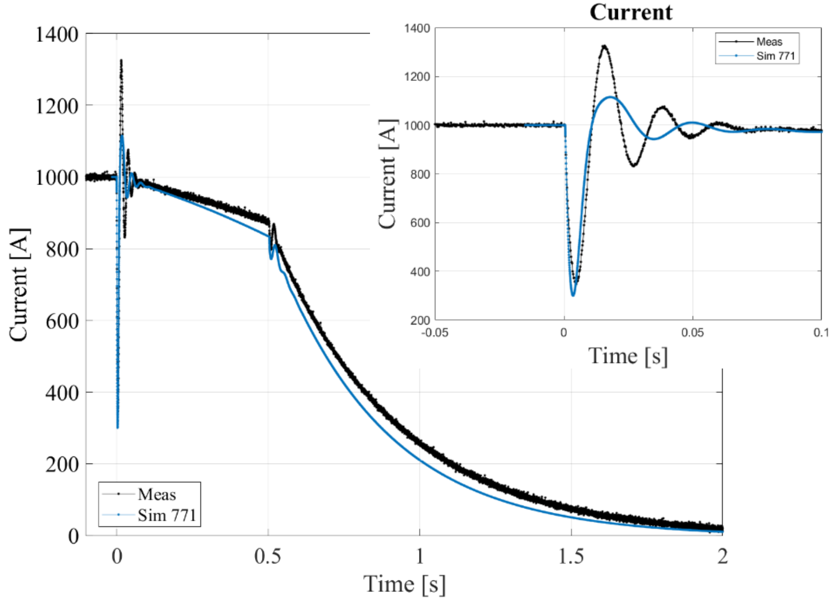
I [A]	EE[s]
2000	0.254

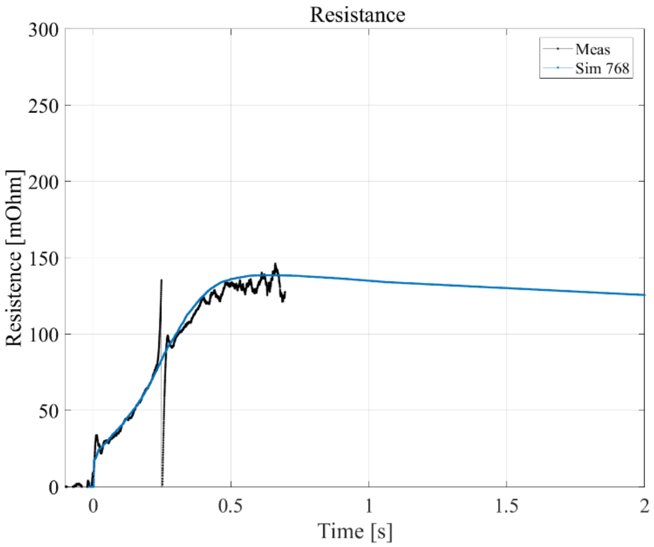
I [A]	EE[s]
1500	0.504

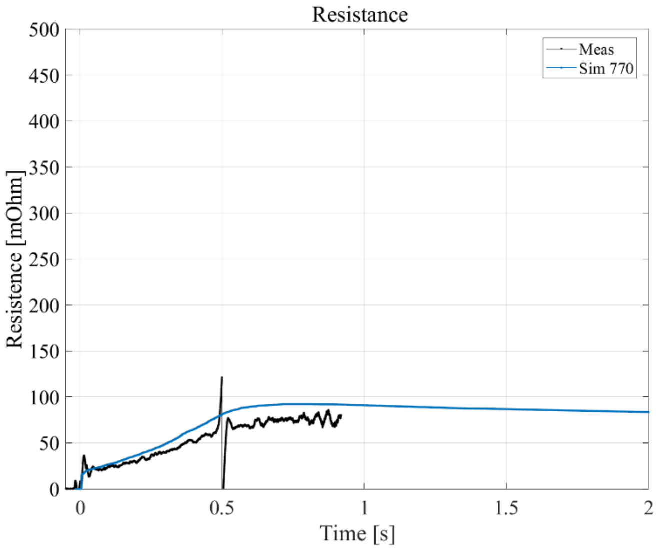
I [A]	EE[s]
1000	0.504

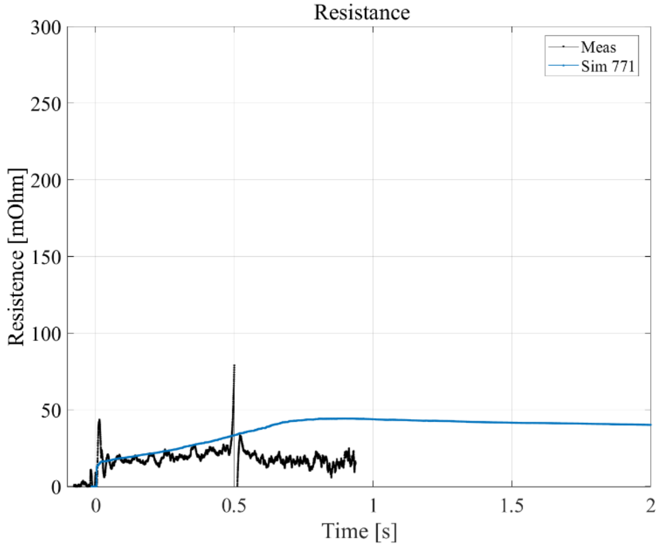










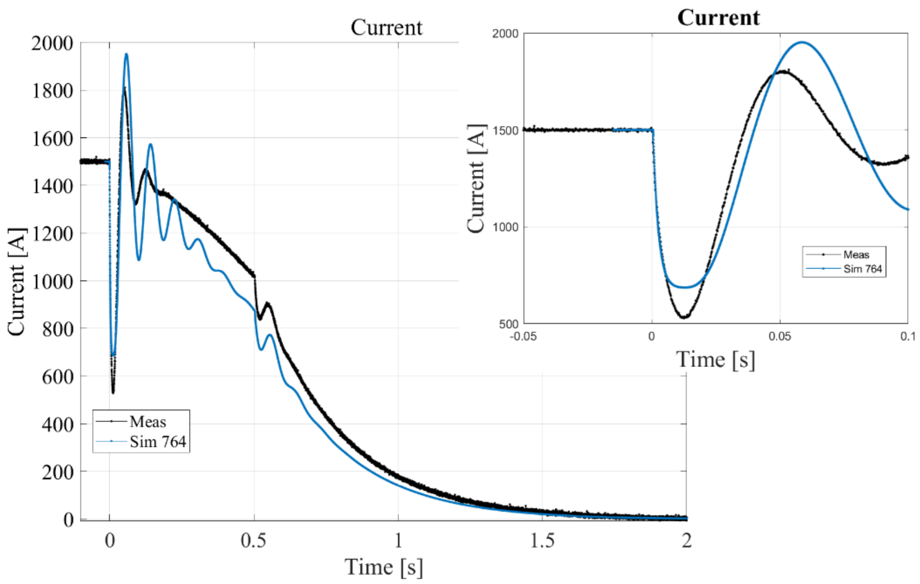


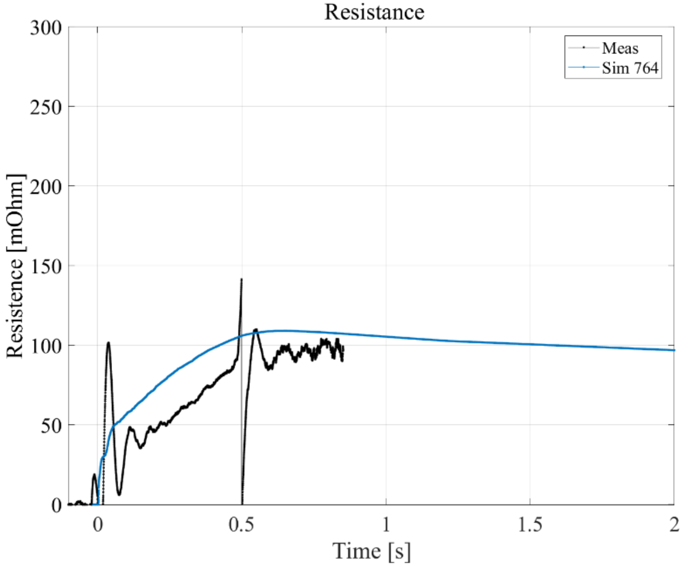
Tests overview

SM18 Ref	Test	T[K]	I[A]	EE (Delay)	CLIQ	QH
	Only EE					
1	1	1.9	1000	✓ (0.004s)	-	-
	QH+ EE					
14	2	1.9	3000	✓ (0.054s)	-	✓ (0.004s)
13	3	1.9	2000	✓ (0.254s)	-	✓ (0.004s)
4	4	1.9	1500	✓ (0.504s)	-	✓ (0.004s)
12	5	1.9	1000	✓ (0.504s)	-	✓ (0.004s)
	CLIQ+EE					
15	6	1.9	3000	✓ (0.054s)	✓ (0.0005s) CLIQ unit1 (650V;8.8mF)	-
9	7	1.9	2000	✓ (0.254s)	✓ (0.0005s) CLIQ unit1 (650V;8.8mF)	-
8	8	1.9	1500	✓ (0.504s)	✓ (0.0005s) CLIQ unit1 (650V;8.8mF)	-
7	9	1.9	1000	✓ (0.504s)	✓ (0.0005s) CLIQ unit1 (650V;8.8mF)	-
3	10	1.9	1500	✓ (0.504s)	✓ (0.0005s) CLIQ unit2 (500V;56.4mF)	-
2	11	1.9	1000	✓ (0.504s)	✓ (0.0005s) CLIQ unit2 (500V;56.4mF)	-
10	12	1.9	1000	✓ (0.504s)	✓ (0.0005s) CLIQ unit1 (500V;8.8mF)	-
11	13	1.9	1000	✓ (0.504s)	✓ (0.0005s) CLIQ unit1 (400V;8.8mF)	-

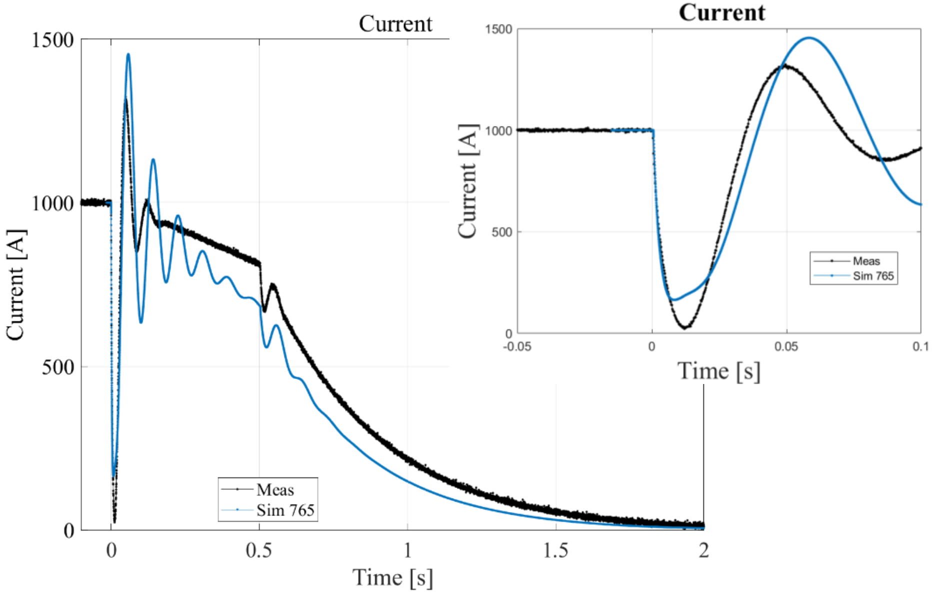
CLIQ1 Test 10/11 (CLIQ+ delay Energy Extraction)

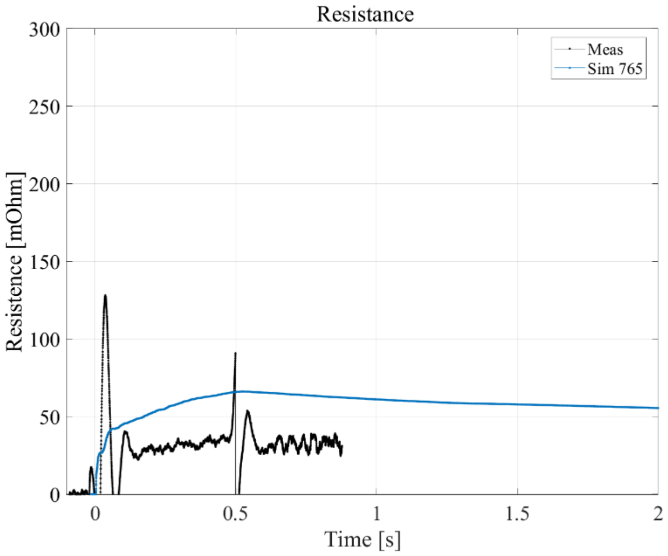
I [A]	EE[s]	CLIQ[s]	CLIQ[V]	CLIQ[mF]	RRR
1500	0.504	0.0005	500	56.4	225





I [A]	EE[s]	CLIQ[s]	CLIQ[V]	CLIQ[mF]	RRR
1000	0.504	0.0005	500	56.4	225





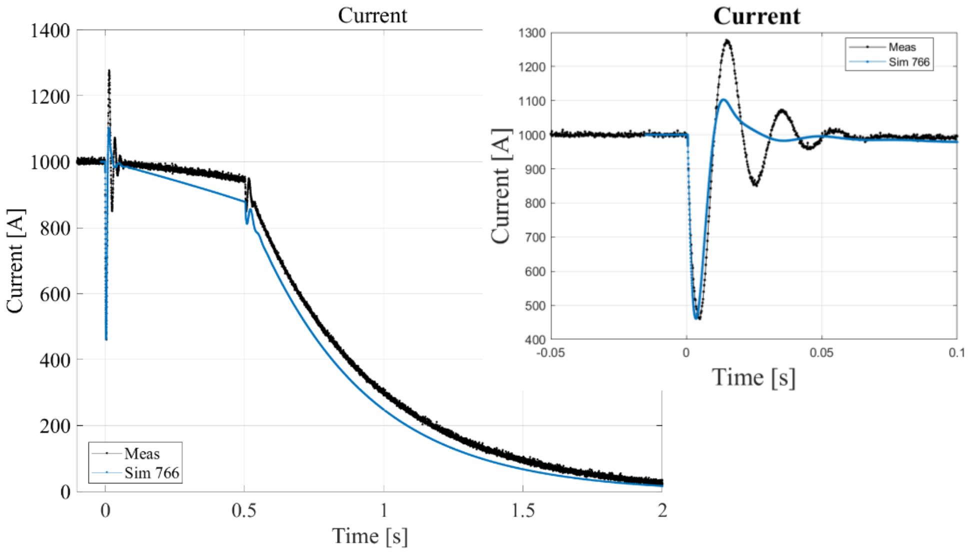
Tests overview

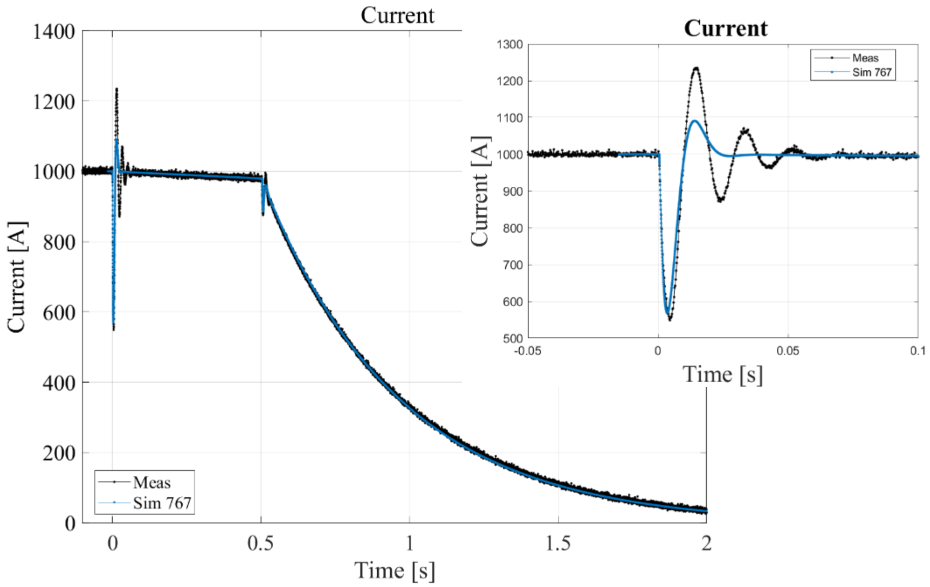
SM18 Ref	Test	T[K]	I[A]	EE (Delay)	CLIQ	QH
	Only EE					
1	1	1.9	1000	✓ (0.004s)	-	-
	QH+ EE					
14	2	1.9	3000	✓ (0.054s)	-	✓ (0.004s)
13	3	1.9	2000	✓ (0.254s)	-	✓ (0.004s)
4	4	1.9	1500	✓ (0.504s)	-	✓ (0.004s)
12	5	1.9	1000	✓ (0.504s)	-	✓ (0.004s)
	CLIQ+EE					
15	6	1.9	3000	✓ (0.054s)	✓ (0.0005s) CLIQ unit1 (650V;8.8mF)	-
9	7	1.9	2000	✓ (0.254s)	✓ (0.0005s) CLIQ unit1 (650V;8.8mF)	-
8	8	1.9	1500	✓ (0.504s)	✓ (0.0005s) CLIQ unit1 (650V;8.8mF)	-
7	9	1.9	1000	✓ (0.504s)	✓ (0.0005s) CLIQ unit1 (650V;8.8mF)	-
3	10	1.9	1500	✓ (0.504s)	✓ (0.0005s) CLIQ unit2 (500V;56.4mF)	-
2	11	1.9	1000	✓ (0.504s)	✓ (0.0005s) CLIQ unit2 (500V;56.4mF)	-
10	12	1.9	1000	✓ (0.504s)	✓ (0.0005s) CLIQ unit1 (500V;8.8mF)	-
11	13	1.9	1000	✓ (0.504s)	✓ (0.0005s) CLIQ unit1 (400V;8.8mF)	-

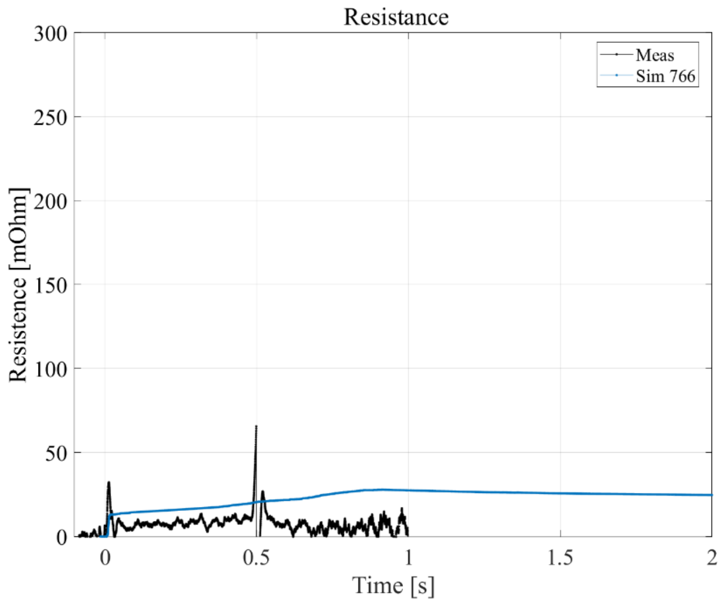
CLIQ2 Test 12/13 (CLIQ+ delay Energy Extraction)

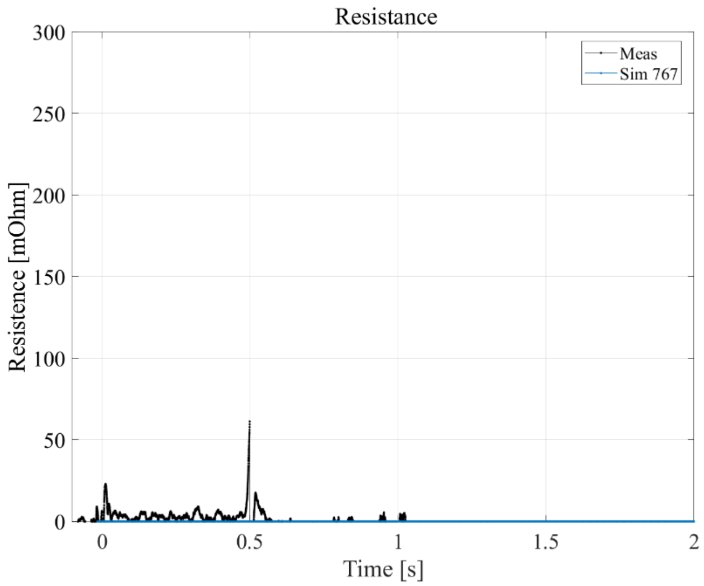
I [A]	EE[s]	CLIQ[s]	CLIQ[V]	CLIQ[mF]	RRR
1000	0.504	0.0005	500	8.8	225

I [A]	EE[s]	CLIQ[s]	CLIQ[V]	CLIQ[mF]	RRR
1000	0.504	0.0005	400	8.8	225









Unknown parameters

"+" represent how much each parameter influences the quench protection transients

Unknown parameters		Energy Extraction	Quench Heaters	CLIQ
Warm circuit resistance	R_c			
Helium fraction in the cable cross section	f_He	+	++	++
Quench velocity propagation	Scaling_vQ		(at high current) + (at low current)	
Residual Resistivity Ratio	RRR	+	+	+
Effective transverse resistivity parameter	f_ro_eff	+		++

Conclusion

- The MQY model was realized using the SWAN notebook; the input were:

I. ROXIE file (.map2d)

II. main parameters of the magnet (cable parameters, heat exchange connections, electrical connection, protection systems, etc).

The use of SWAN, for the generation of LEDET input files, reduces the probability of mistake thanks to the visualizing of the parameters and permit a rapid update in case of new features.

- The new LEDET features for the quench velocity propagation (2D+1D model and quench velocity scaling factor) are tested with the MQY magnet model.
- The model of the MQY was validated using data for different type of transients generated by different quench protection configurations. They have different impact depending on the type of transients.
- The validation of the MQY magnet model in LEDET gave a good agreement with the experimental results.

Future work

- Include the **inter-strand coupling current** in the magnet model

- Improve the LEDET **quench heaters model**

- **Assist, with real-time simulation** at CERN magnet test facility (SM18), for the MQY test campaign that will be performed this year

- Continue the MQY **validation** during the test campaign

- Test MQY in a **wider range of operating parameters**, including different temperature (1.9 K, 4.5 K) and operating current (0.5-4.0 kA)

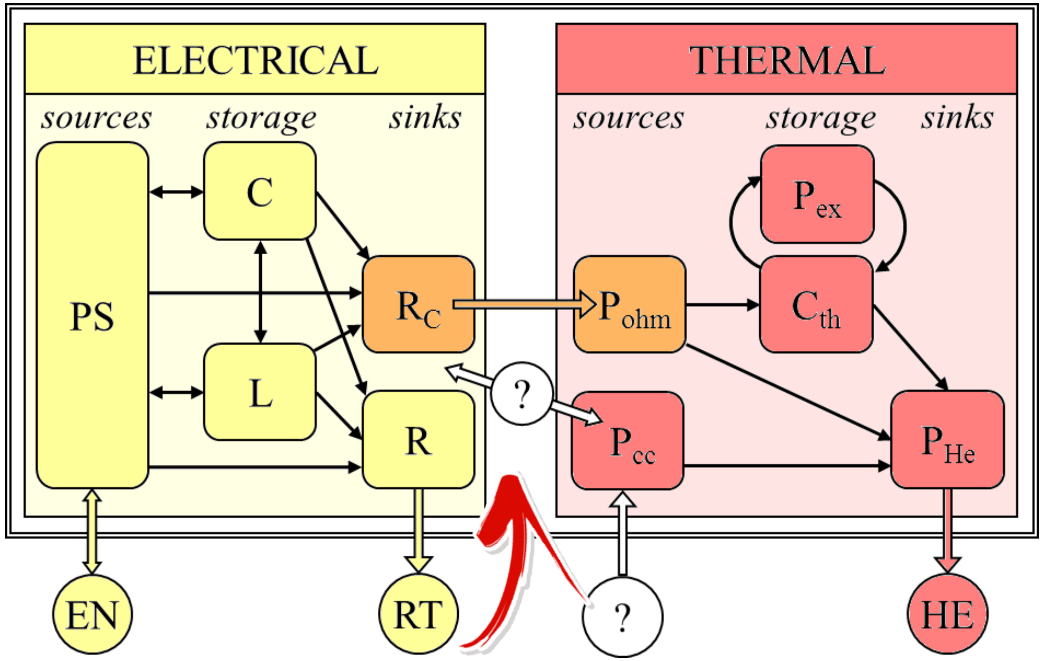
Thanks for the attention!

Any questions?

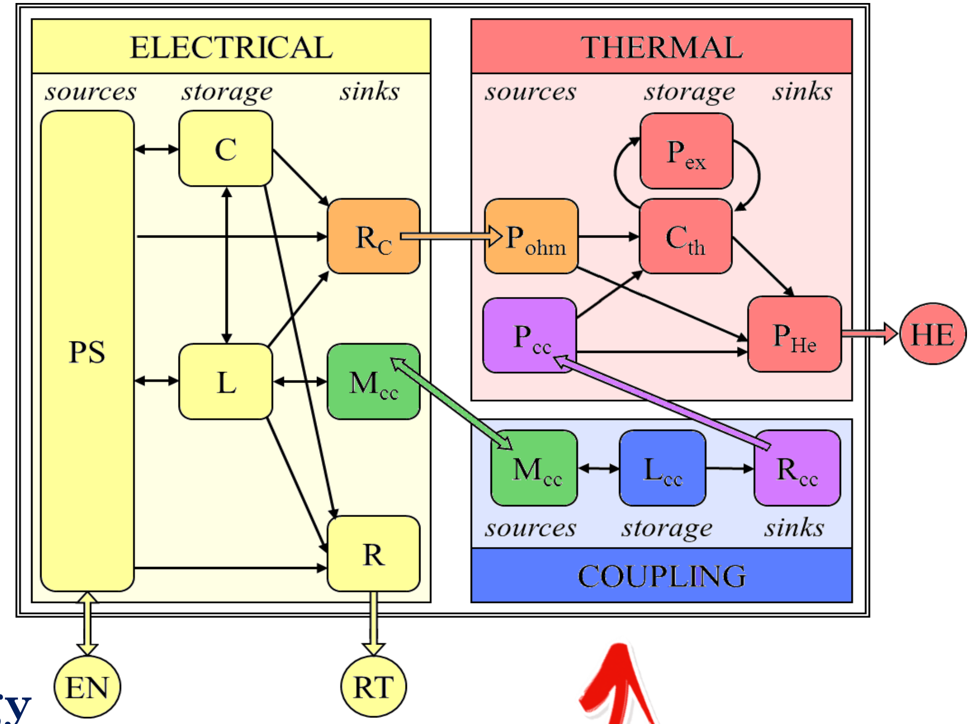
Annex

Why LEDET?

Conventional electro-thermal model:



LEDET electro-thermal model:



What is the effect of **coupling** currents on the electrical circuit?

Where is the **energy** deposited as coupling loss coming from?

LEDET implement this **coupling** mechanism

Courtesy E.Ravaioli

LEDET's main features:

- **Inter-filament** and **inter-strand coupling currents** are included
- Turn-to-turn heat exchange, simplified **helium cooling** included
- Possibility to include Energy-extraction, quench heaters, **CLIQ** transients simulated
- Comes as a .exe file. A typical simulation runs in ~**5 minutes**
- **In-house** tool (FREE).

https://cern.ch/STEAM/LEDET

When the magnetic field change, wires and cables are subject to a **transitory losses**.

Inter-filament coupling loss in wires/strands

Inter-strand coupling loss in cables

Main effects during the **magnet discharge**

Generated **loss** is **heat** deposited in the conductor, which can induce a **transition to the normal state (quench-back)**

Generated **currents** change the local magnetic field, hence influencing the **magnet differential inductance**

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

Frontend advantages

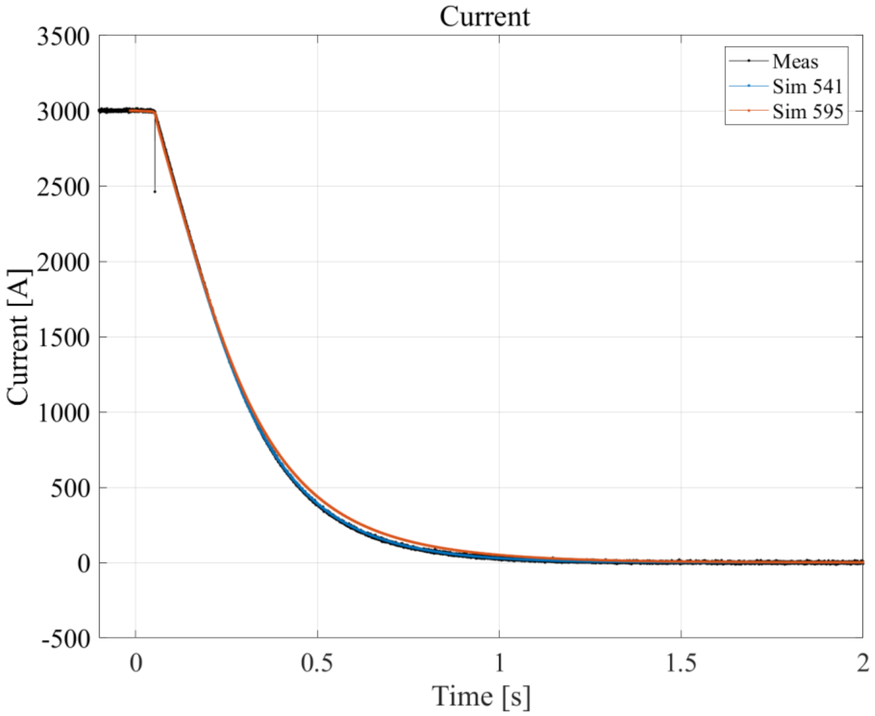
- Develop input file quickly and easily
- Reduce the probability of mistake thanks to the visualization of the parameters
- Same version of the model for different users with the same features
- Rapidly update on the reference model in case of new developed features
- Uniformity among different magnets models

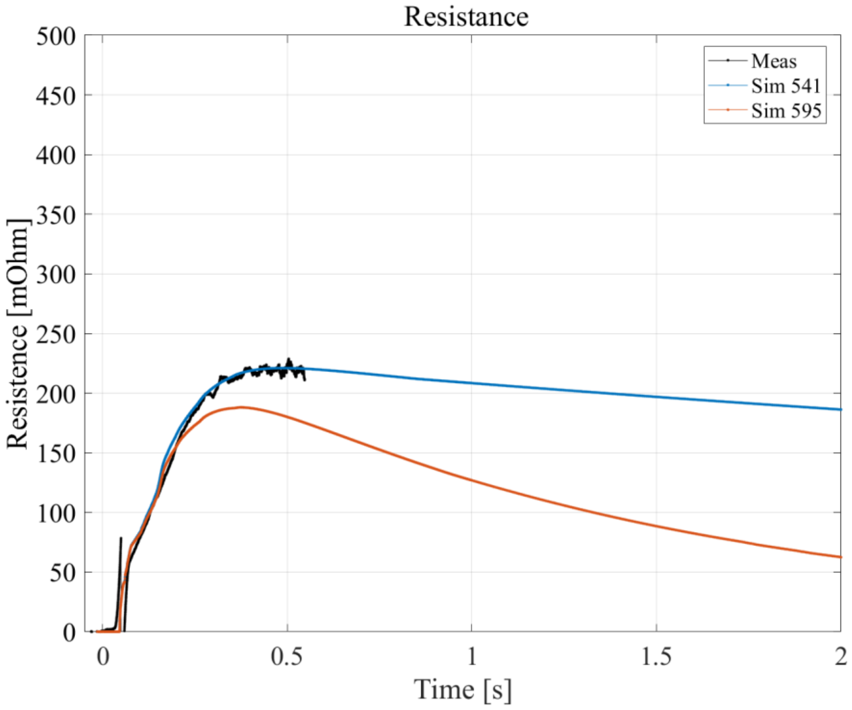
Helium fraction in cable cross section

Test 2 (Quench Heaters + delay Energy Extraction)

I [A]	EE[s]	QH [s]	QH[V]	QH[mF]
3000	0.054	0.004	900	4*7.05

LEDET includes a **feature** for the **helium cooling**.
If it is set to **1** the helium cooling is included in the simulation but with **conductive** transfer only.
If the flag is set to **2** the helium cooling included **conductive** and simplified **convective** heat transfer; including both effect reduces cooling

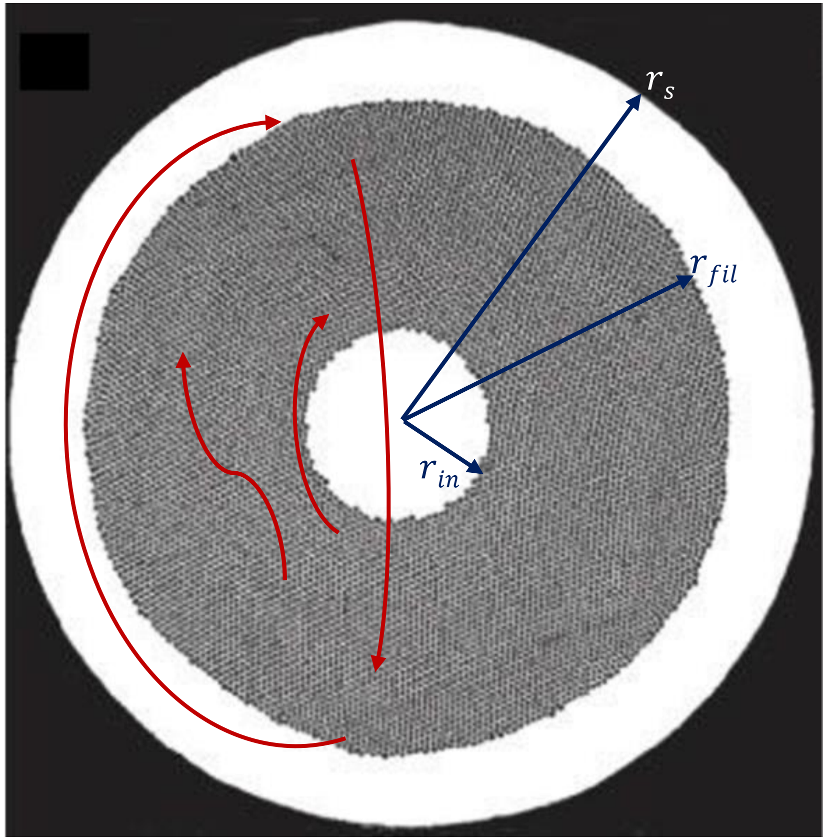




Sim	Flag_HeCooling
541	2
595	1

Effective transverse resistivity parameter

f_ro_eff represent the **effective transverse resistivity parameter**



f_ro_eff depending on the superconductor fraction in the matrix, on the interface resistance between the filaments and the matrix, and on the position of the filaments in the wire cross section.

$$f\_ro\_eff = [\alpha_{in} + \frac{\rho_m}{\rho_{eff,fil}}(\alpha_{fil} - \alpha_{in}) + \alpha_{fil}\frac{1-\alpha_{fil}}{1+\alpha_{fil}}]^{-1}$$

$$\alpha_{in} = (\frac{r_{in}}{r_s})^2$$

$$\alpha_{fil} = (\frac{r_{fil}}{r_s})^2$$

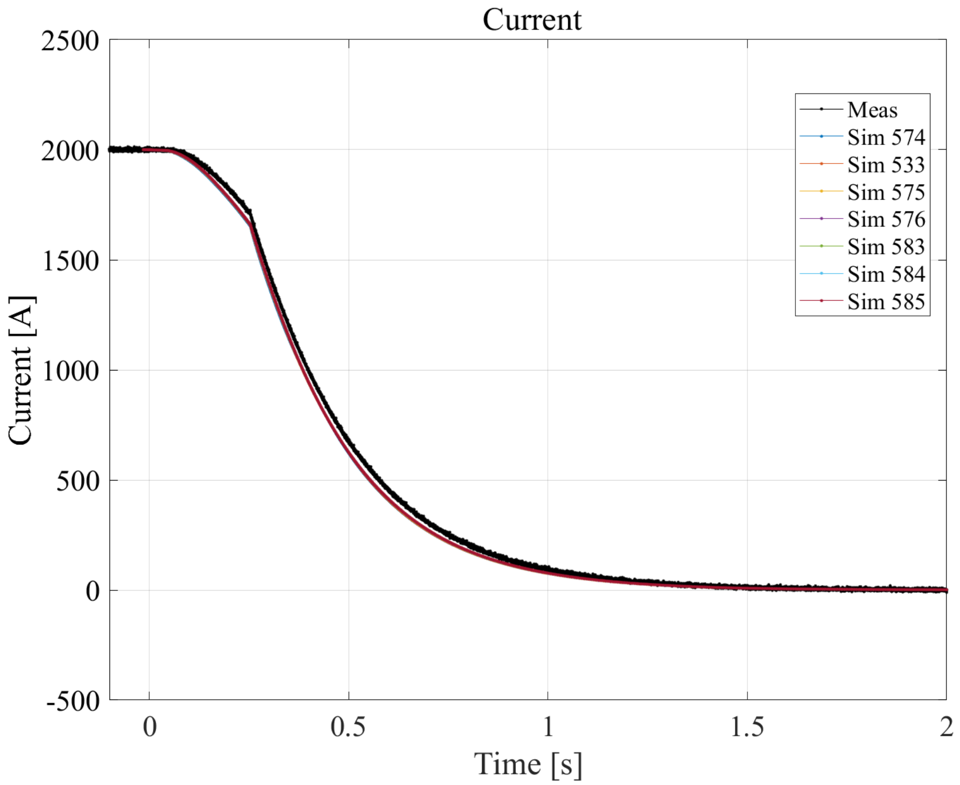
$\rho_{eff,fil}$ is the effective transverse resisiivity$[\Omega m]$

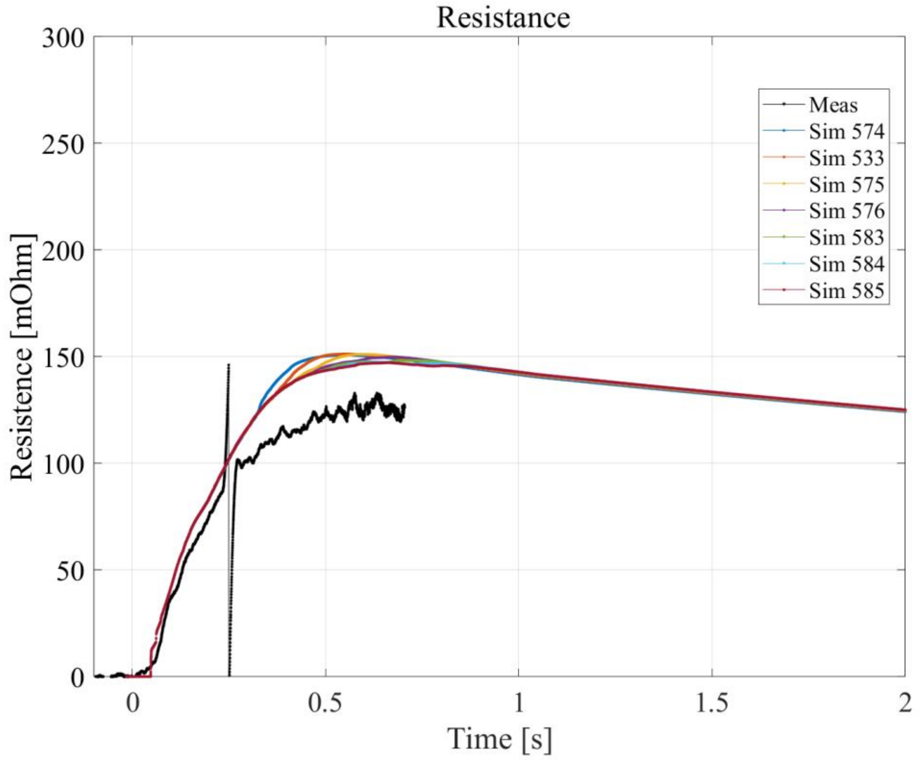
ρ_m is the matrix resisiivity $[\Omega m]$

Quench Heaters + Energy Extraction F_ro_eff effect

Quench Heaters + Energy Extraction

Test	Sim	I [A]	EE[s]	QH [s]	QH[V]	QH[mF]	Tau_IFCC	RRR	F_scaling vQ
3	All	2000	0.254	0.004	900	4*7.05	0.05	225	0.3



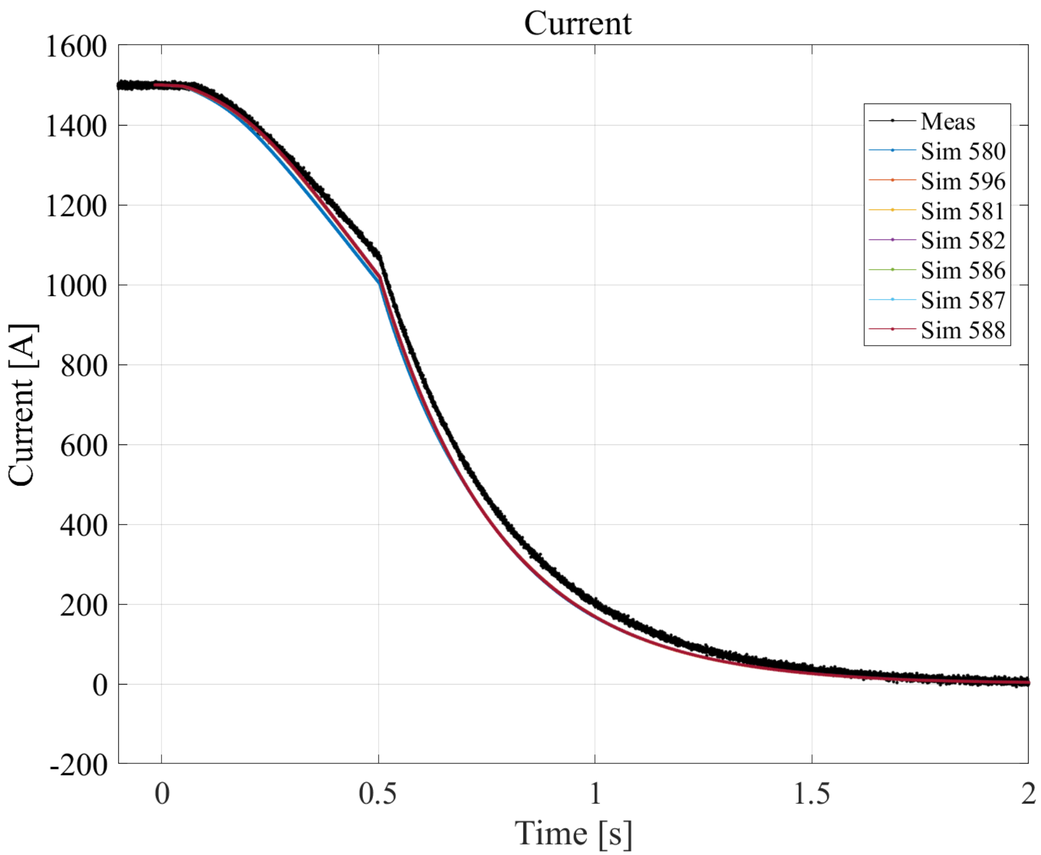


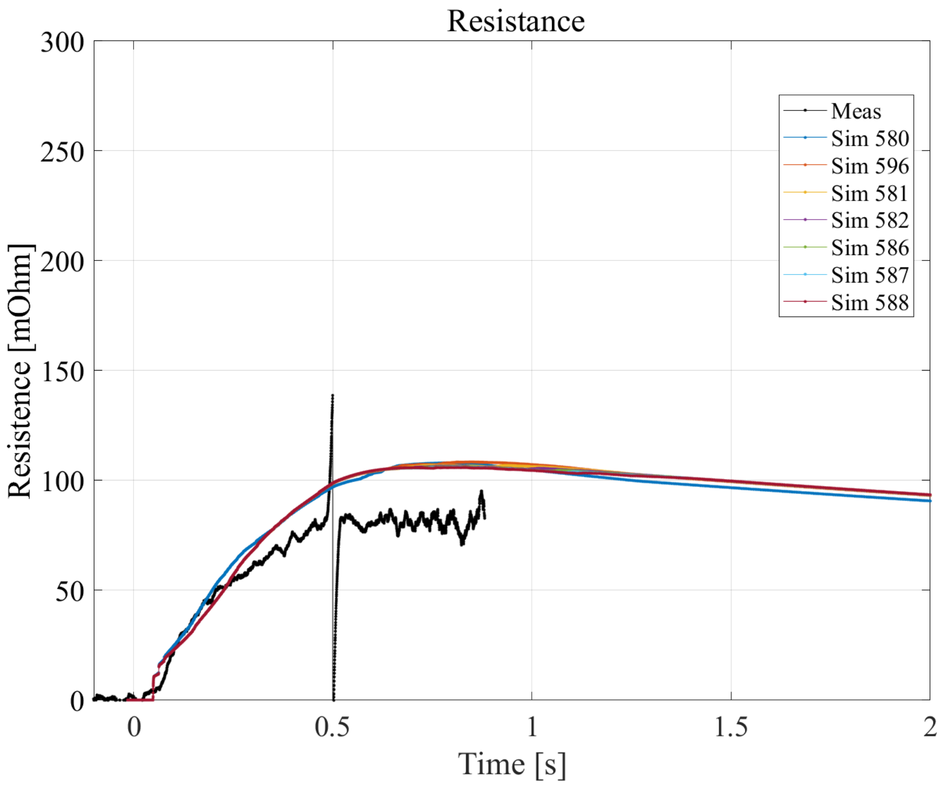
Sim	F_ro_eff
574	1
533	2
575	3
576	4
583	5
584	6
586	7

Quench Heaters + Energy Extraction

Test	Sim	I [A]	EE[s]	QH [s]	QH[V]	QH[mF]	Tau_IFCC	RRR	F_scaling vQ
4	All	1500	0.504	0.004	900	4*7.05	0.05	225	0.1

Sim	F_ro_eff
580	1
596	2
581	3
582	4
586	5
587	6
588	7

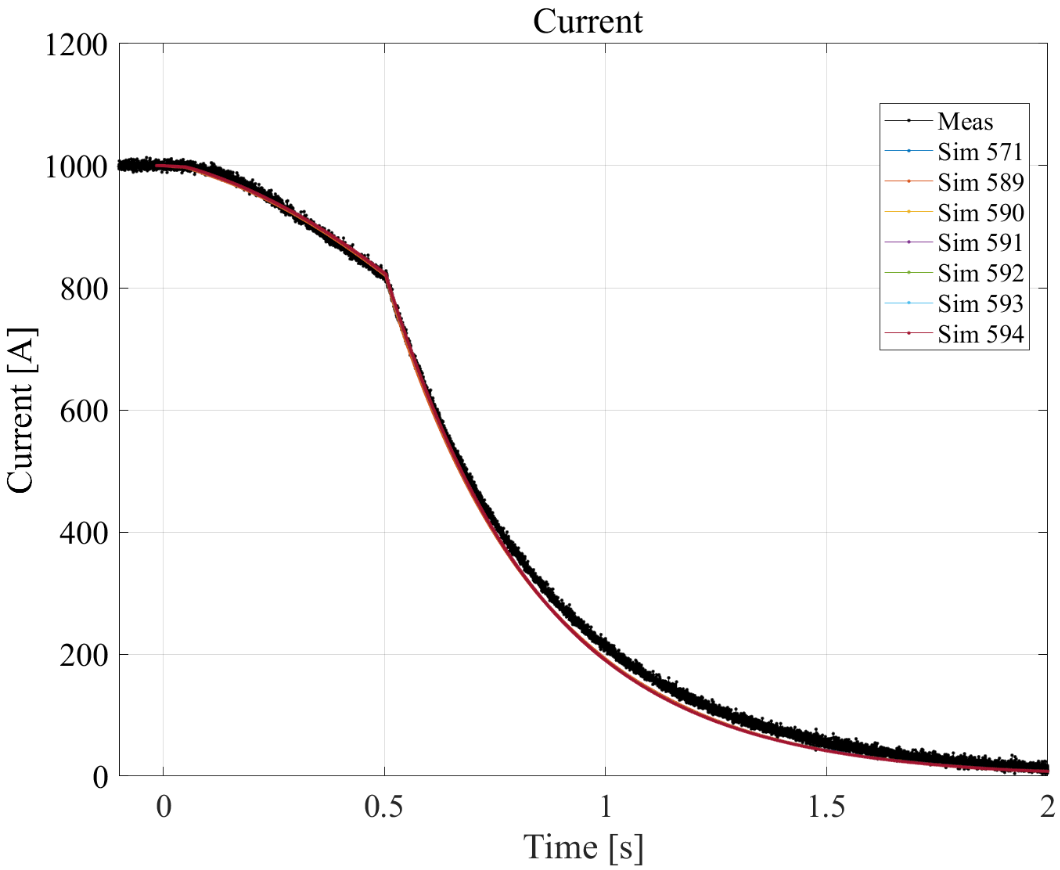


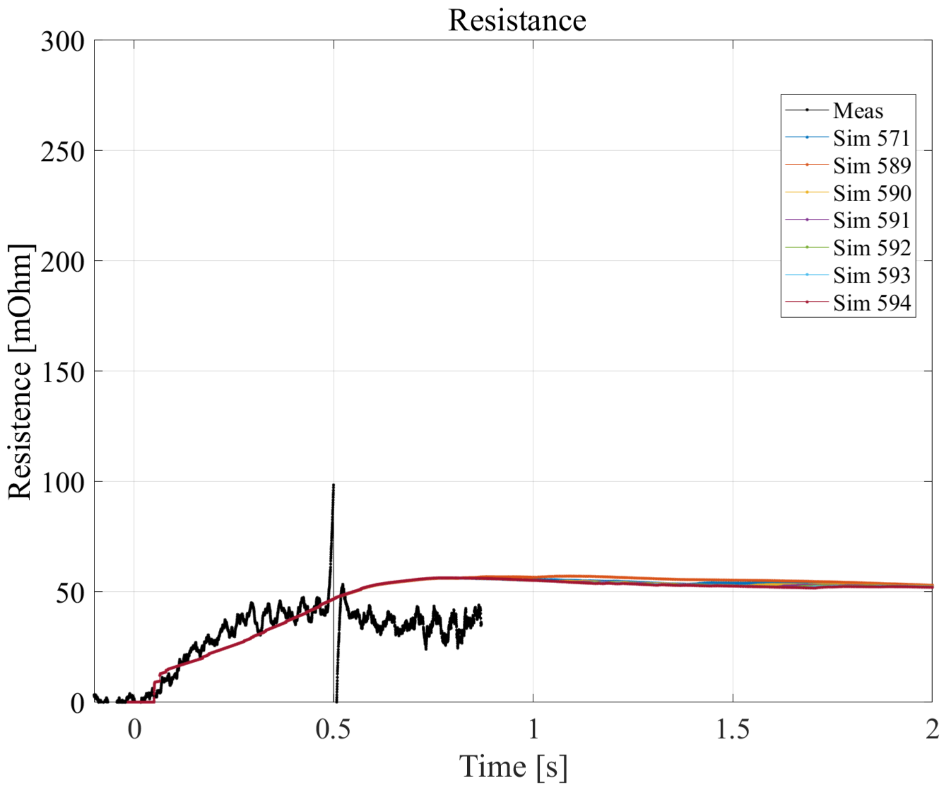


Quench Heaters + Energy Extraction

Test	Sim	I [A]	EE[s]	QH [s]	QH[V]	QH[mF]	Tau_IFCC	RRR	F_scaling vQ
5	All	1000	0.504	0.004	900	4*7.05	0.05	225	0.1

Sim	F_ro_eff
589	1
571	2
590	3
591	4
592	5
593	6
594	7



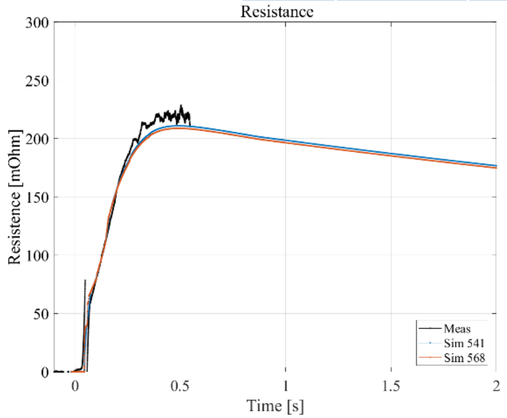


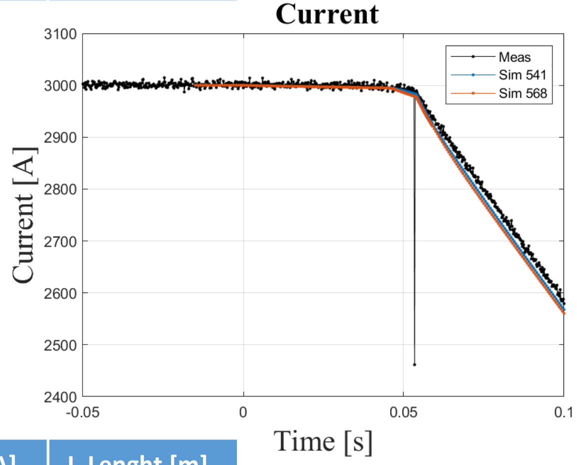
Quench Heaters + Energy Extraction

2D ⟶ 2D+1D

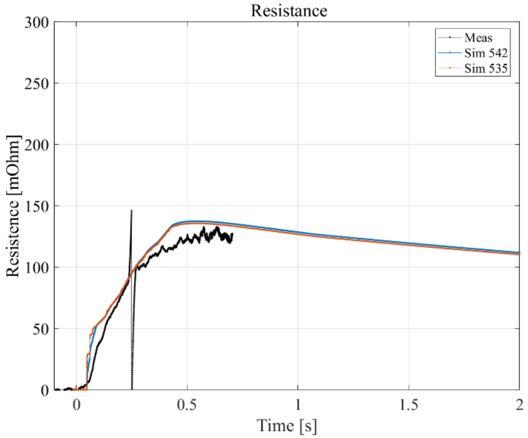
The effects of this **new LEDET's feature** is more visible at low current

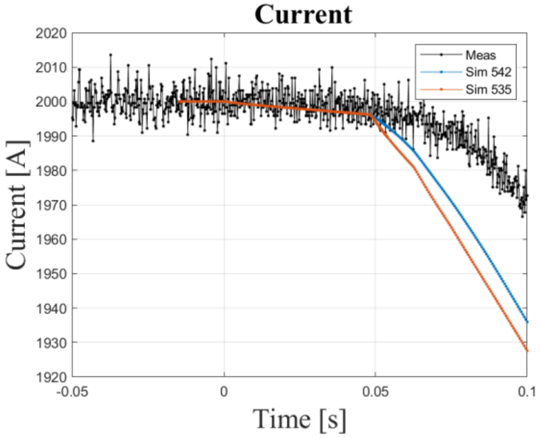
Test	Sim	I [A]	I_Lenght [m]
1	541/568	3000	0.97/3.4



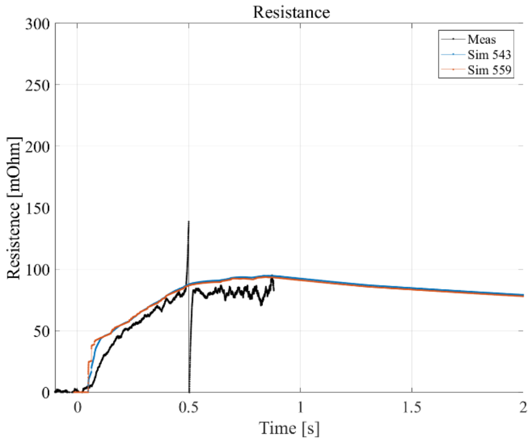


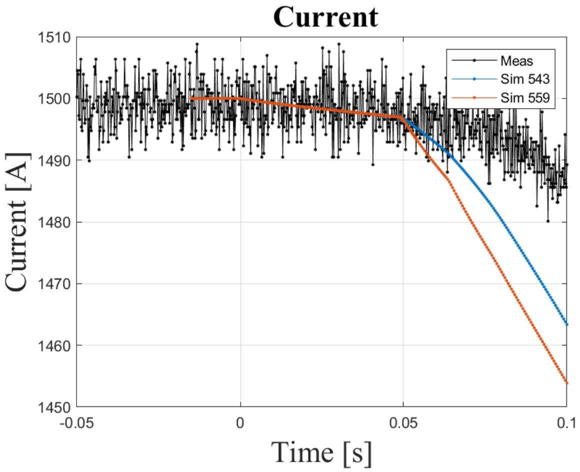
Test	Sim	I [A]	I_Lenght [m]
2	542/535	2000	0.97/3.4



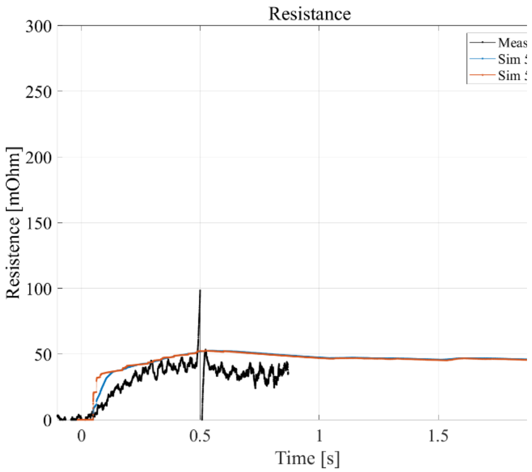


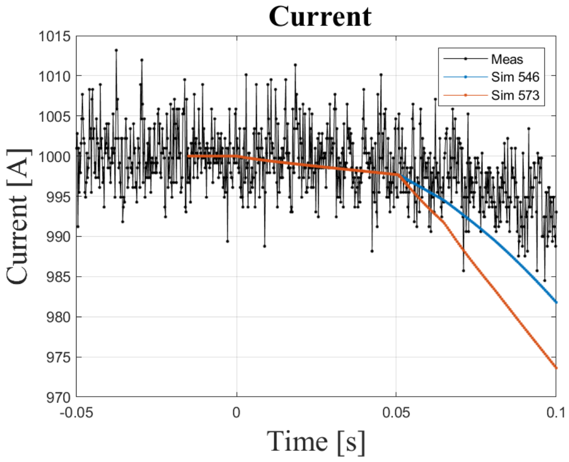
Test	Sim	I [A]	I_Lenght [m]
3	543/559	1500	0.97/3.4





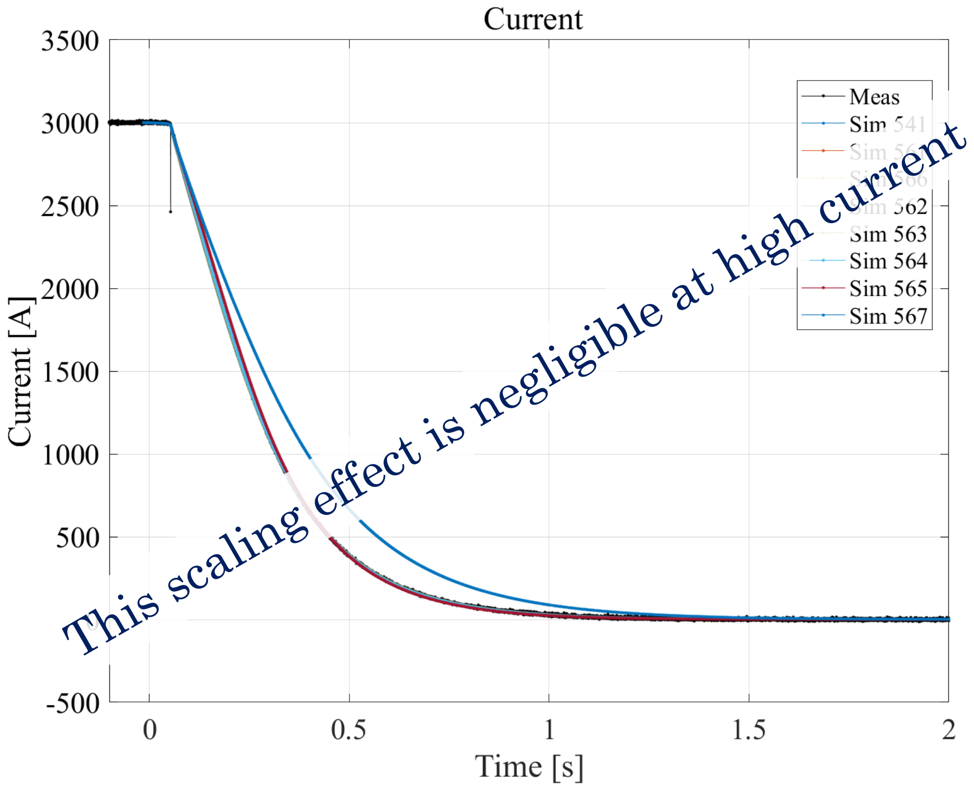
Test	Sim	I [A]	I_Lenght [m]
4	546/573	1000	0.97/3.4





Quench Heaters + Energy Extraction

Test	Sim	I [A]	EE[s]	QH [s]	QH[V]	QH[mF]	RRR
2	All	3000	0.054	0.004	900	4*7.05	225



This scaling effect is negligible at high current

Sim	F_scaling vQ
541	1
561	0.9
566	0.8
562	0.7
563	0.5
564	0.3
565	0.1
567	0