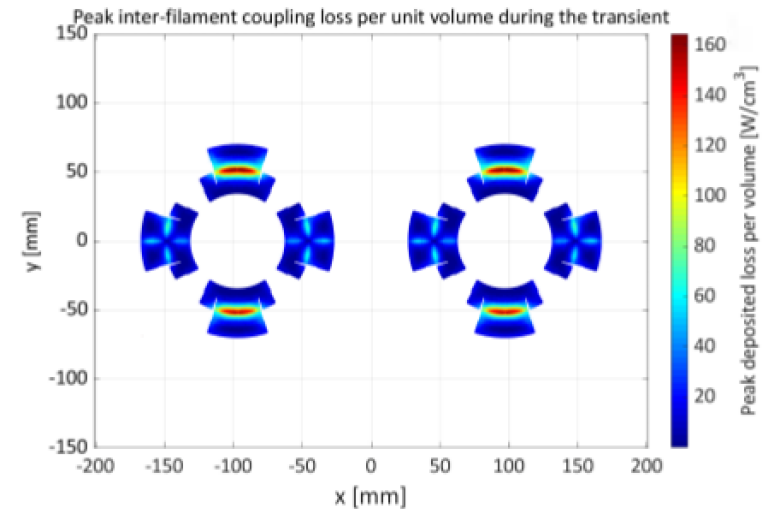
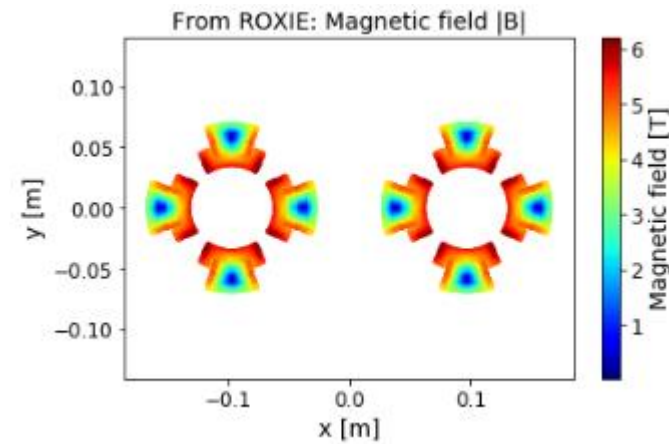
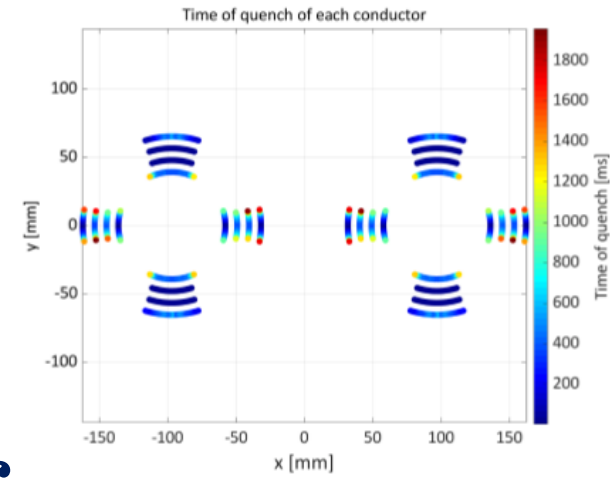
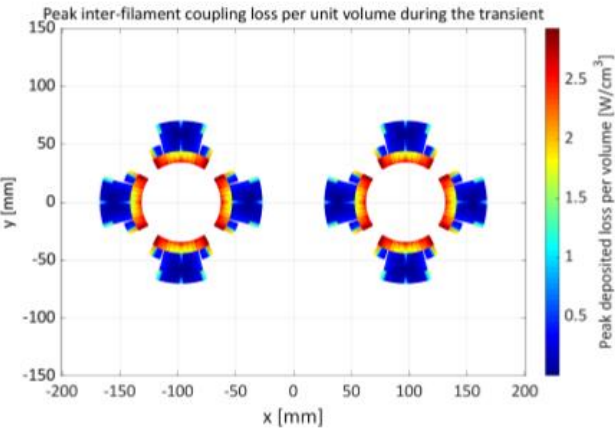


STEAM

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

Federica Murgia
STEAM team
7/11/2019



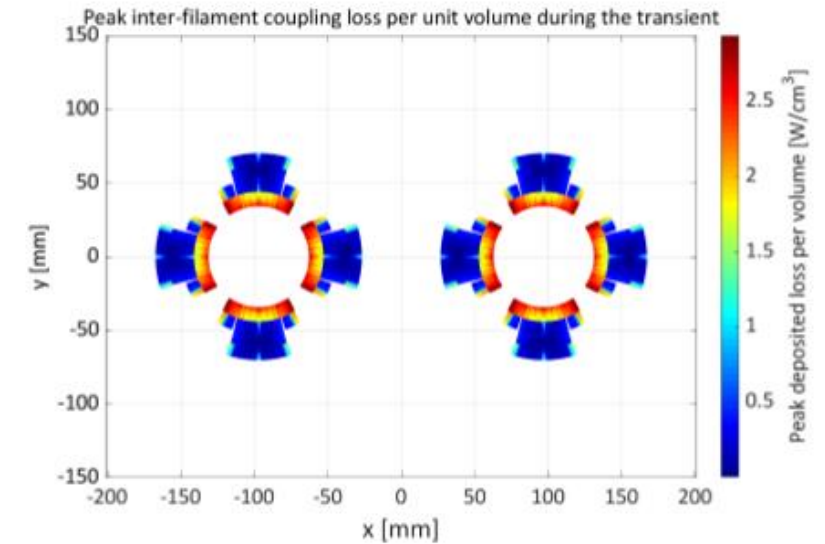
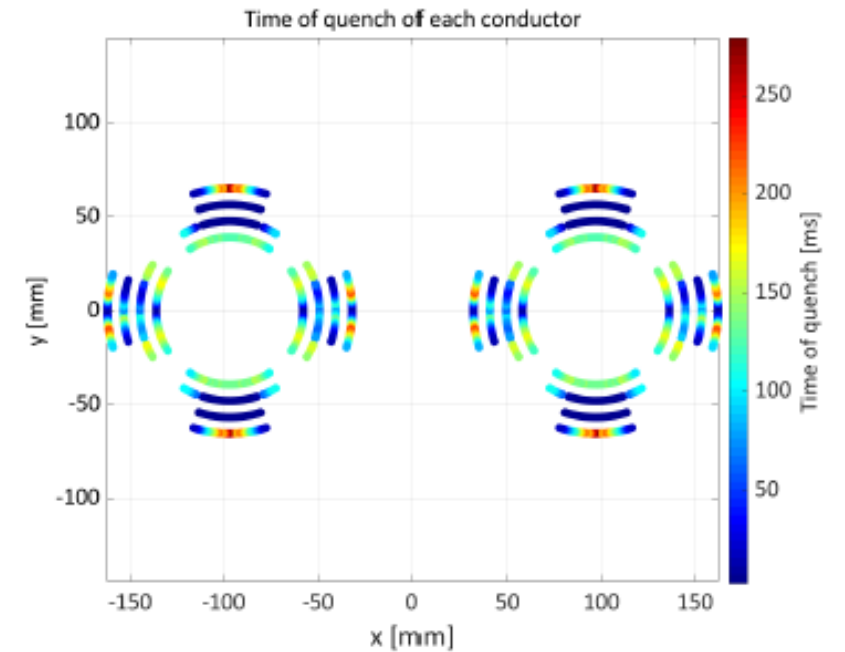
Special thanks to Emmanuele Ravaioli

Section meeting 7/11/2019

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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*

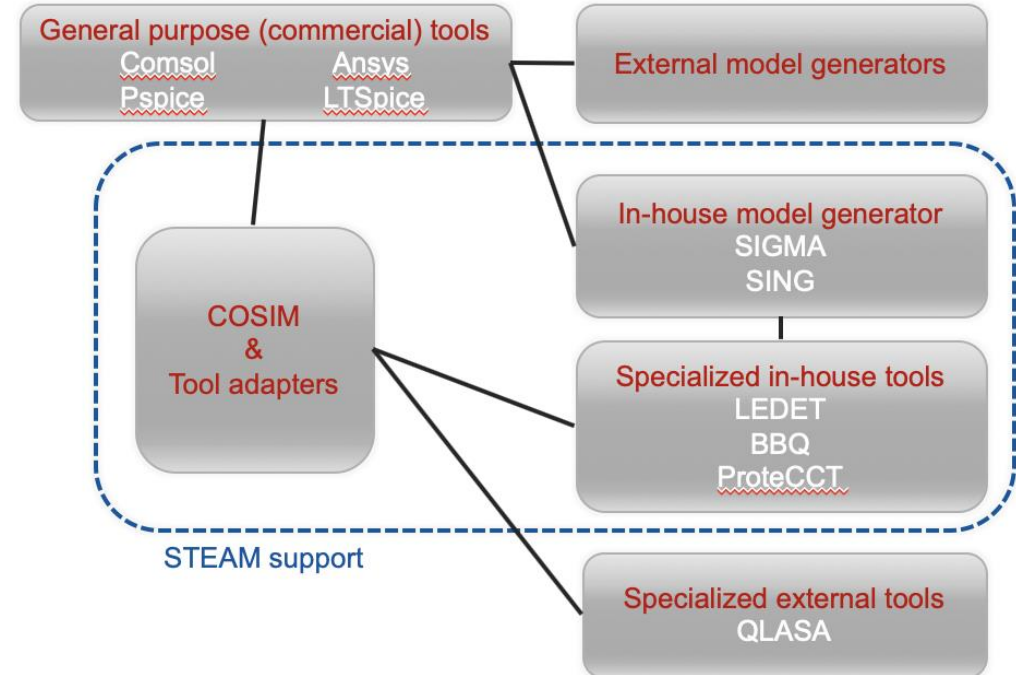


- Quench (training, beam-induced, triggered by QH/CLIQ, quench back)
- Fast Power Abort (converter switch-off and EE activation, voltage waves)
- Shorts (coil-to-ground, coil-to-heater, inter-turn, double short, arcing)
- ELQA tests (FTM, HiPotting, diode tests)
- Quench Detection

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How is it composed?

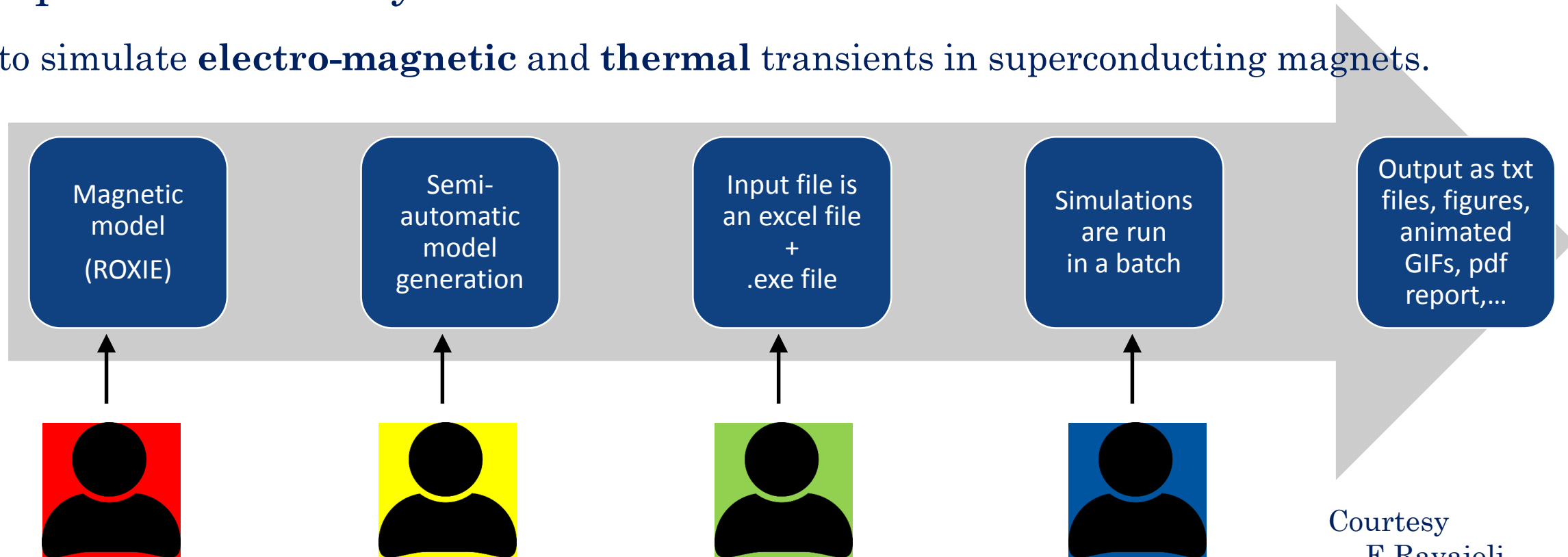
- Variety of tools (both commercial and in-house), each with its own features and advantages.
 - Attractive possibility to co-simulate two or more tools.
 - Tested, cross-checked, and validated.



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?



Field maps from ROXIE

```
In [4]: 1 # Acquire data from ROXIE .map2d file
2 fileName = nameMagnet + '_All_WithIron_WithSelfField.map2d'
3 headerLines = 1
4
5
6 # Plot strand currents and magnetic field
7
8 f = plt.figure(figsize=(24,4))
9 plt.subplot(1, 4, 1)
10 plt.scatter(x, y, s=2, c=I)
11 plt.xlabel('x [m]',**selectedFont)
12 plt.ylabel('y [m]',**selectedFont)
13 plt.title('From ROXIE: Strand currents',**selectedFont)
14 plt.set_cmap('jet')
15 cbar = plt.colorbar()
16 cbar.set_label('Current per strand [A]',**selectedFont)
17 plt.rcParams.update({'font.size': 12})
18 plt.axis('equal')
19
20 plt.subplot(1, 4, 2)
21 plt.scatter(x, y, s=2, c=Bx)
22 plt.xlabel('x [m]',**selectedFont)
23 plt.ylabel('y [m]',**selectedFont)
24 plt.title('From ROXIE: Magnetic field X',**selectedFont)
25 plt.set_cmap('jet')
26 cbar = plt.colorbar()
27 cbar.set_label('Magnetic field [T]',**selectedFont)
28 plt.rcParams.update({'font.size': 12})
29 plt.axis('equal')
30
31 plt.subplot(1, 4, 3)
32 plt.scatter(x, y, s=2, c=By)
33 plt.xlabel('x [m]',**selectedFont)
34 plt.ylabel('y [m]',**selectedFont)
35 plt.title('From ROXIE: Magnetic field Y',**selectedFont)
36 plt.set_cmap('jet')
37 cbar = plt.colorbar()
38 cbar.set_label('Magnetic field Y [T]',**selectedFont)
39 plt.rcParams.update({'font.size': 12})
40 plt.axis('equal')
41
42 plt.subplot(1, 4, 4)
43 plt.scatter(x, y, s=2, c=B)
44 plt.xlabel('x [m]',**selectedFont)
45 plt.ylabel('y [m]',**selectedFont)
46 plt.title('From ROXIE: Magnetic field [B]',**selectedFont)
47 plt.set_cmap('jet')
48 cbar = plt.colorbar()
49 cbar.set_label('Magnetic field [T]',**selectedFont)
50 plt.rcParams.update({'font.size': 12})
51 plt.axis('equal')
52
53 plt.tight_layout()
```

Total number of strands in the field-map from ROXIE = 36032

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



MQV_8Coils_214 - Excel

File Home Insert Page Layout Formulas Data Review View Add-ins Inquire Tell me what you want to do... Federica Murgia Share

Clipboard Font Alignment Number Styles Cells Editing

DAS2 -90

	A	B	C	D	E	F	G
1	Initial temperature [K]	T00	1.9				
2	Magnetic length [m]	L_magnet	3.4				
3	Initial current [A]	I00	1000				
4							
5	Self mutual inductance matrix [H/m]	M_m	0.00185891	0.000902523	0.00104371	0.000902494	2.80754
6			0.000902523	0.00185892	0.000902495	0.00104374	1.51424
7			0.00104371	0.000902495	0.00185891	0.000902494	1.01792
8			0.000902494	0.00104374	0.000902494	0.00185891	2.49234
9			2.80754E-05	1.51424E-05	1.01792E-05	2.49234E-05	0.00
10			6.24517E-05	2.70235E-05	2.41373E-05	5.64921E-05	0.00089
11			5.77227E-05	2.45981E-05	2.76773E-05	6.39428E-05	0.001
12			2.56901E-05	1.05433E-05	0.000015311	2.85814E-05	0.00092
13							
14	Current levels at which the differential inductance is evaluated [A]	fl_L	3.6	3.6	3.6	183	
15	Ratio between differential inductance at different current levels and nominal inductance	fl_L	1.128895341	1.128895341	1.125363959	1.125331444	1.12529
16							
17	Define the coil section where each group of cables is located	GroupToCellSection	2	2	4	4	
18	Polarity of the current in each group of strands	polarities_inGroup	1	1	1	1	
19	Number of half-turns in each group	nT	20	17	15	6	
20	Number of strands in each cable belonging to a particular group	nStrands_inGroup	34	34	34	22	
21	Length of each half turn [m] (default=L_magnet)	L_mag_inGroup	3.4	3.4	3.4	3.4	
22	Strand diameter [m]	ds_inGroup	0.00048	0.00048	0.00048	0.000735	0.00
23	Fraction of superconductor in the strands	f_SC_strand_inGroup	0.444444444	0.444444444	0.444444444	0.363636364	0.36363
24	Effective transverse resistivity parameter (default=1)	f_ro_eff_inGroup	2	2	2	2	
25	Filament twist-pitch [m]	Lp_f_inGroup	0.015	0.015	0.015	0.015	
26	RIR of the conductor in each group of cables	RIR_Cu_inGroup	183.4862385	183.4862385	183.4862385	183.4862385	183.486
27	Type of superconductor (1=Nb-Ti, 2=Nb3Sn, 3=BiSCCO2212)	SCType_inGroup	1	1	1	1	
28	Type of stabilizer (1=Cu, 2=Ag)	SType_inGroup	1	1	1	1	
29	Type of cable insulation (1=G10, 2=kapton)	InsulationType_inGroup	2	2	2	2	
30	Type of filler of voids between adjacent strands (1=G10, 2=kapton, 3=helium, 4=oil)	InternalVoidsType_inGroup	3	3	3	3	
31	Type of filler of voids between strands and insulation layers (1=G10, 2=kapton, 3=external)	ExternalVoidsType_inGroup	2	2	2	2	
32	Bare cable width [m]	wBare_inGroup	0.0082834	0.0082834	0.0082834	0.0082834	0.008
33	Bare average cable height [m]	hBare_inGroup	0.0008433	0.0008433	0.0008433	0.0012745	0.0012
34	Insulation thickness in the width direction [m]	wIns_inGroup	0.0000798	0.0000798	0.0000798	0.0000798	0.000
35	Insulation thickness in the height direction [m]	hIns_inGroup	0.0000798	0.0000798	0.0000798	0.0000798	0.000
36	Strand twist-pitch [m]	Lp_s_inGroup	0.066	0.066	0.066	0.066	
37	Cross-contact resistance [Ohm]	R_c_inGroup	1.00E-05	0.00001	0.00001	0.00001	0.0
38	To0_NbTi_ht_inGroup [K]	To0_NbTi_ht_inGroup	9.2	9.2	9.2	9.2	
39	Bc2_NbTi_ht_inGroup [T]	Bc2_NbTi_ht_inGroup	14.5	14.5	14.5	14.5	
40	c1_ic_NbTi_inGroup [A]	c1_ic_NbTi_inGroup	25941.2	25941.2	25941.2	45910.4	455
41	c2_ic_NbTi_inGroup [A/T]	c2_ic_NbTi_inGroup	-2078.1	-2078.1	-2078.1	-3680	-
42	To0_Nb3Sn [K]	To0_Nb3Sn_inGroup	0	0	0	0	
43	Bc2_Nb3Sn [T]	Bc2_Nb3Sn_inGroup	0	0	0	0	
44	ic_Nb3Sn [A*(1+0.5/m^2)] Based on short-sample measurements	ic_Nb3Sn_inGroup	0	0	0	0	
45	alpha_Nb3Sn for Bordini's parametrization	alpha_Nb3Sn_inGroup	0	0	0	0	
46	Overwrite f_internalVoids	overwrite_f_internalVoids_inGroup	0.098364059	0.098364059	0.098364059	0.099759046	0.09975
47	Overwrite f_externalVoids	overwrite_f_externalVoids_inGroup	0	0	0	0	
48							
49	Electrical order of the half turns	et_order_half_turns	94	686	93	685	
50							
51	Inclination of cables with respect to X axis (including transformations for mirror)	alphasDEG	0	0.8974	1.7948	2.6922	3
52	Rotate cable by a certain angle [deg]	rotation_block	0	0	0	0	
53	Mirror cable along the bisector of its quadrant (0=no, 1=yes)	mirror_block	0	0	0	0	
54	Mirror cable along the Y axis (0=no, 1=yes)	mirrorY_block	0	0	0	0	
55							
56	Indices of the cables exchanging heat with iContactAlongWidth_To along the cable iContactAlongWidth_From		1	2	3	4	
57	Indices of the cables exchanging heat with iContactAlongWidth_From along the cable iContactAlongWidth_To		2	3	4	5	
58	Indices of the cables exchanging heat with iContactAlongHeight_To along the cable iContactAlongHeight_From		1	2	3	4	
59	Indices of the cables exchanging heat with iContactAlongHeight_From along the cable iContactAlongHeight_To		21	22	23	23	
60							
61	Indices of the half-turns that are set to quench at a given time	iStartQuench	100	99	98	97	
62	Time at which each selected half-turn quenches [s]	tStartQuench	99999	99999	99999	99999	
63	Initial length of the hot-spot [m]	lengthHotSpot_StartQuench	0.01	0.01	0.01	0.01	
64	Quench propagation velocity from the hot-spot [m] (2x higher velocity if it propagates)	vQ_StartQuench	40	40	40	40	
65							
66	Resistance of the warm parts of the circuit [Ohm]	R_circuit	0.0046				
67	Resistance of crowbar of the power supply [Ohm]	R_crowbar	0.00002				
68	Forward voltage drop of a diode or thyristor in the crowbar of the power supply [V]	Ud_crowbar	1.4				
69							

Inputs Options Plots Variables

Ready



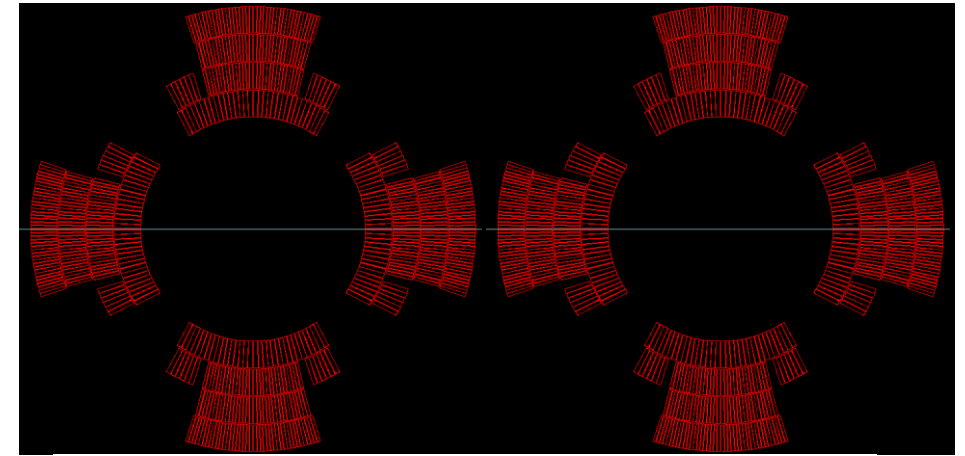
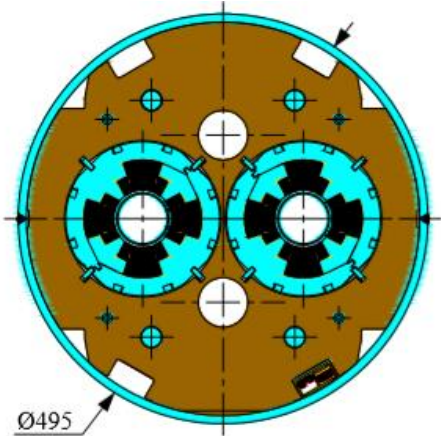
MQY, superconducting quadrupole magnet

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.

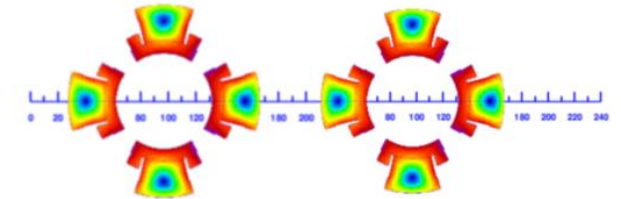
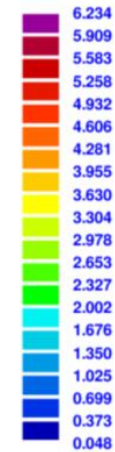


Table 8.4: Main parameters of the MQY matching quadrupole

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 1/2	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



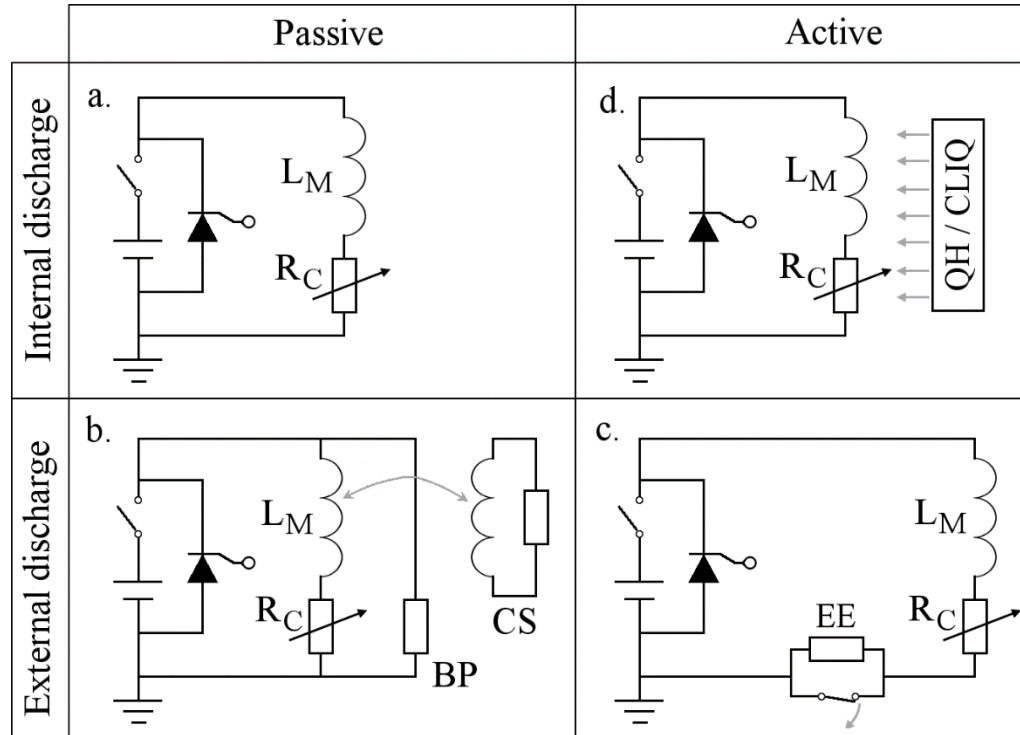
|B| (T)



ROXIE_{10.2}

Why is quench protection needed?

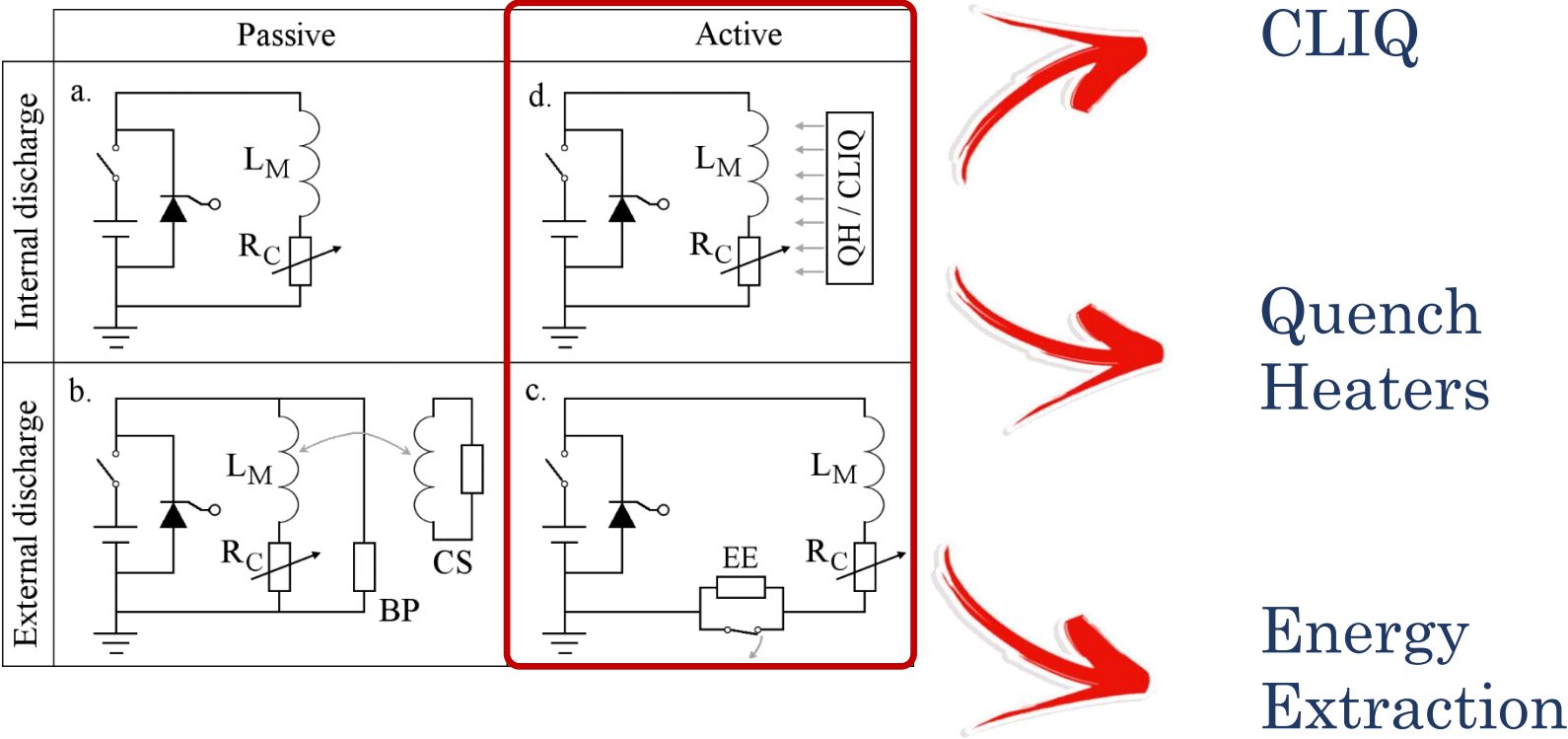
After a quench in a superconducting coil, the magnet current has to be discharged to avoid damage



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

Why is quench protection needed?

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





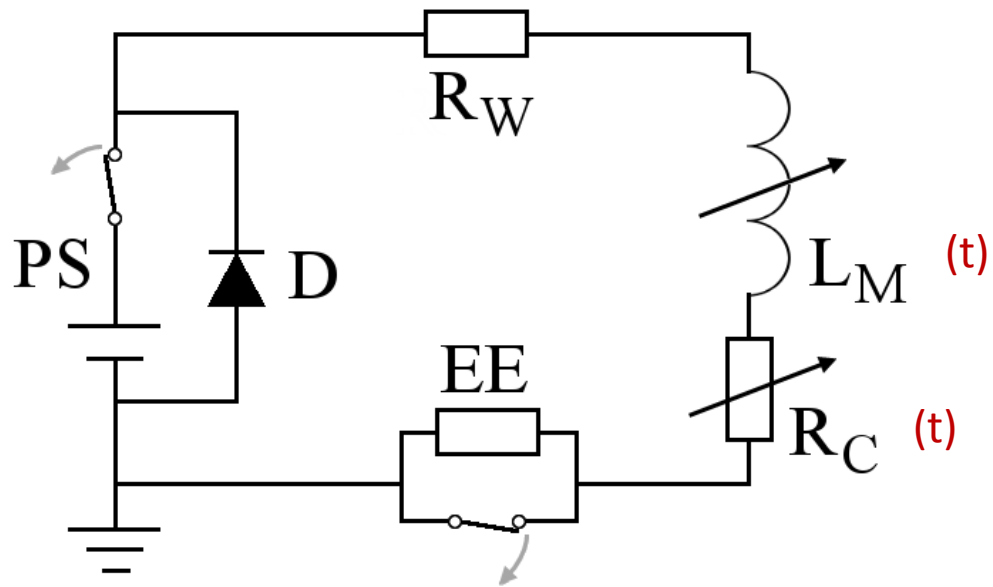
Energy
Extraction



Quench
Heaters



CLIQ



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

Courtesy
E.Ravaioli



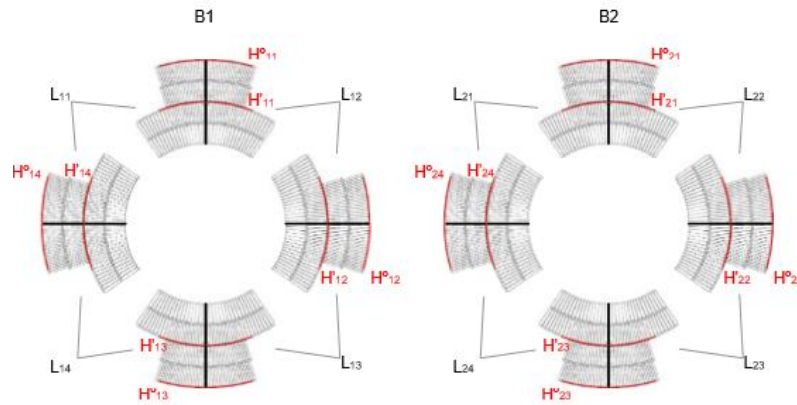
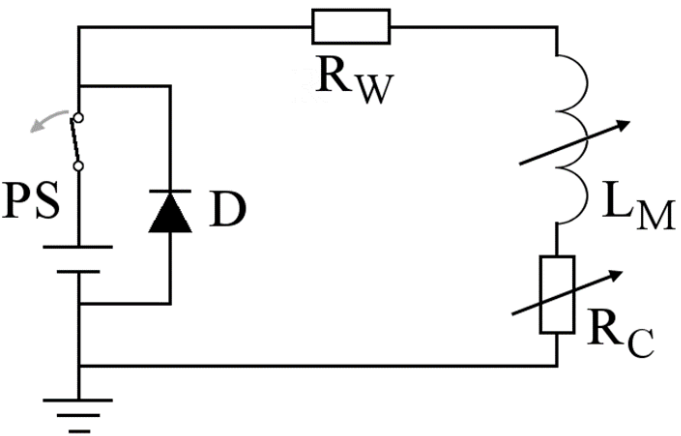
Energy
Extraction



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

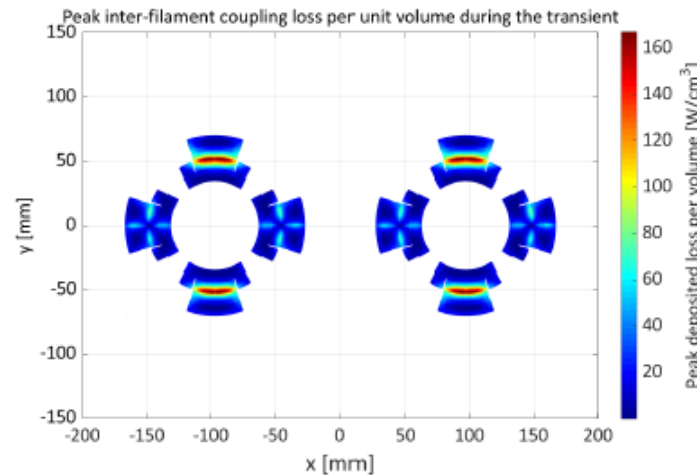
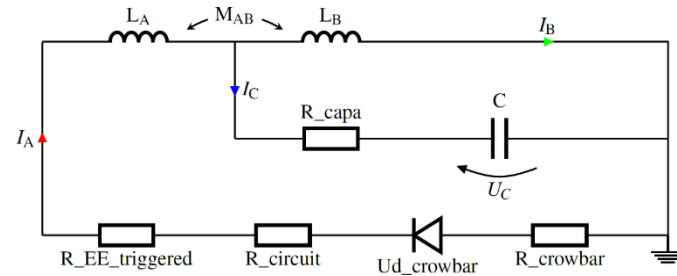
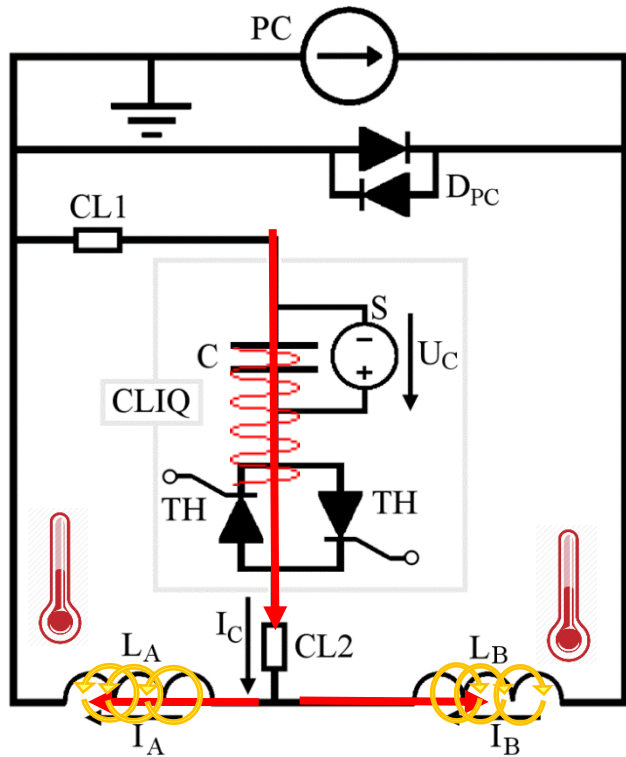


Quench
Heaters



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

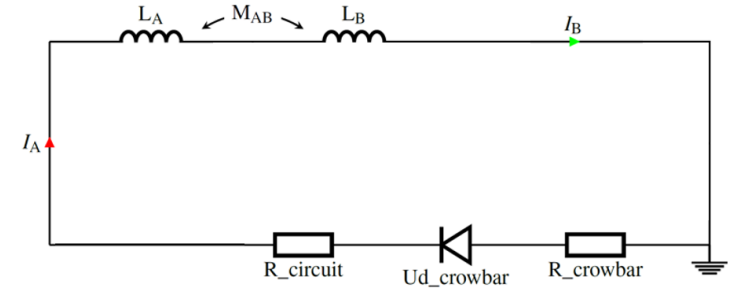
Validation of MQY → Tests overview

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)	-

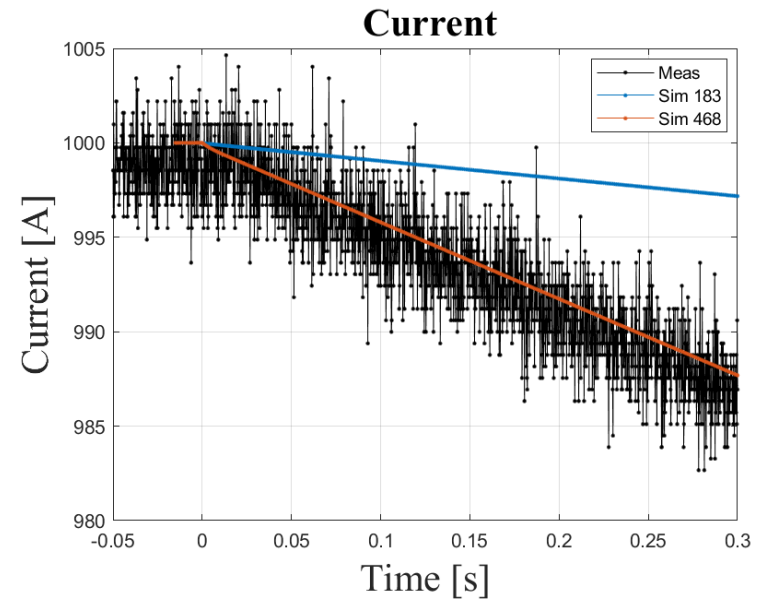
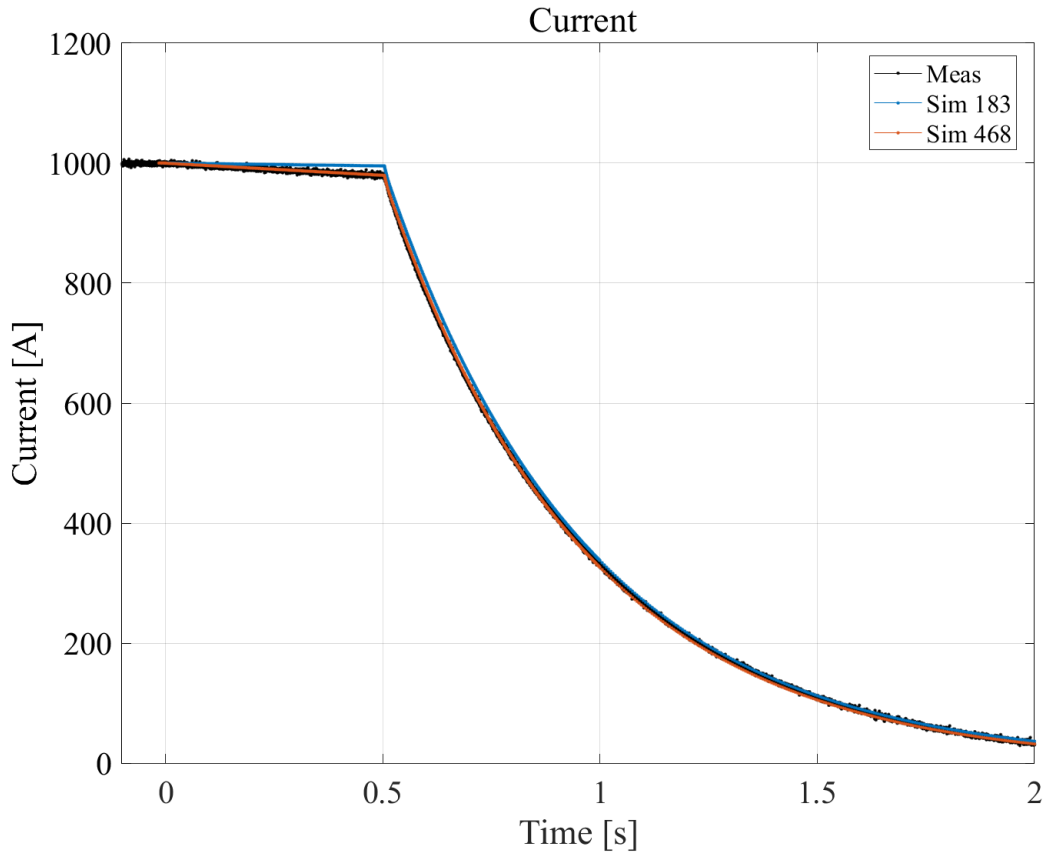
Warm circuit
resistance

Test 1 (Only delay Energy Extraction)

I [A]	EE[s]
1000	0.504



$R_{\text{circuit}} + R_{\text{crowbar}} = 0.0023 \text{ Ohm}$ and $U_{d_{\text{crowbar}}} = 0.7V$

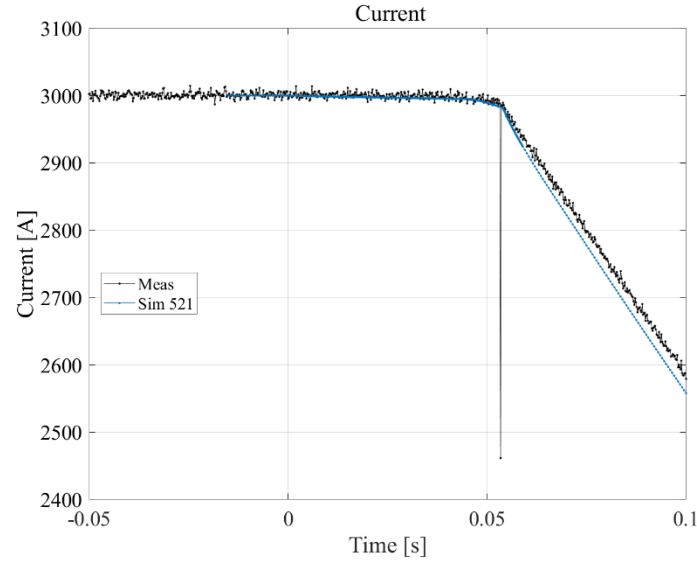
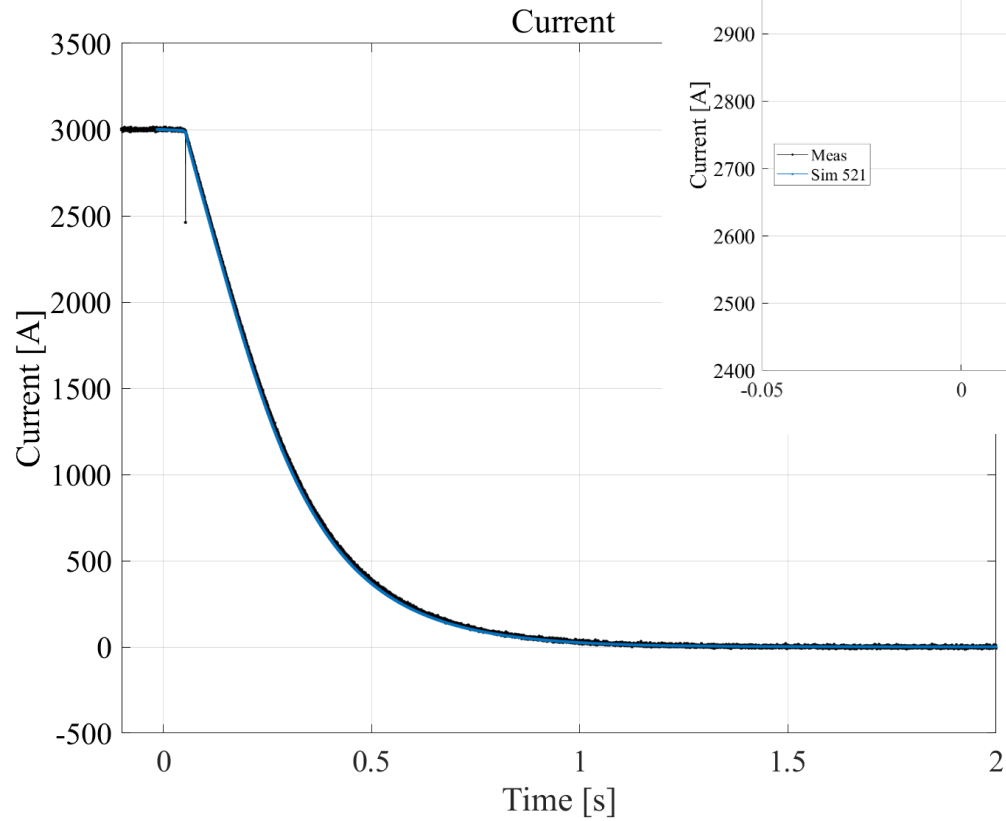


Tests overview

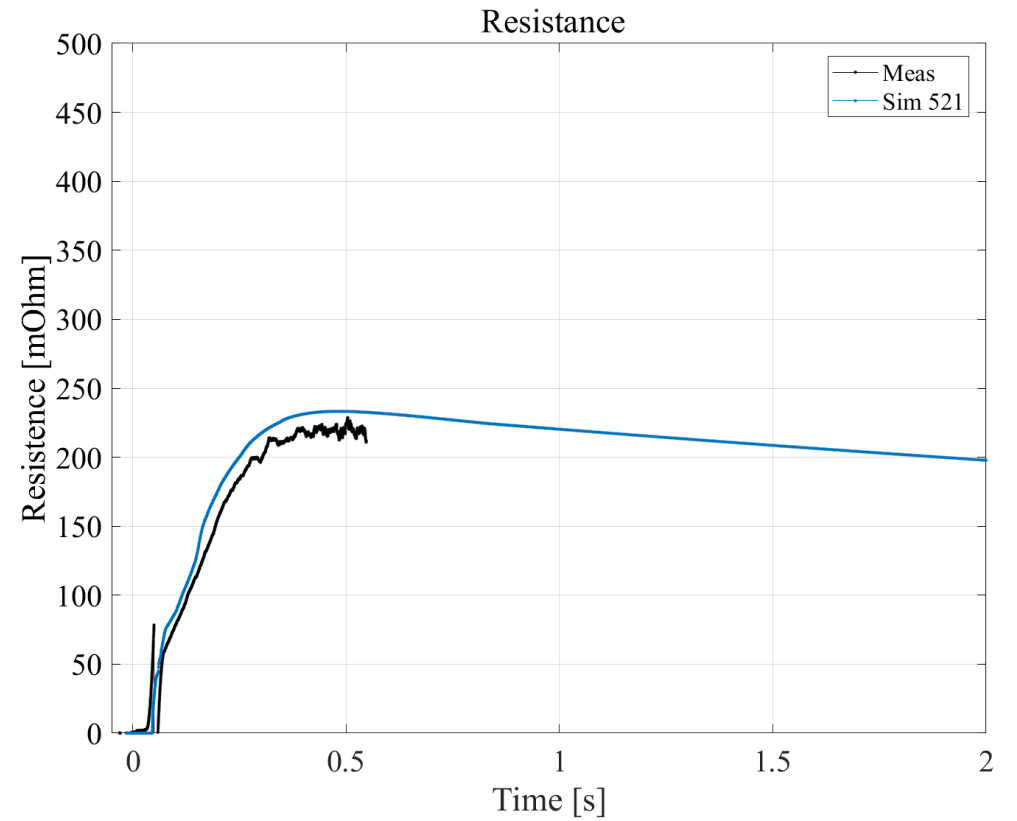
SM18 Ref	Test	T[K]	I[A]	EE (Delay)	CLIQ	QH
	Only EE					
1	1	1.9	1000	✓ (0.004s)	-	-
	QH+ EE					
14	2	1.9	3000	✓ (0.054s)	-	✓ (0.004s)
13	3	1.9	2000	✓ (0.254s)	-	✓ (0.004s)
4	4	1.9	1500	✓ (0.504s)	-	✓ (0.004s)
12	5	1.9	1000	✓ (0.504s)	-	✓ (0.004s)
	CLIQ+EE					
15	6	1.9	3000	✓ (0.054s)	✓ (0.0005s) CLIQ 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 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



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



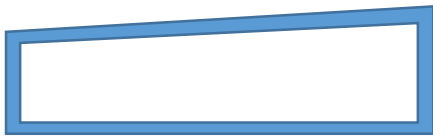
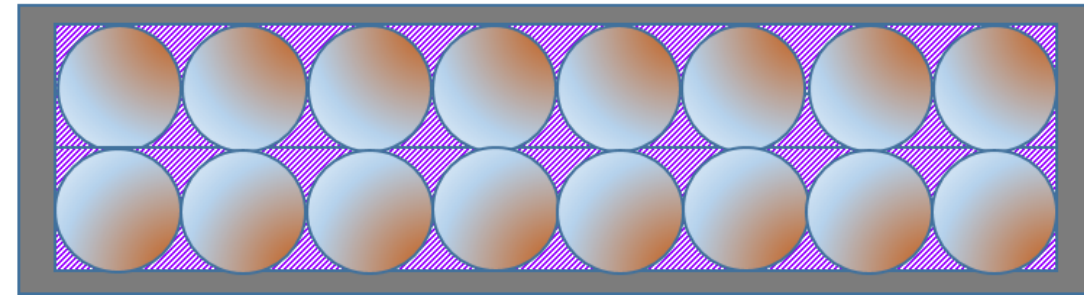
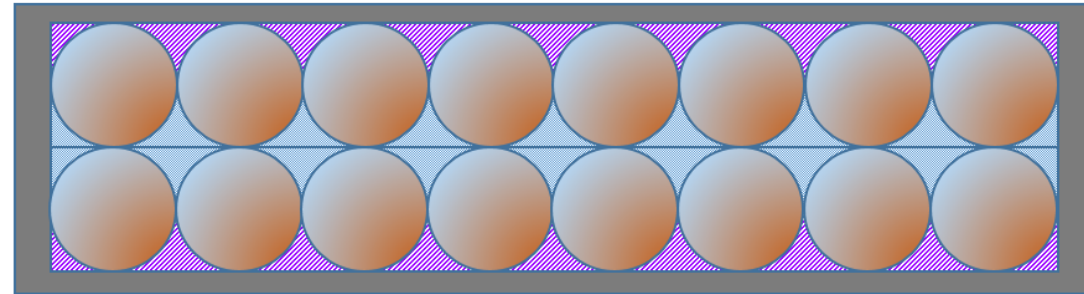
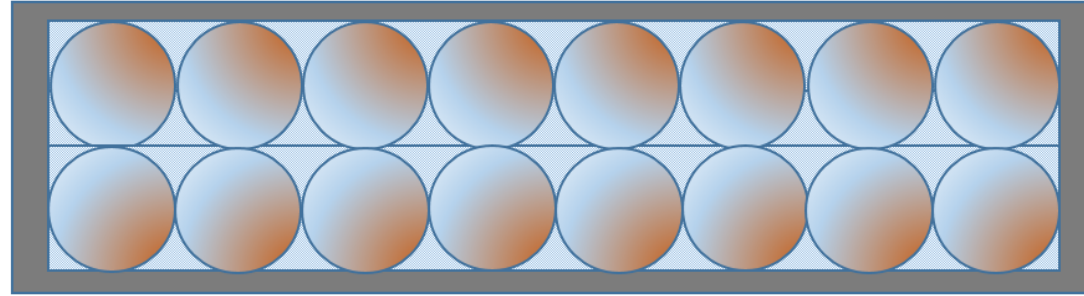
Helium fraction
in cable cross
section

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

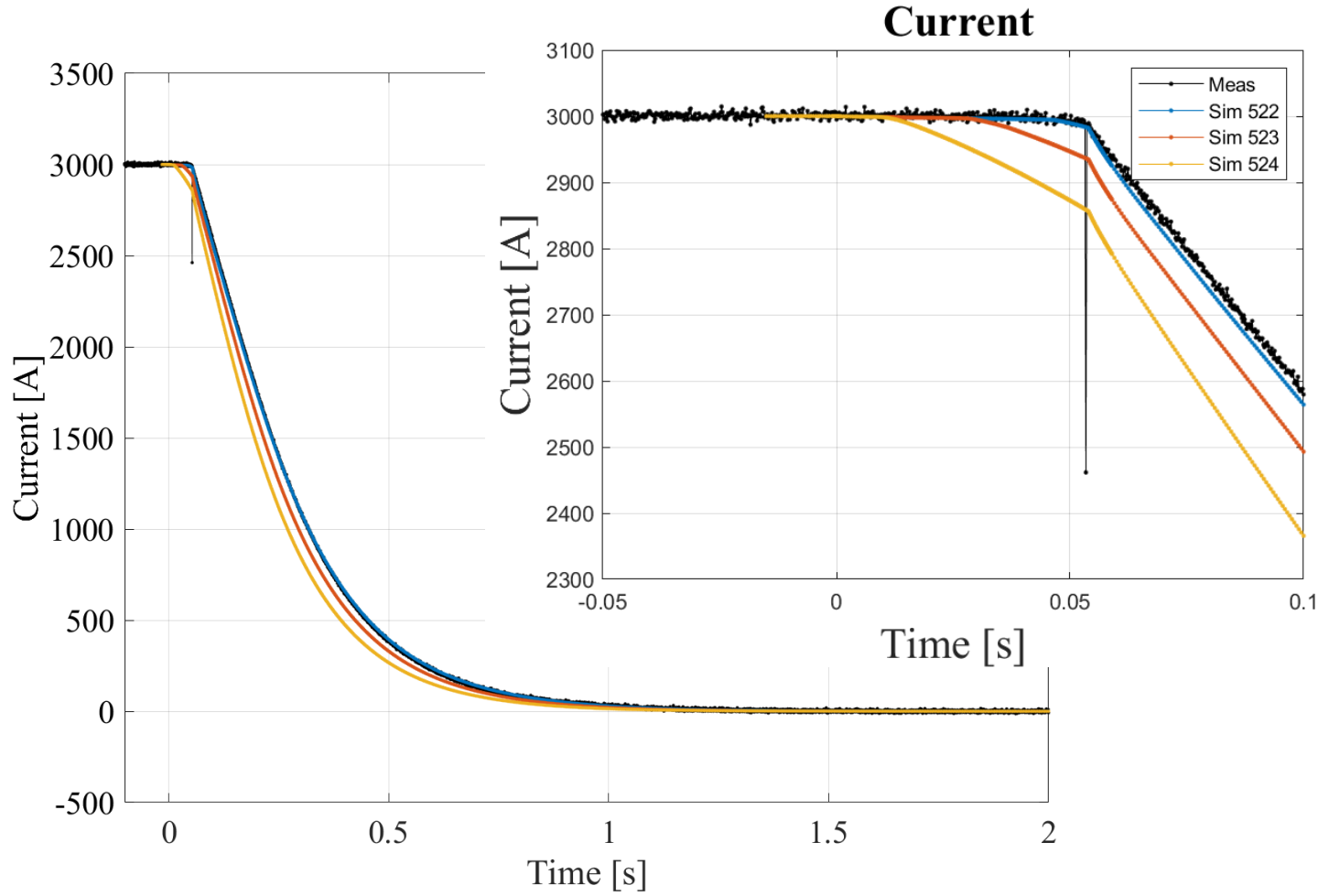
Sim	He_Int	He_Ext
522	0.098	0
523	0.045	0.054
524	0	0.098



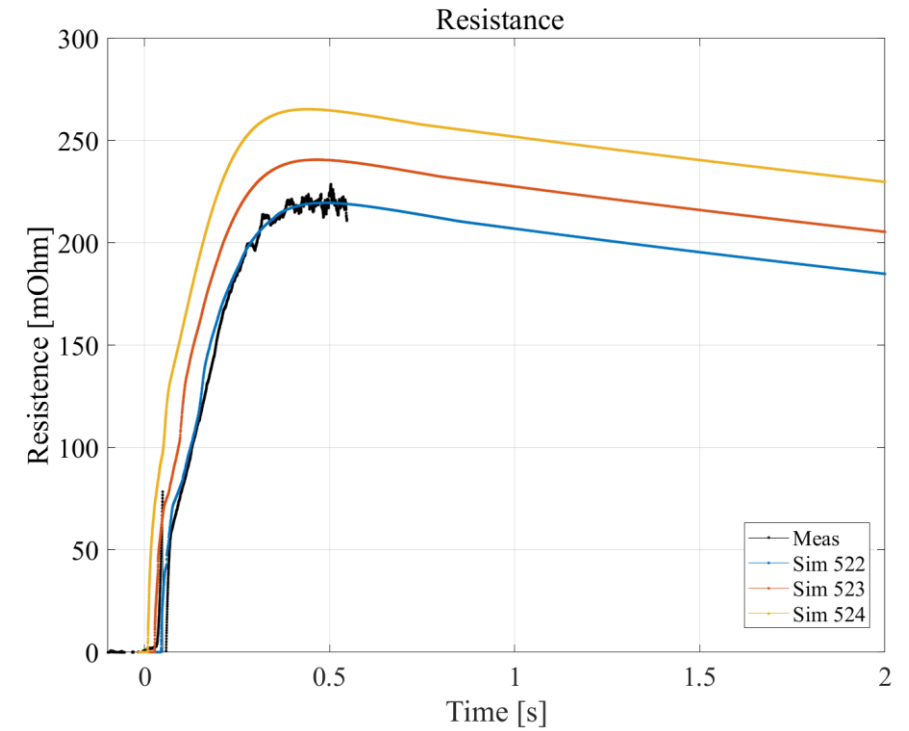
72% strand
17% insulation

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

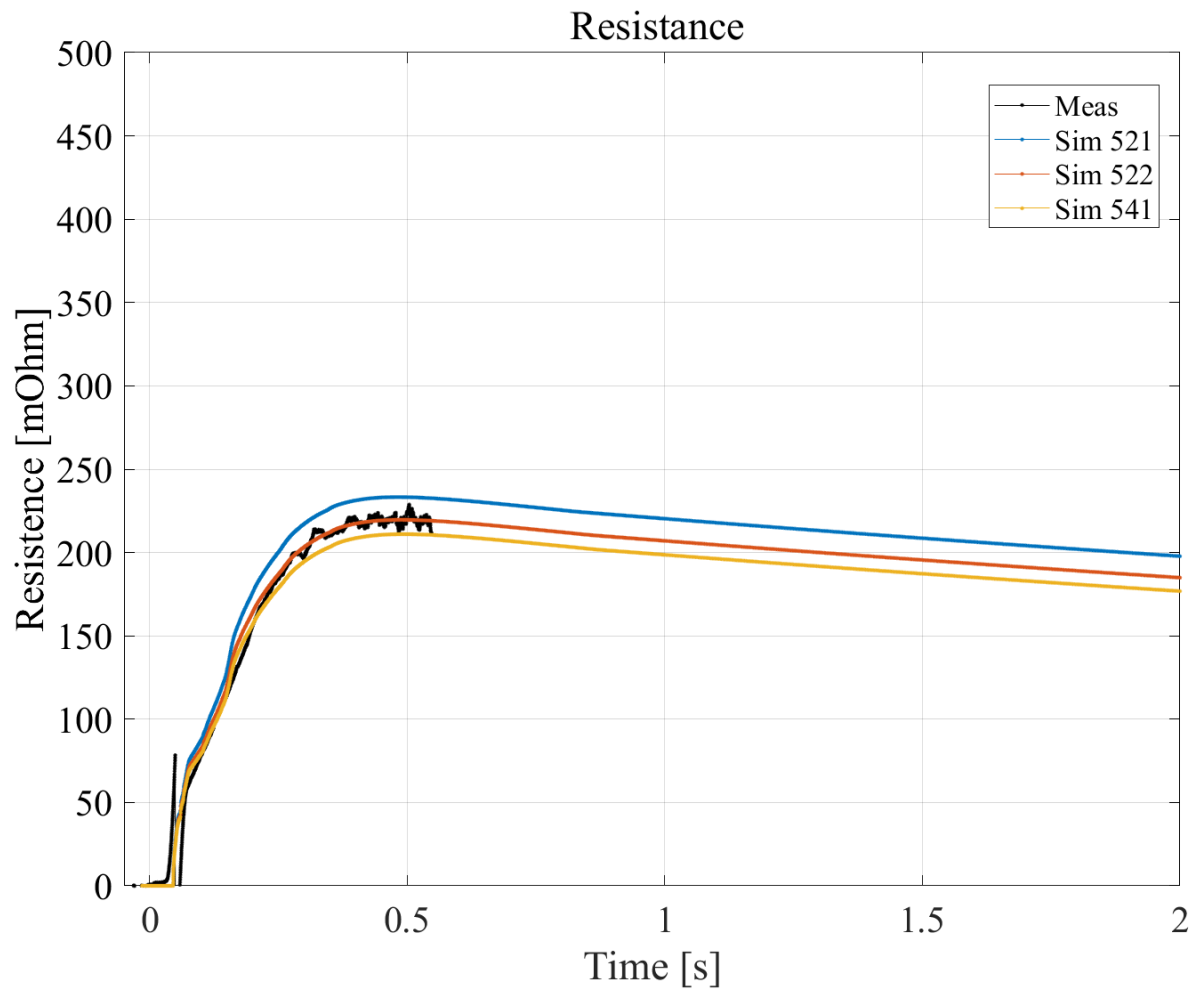
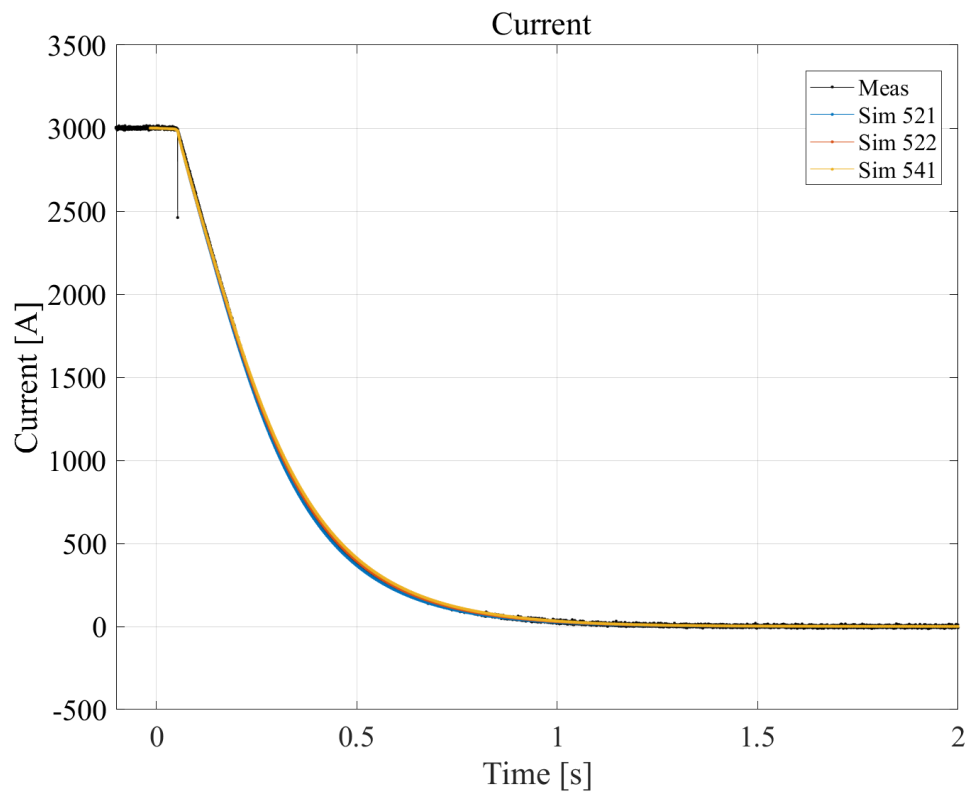


Sim	He_Int	He_Ext
522	0.098	0
523	0.045	0.054
524	0	0.098



Test 2 (Quench Heaters + delay Energy Extraction)

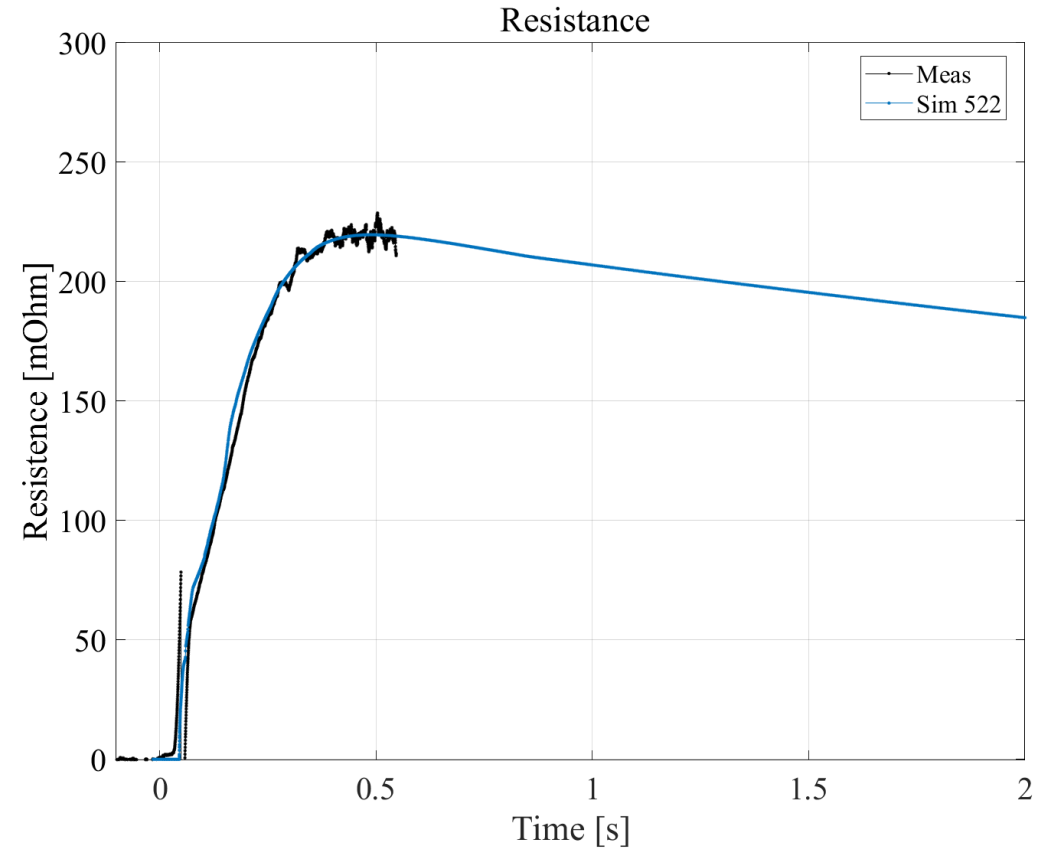
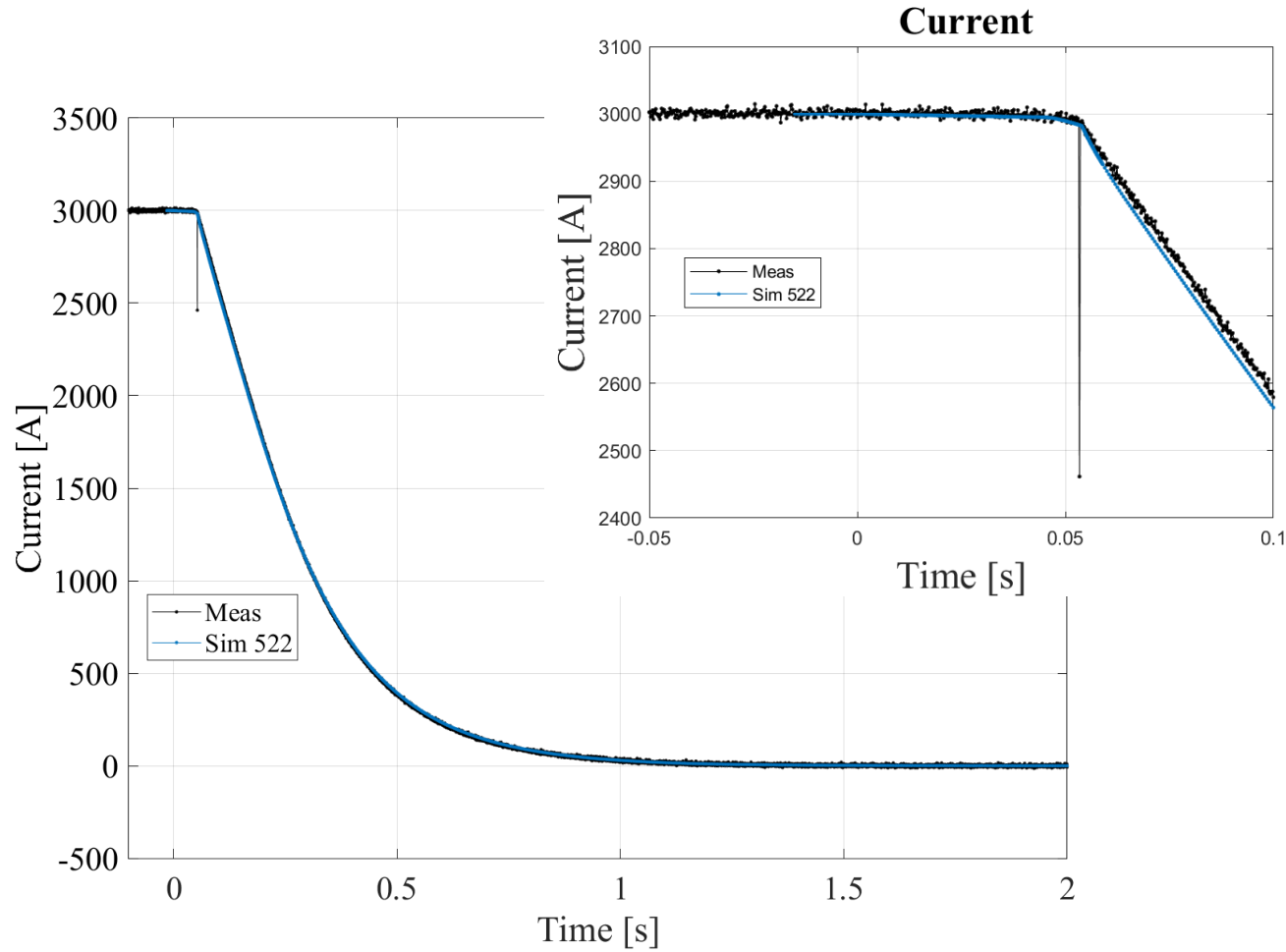
I [A]	EE[s]	QH [s]	QH[V]	QH[mF]
3000	0.054	0.004	900	4*7.05



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

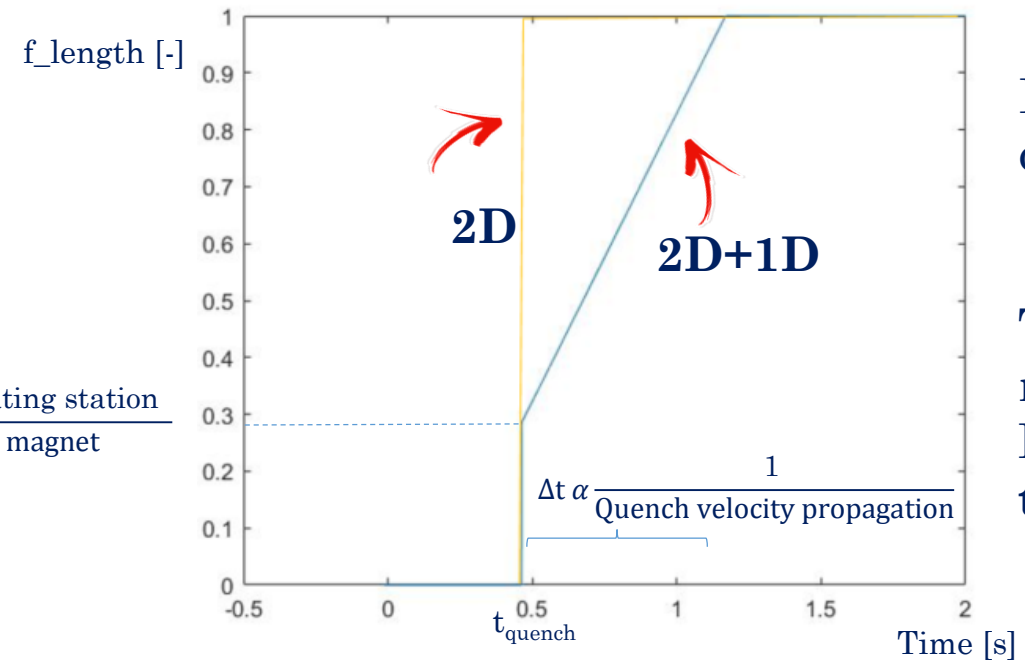
2D → 2D+1D

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.



$\frac{\text{Length heating station}}{\text{Lenght magnet}}$

For each half-turn, $f_{\text{length}}(t)$ is the fraction of quenched conductor in the longitudinal direction

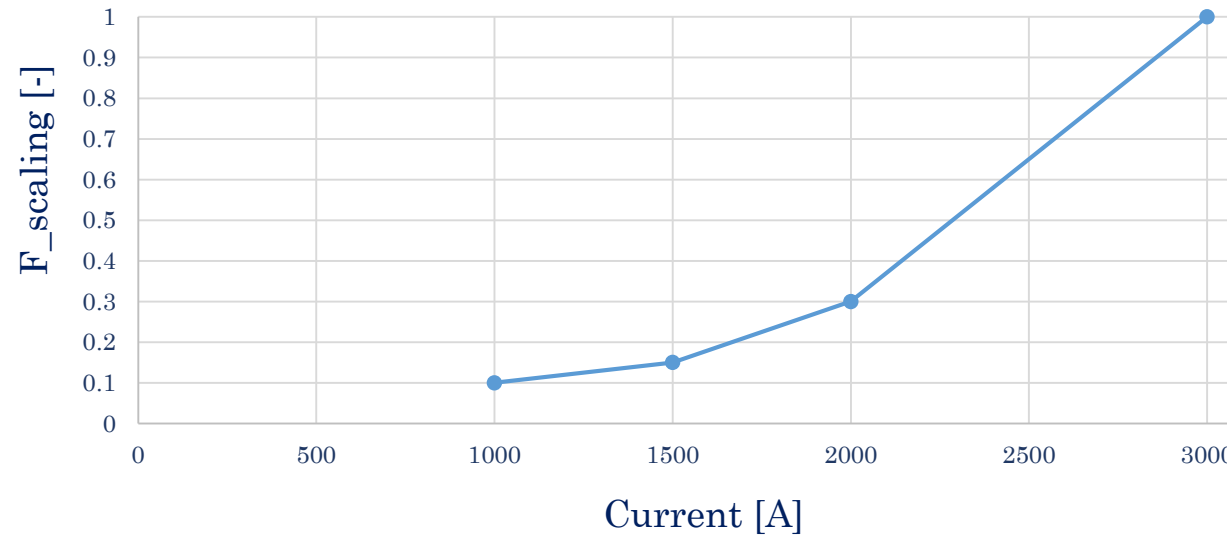
The quench velocity propagation depends on the magnetic field and the current.
LEDET defines the quench velocity propagation turns by turns.



Quench 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.

Quench propagation velocity scaling factor

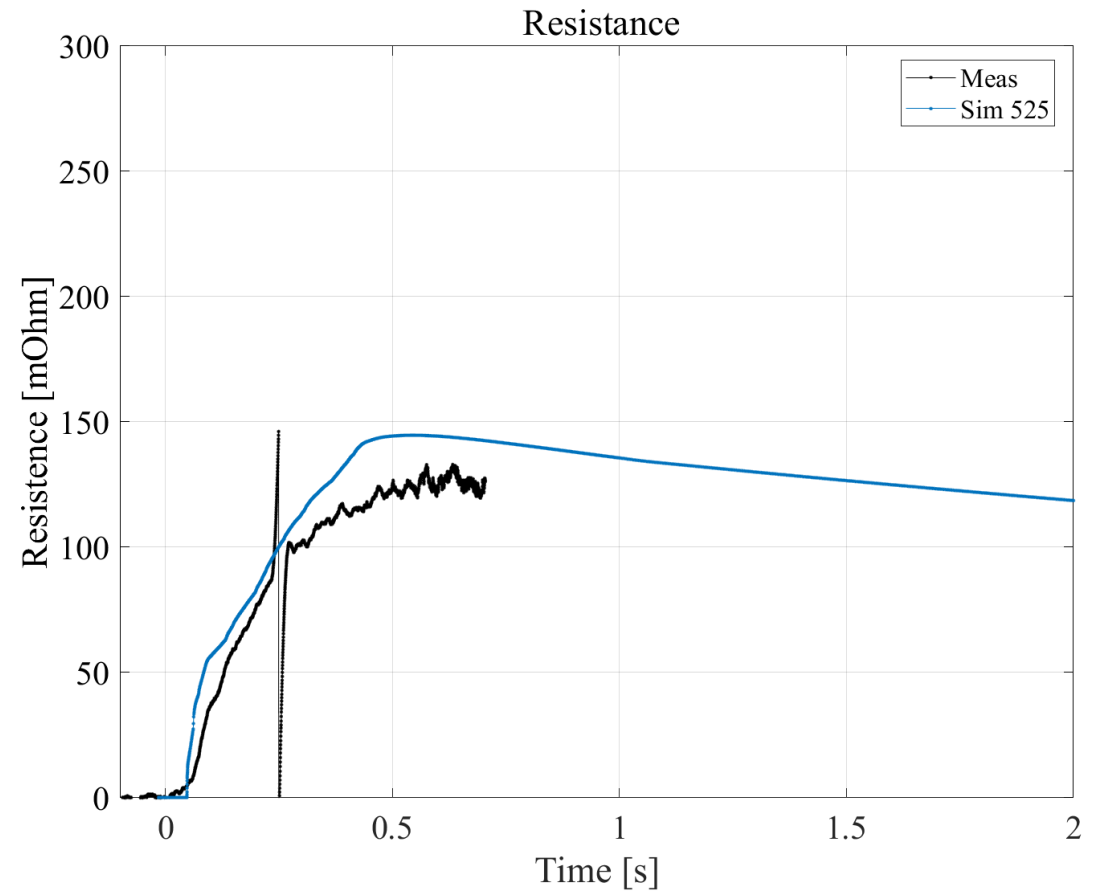
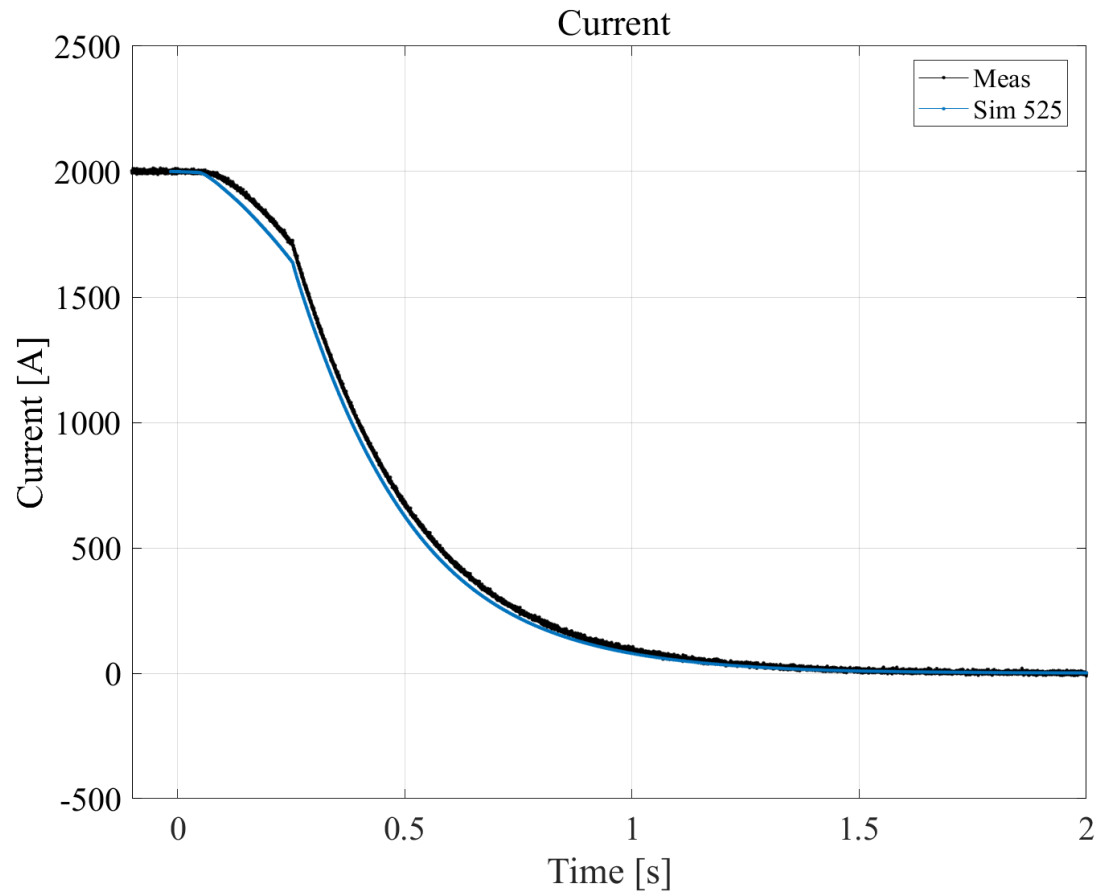


[3] Herman Ten
Kate, Superconducting magnet
quench propagation and
protection, 2013

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

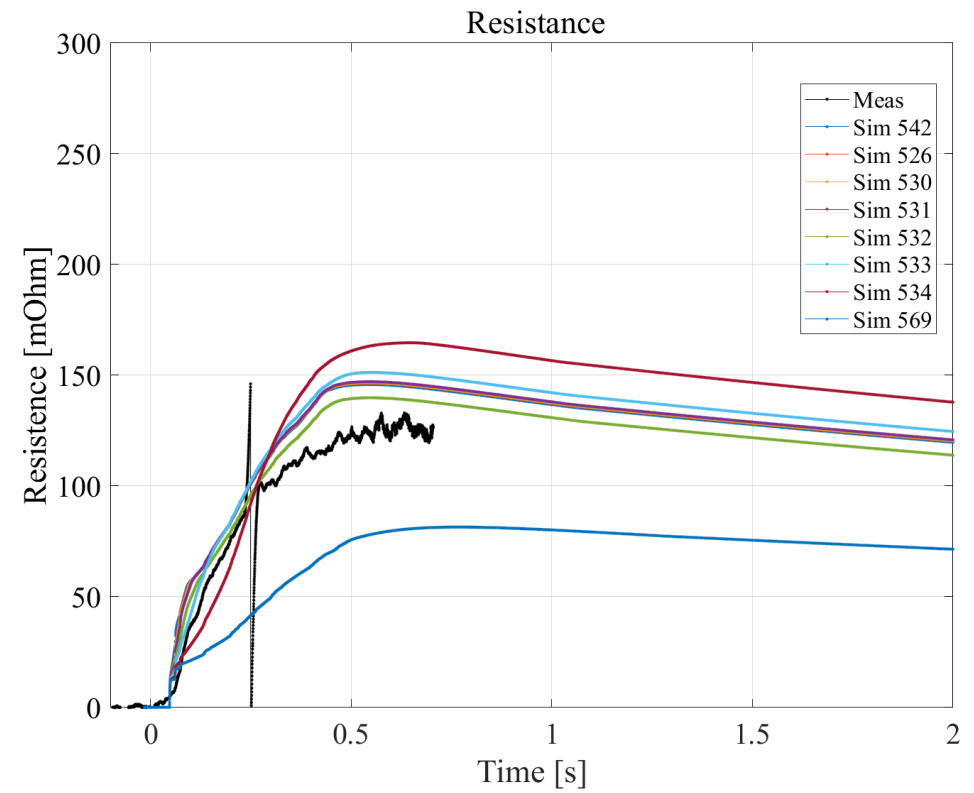
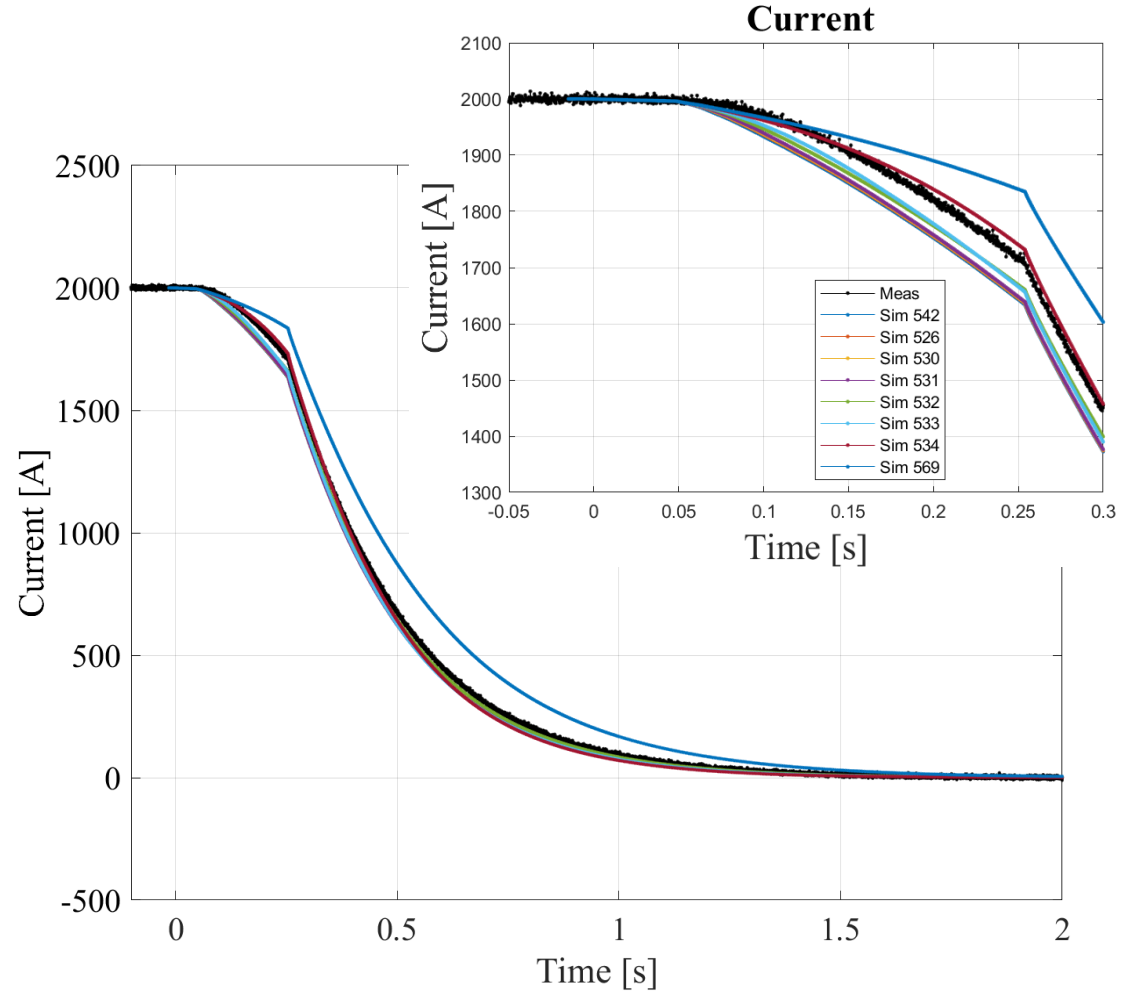
purely 2D model



Quench velocity propagation

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

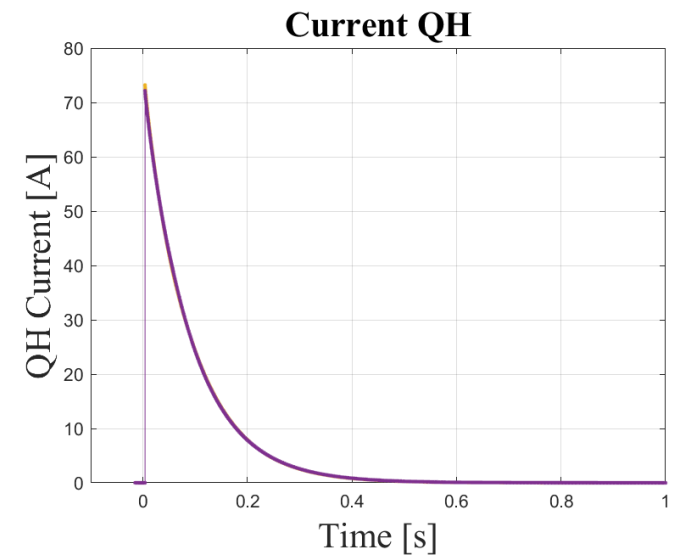
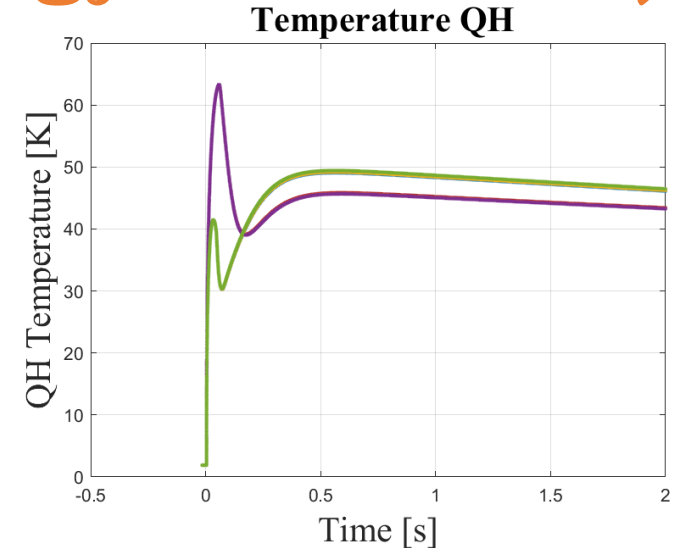
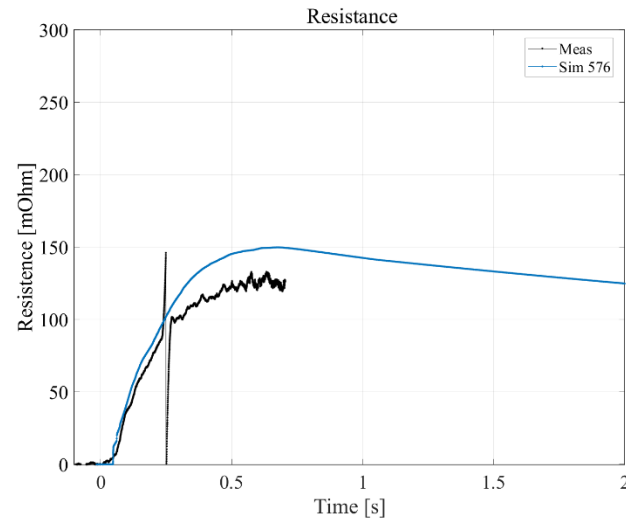
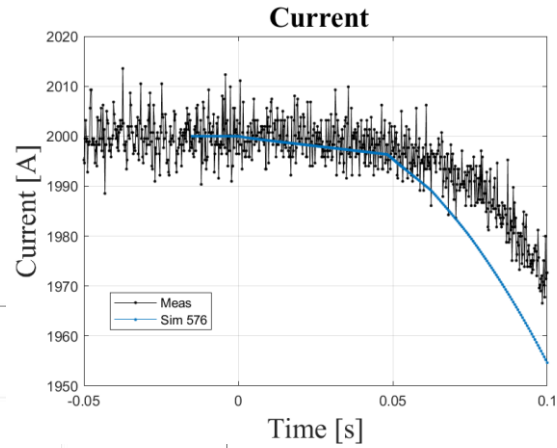
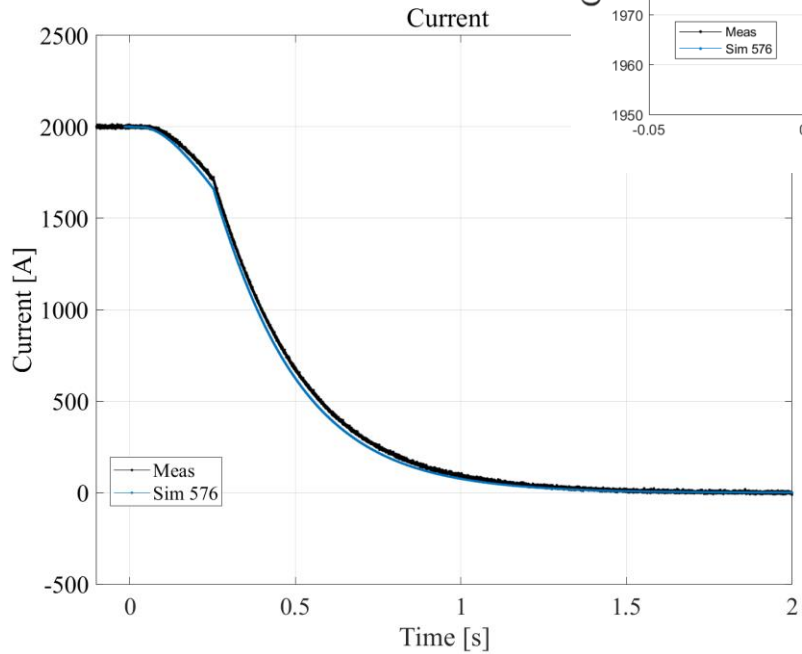


Sim	F_scaling vQ
542	1
526	0.9
530	0.8
531	0.7
532	0.5
533	0.3
534	0.1
569	0



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

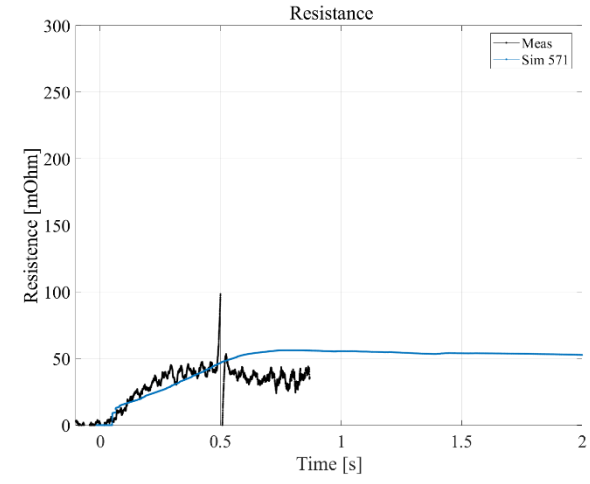
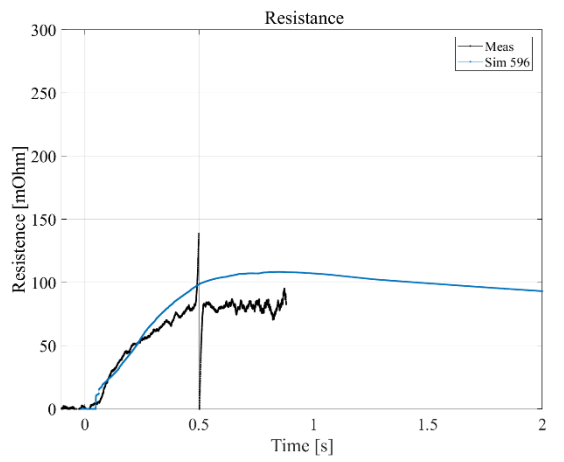
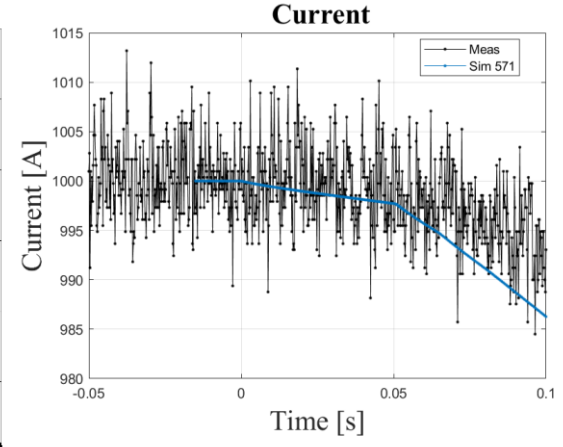
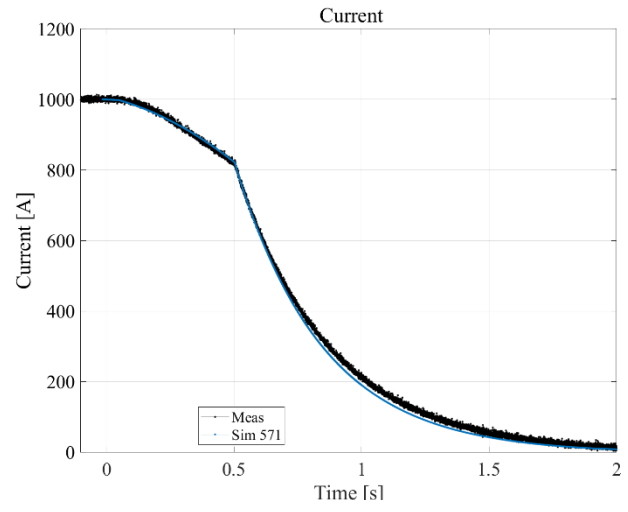
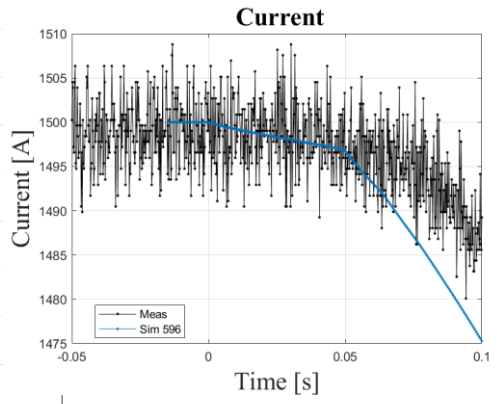
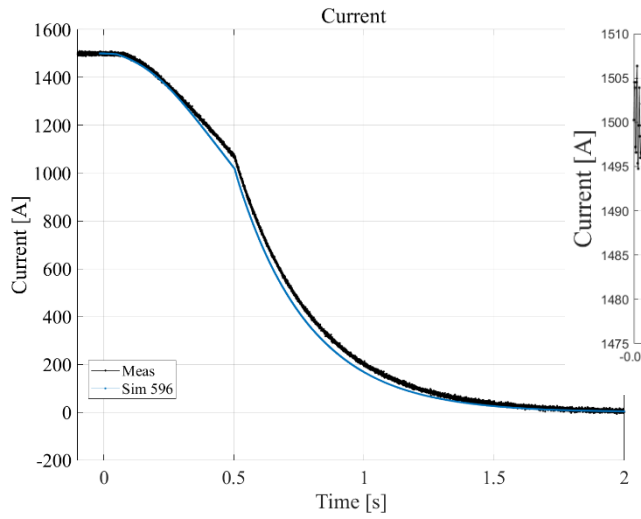


Quench velocity propagation

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



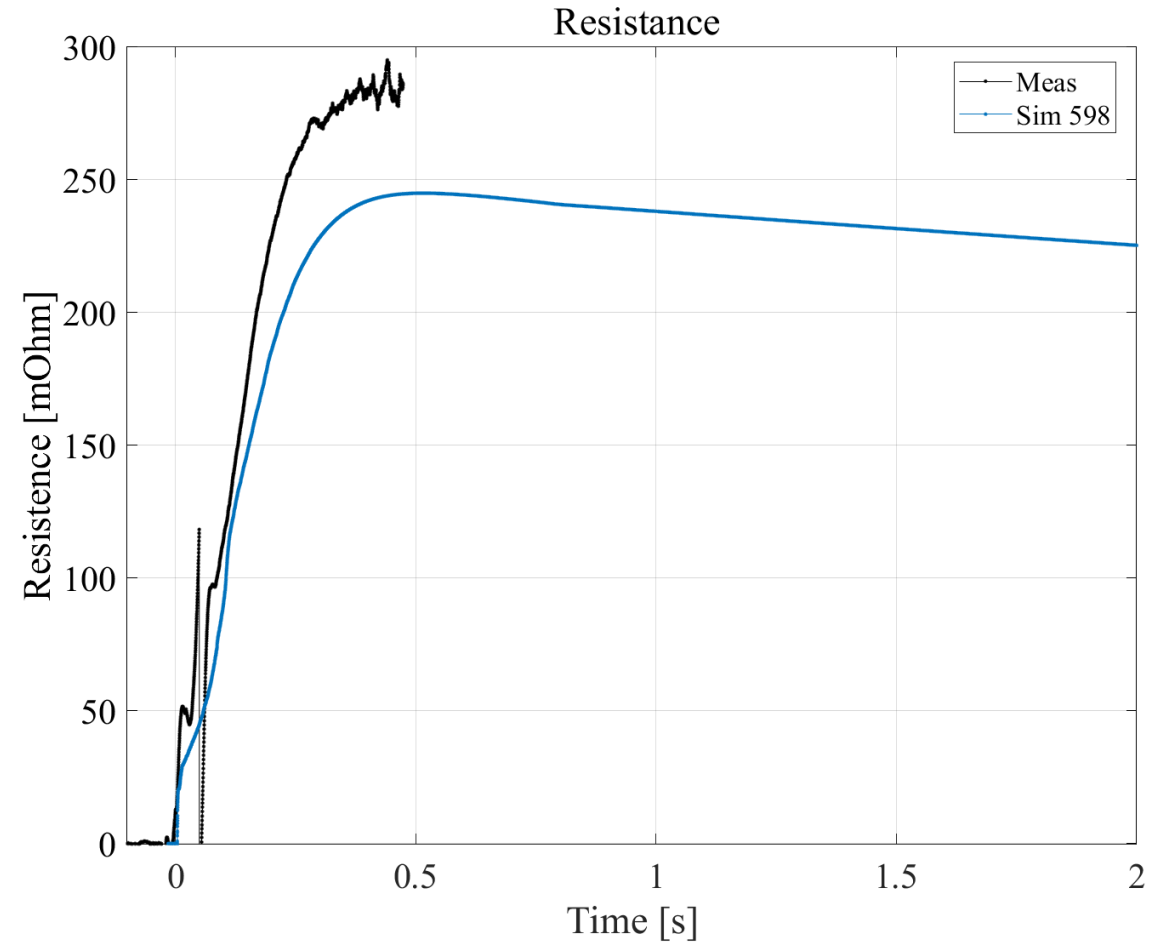
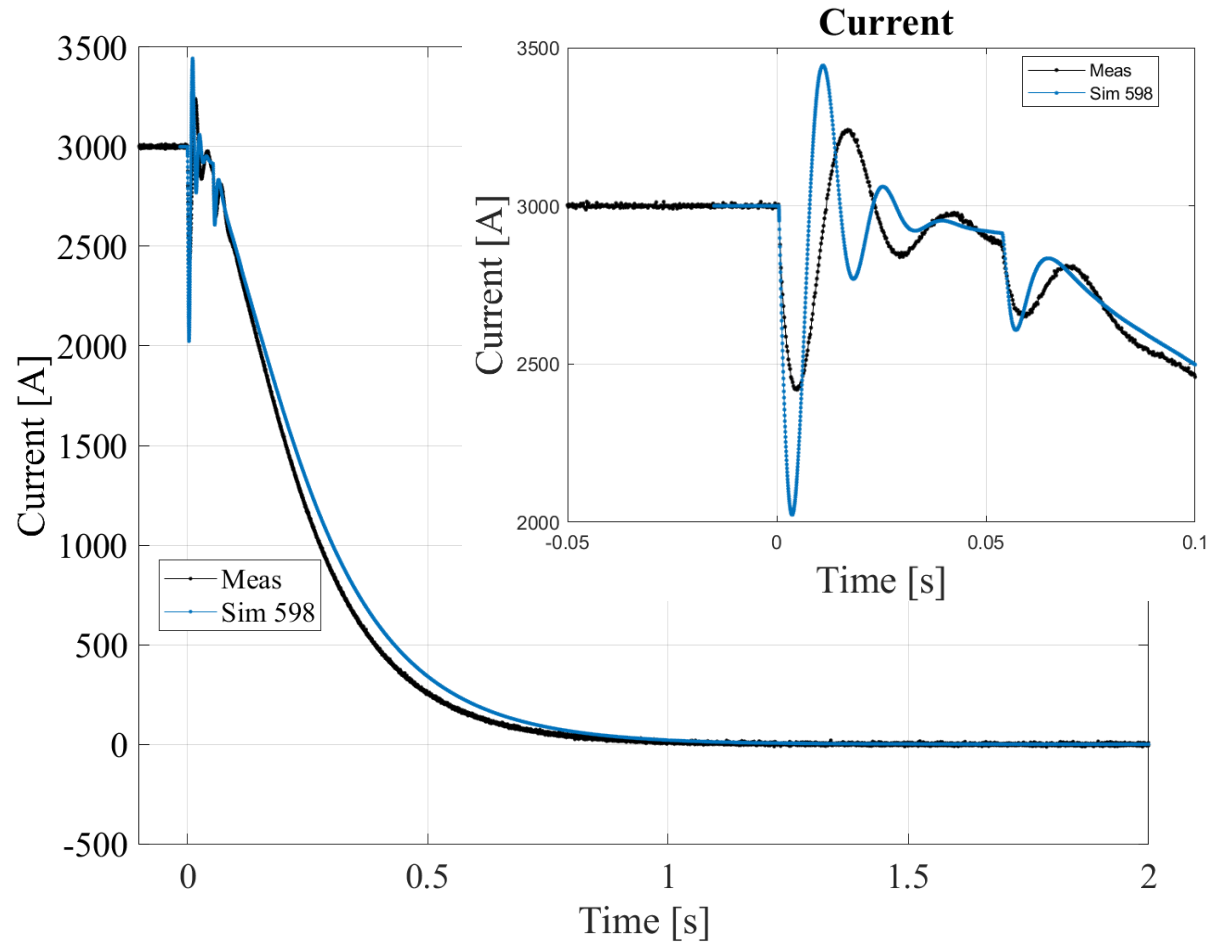
Tests overview

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**.

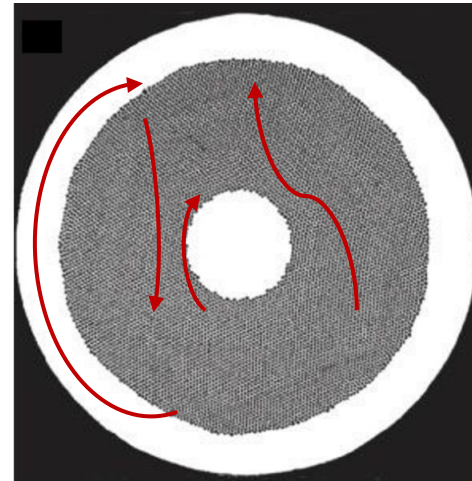
$$\tau_{IFCC} = \frac{\mu_0}{2} \left(\frac{l_f}{2\pi} \right)^2 \frac{1}{\rho_m(T,B) f_{eff}}$$

l_f is the interfilament twist pitch [m]

ρ_m is the matrix resistivity [Ωm]

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

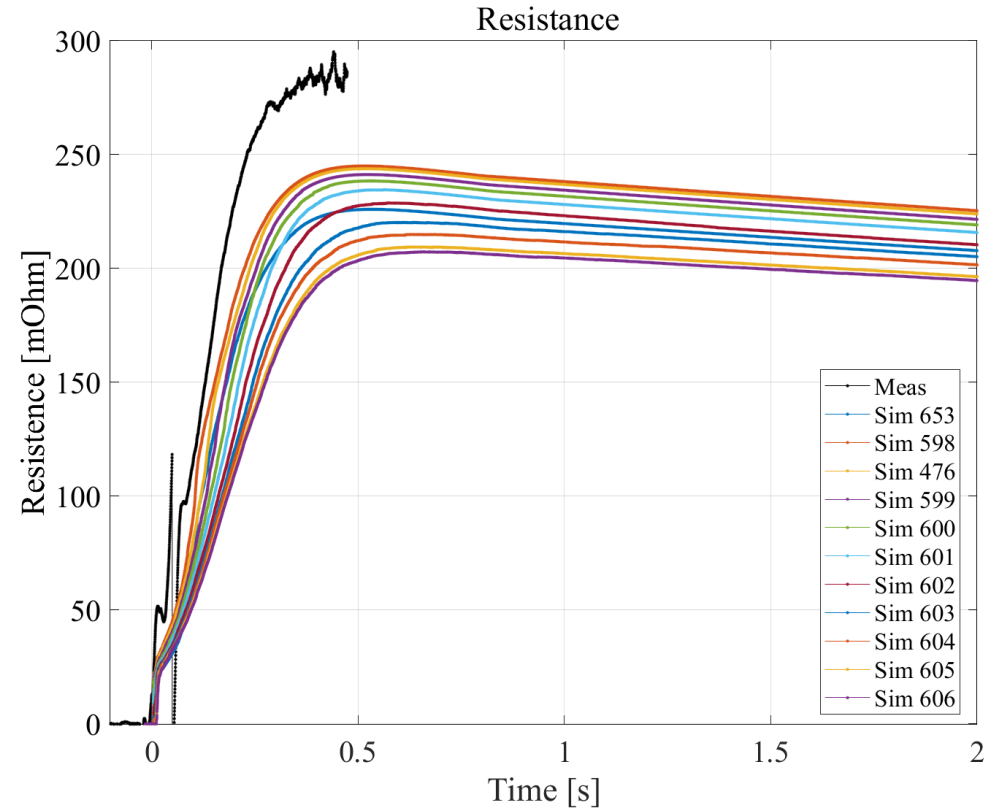
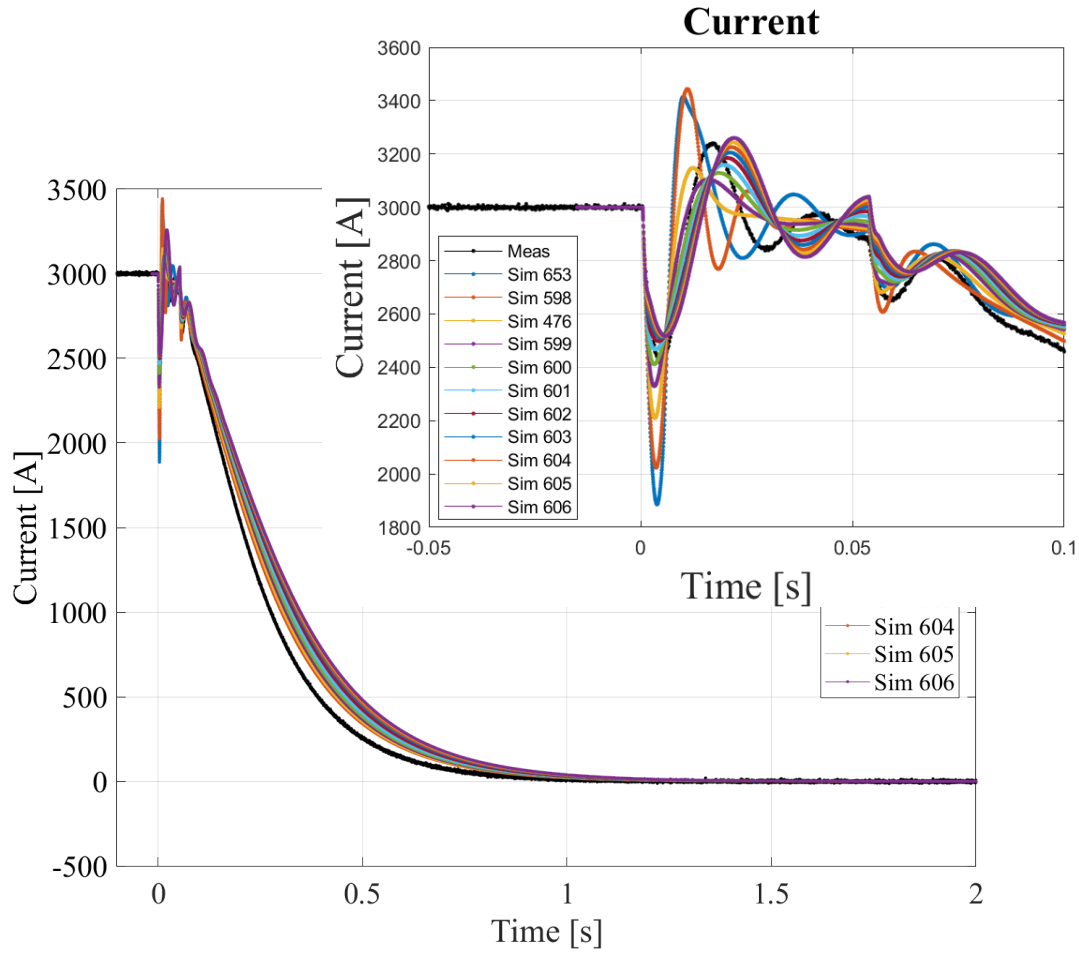
f_{eff} represents the **effective transverse resistivity parameter**. It depends on the superconductor fraction in the matrix, on the interface resistance between the filaments and the matrix, and the position of the filaments in the wire cross



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

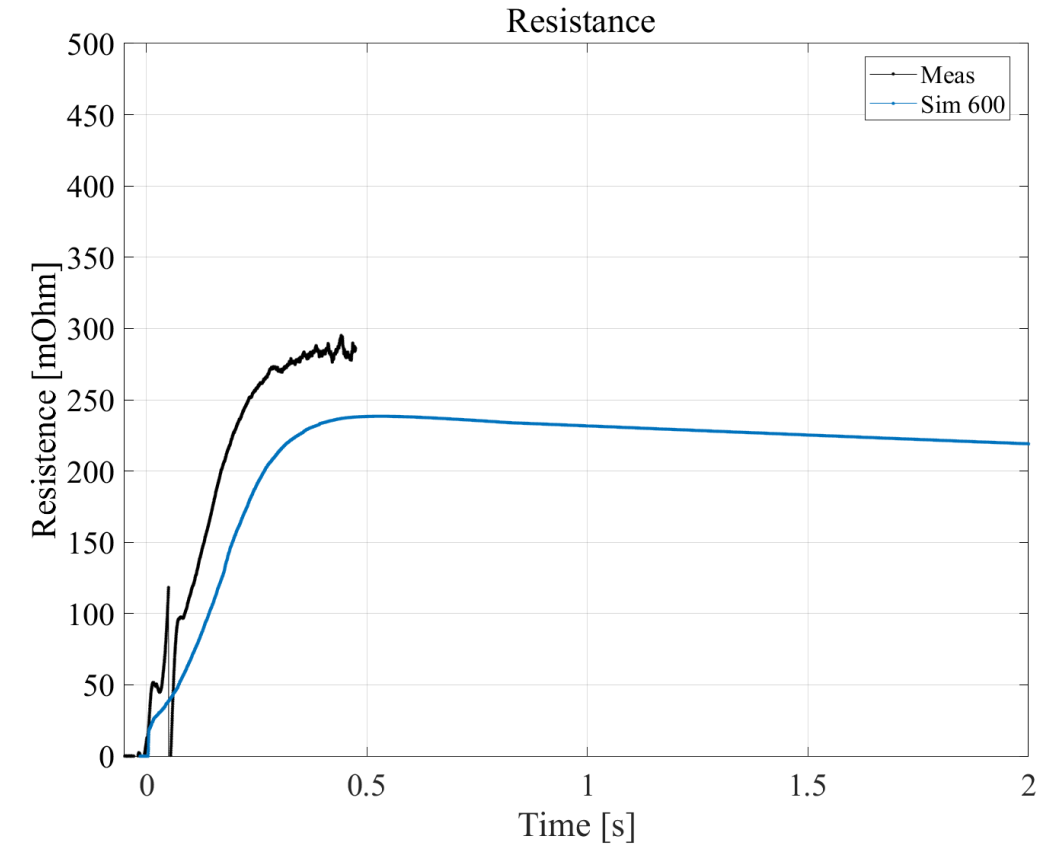
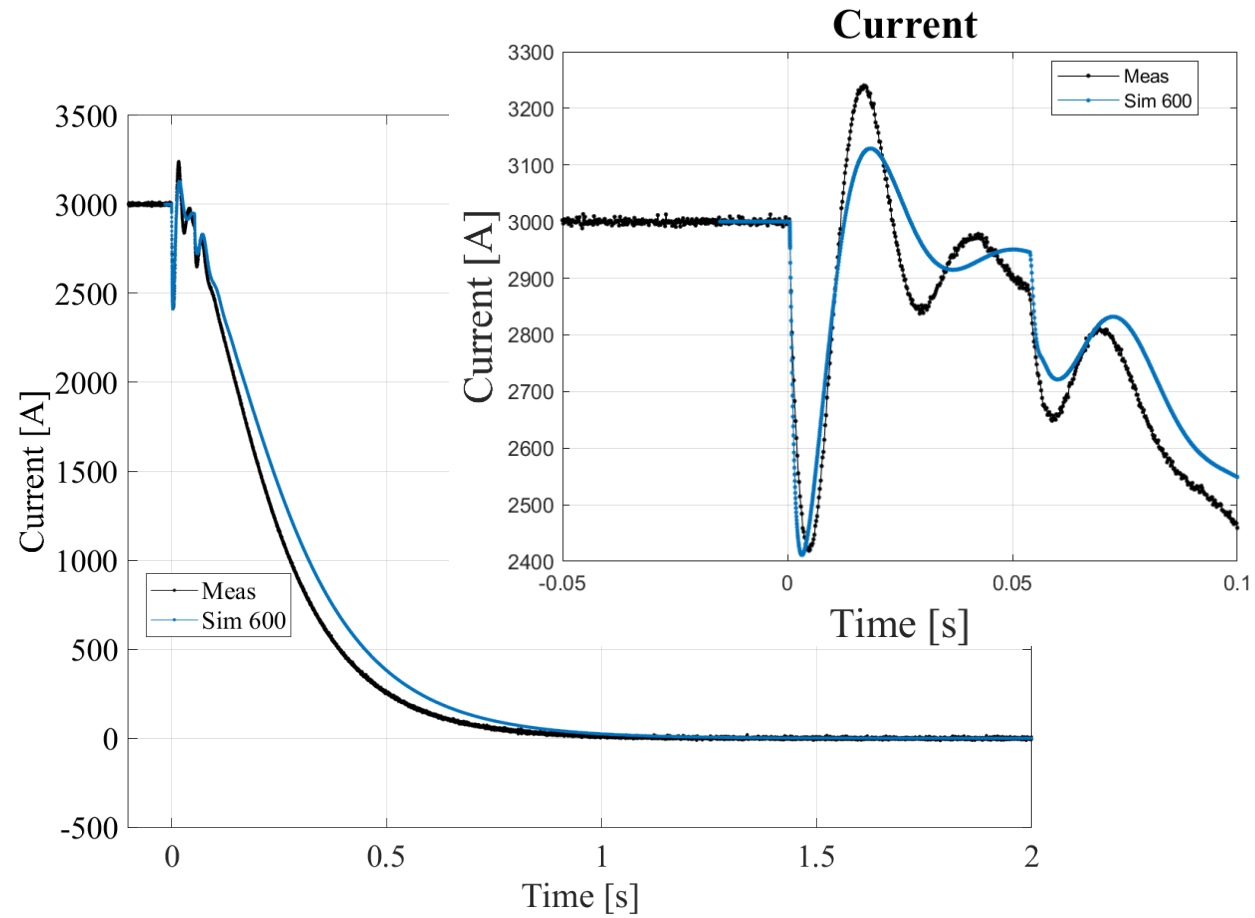


Sim	F_ro_eff
653	0.5
598	1
476	2
599	3
600	4
601	5
602	6
603	7
604	8
605	9
606	10



Test 6 (CLIQ+ delay Energy Extraction)

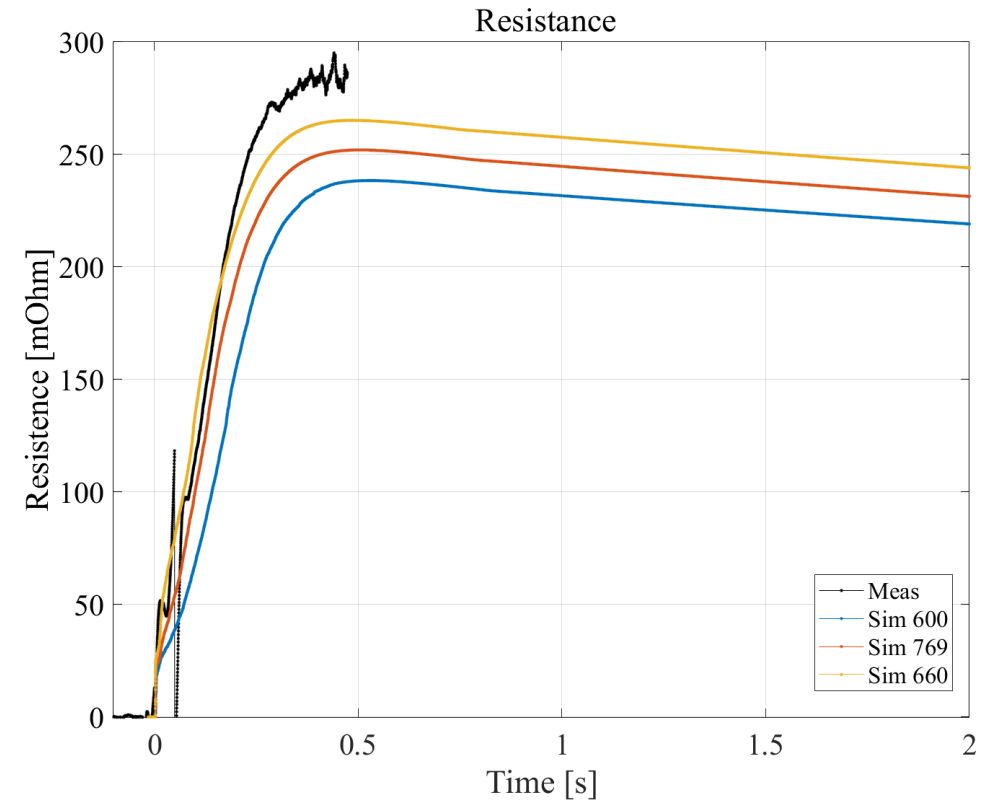
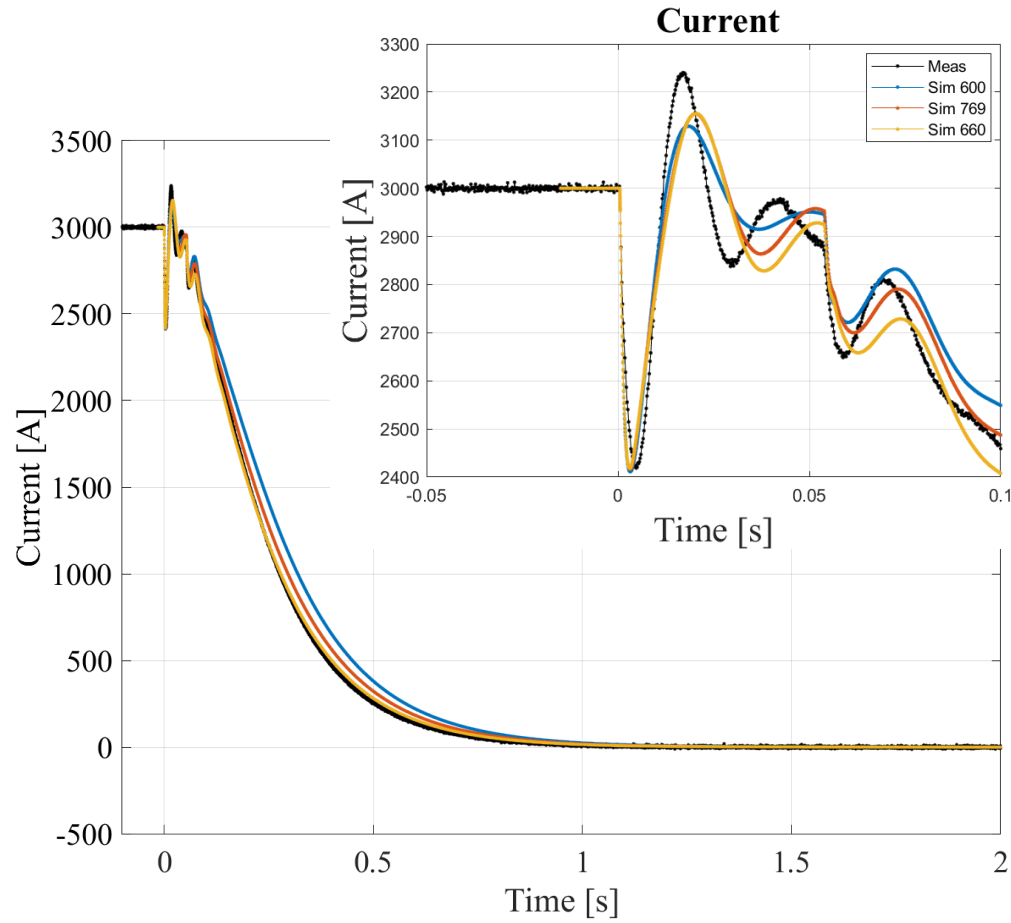
I [A]	EE[s]	CLIQ[s]	CLIQ[V]	CLIQ[mF]	RRR	f_ro_eff
3000	0.054	0.0005	650	8.8	225	4



Test 6 (CLIQ+ delay Energy Extraction)

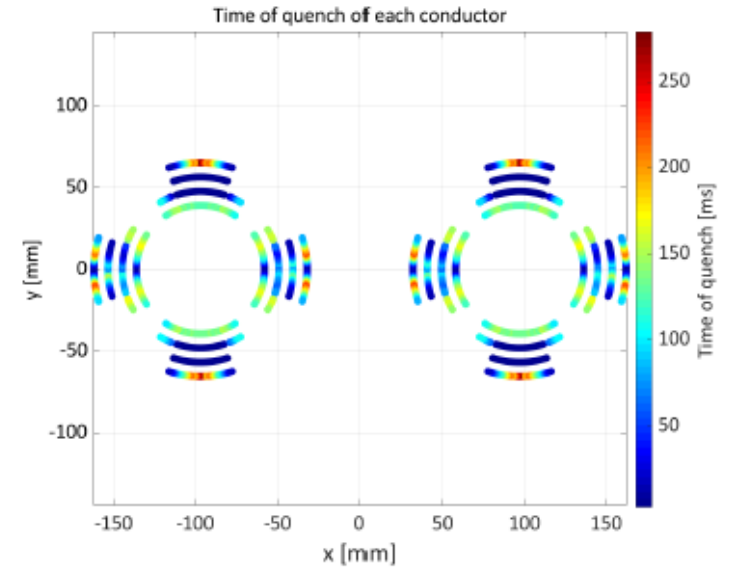
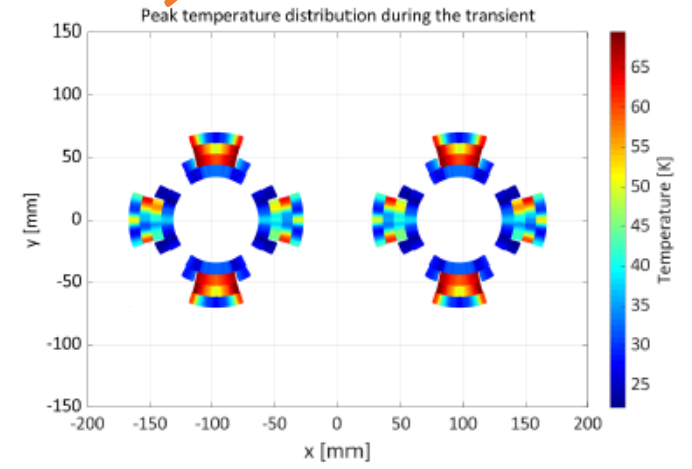
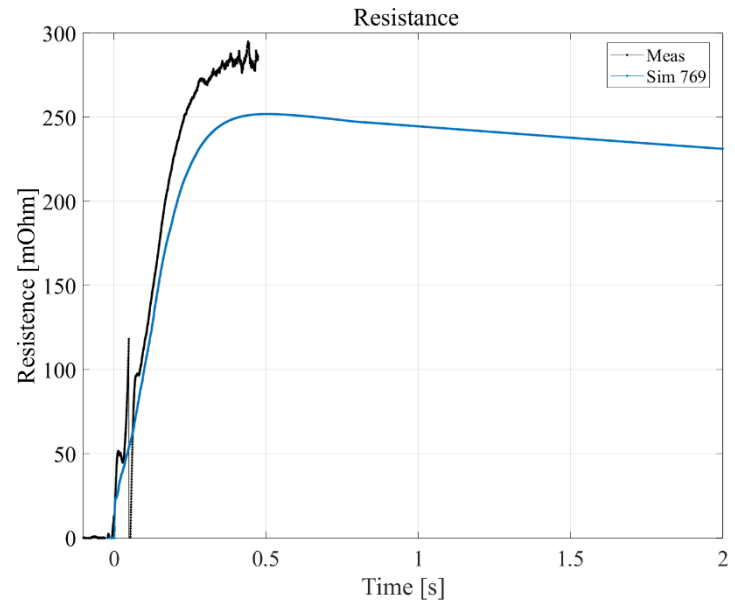
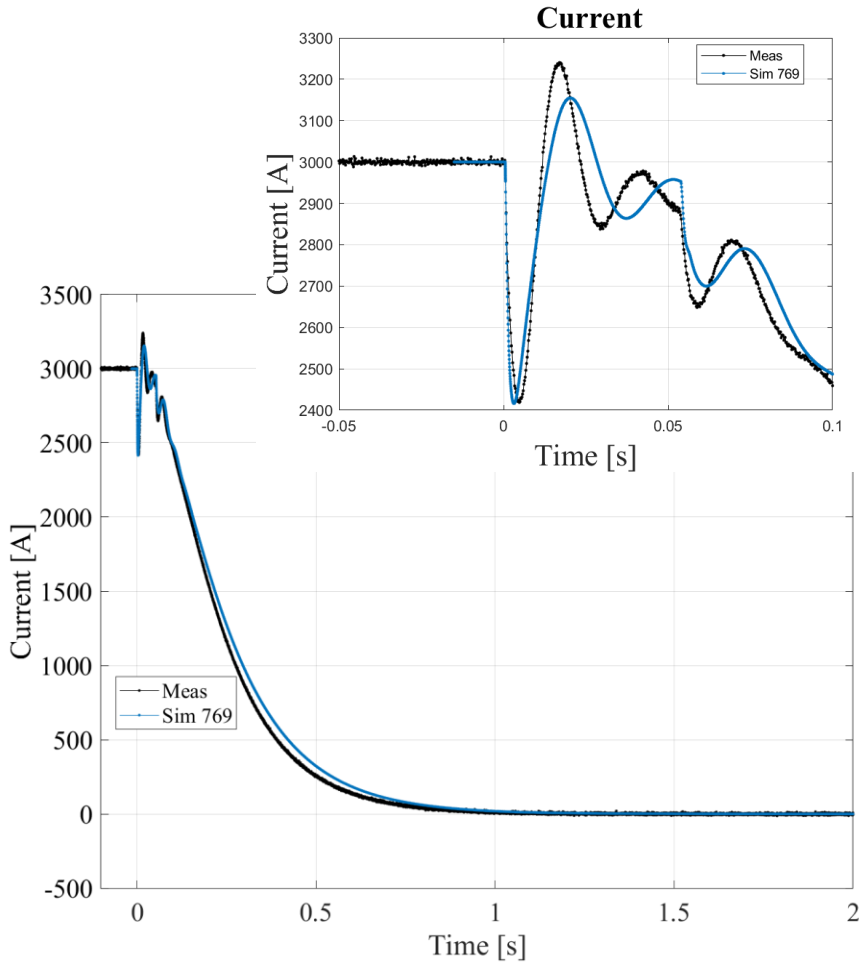
I [A]	EE[s]	CLIQ[s]	CLIQ[V]	CLIQ[mF]	RRR	f_ro_eff
3000	0.054	0.0005	650	8.8	225	4

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



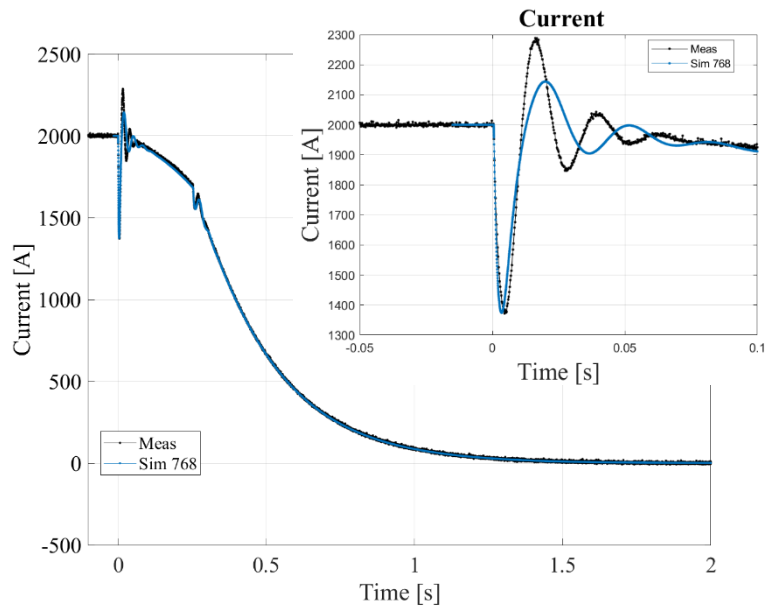
Test 6 (CLIQ+ delay Energy Extraction)

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

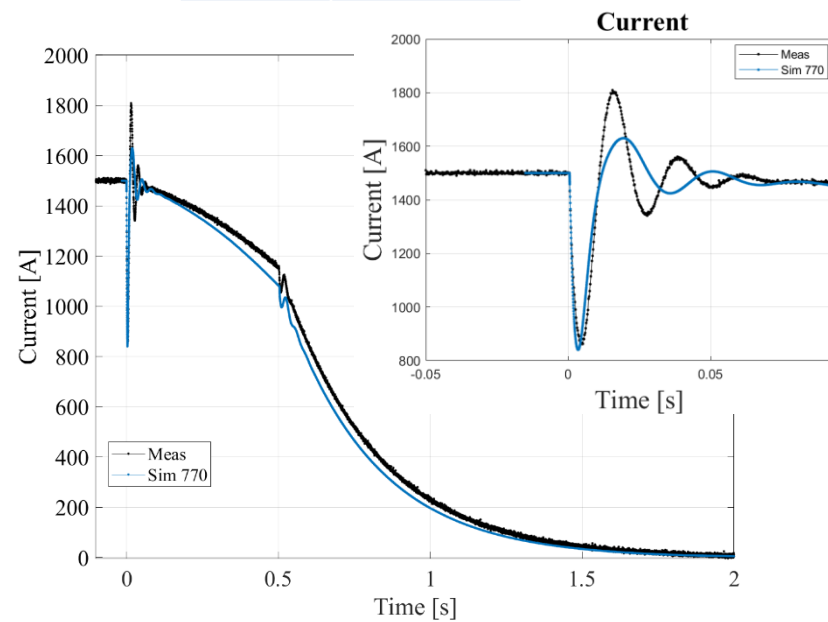


Test 7/8/9 (CLIQ+ delay Energy Extraction)

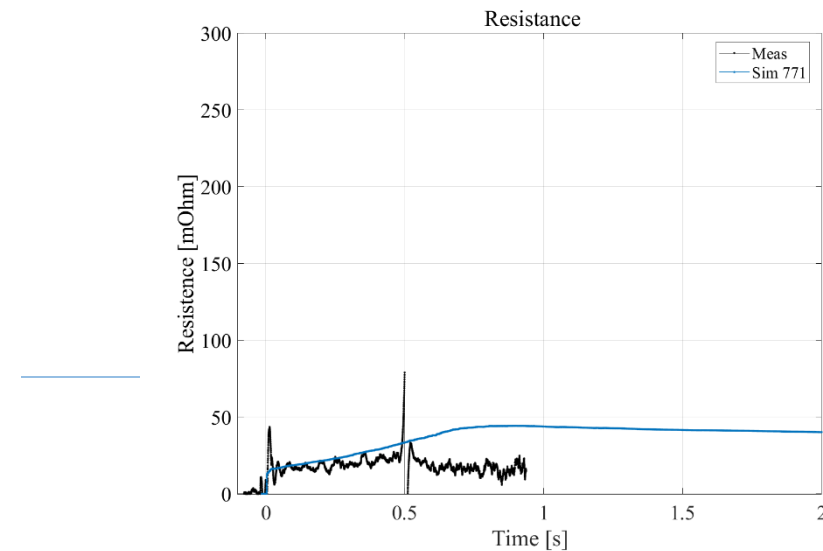
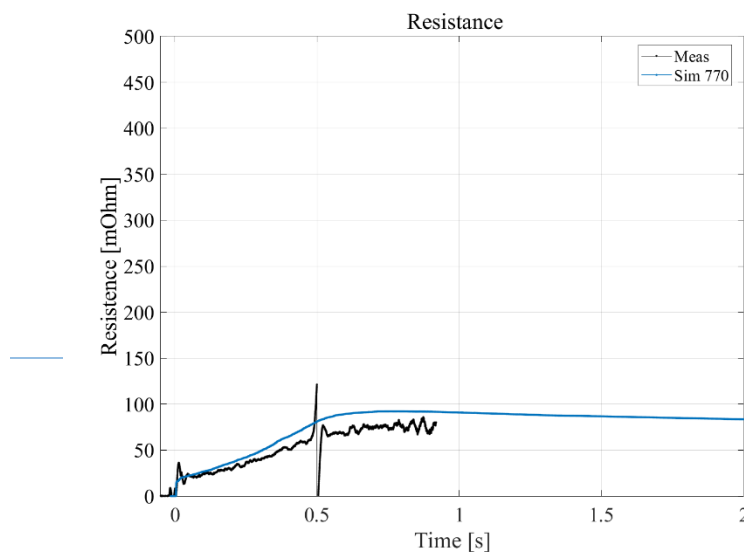
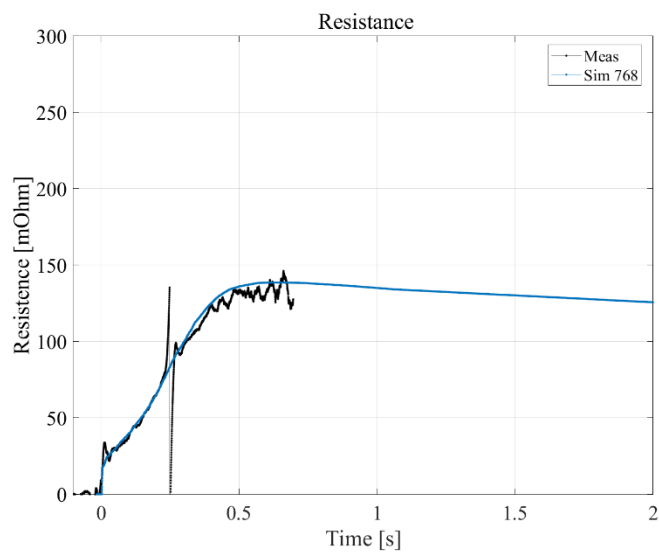
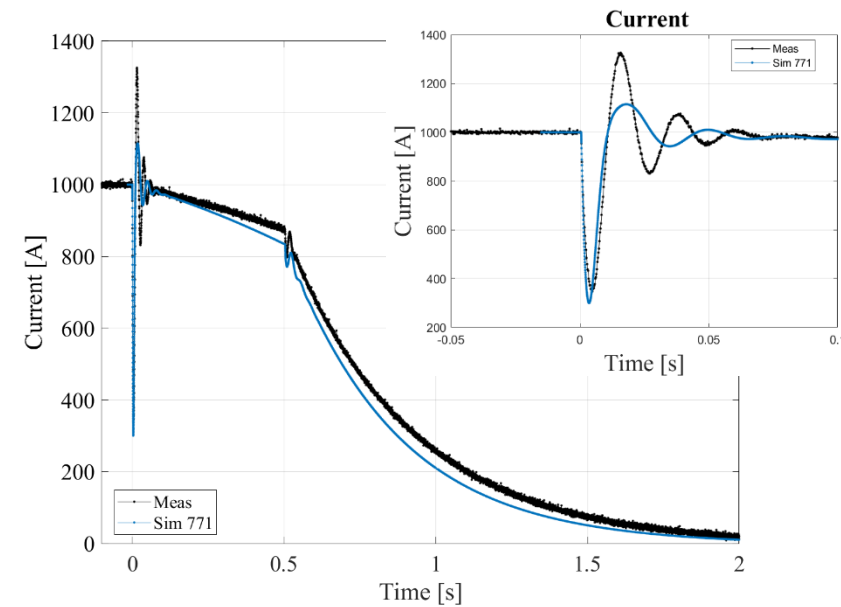
I [A]	EE[s]
2000	0.254



I [A]	EE[s]
1500	0.504



I [A]	EE[s]
1000	0.504



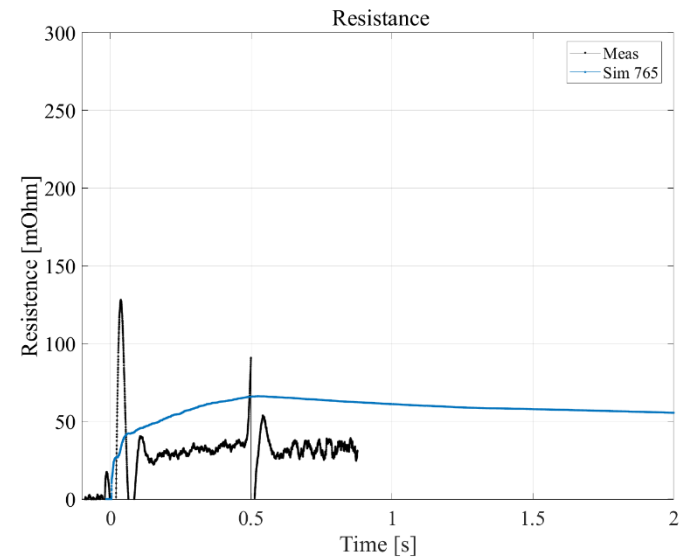
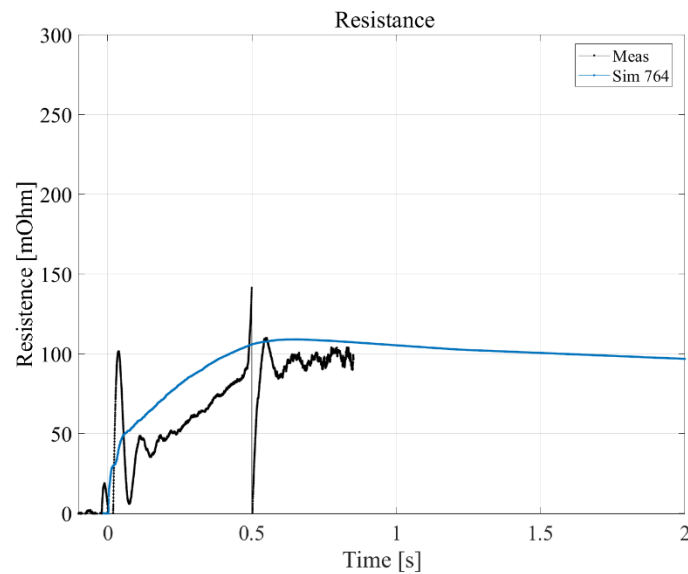
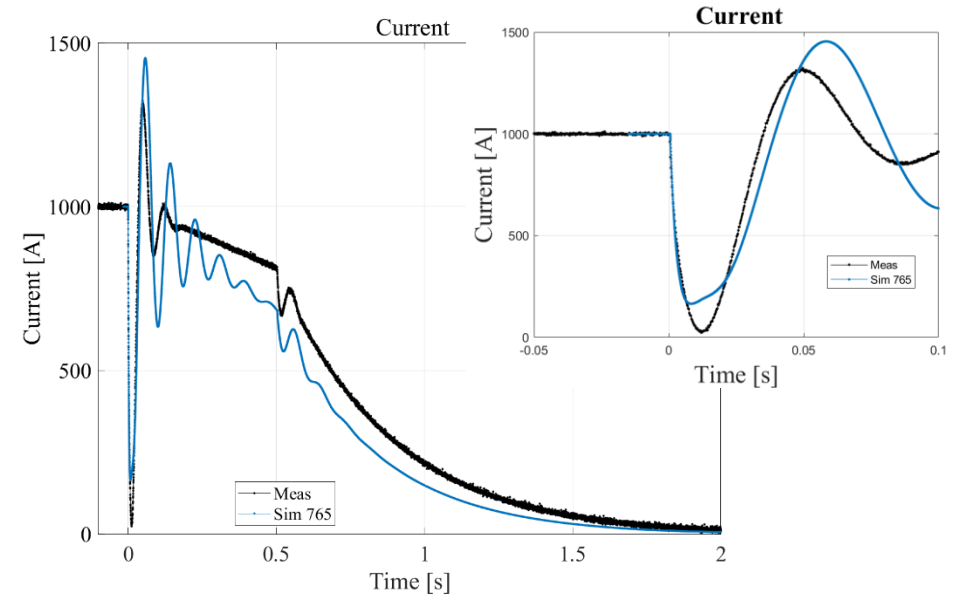
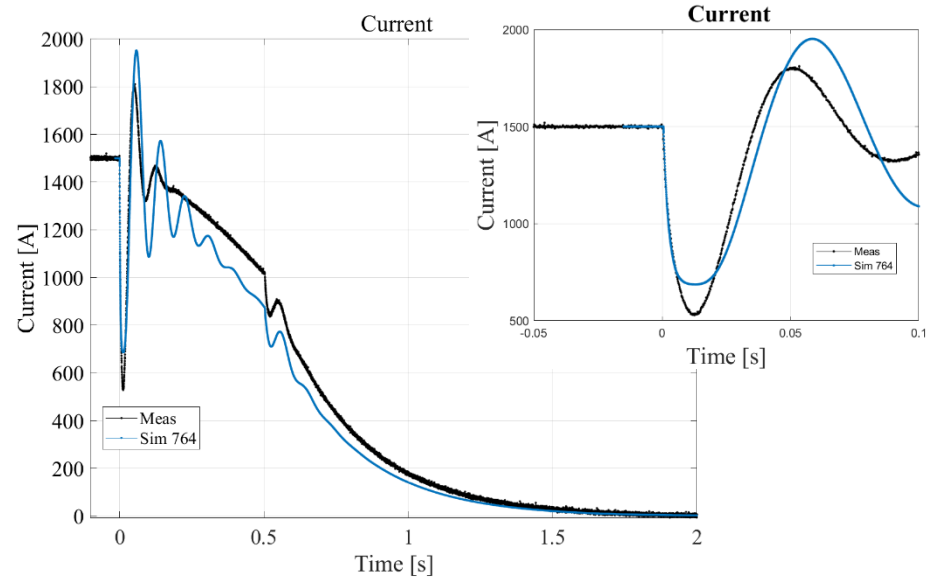
Tests overview

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



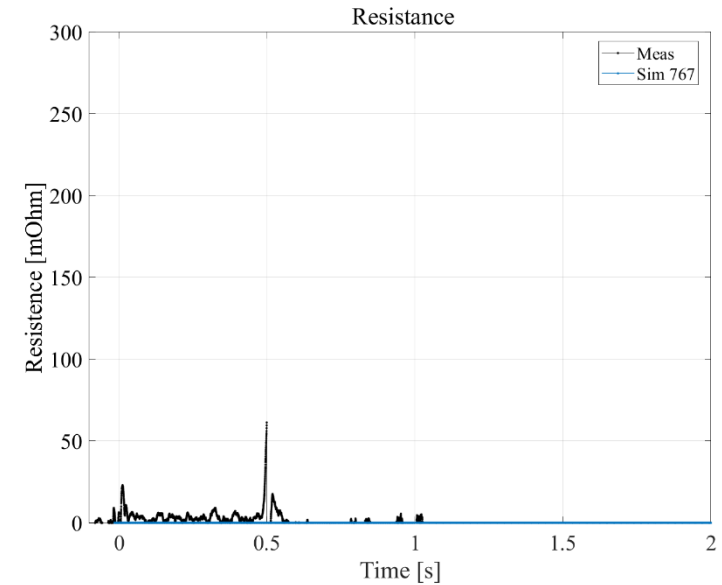
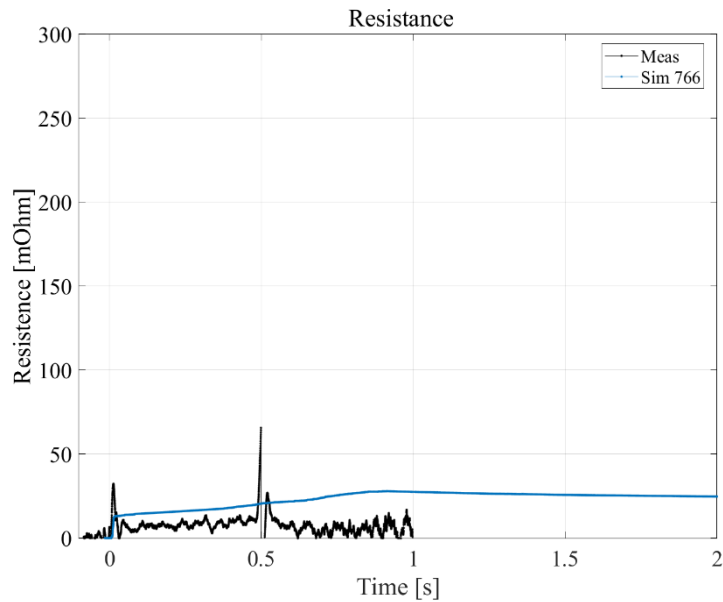
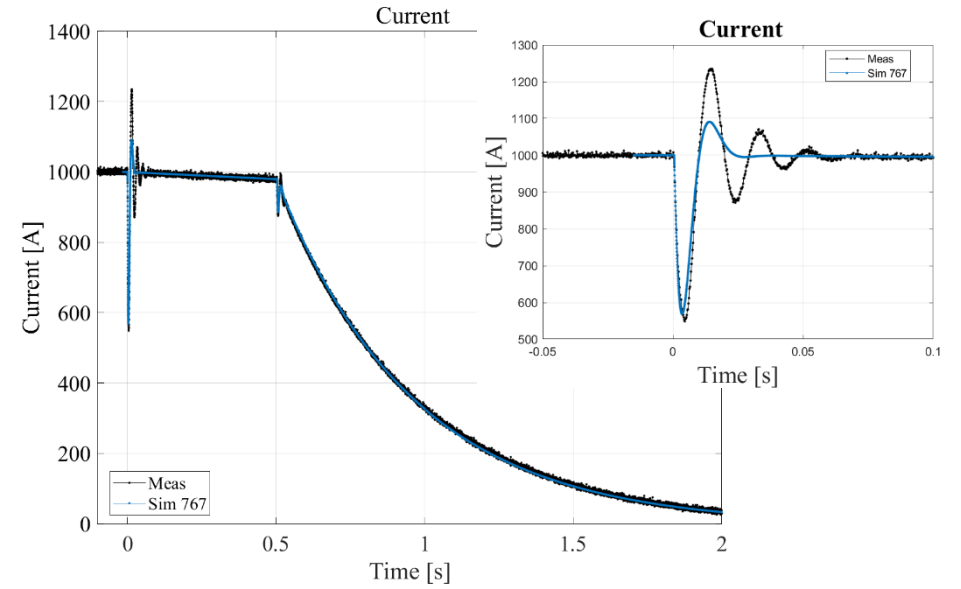
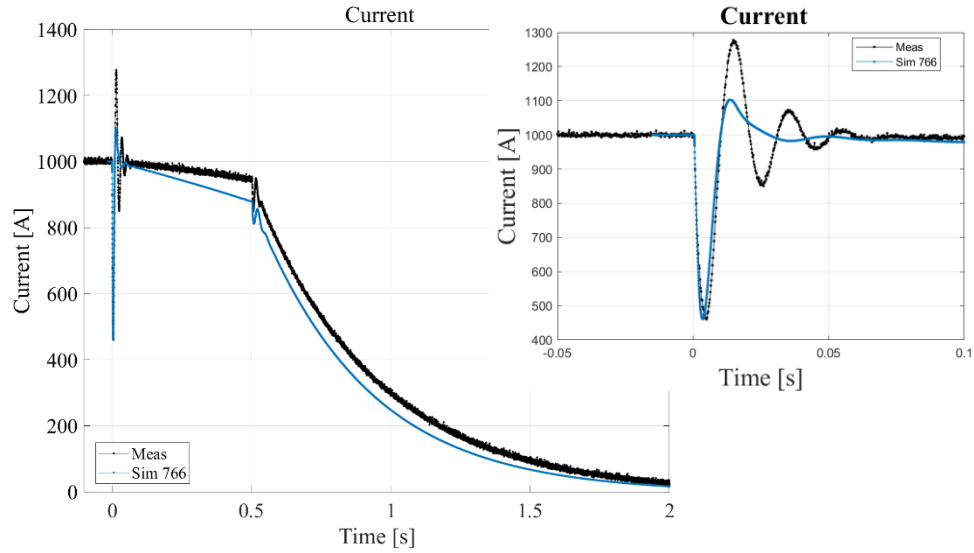
Tests overview

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



Section meeting 7/11/2019

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?

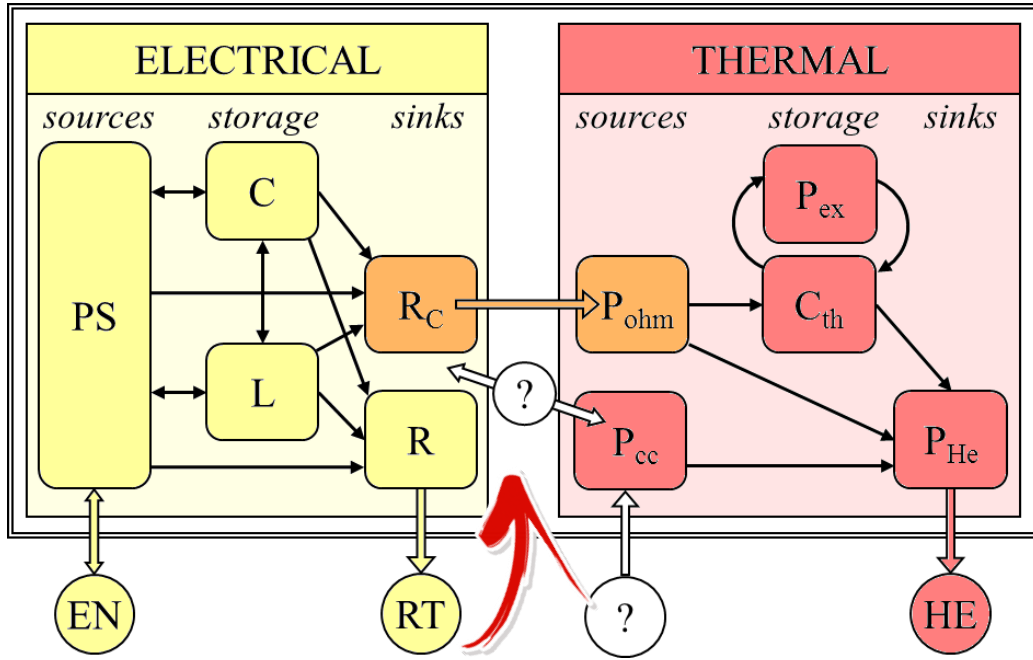


Annex



Why LEDET?

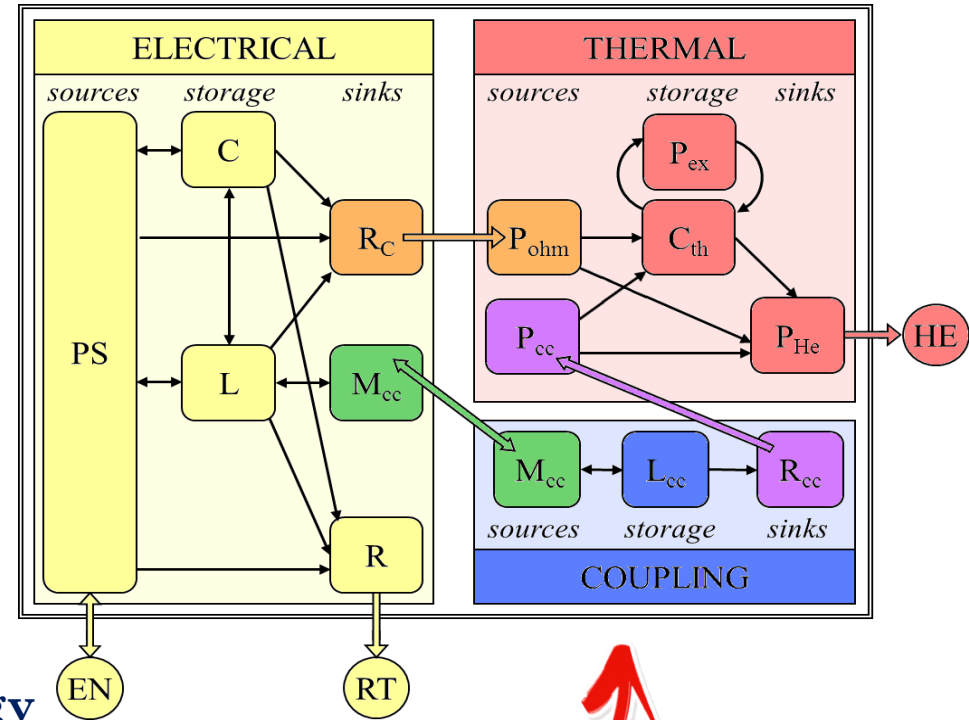
Conventional electro-thermal model:



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

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

LEDET electro-thermal model:



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

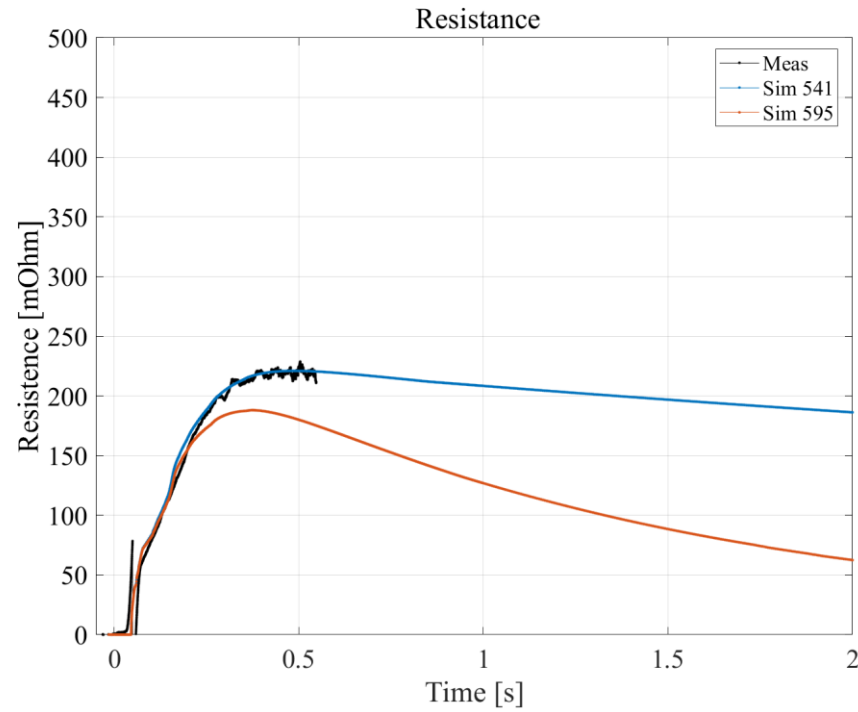
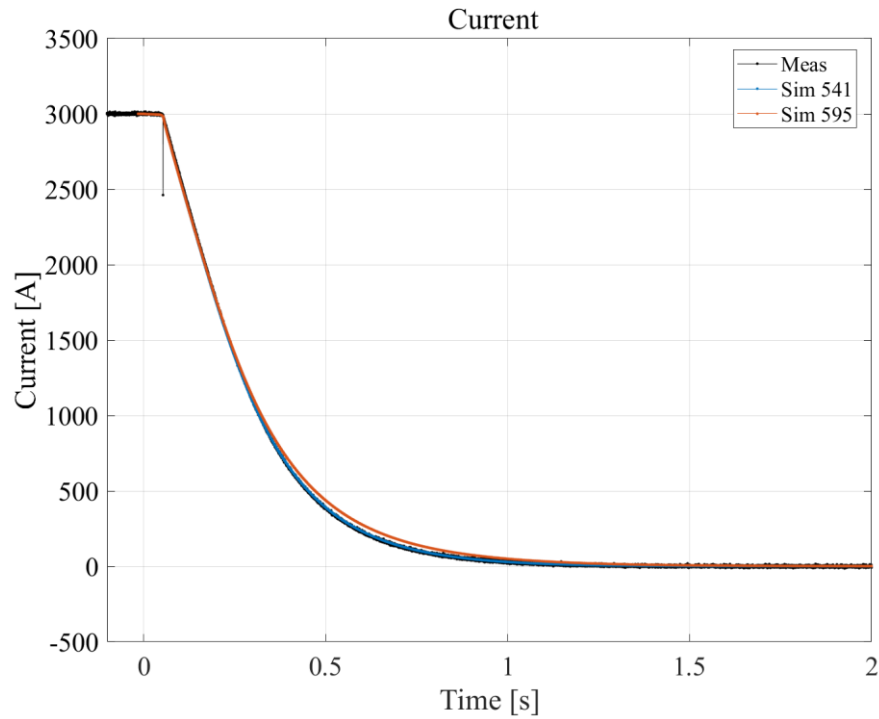
Test 2 (Quench Heaters + delay Energy Extraction)

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.

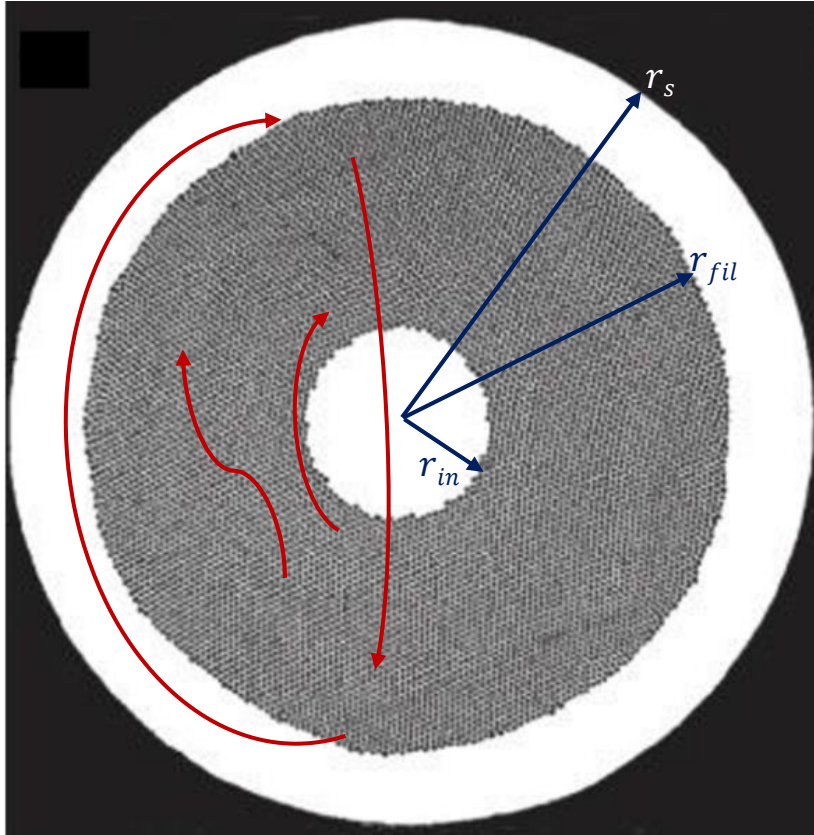
If the flag is set to **2** the helium cooling included **conductive** and simplified **convective** heat transfer; including both effect reduces cooling



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.

$$f_{ro_eff} = \left[\alpha_{in} + \frac{\rho_m}{\rho_{eff,fil}} (\alpha_{fil} - \alpha_{in}) + \alpha_{fil} \frac{1 - \alpha_{fil}}{1 + \alpha_{fil}} \right]^{-1}$$

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

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

$\rho_{eff,fil}$ is the effective transverse resistivity [Ωm]

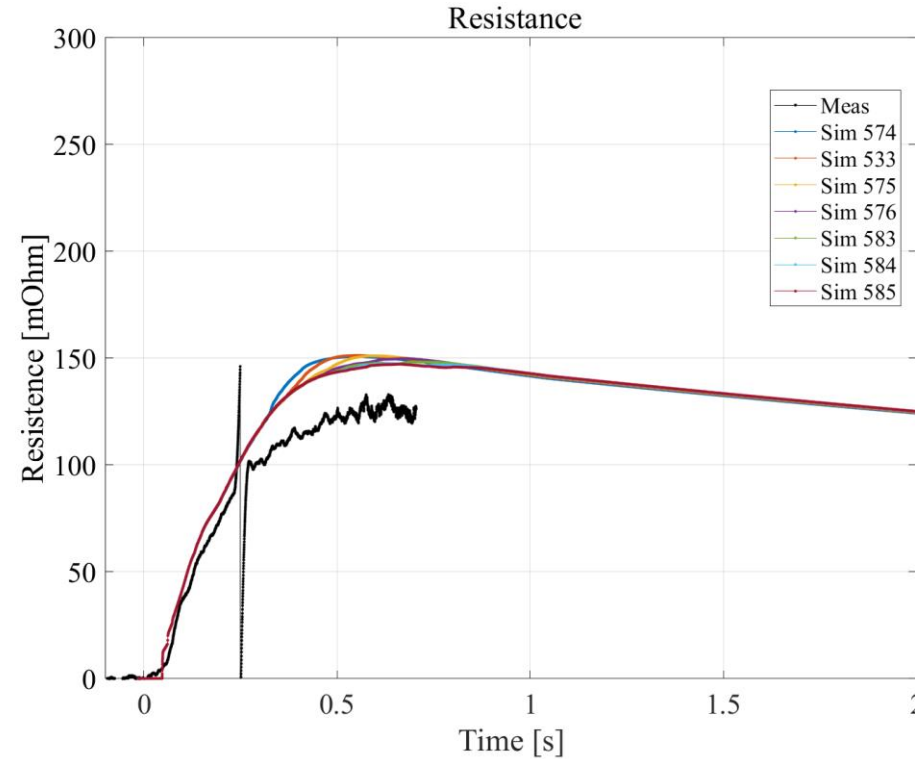
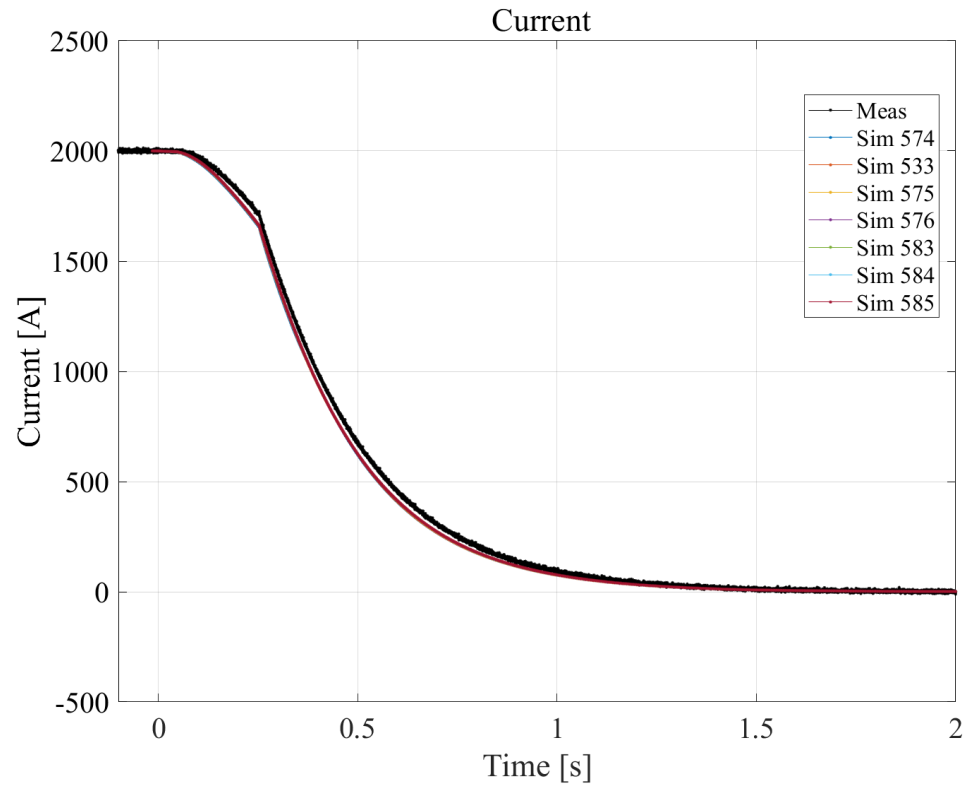
ρ_m is the matrix resistivity [Ωm]

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

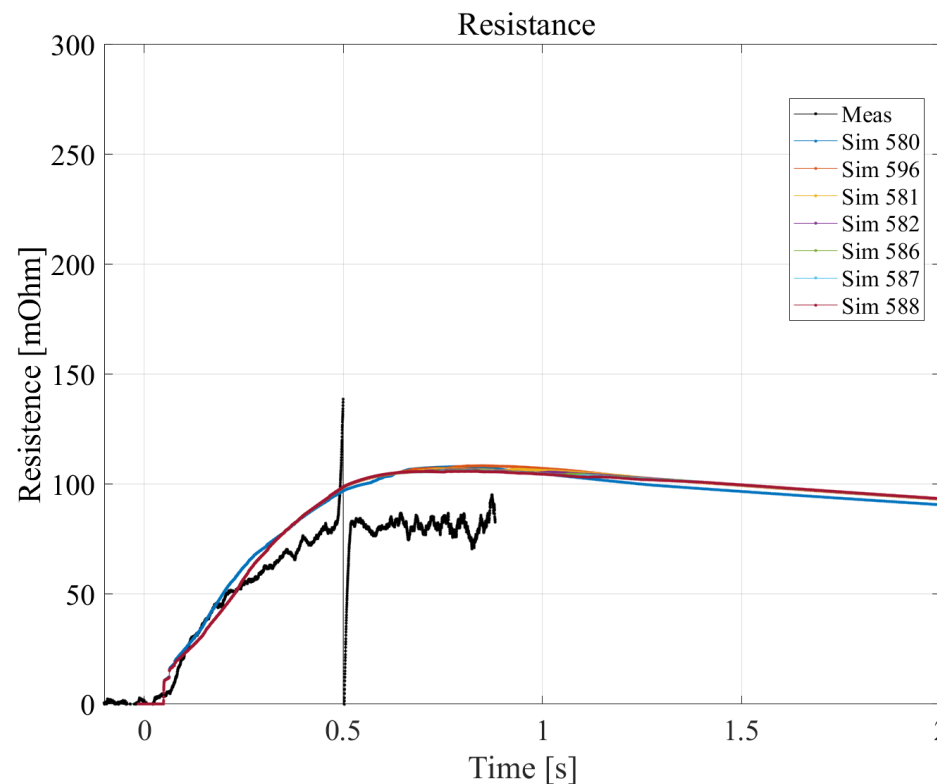
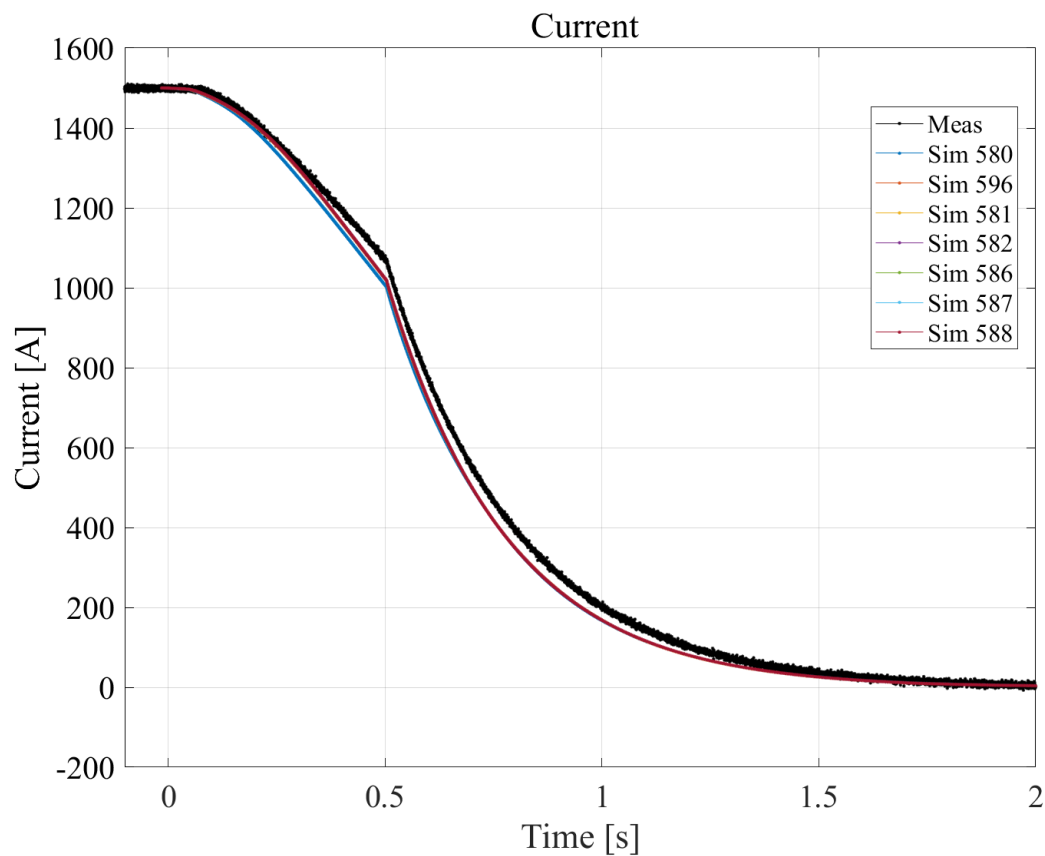


Sim	F_ro_eff
574	1
533	2
575	3
576	4
583	5
584	6
586	7



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

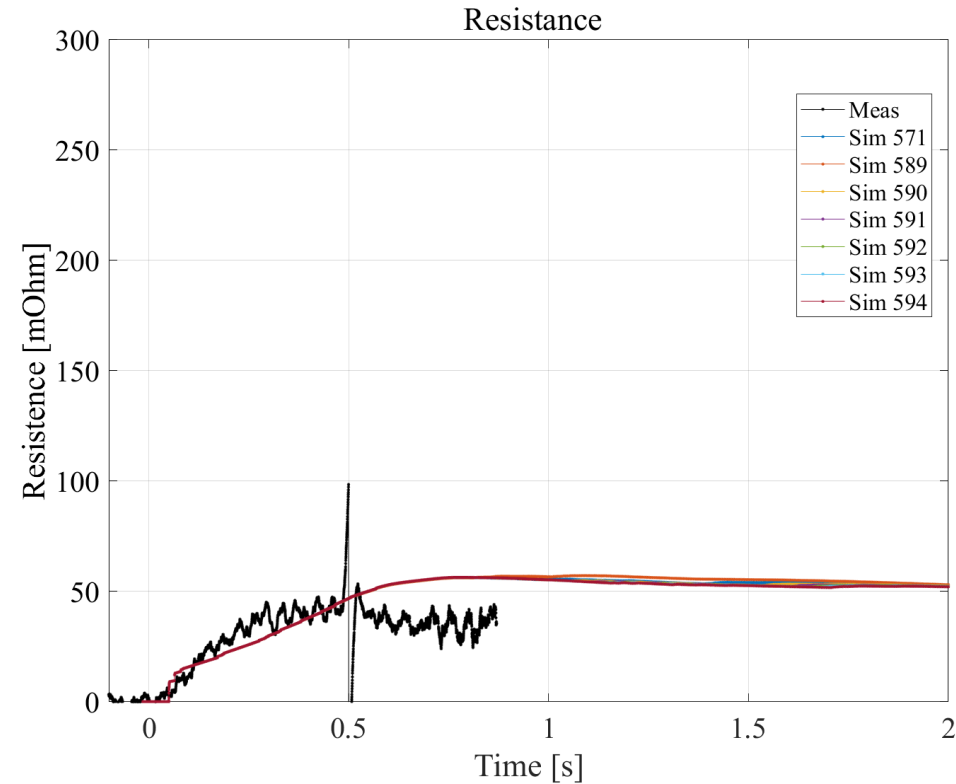
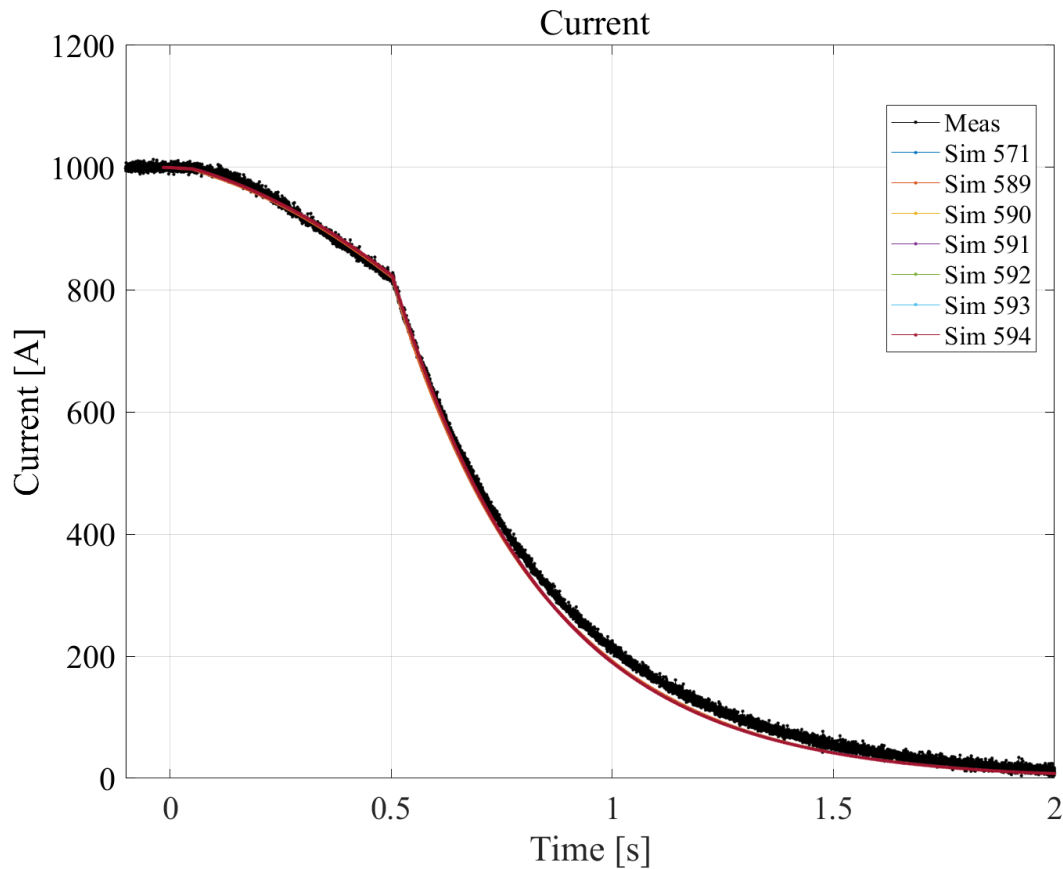


Sim	F_ro_eff
580	1
596	2
581	3
582	4
586	5
587	6
588	7



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

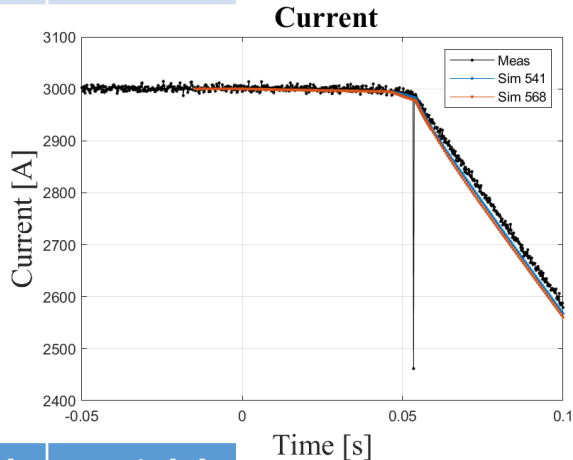
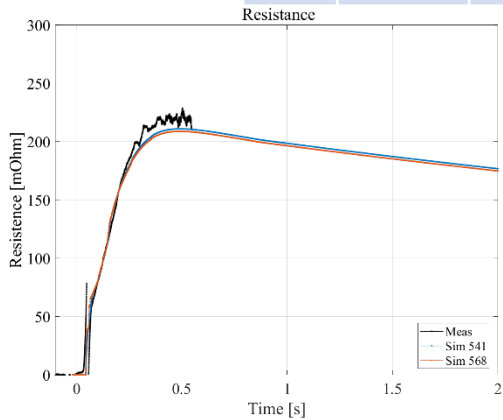


Quench Heaters + Energy Extraction

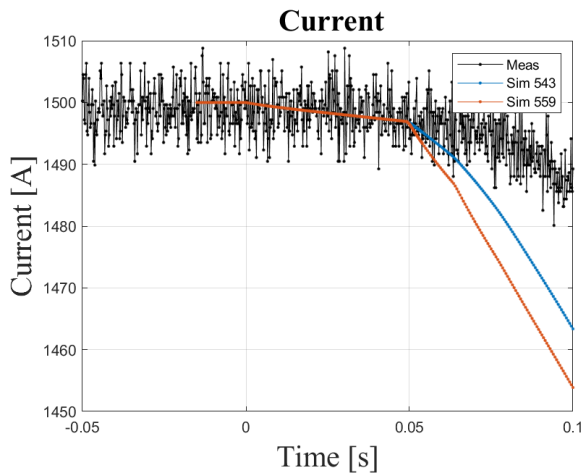
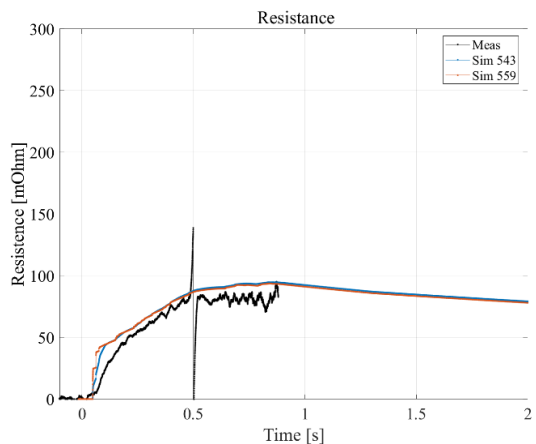
2D → 2D+1D

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

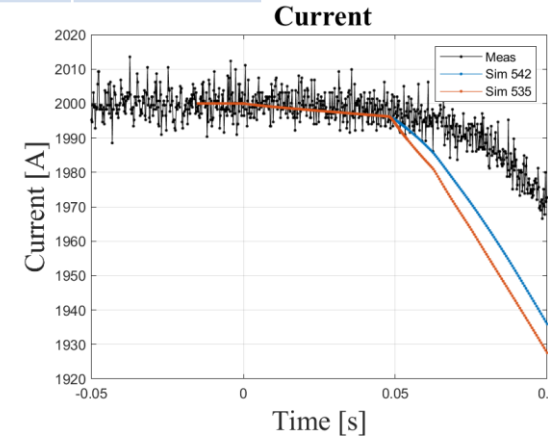
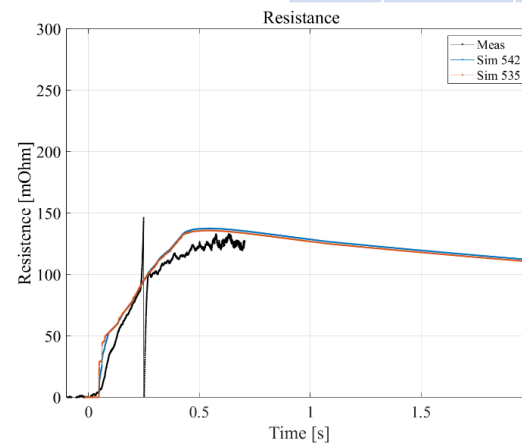
Test	Sim	I [A]	I_Length [m]
1	541/568	3000	0.97/3.4



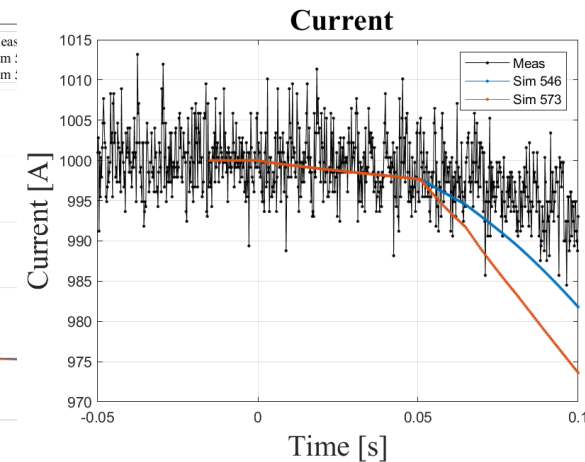
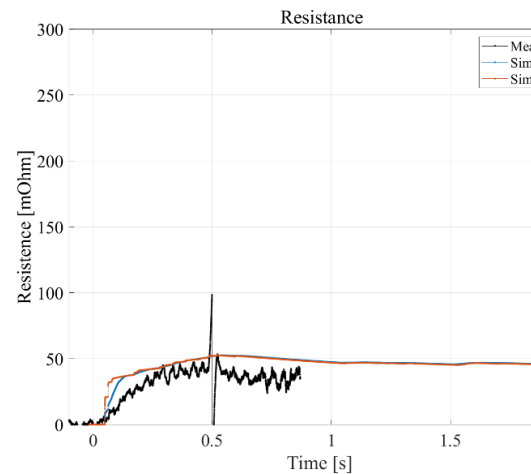
Test	Sim	I [A]	I_Length [m]
3	543/559	1500	0.97/3.4



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

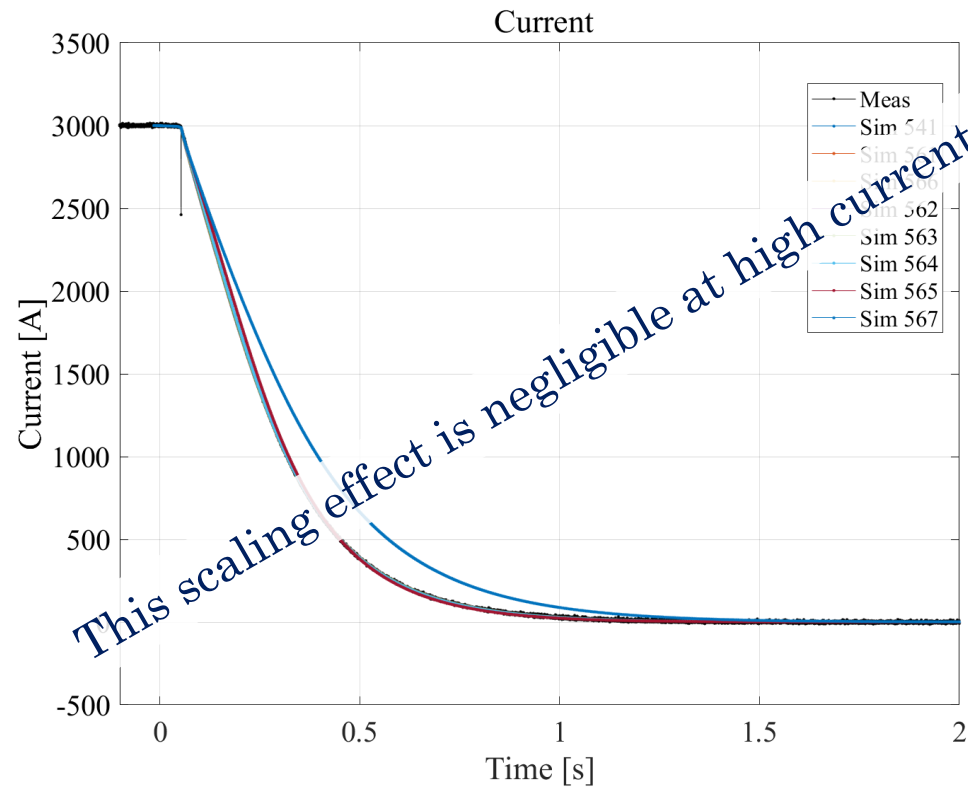


Test	Sim	I [A]	I_Length [m]
4	546/573	1000	0.97/3.4



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



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