West Pomeranian University of Technology, Szczecin

Modeling and analysis of quench in the 15-kA HTS conductor

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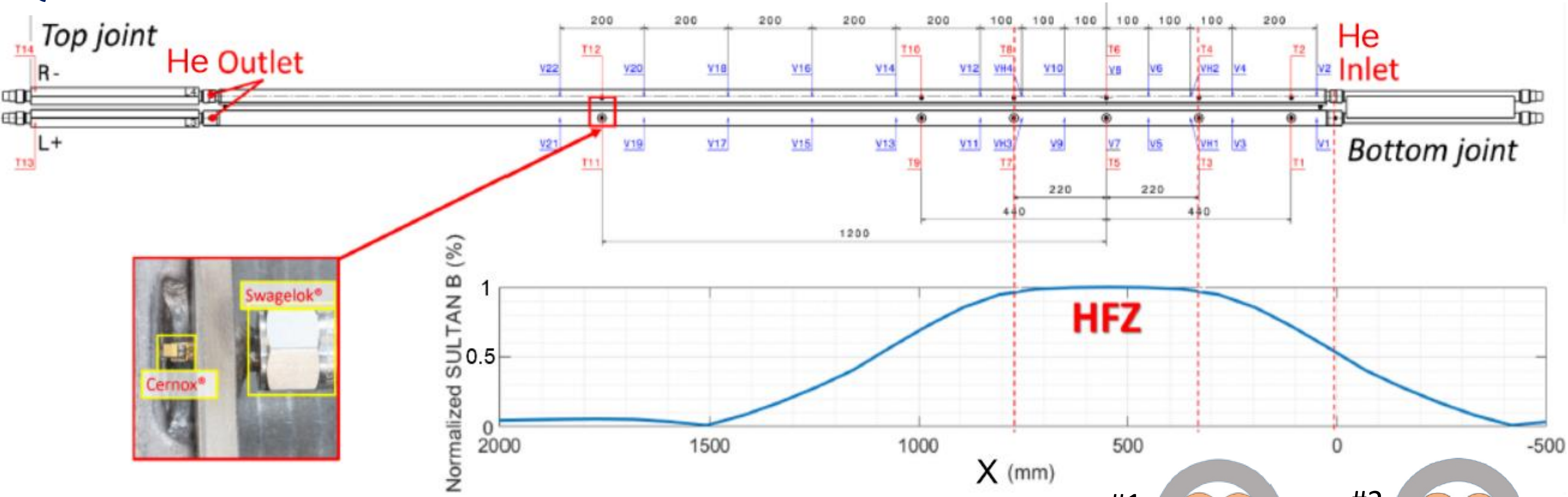
Outline

- Motivation
- Quench experiment
- Reference THEA model and its results vs. experiment
- Extended THEA model and its results vs. Experiment
- Summary and conclusions

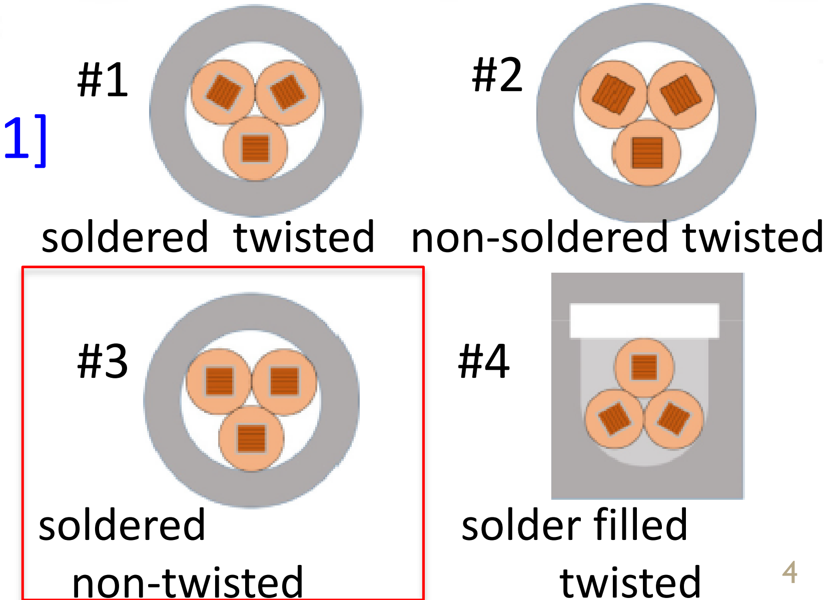
Motivation

- High Temperature Superconductors (HTS) are very promising materials to be applied in future fusion magnets.
- HTS conductors are already considered as a possible option for some components of the EU DEMO magnet system.
- Various HTS cable concepts, e.g. twisted stack cable, cross-conductor (CroCo), Roebel assembled coated conductor (RACC), conductor on round core (CORC®), have been proposed.
- Geometric and thermo-physical characteristics of HTS and LTS conductors differ significantly.
- Numerical simulations of HTS conductors operation may require specific approaches, particularly for fast transient processes (e.g. quench).
- To provide data for for testing different numerical models and tuning their parameters, a series of dedicated HTS 15-kA subsize samples with different geometries were produced and tested at the SULTAN test facility, in the scope of international collaboration between EUROfusion and China

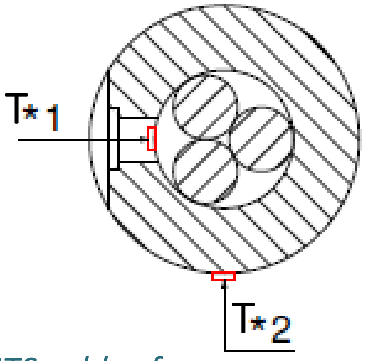
QUENCH EXPERIMENT



Scheme of the samples instrumentation and the samples layout [1]

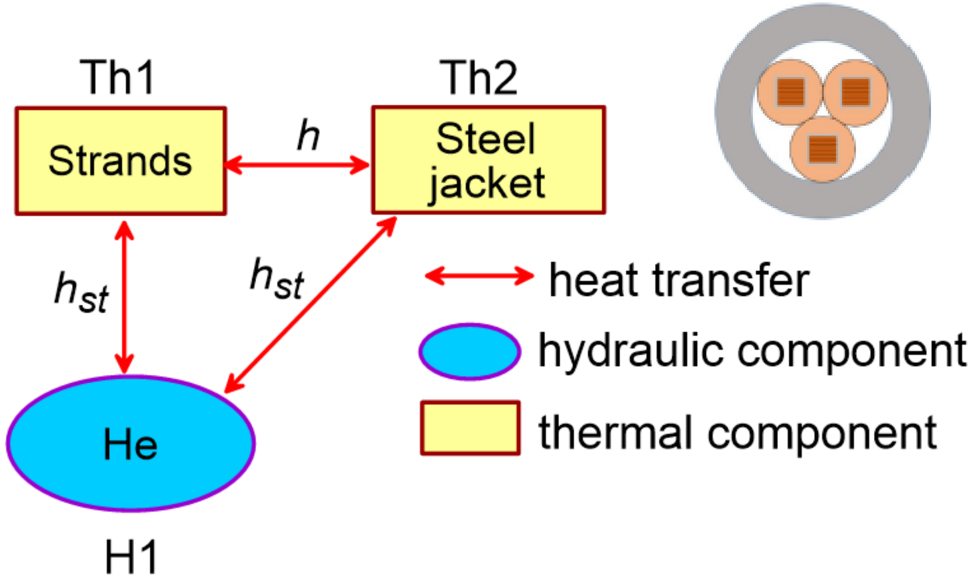


Sample #3 with the REBCO tapes wide face perpendicular to the magnetic field and run **SPC2 190808** (slow heating) were selected as a reference for our analysis



[1] O. Dicuonzo, Electromechanical investigations and quench experiments on sub-size HTS cables for high field EU-DEMO Central Solenoid, PhD Thesis, EPFL-SPC 2022

THEA reference model of the conductor



Thermal resitance (mK/W):

$$R_{th} = 1/(hp)$$

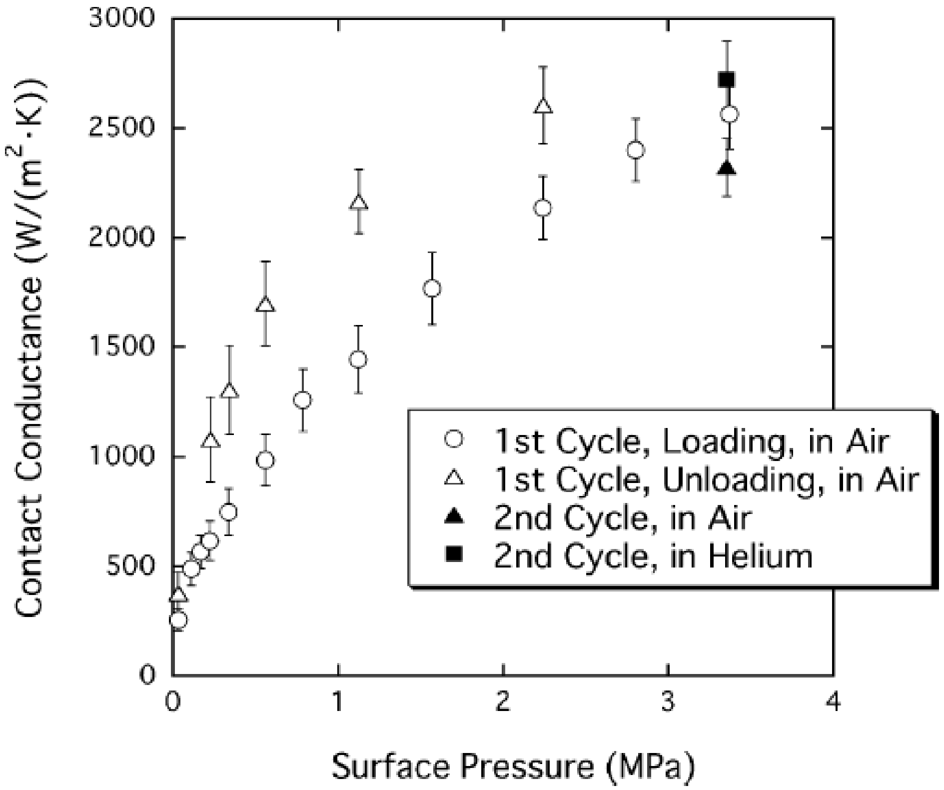
p – contact perimeter strands-jacket assumed to be **1.5 mm**

Standard smooth tube heat transfer and friction factor correlations were used for the hydraulic component.

Uncertain model parameters: *h*, *p* and copper RRR

RRR ~ 40 – 60 [1]

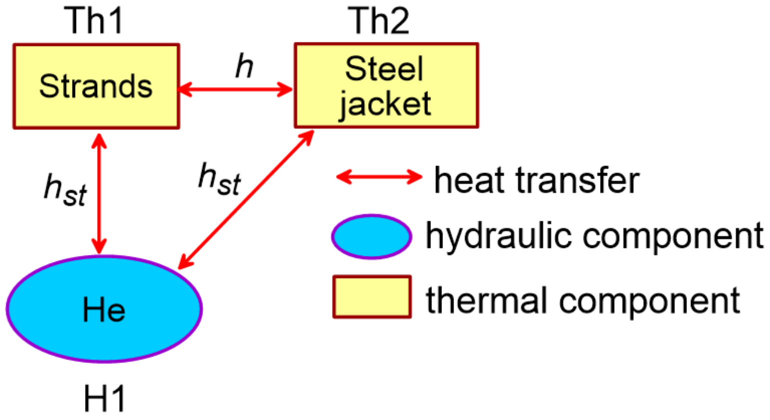
h W/(m²K)	R_{th} (mK/W)	RRR (-) 40	55	60	80	100
500	1,330	X	X	X	X	X
1200	0,550	X		X		
2000	0,333			X		
4000	0,167	X		X		
6000	0,111	X		X	X	X
8000	0,083			X		



[2] K. Takahata, et al., Thermal Contact Conductance Between the Bundle and the Conduit in Cable-in-Conduit Conductors IEEE Trans. Appl. Supercond. 14 (2004) 1477-80

THEA reference model of the conductor

h W/(m²K)	R_{th} (mK/W)	RRR (-) 40	55	60	80	100
500	1,330	X	X	X	X	X
1200	0,550	X		X		
2000	0,333			X		
4000	0,167	X		X		
6000	0,111	X		X	X	X
8000	0,083			X		



Thermal resitance (mK/W):

$$R_{th} = 1/(hp)$$

p – contact perimeter strands-jacket assumed to be 1.5 mm

Standard smooth tube heat transfer and friction factor correlations were used for the hydraulic component.

Boundary conditions

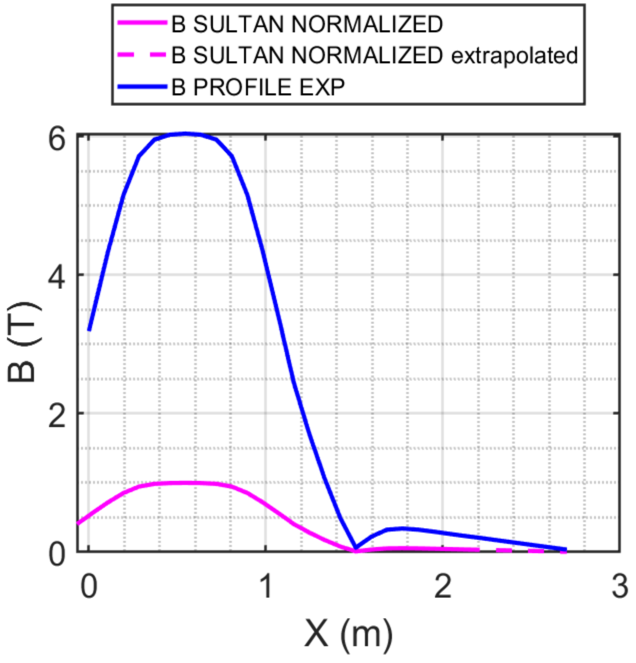
T_{in} = f(Time) (from experiment)

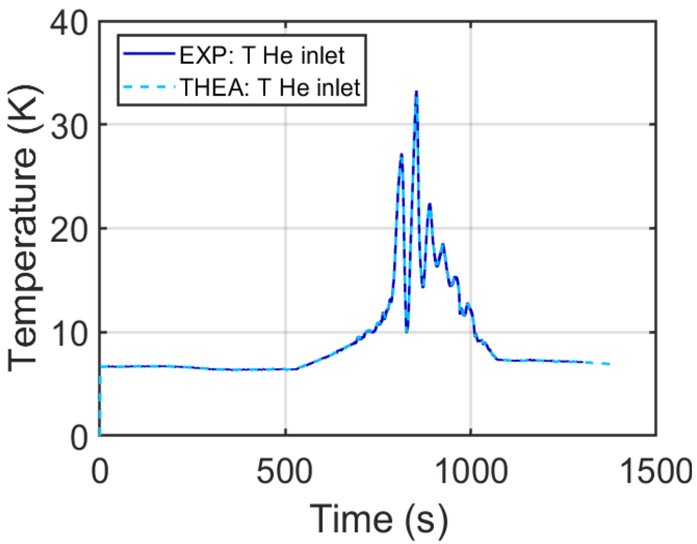
Δp = 30 Pa

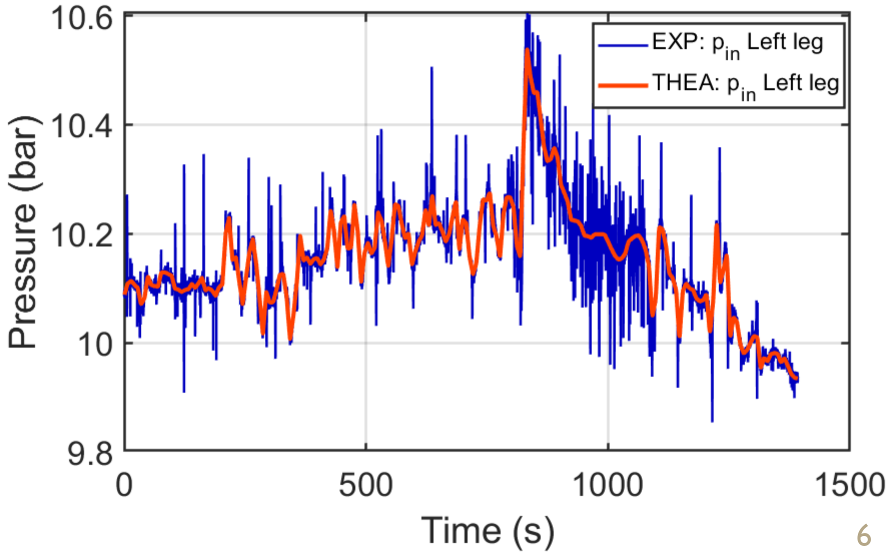
p_{in} = 10.2 bar = const

or

p_{in} = f(Time) (from experiment)





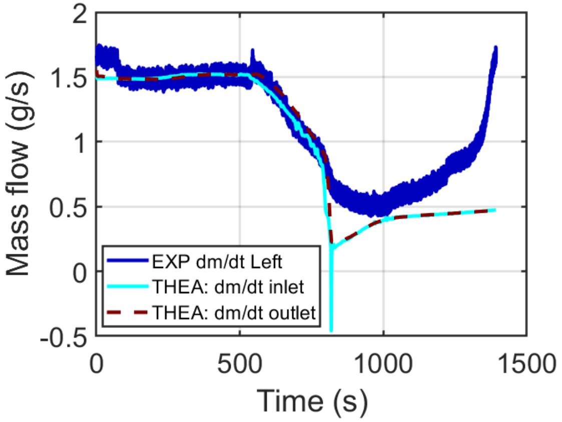


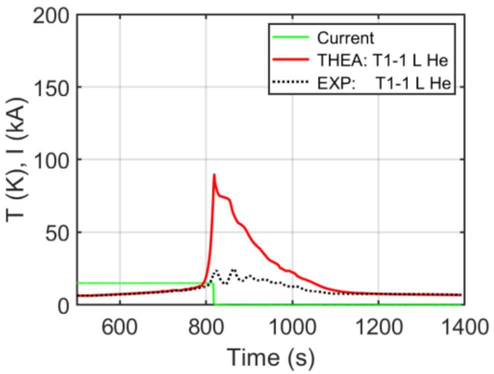
THEA reference model results vs. experiment

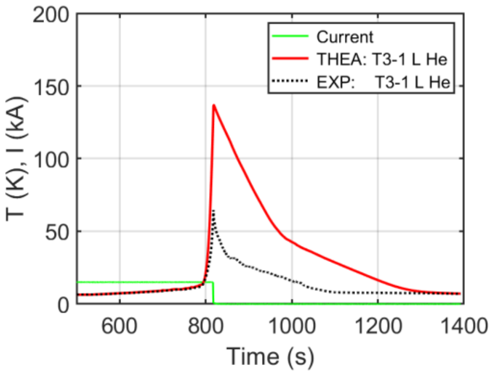
h W/(m²K):	R_{th} (mK/W):	RRR (-): 40	55	60	80	100
500	1,330	X	X	X	X	X
1200	0,550	X		X		
2000	0,333			X		
4000	0,167	X		X		
6000	0,111	X		X	X	X
8000	0,083			X		

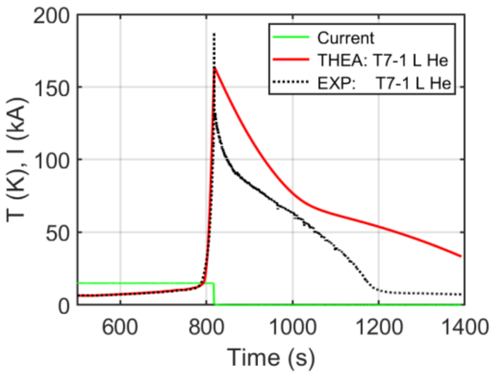
RRR 40 all Cu in the cable, h = 500 W/(m²K)

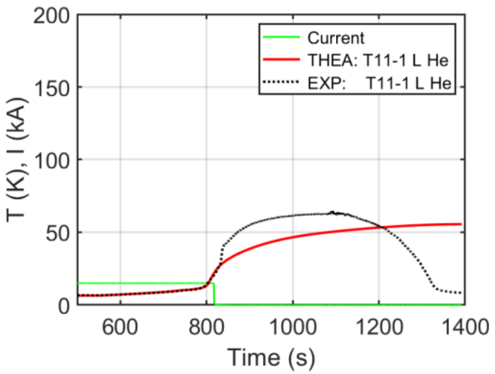
boundary conditions: p_{in} = const

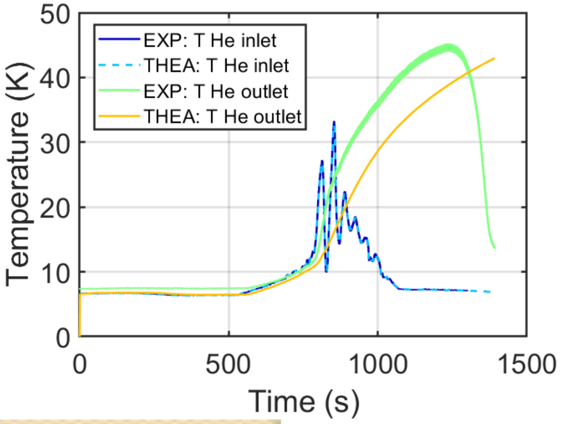


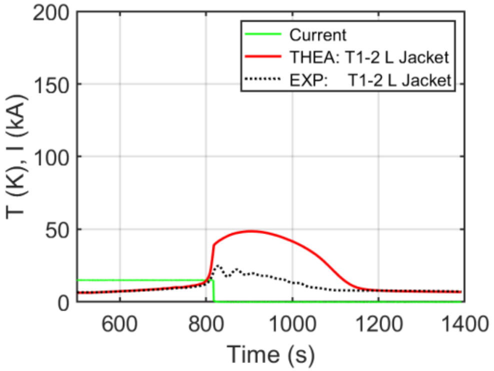


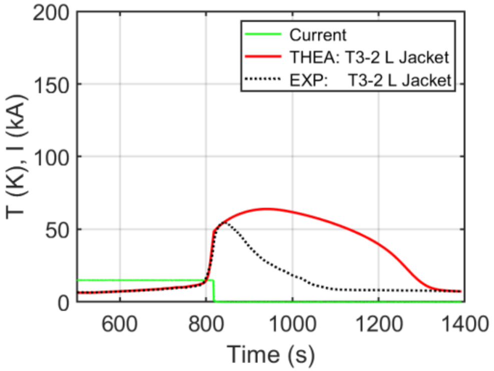


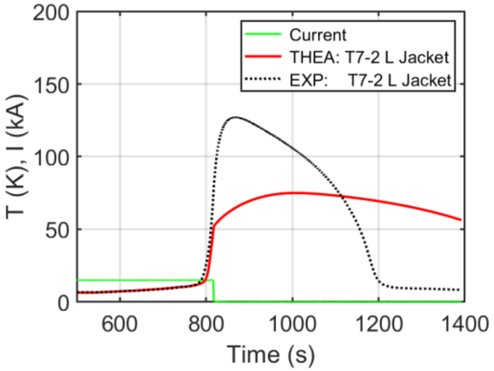


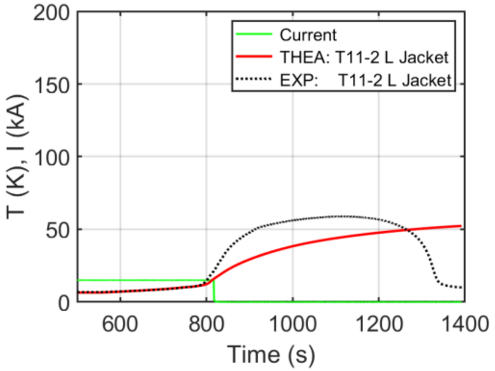










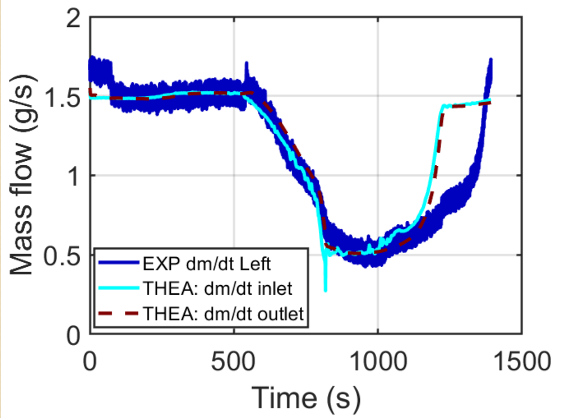


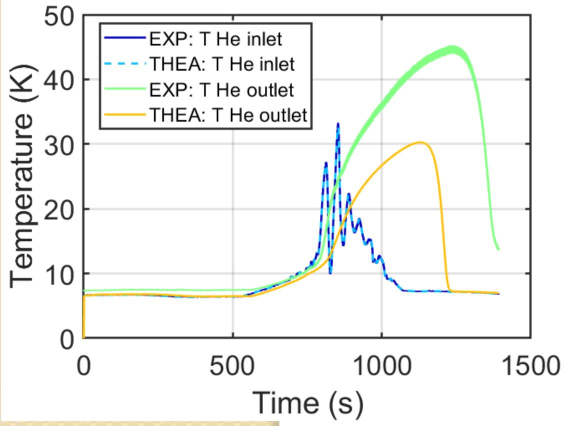
THEA reference model results vs. experiment

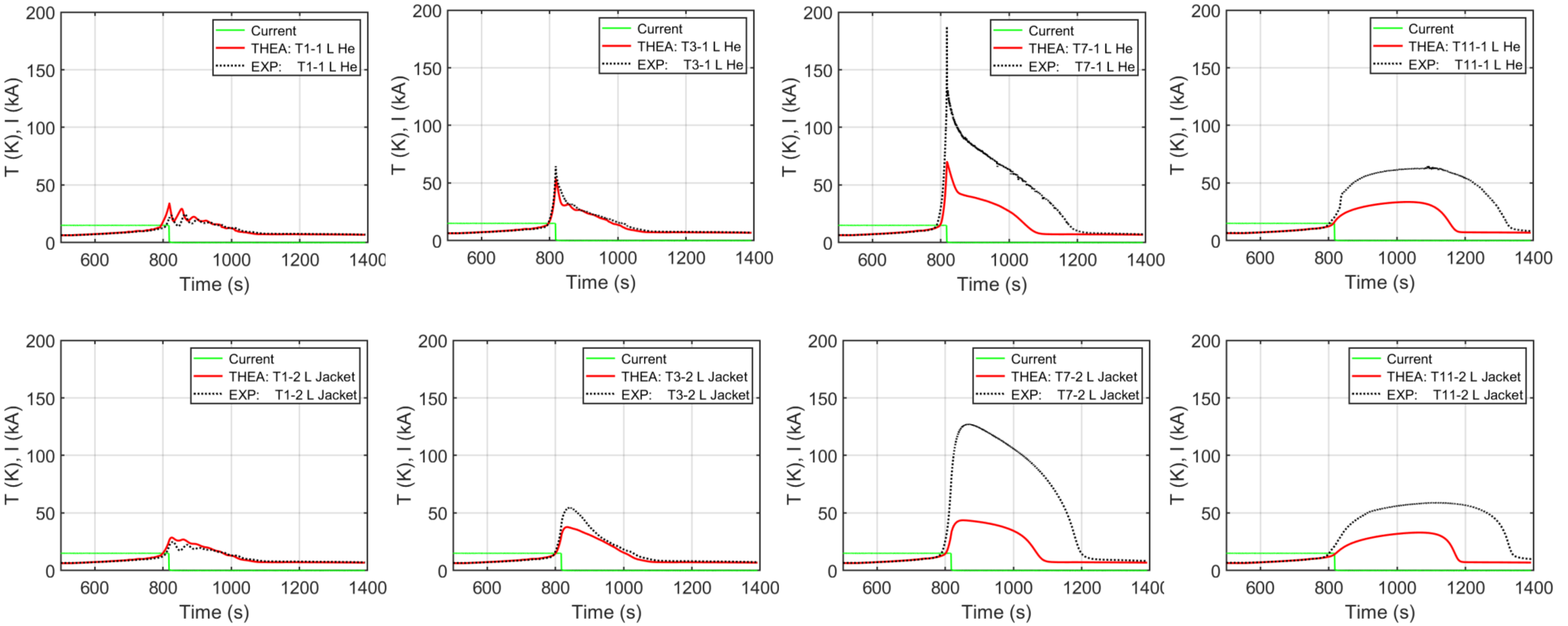
h W/(m²K):	R_{th} (mK/W):	RRR (-): 40	55	60	80	100
500	1,330	X	X	X	X	X
1200	0,550	X		X		
2000	0,333			X		
4000	0,167	X		X		
6000	0,111	X		X	X	X
8000	0,083			X		

RRR 40 all Cu in the cable, h = 6000 W/(m²K)

boundary conditions: p_{in} = const







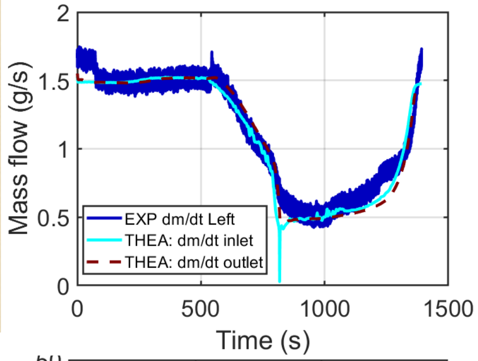
THEA reference model results vs. experiment

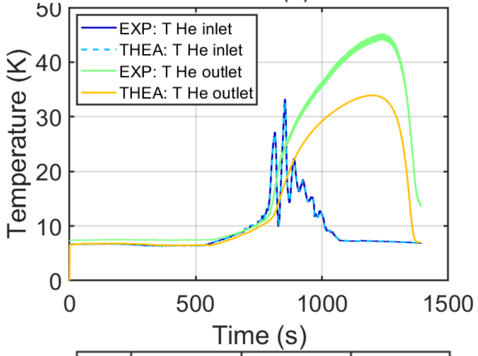
h W/(m²K):	R_{th} (mK/W):	RRR (-): 40	55	60	80	100
500	1,330	X	X	X	X	X
1200	0,550	X		X		
2000	0,333			X		
4000	0,167	X		X		
6000	0,111	X		X	X	X
8000	0,083			X		

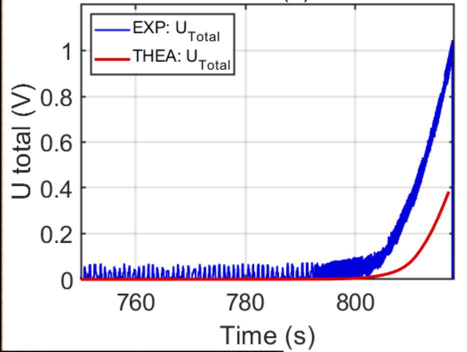
RRR 40 all Cu in the cable, h = 4000 W/(m²K)

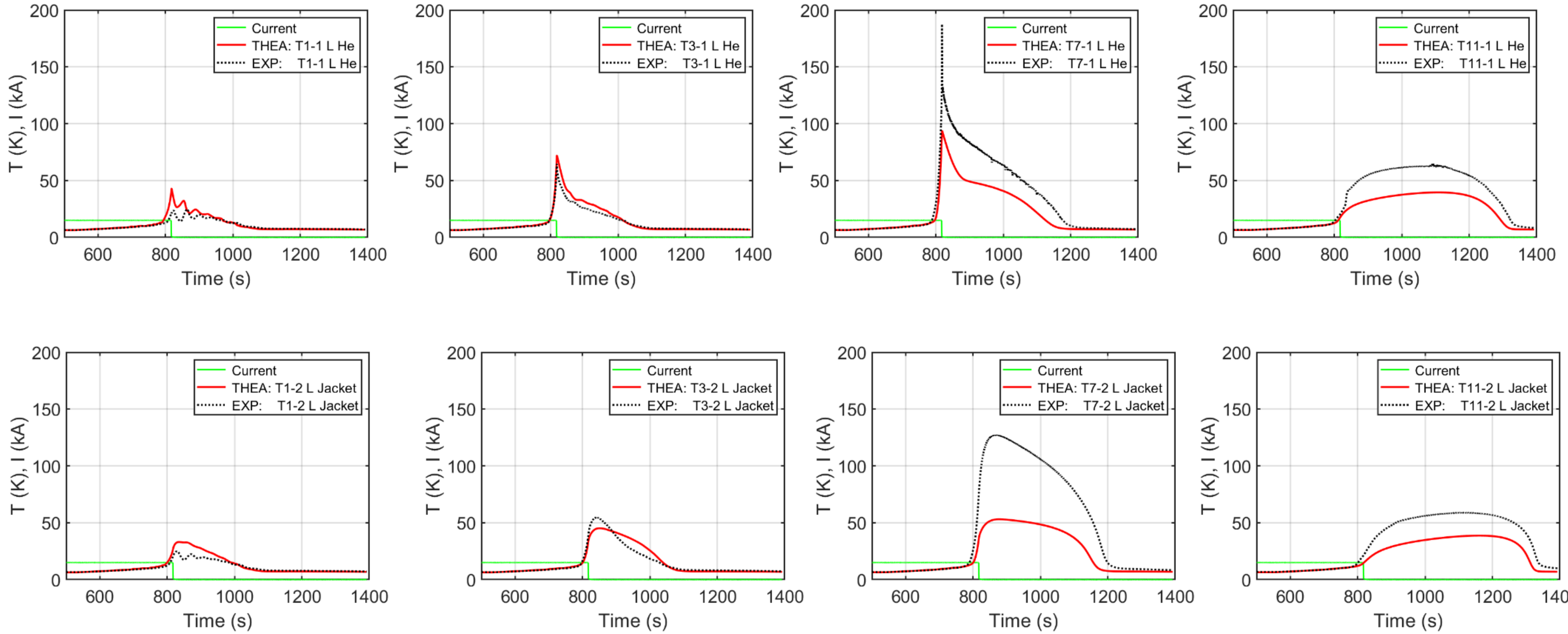
boundary conditions: p_{in} = const

Almost identical results were obtained for different pairs (RRR, h), e.g. (80, 500 W/(m²K))









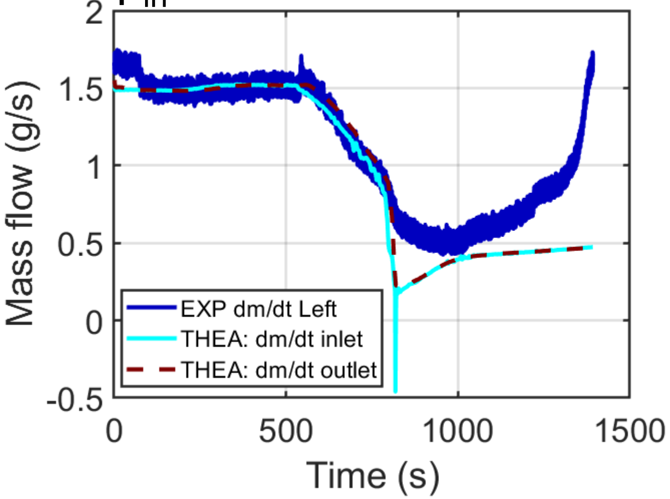
Effect of the pressure boundary condition

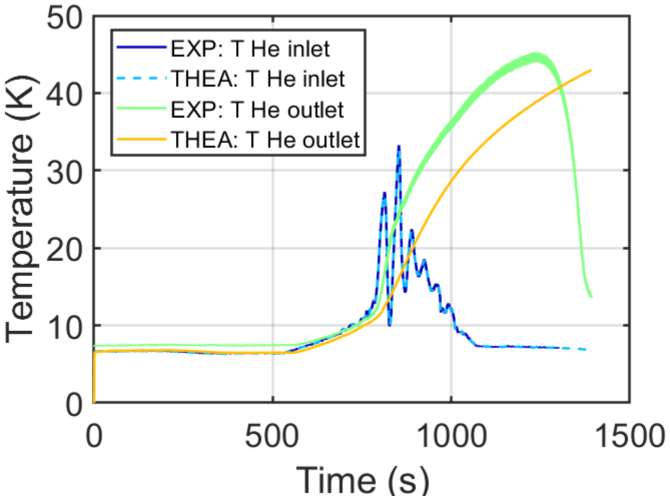
		RRR (-):				
h W/(m²K):	R_{th} (mK/W):	40	55	60	80	100
500	1,330	X	X	X	X	X
1200	0,550	X		X		
2000	0,333			X		
4000	0,167			X		
6000	0,111	X		X	X	X
8000	0,083			X		

RRR 40 all Cu in the cable, h = 500 W/(m²K)

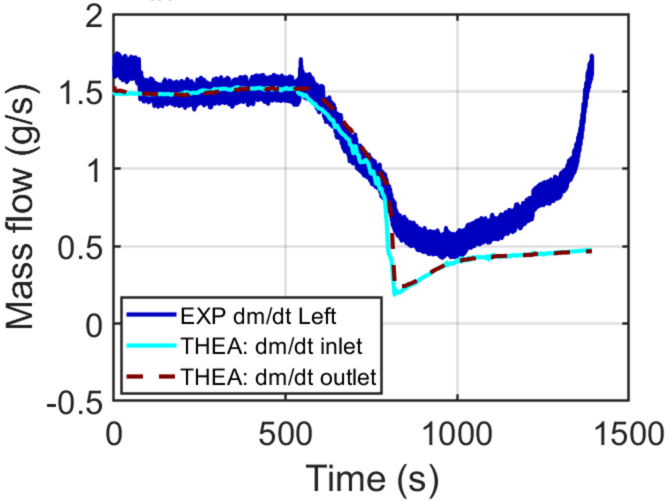
boundary conditions:

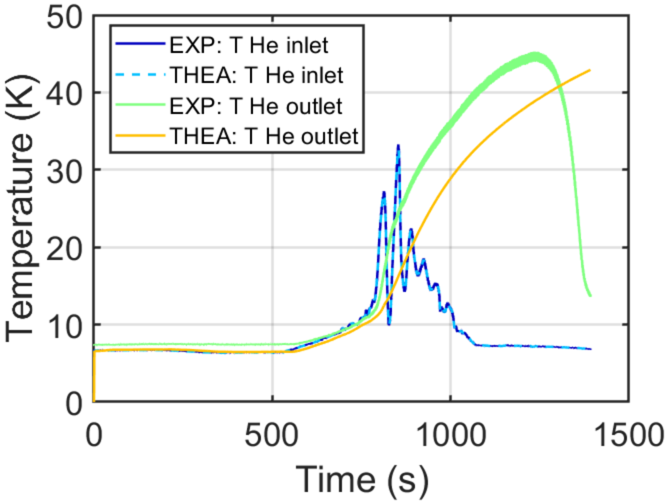
p_{in} = const



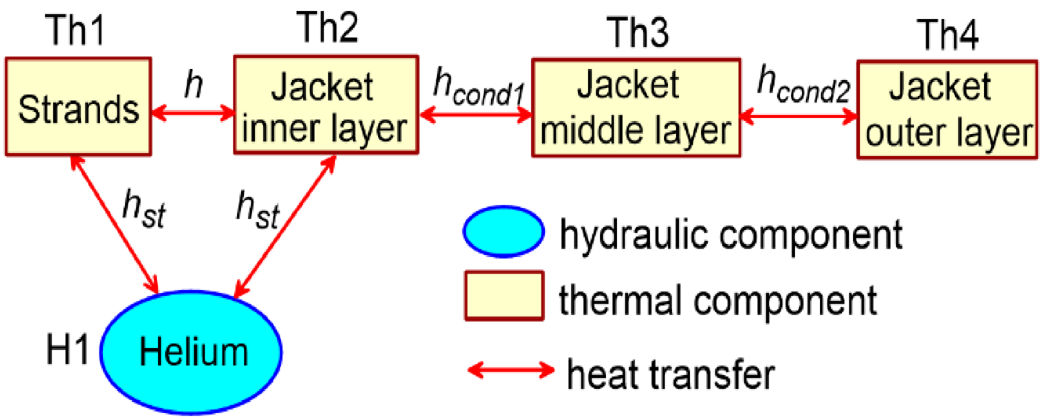


p_{in} = f(Time) (from experiment)





Extended THEA model: radial heat conduction in the jacket added [3]



- thermal resistance due to radial heat conduction in the jacket

$$R_{th1} = \frac{\ln\left(\frac{d_2}{d_1}\right)}{2\pi k_{st}(T_{av1})}$$

$$R_{th2} = \frac{\ln\left(\frac{d_3}{d_2}\right)}{2\pi k_{st}(T_{av2})}$$

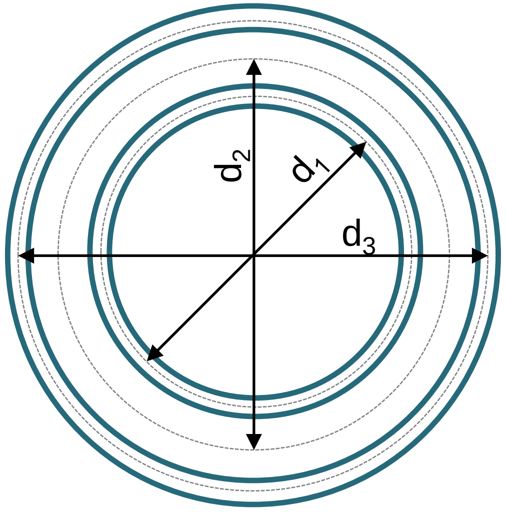


Table 13: Thermal Conductivity of 316 LN, from ITER DRG1.

(K)	(W/K/m)
4	0.21
6	0.4
10	0.78
12	0.98
14	1.2
16	1.43
20	1.9
25	2.55
30	3.18
40	4.51
50	5.6
80	8.2
100	9.4
120	10.46
150	11.71
200	13.06
273	14.7
300	14.67
366.3	14.5
588.6	17.8
921.9	22.3
1144	25.2

[3] M. Lewandowska, et al., Steady-state transverse heat transfer in a single channel CICC, Cryogenics 110 (2020) 103124

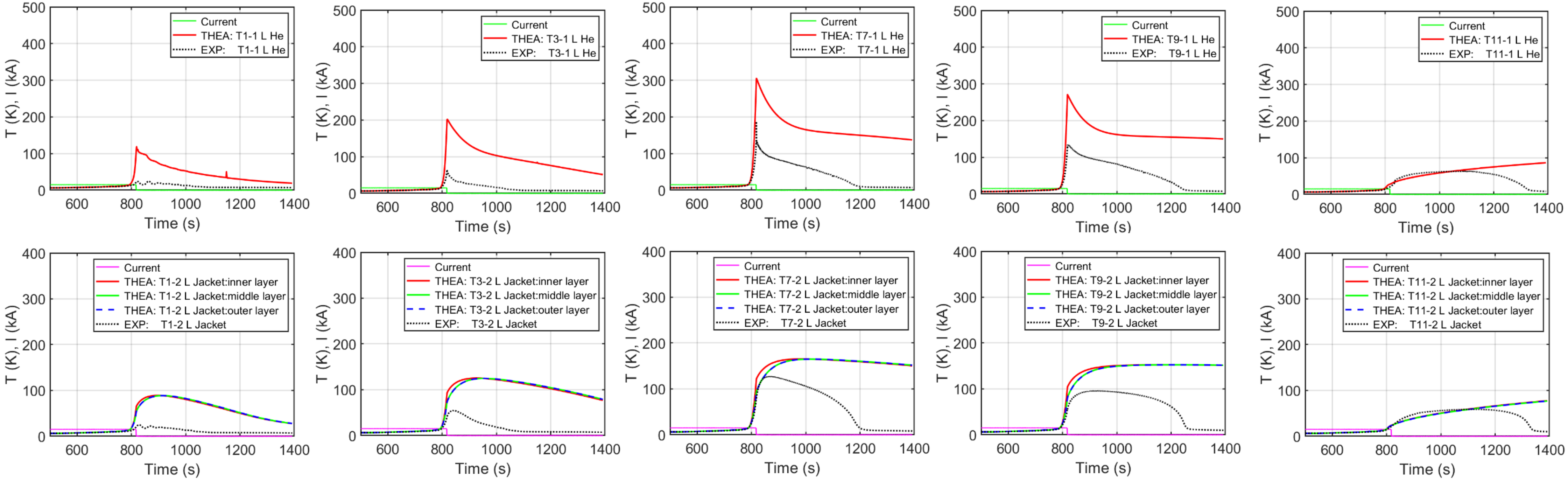
THEA extended model results vs. experiment

h W/(m²K):	R_{th} (mK/W):	RRR (-): 40	55	60	80	100
500	1,330	X	X	X	X	X
1200	0,550	X		X		
2000	0,333			X		
4000	0,167	X		X		
6000	0,111	X		X	X	X
8000	0,083			X		

RRR 40 all Cu in the cable, h = 4000 W/(m²K)

boundary conditions:

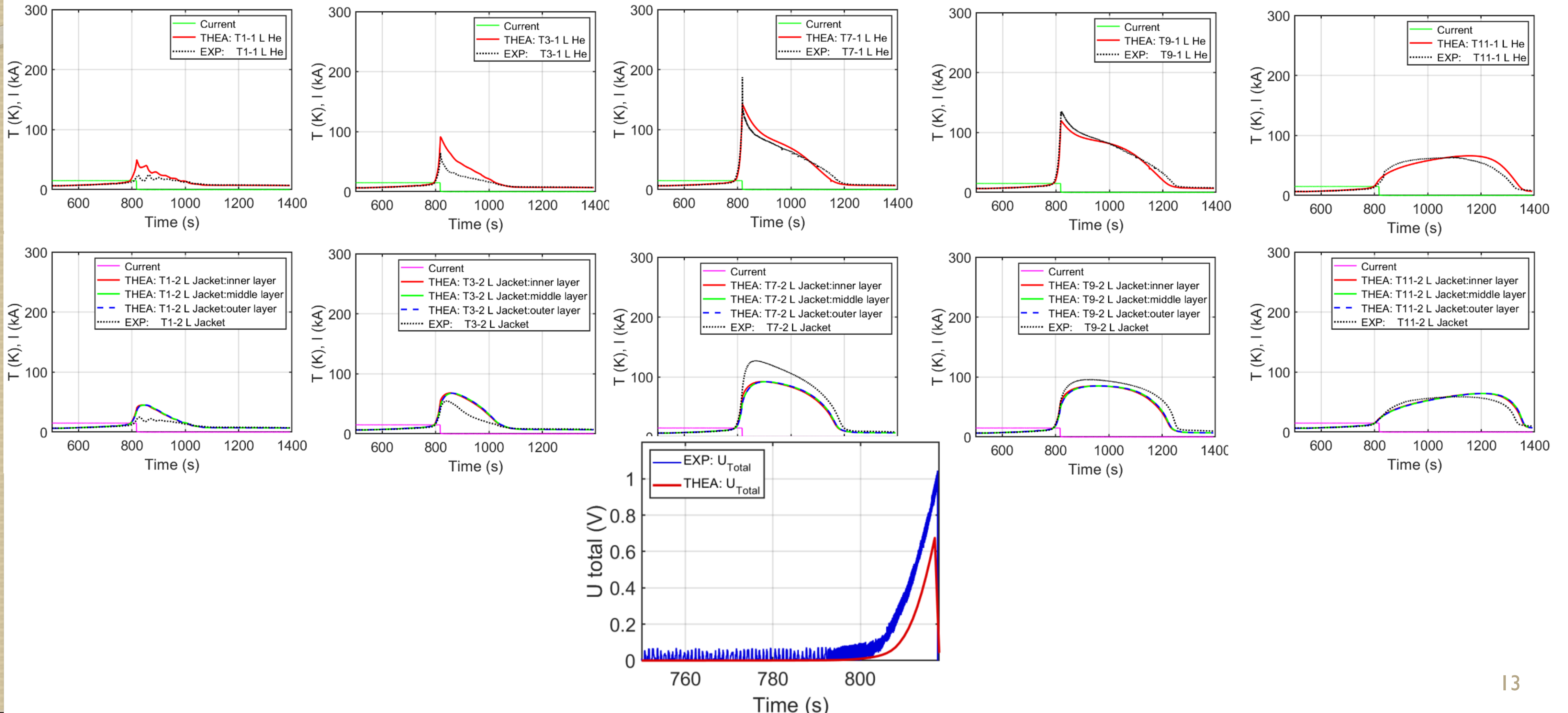
p_{in} = f(Time) (from experiment)



THEA extended model results vs. experiment

RRR = 80 - Cu in profiles, RRR = 53 - Cu in tapes
h = 4000 W/(m^{2}K)
boundary condition:
p_{in} = f(t) (from experiment)

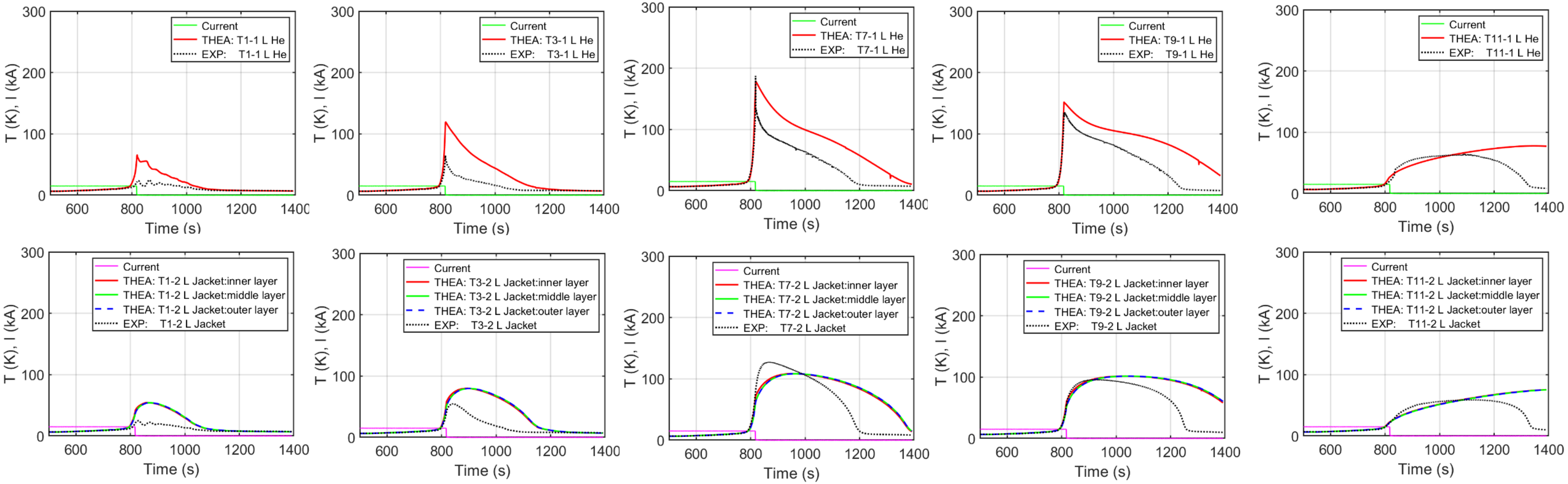
h W/(m^{2}K):	R_{th} (mK/W):	RRR (-): 40	55	60	80	100
500	1,330	X	X	X	X	X
1200	0,550	X				
2000	0,333			X		
4000	0,167	X →		X →	X	
6000	0,111	X		X	X	X
8000	0,083			X		

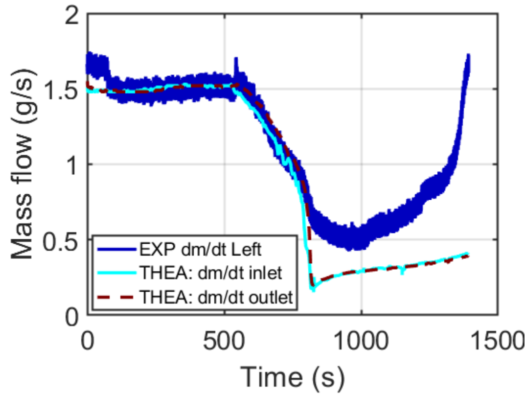


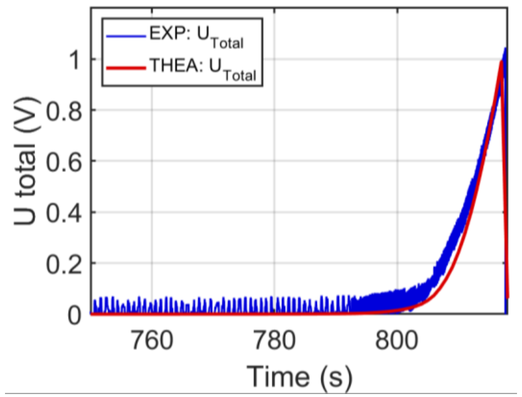
THEA extended model results vs. experiment

RRR = 60 - Cu in profiles, RRR = 53 - Cu in tapes
h = 2000 W/(m²K)
boundary condition:
p_{in} = f(t) (from experiment)

		RRR (-):				
h W/(m²K):	R_{th} (mK/W):	40	55	60	80	100
500	1,330	X	X	X	X	X
1200	0,550	X		X		
2000	0,333			X	X	
4000	0,167	X		**X** ←	X	
6000	0,111	X		X	X	X
8000	0,083			X		



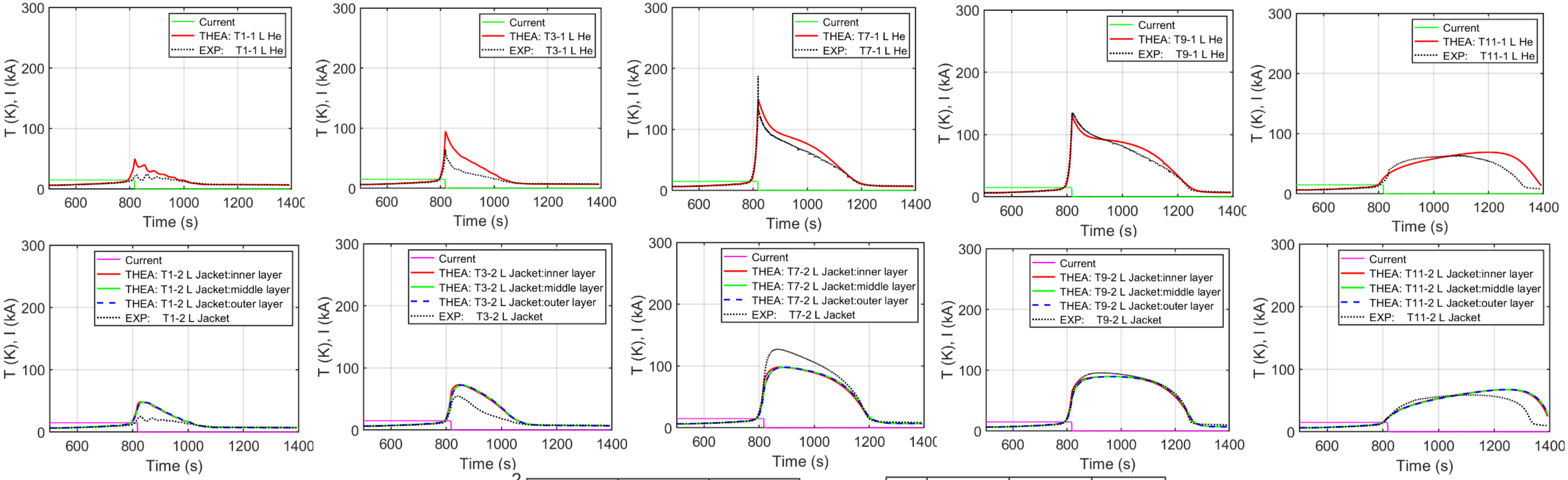


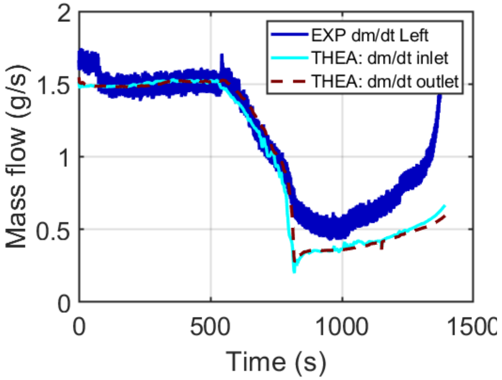


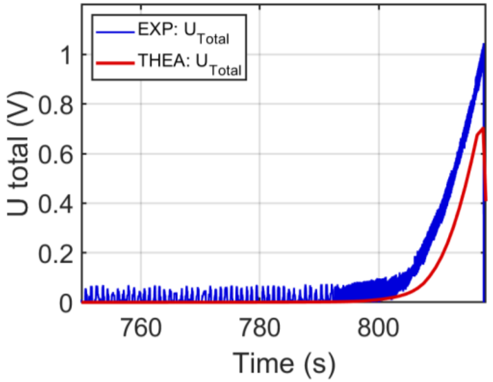
THEA extended model results vs. experiment

		RRR (-):				
h W/(m²K):	R_{th} (mK/W):	40	55	60	80	100
500	1,330	X	X	X	X	X
1200	0,550	X		X		
2000	0,333			X	X	
4000	0,167	X		X	X	
6000	0,111	X		X	X	X
7000	0,083			X		

RRR = 60 - Cu in profiles, RRR = 53 - Cu in tapes
h = 7000 W/(m²K)
boundary condition:
p_{in} = f(t) (from experiment)

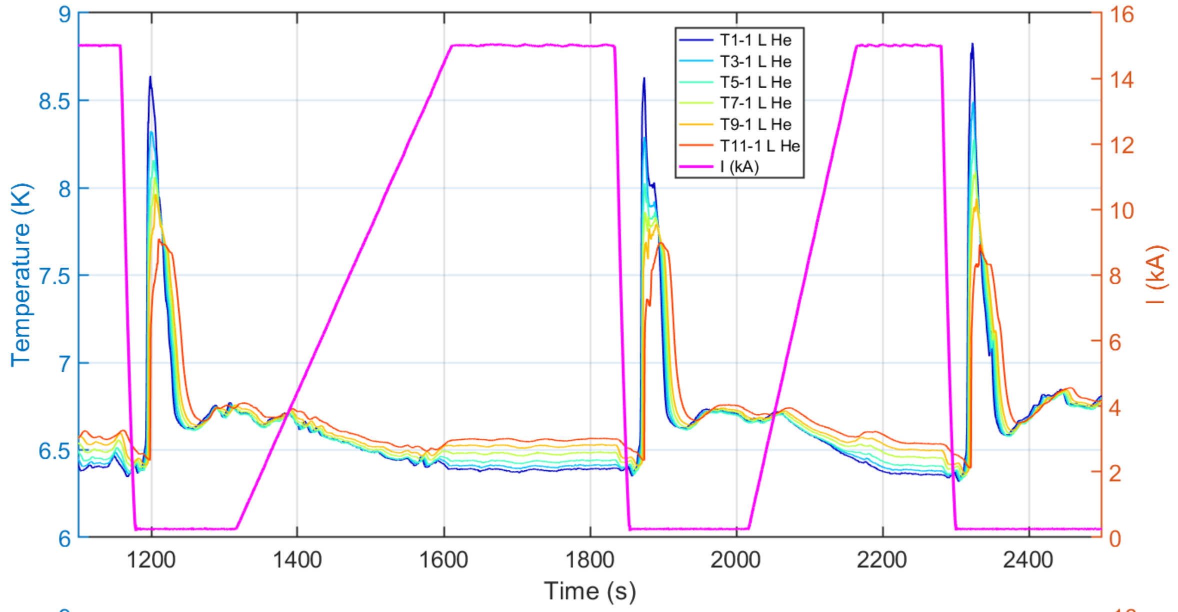


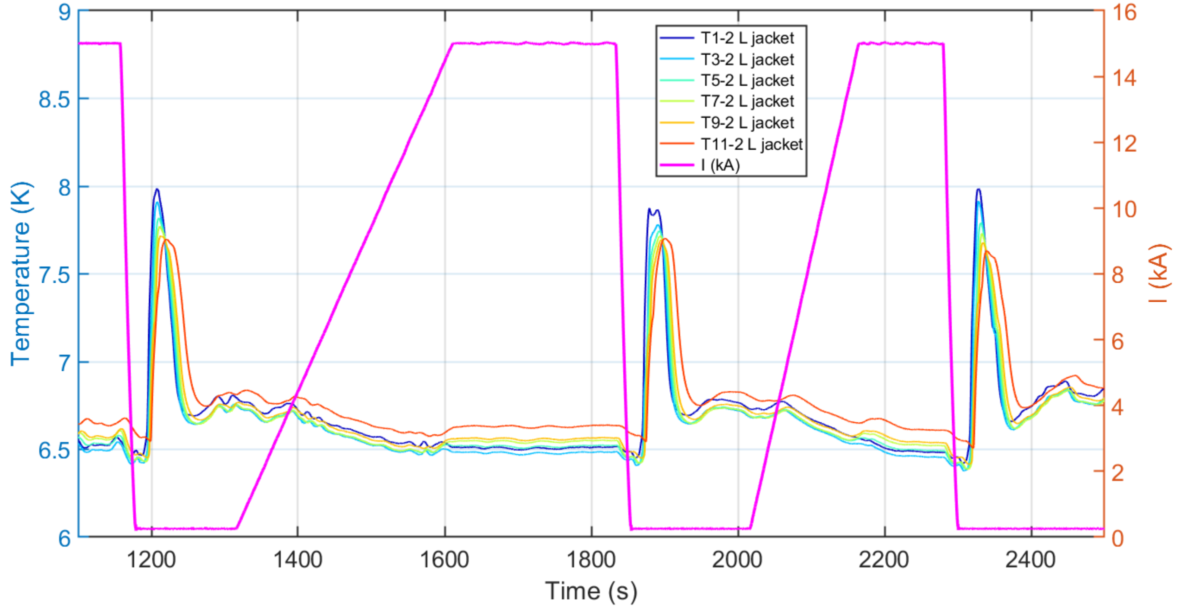




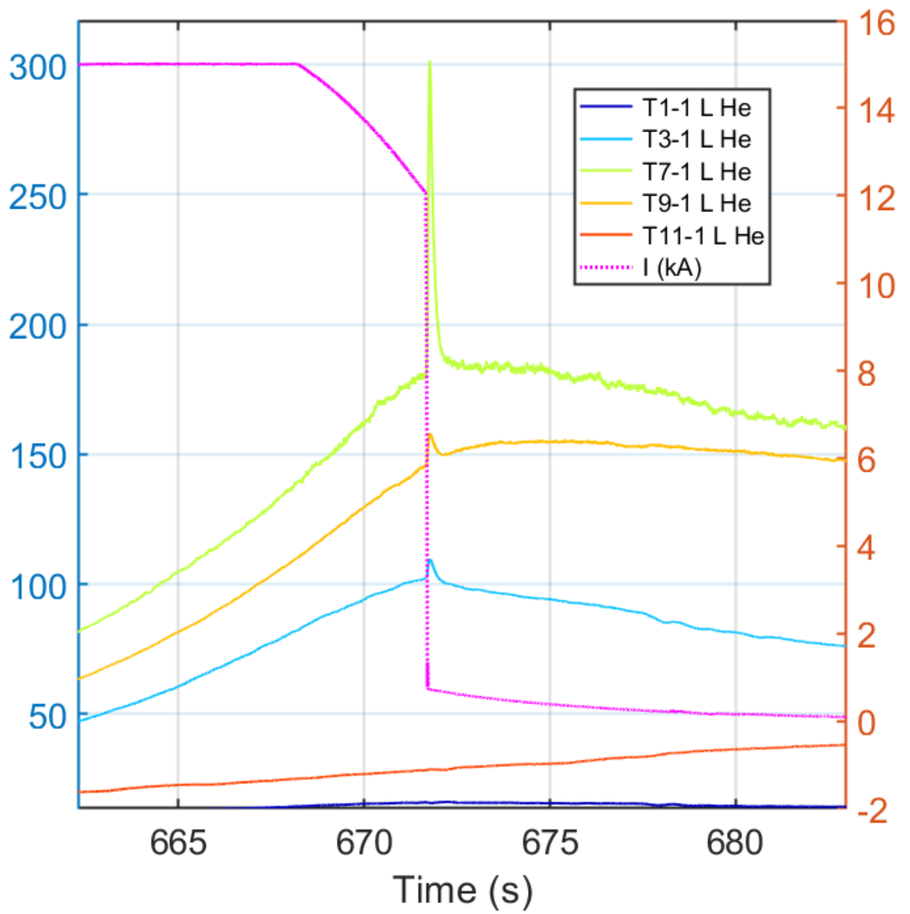
Temperature spike during the current dump

Run SPC2_180803





Run SPC2_180807



Run SPC2_180803: $t_{dump} \sim 20$ s

Run SPC2_180807: $t_{dump} \sim 0.1$ s

Possible explanation ???

Summary and conclusions (I)

- Quench experiment on several subsize 15-kA HTS conductors was performed by the EPFL-SPC team in 2021.
- The reference THEA model of the sample #3 (all strands treated as a single thermal component), was created and simulations of the selected run of the quench experiment were carried out for the wide range of values of the uncertain model parameters (copper RRR and thermal resistance R_{th}).
- For several pairs of values (RRR, R_{th}), e.g. (40, 0.167 m·K/W), (80, 1.33 m·K/W), etc., the experimental time evolution of the mass flow rate as well as the jacket and He temperatures at the locations 1 and 3 agreed well with the simulations results. However, the temperatures measured at other locations (5, 7, 9, 11 and outlet) obtained from simulations were much lower than the respective experimental values, only the qualitative shape of these time characteristics was captured correctly. Also voltage values resulting from our simulations were much too low as compared to the respective experimental voltage readings.
- The reference model confirmed to be insufficient for reliable simulations of quench in HTS samples, although such an approach was successfully applied for LTS conductors.

Summary and conclusions (II)

- A more advanced THEA model with jacket divided into 3 components was prepared and tested
- For some pairs of values (RRR, R_{th}), e.g. (80, 0.167 m·K/W), (60, 0.095 m·K/W), the experimental time evolution of the mass flow rate as well as the jacket and He temperature agreed reasonably well with the simulations results, except the temperature spike occuring during the current dump. The voltage values resulting from our simulations were improved (w.r.t. the reference model) but still a bit too low as compared to the respective experimental voltage readings.
- If the values of (RRR, R_{th}) were tuned to reproduce well the voltage evolution and the maximum hot spot temperature, other TH characteristics (mass flow rate and temperature evolution, particularly during the recooling phase) were far from the experiment.
- As a next step spliting strands into 2 thermals (copper profiles + HTS stacks) or introducing temperature dependent *h* could be considered.
- An additional effect (AC losses?) could be included in the model to explain the observed temperature spikes during the current dump?

Thank you very much for your attention

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This scientific work has been published as part of the international project called 'PMW', co-financed by the Polish Ministry of Science and Higher Education within the framework of the scientific financial resources for 2022-2023 (contract No. 5251/HEU-EURATOM/2022/2).