Chats 2023
Applied Superconductivity

Nuclear Engineering MOdeling Group

Politecnico di Torino
1859

Analysis and modelling of the quench experiment on HTS sub-sized cable-in-conduit conductors for fusion applications

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Outline

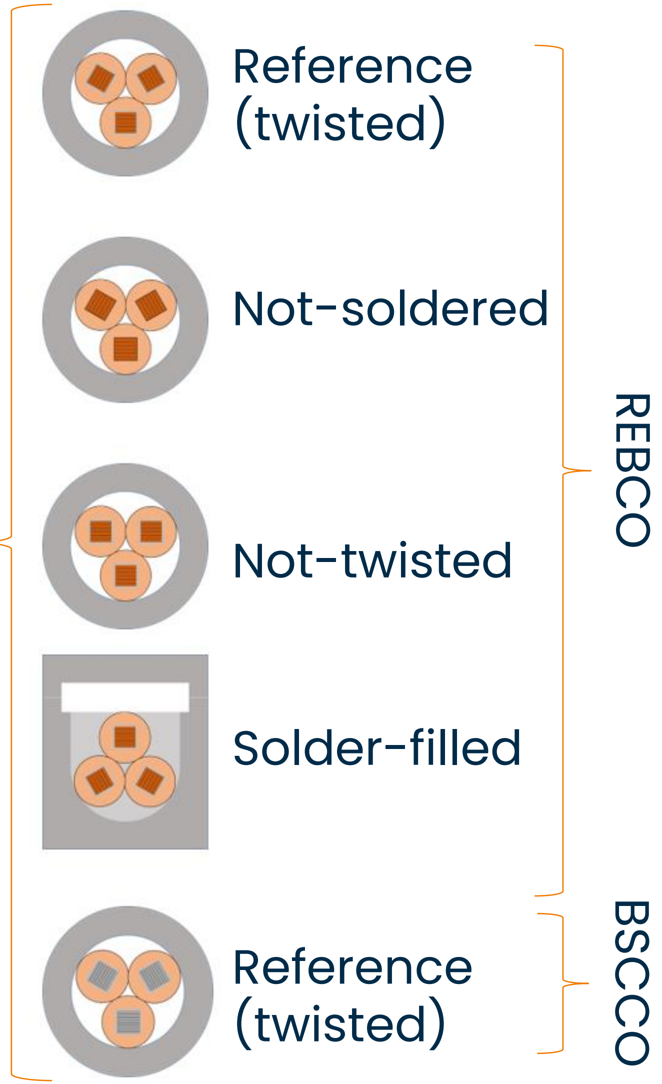
- Introduction & aim
- Experimental setup
- BSCCO conductor
  - Analysis of the experimental data
  - 1D model
- Solder-filled REBCO conductor
  - Analysis of the experimental data
  - 1D model
- Conclusions and perspective

Introduction & aim

- Quench propagation tests in HTS conductors (EU-CN collaboration within EUROfusion Consortium) started in 2020 in SULTAN
- SULTAN was recently upgraded [O. Dicuonzo et al., IEEE TAS, 2021]
- SPC conductors tested in 2020-2021
  ENEA and KIT will follow later this year
- Reference and not-twisted conductor already analyzed
  [A. Zappatore et al. submitted to Cryogenics]

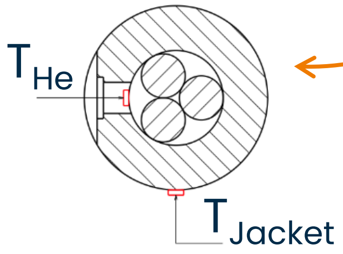
Aim of this work:

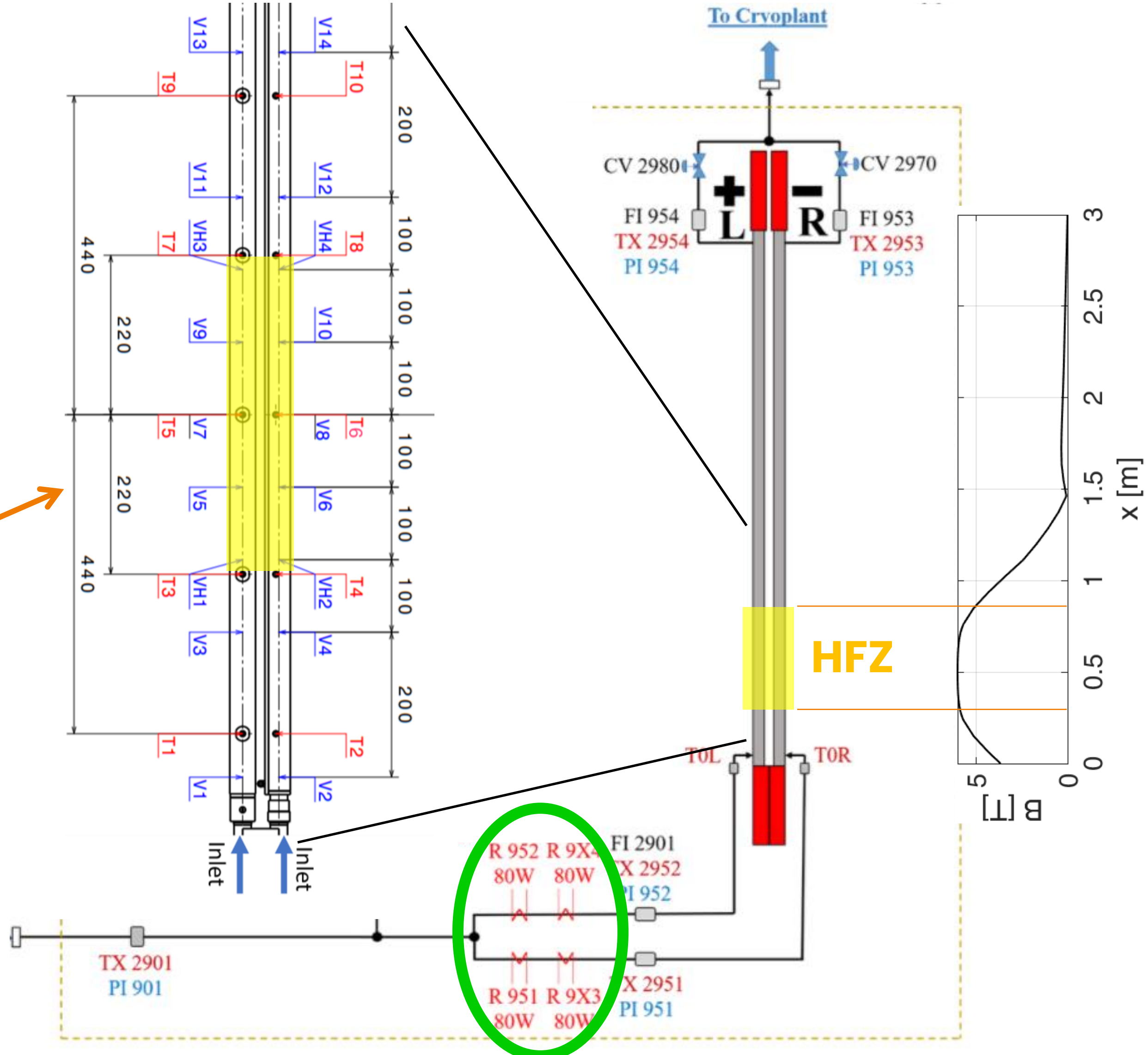
- Analyze the experimental results of BSCCO and solder-filled conductors
- Develop, implement in the H4C code [A. Zappatore et al., SuST, 2020] and validate the corresponding thermal-hydraulic and electric model



Experimental setup

- Quench tests:
  - direct PS keeps the current constant
  - quench induced **heating the He at the inlet**
  - current is dumped when a T threshold is reached
- Different mass flow rates and field/current combinations were tested
- Different heating strategies (continuous vs. heat pulse
- Voltage, He and jacket temperatures were measured along the conductors

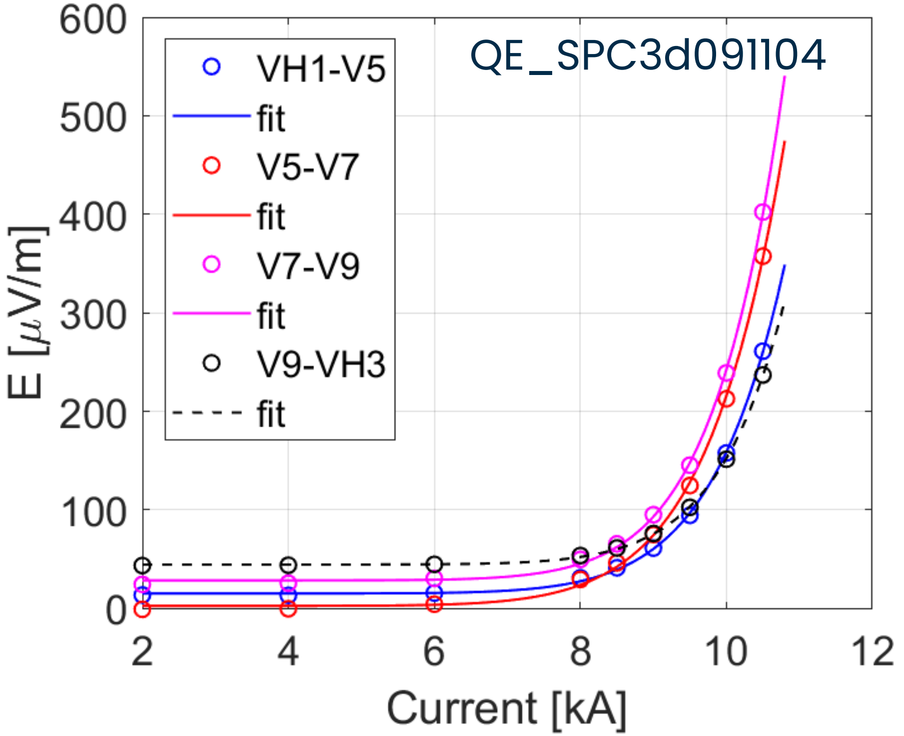




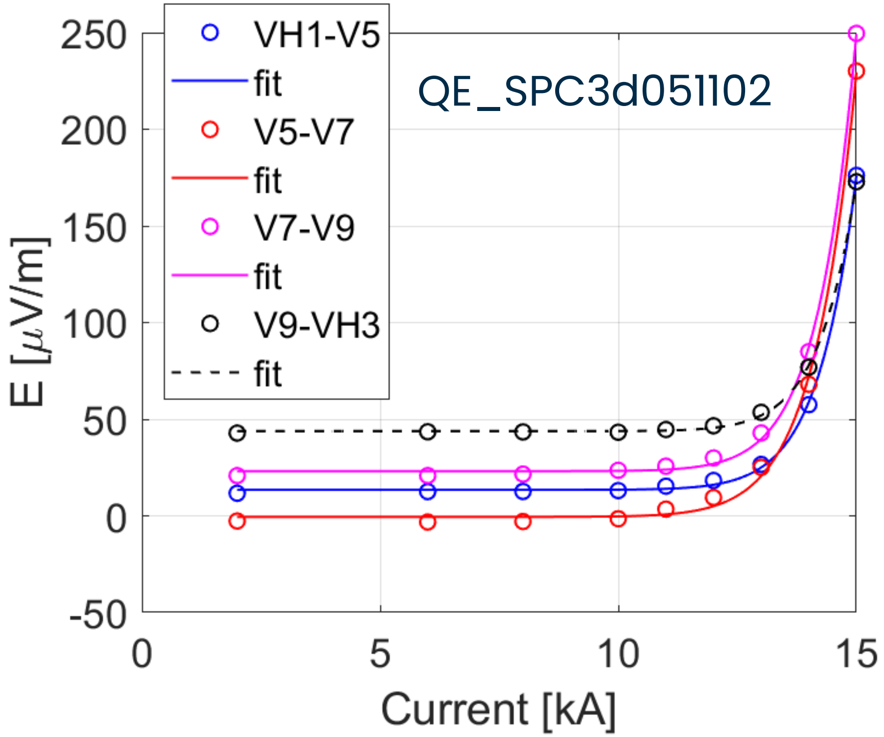
BSCCO conductor – DC performance

- I_C and n-value from fit $E = E_0 + E_C \left(\frac{I}{I_C(B,T)}\right)^n, E_C = 100\ \mu V/m$
- Lower n-value as magnetic field increases expected from tape measurements [T. Benkel, EPJAP, 2017]

- I_C(9 T, 20 K) = 9.6 kA
- n-value = 11.1

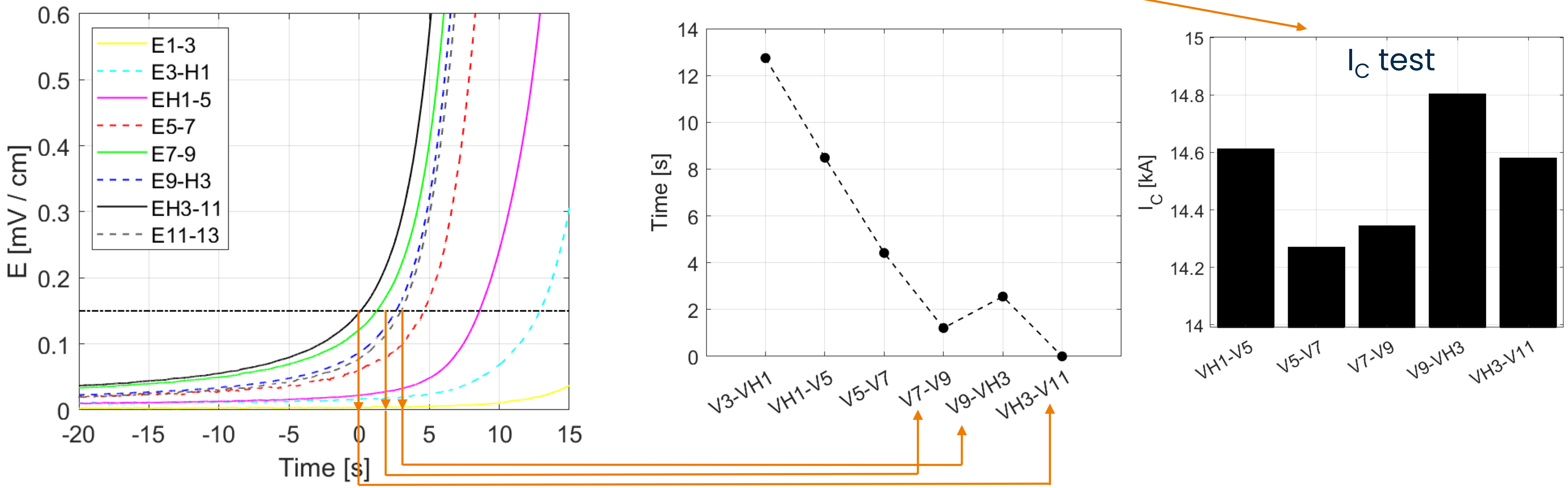


- I_C(4 T, 18 K) = 14.5 kA
- n-value = 18.2



BSCCO conductor – NZPV analysis (I)

In most quench shots, first signal crossing the threshold is VH3-V11, then V7-V9, then V9-VH3 → non-uniform quench propagation close to quench initiation region. Probably due to non-uniformity in $I_C(x)$ → analyzed with numerical model



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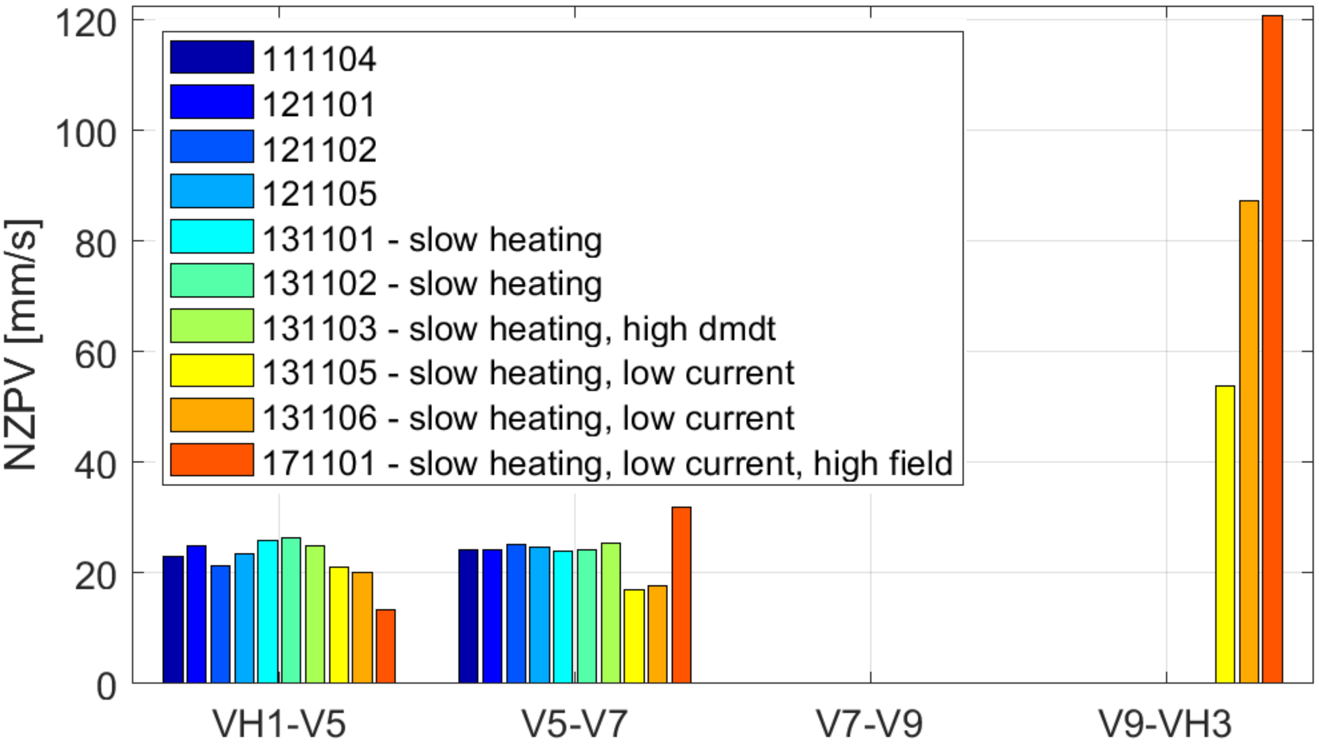
BSCCO conductor – Normal Zone Propagation Velocity (NZPV) analysis (II)



- NZPV (high J_{Cu}) ~ 20–24 mm/s
- NZPV (low J_{Cu}) ~ 17–20 mm/s
- Slow heating → small impact on NZPV
- NZPV with higher B increases, because margin decreases

BSCCO conductor – Simulation setup

Boundary conditions

Fluid model:

- Inlet temperature: T1-1(t) or T2-1(t)
- Inlet and outlet pressure: such that the mass flow rate agrees with the measured one

Thermal model:

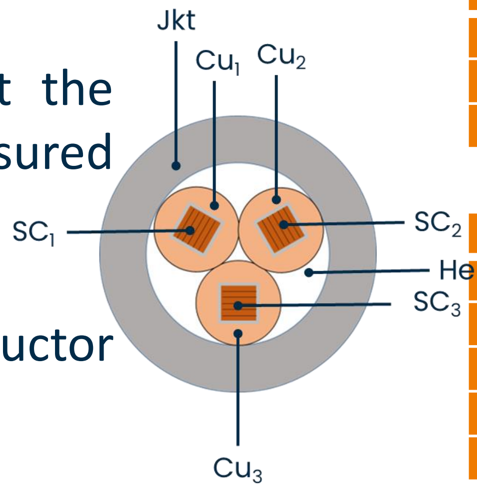
- Zero heat flux (adiabatic) at both conductor ends

Current model:

- Imposed current in SC at conductor outlet
- Zero current gradient at conductor inlet

In case of twisting, the angular dependence of the J_C is taken into account

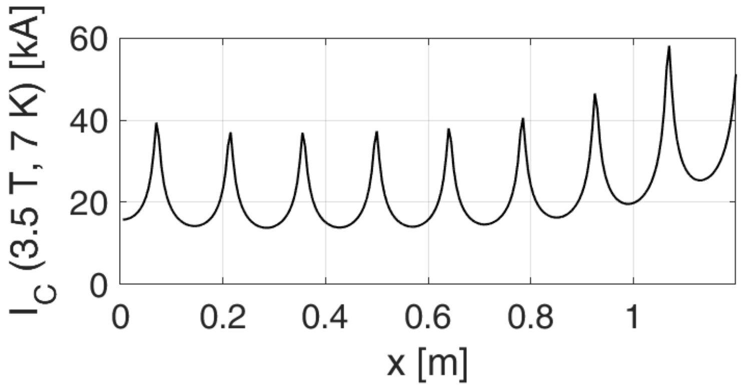
H4C model



Interface parameters & constitutive relations

Electric contact resistance	[μΩ/m]
Stack-Copper	0.4
Copper-Copper	8
Copper-Stainless steel	100

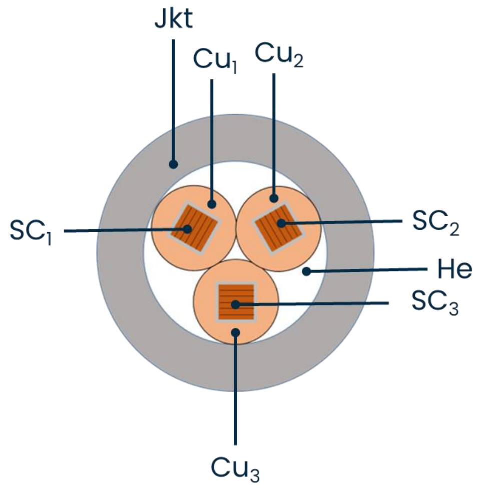
Thermal contact resistance	[m² K/W]
Stack-Copper	$8 \cdot 10^{-5}$
Copper-Copper	$1 \cdot 10^{-3}$
Copper-Stainless Steel	**to be calibrated**
Friction factor correlation	Petukhov
Nusselt number correlation	Dittus-Boelter



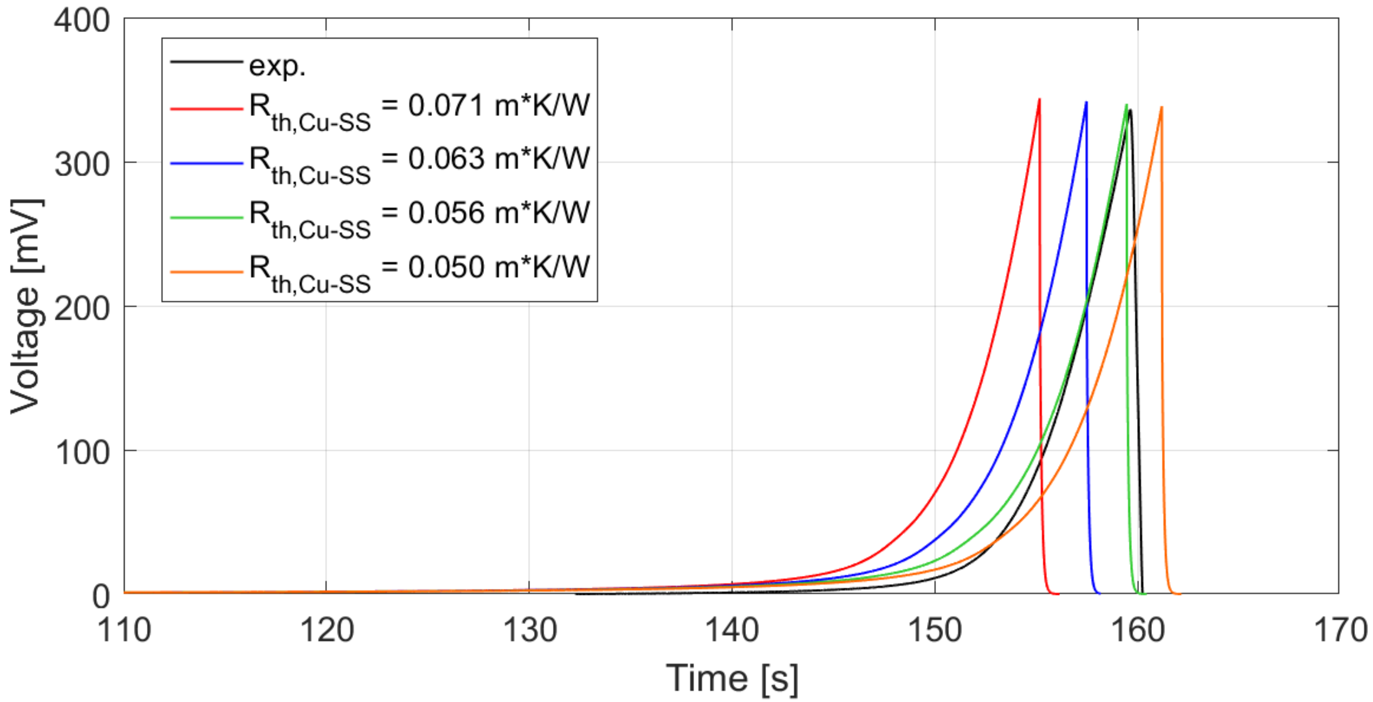
Electric contact resistances from [N. Bykovskiy,2017], [A. Zappatore, 2021], [M. Vogler, 1993]
Thermal contact resistances from [Y. A. Cengel, Fundamentals of Thermal-Fluid Sciences, 2017]

BSCCO conductor – Calibration of $R_{th, Cu-SS}$

- Availability of thick jacket thermal capacity depends on $R_{th, Cu-SS}$
- Same ballpark of non-twisted and reference conductors $R_{th, Cu-SS}$ = 0.083 K m/W (slightly lower here) as well as measurement done at KIT [0.05 – 0.25 K m/W] [N. Bagrets et al., IEEE TAS, 2022]



H4C model

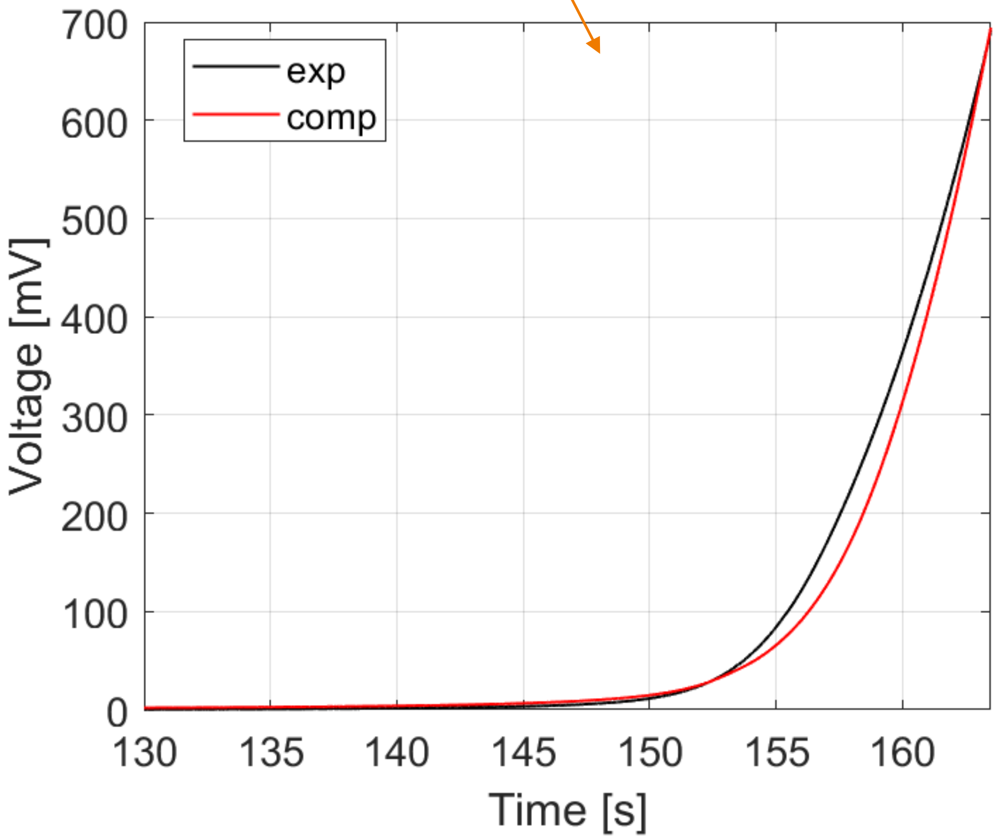


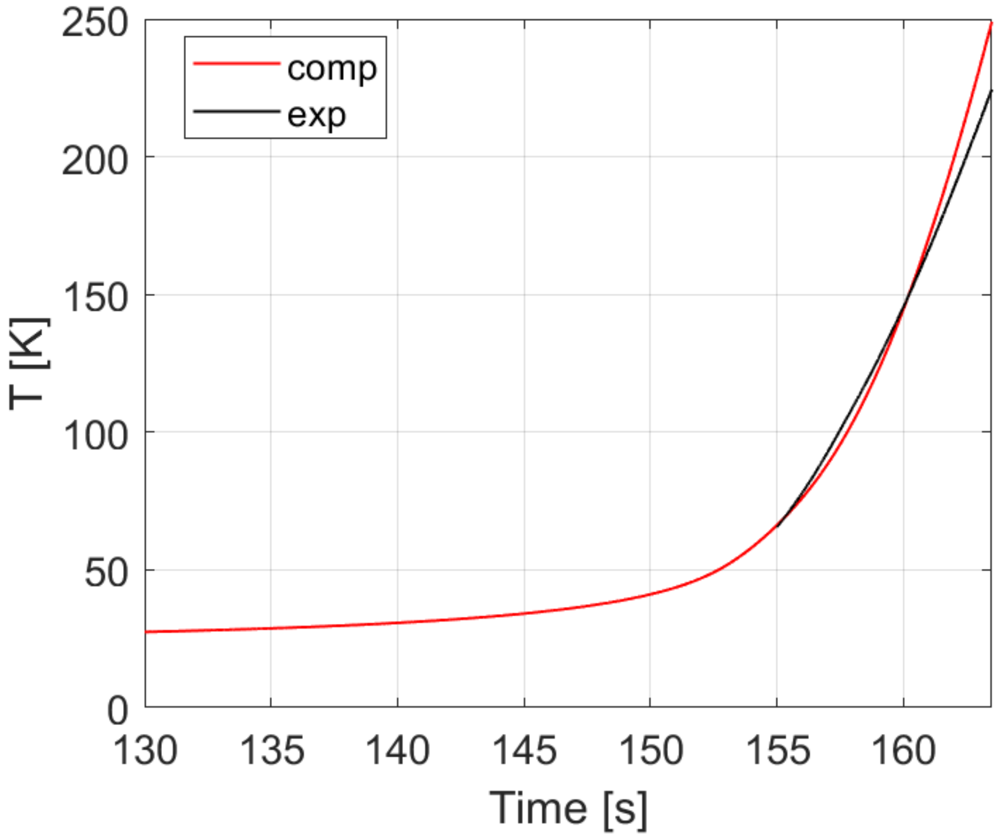
Contact length assumed equal to 2 mm

BSCCO conductor – high J_{Cu} (I)

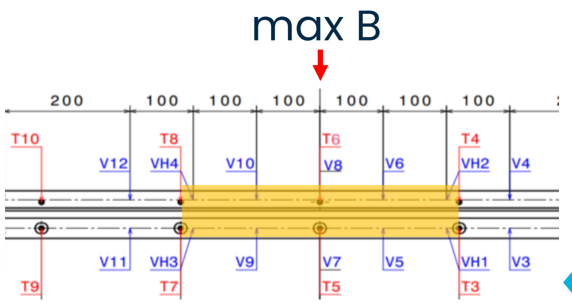
121105 (BSCCO)
4 T, 15 kA
Dump at **135 K**

- Calibrated parameter kept constant
- Experimental hotspot temperature is evaluated assuming all the current is flowing in Cu and jacket
- Good agreement on total voltage and hotspot temperature



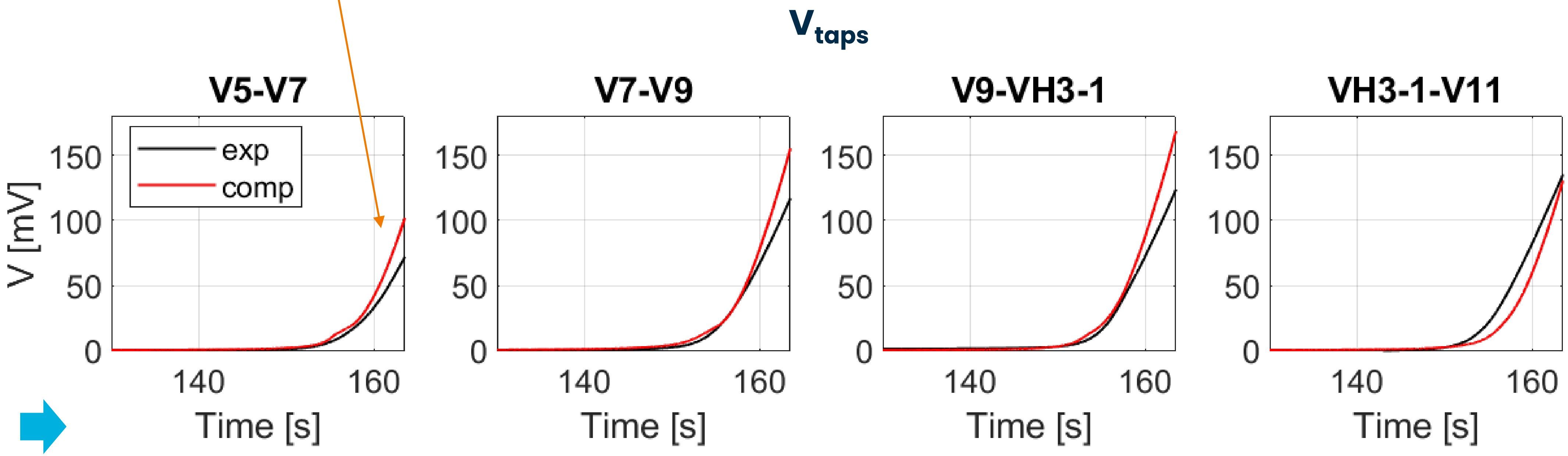


BSCCO conductor – high J_{Cu} (II)

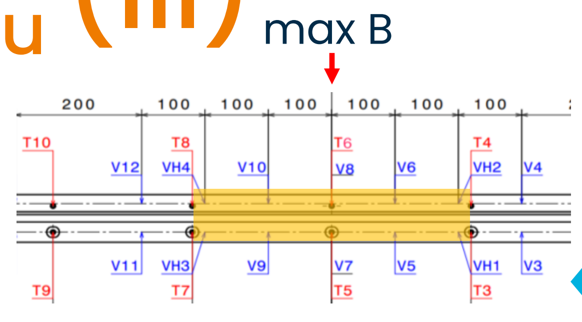


121105 (BSCCO)
4 T, 15 kA
Dump at **135 K**

Voltage rise at local level is
- reproduced correctly in terms of spatial distribution (i.e., max V is inV7-V9, V9-VH3)
- but is faster above 50 mV → impact of $J_C(x)$ discussed later

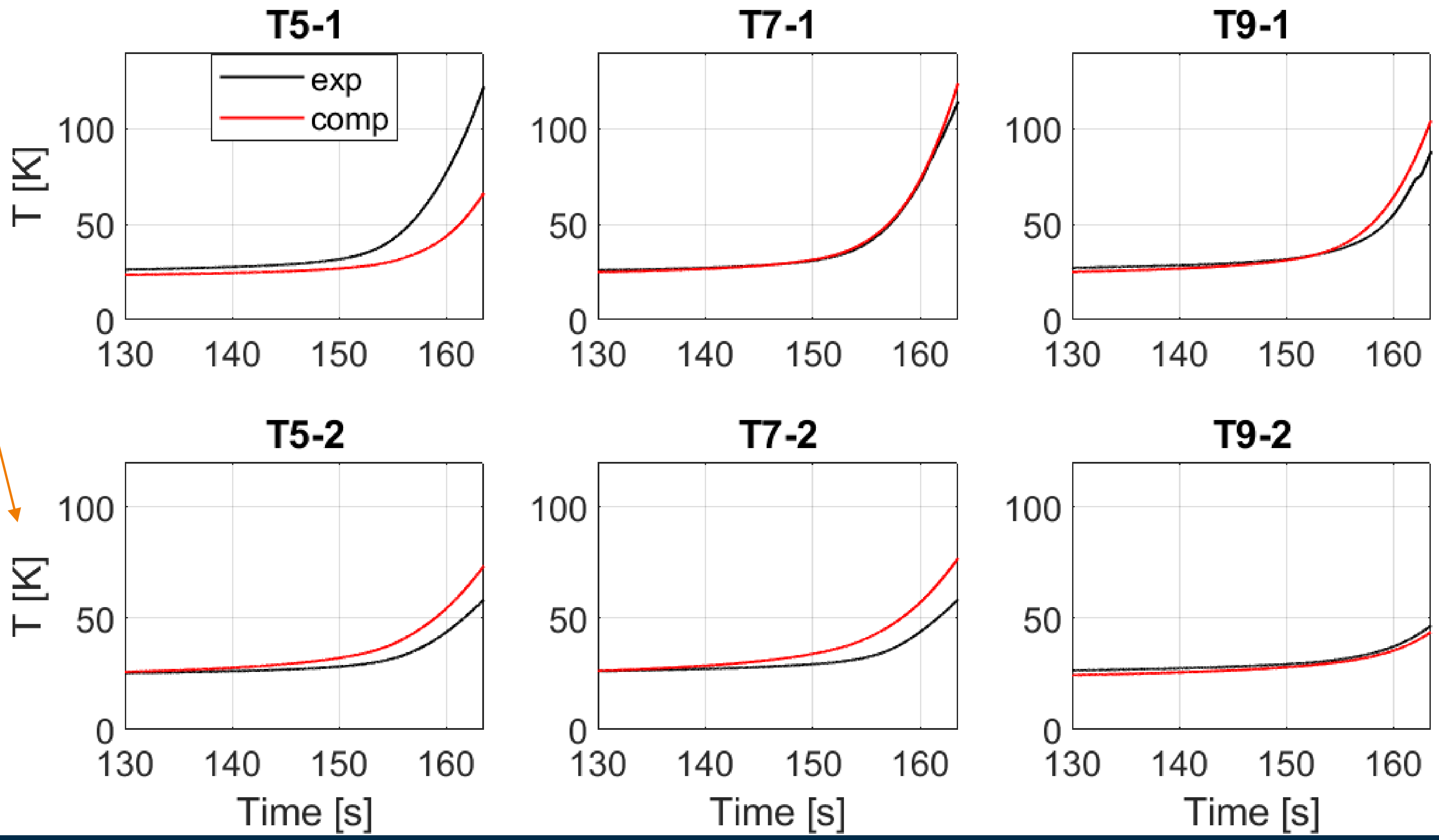


BSCCO conductor – high J_{Cu} (III)



Temperature rise at local level is

- reproduced correctly in terms of maximum value (T7-1)
- slightly overestimated on the jacket → impact of jacket discretization discussed later

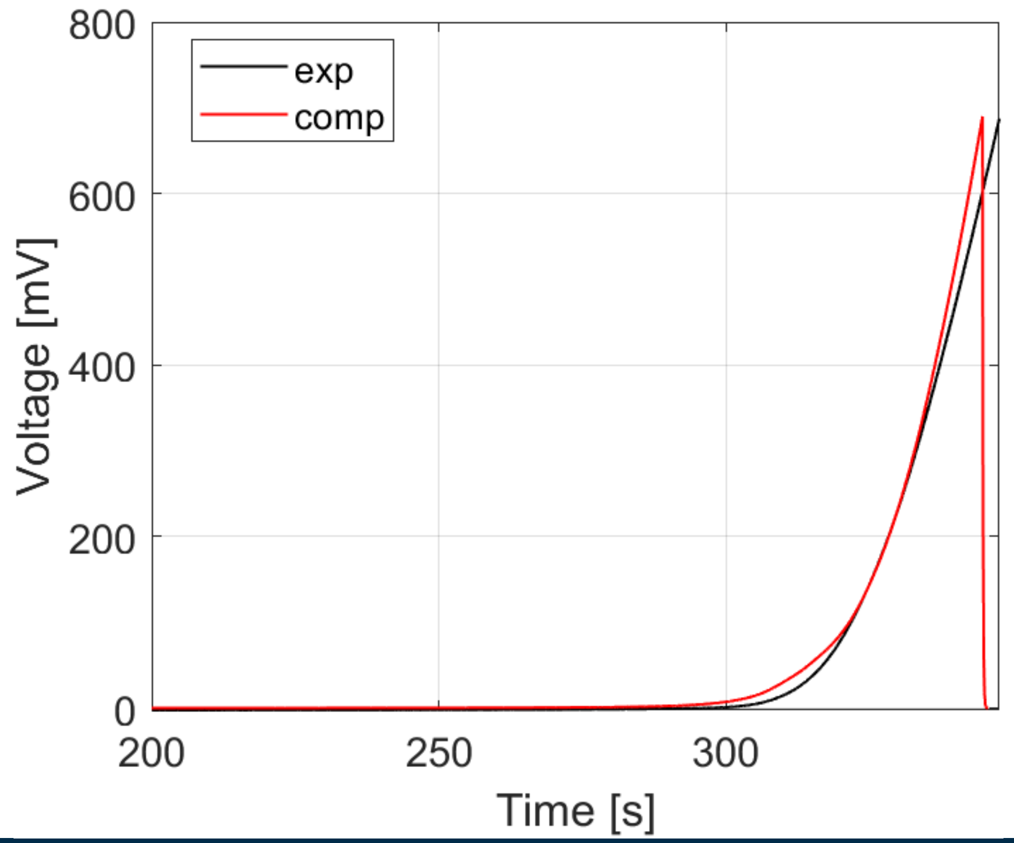


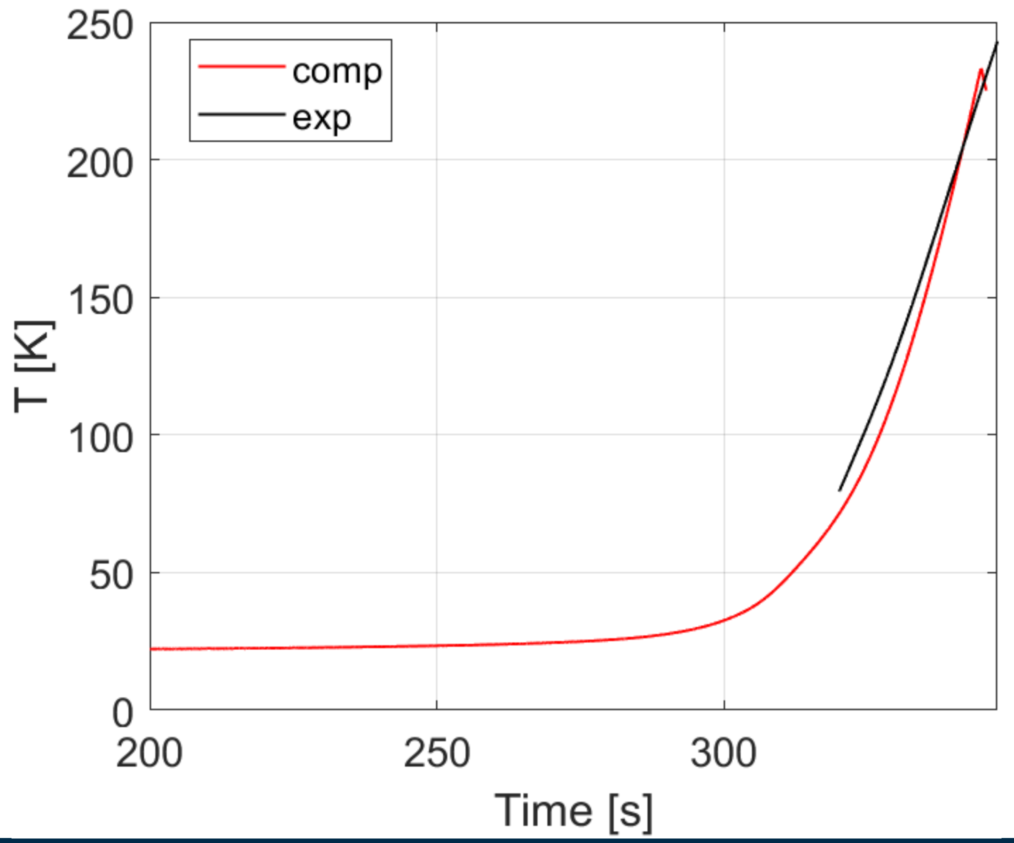
121105 (BSCCO)
4 T, 15 kA
Dump at **135 K**

BSCCO conductor – low J_{Cu} (I)

- Calibrated parameters same as before
- Faster voltage rise is evident in this case also on the total voltage

171101 (BSCCO)
9 T, 9.5 kA
Dump at **160 K**

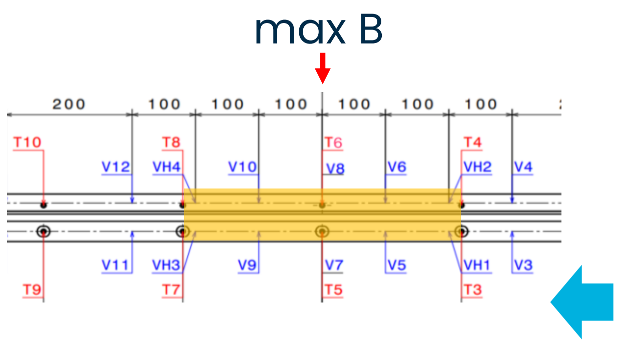




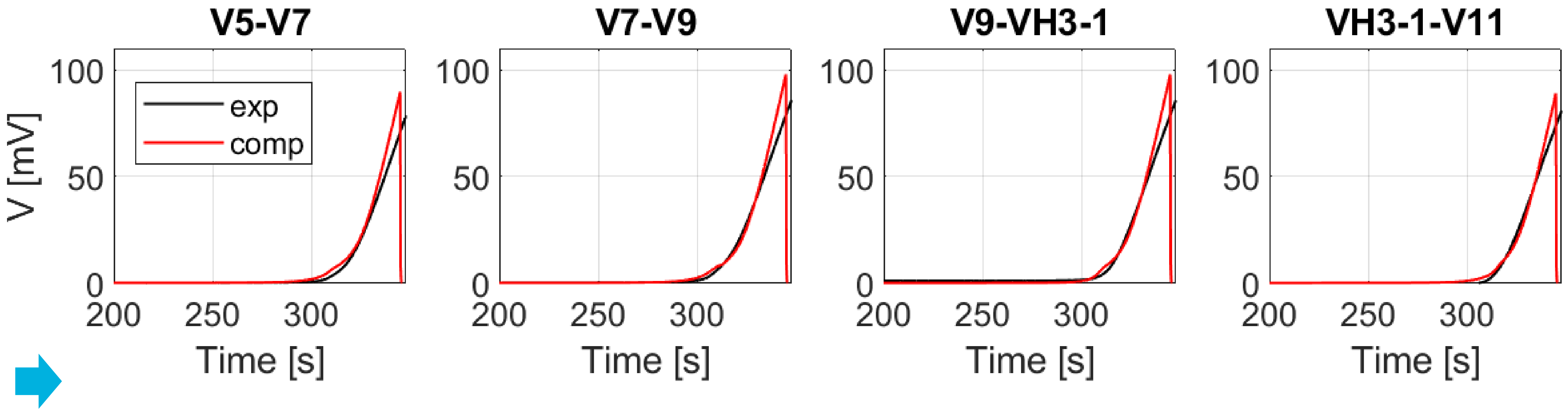
BSCCO conductor – low J_{Cu} (II)

Voltage and temperature rise at local level are well reproduced

Better agreement than in 121105 because here slow heating → slower evolution of the transient → easier to capture



171101 (BSCCO)
9 T, 9.5 kA
Dump at **160 K**

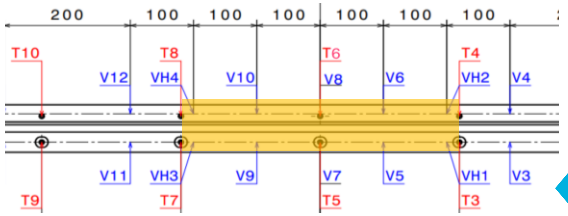


BSCCO conductor – low J_{Cu} (III)

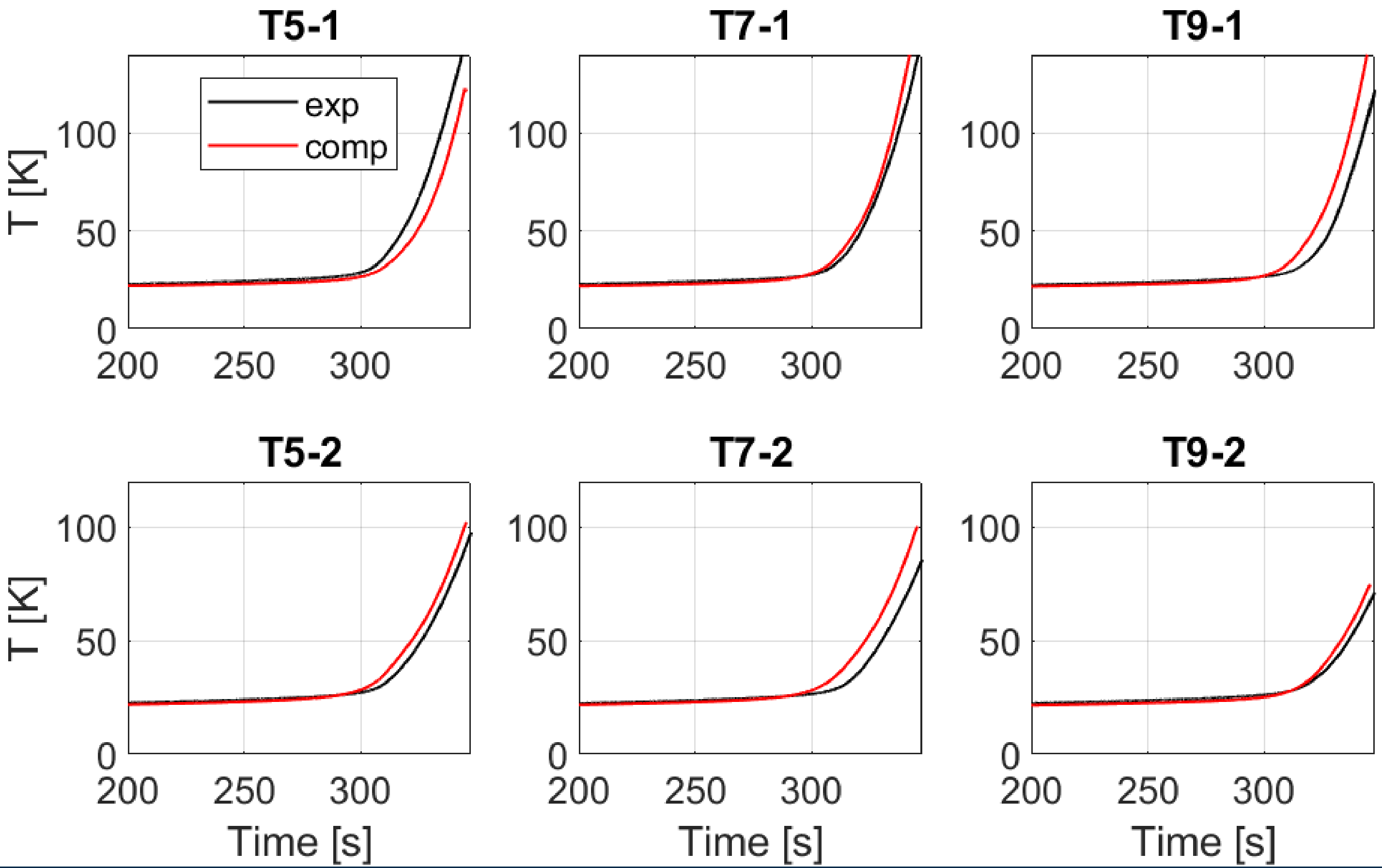
Voltage and temperature rise at local level are well reproduced

Better agreement than in 121105 because here slow heating → slower evolution of the transient → easier to capture

max B



171101 (BSCCO)
9 T, 9.5 kA
Dump at **160 K**

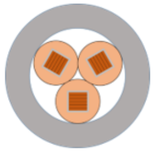


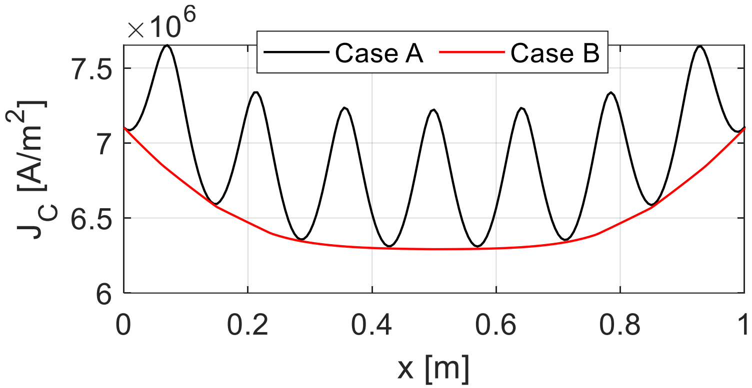
BSCCO conductor – Effect of twisting

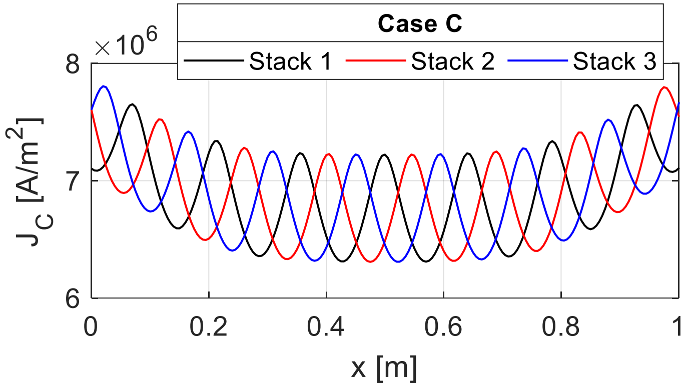
Case A: start angles = [0, 0, 0]

Case B: no twisting

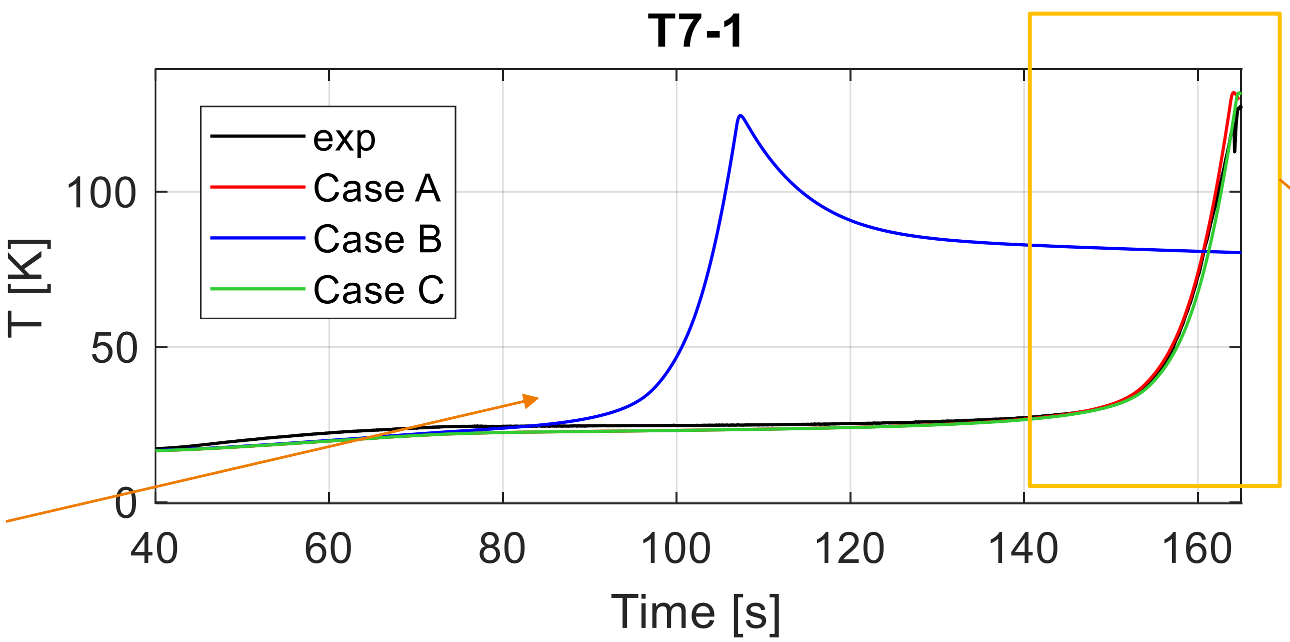
Case C: start angles = [0, 120, 240]

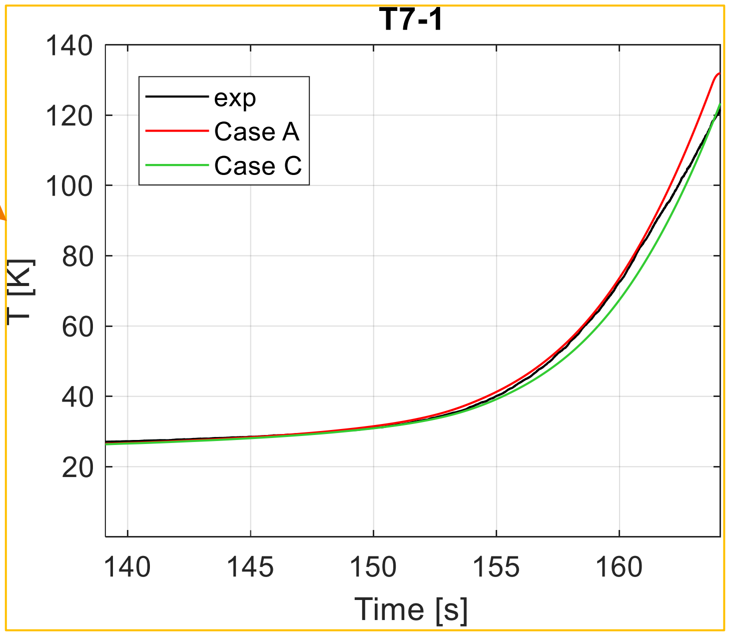




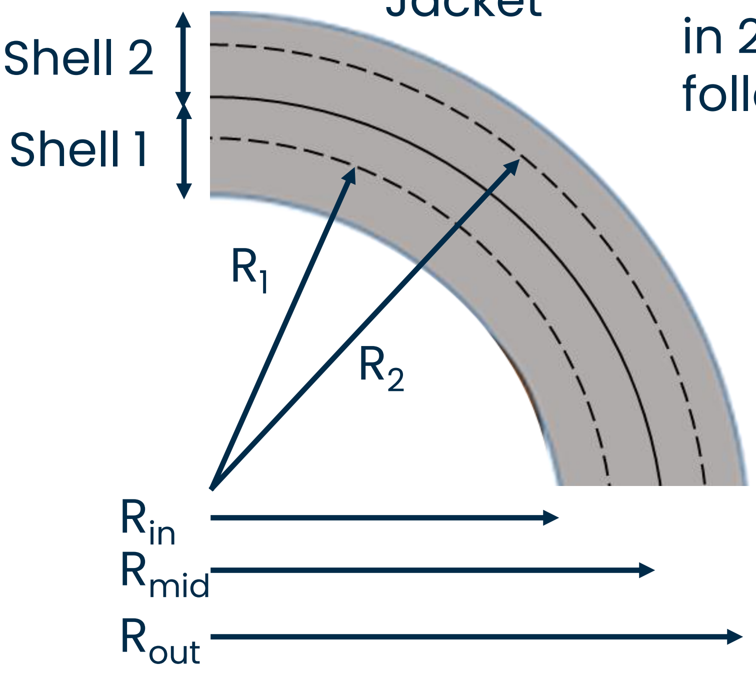


- If twisting is considered, start angles have negligible effect on the results
- If twisting is not considered, "average" I_C is lower → quench initiation is strongly anticipated





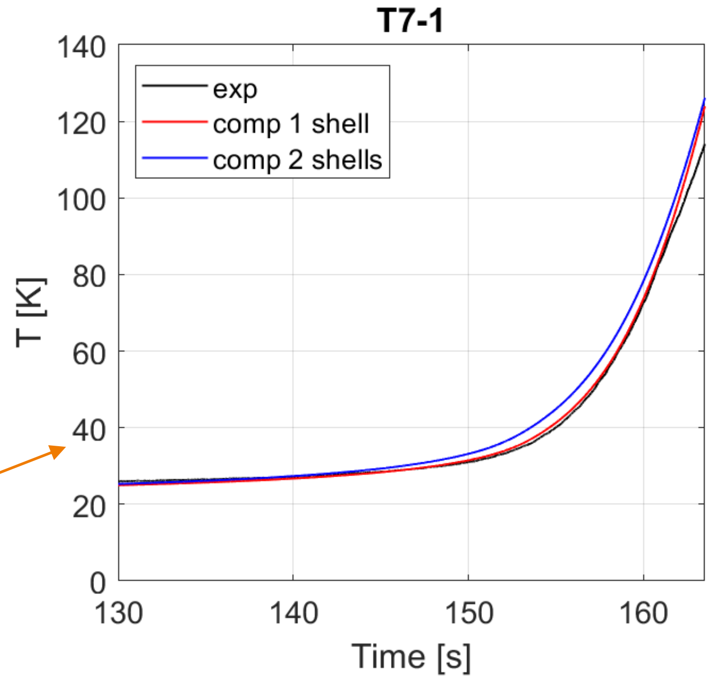
BSCCO conductor – Effect of jacket radial discretization

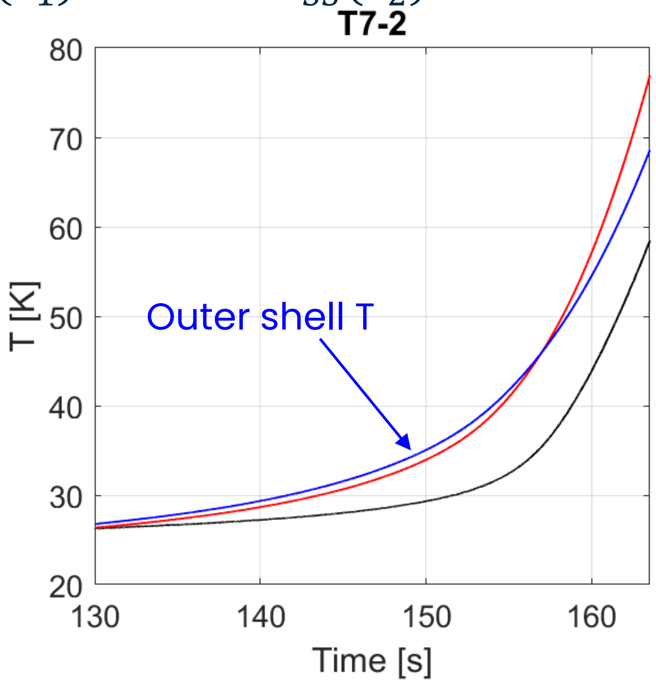


To account for non negligible diffusion time (wrt quench time scale) → split in 2 shells (lumped in R_1 and R_2) the jacket discretization, connected by the following resistance:

$$R_{SS_1-SS_2} = \frac{1}{\dfrac{D_{in}\log\left(\dfrac{D_{mid}}{D_{in}}\right)}{2k_{SS}(T_1)} + \dfrac{D_{in}\log\left(\dfrac{D_{out}}{D_{mid}}\right)}{2k_{SS}(T_2)}}$$

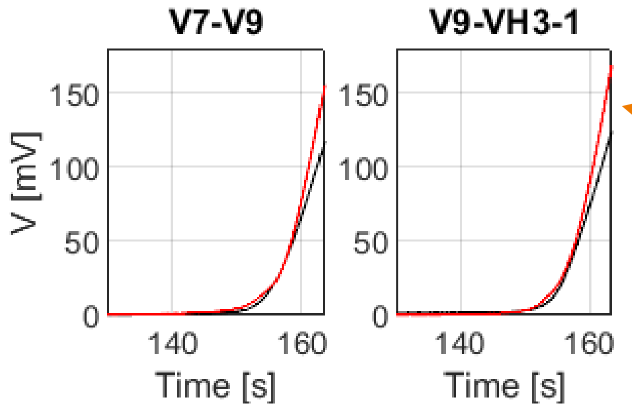
After recalibration of $R_{th,CU-SS}$, negligible effect on T_{He}



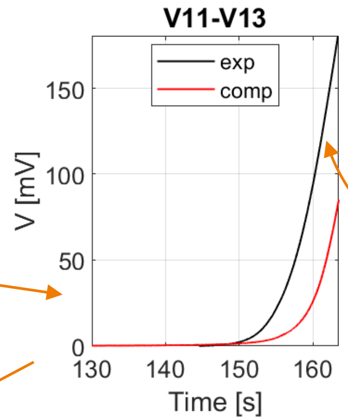


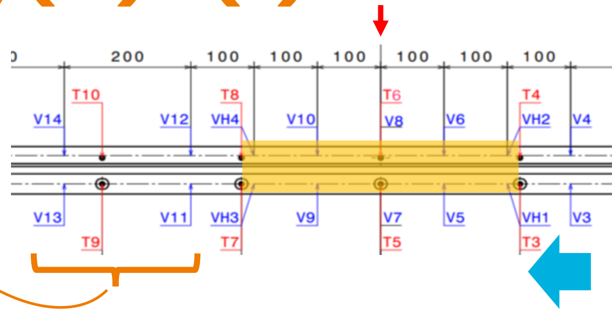
~ 10 K decrease in T_{jacket} if 2 shells are considered

BSCCO conductor – Effect of $J_C(x)$ $(I)_{max\ B}$

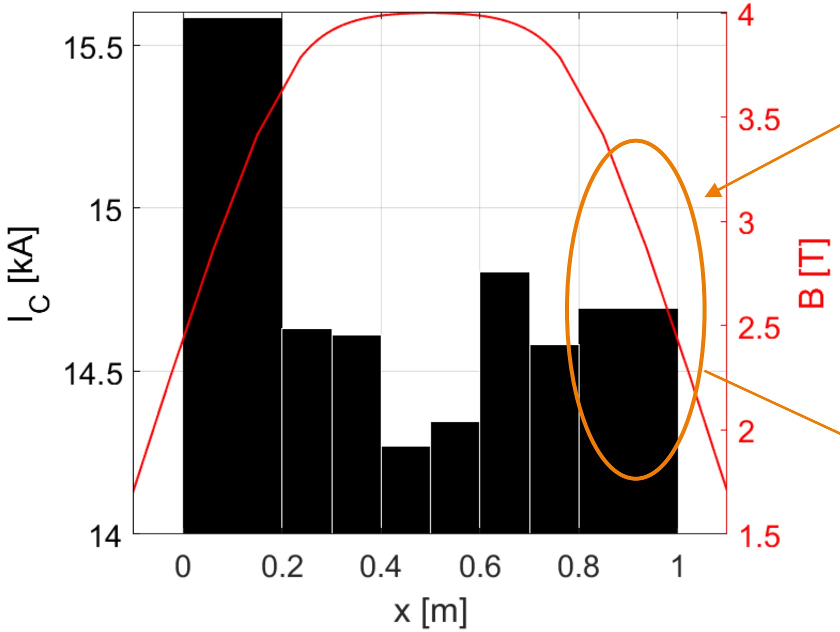


Comp. V rises faster than exp. in HFZ → check in low B region → behavior is reversed



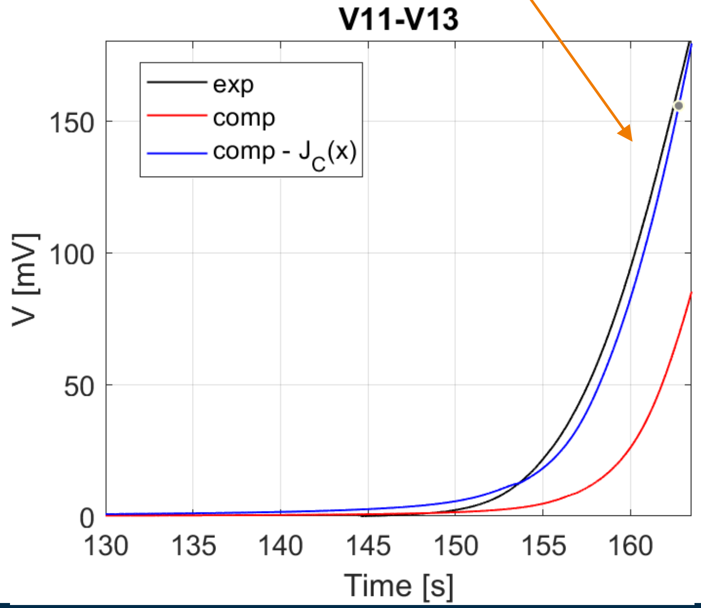


Check DC performance (I_C)



IC(3.5-2.5 T) ~ IC(4 T) → ~5% degradation in x=[0.8 1.0] m

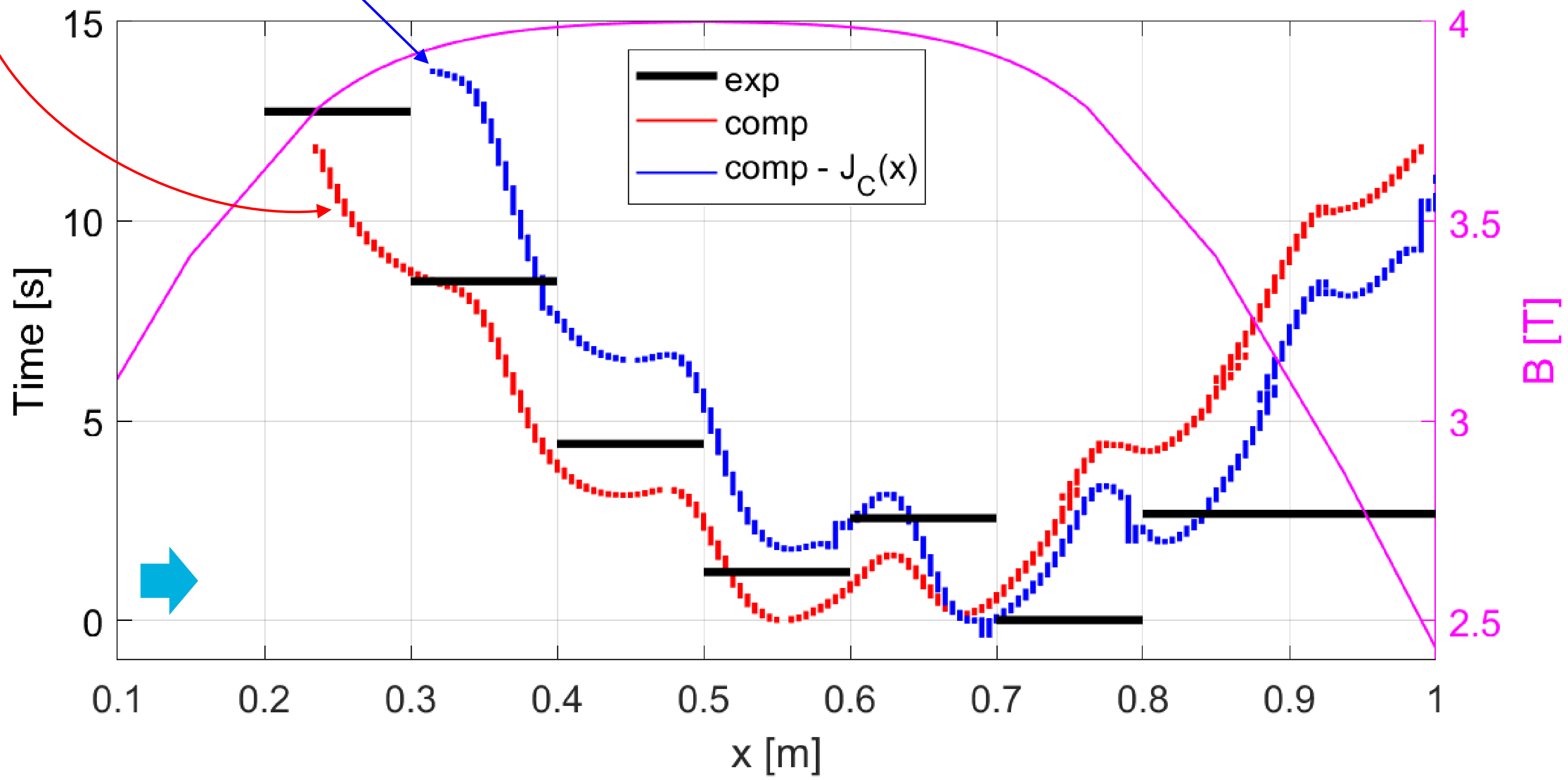
Accounting for $J_C(x)$ strongly improves agreement



BSCCO conductor – Effect of $J_C(x)$ (II)

Mark NZ front when E = 15 mV/cm

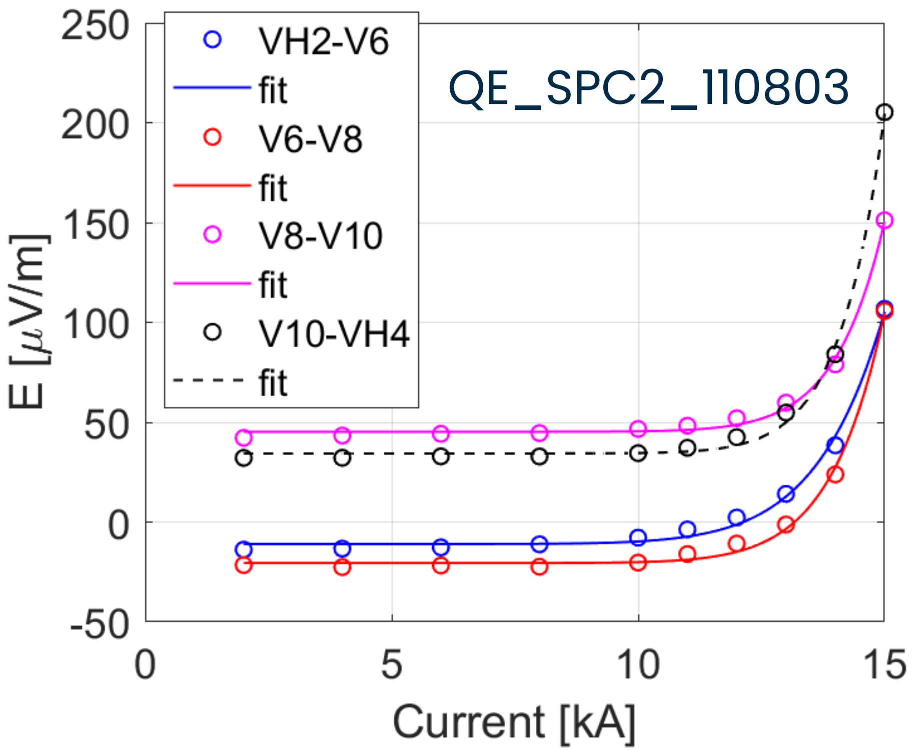
- If no info on J_C degradation → symmetric propagation wrt x = 0.63 m
- If $J_C(x)$ accounting for degradation → (average) measured E(x) is better reproduced



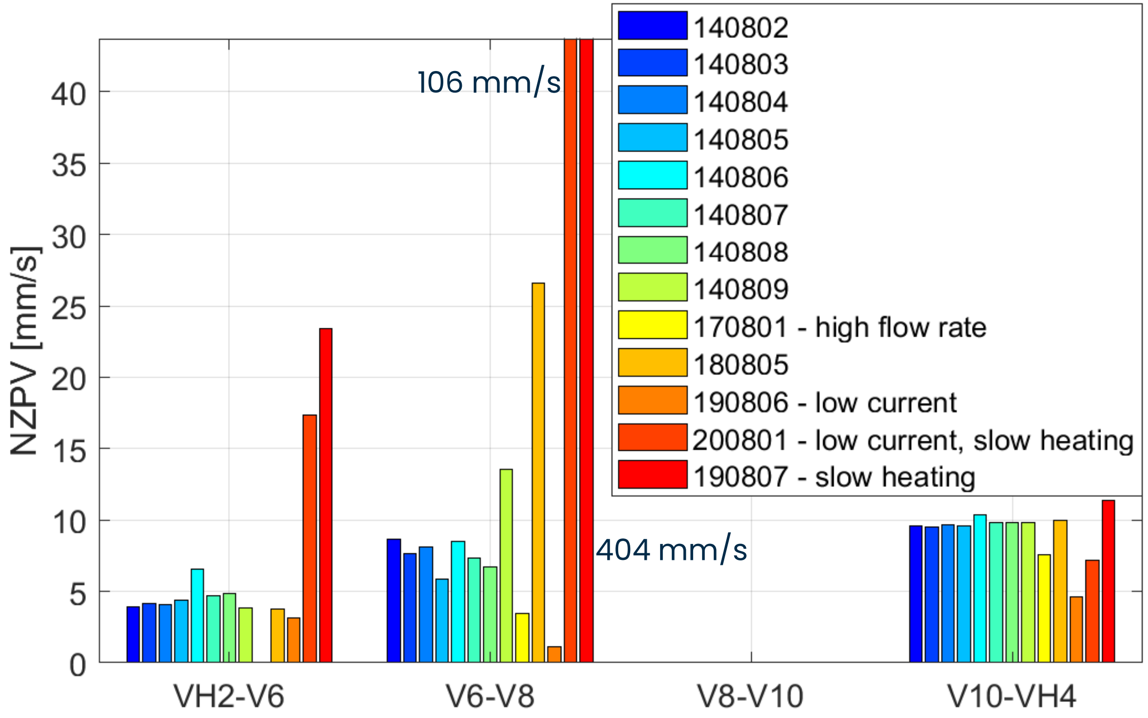
- Initiation in x = [0.7-0.8]
- Symmetric propagation wrt x = [0.7-0.8]
- E = 15 mV/cm in x = [0.7-0.8] *before* than in x = [0.5-0.6]

Solder-filled REBCO conductor DC performance & NZPV

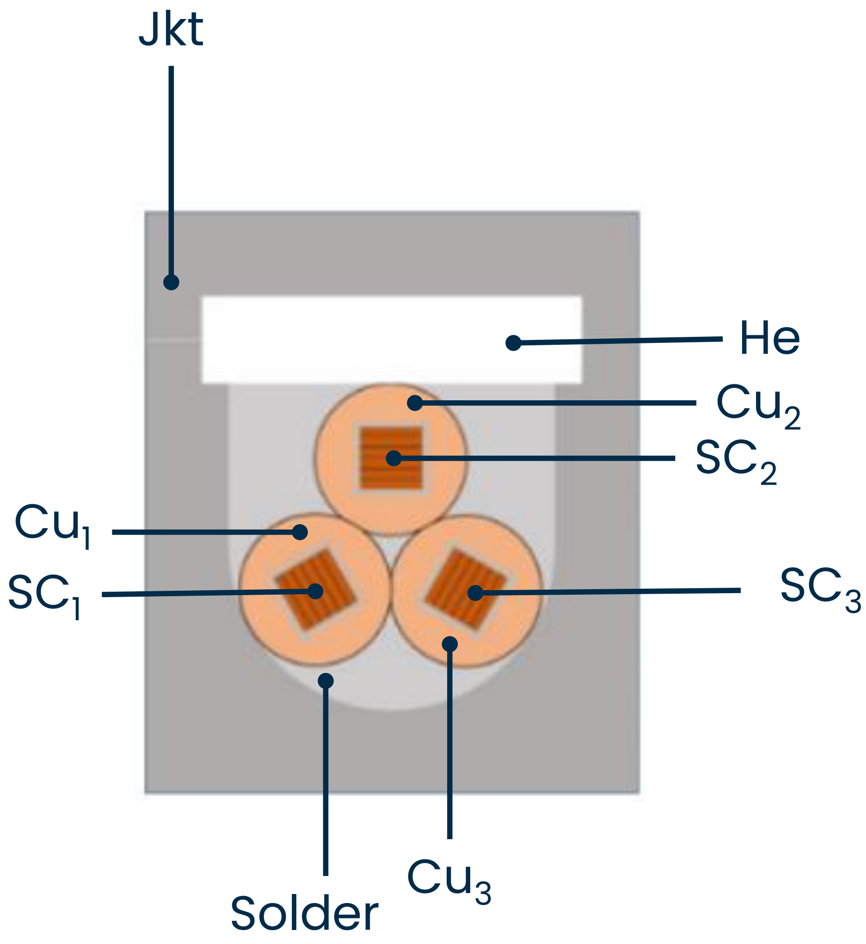
- I_C(7 T, 7 K) = 14.8 kA
- n-value = 14.4



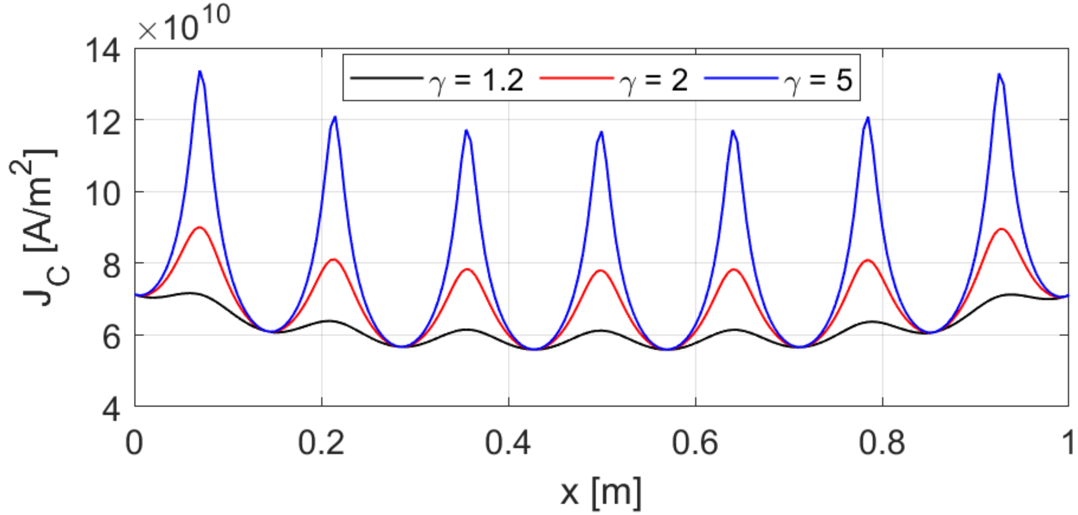
- NZPV is 5-10 mm/s (larger heat capacity due to solder wrt other REBCO conductors tested)
- Slow heating leads to much higher NZPV
- Low J_{Cu} → lower NZPV



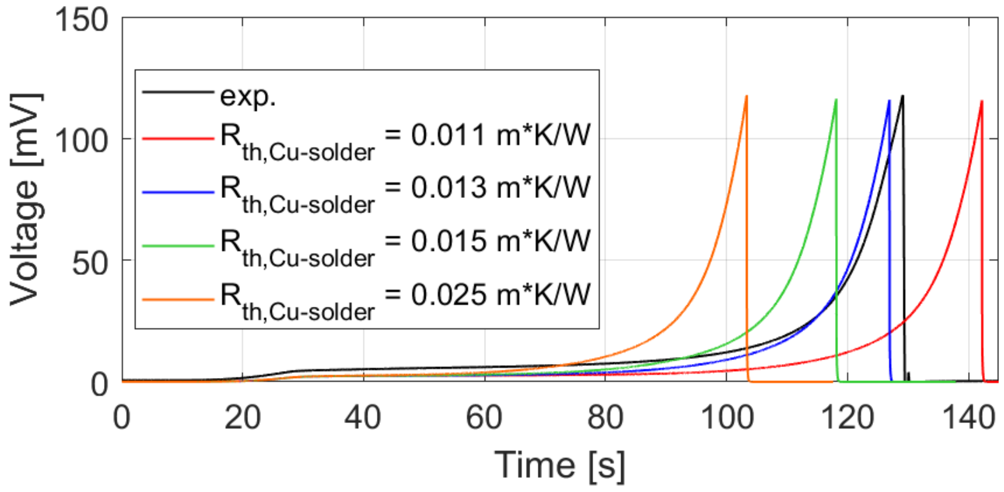
Solder-filled H4C model & calibration



H4C model



For $\gamma > 1.5$, no quench can be achieved, no matter the value of the thermal resistances



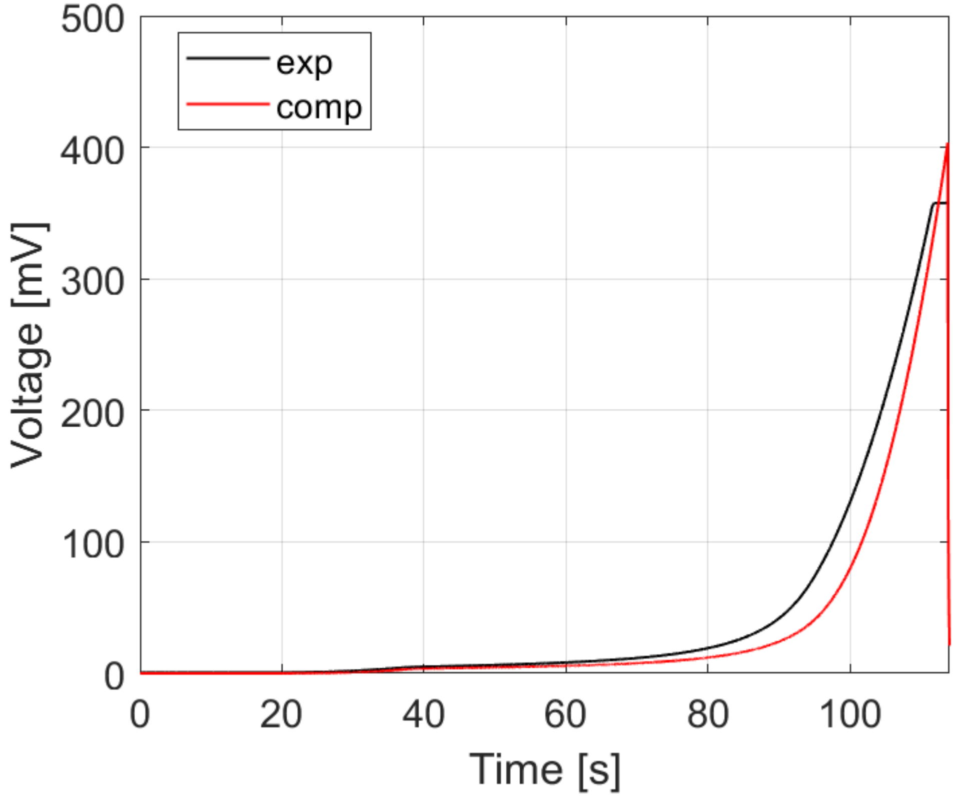
Multiple thermal resistances to be calibrated

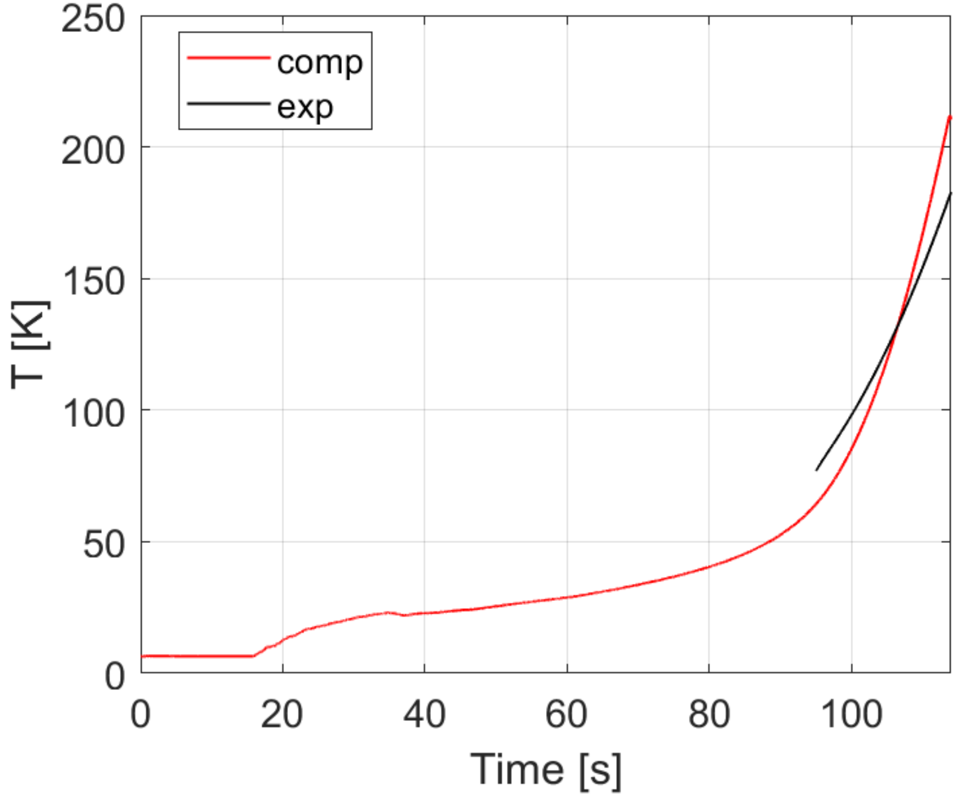
Here, fixed values of $R_{th,\ Cu\text{-}SS}$ (from previous conductors) and $R_{th,\ Solder\text{-}SS}$ and calibrate $R_{th,\ Cu\text{-}Solder}$

Solder-filled REBCO conductor – high J_{Cu} (I)

140809 (Solder-filled)
6.5 T, 15 kA
Dump at **130 K**

- Calibrated parameters are kept constant
- Slower rise (both in total V and hotspot temperature) below 500 mV, then faster than measured (as for the BSCCO conductor) → possible impact of different strategies for the discretization of the cross-section will be investigated

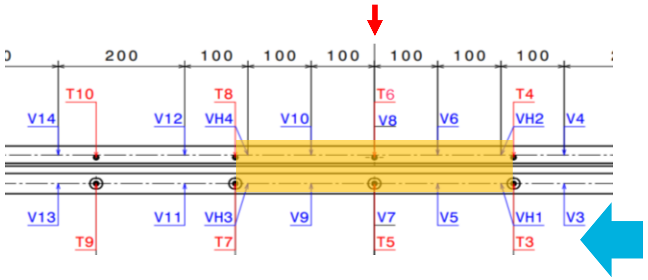




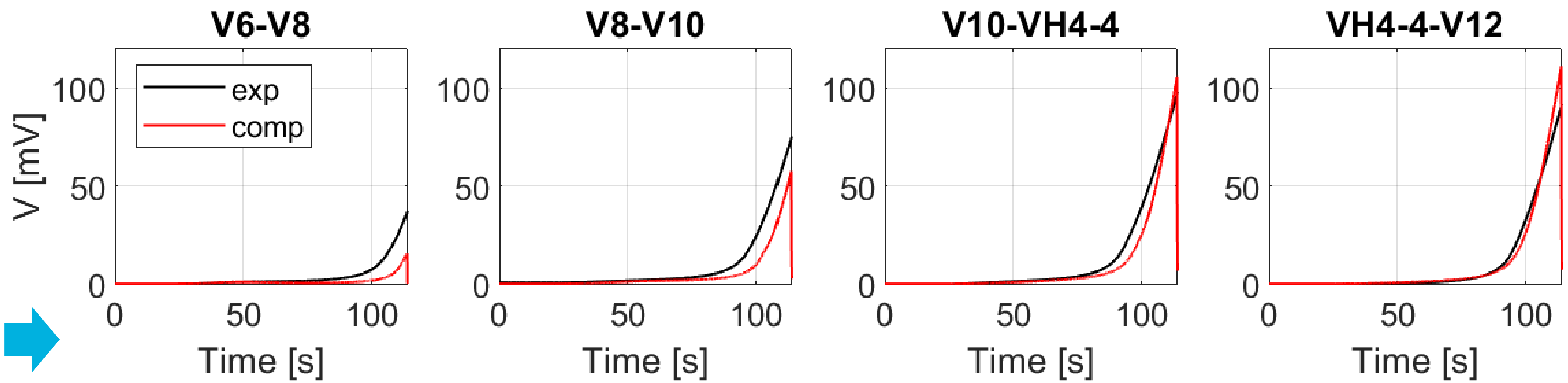
Solder-filled REBCO conductor – high J_{Cu} (II)

140809 (Solder-filled)
6.5 T, 15 kA
Dump at **130 K**

max B



- Quench propagation shifted towards the outlet is well captured by the model



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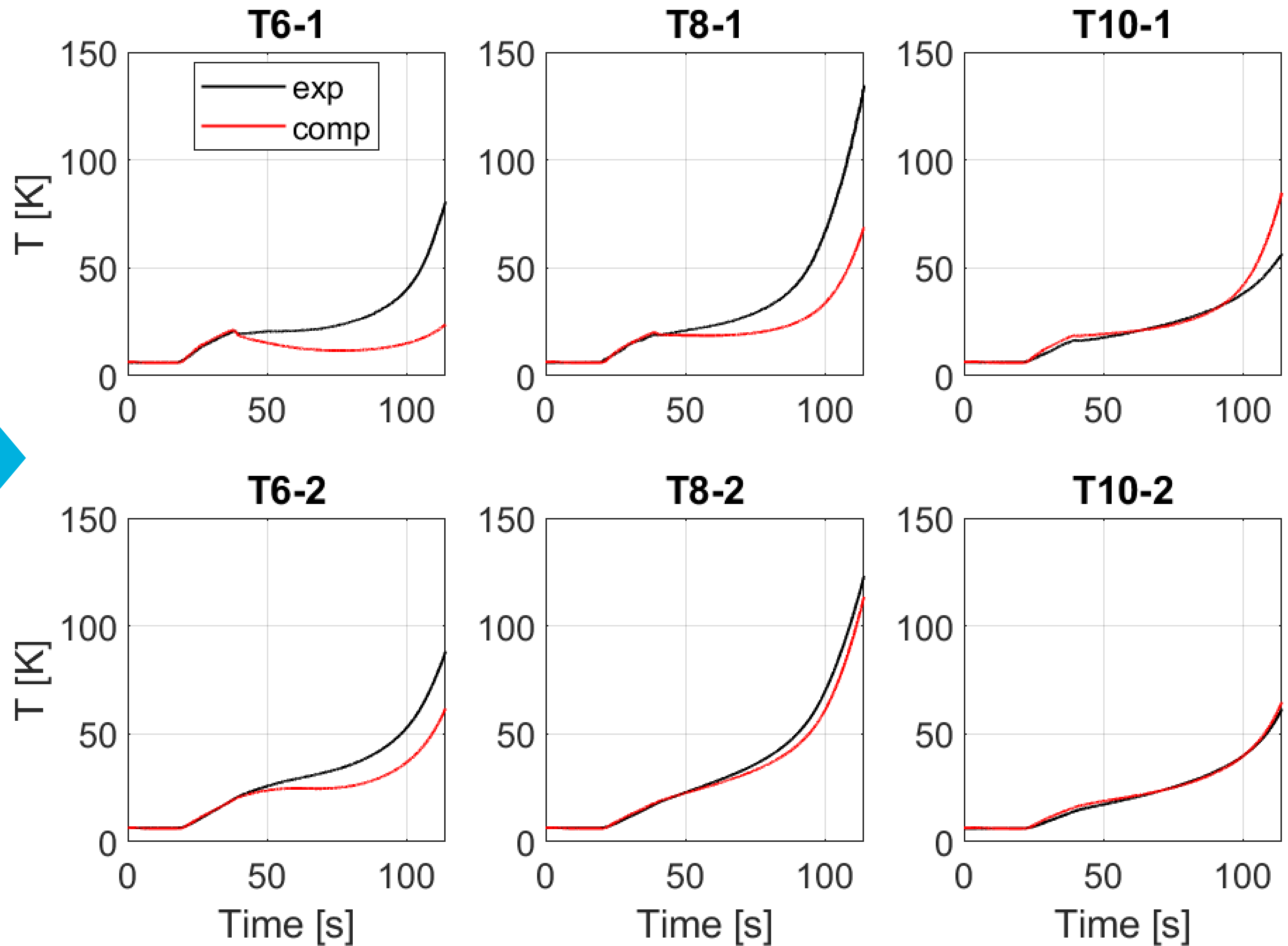
Solder-filled REBCO conductor – high J_{Cu} (III)

140809 (Solder-filled)
6.5 T, 15 kA
Dump at **130 K**

- Temperature rise close to the inlet does not match well with data, but high temperature region is better reproduced

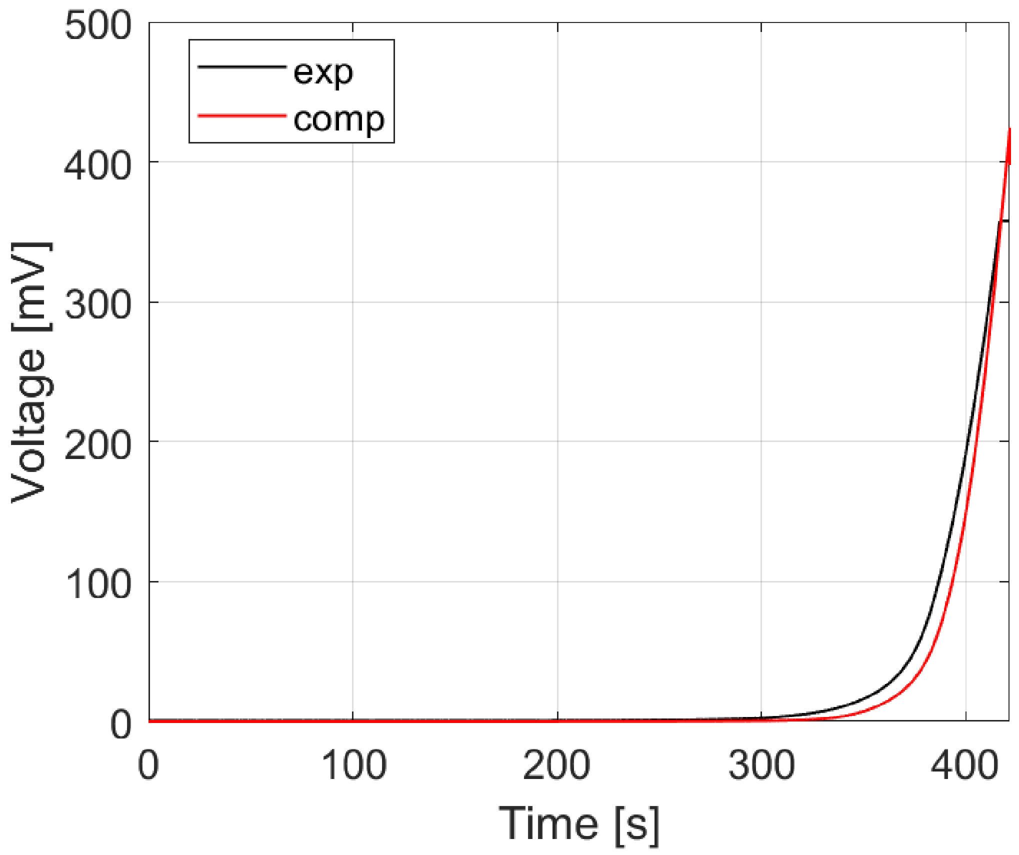
- Due to better coupling with jacket, T sensor on jacket gives T ~ T_{He}

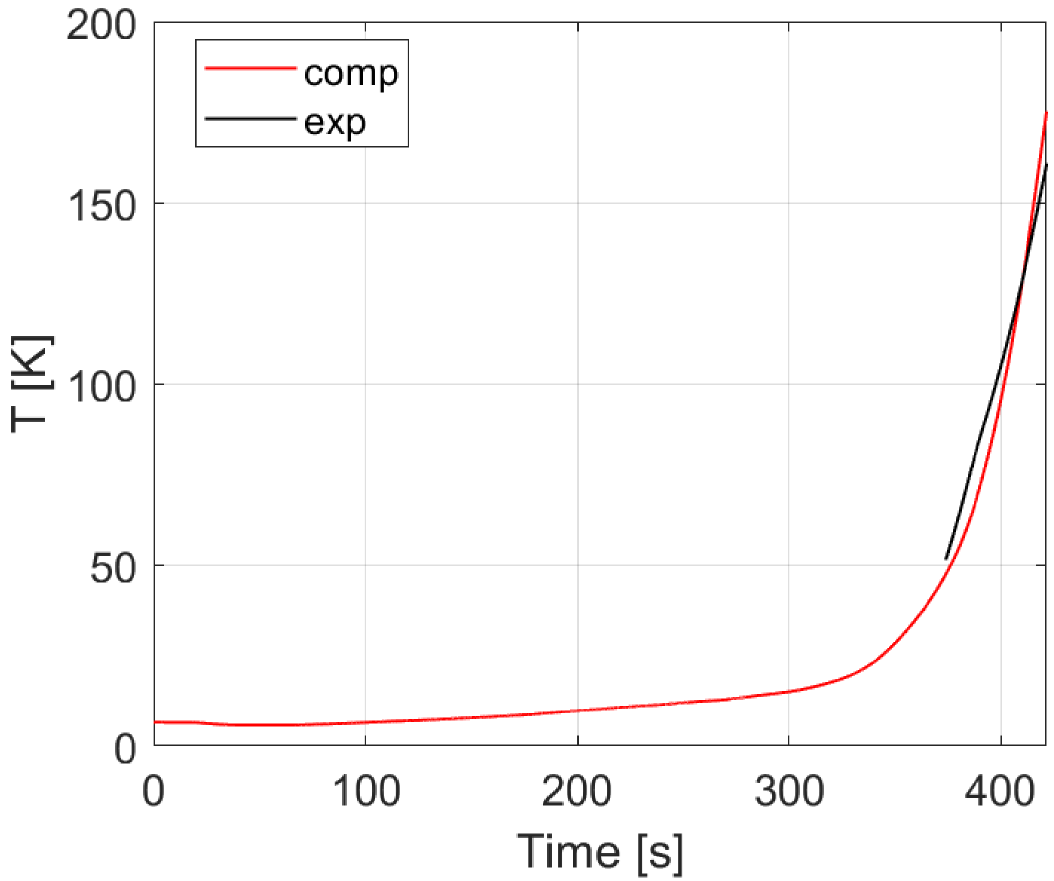


Solder-filled REBCO conductor – low J_{Cu} (I)

200801 (Solder-filled)
10.78 T, 11 kA
Dump at **130 K**

- Calibrated parameters kept constant
- Here less evident differences than in high J_{Cu} case because slow heating and low J_{Cu} → slower transient

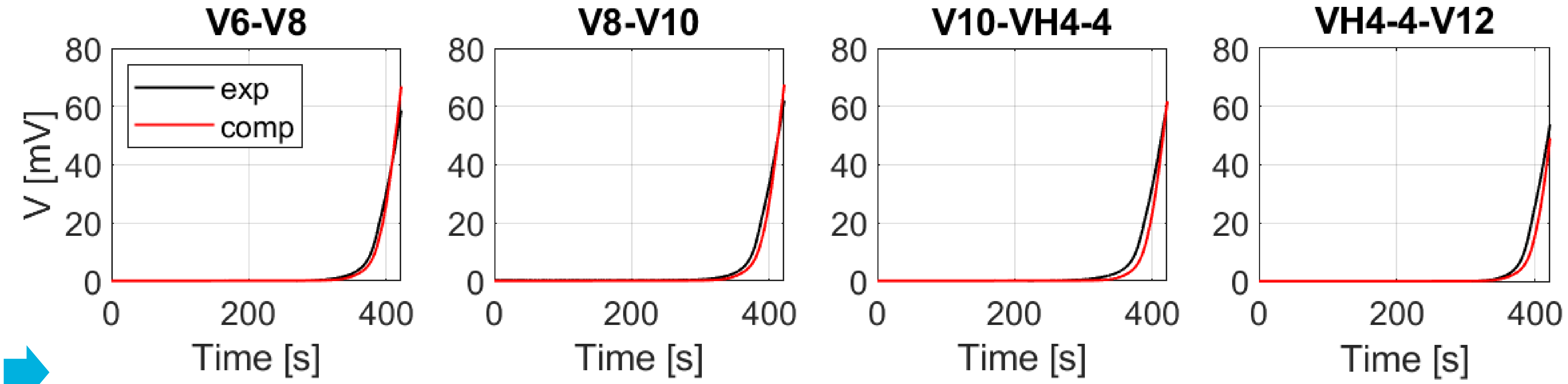




Solder-filled REBCO conductor – low J_{Cu} (II)

200801 (Solder-filled)
10.78 T, 11 kA
Dump at **130 K**

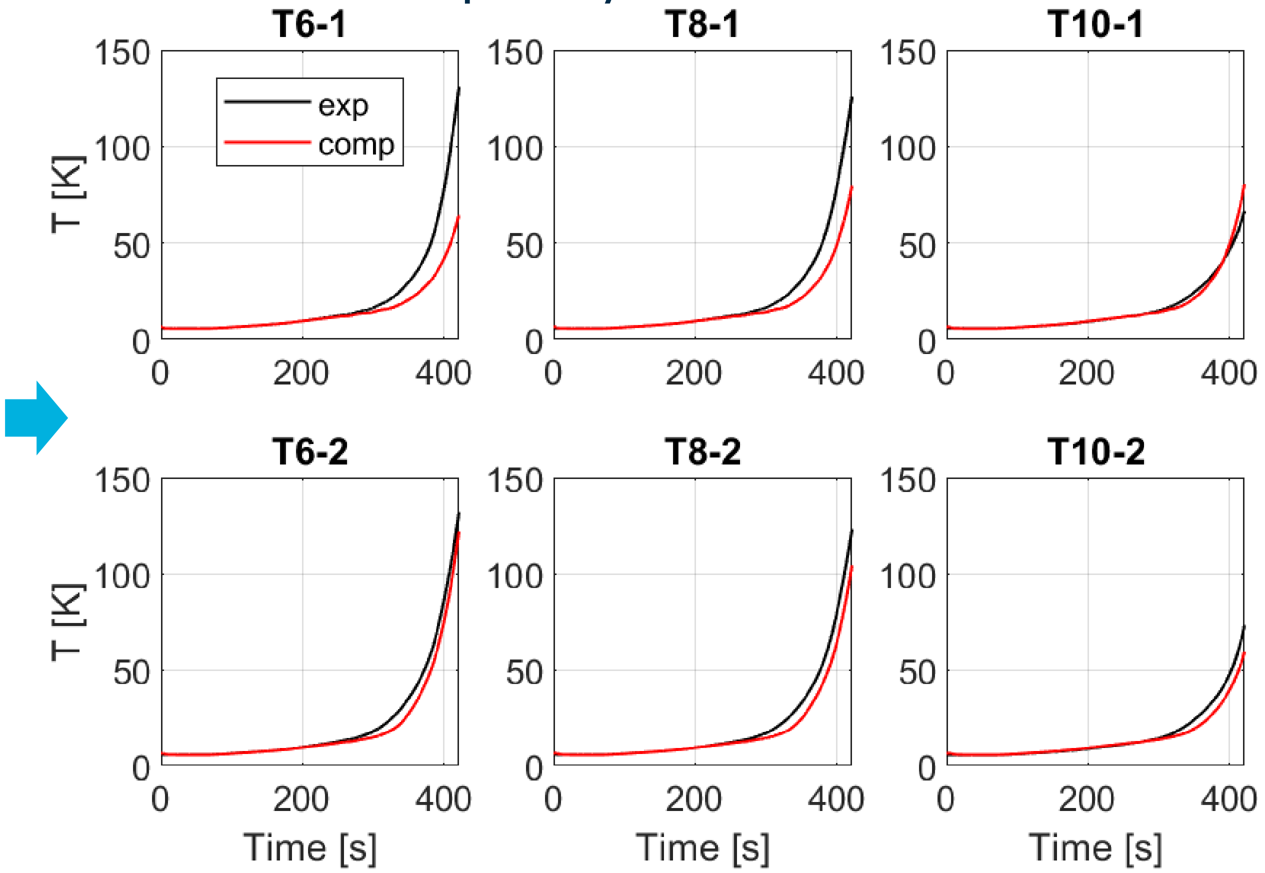
- Also locally, the agreement is better than high J_{Cu} case
- Currently looking into discretization of the cross-section (to more correctly account for thermal capacity)



Solder-filled REBCO conductor – low J_{Cu} (III)

200801 (Solder-filled)
10.78 T, 11 kA
Dump at **130 K**

- Also locally, the agreement is better than high J_{Cu} case
- Currently looking into discretization of the cross-section (to more correctly account for thermal capacity)



Conclusions and perspective

- The analysis of the NZPV shows that the “BSCCO” conductor behaves similarly to the “non-twisted” and “reference” ones (NZPV ~ 20-24 mm/s) while the “solder-filled” conductor has a lower NZPV (~ 5-10 mm/s)

- The H4C model of the “BSCCO” and “solder-filled” conductors have been developed and validated against global and local experimental data with a good agreement

- Accounting for twisting and distribution of J_C has strong impact on the agreement with the measured data

- Next steps:
  - different discretization strategies for the solder-filled conductor will be investigated
  - quench propagation in operating conditions relevant for fusion coils will be analyzed with the validated models

backup

Solder-filled conductor

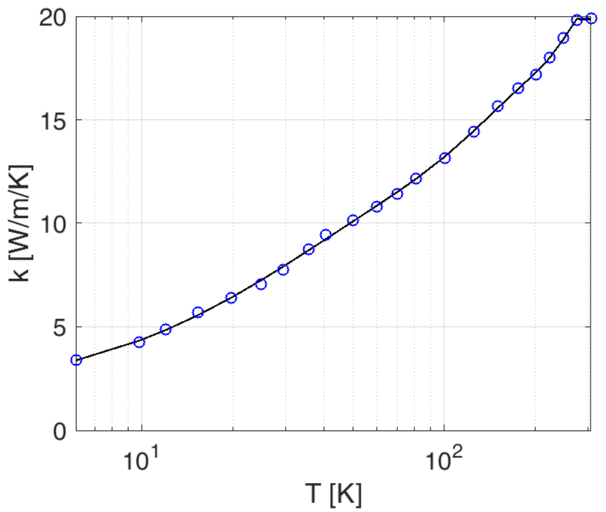
DC performance:

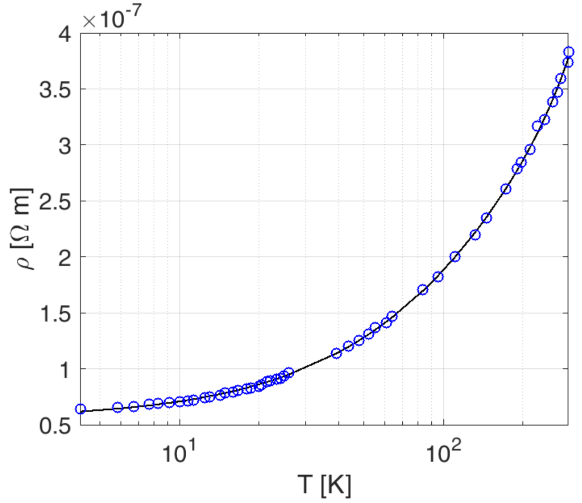
$I_C(7\ T, 7\ K) =\ 14.8\ kA$

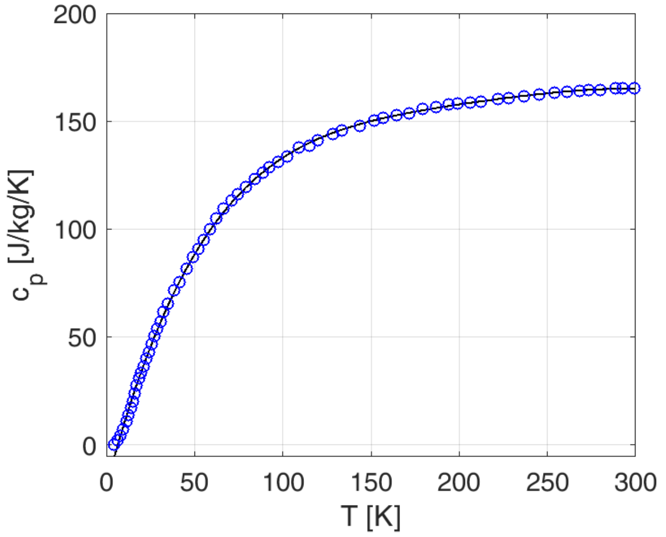
n-value = 14

Building the model:

Solder thermophysical property (Bi57Sn42Ag1, [O. Dicuonzo, personal communication]) → data at RT and 4.2 K, decent fit with In67Bi33

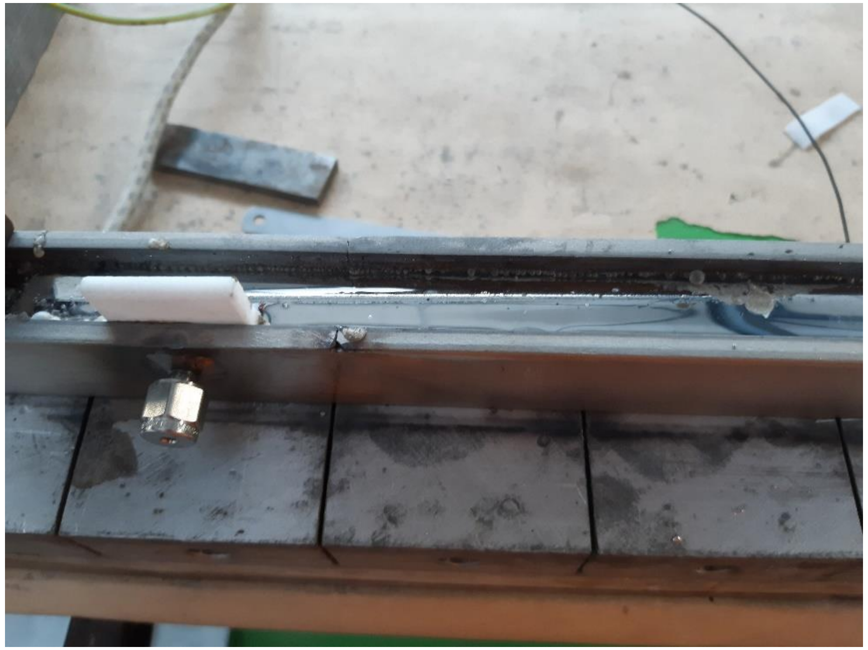






Focus on T_{He} measurement (courtesy of O. Dicuonzo)

A possible reason could be linked to how He temperature is measured (which differs from all the others, perhaps measurement is altered by recirculation in the groove?)



We inserted a Teflon piece in front of the swagelock (through which the He sensor is inserted), that remained during the solder filling process

So we obtained a hole where the He could flow.
The jacket T sensor is placed on the opposite side of the helium channel