Quench test and analysis of HTS Cable-In-Conduit Conductors for fusion applications

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Outline

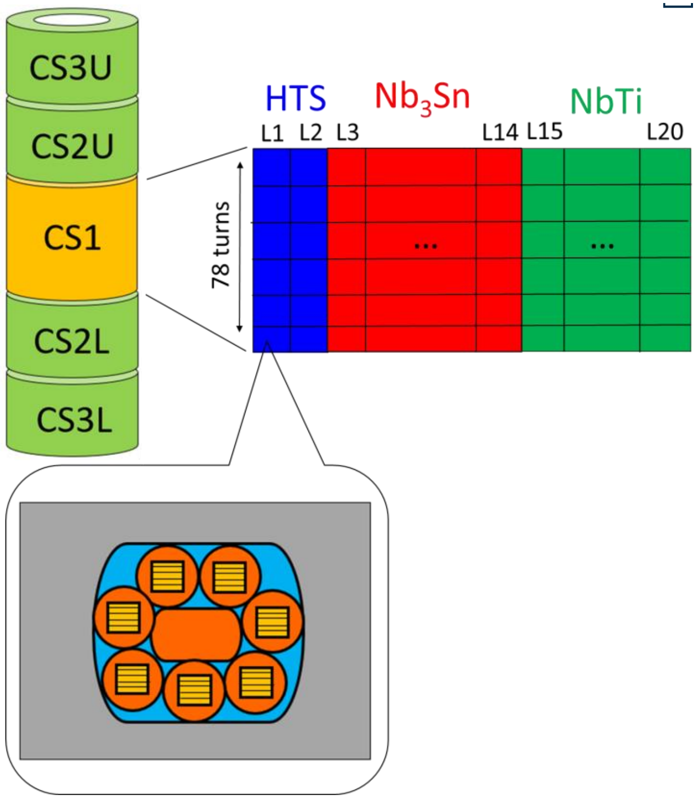
- Introduction
- Experimental setup & results
- Simulation setup & results
- Conclusions and perspective

Introduction

- Worldwide growing interest in HTS conductors for fusion applications

[P. Bruzzone et al, *Nucl. Fus.*, 2018]

- In EUROfusion, option to build a hybrid (HTS+LTS) DEMO CS under investigation
  [X. Sarasola et al, *IEEE TAS*, 2020]



- Until 2020, no experiments on quench propagation in HTS CICC → EUROfusion sponsored experimental campaign on several HTS CICC proposals

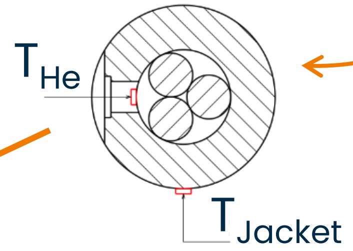
- **Here: quench experiment & model of the (sub-scaled) SPC CICCs**

Aim of the work

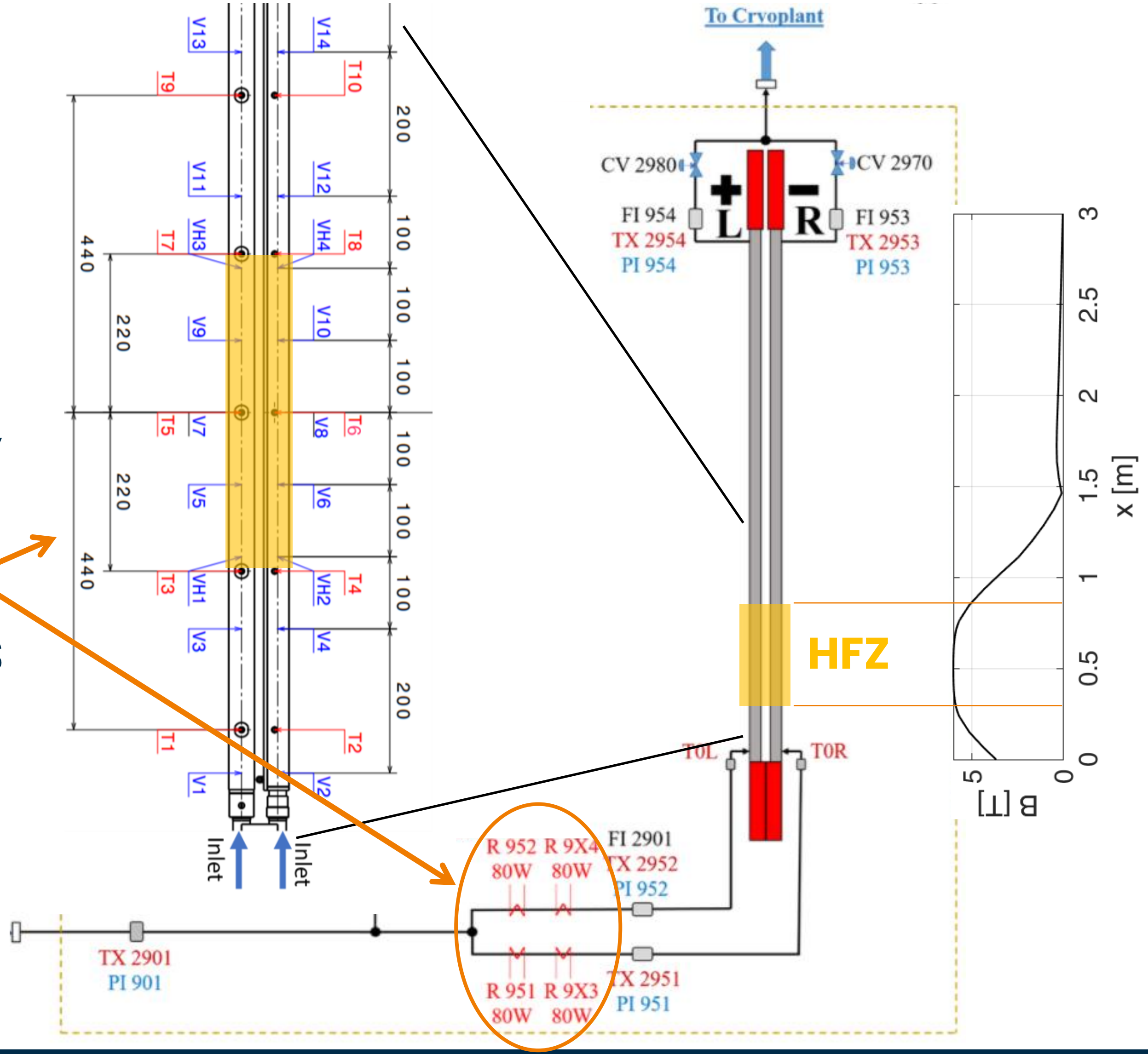
- To analyze the quench propagation experimental results
- To develop a TH/EL numerical model and validate it against measurements

Experimental setup (I)

- Tests were performed in (upgraded) SULTAN [O. Dicuonzo et al., IEEE TAS, 2021]
- Test program included:
  - DC characterization (at different I, T, B)
  - Quench tests: direct PS keeps the current constant, quench is **induced heating the He at the inlet**, current is dumped when a T threshold is reached
  - Hydraulic test with different mass flow rates
- Voltage, He and jacket temperatures were measured along the conductors



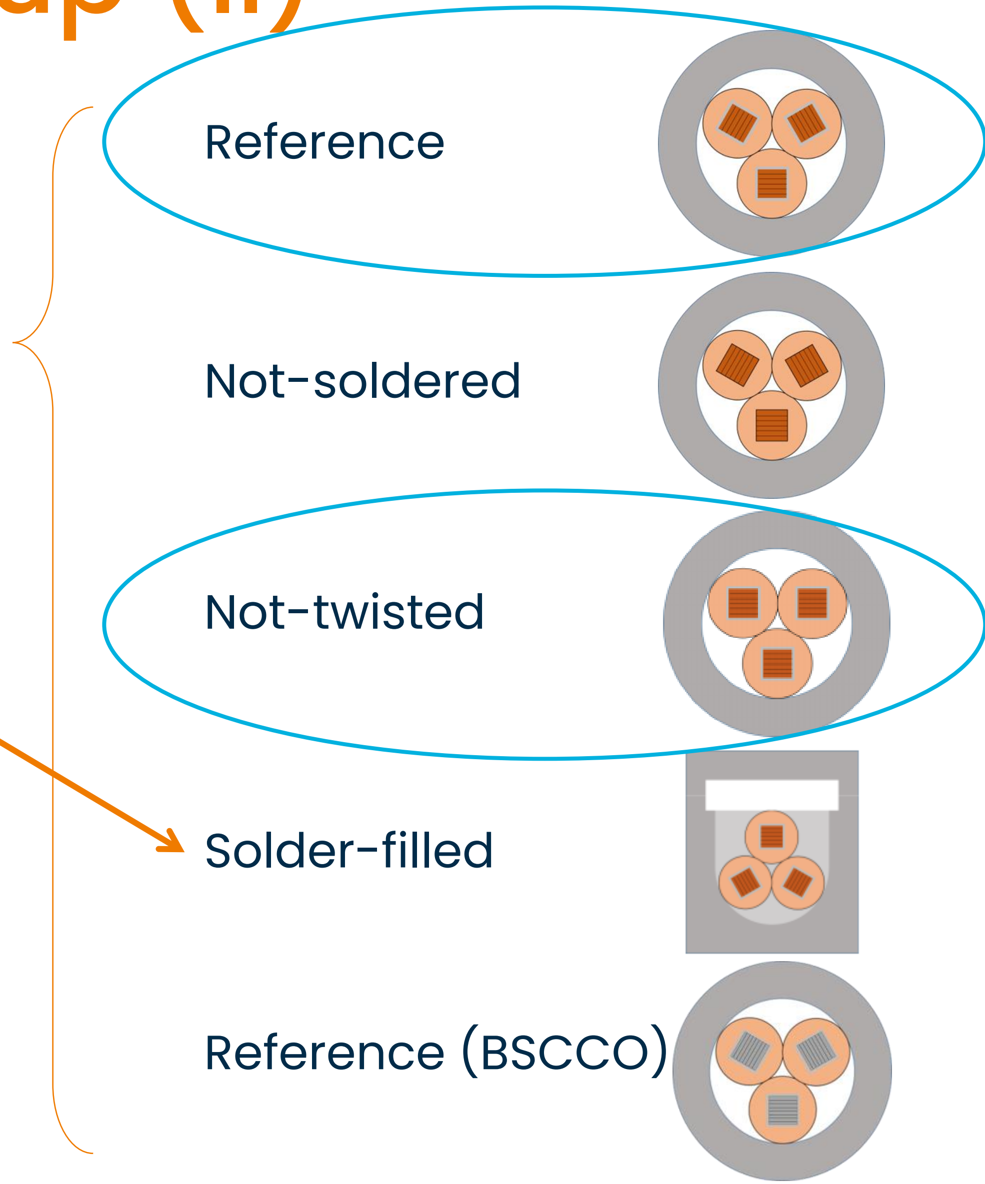
Note: no T sensors on the strands!



Experimental setup (II)

[O. Dicuonzo et al., IEEE TAS, 2021]

5 different conductors (designed and manufactured by SPC, scaling down to 15 kA their HTS CICC 50 kA concept [1]) were tested



- Not-soldered conductor was damaged
- Solder thermo-physical properties not yet available
- Interest in REBCO CICCs (tapes by SST)

Here: focus on reference and not-twisted conductors

[1] R. Wesche et al., *Fus. Eng. Des.*, 2017

DC performance

DC tests used to retrieve fundamental quantities for quench simulations (I_C, n)

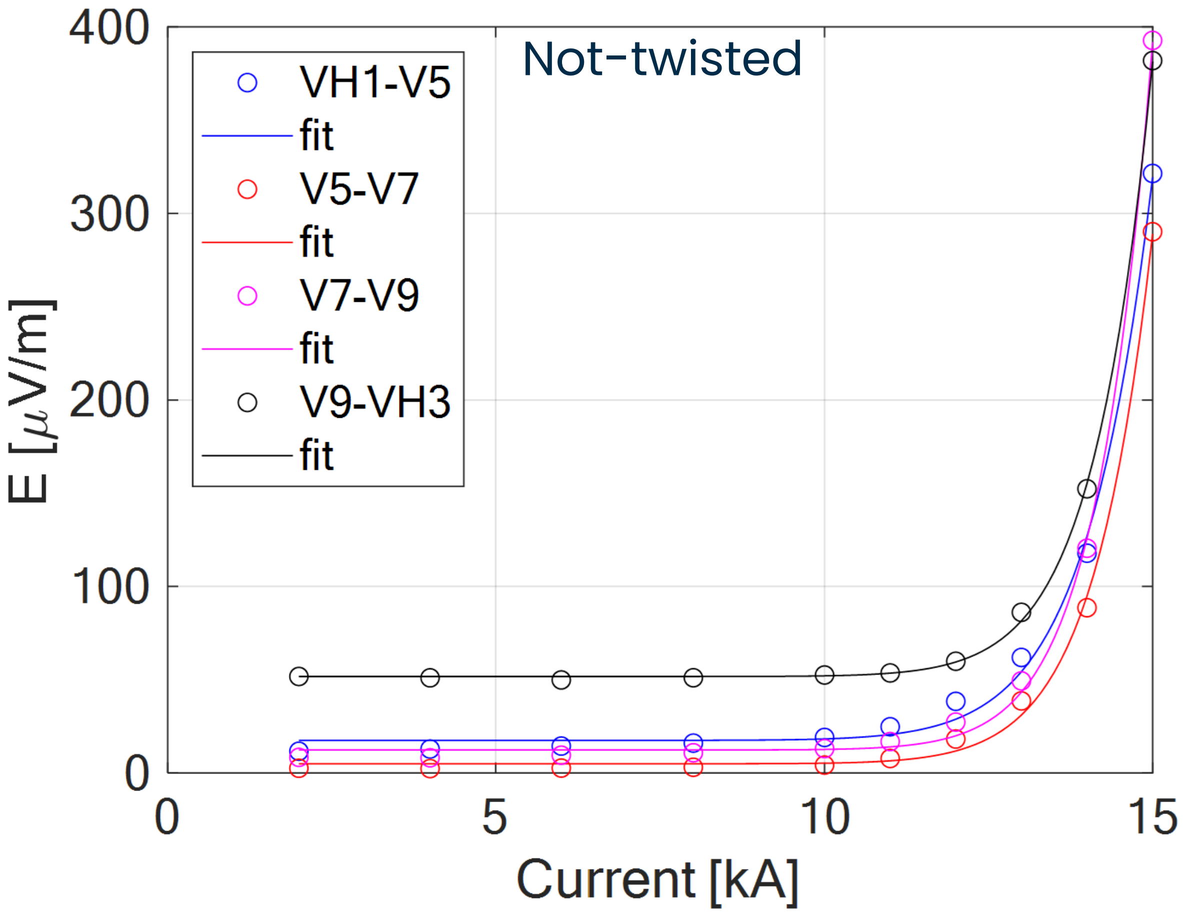
Fit measurements with power law to quantify I_C and n

$$E = E_{offset} + E_C \left(\frac{I}{I_C}\right)^n$$, EC = 100 $\mu V/m$

Find A_{SC}, given I_C and J_C scaling [2]

$$A_{SC} = \frac{I_C}{J_C(B,T)}$$

Conductor	Critical current (kA)	n-value	T_{CS} (K)
Not-twisted	13.9 (7 K, 7 T)	16.4	7.17 (15 kA, 6 T)
Reference	14.5 (5.6 K, 4 T)	8.6	6.96 (15 kA, 3.5 T)

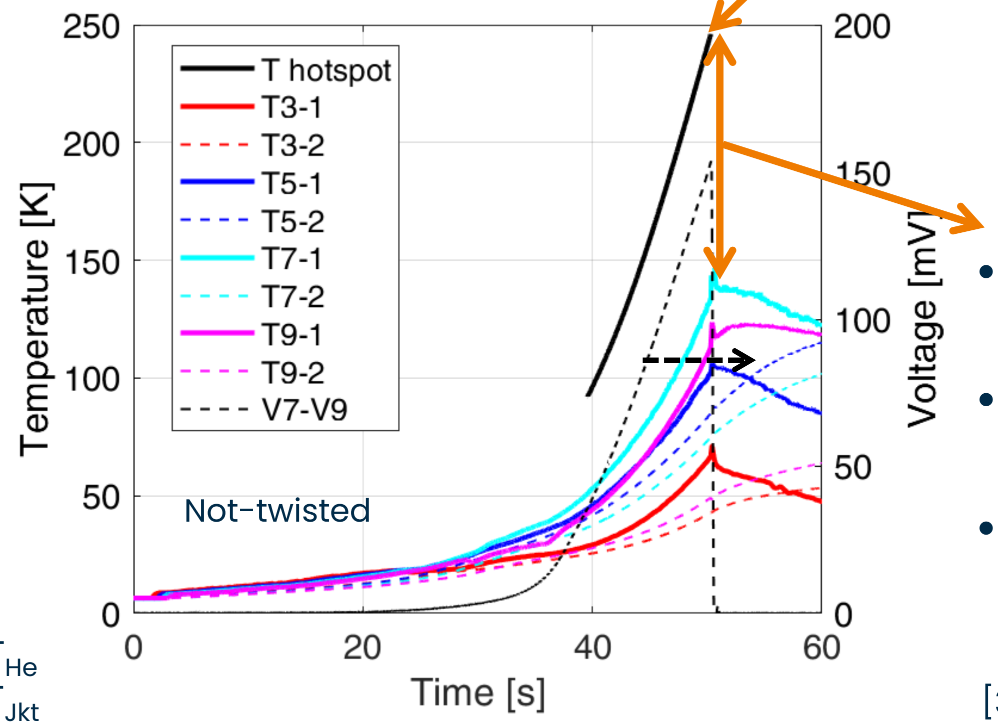


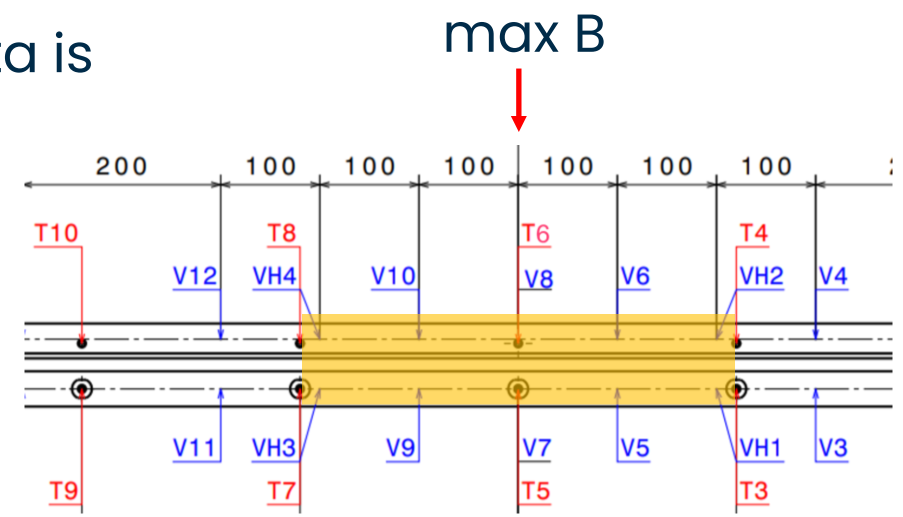
[2] R. Heller et al., IEEE TAS, 2016

Experimental results – Hotspot temperature

Typically [3], a way to reconstruct (approximately) the maximum temperature starting from experimental data is through the stabilizer (copper) resistivity:

$$V7 - V9 = \rho_{el,cu}(T, B, RRR)\frac{L}{A_{Cu}} \cdot I_{strand}$$





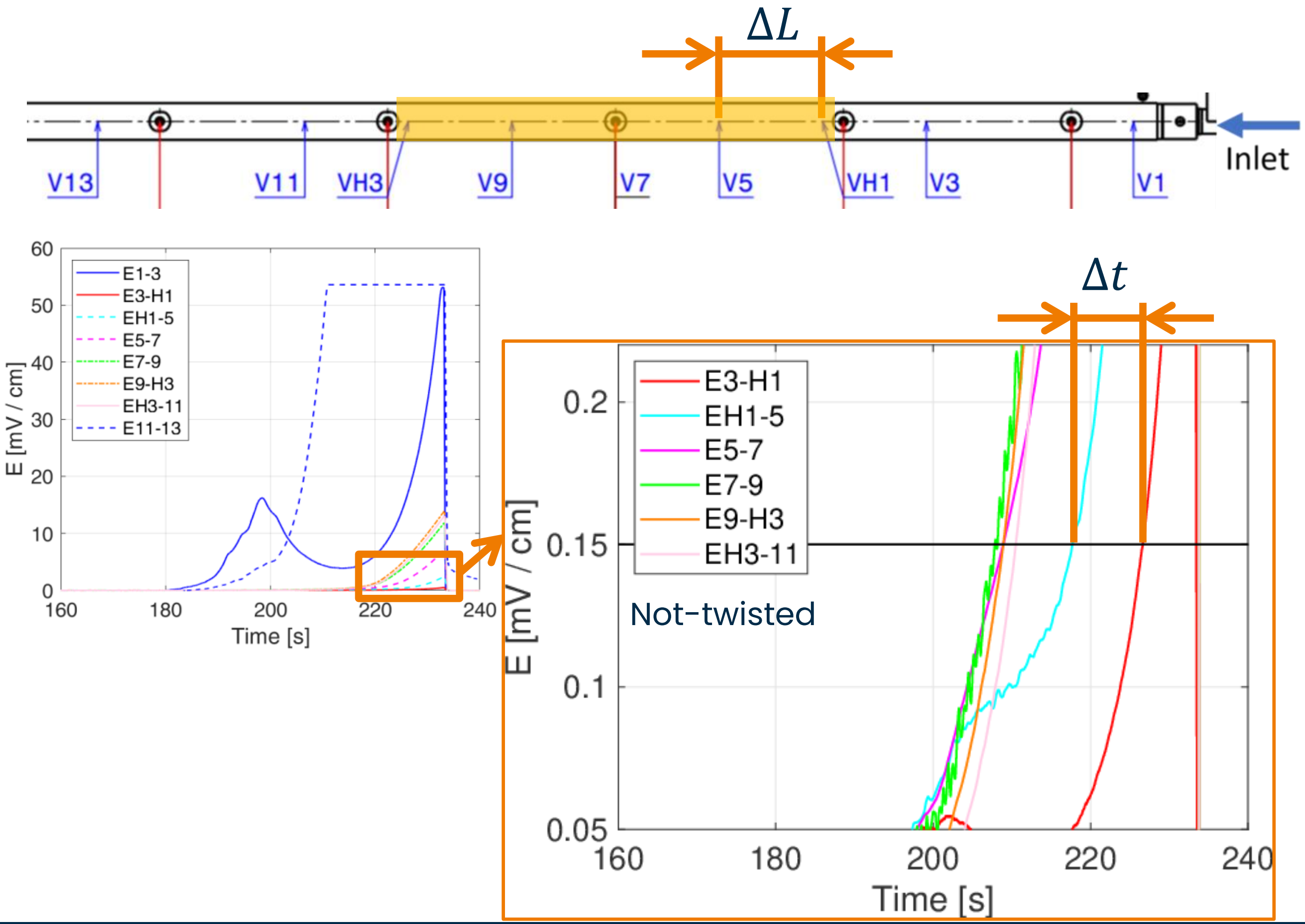
- Difference between measured T_{He} and *average* $T_{hotspot}$ >100 K at the dump! ← low wetted perimeter
- Challenge for next experiments: try to *measure* $T_{hotspot}$ (i.e., on the strand)
- Total voltage = 300 mV → $T_{hotspot}$ 125 K

T#-1 → T_{He}
T#-2→ T_{Jkt}

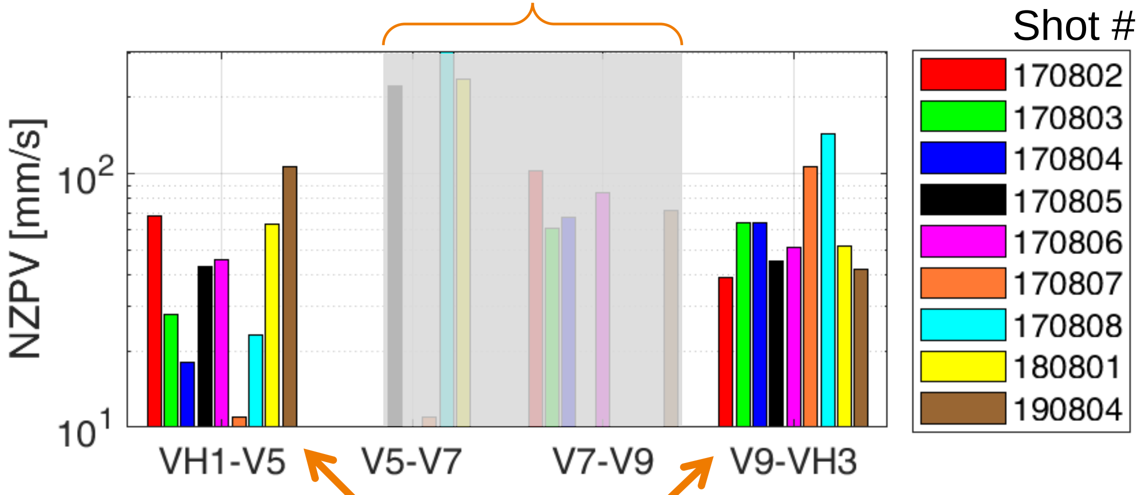
[3] R. Zanino et al., SUST, 2018

Experimental results – NZPV

Methodology: compute the speed of the quench front as the ratio of the distance between two adjacent voltage taps and the time needed to cover that distance: $\mathrm{NZPV} = \Delta L / \Delta t$



Quench initiation is always close to V7, thus V5-V7 and V7-V9 are not reliable



NZPV is within 22 and 90 mm/s

Further investigations are ongoing to reduce the spread of the NZPV values

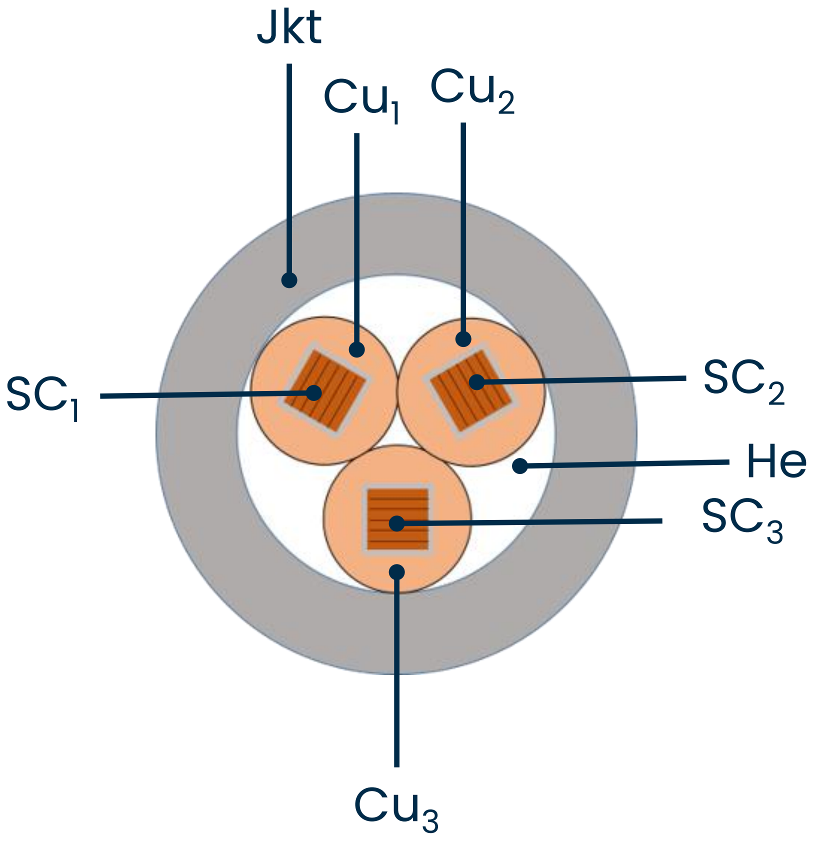
H4C model

The H4C code simulates an arbitrary number of 1D thermal, fluid and electric regions [A. Zappatore et al., SuST, 2020]

Here: a thermal and electric region is assigned to

- each stack
- each copper profile
- the jacket

A single region is used for the He



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

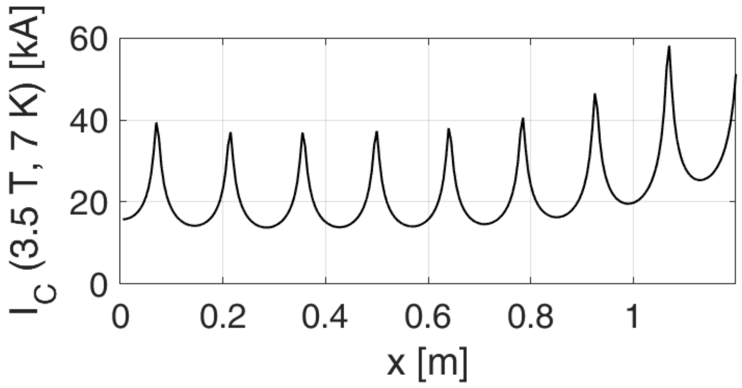
Current model:
- Imposed current in SC at conductor outlet
- Zero current gradient at conductor inlet

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

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 (**to be calibrated**)

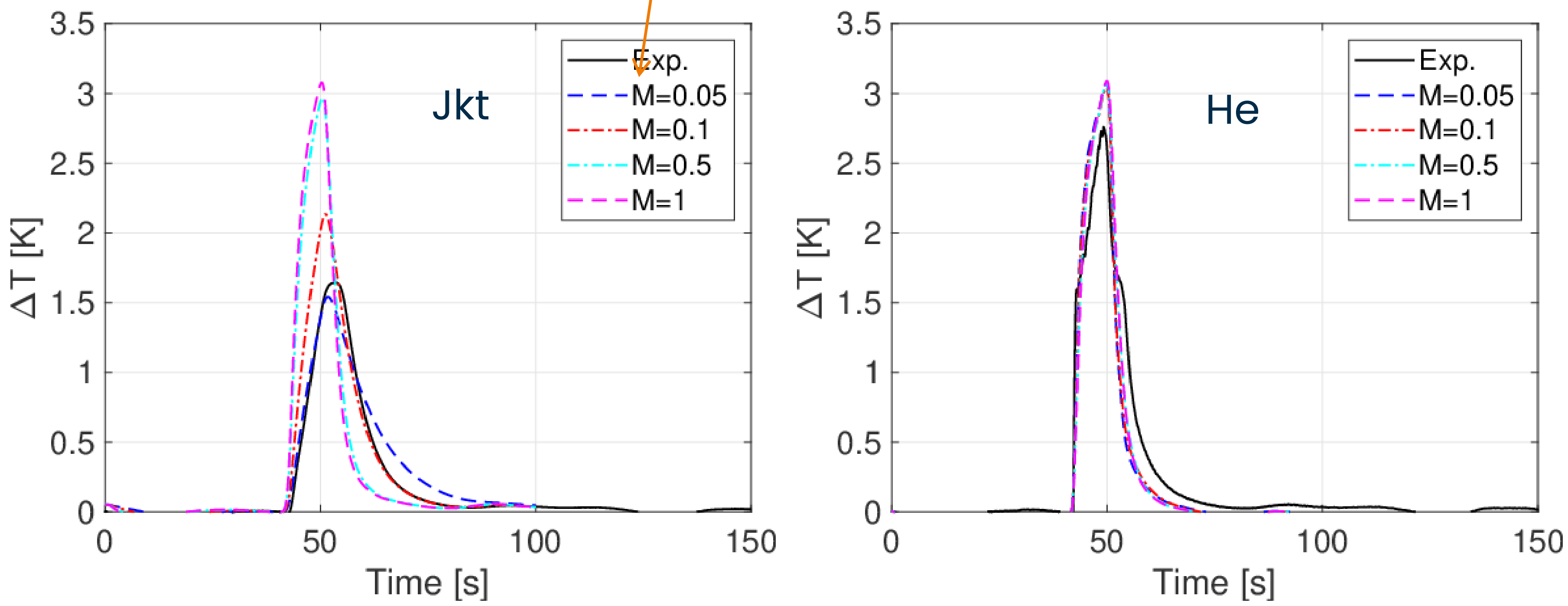


Electric contact resistances from [N. Bykovskiy,2017], [A. Zappatore, 2021], [M. Vogler, 1993]
Thermal contact resistances from [Y. A. Cengel, Fundamentals of Thermal-Fluid Sciences, 2017]

Model calibration (He HTC)

Heat slugs are used to calibrate (on not-twisted, cross-checked on reference) the He heat transfer coefficient:

$$HTC_{calibrated} = M \cdot HTC_{Dittus-Boelter}$$

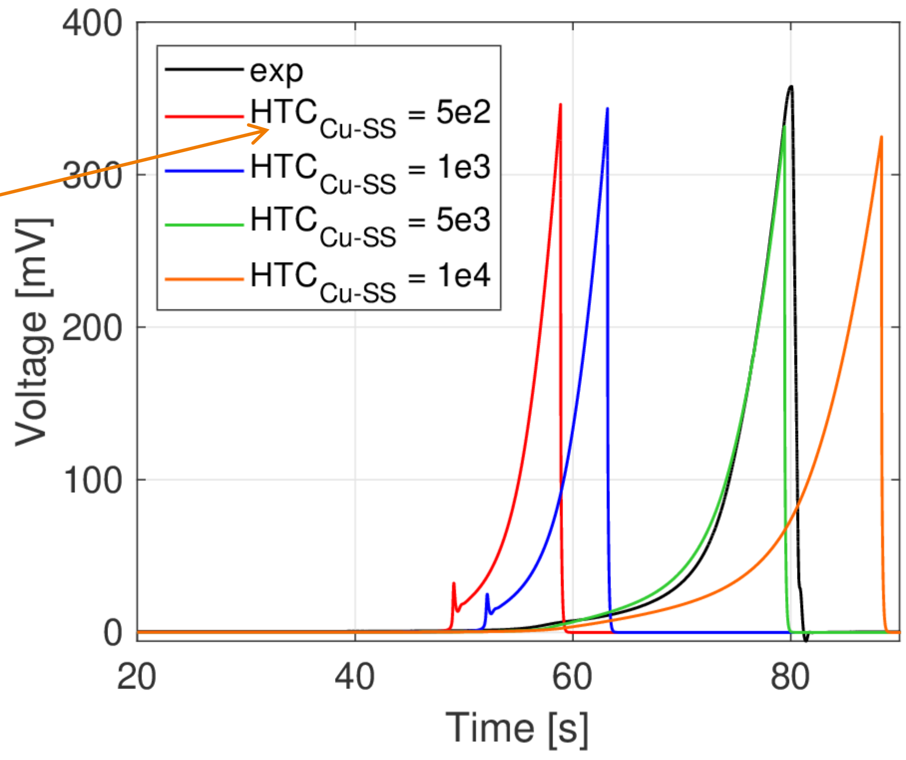


Model calibration (Cu-SS contact resistance)

Quench on L2 are used to calibrate the thermal contact resistance between copper and the steel jacket

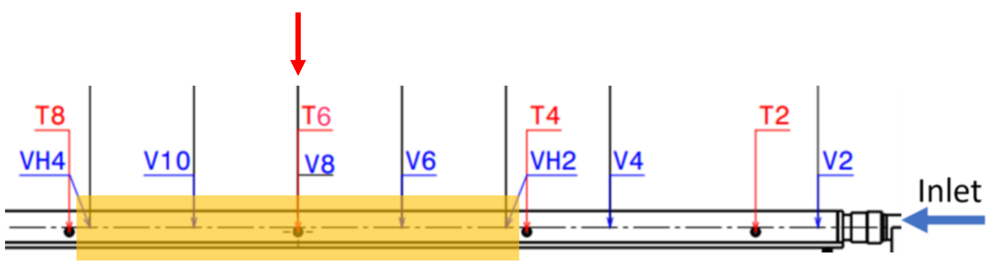
$$HTC_{calibrated} = HTC_{Cu-SS} \left[{}^{W}/_{m^2 K} \right]$$

It has strong impact on voltage rise → the smaller HTC_{Cu-SS}, the faster the temperature increase in the stacks

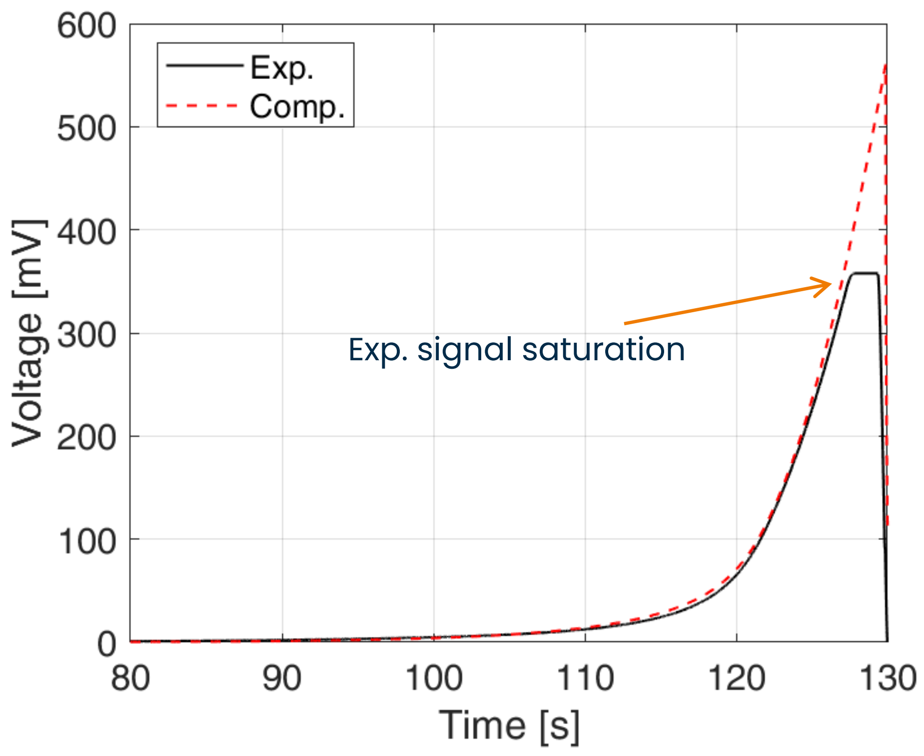


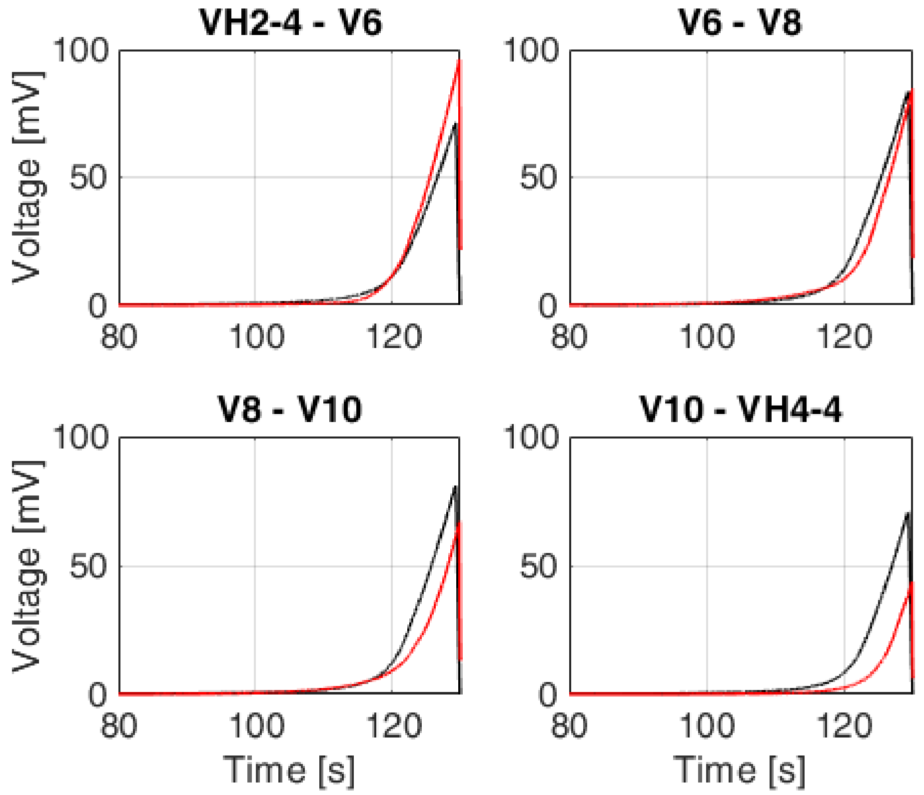
Results – R3 (I)

All model parameters calibrated on L2 data are kept frozen for the simulation on R3



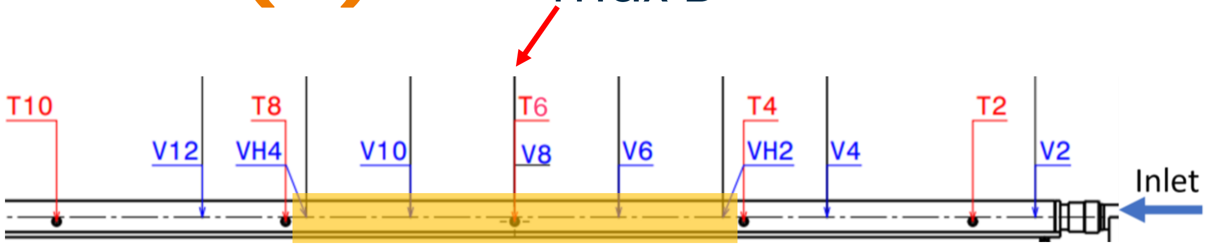
- Total voltage rise is very well reproduced by the simulation
- Local voltage rise shows slight overestimation towards the upstream boundary of the HFZ and an underestimation on the other side (however, these are the most challenging quantities to reproduce!)





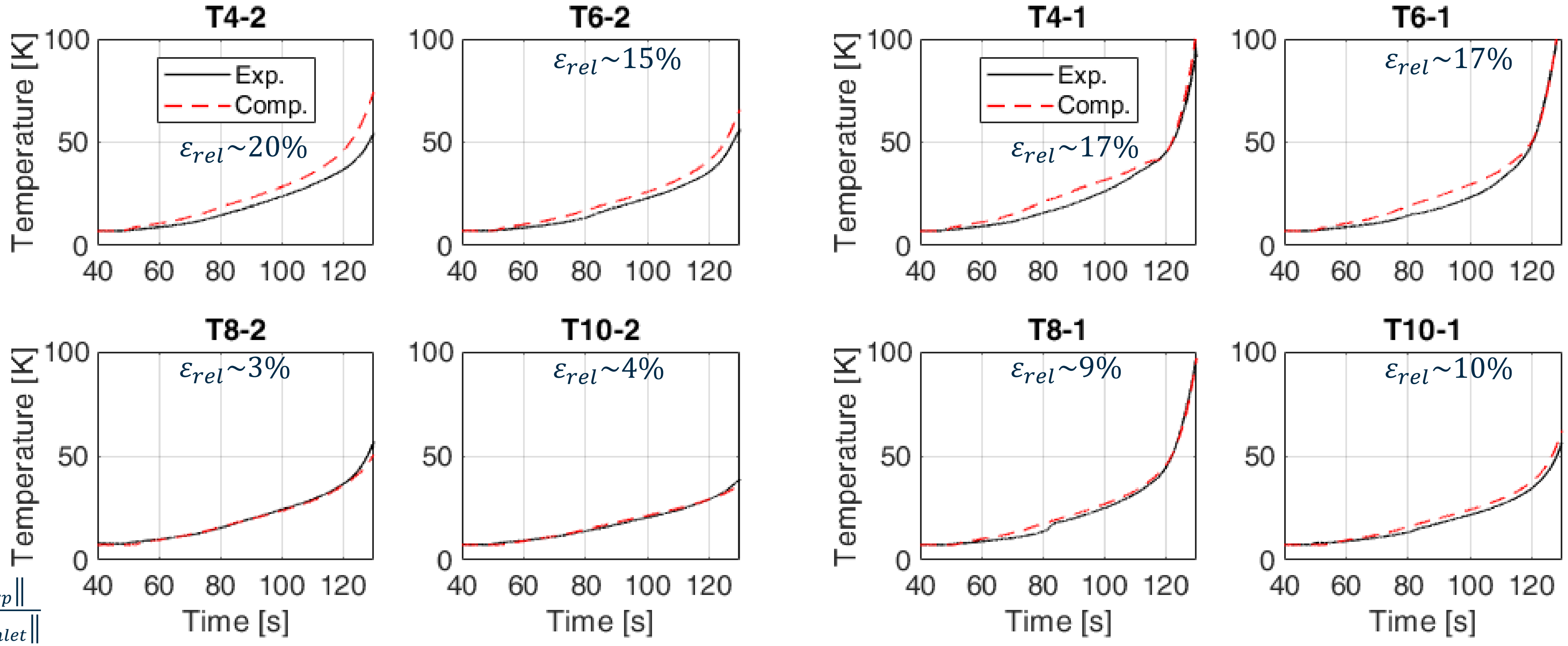
Results – R3 (II)

Both jacket and helium temperature in the high field zone are well reproduced → the model can be used to analyze the experiments



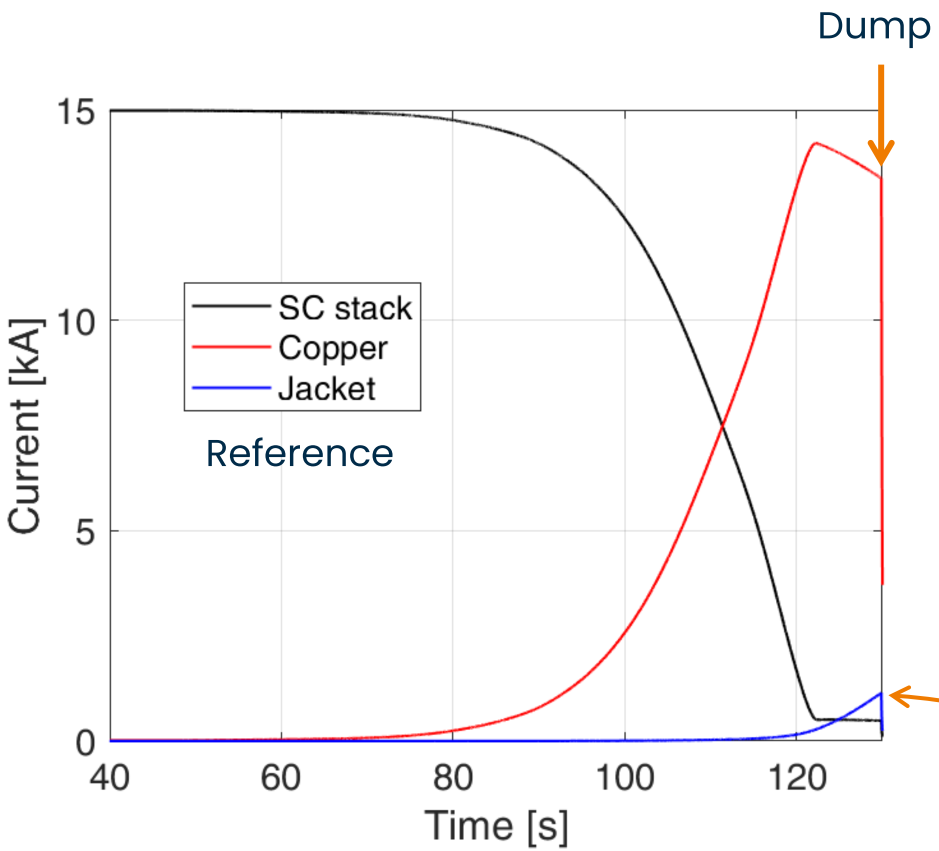
Jacket

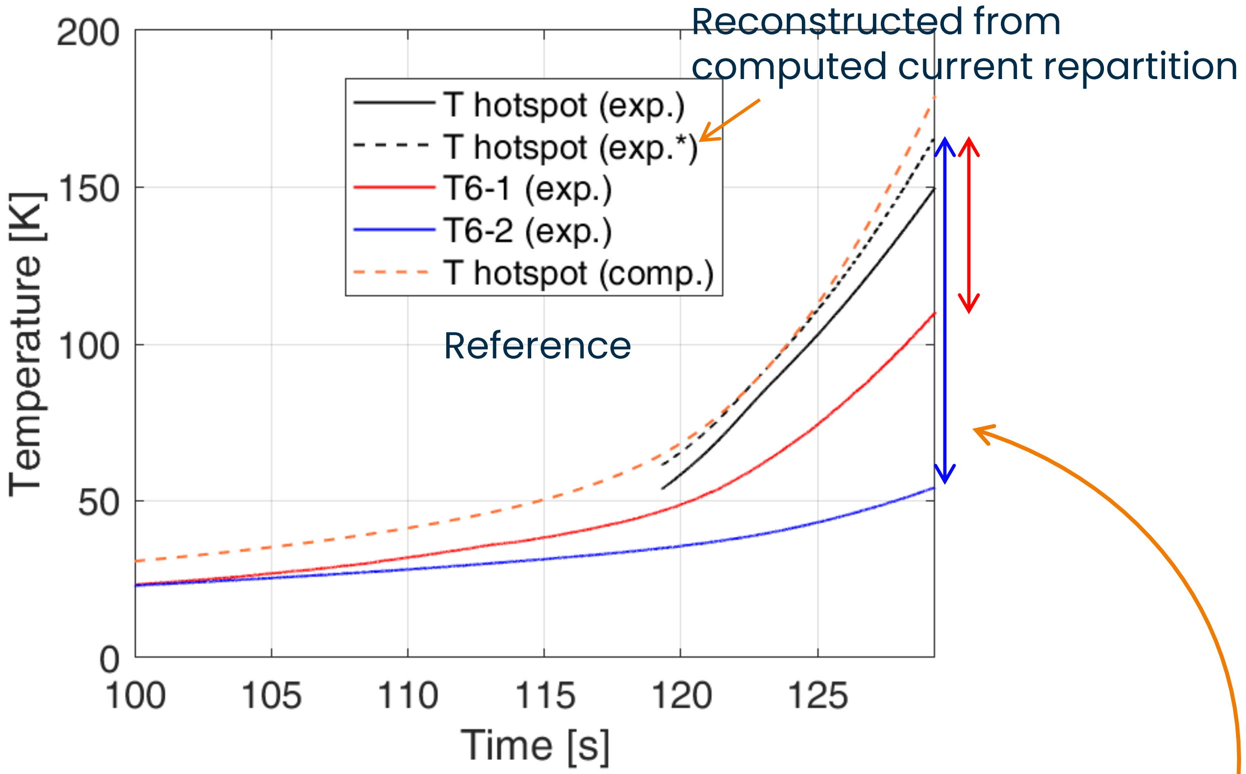
Helium



$$\varepsilon_{rel} = \frac{\|T_{comp} - T_{exp}\|}{\|T_{exp} - T_{exp,inlet}\|}$$

Current repartition & hotspot temperature





The current flows *slowly* (~ 40 s) from the SC stacks to the copper profiles

Before the dump, ~ 1.1 kA are flowing in the jacket

- If current repartition is neglected, virtual sensor underestimates by ~10% the hotspot temperature
- The comp. hotspot temperature is in very good agreement with the virtual sensor (within 7%)
- strong thermal difference (50 K wrt He and >100 K wrt jacket) within the conductor confirmed

Conclusions and perspective

- The analysis of the quench experiment of an HTS SPC-like conductor was carried out, finding
  - Hot-spot temperature ~170 K (with total voltage ~0.5 V)
  - Normal zone propagation velocity around 50 mm/s
- The H4C model was calibrated and then validated against experimental data (maximum error 20%) and it gave an insight on the hotspot temperature
- In perspective, the analysis of the other samples will be carried out along with other conductors to be tested

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