A critical assessment of the issues in the thermal modeling of an HTS CroCo conductor for the EU DEMO TF coils

A. Zappatore[a], W. H. Fietz[b], R. Heller[b], L. Savoldi[a], M. J. Wolf[b] and R. Zanino[a]

[a]*NEMO group, Dipartimento Energia, Politecnico di Torino, Torino, Italy*
[b]*Karlsruhe Institute of Technology, Karlsruhe, Germany*

Outline

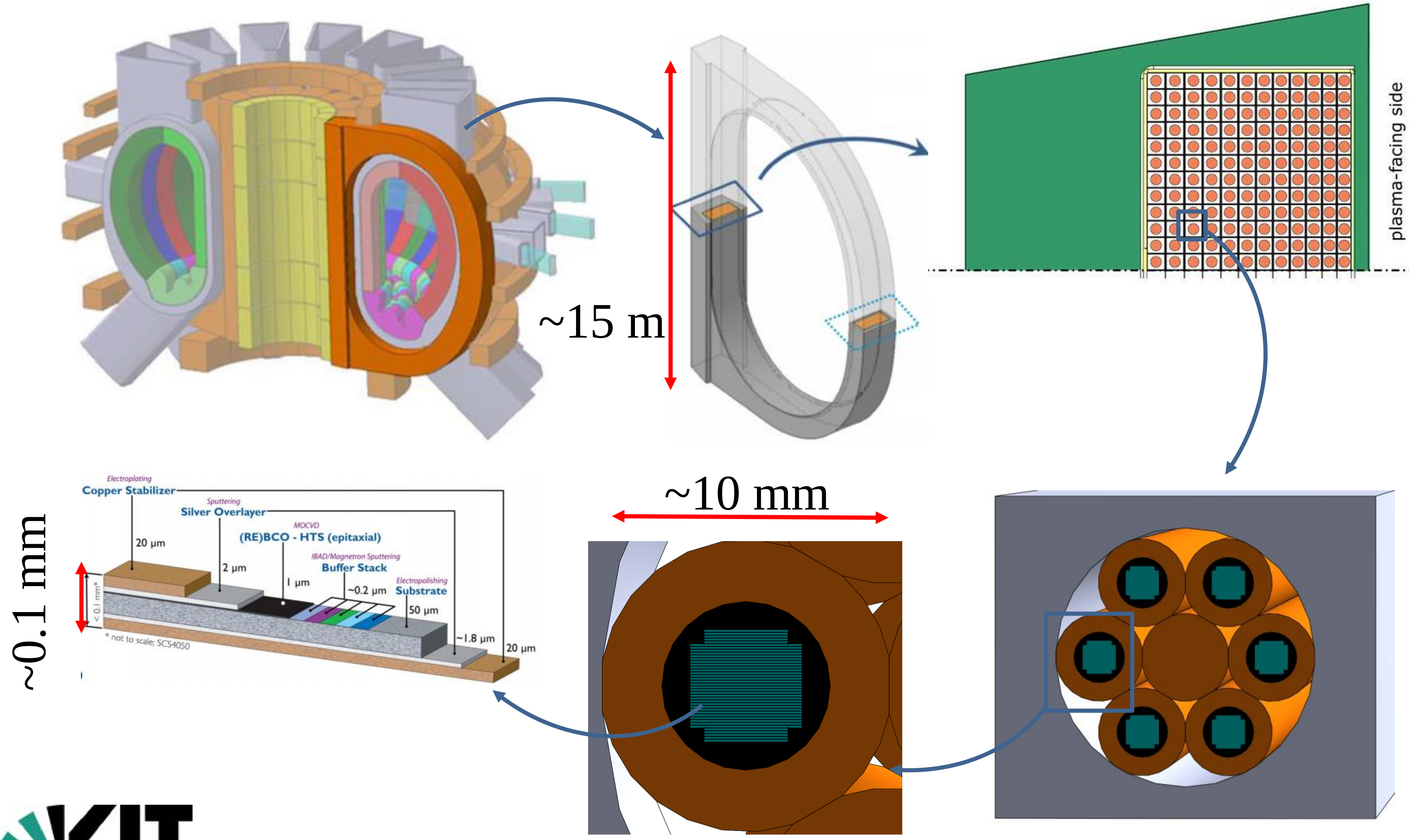
- Aim of the work
- Multi-scale problem
- Rationale
- Material properties
- Characteristic time scales
- Characteristic space scales
- Simulation setup
- Results
- Conclusions and perspective

Aim of the work

Test the reliability of the typical 1D model adopted for LTS conductors (4C, VENECIA, THEA, …) on the analysis of HTS conductors for fusion applications

Highlight the issues and possible solution, e.g. new models, to catch the relevant quantities during typical thermal-hydraulic transients in fusion magnets

Multiscale problem (I) – Space scale



Multiscale problem (II) – Time scale

Normal operation:

- TF: nuclear heat load (steady during burn ~7200 s, switch on/off at SOF/EOF)
- CS: initial magnetization = 1 s
- PF: shortest time scale = initial charge (30 s)

CS and PF current variation induce AC losses also on TF coils, but so far they have not been taken into account (or even never quantified?)

Off-normal operation:

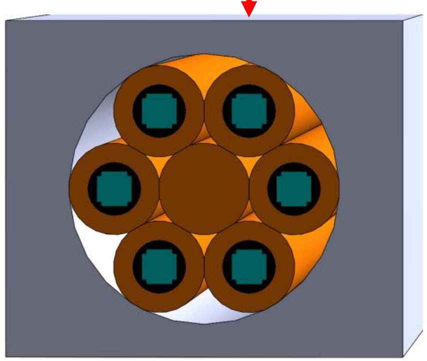
- Quench propagation ~1 s (see below)

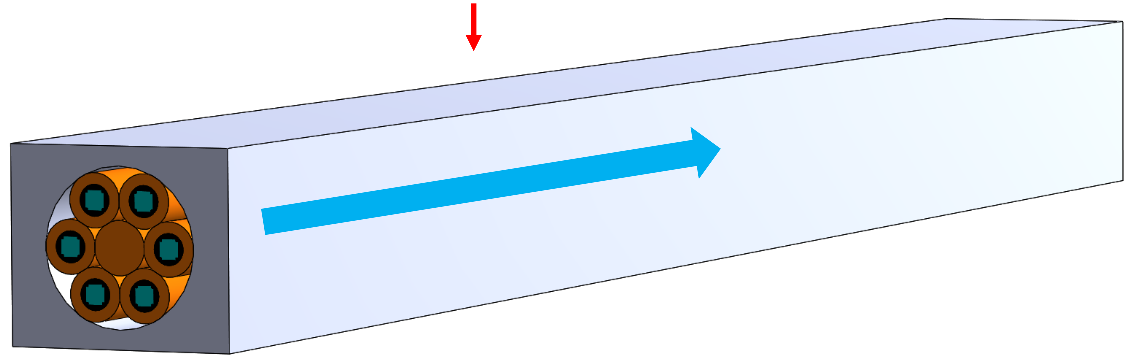
Rationale

Thermo-hydraulic in forced flow CICC

Conduction + convective heat transfer to He (normal to centerline). <u>Time scale <~1s</u>

Advection + diffusion (dominated by He flow, parallel to centerline) <u>Time scale (He transit time) ~10^3 s</u>





Very different wrt LTS CICC→investigation needed on time and space scales on the 2D CICC **cross-section**

HERE

Similar to LTS CICC and same order of normal operation thermal driver → 1D approximation of fluid and solids along the conductor will be kept

POLITECNICO DI TORINO
nemo

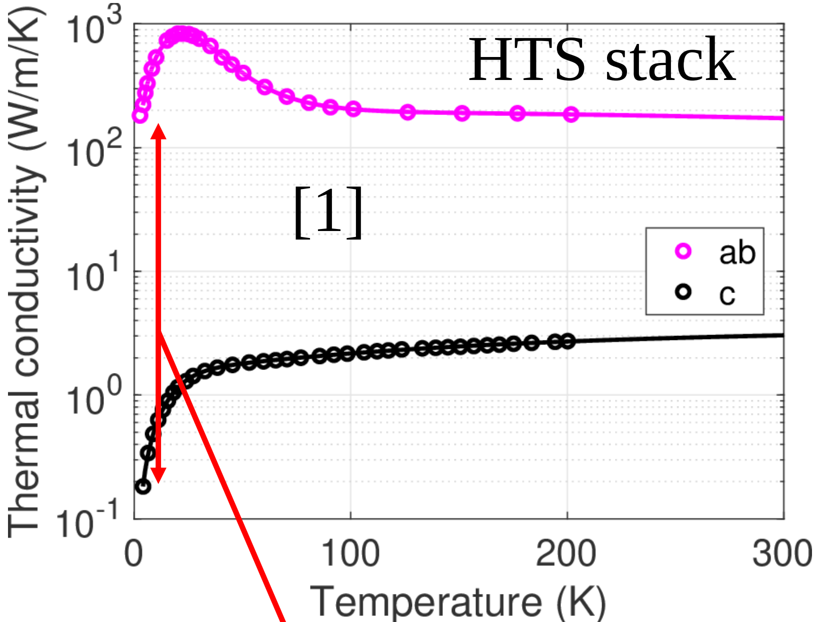
Characteristic time scales (I) - Definition

Characteristic time of the heat transfer to He = $\boldsymbol{\tau_c} = \frac{\rho \cdot c \cdot A_{cross}}{h \cdot P_w}$

Diffusion time = $\boldsymbol{\tau_d} = \frac{\delta^2}{\alpha}$

Characteristic length

Thermal diffusivity = $\frac{k}{\rho \cdot c}$



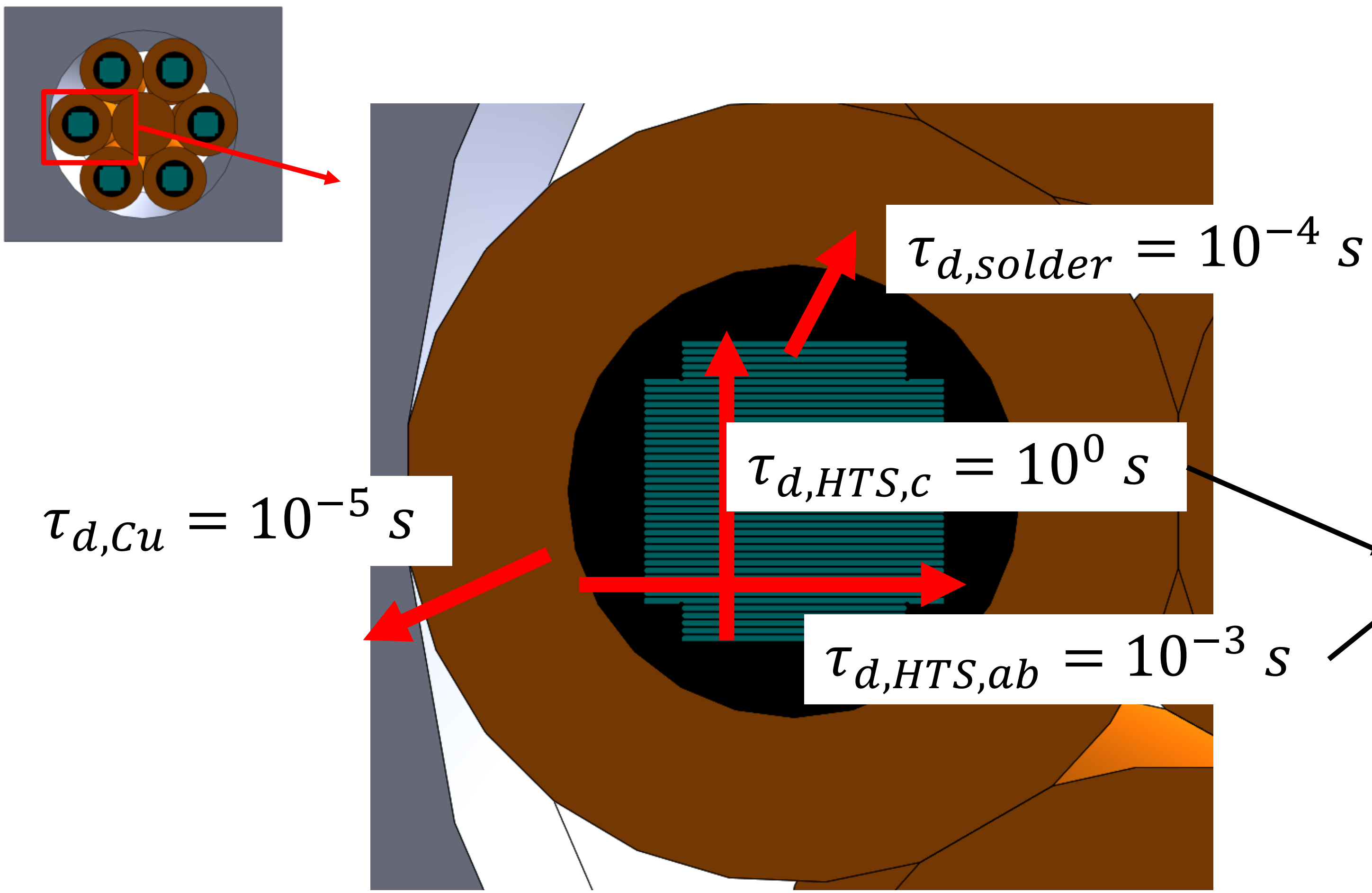
~3 orders of magnitude at low temperature→ strong anisotropy

[1] N. Bagrets, W. Goldacker, A. Jung, and K.-P. Weiss, Thermal Properties of ReBCO Copper Stabilized Superconducting Tapes, IEEE TAS, 23(3), 2013

KIT Karlsruhe Institute of Technology

Characteristic time scales (II) – HTS macro-strand

@ 4.5 K

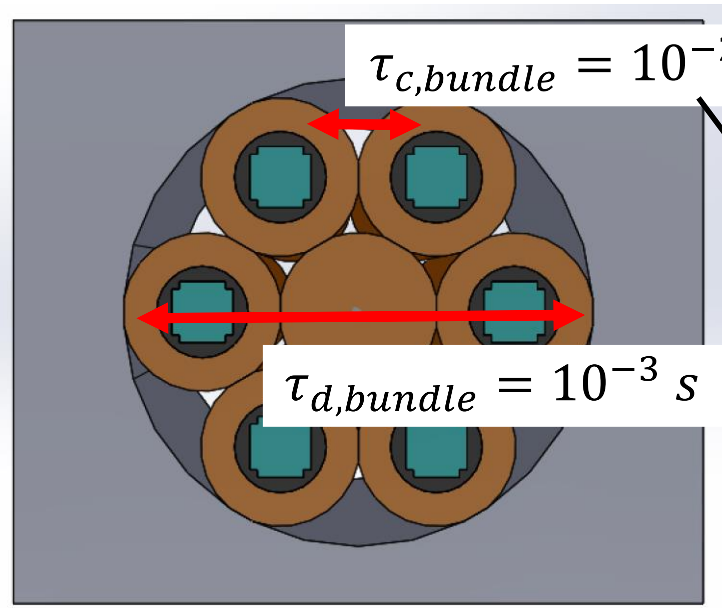


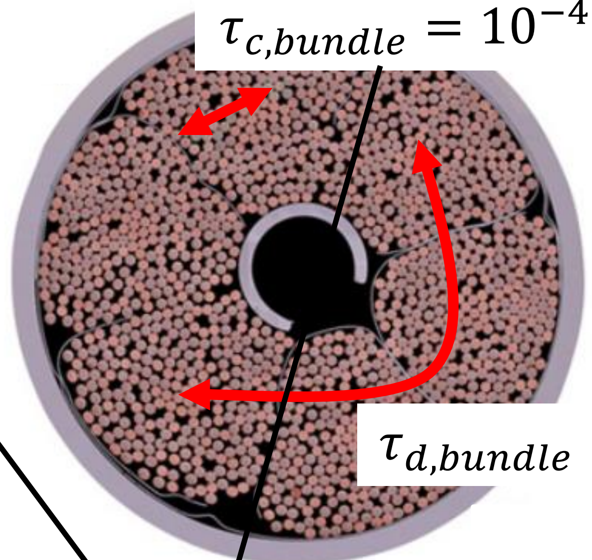
Strong anisotropy in thermal conductivity implies very different diffusion time scales within the stack

POLITECNICO DI TORINO

Characteristic times scales (III) HTS vs. LTS bundle

Considering all the solids lumped in only 1 region with equivalent (weighted on the cross section) material properties:





⇩

Therefore we can lump the cross section in only one region? It depends…

Difference mainly due to big difference in wetted perimeter (18 cm vs. 3 m!)

Characteristic space scales

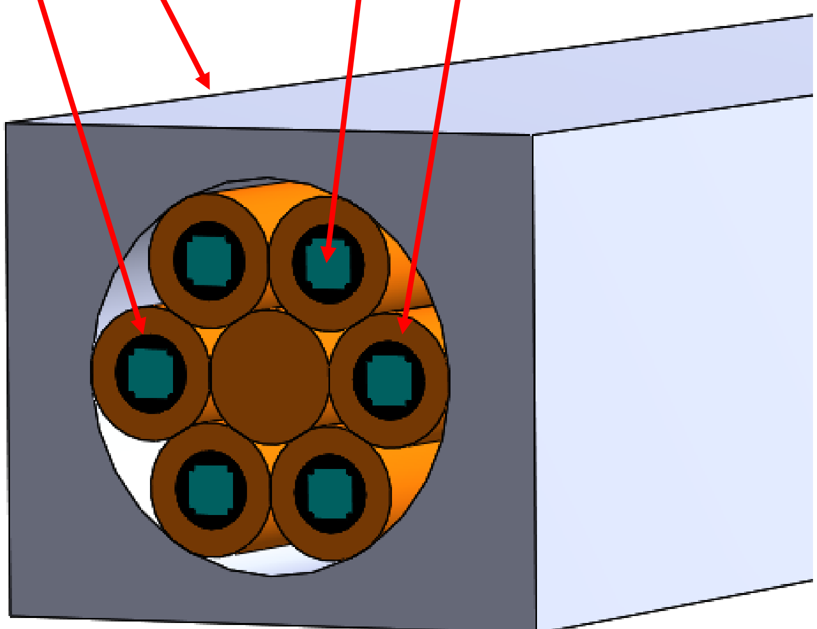
$$Biot = \frac{R_{cond}}{R_{conv}} = \frac{h \cdot L_c}{k}$$ →

If **Bi<0.1**, thermal gradients in the solid are negligible with respect to those in the fluid → the solid dimension can be lumped without considering the conduction

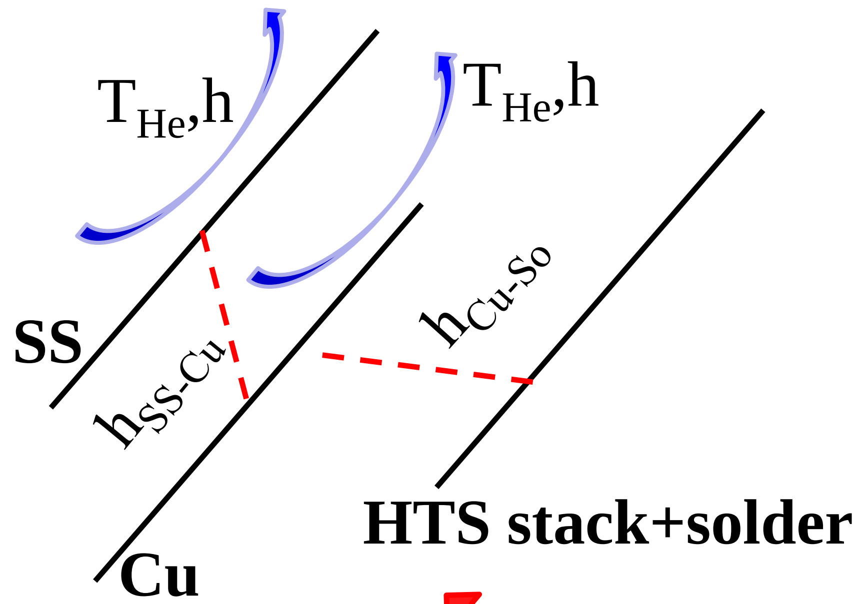
	Tape		**LTS (bundle)**
direction	ab	c	isotropic
Characteristic length (mm)	4 (along tapes in cross section)	4 (normal tapes in cross section)	40
Thermal conductivity (W/m/K)	244.80	0.21	354.50
Bi	0.0016	**1.9**	0.011

3D(2D) model vs. 1D(0D) model

SS jacket, Cu seamless tubes, Solder, HTS stack are simulated (no twisting considered)



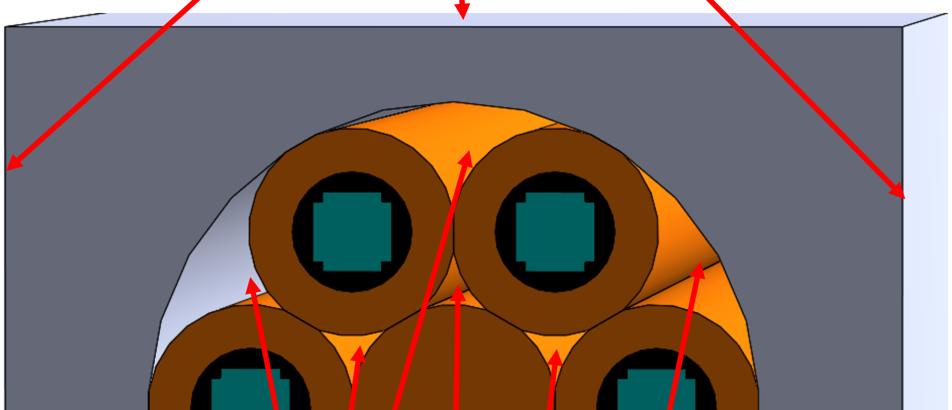
3 different 1D solid regions are simulated: SS jacket, Cu and HTS stack+solder



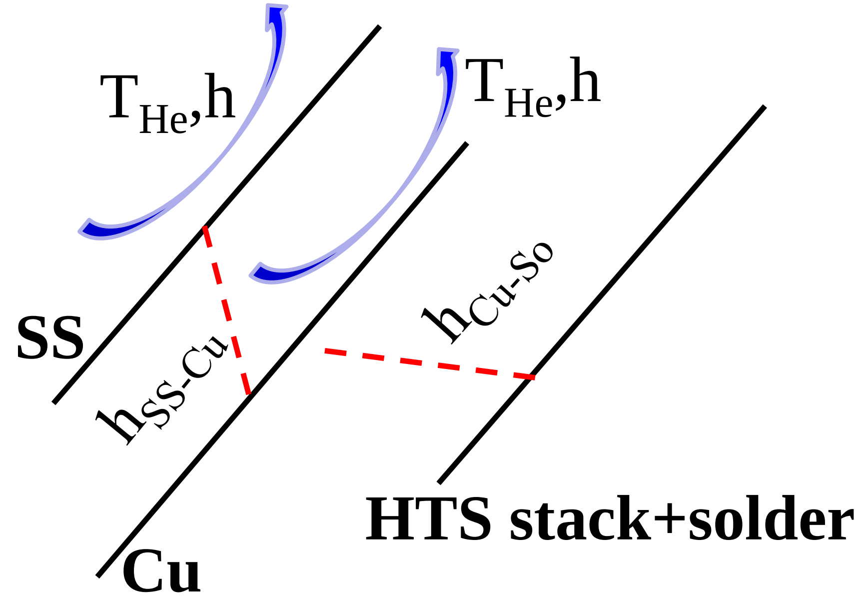
Lumping the main solid regions

Simulation setup

Adiabatic



Robin-type BC: T_{He}=4.5 K,
h = 100 W/m^2/K

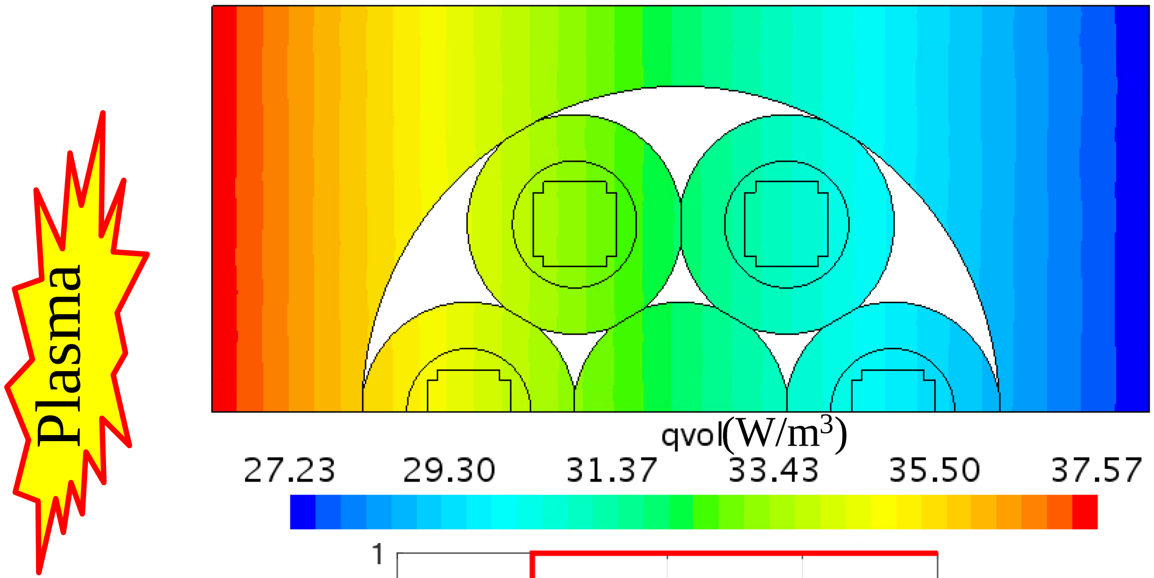


T_{He}=4.5 K
h = 100 W/m^2/K
$h_{SS\text{-}Cu}$ = 0
$h_{Cu\text{-}So}$= 10^6 W/m^2/K

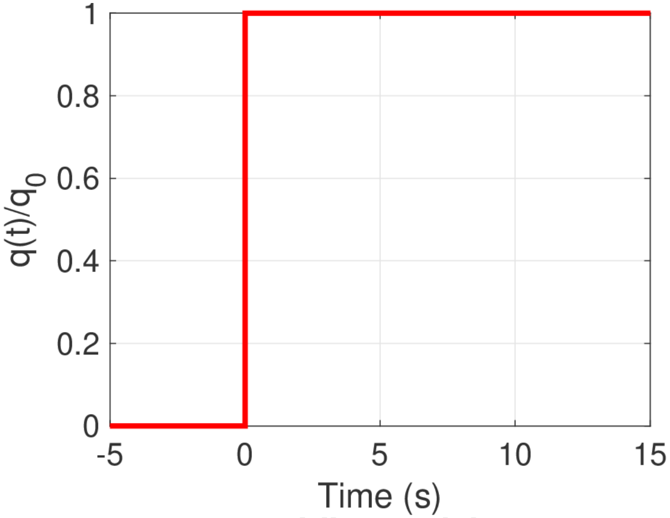
Perfect thermal coupling

Thermal driver: dependent on the transient simulated, see below
Initial temperature = 4.5 K in each region

Driver - Burn



Exponential spatial distribution of the nuclear heat load

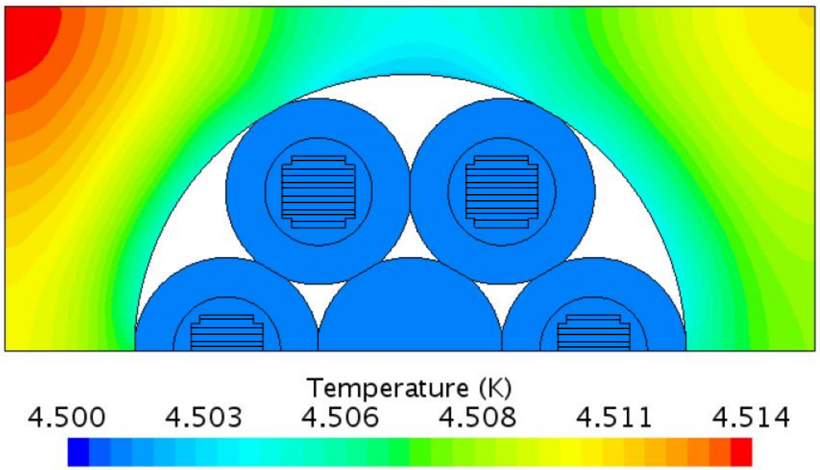


Step at SOF, then steady at its maximum value

Karlsruhe Institute of Technology

Results - Burn

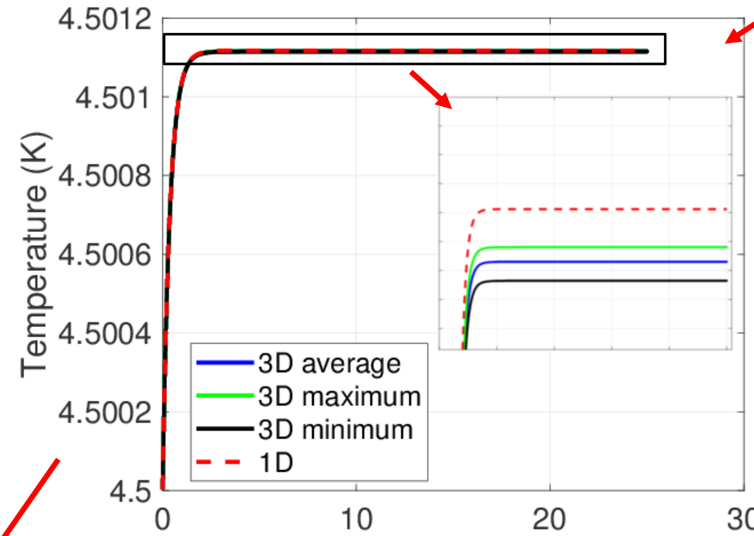
3D model



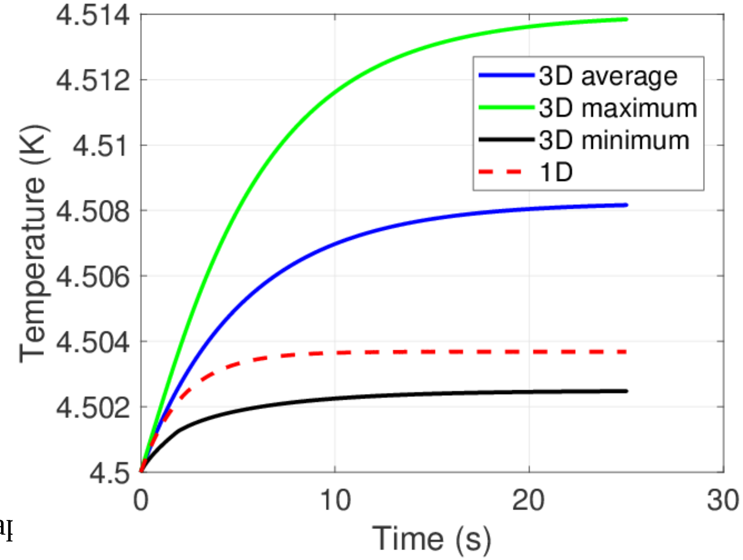
Temperature map at steady state. Non-uniformity in SS jacket, but not relevant

1D model

Strands



Jacket



The temperature in the strands (Cu+HTS+solder) is perfectly reproduced by the 1D model. The average temperature in the jacket is representative of the average value coming from the 3D model

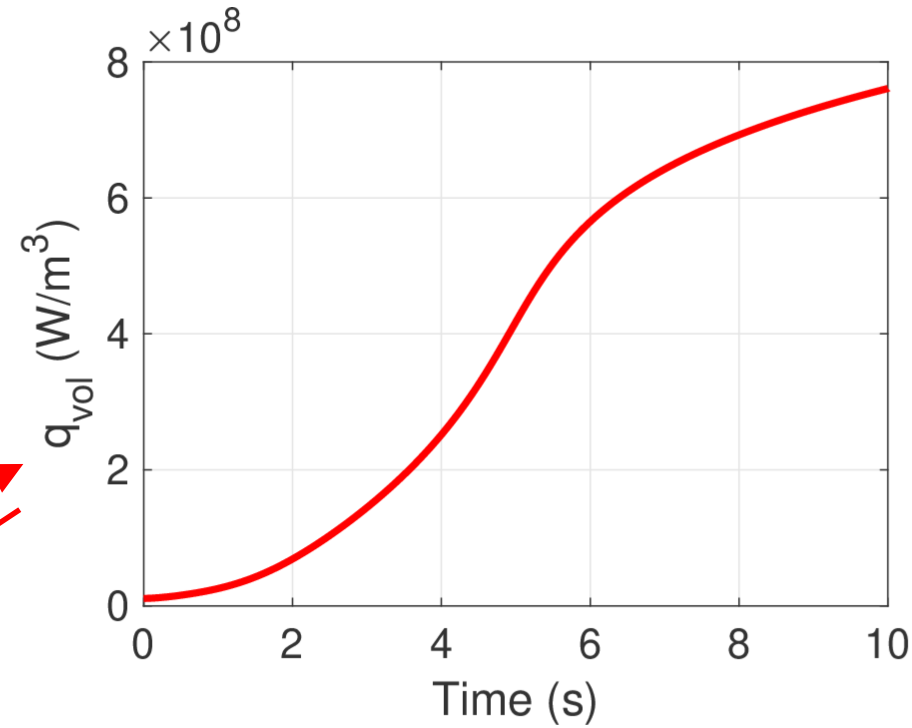
Driver - Quench

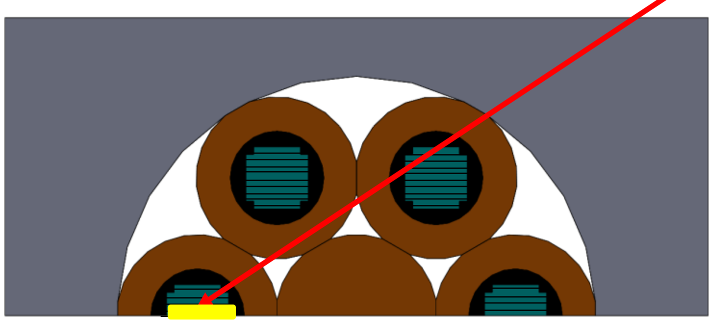
Adiabatic quench of a single tape → Simple estimation of quench power deposition and characteristic time

$$\rho c A_{stack} \cdot \frac{dT}{dt} = \rho_{el} \cdot \frac{I_{tape}^2}{A_{tape}}$$

⇩

$$\rho c \cdot \frac{dT}{dt} = q_{vol} = \rho_{el} \cdot \frac{I_{tape}^2}{A_{stack} \cdot A_{tape}}$$

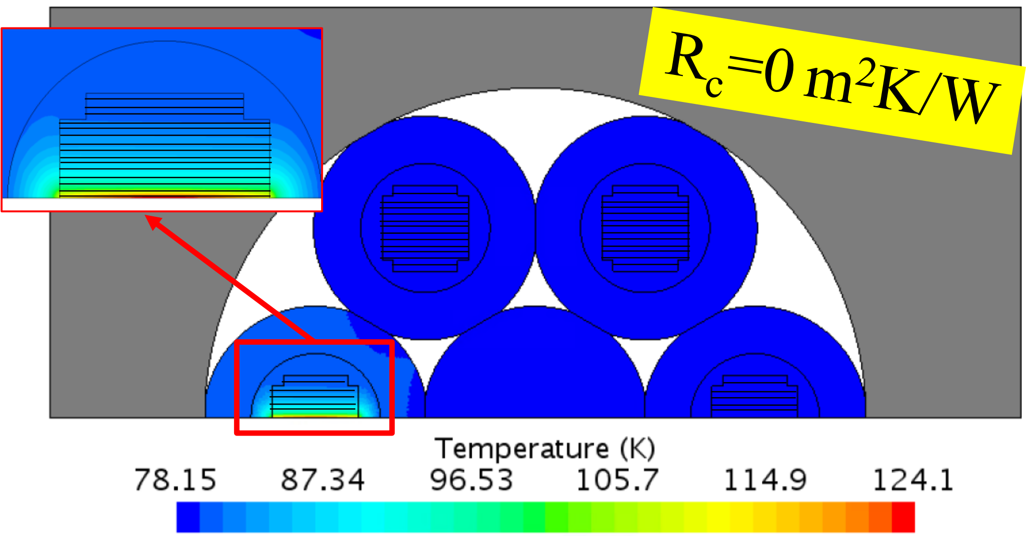




Parametric study on *contact resistance* (*R_c*) between macrostrands and on *orientation* of the tapes is performed

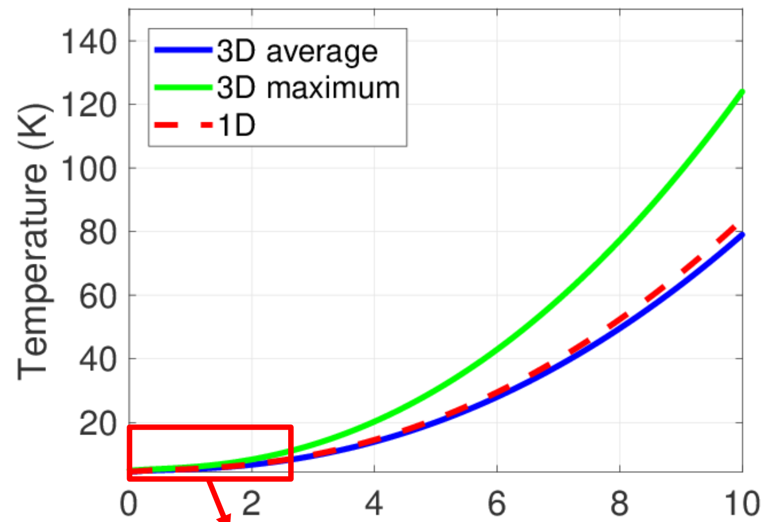
Results – Quench (I)

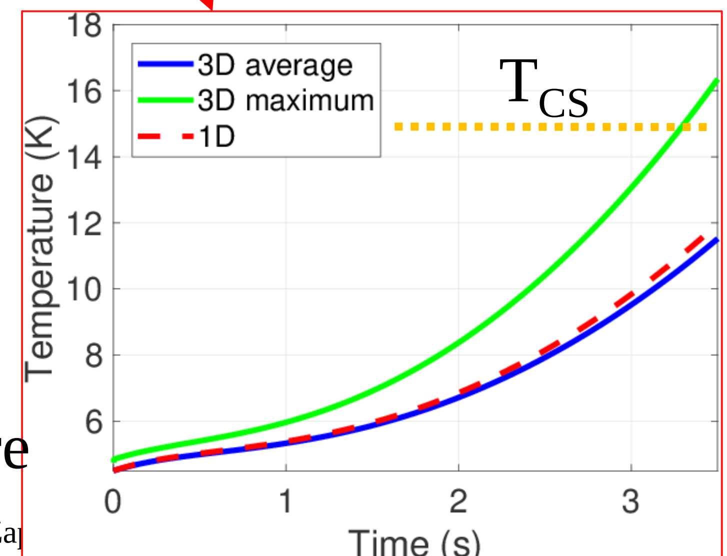
3D model
Temperature map at 10 s



Strongly non-uniform temperature distribution on the cross section

1D model



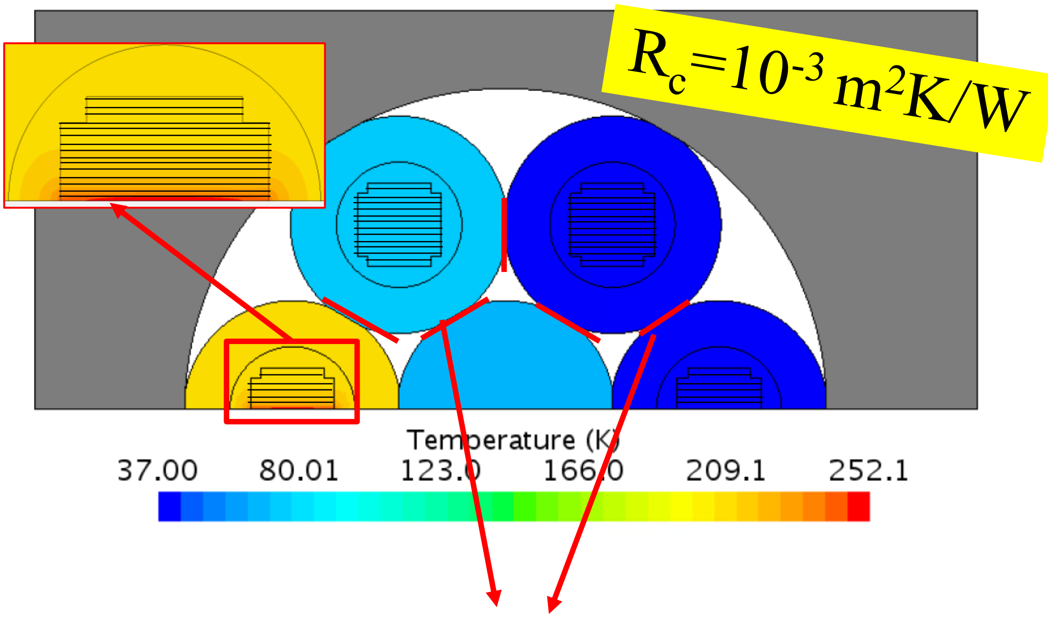


The 1D model computes progressively wrong maximum, i.e. hotspot, temperature

Results – Quench (II)

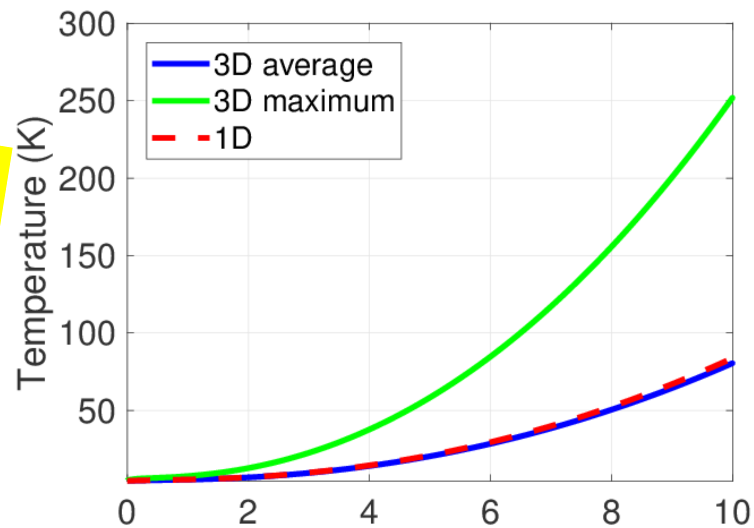
3D model

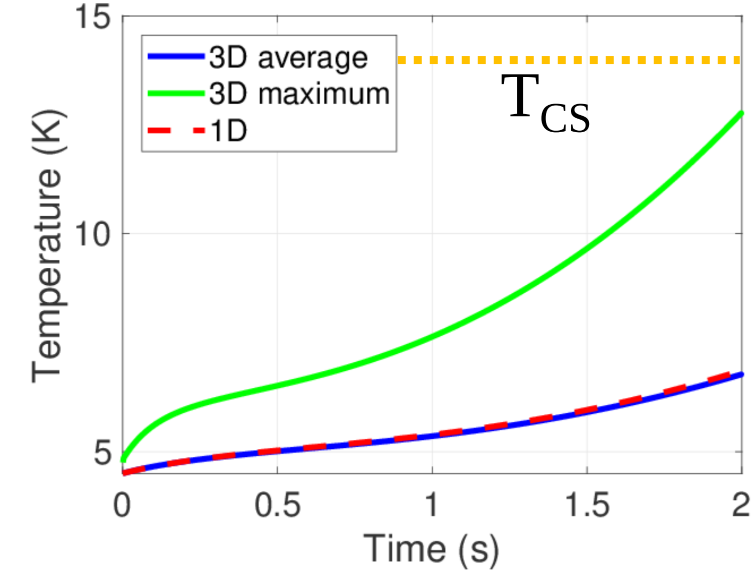
Temperature map at 10 s



If realistic contact resistance between macrostrands is taken into account (10^{-3} m^{2}K/W, 2 mm contact length) the picture is much worse!

1D model





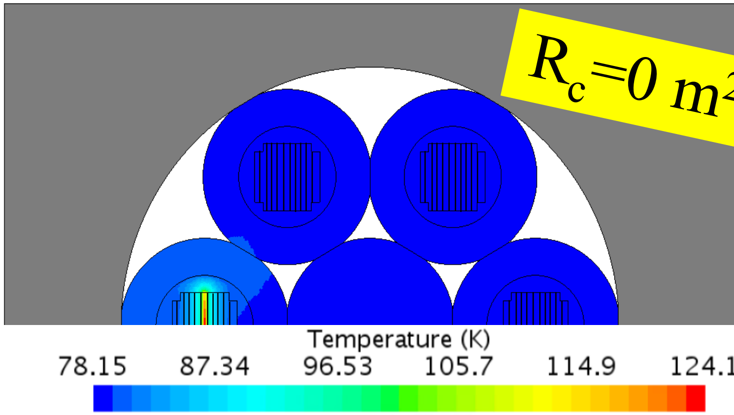
Results – Quench (III)

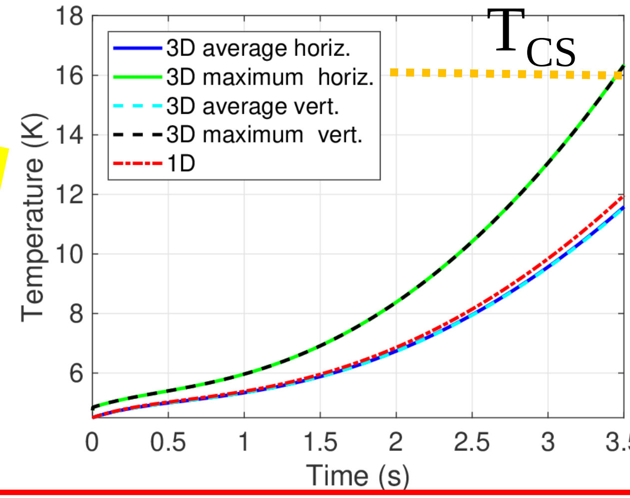
3D model

Temperature map at 10 s

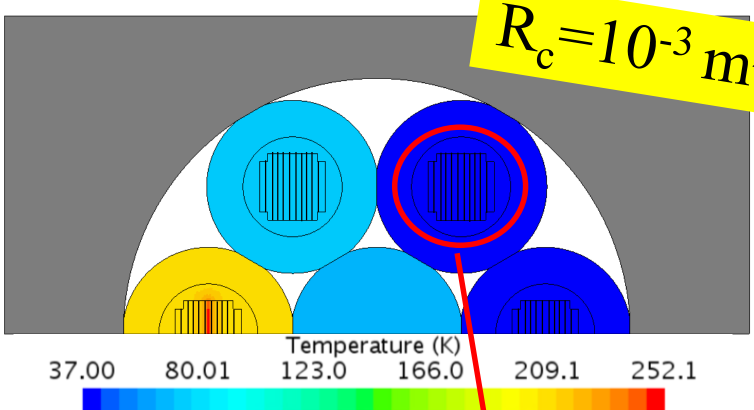
1D model

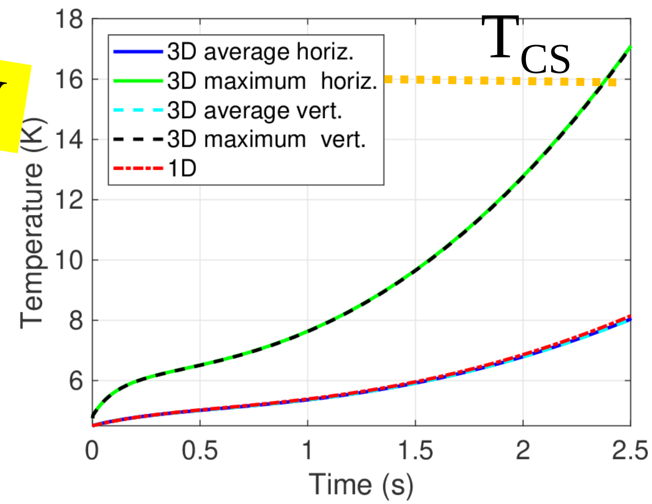
R_c=0 m^2K/W





R_c=10^{-3} m^2K/W





⇨ If **tapes oriented vertically**

→same results!

Conclusions and perspective

The assessment of the relevant time and space scales of the HTS CroCo conductor for the EU DEMO TF coil have been performed

On long, e.g. normal operation, transients, a 1D model along the conductor direction is considered to be sufficient to estimate reliably the temperature margin distribution

On short, e.g. quench propagation, transients, the temperature non uniformity becomes very important, therefore more sophisticated models must be used

In perspective, a macro-strand model able to reproduce the hot-spot temperature evolution will be developed.