

# Modelling of hysteresis losses in HTS Cable-in-Conduit Conductors for large scale applications

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  - Losses in square stacks
- TH model
  - Temperature margin
- Alternative concept: rectangular stack
- Open issue: upper/lower modules
- Conclusions and perspective

# Introduction

The magnet system of the EU DEMO is under design within the EUROfusion Consortium

Two options are being evaluated for the CS coil:

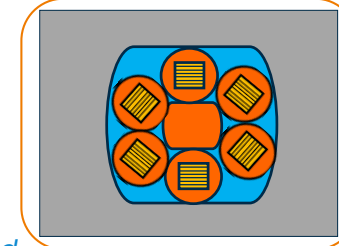
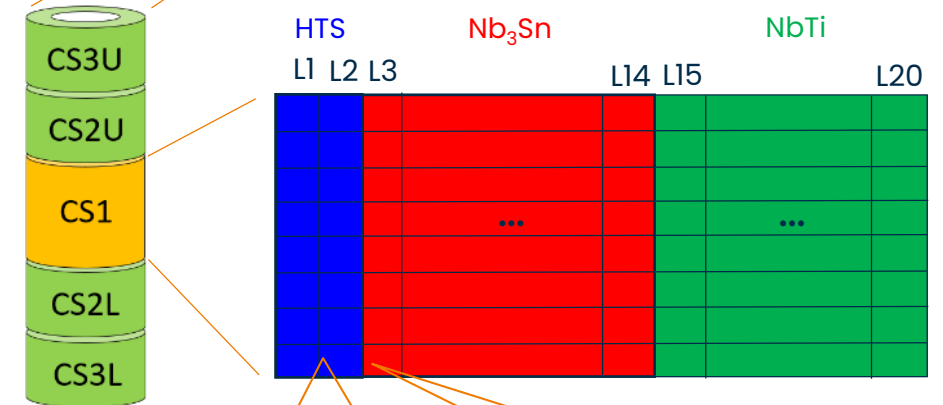
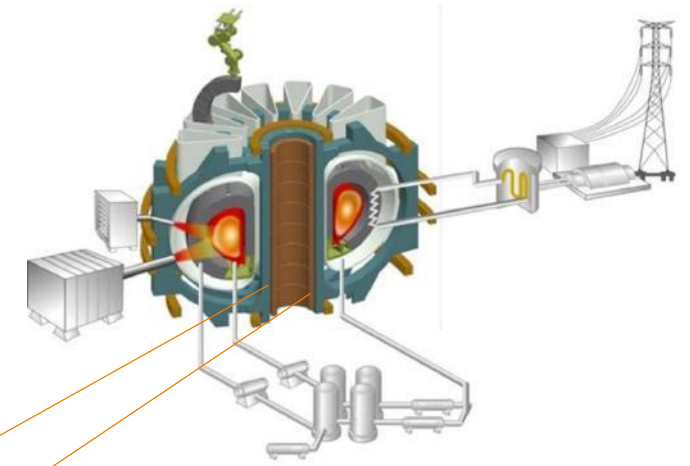
- $Nb_3Sn$  only, pancake wound (ITER-like)
- Hybrid HTS- $Nb_3Sn$ -NbTi layer wound

The CS is pulsed, but for HTS only *coupling losses* have been considered so far in the design verification analysis

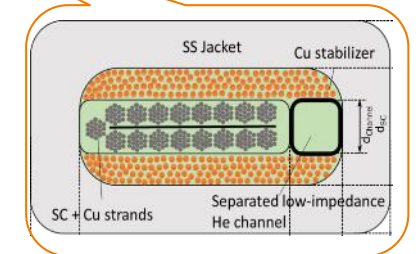
It has been shown that hysteresis losses could be orders of magnitude larger than coupling losses [1]

Aim of the work is two-fold:

- Quantify the hysteresis losses in DEMO relevant conditions
- Quantify the temperature margin during normal operation



Six stacks twisted around a central core



[R. Kembleton et al, *Fus. Eng. Des.*, Jan. 2022]  
[V. Corato et al., *Fus. Eng. Des.*, Jan. 2022]

[1] D. Uglietti et al, *Cryogenics*, Sep. 2020

# Hysteresis losses in stacks – FEM modelling

- 2D H-formulation implemented in COMSOL is adopted

- Well established homogenization technique to deal with large number of tapes [2]:

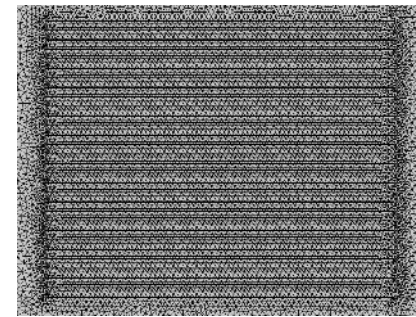
$$J_{C,eq} = J_C \times f_{HTS}, \text{ where } f_{HTS} = n_{tapes} \times h_{HTS} / h_{stack}$$

$$J_C = J_C(B_{\parallel}, B_{\perp}) = \frac{J_{C0}}{\left(1 + \frac{\sqrt{k^2 B_{\parallel}^2 + B_{\perp}^2}}{B_0}\right)^{\alpha}}$$

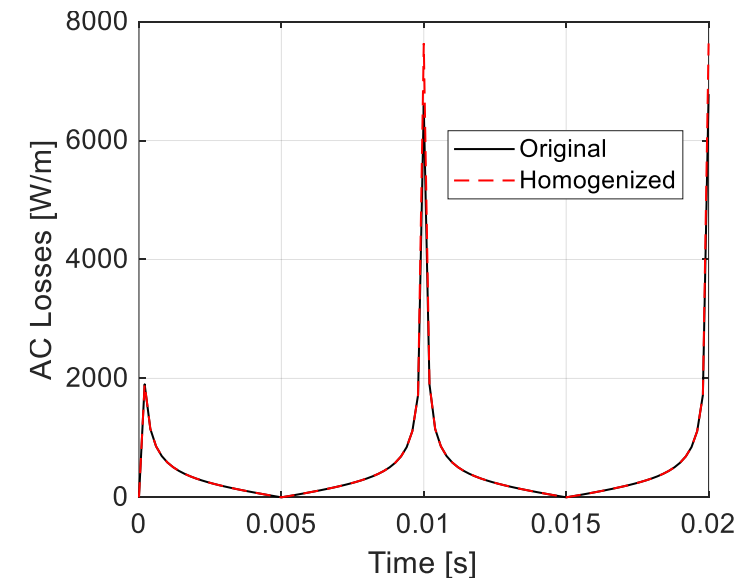
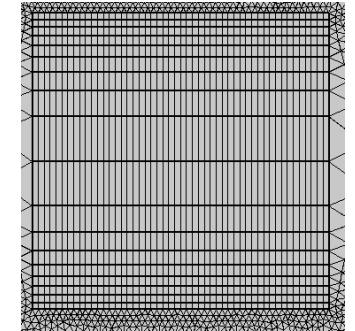
- $J_{C0} = 5.2 \cdot 10^{12} \text{ A/m}^2$ ,  $k = 0.257$ ,  $\alpha = 0.7$ ,  $B_0 = 42.7 \text{ mT}$
- E-J power law,  $n = 27$ ; stack dimensions:  $3.3 \times 3.3 \text{ mm}^2$
- No transport current is considered

[2] V. Zermeno et al, J. Appl. Phys., 2013

30 tapes  
modelled in detail

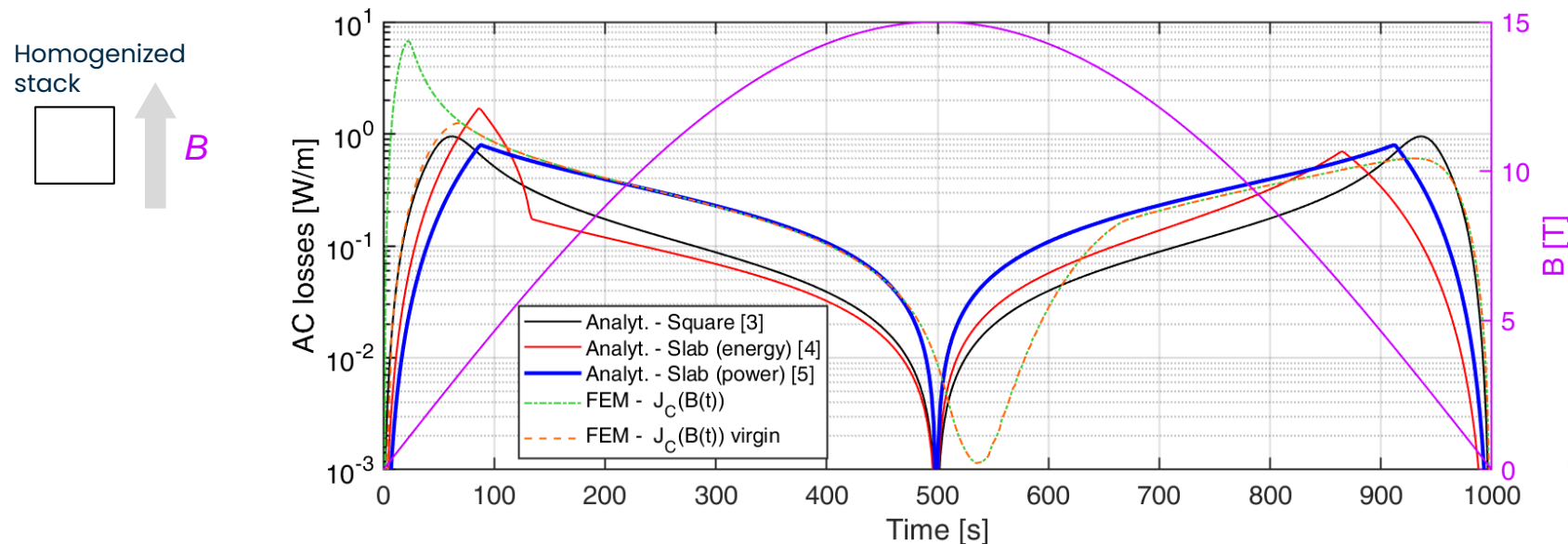


Homogenized  
stack



# Hysteresis losses in stacks – an. formulae

- AC losses (power) computed by FE model matches the analytical solution developed for slabs, i.e., at  $B > B_p$
- At low field ( $B < B_p$ ), shape is important → good match with formulae developed for square/rectangular shapes
- Ramp-up generates more power than ramp-down



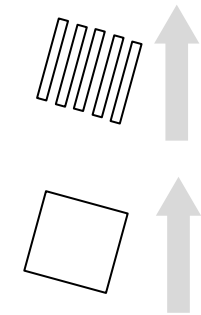
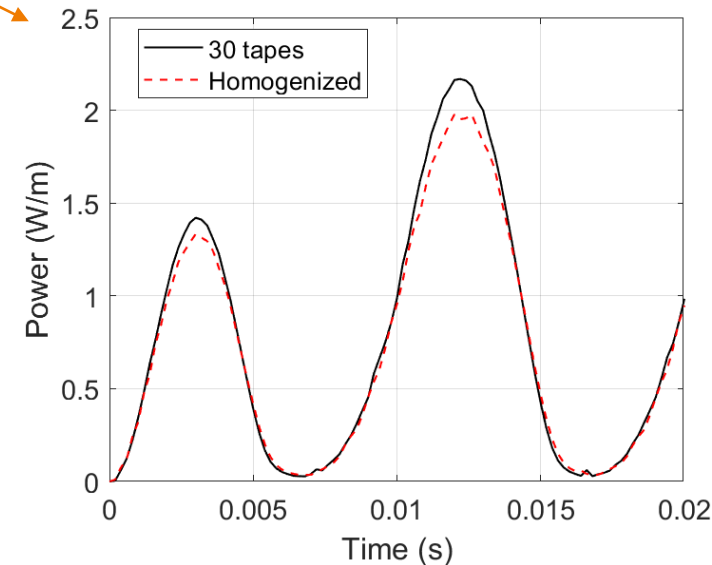
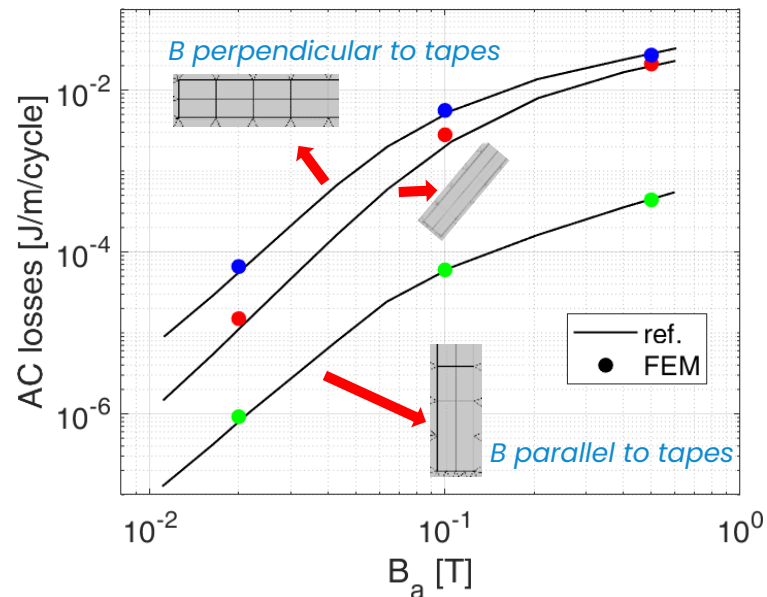
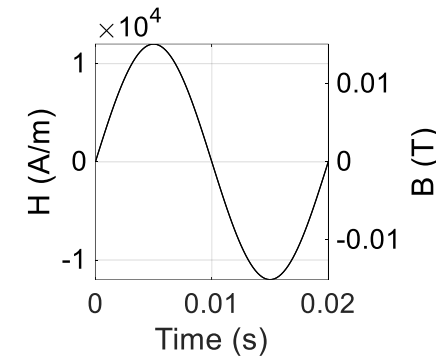
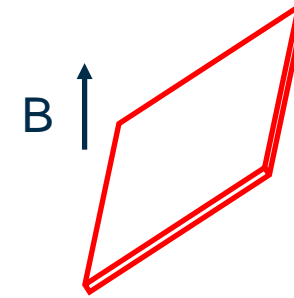
- [3] E. Pardo et al., *Supercond. Sci. Technol.*, 2004  
[4] Y. Iwasa, *Case study in superconducting magnet design*, 2<sup>nd</sup> ed., Springer, 2009  
[5] S. Awaji et al., *IEEE Trans. Appl. Supercond.*, 2015

- Analytical formulae provide useful figures for fast evaluation and guidance to conductor designers
- However, TH model needs the power evolution as input and its accuracy is important
- On the other hand, FEM modelling and homogenization techniques are well documented mainly for fields perpendicular to the wide tape face, while, in HTS conductor for fusion, stacks are typically (randomly) tilted with respect to the main field component → need for benchmark

# Hysteresis losses – benchmark for tilted tapes and stacks

Literature data available in literature for tilted tapes:

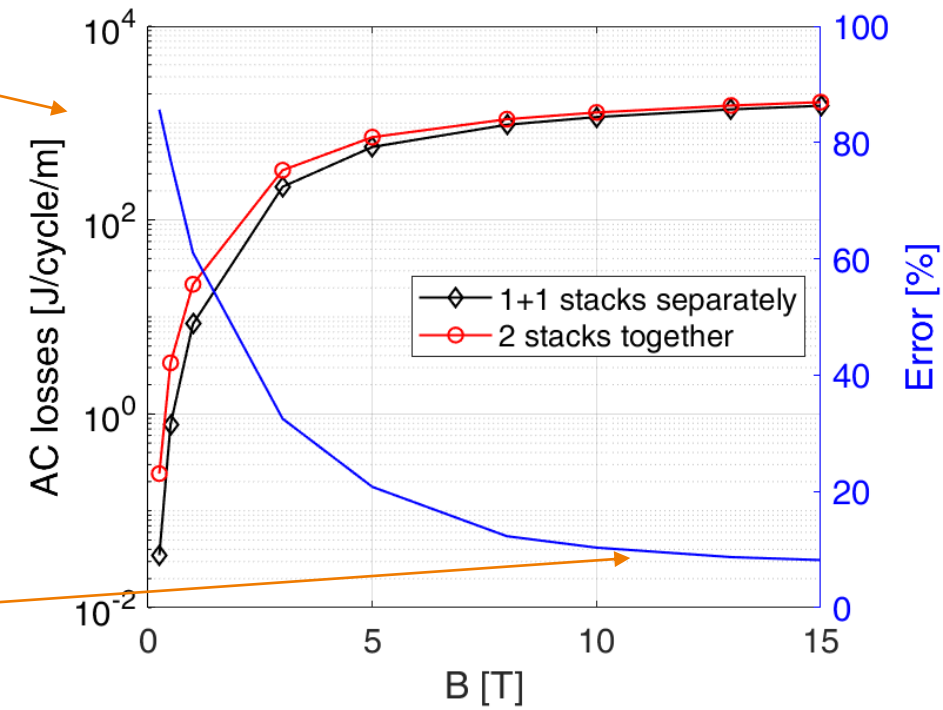
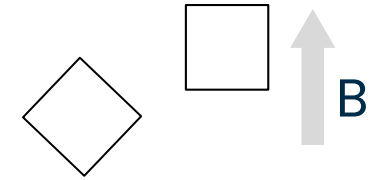
- Benchmark model for single tapes with different angles
- Simulate the tilted stack (up to 85 deg) in detail (30 tapes) to benchmark the tilted homogenized stack model



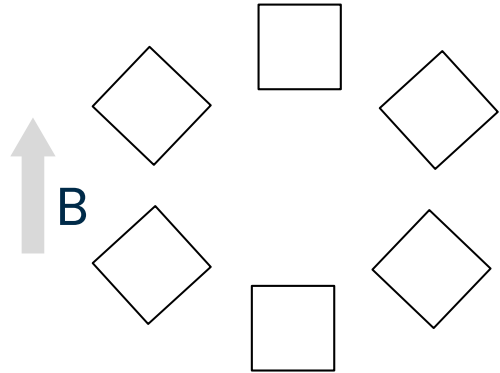
Reference for tilted tapes is Gu F. et al., *IEEE Trans. Appl. Supercond.*, 2019

# Hysteresis losses – interaction between stacks

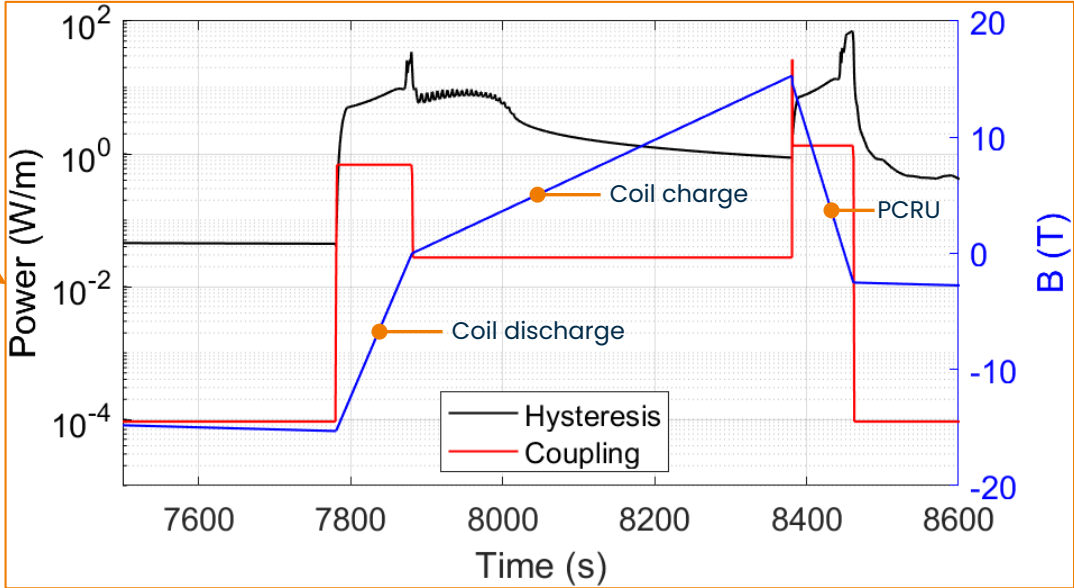
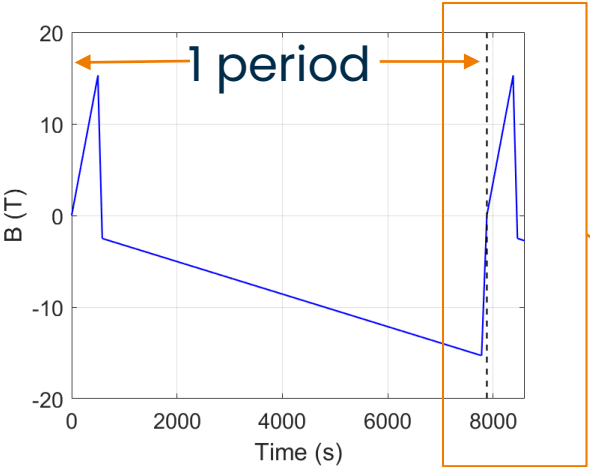
- To save computational time, a possible way could be to simulate a single stack with different tilt angles
- Numerical test: compare total losses computed in two stacks as
  - the sum of the losses in the two stacks *simulated separately*
  - the sum of the losses in the two stacks *simulated together*
- Only at high fields, i.e., larger than the penetration field of 1 stack ( $\sim 3\text{-}4\text{ T}$ ), the coupling between the stacks becomes negligible, thus the stacks need to be simulated together at least up to 4-5 T



# Hysteresis in cable proposals



- Magnetic field cycle (starting from virgin state) is simulated on 6 stacks together
- Hysteresis losses are almost always much larger than coupling losses (computed as  $P_c = \frac{n\tau}{\mu_0} S \left(\frac{dB}{dt}\right)^2$ , where  $n\tau = 75 \text{ ms}$ ,  $S = 700 \text{ mm}^2$ )
- Largest deposition takes place during coil discharge, charge and plasma current ramp up phases





# 1D thermal + hydraulic + electric model

Design requirements for EU DEMO:  $\Delta T_{mar}^{min} > 1.5$  K, where  $\Delta T_{mar}^{min} = \min(T_{CS}(x, t) - T_{Co}(x, t))$

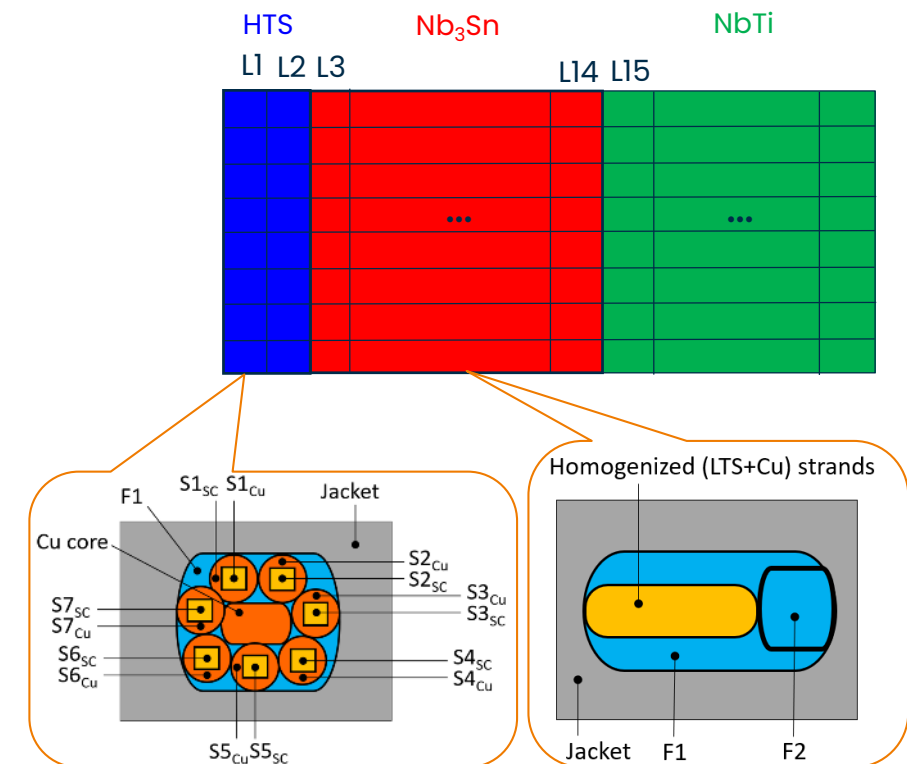
To compute  $T_{co}(x, t)$ , 1D (along the conductor axis) TH models are used. Here, the H4C code [6] is used

The cross-section of the conductor can be discretized with an arbitrary number of thermal, electric and fluid region.

It solves 1D, transient:

- In solid regions:
  - Heat conduction equation for **temperature** (here AC losses are the driver!)
  - Diffusion-like equation for the **current** distribution
- In fluid regions: Euler-like set of PDEs for **He speed, pressure, temperature**.

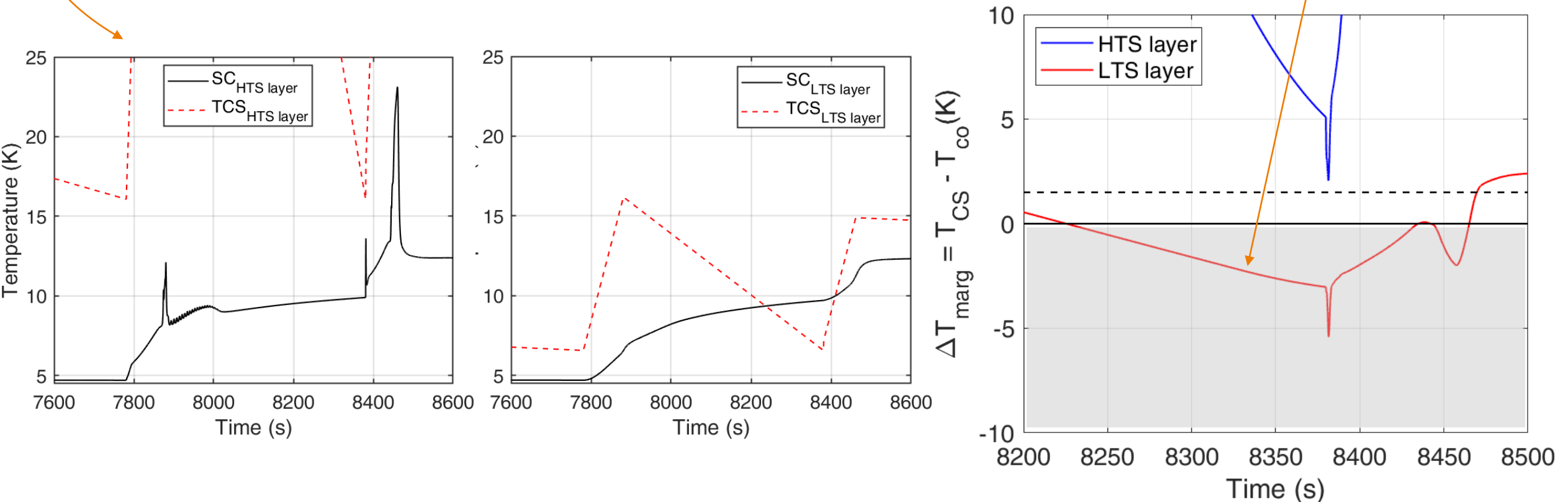
The model is also able to take into account inter-layer and inter-turn heat transfer



[A. Zappatore et al., *IEEE Trans. Appl. Supercond.*, 2022  
[6] A. Zappatore et al, *Supercond. Sci. Technol.*, 2019

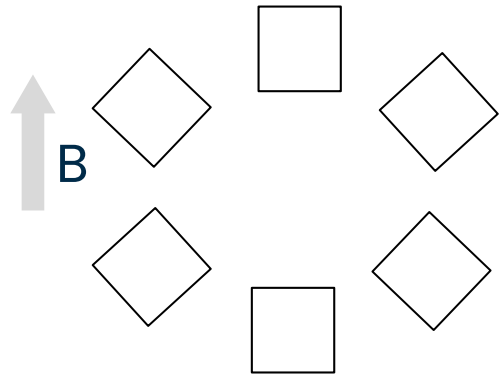
# Temperature and temperature margin in HTS and LTS layers (CS1)

- Margin in HTS layer is still acceptable ( $> 1.5$  K)
- LTS layer is heated by conduction from the HTS layers, leading to negative temperature margin  $\rightarrow$  *look for lower loss alternative*



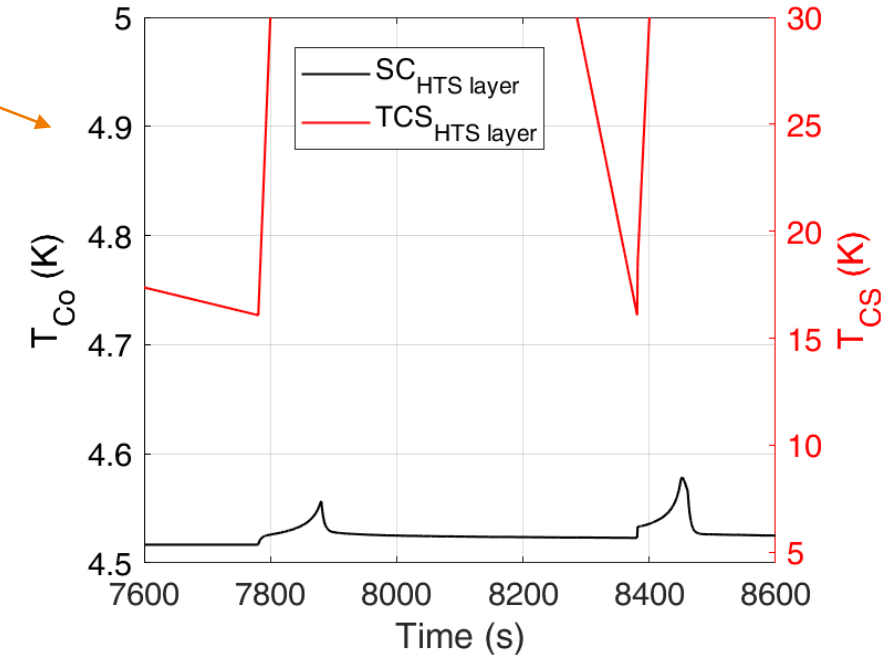
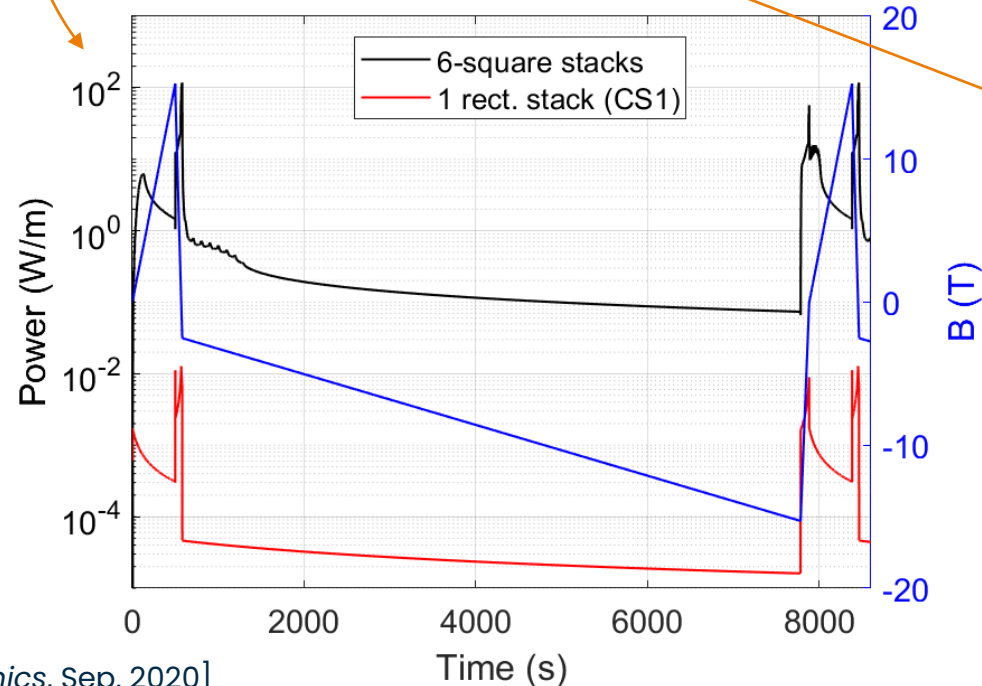
# Untwisted, rectangular stack (in CS1)

- Losses modelled in 1 single tape of the stack, taking advantage of the very low  $B_p$ , thus of the negligible coupling between the tapes
- Much lower losses than in the conductor made of square, twisted-stacks
- Safe margin to operate, negligible heating to LTS layers



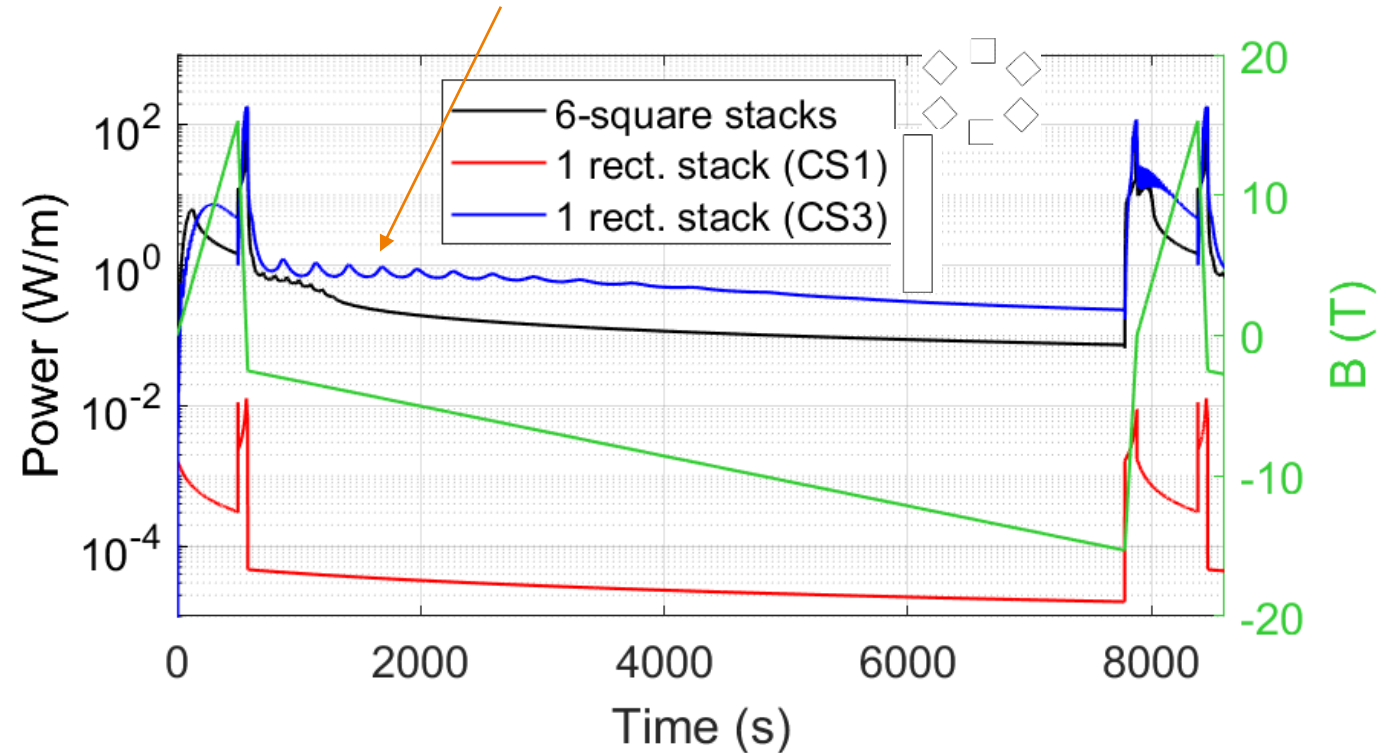
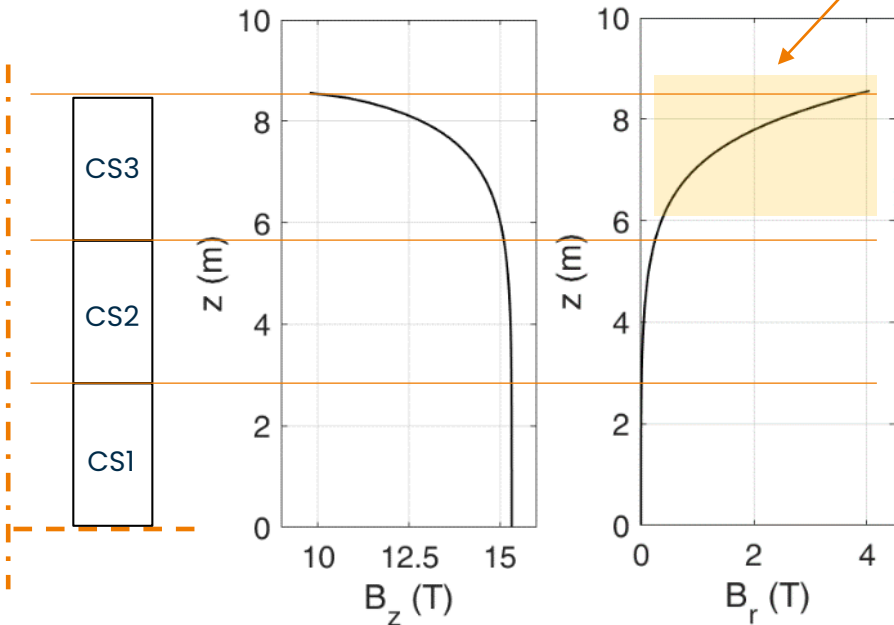
CS1 : field parallel to the wide side of the stack

As proposed in [D. Uglietti et al, *Cryogenics*, Sep. 2020]

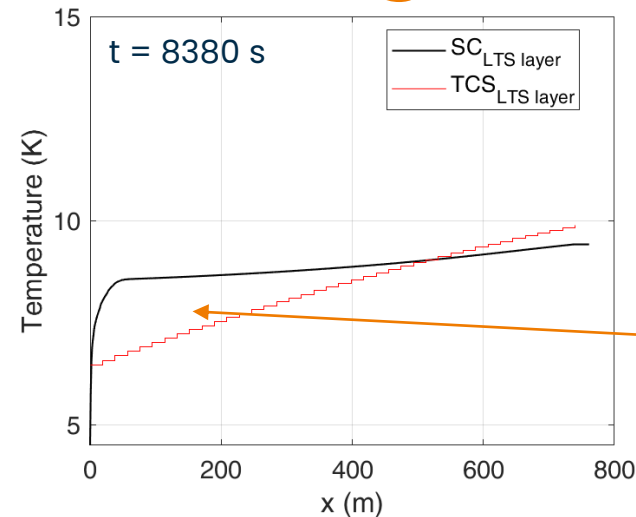
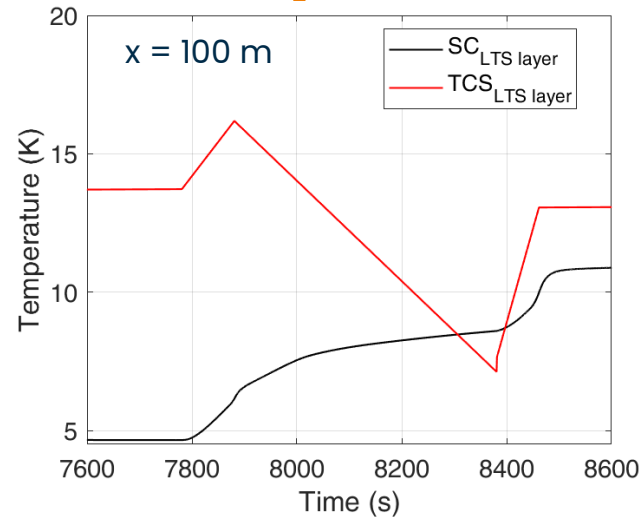
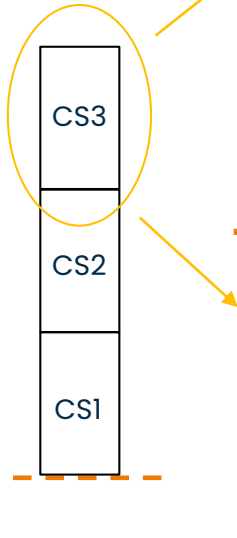
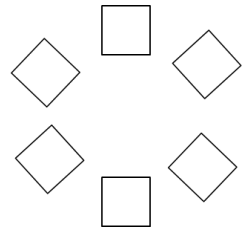


# Open issue: Upper (and lower) modules - Losses

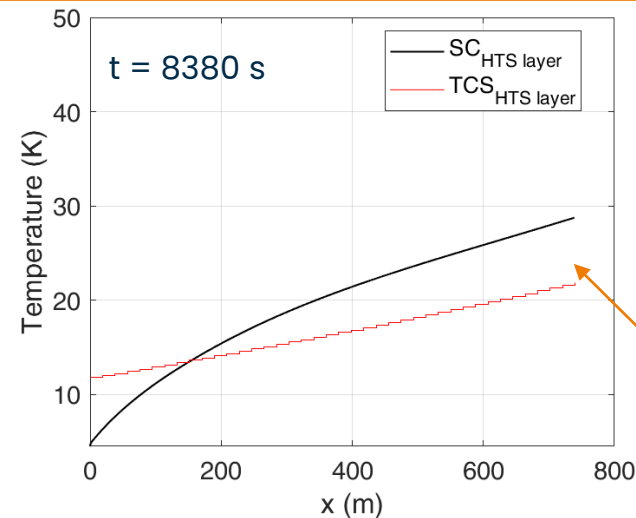
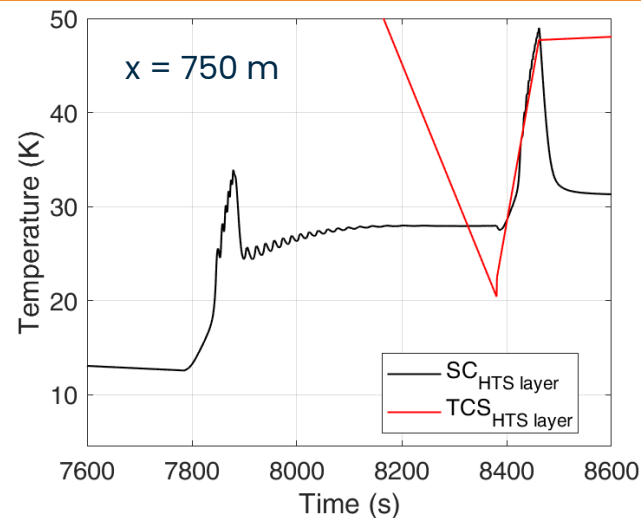
- Single rectangular stack  $\rightarrow$  larger losses in upper/lower modules due to non-negligible perpendicular field component
- Losses computed with homogeneous model  $\rightarrow$  in last turn, larger losses than in conductor with square stacks



# Open issue: Upper (and lower) modules - Temperature margin(II)



If CS3 equipped with square stacks, large losses in the first turns, where  $T_{CS}$  is low  $\rightarrow$  still negative margin on LTS layer



If CS3 equipped with long-rectangular stack, large losses in the last turns, where  $T_{CS}$  is higher  $\rightarrow$  but negative margin in HTS layer  $\rightarrow$  room for optimization!

# Conclusions and perspective

- Hysteresis losses in HTS conductors for (pulsed) fusion magnets have been quantified, with FEM EM models, in different conductor concepts and position in the CS coil
- With the coil TH model, the temperature margin has been analyzed, showing that the current conductor concept produces too large losses that can be strongly reduced with a different (and simpler) design
- However, how to reduce the losses in the upper and lower modules is still an open issue
- In perspective, the impact of the presence of transport current will be evaluated and a two-way coupling between EM and TH model will be developed, to account for  $J_c$  dependence on T.



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# BACKUP



# Temperature in CSI, square stacks

