Modeling quench propagation in the ENEA HTS CICC

A. Zappatore[1], A. Augieri[2], R. Bonifetto[1], G. Celentano[2], L. Savoldi[1], A. Vannozzi[2] and R. Zanino[1]

[1]NEMO group, Dipartimento Energia, Politecnico di Torino, Torino, Italy

[2]ENEA Frascati Research Center – Superconductivity Laboratory, FSN Department, Frascati, Italy

Outline

- Roadmap of our HTS magnet modeling effort
- Aim of this work
- The ENEA HTS CICC
- Preliminary analysis
- 1D model description
- Results
- Conclusions and perspective

POLITECNICO DI TORINO

H4C roadmap

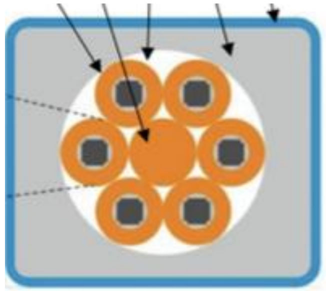
Target: to develop an ***HTS magnet model***
First, an *HTS CICC model* needs to be developed

- ✓ CICC model development
- ✓ Verification
- Validation
- Integration in the 4C suite
- HTS magnet model: **H4C**

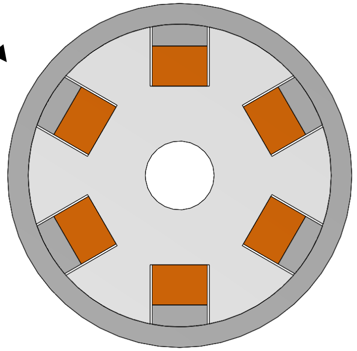
Quench tests in 2020 @ SULTAN → Validation

Preliminary analysis to guide the development of the 1D CICC model [1]

[1] A. Zappatore et al., SuST **32**(8), 2019



Presented at CHATS2019 (KIT HTS CICC)



Here focus on ENEA HTS CICC

POLITECNICO DI TORINO

Aim of this work

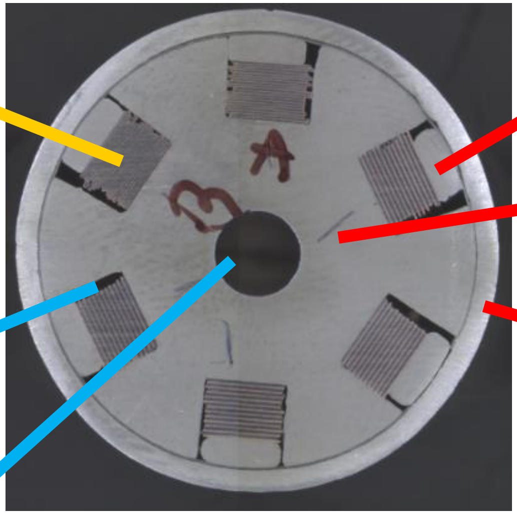
- Develop a 1D model of the ENEA HTS CICC
- Calibrate the free model parameters through dedicated experiments
- Apply the 1D conductor model to the analysis of quench propagation in the ENEA HTS CICC

The ENEA HTS CICC

6 slots (4.3 mm x 4.3 mm) equipped with 20 REBCO non-soldered 4-mm-wide tapes each

Side channels in each slot

5 mm ϕ central hole for SHe cooling



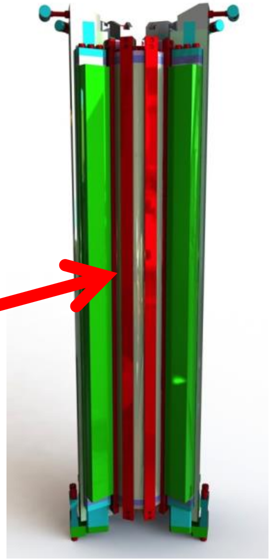
22 mm

Aluminum filler to hold the HTS stack in position

Aluminum core with twisted slots

Aluminum round jacket 1.5 mm thick

Application in the medium term: HTS CS insert for the Divertor Tokamak Test (DTT) facility currently under design in Italy



Preliminary analysis

Aim: understand qualitatively if LTS 1D codes (key feature: uniform *T* and *J* on the cross-section) for TH analysis are OK also for HTS CICC

Fluid model

$Pe = Re\ Pr >> 1$

For SHe flow modelling a **1D** model along the conductor is sufficient

Solid model

$Bi_{stack} > 1\ ,\ Bi_{core} > 1$

For thermal modelling of the cross section 1 region (as in LTS TH models) is NOT sufficient

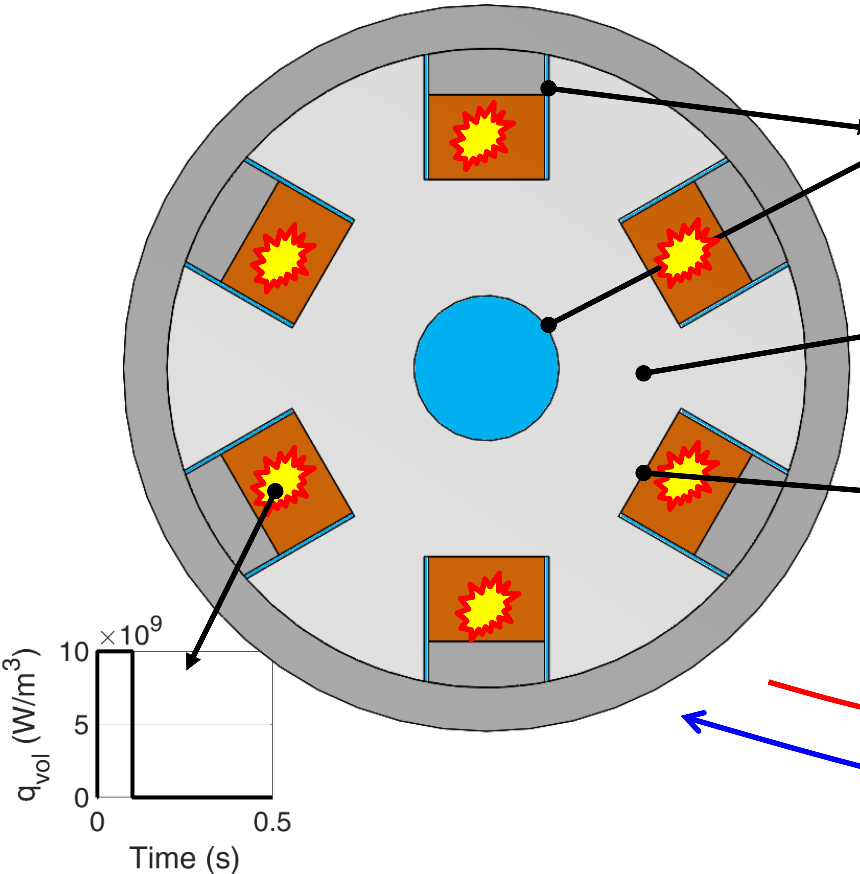
Detailed model of the cross-section to obtain guidelines for the development of the CICC model [1]

[1] A. Zappatore et al., *SuST* **32**(8), 2019

Detailed 0D+2D electro-thermal model of the CICC cross section

Aim of the detailed model: understand how different regions of the conductor cross-section can be lumped to develop a 1D conductor model (along)

2D Thermal

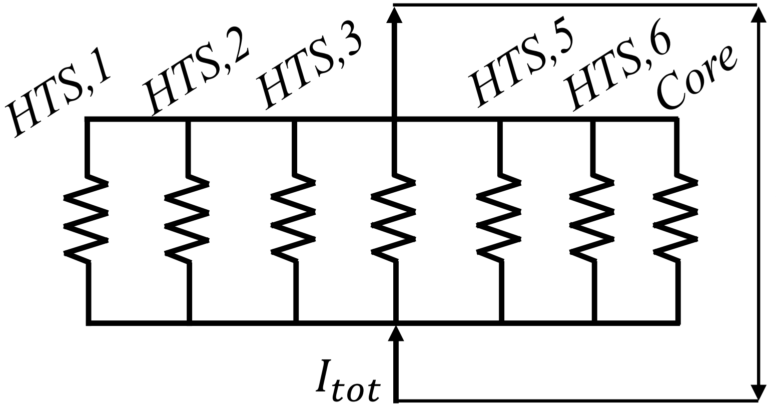


Convection with He at T=4.5 K, h=5000 W/(m²K)

Heat conduction in solids

Thermal contact resistance

0D Electric

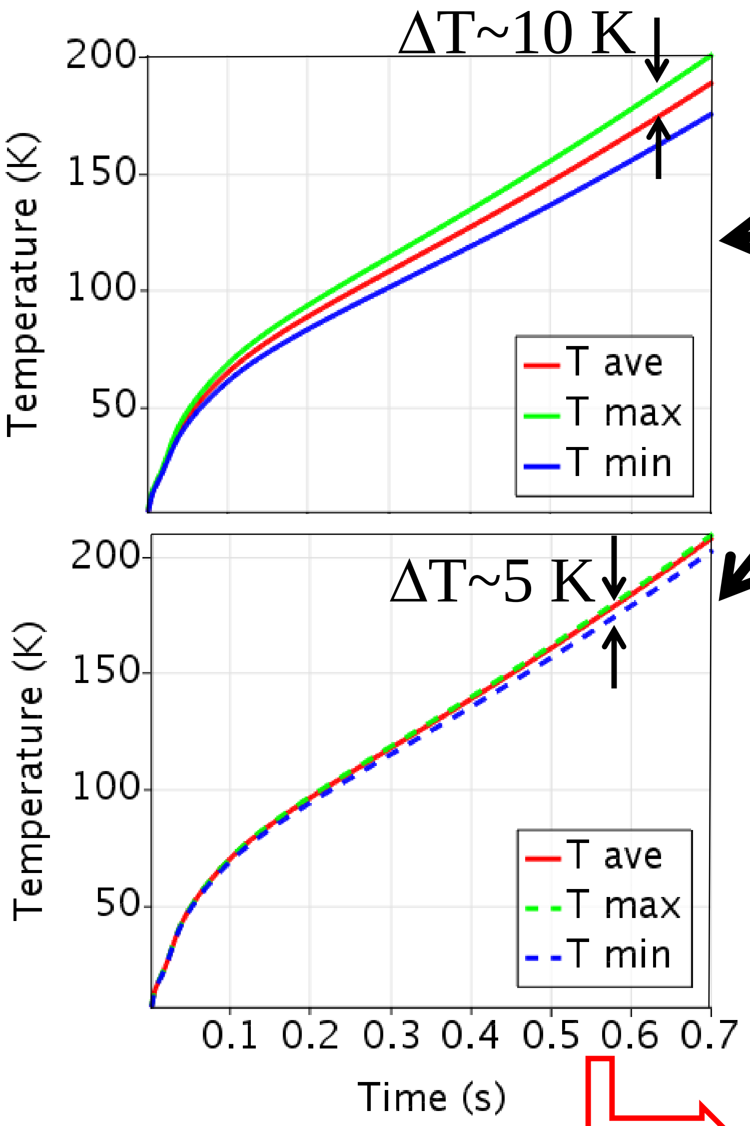


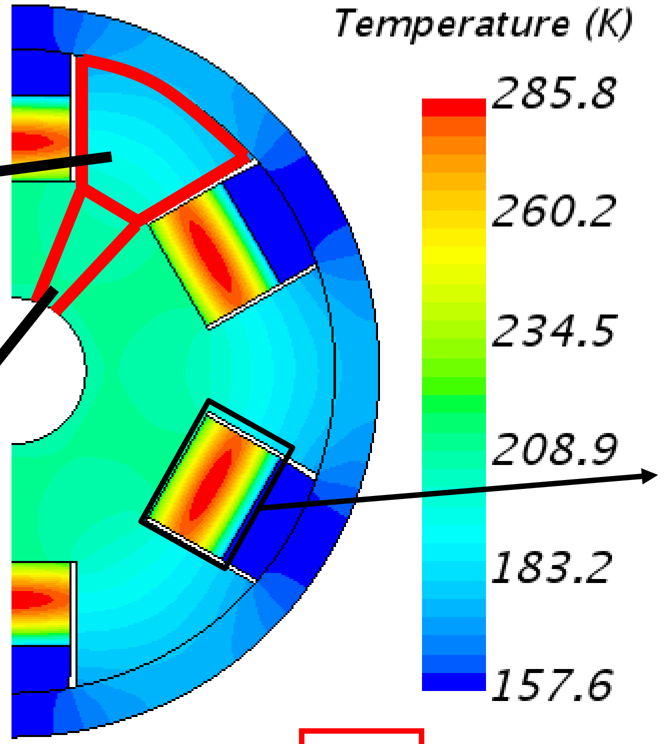
$$
\begin{cases}
V = R_{Al} I_{Al} \\
V = V_C \left(\dfrac{I_{HTS,i}}{I_{C,i}(B,T)} \right)^n \\
I_{tot} = I_{Al} + \displaystyle\sum_{i=1}^{N_{Stack}} I_{HTS,i}
\end{cases}
$$

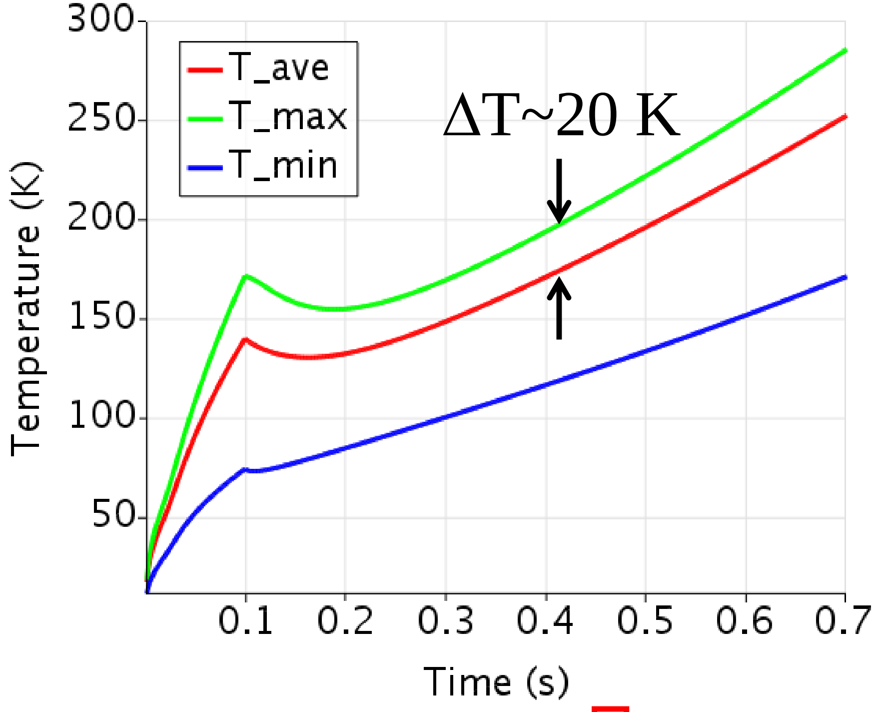
T

$q_i = R I_i^2$

Results







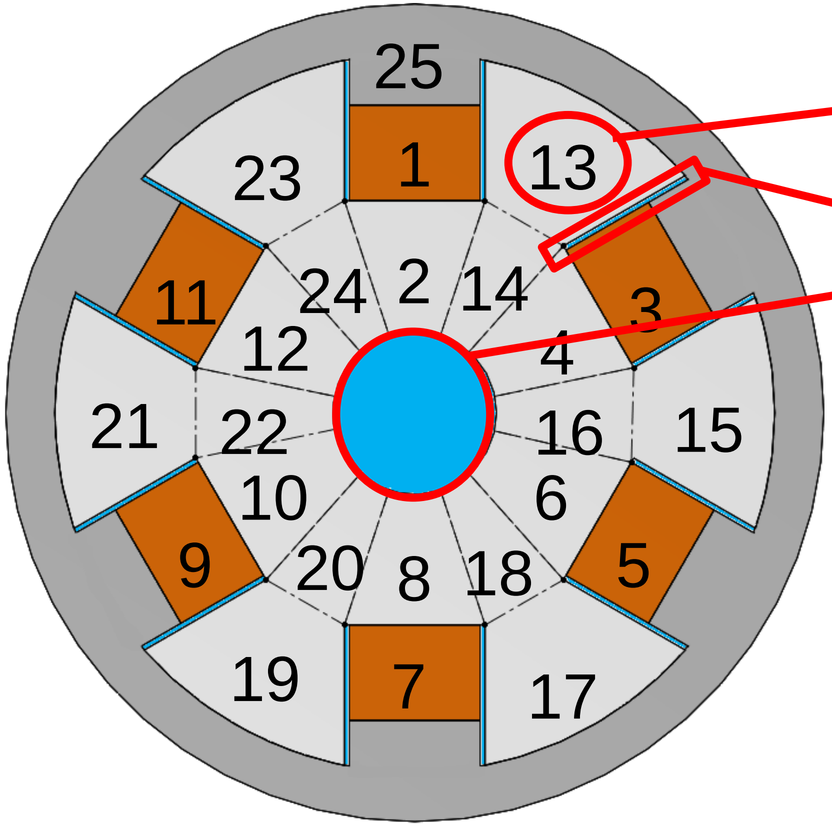
Temperature differences ΔT > 50 K arise within the conductor

Regions with ΔT < 20 K are lumped

Multi-regions 1D model is needed

1D thermal + hydraulic + electric model

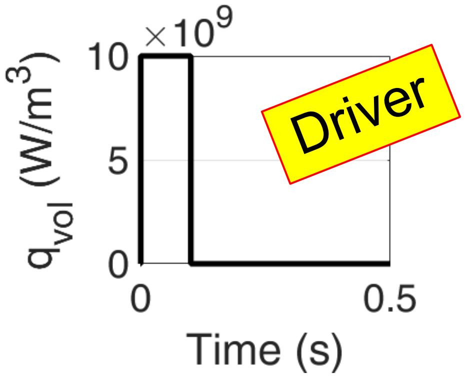
POLITECNICO DI TORINO



- Heat conduction in solids (25 regions) — **Thermal model**
- Euler-like set of PDEs for SHe speed, pressure, temperature (13 regions) — **Fluid flow model**
- Diffusion-like equation for the current along the different solids (25 regions) — **Electric model**

Op. condition

T_{He}=4.5 K
L= 132 m
B= 17.1 T
I=32 kA

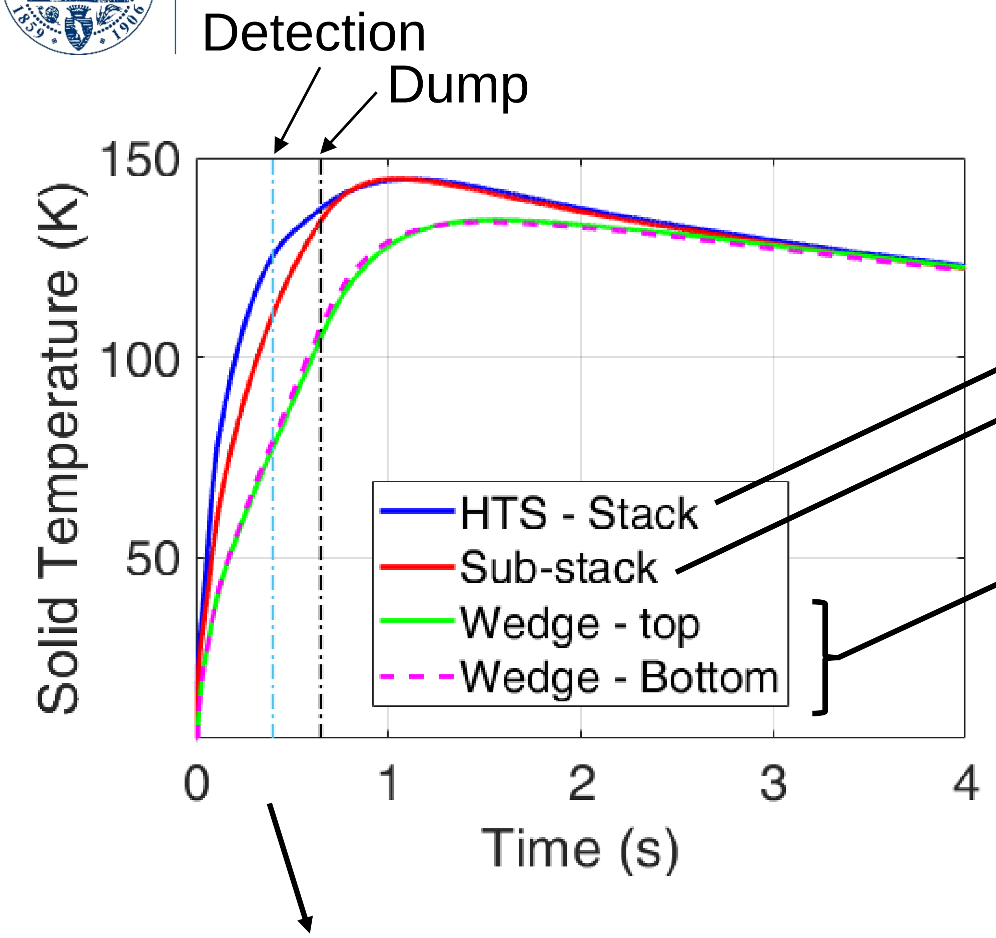


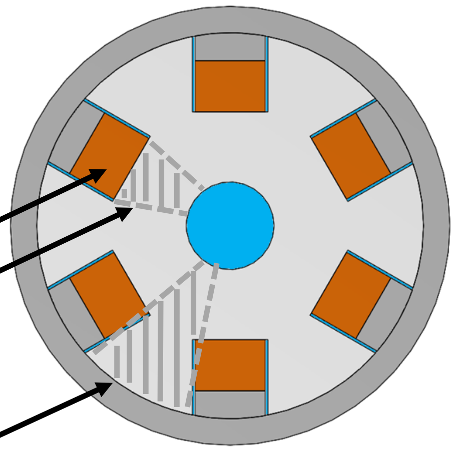
Interfaces

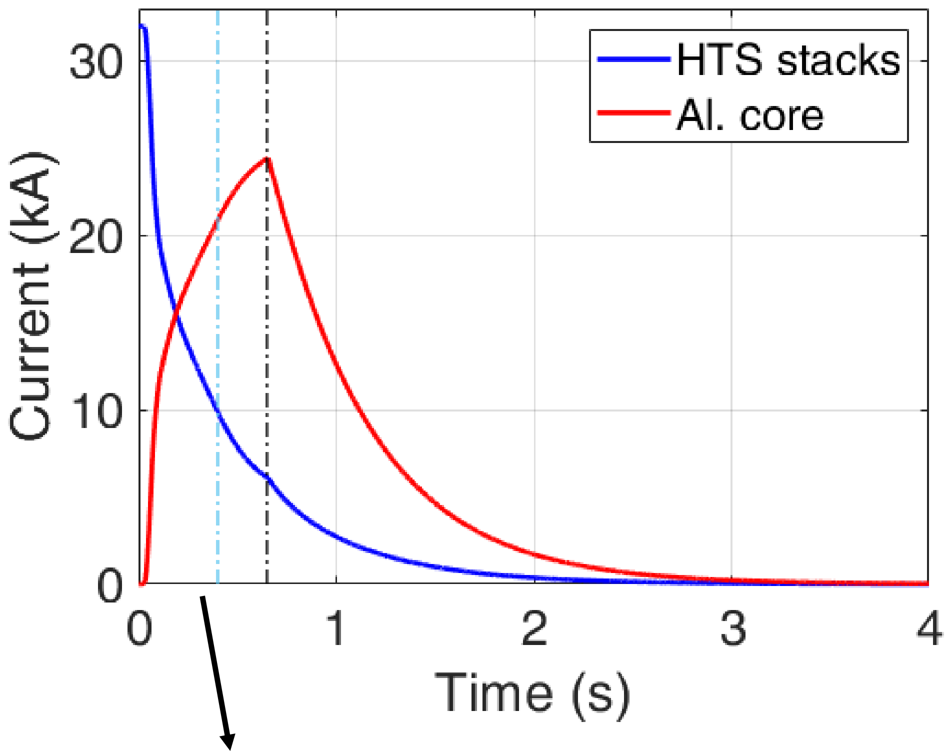
- Solid – solid
  - Thermal
    - Core – jacket: 11400 W/(m²K) [2]
    - Core – stack: 32000 W/(m²K) [2]
  - Electric
    - Linear resistance: 0.4 mΩ/m **[exp.]**
- Solid – fluid: heat transfer coefficient **from CFD**

[2] Y. A. Cengel, Fundamentals of Thermal-Fluid Sciences, 2017

Results (I)



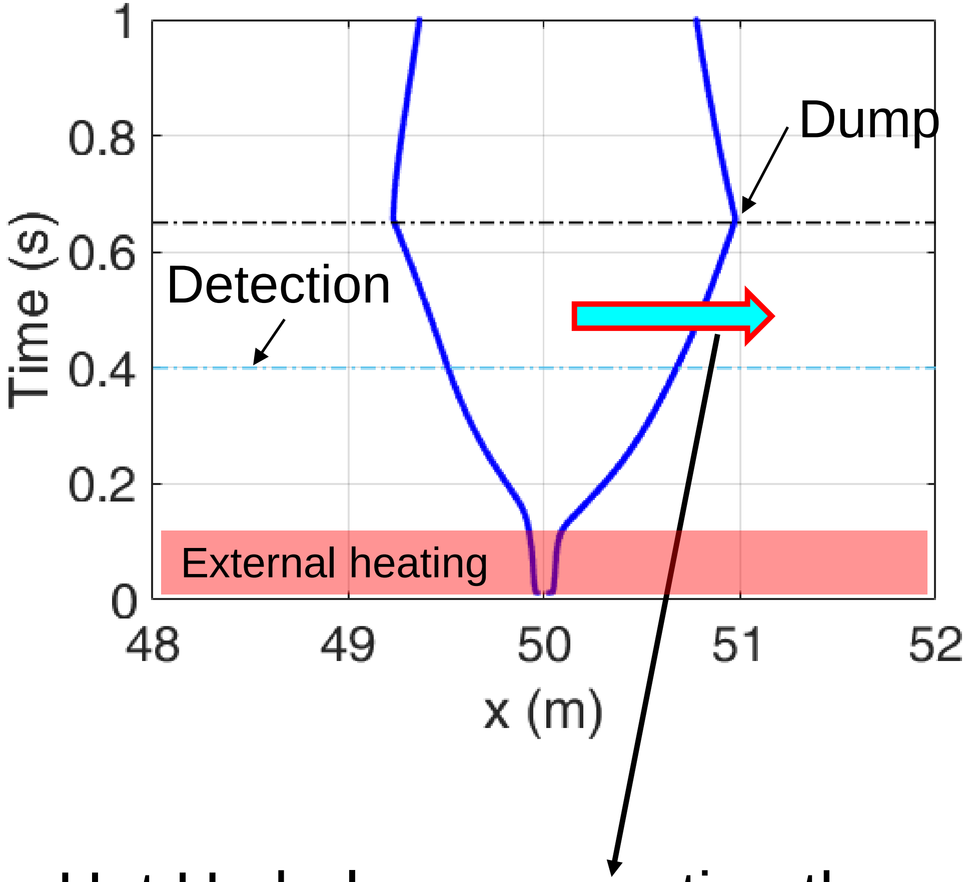




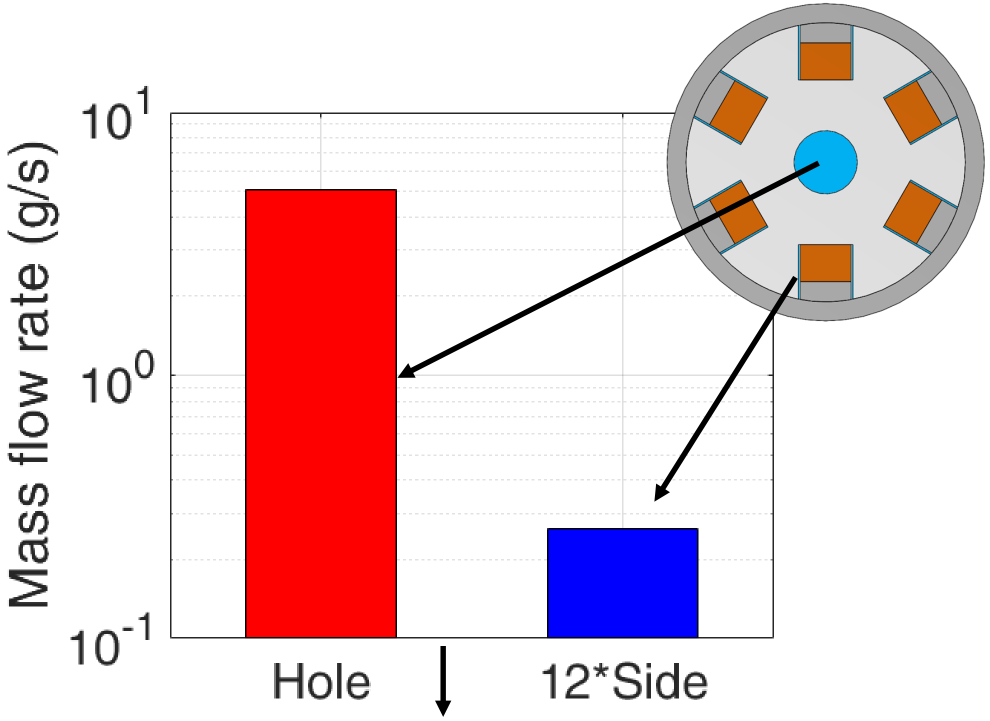
Temperature differences between stacks and core > 40 K→ issues on thermal stresses to be addressed in the future

- Inter-slot resistance low enough to guarantee current redistribution from the HTS stacks to the core
- Before the dump, the aluminum core arrives to carry most of the current, due to temperature increase in the tapes stabilizer

Results (II)



Hot He helps propagating the quench downstream

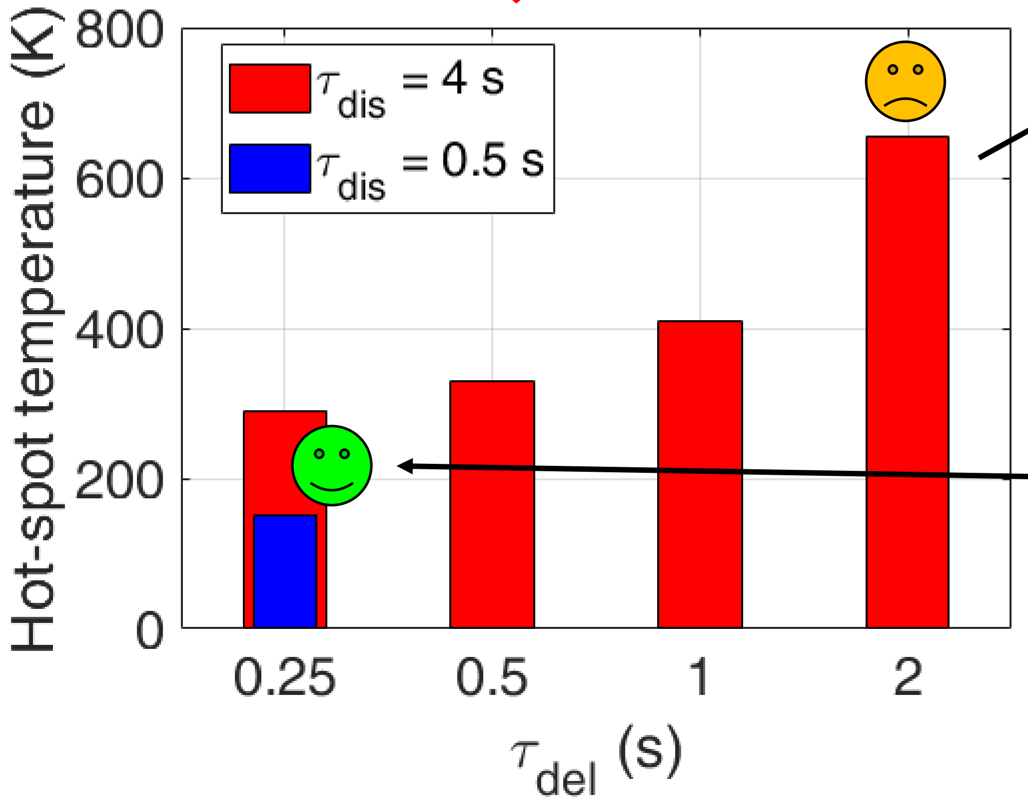


Total dm/dt in side channels ~ 1/20 dm/dt in hole

Limited cooling capabilities of He flow in side channels

Results (III)

- The DTT CS will have delay time (τ_{delay}) = 2 s and current discharge time (τ_{dis}) = 4 s BUT
- τ_{delay} and τ_{dis} for the CS insert are still an open issue in the design



Same τ_{dis} for CS and insert ➔ too high hot-spot temperature

- Warning bell for quench propagation and current dump in an HTS magnet
- Foresee different strategy for the discharge of the CS insert

POLITECNICO DI TORINO

Conclusions and perspective

- A 1D thermal-hydraulic-electric model has been developed and applied to the analysis of quench propagation in the ENEA HTS CICC

- The model shows that
  - Large temperature differences arise in the CICC cross-section
  - The current redistributes from the stacks to the slotted core

- The delay time for the quench detection in the DTT CS insert coil and the current discharge time should stay below 0.5 s, otherwise the hot-spot temperature becomes too high

- In perspective, the CICC model will be:
  - validated against the quench tests foreseen in 2020 @ SULTAN
  - embedded in the H4C magnet model (which already includes winding pack, coil casing and cryogenic circuit) to analyze the performance of an HTS magnet