Modeling quench propagation in the ENEA HTS CICC

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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
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**

Quench tests in 2020 @ SULTAN

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

**HTS magnet model:** **H4C**
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 $\phi$ central hole for SHe cooling

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

\[ \text{Bi}_{\text{stack}} > 1, \text{Bi}_{\text{core}} > 1 \]

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 \( T = 4.5 \text{ K}, h = 5000 \text{ W/(m}^2\text{K)} \)
- Heat conduction in solids
- Thermal contact resistance

0D Electric

\[
\begin{align*}
V &= R_{Al} I_{Al} \\
V &= V_C \left( \frac{I_{HTS,i}}{I_{C,i}(B,T)} \right)^n \\
I_{tot} &= I_{Al} + \sum_{i=1}^{N_{Stack}} I_{HTS,i}
\end{align*}
\]

\( q_i = RI_i^2 \)
Temperature differences $\Delta T > 50$ K arise within the conductor. Regions with $\Delta T < 20$ K are lumped. A Multi-regions 1D model is needed.
1D thermal + hydraulic + electric model

- Heat conduction in solids (25 regions)
- Euler-like set of PDEs for SHe speed, pressure, temperature (13 regions)
- Diffusion-like equation for the current along the different solids (25 regions)

**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

**Op. condition**
- \( T_{He}=4.5 \text{ K} \)
- \( L = 132 \text{ m} \)
- \( B = 17.1 \text{ T} \)
- \( I=32 \text{ kA} \)

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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)

- Total $dm/dt$ in side channels
  - $\sim 1/20$ $dm/dt$ in hole
- Limited cooling capabilities of He flow in side channels
- Hot He helps propagating the quench downstream
- External heating
- Detection
- Dump
Results (III)

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

![Graph showing hot-spot temperature versus delay time](image)

- Same $\tau_{\text{dis}}$ for CS and insert $\Rightarrow$ 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
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