Task: MAG-S.01.03-T025

Thermal-hydraulic analysis of the DEMO winding packs (2024)

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Task specification

Description:

The task is focused on thermal-hydraulic analyses of the available designs of the DEMO conductors and winding packs, in continuation of the efforts of 2023. In particular we foresee the following activities:

(i) continuation of the thermal-hydraulic analysis of the normal operation of the CORC conductor to be used in the HTS insert of the DEMO hybrid CS,

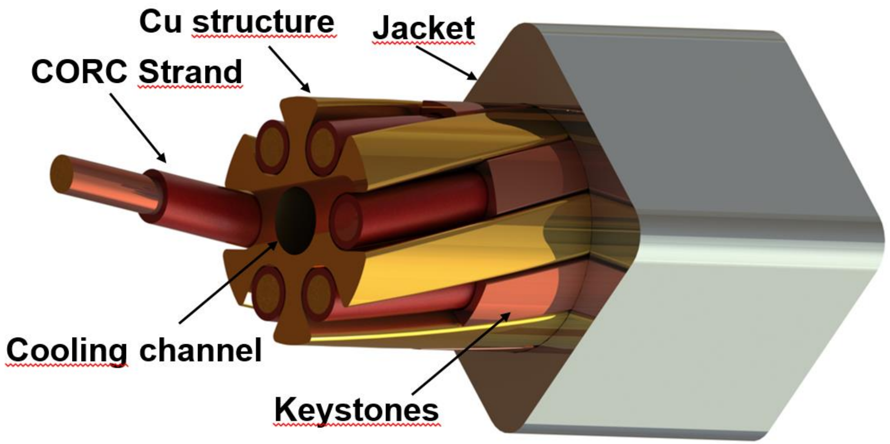
(ii) analysis of the results of the SULTAN test of the HTS conductors, e.g. CORC conductor designed to be used in the HTS insert of the DEMO hybrid CS

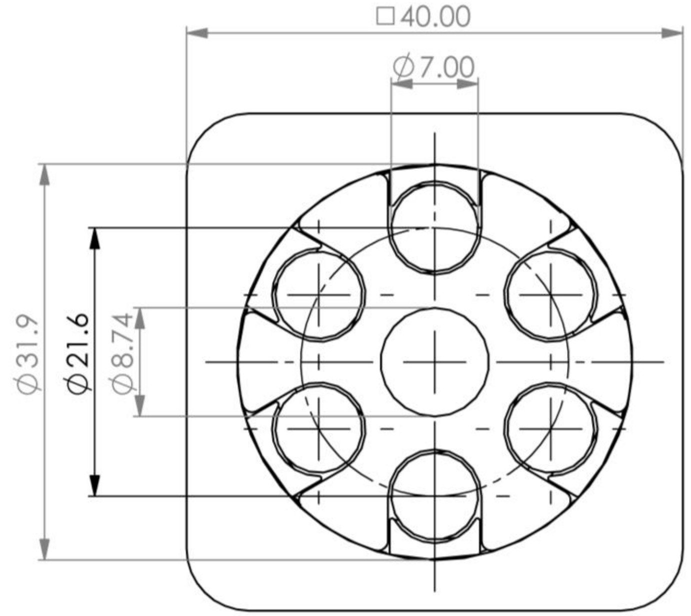
(iii) contribution to the thermal-hydraulic analysis of HTS part of the hybrid DEMO CS coil designed by CEA

Thermal-hydraulic analysis of the CORC based conductor (ACT design [1]) to be used in the HTS insert of the DEMO hybrid CS

- Conductor characteristics

Description (Unit)	**Value**
Max. magnetic field (design) (T)	18
Conductor length, L (m)	736.9
Helium channel diameter (mm)	8.74
Channel cross section (mm^2)	59.96
Cu structure cross section – with keystones (mm^2)	490.3
Jacket cross section (mm^2)	780.4
Single CORC strand	
REBCO cross section (mm^2)	0.370
Copper in tapes cross section (mm^2)	2.057
Copper in core cross section (mm^2)	22.90
Hastelloy cross section (mm^2)	10.29
Silver cross section (mm^2)	0.782





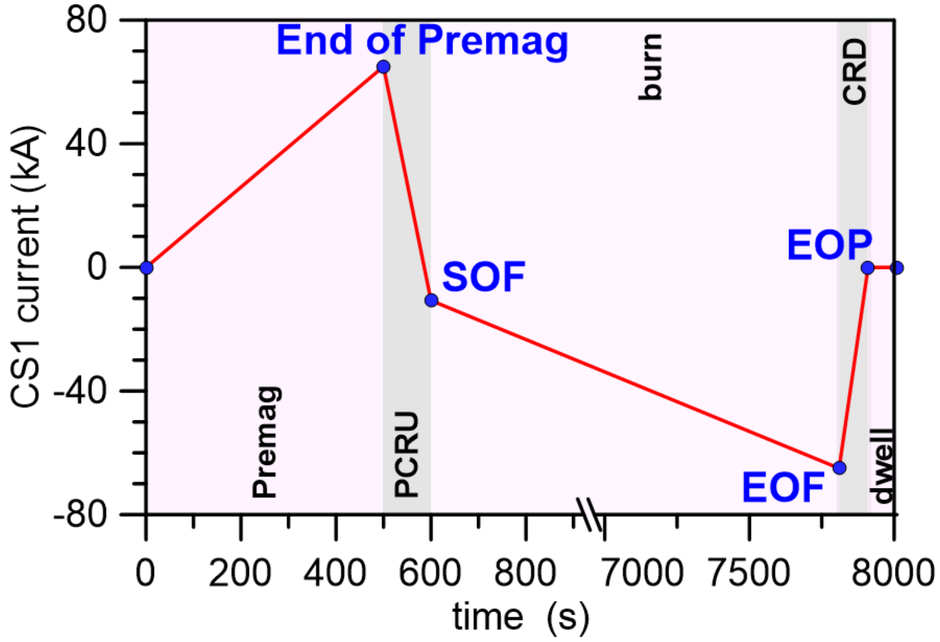
[1] Development of HTS CORC® Cables and Joints for use in Magnets for Fusion Weiss, J.D., presented at EUCAS 2019. https://www.advancedconductor.com/wp-content/uploads/2020/03/Weiss-EUCAS-2019.pdf

- Scaling law for the SuperPower tapes in the form taken from [2]:

$$I_c(B,T) = \frac{C}{B}\left(\frac{B_{irr}(T)}{B_{irr0}}\right)^{\beta}\left(\frac{B}{B_{irr}(T)}\right)^{p}\left(1-\frac{B}{B_{irr}(T)}\right)^{q} \qquad B_{irr}(T) = B_{irr0}\left(1-\frac{T}{T_c}\right)^{\alpha}$$

where B_{irr0} = 120 T, T_c = 92.83 K, α = 1.7059, β = 1.8250, p = 0.4786, q = 2.5149, A=6363.2 kA/T.
The values of α, β, p, q were fitted to the experimental Jc (B,T) data for the SuperpPower tapes [3], whereas the value of A was selected to get $I_{op\ max}$ = 80% I_c (18 T , 4.5 K).

- Assumed current scenario



Point	t(s)	I(A)
Start of current cycle	0	0
End of Premag	500	65000
SOF	600	-10716
EOF	7810	-65000
EOP	7910	0
End of current cycle	8010	0

[2] O. Dicuonzo, Electromechanical investigations and quench experiments on sub-size HTS cables for high field EU-DMO Central Solenoid. PhD Thesis, EPFL-SPC 2022.
[3] V. Lombardo, et al., IEEE Trans. Appl. Supercond. 21 (2011) pp. 3247-325.

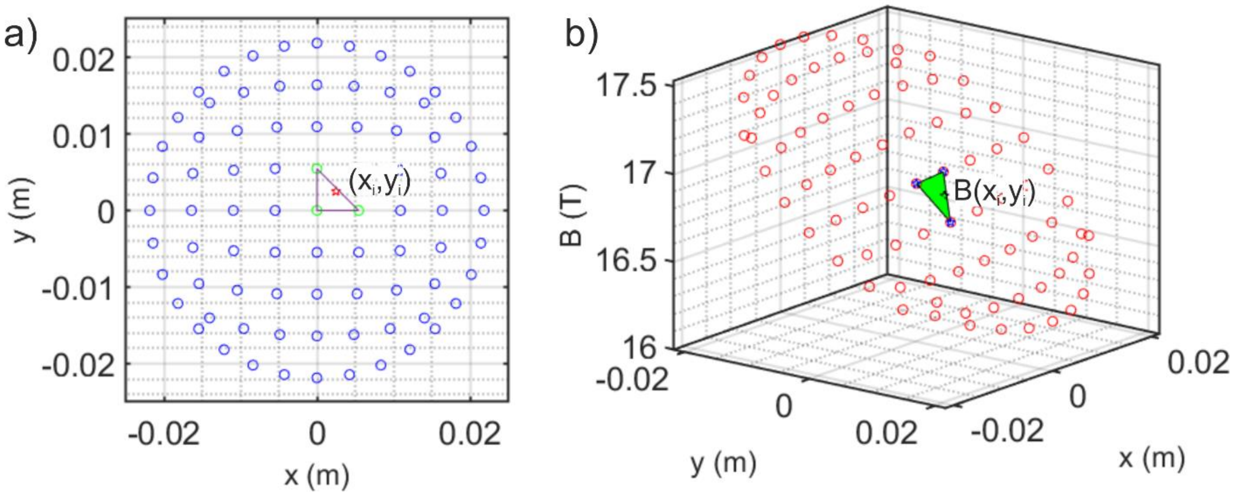
- Effective magnetic field profiles at the characteristic points of the cycle

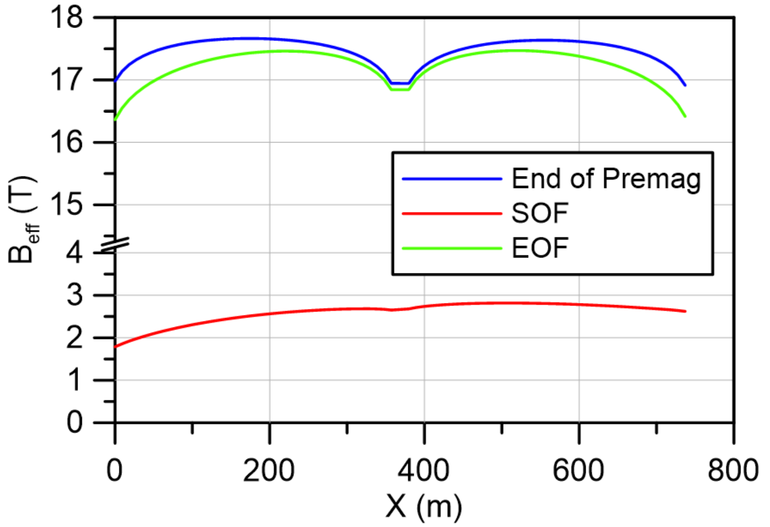
Lorenzo provided us the magnetic field (at 81 points in the conductor cross section for each turn) computed for a tentative coil design. The effective MF at the beginning/end of each turn of the CS1 module was obtained by solving the equation:

$$J_c(B_{eff},T) = \left[\frac{1}{A_{cable}} \iint_{A_{cable}} \left(\frac{1}{J_c(B(x,y),T)} \right)^n dxdy \right]^{-1/n}$$

B_{eff} was calculated for n = 15 and T ≈ T_{op} + 1.5 K = 6.2 K.

We developed a dedicated procedure to calculate the integral using 81 data points in the cable cross section. To calculate the MF at any given point (x_i, y_i) in the cable cross section (indicated as a red star), the 3 nearest nodes were found, which determined the position of the respective B(x,y) plane (a green triangle). The B(x_i, y_i) value was estimated from the B(x,y) plane equation.





Heat loads – hysteresis losses

The magnetization loss (in kJ/m³/cycle, normalized to the HTS tapes volume) was calculated based on the experimental fit obtained for the CORC conductor designed by ASIPP [4]:

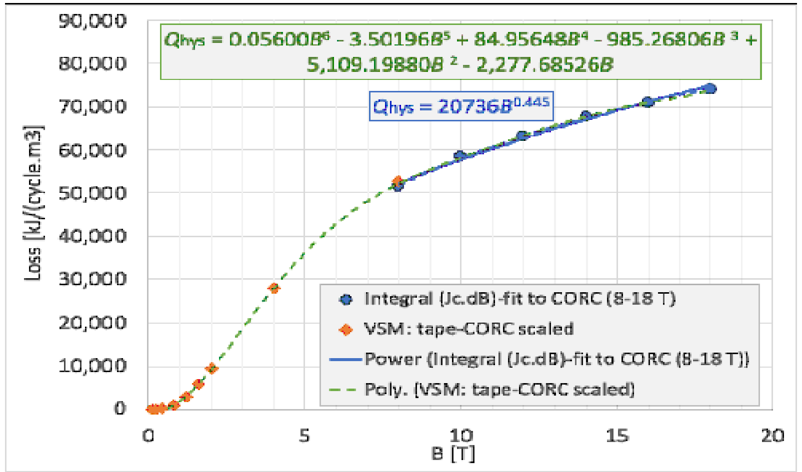
$$Q_{hys}(B) = \begin{cases} c_1 B^3 & \text{for } 0 < B < 0.903\ \text{T} \\ aB^6 + bB^5 + cB^4 + dB^3 + eB^2 + fB & \text{for } 0.903\ \text{T} < B < 13.369\ \text{T} \\ a_1 B^{b_1} & \text{for } 13.369\ \text{T} < B < 18\ \text{T} \end{cases}$$

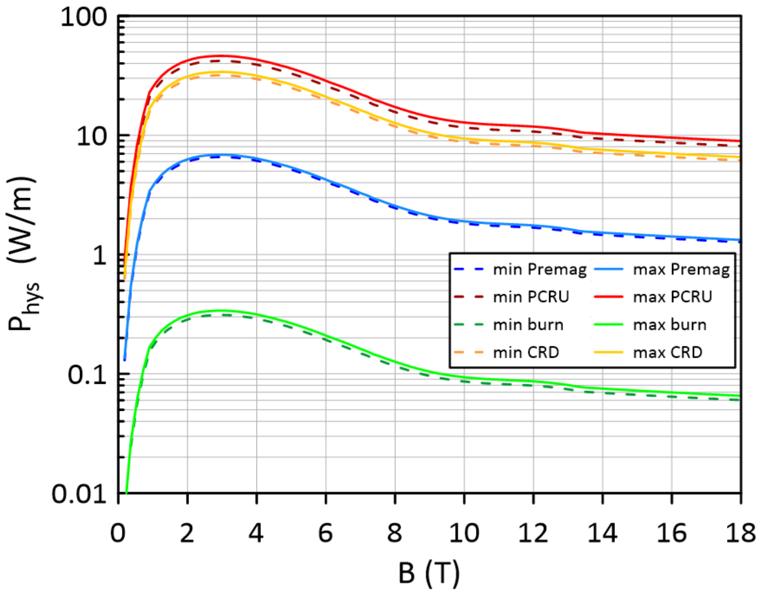
where: a = 0.05600, b = -3.50196, c = 84.95648, d = -985.26806, e = 5 109.19880, f = - 2 277.68526, a_1 = 0.05600, b_1 = -3.50196.

The respective expression for the thermal power of hysteresis losses (in W/m) is:

$$P_{hys}(B) = C_{phase} A_{tapes} \frac{dQ_{hys}}{dt}$$

$$P_{hys}(B) = C_{phase} A_{tapes} \left| \frac{dB}{dt} \right| \begin{cases} 3c_1 B^2 & \text{for } 0 < B < 0.903\ \text{T} \\ 6aB^5 + 5bB^4 + 4cB^3 + 3dB^2 + 2eB + f & \text{for } 0.903 < B < 13.369\ \text{T} \\ a_1 b_1 B^{(b_1 - 1)} & \text{for } 13.369\ \text{T} < B < 18\ \text{T} \end{cases}$$





Heat loads – coupling losses

The coupling loss per unit length of conductor in a field ramped at a uniform rate was calculated as [5]:

$$P_{coupling}(x) = \frac{n\tau S}{\mu_0}\left(\frac{dB_{eff}(x)}{dt}\right)^2$$

$$= \frac{n\tau S}{\mu_0}\left[\left(\frac{dB_{eff\,r}(x)}{dt}\right)^2 + \left(\frac{dB_{eff\,z}(x)}{dt}\right)^2\right]$$

where n - demagnetization factor,

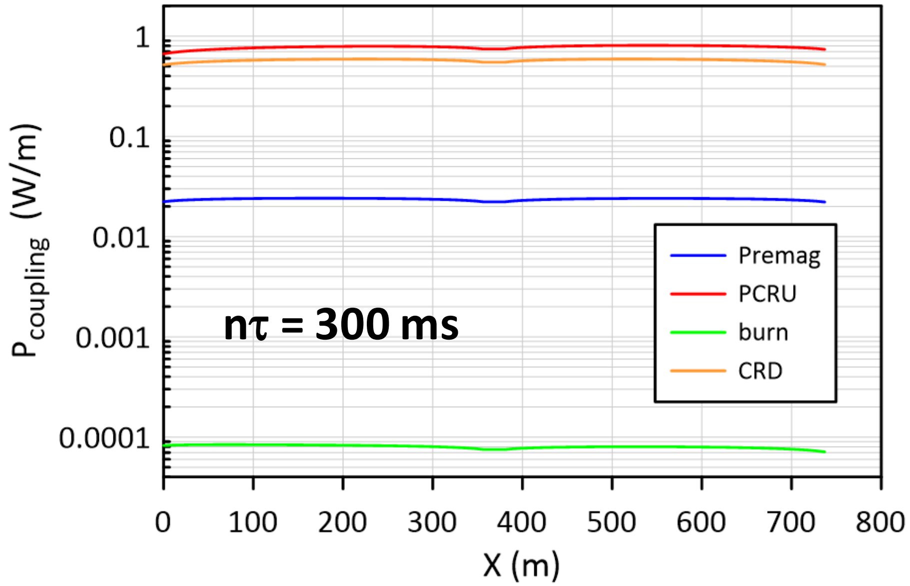
τ - time constant

S - superconducting tapes cross section.

The values of $\dot{B}_{eff\,r}(x)$ and $\dot{B}_{eff\,z}(x)$ during the Premag, PCRU, burn and CRD phases were estimated using the respective $B_{eff\,r}\,(x)$and $B_{eff\,z}(x)$values at the beginning and end of the given phase, e.g.

$$\dot{B}_{eff}\,(x)_{PCRU} = \frac{[B_i(x)_{SOF} - B_i(x)_{Premag}]}{100\,s} \qquad i = r, z$$

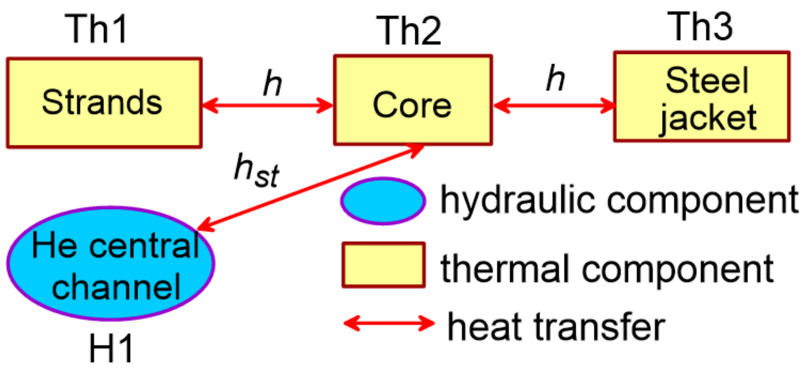
the analysis was performed for the trial value of $n\tau$ = 300 ms [6].

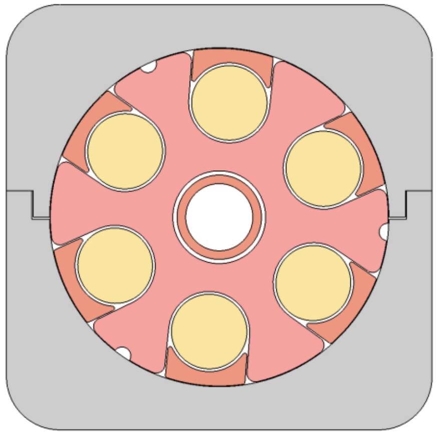


[5] M. N. Wilson, Superconducting Magnets, Clarendon Press 1983.

[6] K. Yagotintsev, et al., Superconductor Science and Technology 33 (2020) Art. No. 085009 (14pp).

THEA model

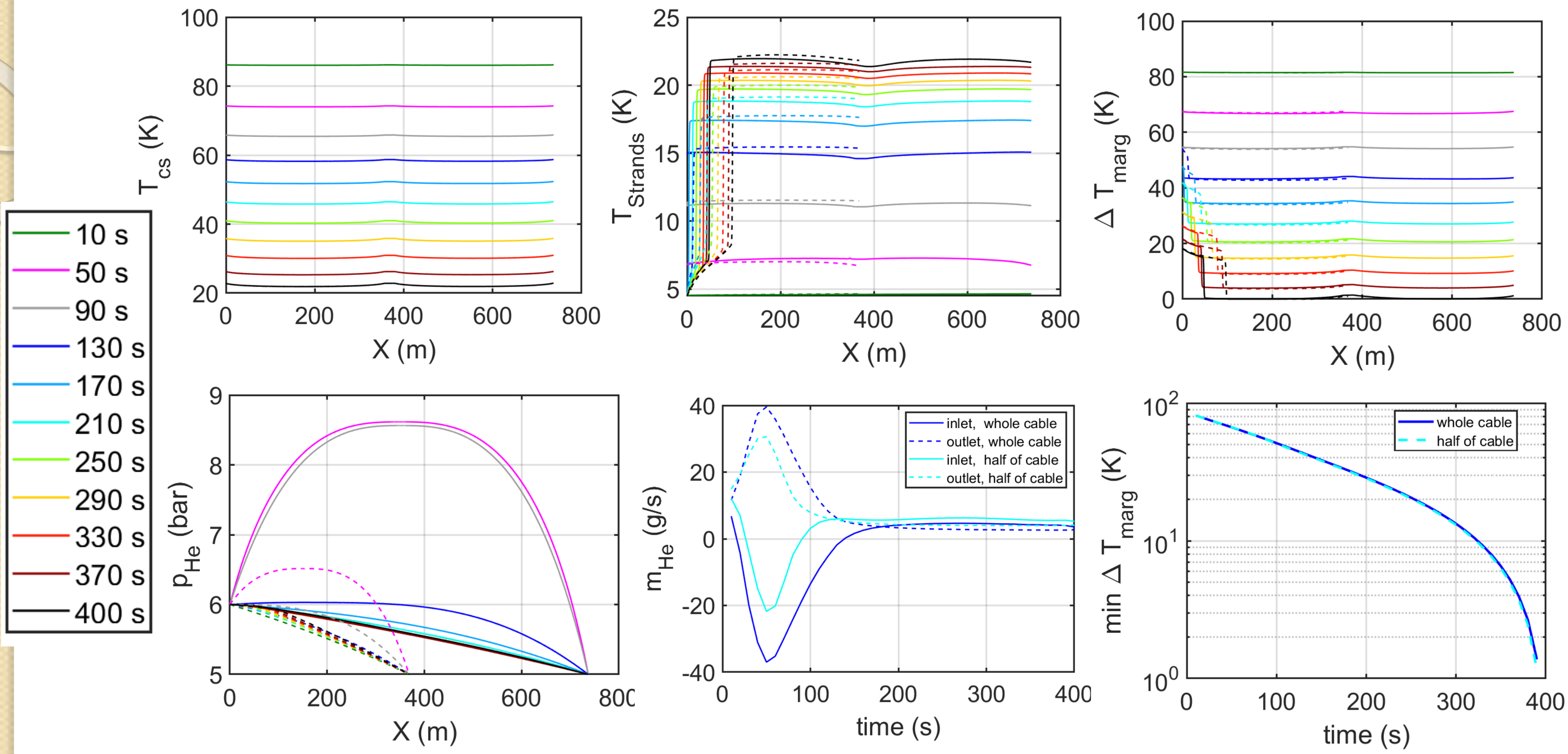




- We assumed cooling conditions (T_{in} = 4.5 K, p_{in} = 6 bar, Δp = 1 bar) and thermal links between the conductor components typical for TH simulations of the EU-DEMO conductors [7]
- We performed the validation of the THEA conductor model by comparison with predictions of the steady state model [8,9] at the „Pseudo – end of Premag" state (with operating current and B profile corresponding to the end of Premag but at no heat load)
- Two cases were considered:
  - full length of the conductor (corresponding to single CS1 module)
  - half lenghth of the conductor (corresponding to the CS1 module split into two sub-modules (CS1L and CS1U) located one above the other).

[7] L. Savoldi and R. Zanino, Common approach for thermal-hydraulic calculations, Memo for WPMAG-2.1-D01 (2016) https://idm.euro-fusion.org/?uid=2LMECE
[8] M. Lewandowska, K. Sedlak, IEEE Trans. Appl. Supercond. 24 (2014) Art. No 4200305
[9] M. Lewandowska, A. Dembkowska, R. Heller, M. Wolf, Cryogenics 96 (2018) 125-132

Results for the Premag phase



We planned to simulate two subsequent current cycles, but in both considered cases (full and half conductor length), the temperature margin dropped to 0 and the conductor quenched close to the end of the first Premag phase (for t ≈ 400 s).

Summary and conclusions

- Thermal – hydraulic analysis of the CORC HTS conductor designed by ACT for the innermost layer of the DEMO CS1 coil at normal operaing conditions was performed.
- Simplified current scenario (without breakdown) was considered and heat loads due to the hysteresis and coupling losses were taken into account.
- The model of hysteresis losses was based on the experimental fit obtained for the ASIIP CORC conductor was considered, which provided much higher values than the preliminary analytical model adopted in our 2023 analysis.
- Time evolution of the minimum temperature margin during the Premag phase was studied.
- In both considered cases (full conductor length – corresponding to a single CS1 module, and half conductor length – CS1 module split into two submodules CS1L and CS1U), for the assumed $J_c(B,T)$ scaling law and model of heat loads and, the temperature margin was too small and conductor quenched close to the end of the Premag phase.
- Generation of magnetization losses in the considered CORC® conductor should be studied in more details, if possible, also experimentally. It would be advisable to undertake some efforts to reduce the heat load due to magnetization losses on the cable, e.g. by using striated tapes.

Analysis of the results of the SULTAN test of the HTS conductors

- In our THEA simulations of the normal operation of the CORC conductor (ACT design) for the HTS insert of the DEMO hybrid CS, several assumptions regarding the $J_c(B,T)$ scaling law, n value, heat loads due to AC losses, had to be done due to the lack of the reliable experimental data. We hoped to extract this information from the results of the SULTAN test of this CORC conductor. However, both test campaigns were unsuccessful due to some issues with the sample ☹
- In this situation, instead of the analysis of the SULTAN test of the ACT CORC sample, we decided to continue the simulations and analysis of selected runs of the quench experiment. Our work is focused on incorporating a temperature and surface pressure-dependent contact strands-jacket heat transfer coefficient into the model.

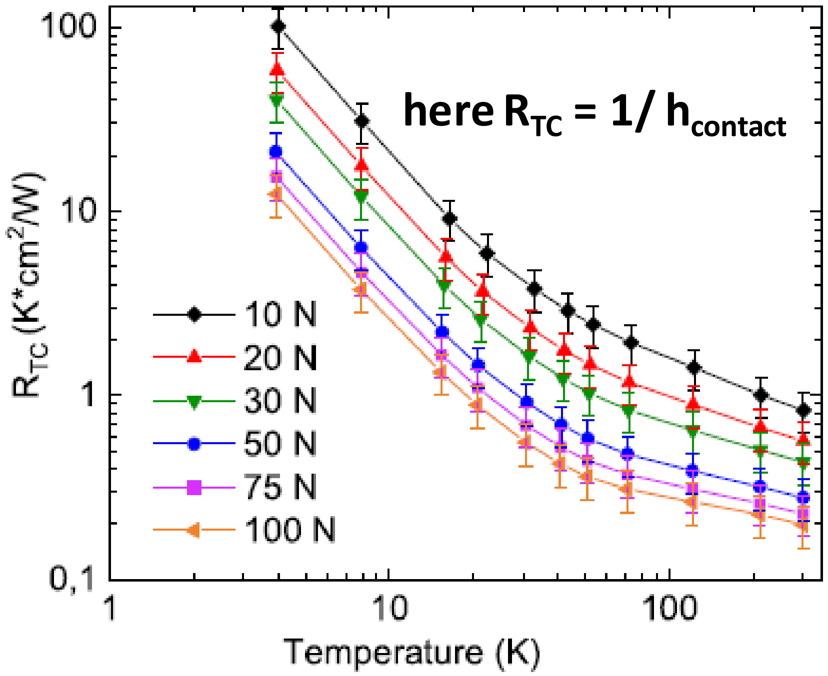
Motivation

- In numerical models of superconducting cables there are several uncertain parameters significantly affecting their thermal-hydraulic behavior, such as e.g.:
  - the convective strands-helium heat transfer coefficient (h_{conv}),
  - the contact strands-jacket heat transfer coefficient ($h_{contact}$ or the respective thermal resistance $R_{th} = 1/(h_{contact} \cdot p_{contact})$),
  - copper RRR.

  It is typically assumed that $h_{contact}$ is constant, whereas h_{conv} is estimated using the standard smooth tube Dittus-Boelter correlation or its modifications.

$$h_{conv} = Nu \frac{k_{He}}{D_h} \qquad Nu_{DB} = 0.023 \mathrm{Re}^{0.8} \mathrm{Pr}^{0.4}$$

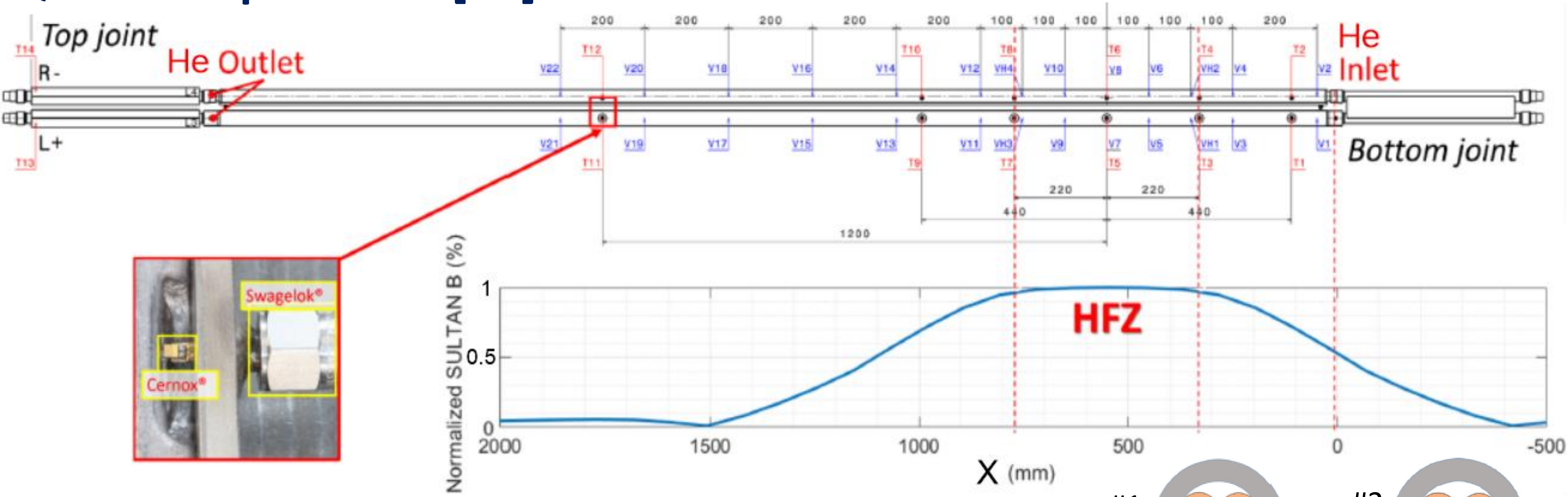
- Recent experimental work [1] revealed that **R_{th} strongly depends on temperature and the applied contact force (or the respective surface pressure). This dependence should be incorporated in the TH models.**



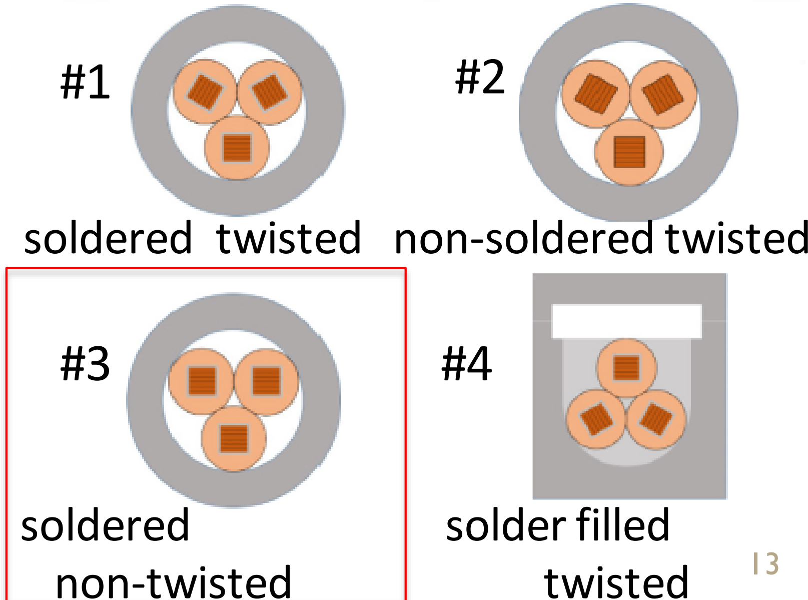
Thermal contact resistance for copper - stainless steel stack [10]

[10] *N. Bagrets, et al., IEEE Trans. Appl. Supercond. 32 (2022) Art. No. 8800205*

Quench Experiment [11]

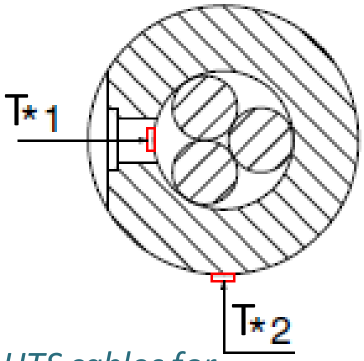


Scheme of the samples instrumentation and the samples layout



Sample #3 with the REBCO tapes wide face perpendicular to the magnetic field and was selected as a reference for our analyses

Copper RRR (measured) $\sim$ 40 – 60

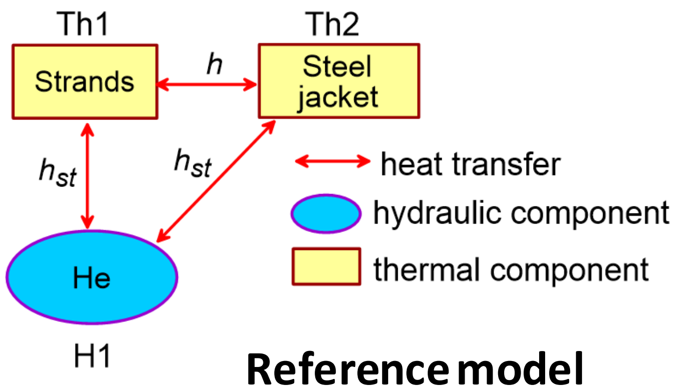


[11] *O. Dicuonzo, Electromechanical investigations and quench experiments on sub-size HTS cables for high field EU-DEMO Central Solenoid, PhD Thesis, EPFL-SPC 2022*

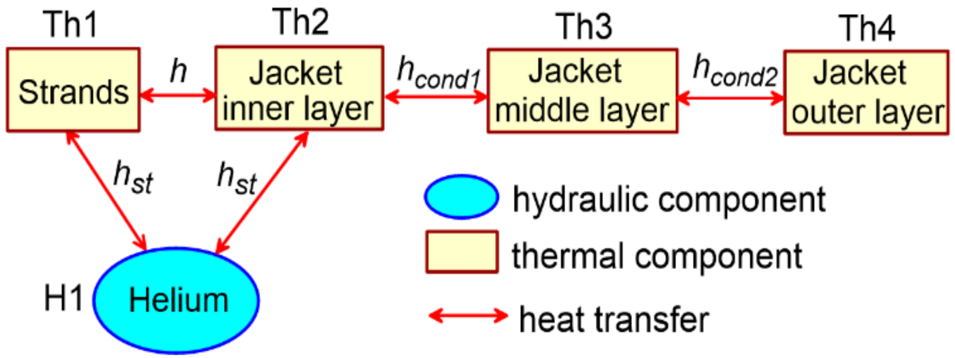
Earlier analyses with constant $h_{contact}$ (R_{th})

- In 2022 the Polito team simulated selected runs the Quench Experiment (**run 170802:** heat pulses propagation and **run 190808**: quench induced by slow heating of helium at the inlet) using a complex multicomponent H4C model, with constant copper **RRR = 100**, and h_{conv} calculated with the Dittus-Boelter correlation multiplied by the constant factor M. It was reported, that the best agreement between the simulations' results and the experiment was obtained for **M = 0.05** and **R_{th} = 0.083 m·K/W** [12].

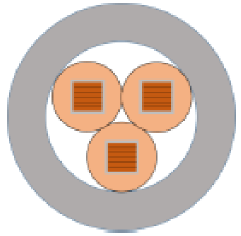
- In 2022-2023 we performed parametric simulations of the **run 190808**, using two THEA models with different levels of complexity, for various pairs of the uncertain model parameters: (RRR,R_{th}) and h_{conv} calculated with the Dittus-Boelter correlation (M=1). The best agreement between the simulations' results and the experiment was obtained with the **extended model** for **RRR = 60** and **R_{th} = 0.095 m·K/W** [13]. However, when we used these values to simulate heat pulses propagation from the **run 170802**, the results were not quite satisfactory.



Reference model



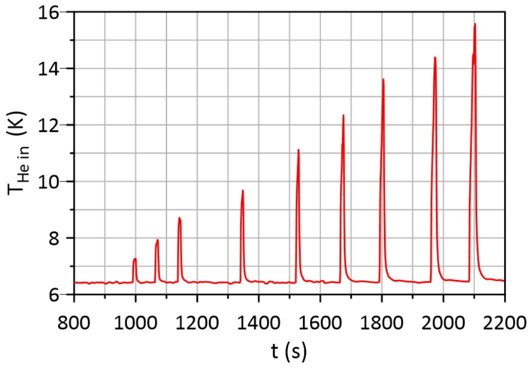
Extended model



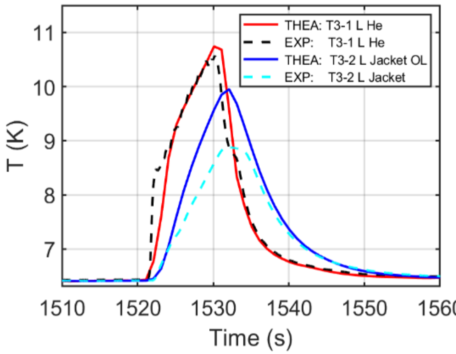
[12] A. Zappatore, et al., Cryogenics 132 (2023) Art. No 103695.
[13] M. Lewandowska, et al., Cryogenics 141 (2024) Art. No 103889.

Goal and scope of the present study

- In the present work, we implemented the temperature and surface pressure dependent $h_{contact}$ /R_{th} in the THEA extended model [4] and simulated selected runs of the Quench Experiment (**run 170802** and **run 190808**), to check if this assumption allows for more accurate reproduction of the experimental results.
- As a first step we applied the THEA model with variable $h_{contact}$ to simulate the heat pulse propagation (we considered **first 7 heat pulses with increasing amplitude in the experimental run 170802**, no quench, no Joule heat generation => relatively low temperatures)



- In order to quantitatively evaluate the consistency of simulation results with experimental data, we introduced several metrics, including:
    - Integral Absolute Error (IAE): $IAE = \int_{t1}^{t2} |T_{exp} - T_{sim}|dt$
    - Relative Integral Absolute Error (RIAE): $RIAE = \frac{IAE}{\int_{t1}^{t2} T_{exp}\, dt} \cdot 100\%$
    - Relative Amplitude Error (RAE): $\frac{\Delta T_{max}}{T_{max}} = \frac{|\max T_{exp} - \max T_{sim}|}{\max T_{exp}} \cdot 100\%$



- As a 2nd step quench simulations were performed and the final tuning of model parameters was done

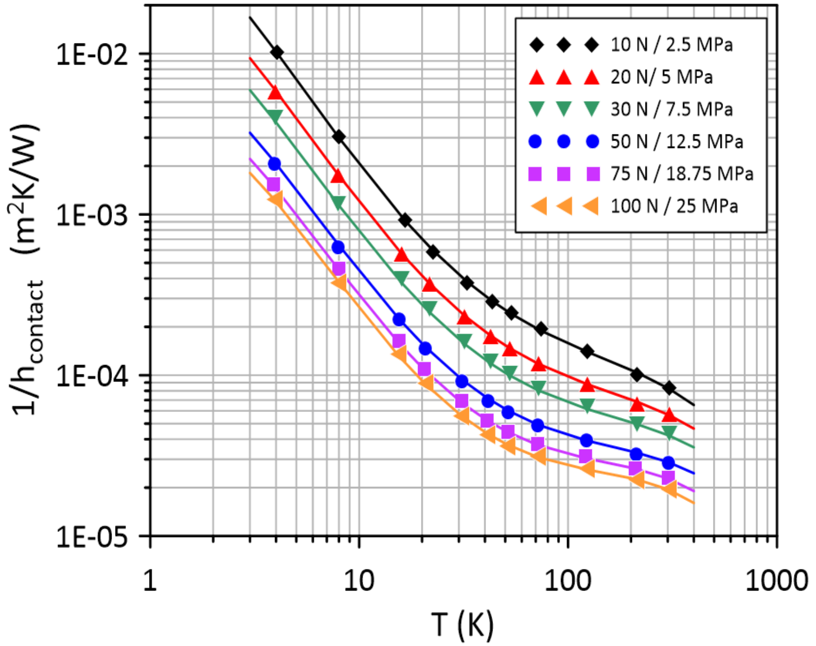
Fitting the $R_{TC} = 1/h_{contact}$ experimental data [10]

- We developed an analytical formula for $R_{TC}(T,F)$ in the following form, which reproduced very well the experimental data, and we implemented it in THEA (UserThermalResistance)

$$\ln R_{TC} = p_0(F) + p_1(F)x + p_2(F)x^2 + p_3(F)x^3 + p_4(F)x^4$$

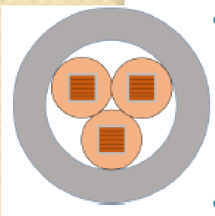
$$x = \ln T$$

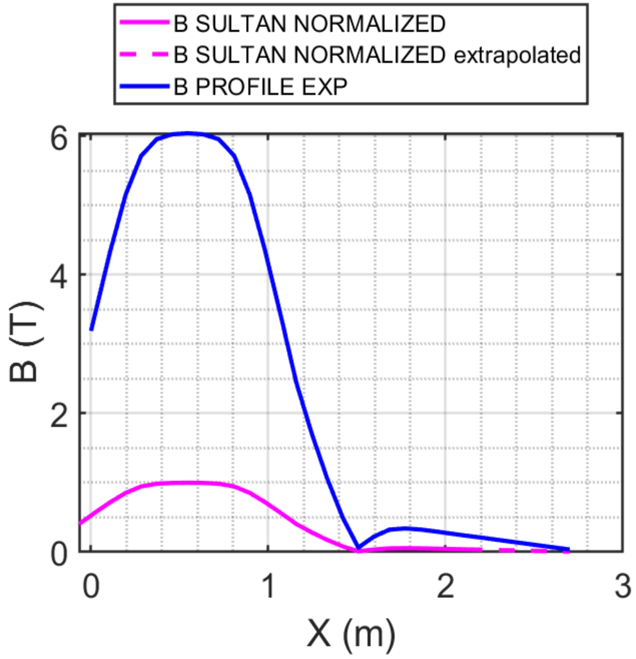
$$p_i(F) = u_{0i} + u_{1i}F + u_{2i}F^2 + u_{3i}F^3$$



Comparison of our fit with experimental data

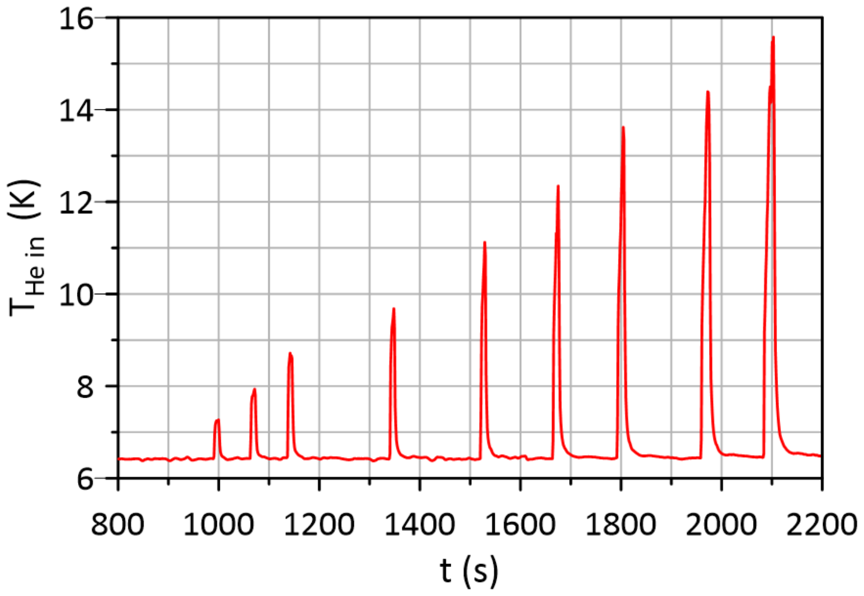
- **Problems:**
  - The obtained fit may not be accurate outside the experimental T and F ranges => restriction for our analysis
  - all strands are treated in the model as a single 1D component, whereas the contact strands-jacket force resulting from the Lorenz force is not the same for different strands => **the average contact surface pressure instead of F**
  - the profile of the average strands-jacket contact surface pressure along the conductor should be proportional to the Lorentz force and thus to the magnetic field profile, but the exact values are unknown (a dedicated mechanical analysis would be desired) => **parametric approach, p_{max} – one of the model parameters to be tuned (2.5 MPa ≤ p_{max} ≤ 25 MPa)**

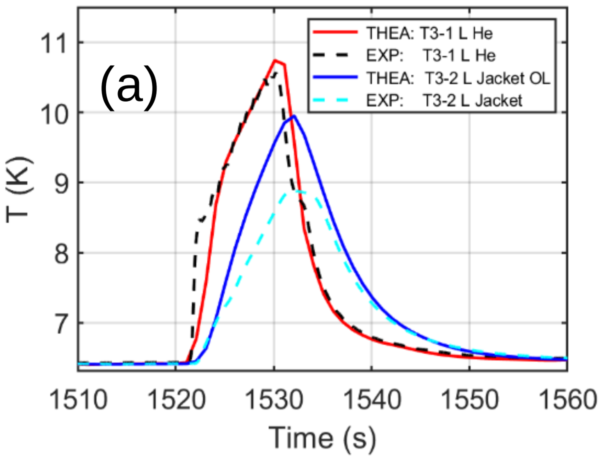


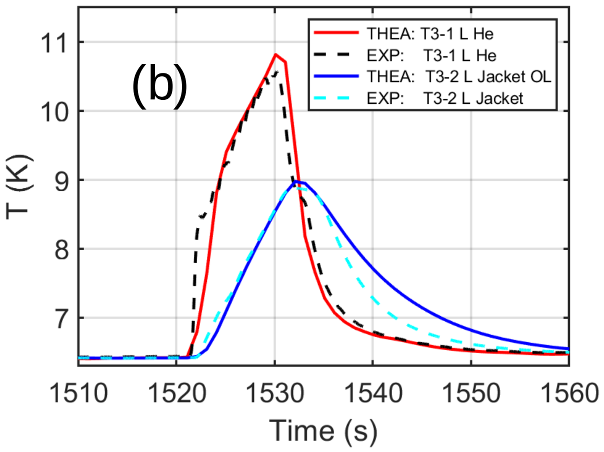


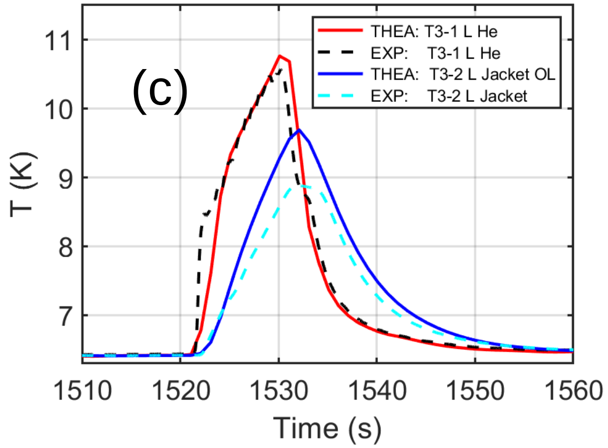
Parametric simultions of the heat pulse propagation (run 170802)

- We performed simulations with RRR = 50 and variable $h_{contact}$ = f(p,T) for the extreme values of the maximum strands-jacket contact surface pressure (p_{max} = 2.5 MPa and p_{max} = 25 MPa).
- The max $T_{jacket\ OL}$ values were typically higher than in experiment. => Following [12] we introduced a multiplier (M) to the Dittus-Boelter correlation reducing convective heat transfer between helium and the solid cable components.





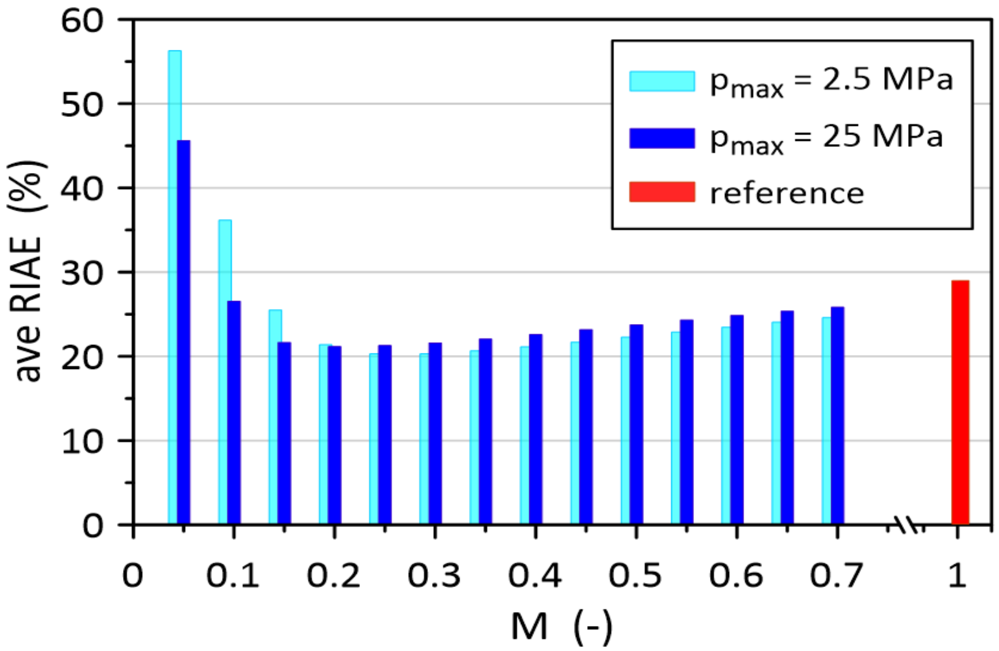


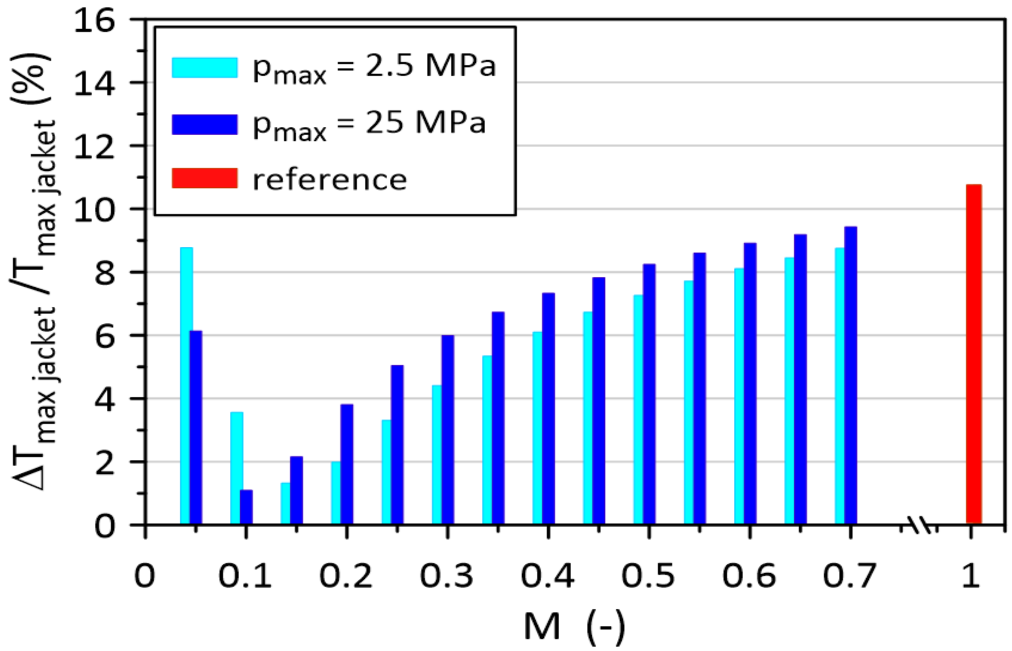


Typical simuation results; pulse 5: (a) R_{th} = 0.095 m·K/W = const, M=1 [13] (reference case); (b) R_{th} = f (p,T), M = 0.2, p_{max} = 2.5 MPa; (c) R_{th} = f (p,T), M = 0.53, p_{max} = 5 MPa.

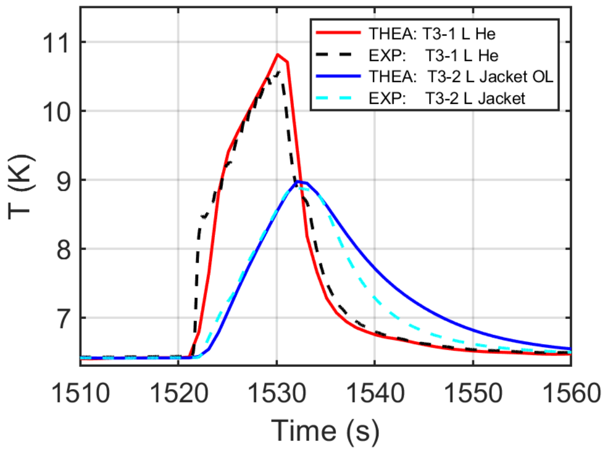
Parametric simultions of the heat pulse propagation (run 170802)

RIAE and RAE_{jacket} averaged over all considered pulses and temperature sensors



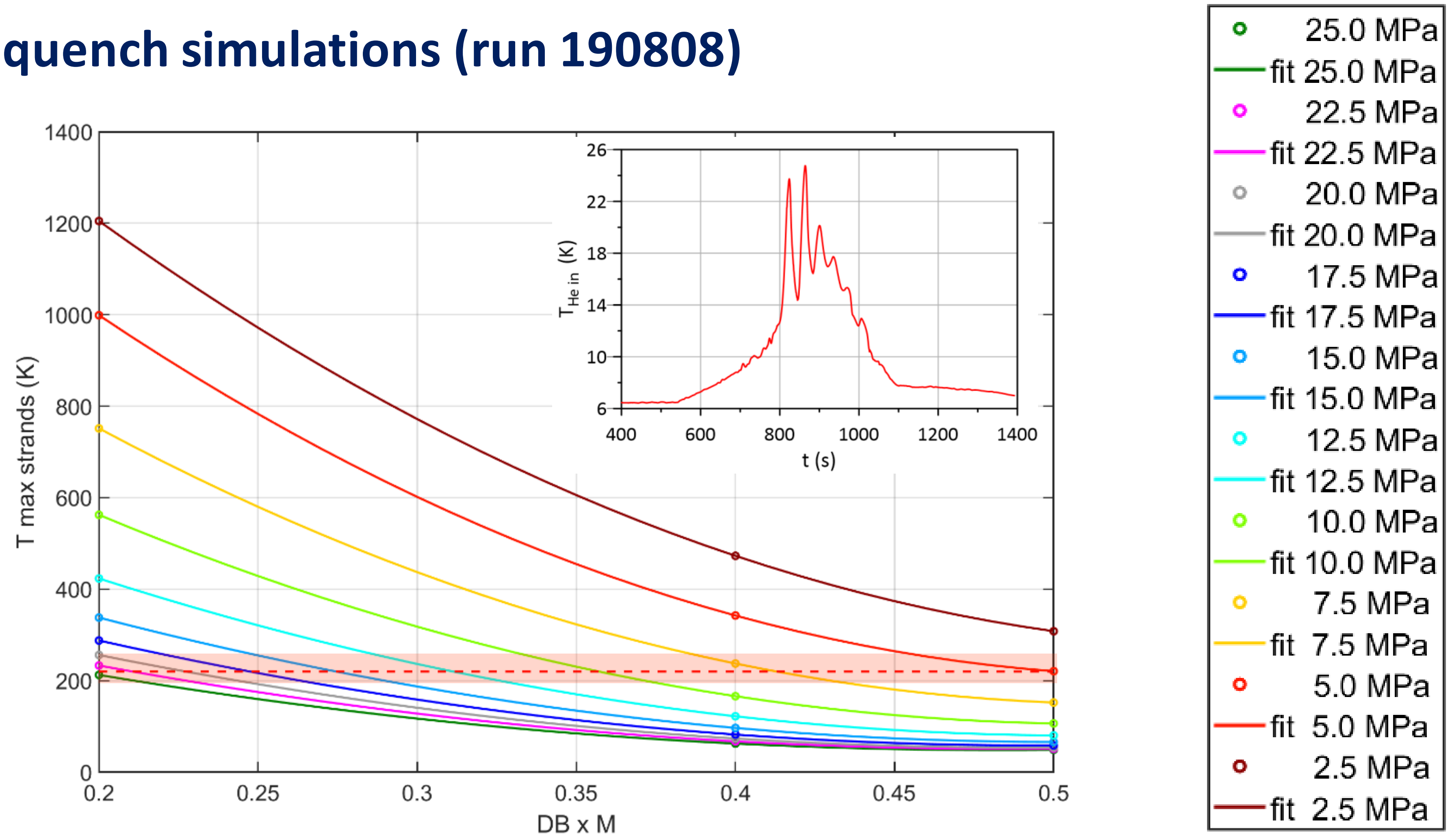


- The results were not very sensitive to the choice of p_{max}. The lowest values of ave RIAE and ave RAE were observed for relatively low M values (M = 0.3 and M = 0.1, respectively).
- At very low M values, for which the pulse amplitude was reproduced correctly, the recooling phase observed in the simulations was too long => increase of the ave RIAE value. The recooling phase was well captured for M ≥ 0.4.
- This may indicate that there is a factor inluencing the readings of the thermometers located at the jacket surface, which was not included in our model (e.g. contact resistance betwen the jacket wall and temperature sensor?)



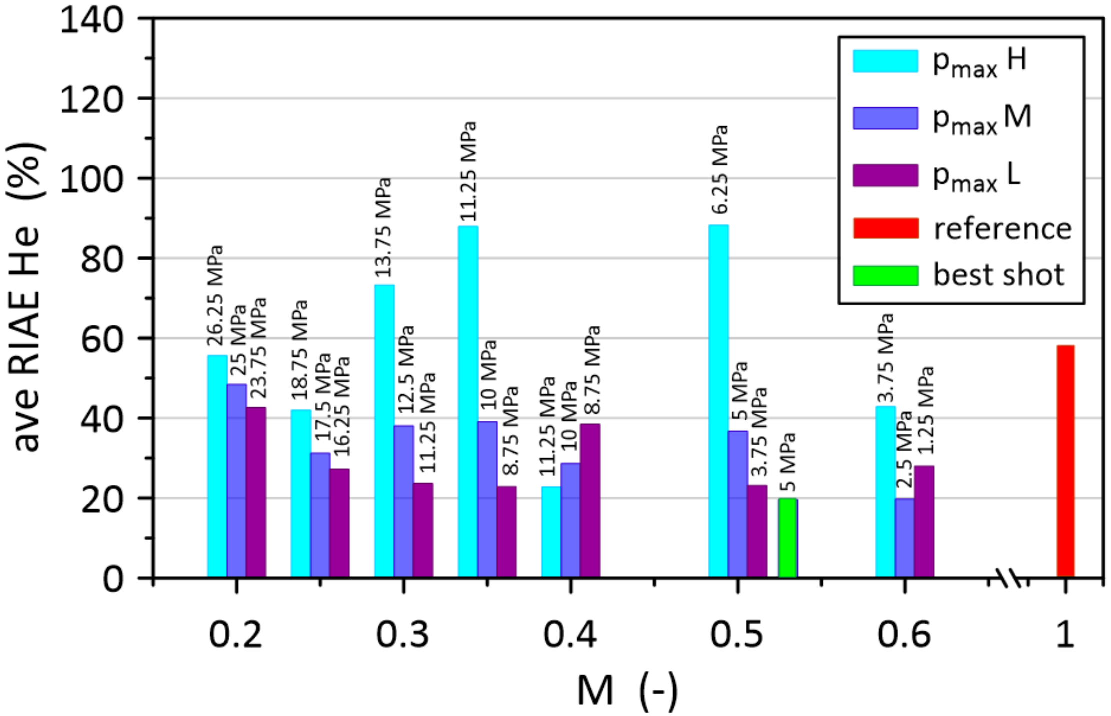
M = 0.2, p_{max} = 2.5 MPa

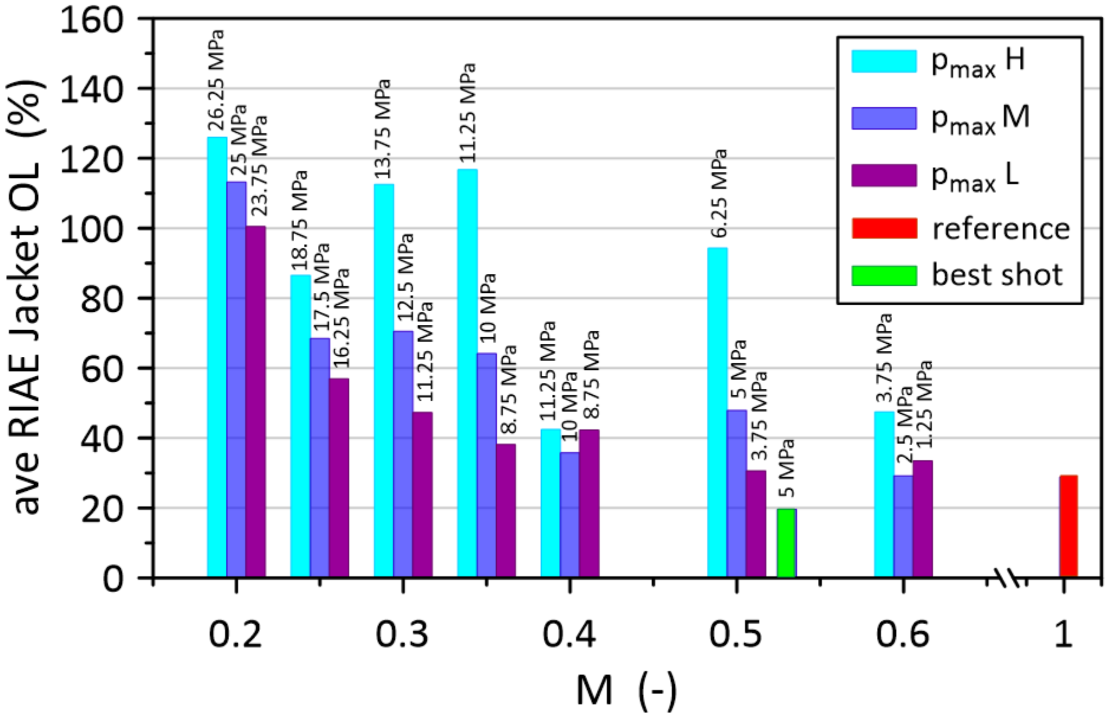
Parametric quench simulations (run 190808)



- Preliminary quench simulations were performed for RRR = 50, **M = 0.2, 0.4 and 0.5** and the whole considered p_{max} range (**2.5 MPa ≤ p_{max} ≤ 25 MPa)**. These results were very sensitive to the choice of M and p_{max}
- We identified the pairs of parameters (M, p_{max}) for which the value of the hot spot temperature resulting from simulations were close the expected experimental value, and then conducted further quench simulations using nearby (M, p_{max}) values.

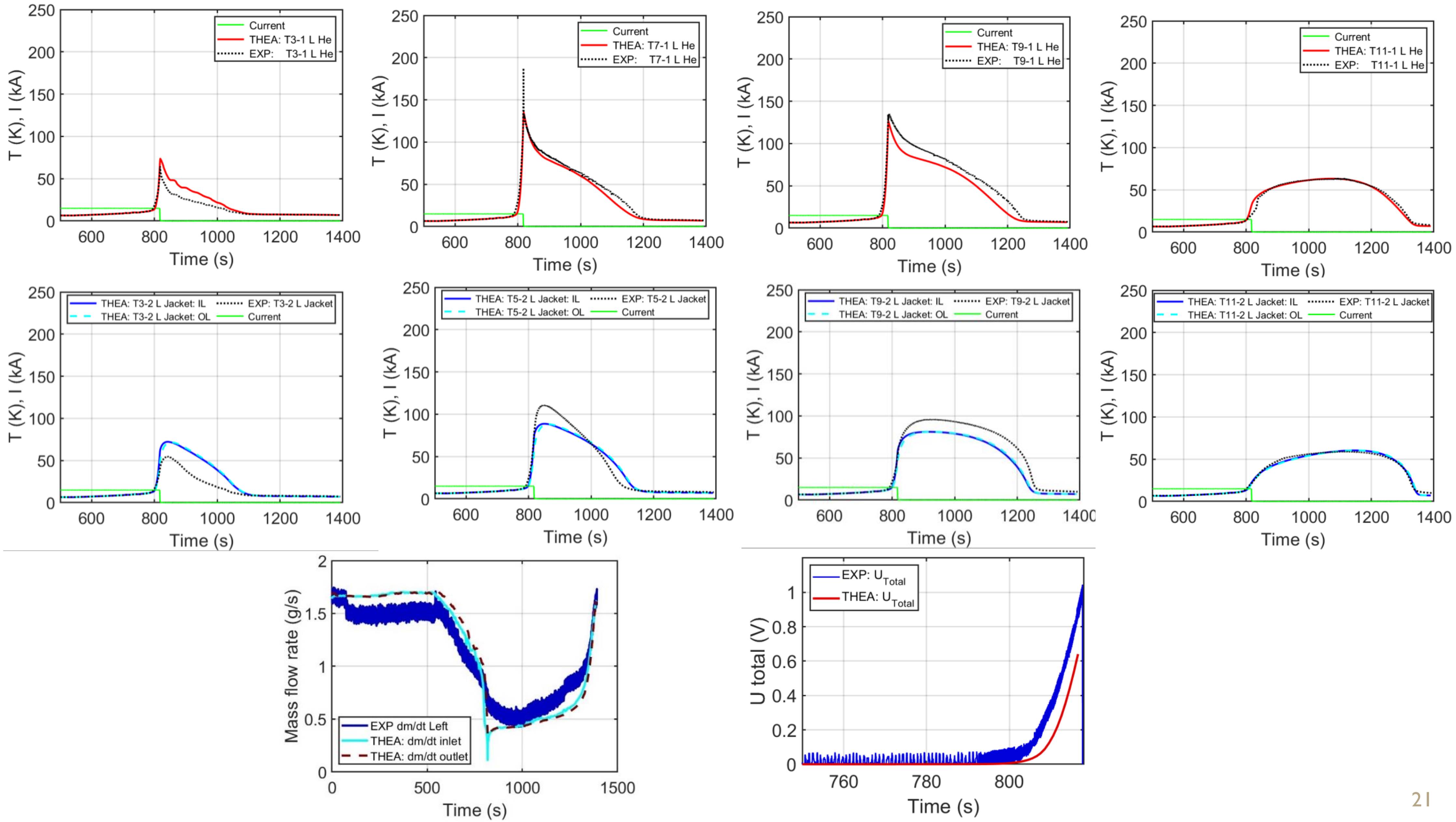
Parametric quench simulations (run 190808)





- Low values of ave RIAE He and ave RIAE Jacket OL values were observed for M of about 0.35 -0.6.
- We performed several further simulations for M in this range and the lowest values of both considered integral indicators we obtained for the pair: **M = 0.53, p_{max} = 5 MPa**.

Quench simulations results obtained for the best shot (M = 0.53, p_{max} = 5 MPa)



Summary and conclusions

- According to the recent experimental results [10] the contact thermal resistance between the solid conductor components strongly depends on temperature and surface pressure. We obtained an analytical expression $1/h_{contact} = f(T,F)$ which very accurately reproduces the experimental data [10]. We implemented it in the extended THEA model [13] and performed simulations of two selected runs of the Quench Experiment [12].
- The strands-jacket surface pressure profile along the condsidered conductor is unknown (a dedicated mechanical analysis would be desirable). In this situation we assumed that it was proportional to the magnetic field and treated its maximum value as the model parameter to be tuned.
- We introduced a few metrics to quantify the consistency of simulation results with experimental data .
- Simulations of the heat pulse propagation (run **170802**) were performed. These results were not very sensitive to the choice of the values of p_{max} (in the range 2.5 – 25 MPa) and M (in the range 0.15-0.50). The best agreement between the pulse amplitude simulation and experiment was obtained for M ≈ 0.2, however for such low M values the recooling phase was not reproduced accurately.
- Quench simulations (run **190808)** were performed. These results strongly depended on the (M, p_{max}) values, because of the feedback between the strands-He-jacket heat exchange and Joule heat generation. We selected the pair: **M = 0.53, p_{max} = 5 MPa** for which the lowest values of both considered integral indicators (ave RIAE He and ave RIAE jacket OL) were observed. The agreement between the simulations and experimental results was significantly improved w.r.t. the reference best simulation results obtained with the constant $h_{contact}$ [13].

Plans for 2025

- TH analysis of HTS part of the hybrid DEMO CS coil designed by CEA

  This activity has already started in 2024 – we received from the CEA colleagues the coil and conductors data and we got familiar with them. We would like to continue this work in 2025.

- TH analysis of other possible layouts of the CORC condutor (ACT design) for the innermost layer of the DEMO CS coil was requested by Arend to study the impact of the coolig channel diameter and/or additional cooling channels on the minimum temperature margin.

- Contribution to TH of the DEMO CS/PF coils designed by SPC is also foreseen

Thank you very much for your attention

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