West Pomeranian University of Technology, Szczecin

Analysis on the results of the Quench Experiment taking into account variable contact strands-jacket heat transfer coefficient

Monika LEWANDOWSKA[a,b], Aleksandra DEMBKOWSKA[a,b], Kamil SEDLAK[c]

(a) Institute of Nuclear Physics Polish Academy of Sciences, Kraków, Poland

(b) West Pomeranian University of Technology, Szczecin, Poland

(c) EPFL-SPC, 5232 Villigen PSI, Switzerland

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Outline

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  - Simulations of the heat pulse propagation
  - Quench simulations
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Introduction (I)

- High Temperature Superconductors (HTS) are very promising materials to be applied in future fusion magnets. HTS conductors are already considered as a possible option for some components of the EU DEMO magnet system.
- Various HTS cable concepts, such as e.g.: twisted stack cable, cross-conductor (CroCo), Roebel assembled coated conductor (RACC), conductor on round core (CORC®), aligned stacks transposed in Roebel arrangement cable (ASTRA), vacuum pressure impregnated, insulated, partially transposed, extruded, and roll-formed cable (VIPER) have been proposed.
- Geometric and thermo-physical characteristics of HTS and LTS conductors differ significantly. Numerical simulations of HTS conductors operation may require specific approaches, particularly for fast transient processes (e.g. quench).
- To provide data for for testing different numerical models and tuning their parameters, a series of dedicated HTS 15-kA subsize samples with different geometries were produced and tested at the SULTAN test facility, in the scope of the international collaboration between EUROfusion and China. As a result of this Quench Experiment a huge experimental database has been created.

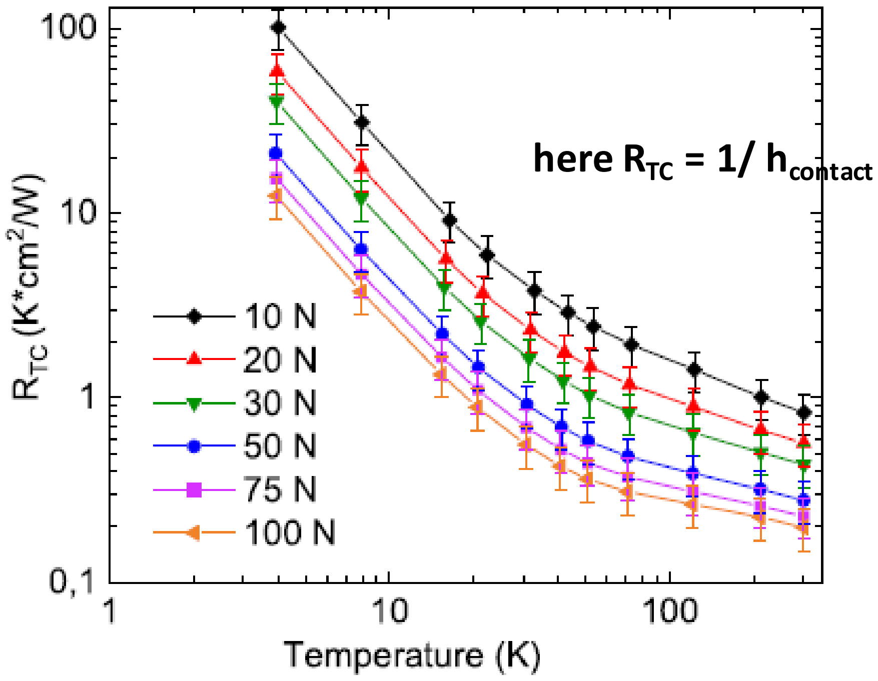
Introduction (II)

- 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.

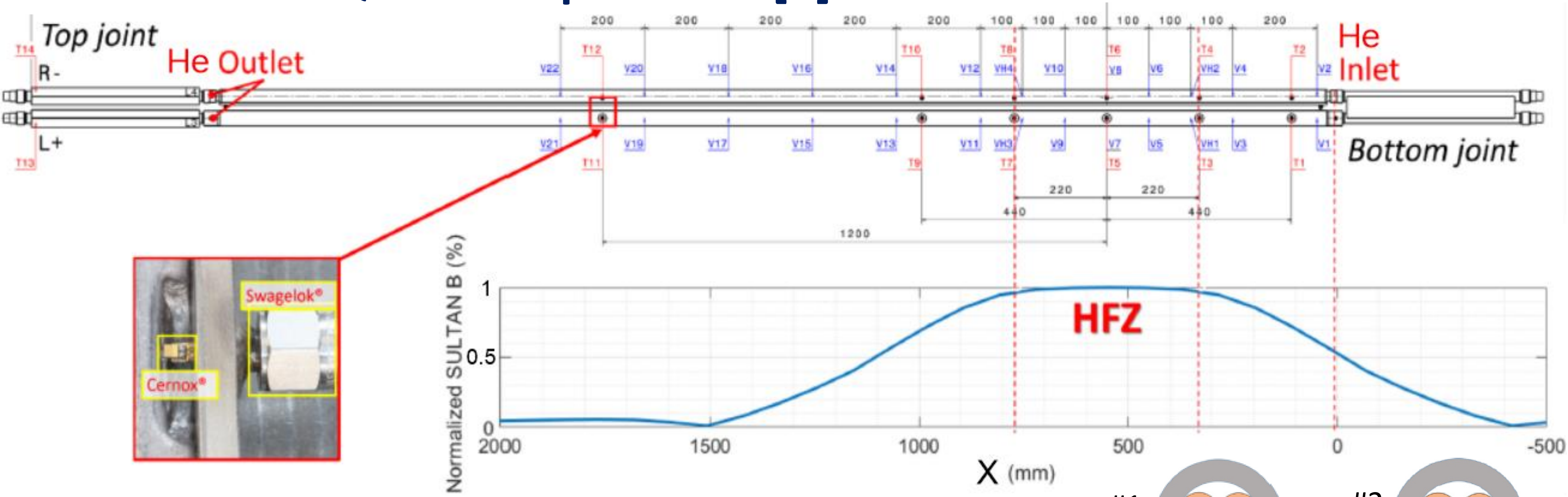
$$h_{conv} = Nu \frac{k_{He}}{D_h} \qquad Nu_{DB} = 0.023 \mathrm{Re}^{0.8} \mathrm{Pr}^{0.4}$$

- 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.**



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

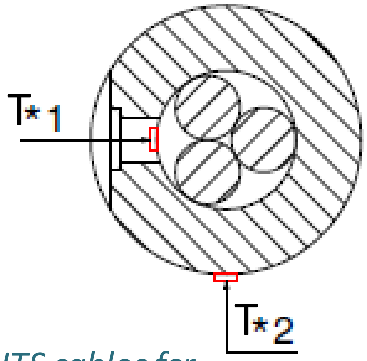
Introduction – Quench Experiment [2]

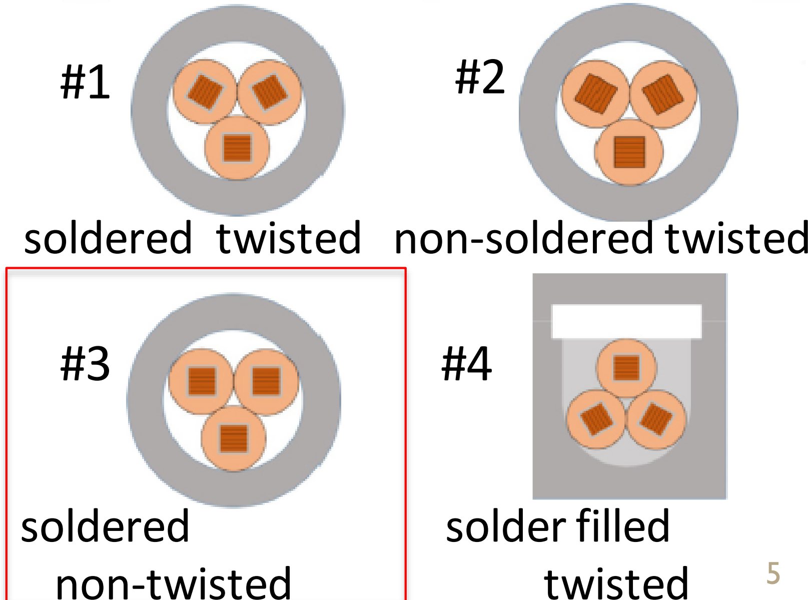


Scheme of the samples instrumentation and the samples layout

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

Copper RRR ~ 40 – 60



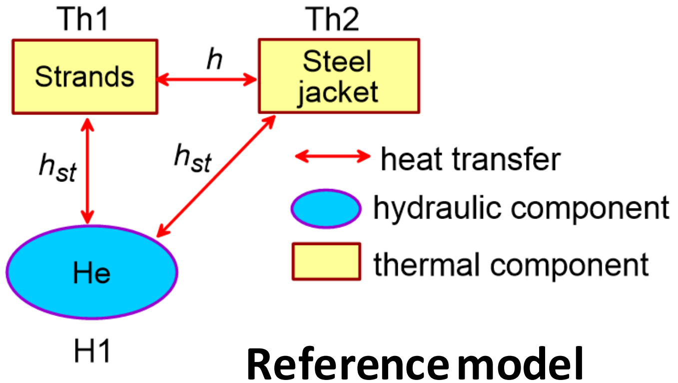


[2] O. Dicuonzo, Electromechanical investigations and quench experiments on sub-size HTS cables for high field EU-DEMO Central Solenoid, PhD Thesis, EPFL-SPC 2022

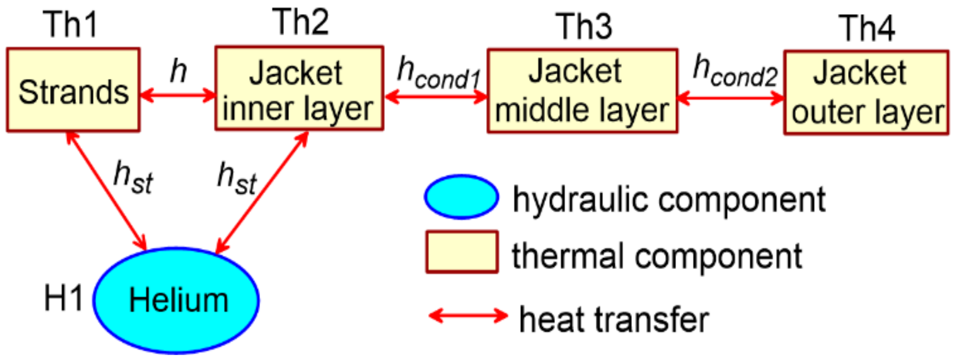
Introduction – earlier analyses with constant $h_{contact}$ (R_{th})

- 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** [3].

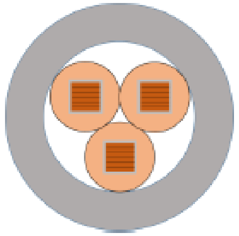
- In 2022-2023 we performed parametric simulations of the **run 190808**, using two THEA models with different levels of complexity, for various pairs of the uncertain model parameters: (RRR,R_{th}) and h_{conv} calculated with the Dittus-Boelter correlation. The best agreement between the simulations' results and the experiment was obtained with the **extended model** for **RRR = 60** and **R_{th} = 0.095 m·K/W** [4]. However, when we used these values to simulate heat pulses propagation from the shot 170802, the results were not quite satisfactory.



Reference model



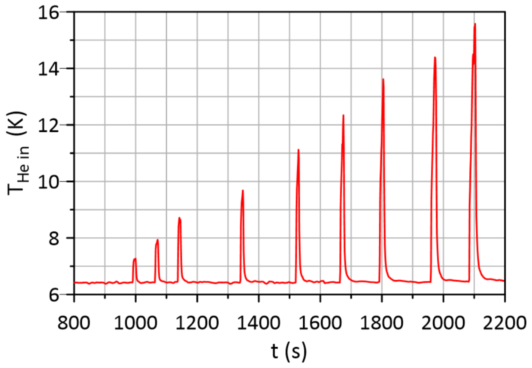
Extended model

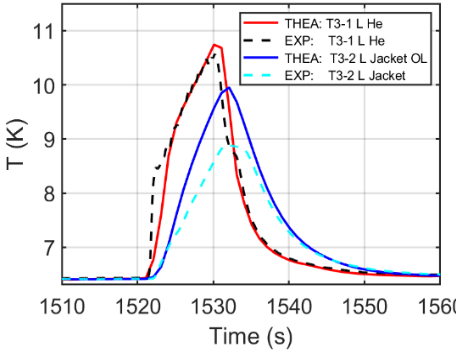


[3] A. Zappatore, et al., Cryogenics 132 (2023) Art. No 103695.
[4] M. Lewandowska, et al., Cryogenics 141 (2024) Art. No 103889.

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): $RIAE = \dfrac{IAE}{\int_{t1}^{t2} T_{exp}\,dt} \cdot 100\%$
  - Relative Amplitude Error (RAE): $\dfrac{\Delta T_{max}}{T_{max}} = \dfrac{\max T_{exp} - \max T_{sim}}{\max T_{exp}} \cdot 100\%$





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

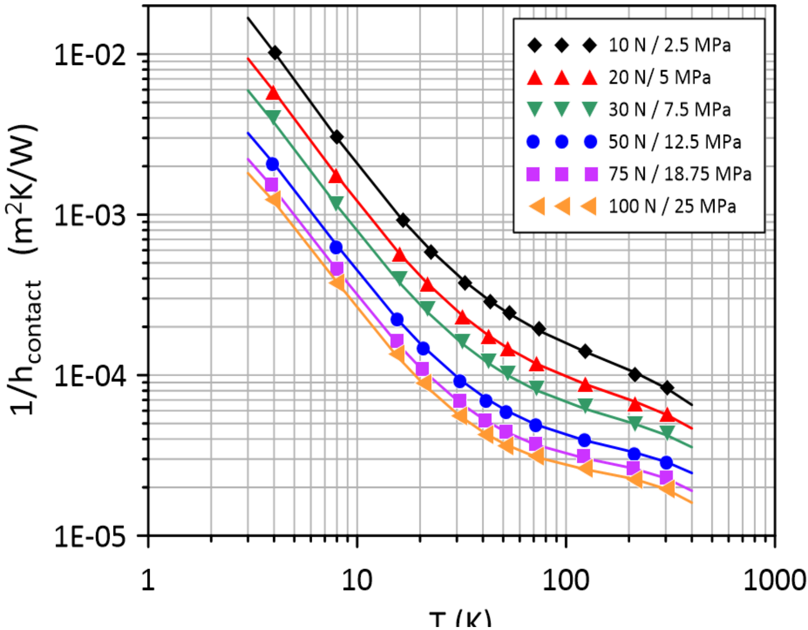
Fitting the $R_{TC} = 1/h_{contact}$ experimental data [1]

- 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)

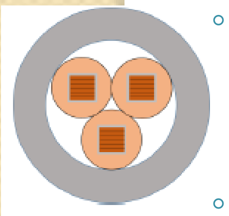
$$\ln R_{TC} = p_0(F) + p_1(F)x + p_2(F)x^2 + p_3(F)x^3 + p_4(F)x^4$$

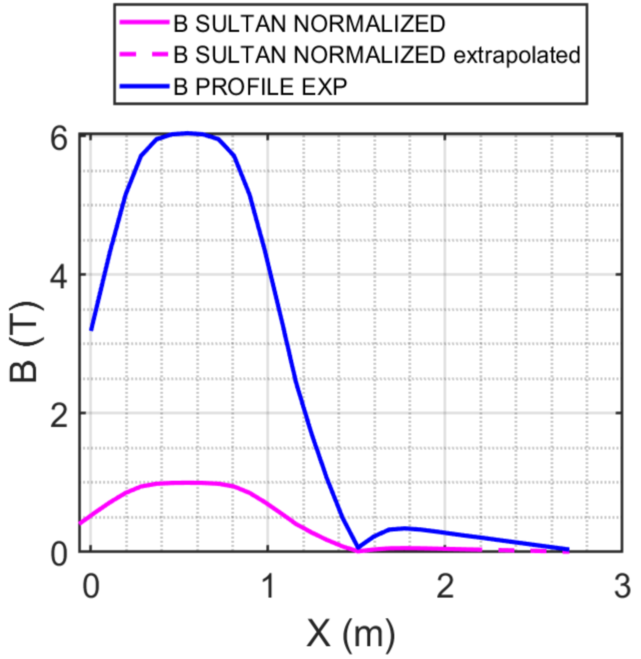
$$x = \ln T$$

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



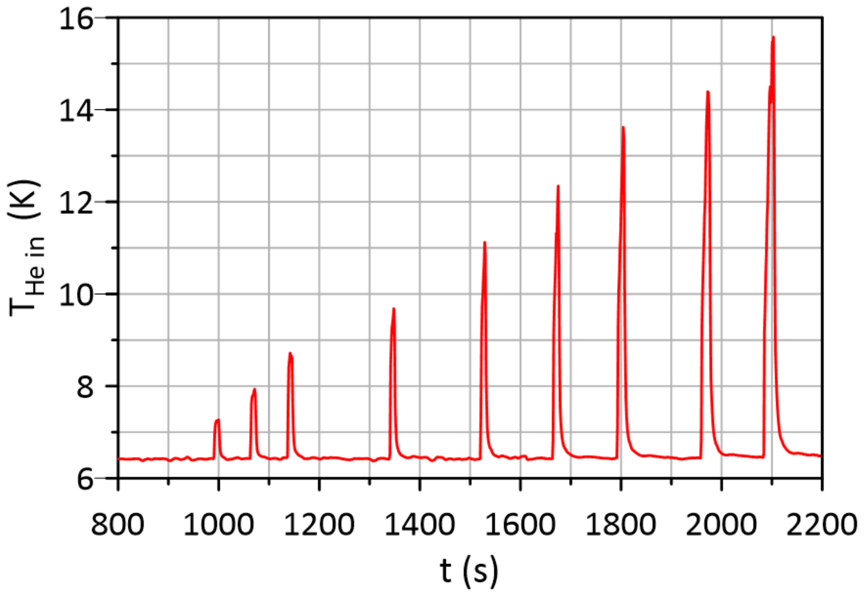
- **Problems:**
  - The obtained fit may not be accurate outside the experimental T and F ranges => restriction for our analysis
  - all strands are treated in the model as a single 1D component, whereas the contact strands-jacket force resulting from the Lorenz force is not the same for different strands => **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)**

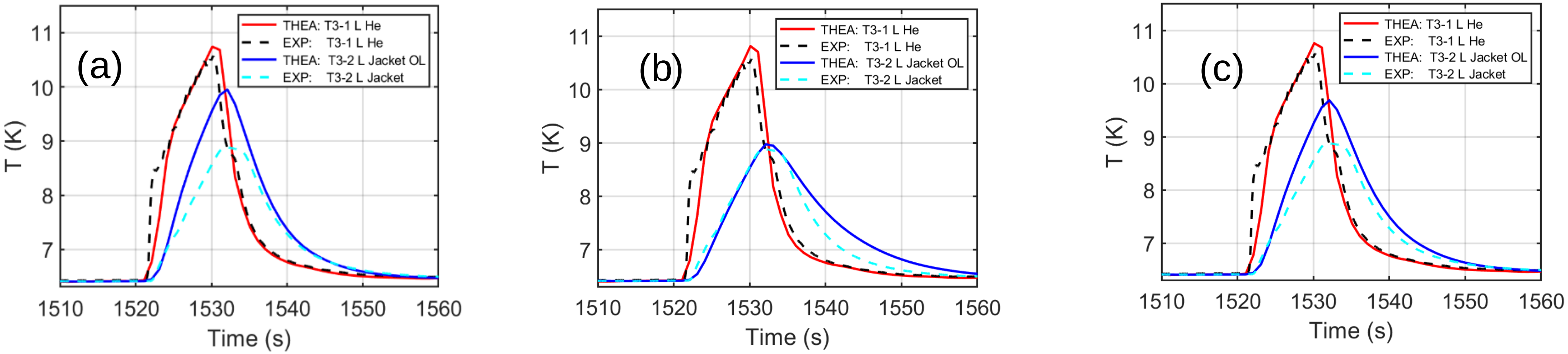




Parametric simultions of the heat pulse propagation (run 170802)

- 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 [3] we introduced a multiplier (M) to the Dittus-Boelter correlation reducing convective heat transfer between helium and the solid cable components.

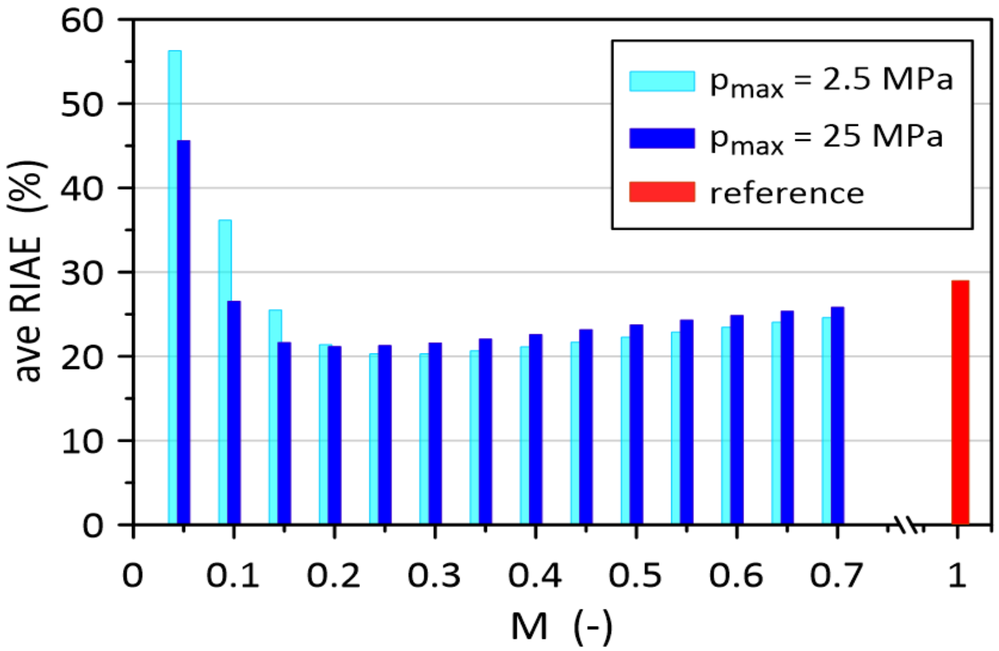


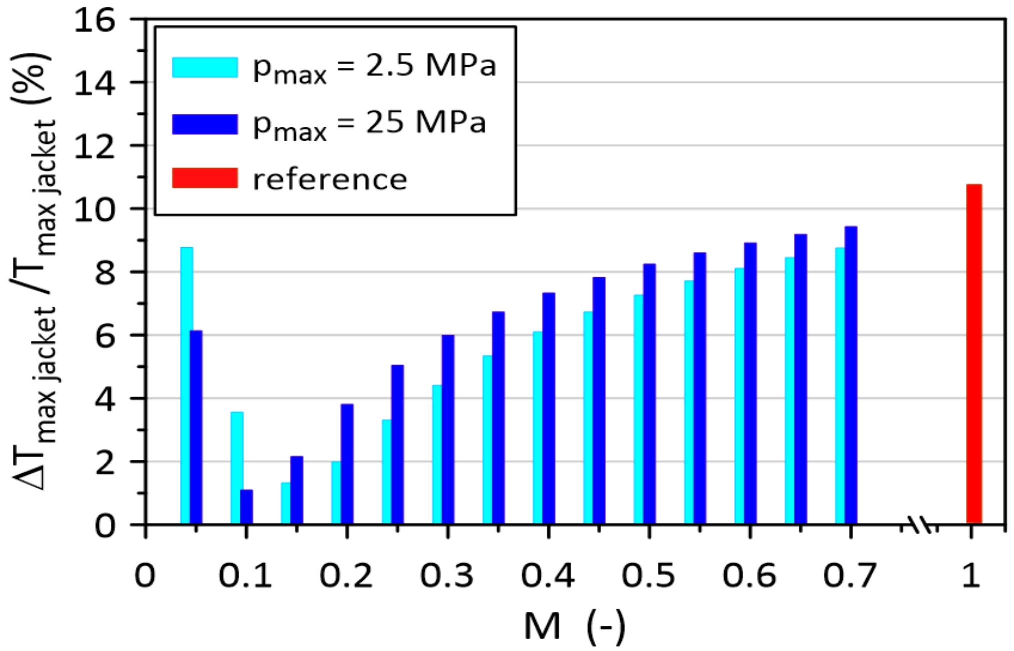


Typical simuation results; pulse 5: (a) R_{th} = 0.095 m·K/W = const, M=1 [4] (reference case); (b) R_{th} = f (p,T), M = 0.2, p_{max} = 2.5 MPa; (c) R_{th} = f (p,T), M = 0.53, p_{max} = 5 MPa.

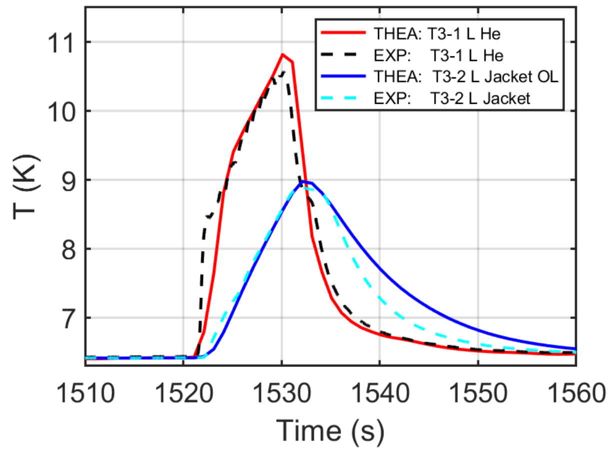
Parametric simultions of the heat pulse propagation (run 170802)

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



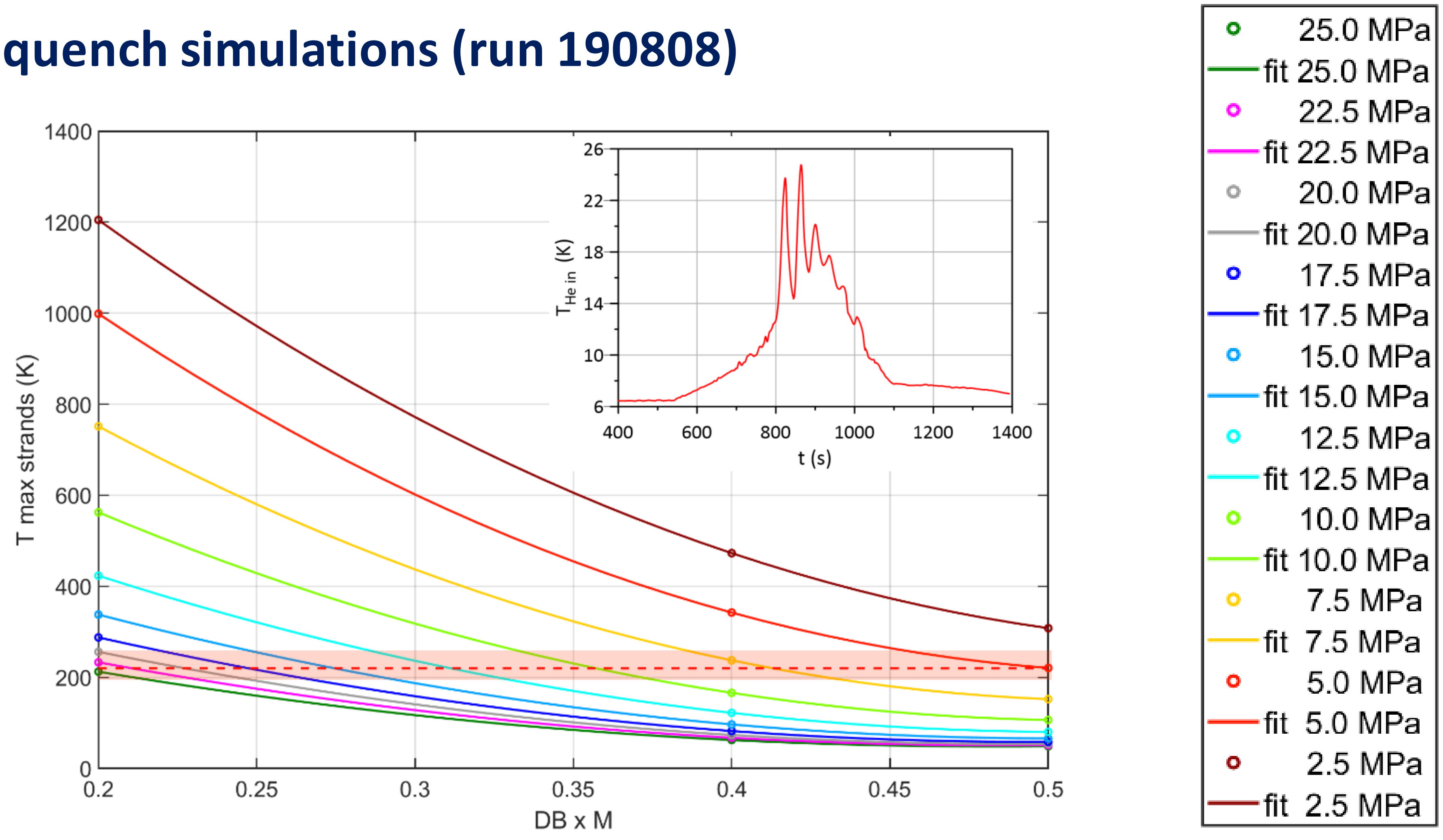


- The results were not very sensitive to the choice of p_{max}. The lowest values of ave RIAE and ave RAE were observed for relatively low M values (M = 0.3 and M = 0.1, respectively).
- At very low M values, for which the pulse amplitude was reproduced correctly, the recooling phase observed in the 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?)



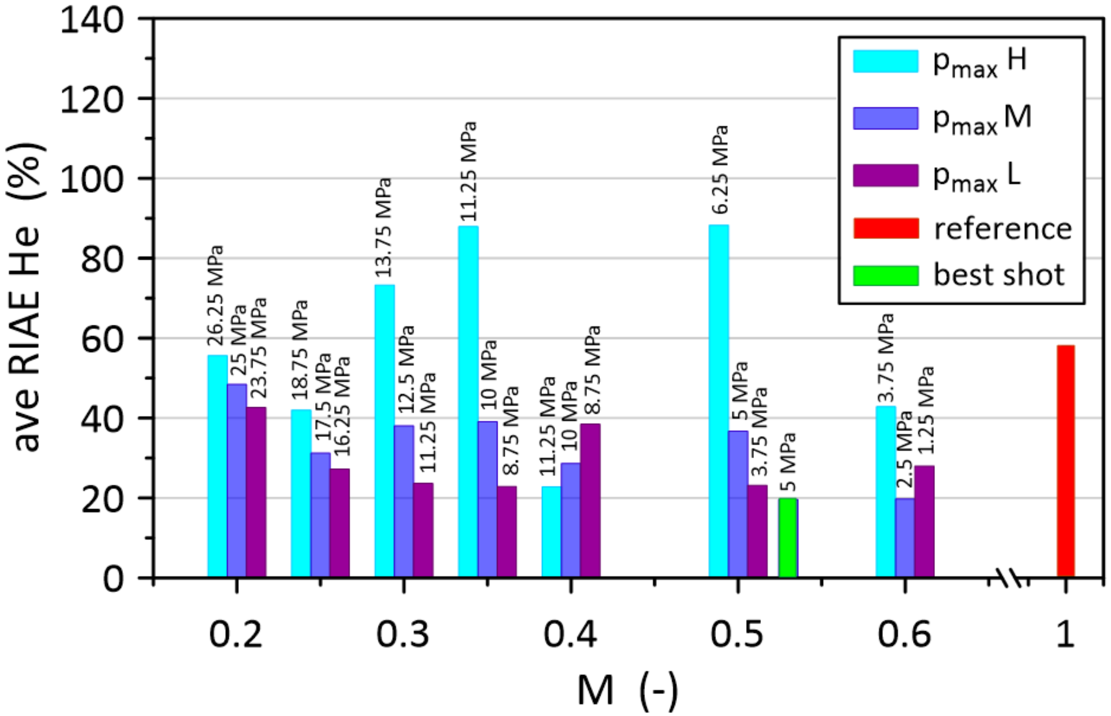
M = 0.2, p_{max} = 2.5 MPa

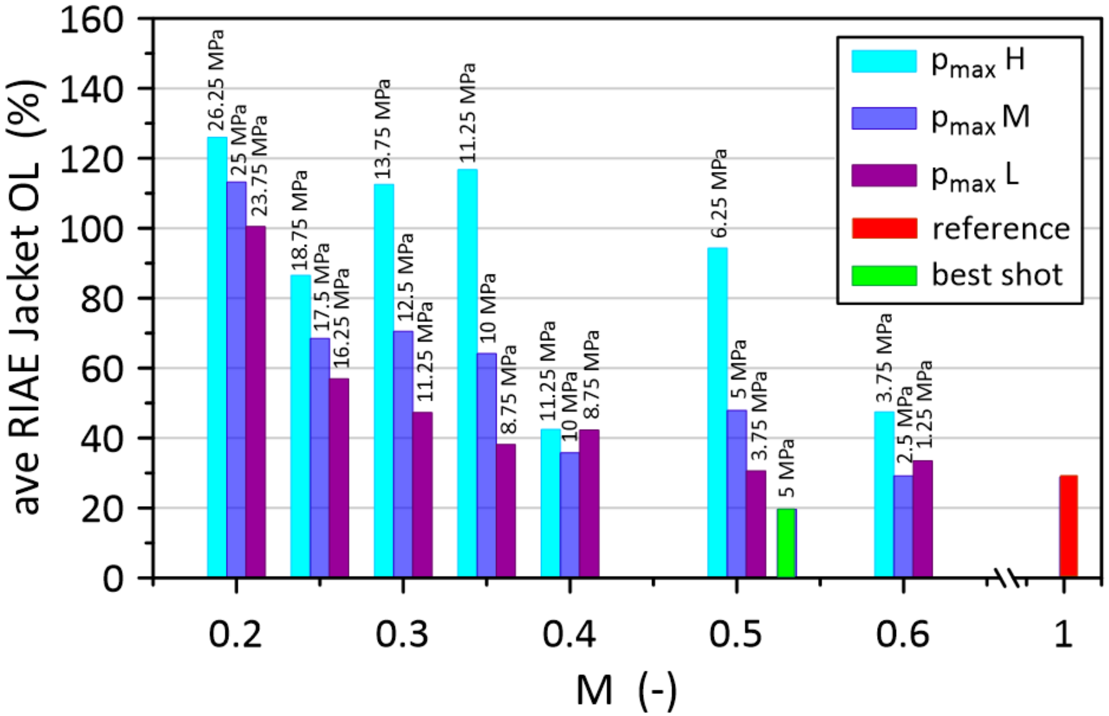
Parametric quench simulations (run 190808)



- 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.

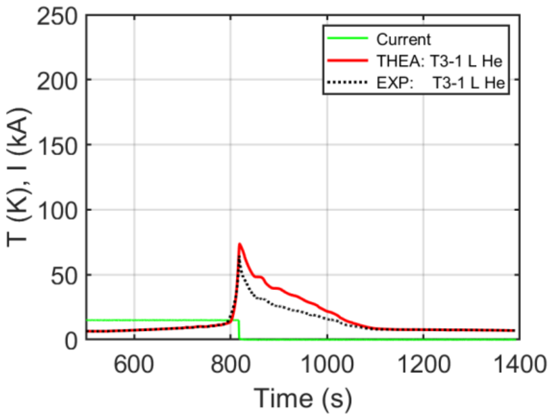
Parametric quench simulations (run 190808)

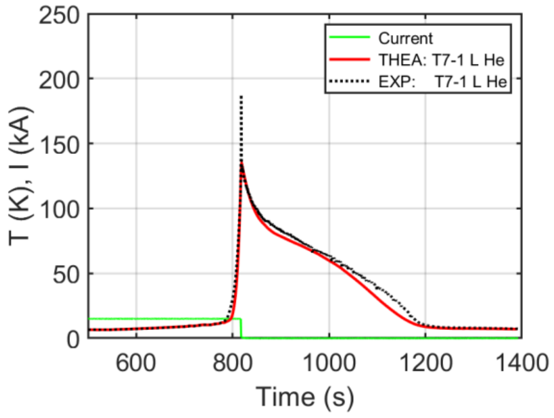


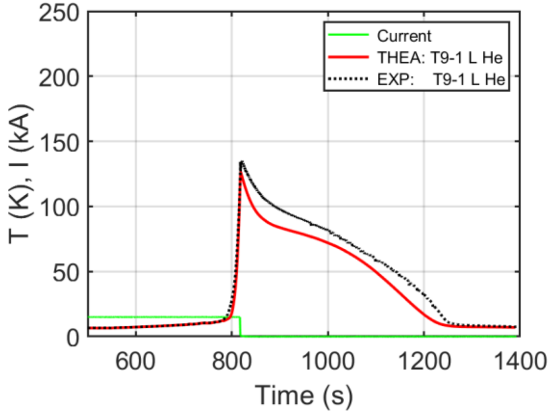


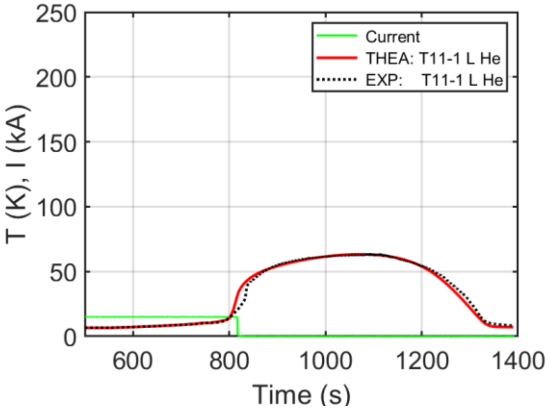
- Low values of ave RIAE He and ave RIAE Jacket OL values were observed for M of about 0.35 -0.6.
- We performed several further simulations for M in this range and the lowest values of both considered integral indicators we obtained for the pair: **M = 0.53, p_{max} = 5 MPa**.

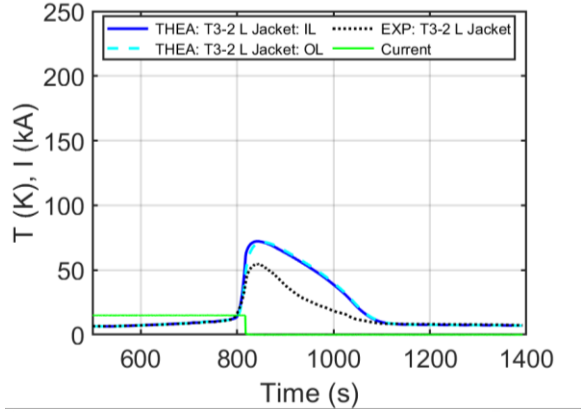
Quench simulations results obtained for the best shot (M = 0.53, p_{max} = 5 MPa)

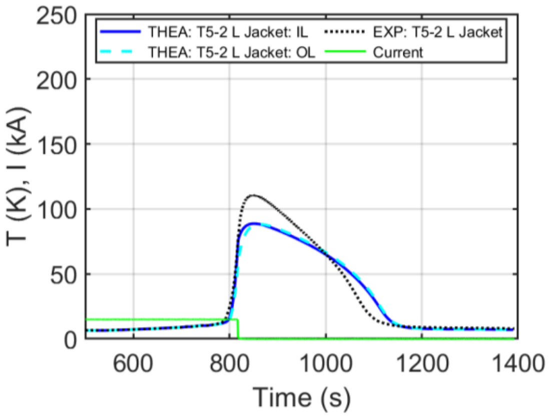


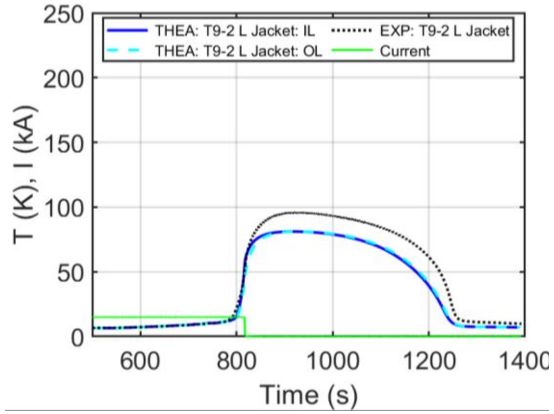


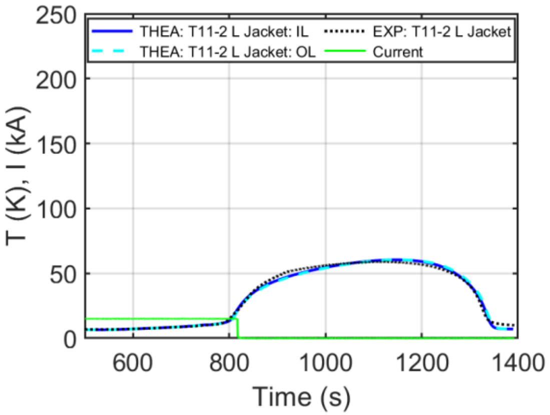


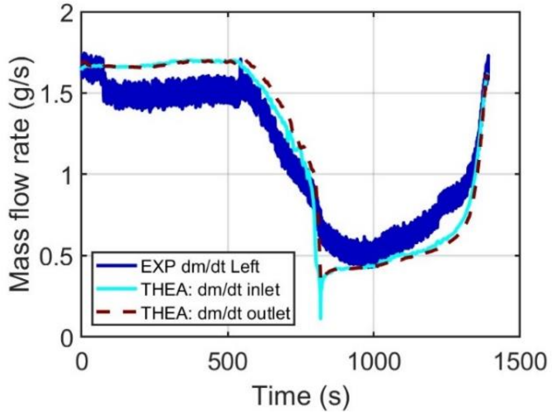


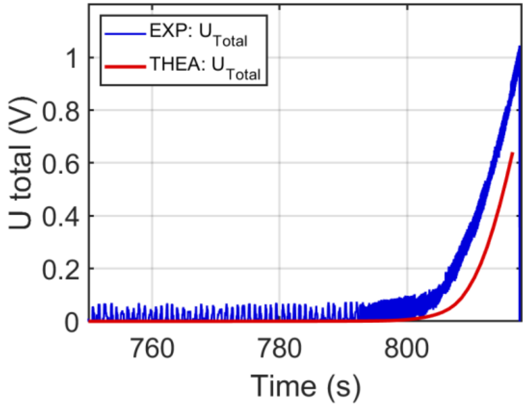












Summary and conclusions

- According to the recent experimental results [1] 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 [1]. We implemented it in the extended THEA model [4] and performed simulations of two selected runs of the Quench Experiment [2].
- 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 some 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 0.15-0.40). 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 $h_{contact}$ [4].

Thank you very much for your attention

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