Modeling pulsed scenarios of HTS current leads for Tokamak operation

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Outline

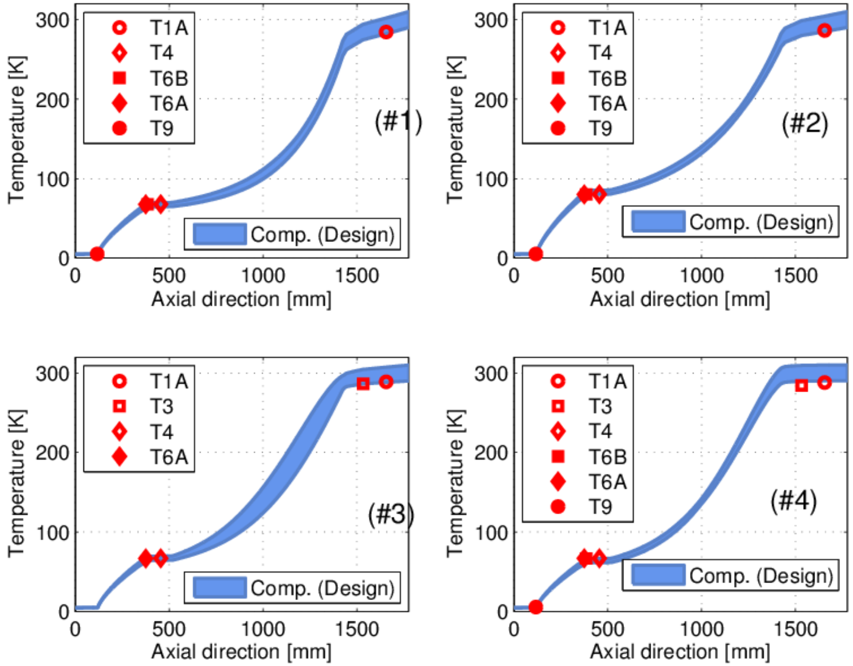
- Introduction and aim of the work
- JT-60SA CL experimental campaign
- Model description and calibration
- Results
- Conclusions and perspectives

Introduction (I)

- HTS CLs can strongly reduce the heat load @ 4.5 K and power consumption of the refrigerator.
- The main components are:
  - Meander flow type HX;
  - HTS module;
  - LTS linker;
- Modeling of the CLs is crucial because:
  - optimization of CL operation for pulsed coils;
  - they are supplied by the cryoplant.

Introduction (II)

- The CURLEAD model has been applied to the thermal-hydraulic analysis of the prototype ITER CC CLs [R. Heller et al, Cryogenics, in press (2016)] → very good agreement found in steady state operation



Aim of the work

…but in pulsed mode…

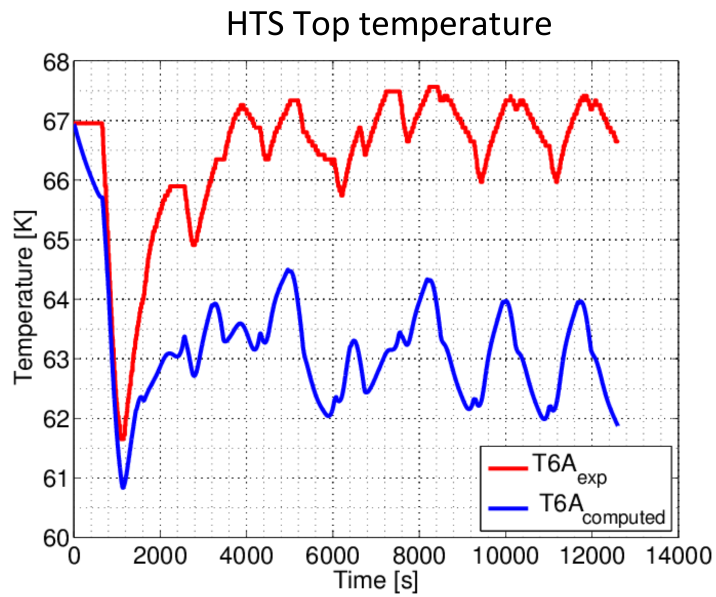
Only qualitative agreement due to:

1.incomplete experimental data set

→ **Look at other database: JT-60SA CLs tested @ KIT**

2.some physical aspects not modeled?

→ **Improve the model → Assess the improved capability to reproduce exp. data**



[R. Heller et al, Cryogenics, in press (2016)]

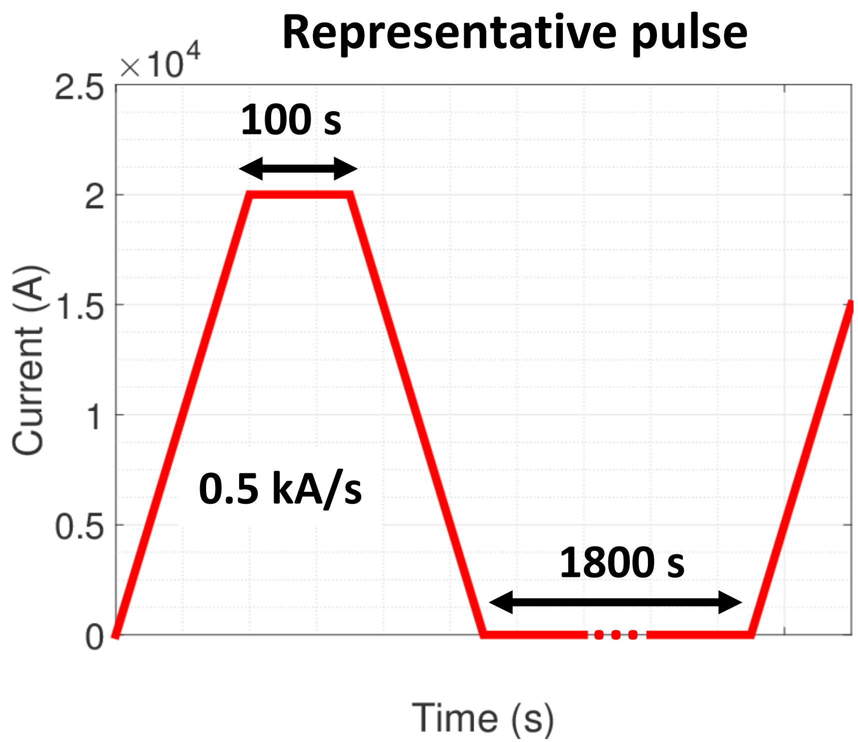
JT-60SA experimental campaign

- KIT is the responsible for design, construction and testing of the JT-60SA CLs;

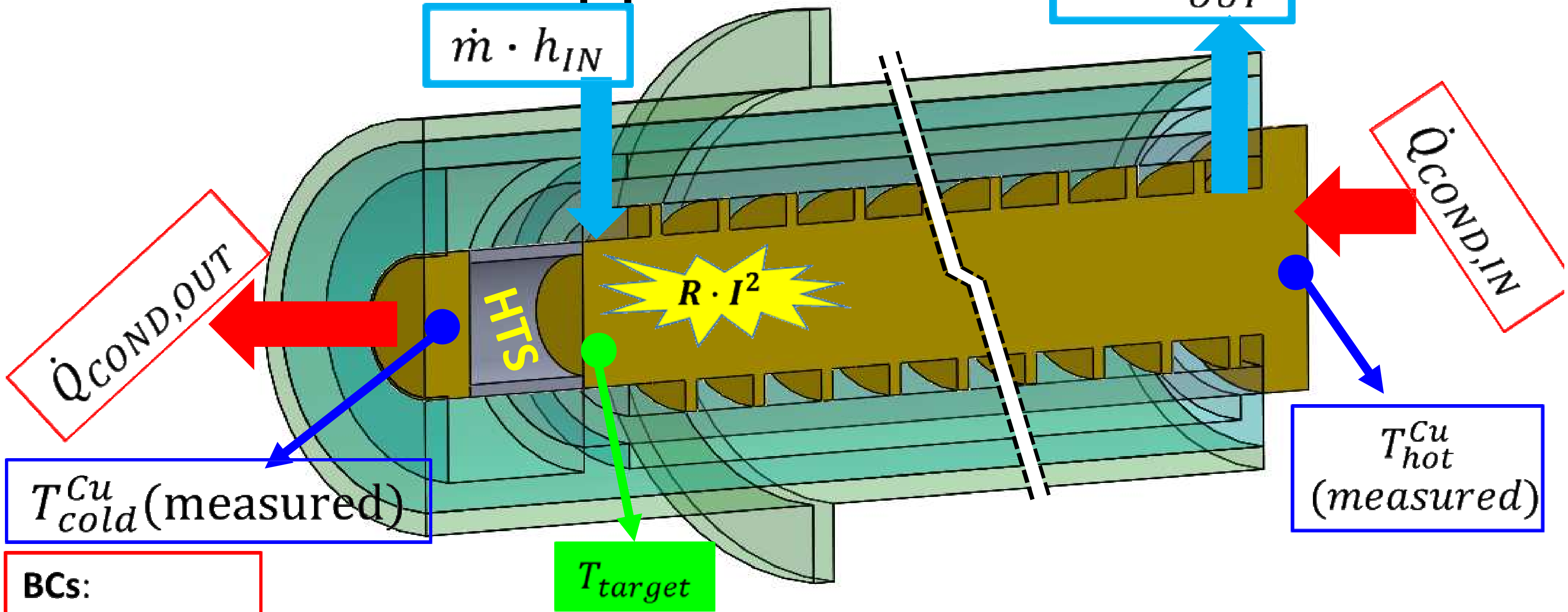
- JT-60SA CLs tests were done to simulate a representative current scenario (7 pulses)

- Steady state tests at zero and nominal current were done as well

tested @ KIT in 2015



Model description (I)
Copper & He



BCs:

- T_{cold}^{Cu}
- T_{hot}^{Cu}
- $\dot{m} \cdot h_{IN}$

IC:

- From steady state simulation

+

$$\rho c_p A \frac{\partial T_{Cu}}{\partial t} = $$
$$= \frac{\partial Q_{cond,x}}{\partial x} + P'_{el} + P'_{ext} - hP(T_{Cu} - T_{He})$$
$$hP(T_{Cu} - T_{He}) = \dot{m} \cdot c_{p,He} \cdot \frac{dT_{He}}{dx}$$
$$\frac{dp}{dx} = f \cdot \frac{\dot{m}^2}{2\rho_{He} A_c^2 d_H}$$

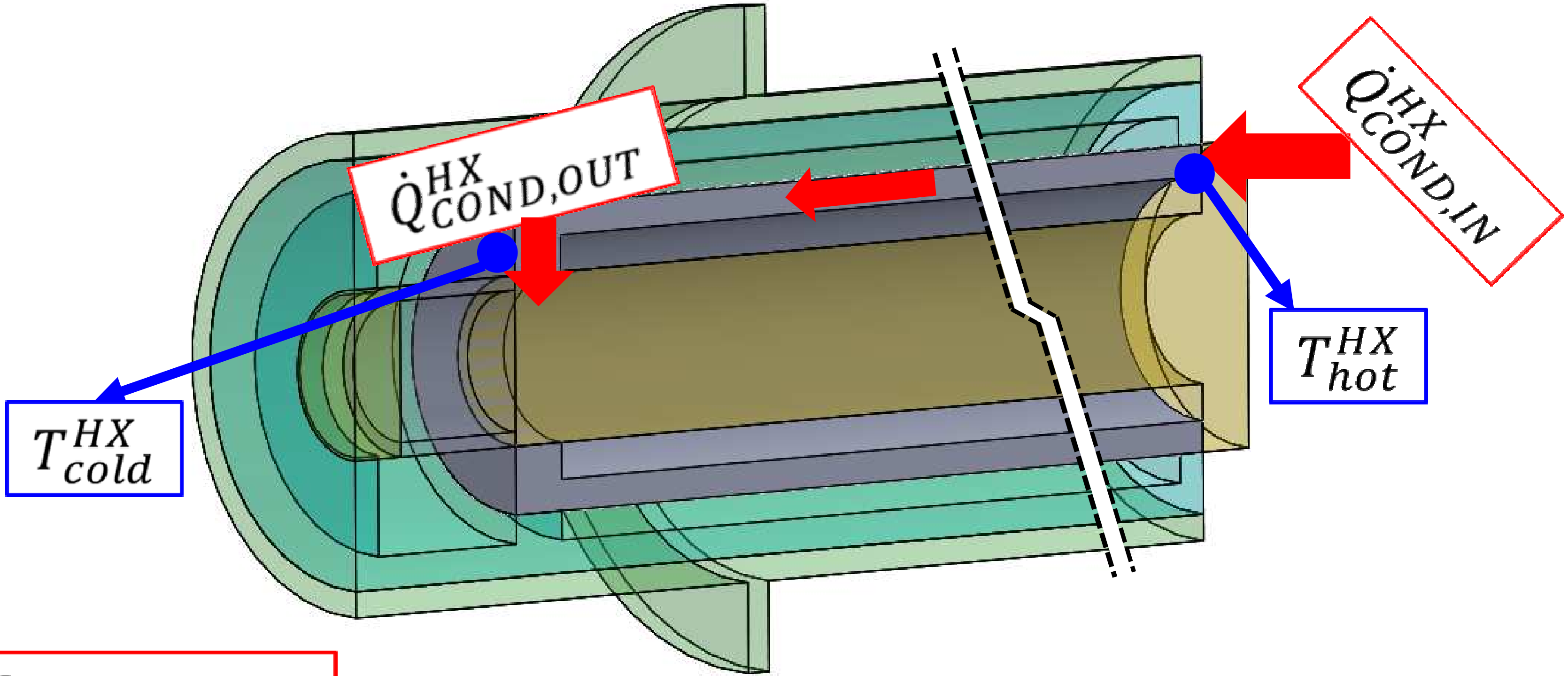
+

f, h derived via CFD based correlations

→

$\dot{Q}_{COND,IN}$, $\dot{Q}_{COND,OUT}$, h_{OUT}, $\Delta p, T_{target}$

Model description (II) – HX shell axial heat conduction



BCs:

- $T^{HX}_{cold} = T^{Cu}_{interf}$
- $T^{HX}_{hot} = T^{Cu}_{hot}$

IC:

- From steady state simulation

+

$$\rho_{SS} c_{p,SS} A \frac{\partial T_{HX}}{\partial t} = \frac{\partial Q_{cond,x}}{\partial x}$$

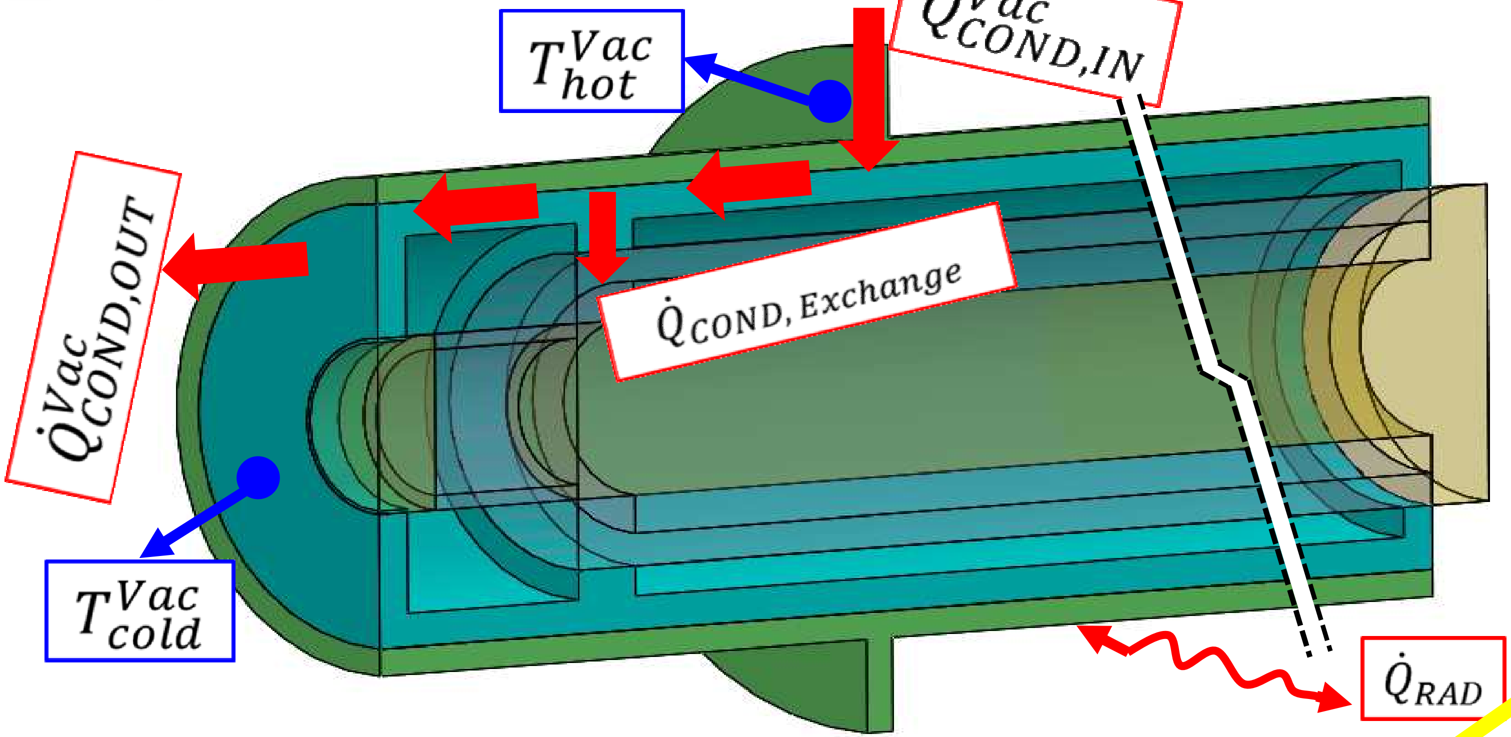
→

$\dot{Q}^{HX}_{COND,IN}$

$\dot{Q}^{HX}_{COND,OUT}$

$\dot{Q}^{HX}_{COND,OUT}$ is entirely deposited on the HX-HTS interface!

Model description (III) – Vacuum shell



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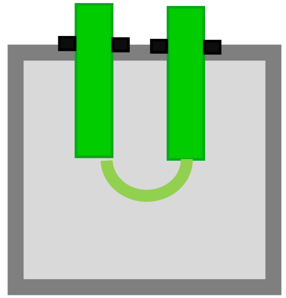


Exp. setup

$$f(x)=\begin{cases} 1 & \text{if } x \in \text{target region} \\ 0 & \text{otherwise} \end{cases}$$

BCs:

- $T_{cold}^{Vac} = T_{cold}^{Cu}$
- $T_{hot}^{Vac} = 300\ K$

IC:

- From steady state simulation

+

$$\rho_{SS} c_{p,SS} A \frac{\partial T_{Vac}}{\partial t} = \frac{\partial Q_{cond,x}}{\partial x} - \frac{T_{Vac} - T_{Cu}}{R_c} f(x)$$

$$q_{rad} = \sigma \cdot \varepsilon_{G10} \cdot A \cdot (T_{cryo}^4 - T_{Vac}^4)$$

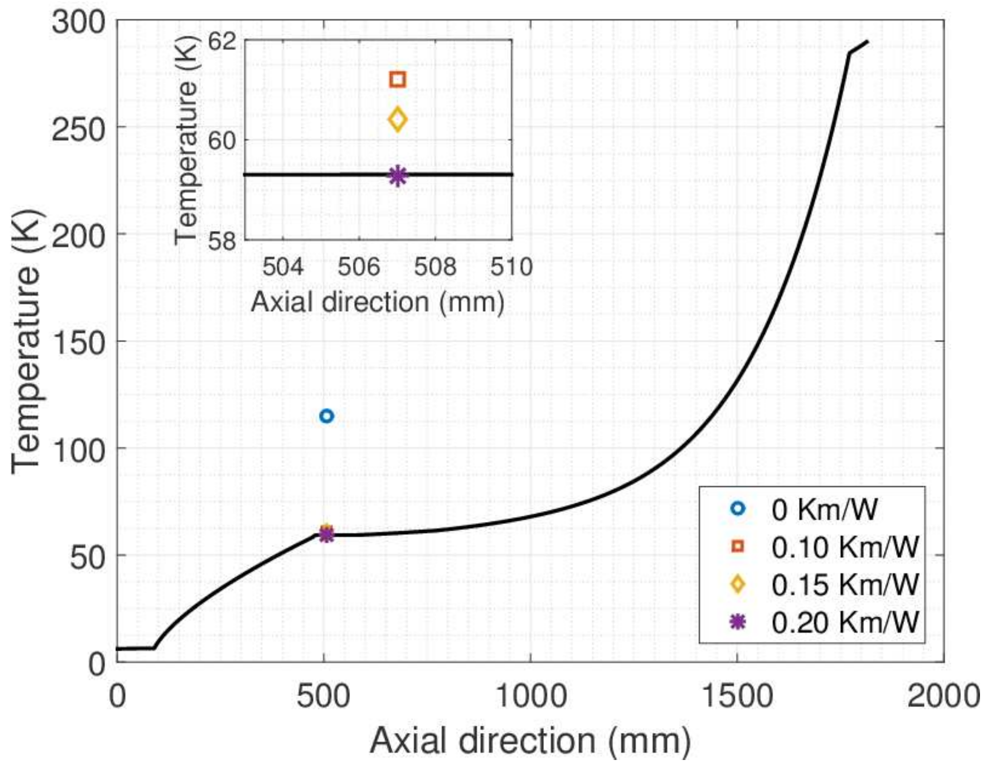
→

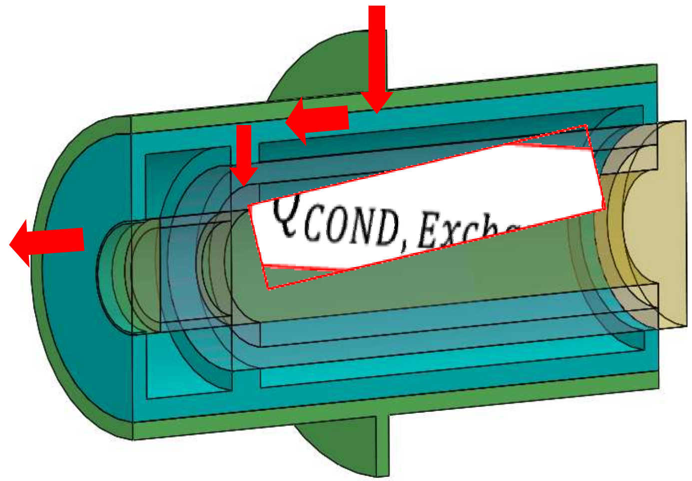
$\dot{Q}_{COND,Exchange}$
$\dot{Q}_{COND,IN}^{Vac}$
$\dot{Q}_{COND,OUT}^{Vac}$

Calibrated in steady state run at 0 kA

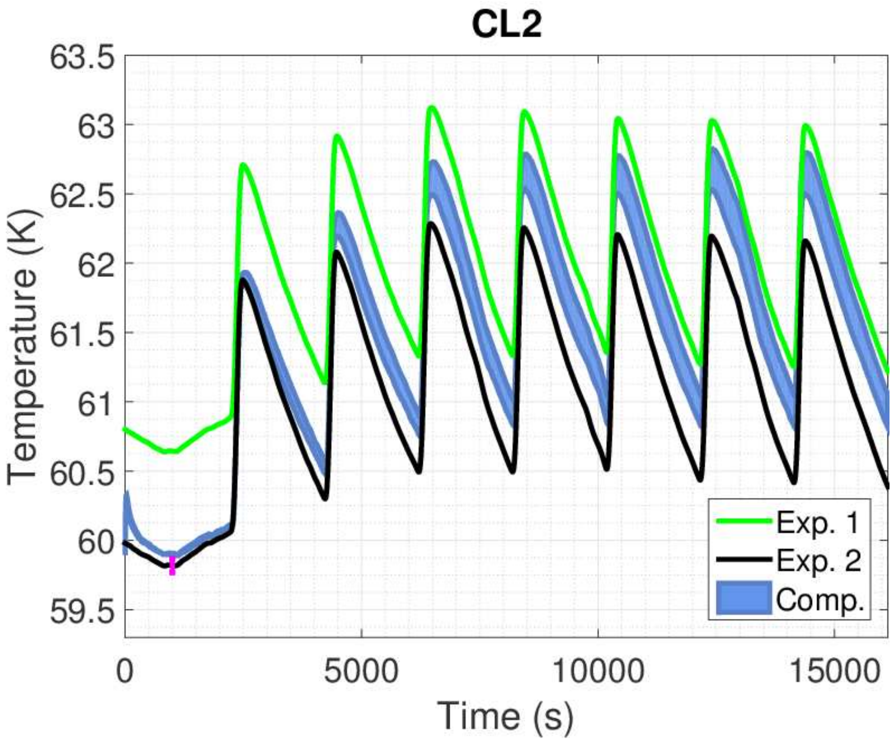
Calibration of R_C

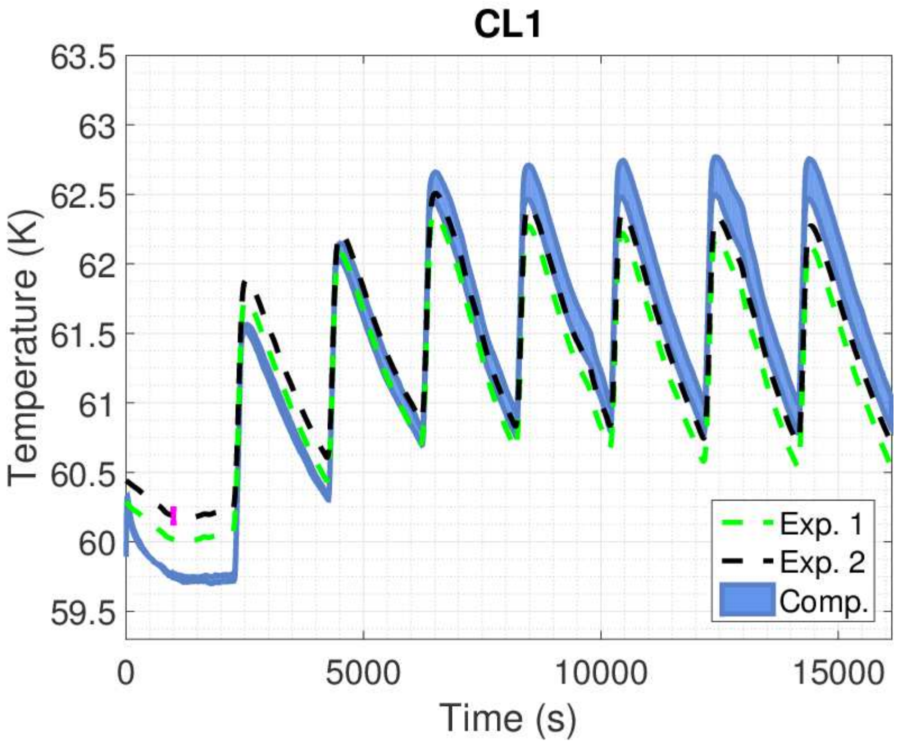
→ The value of the R_C is adjusted in steady state simulation (zero current) to match the experimental and the simulated T_{target}





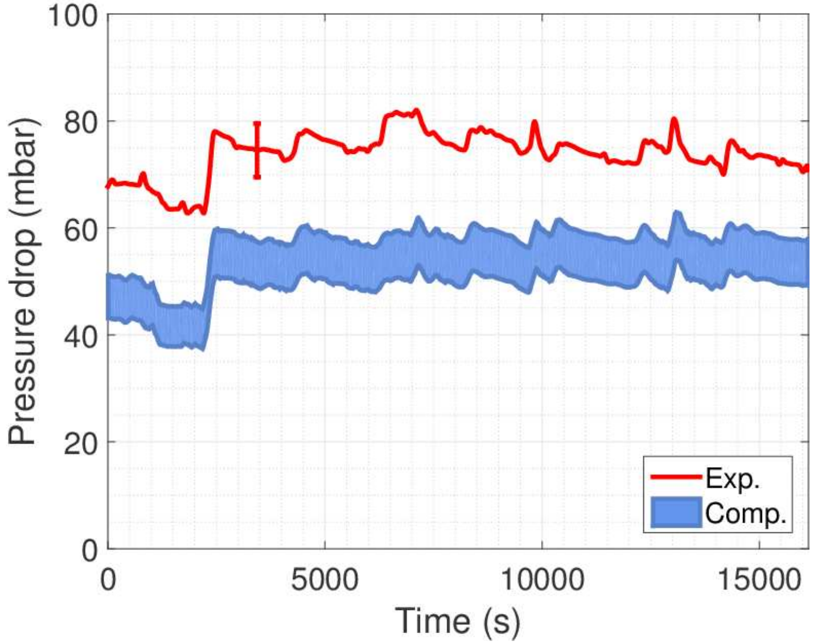
Results (I): T_{target} evolution





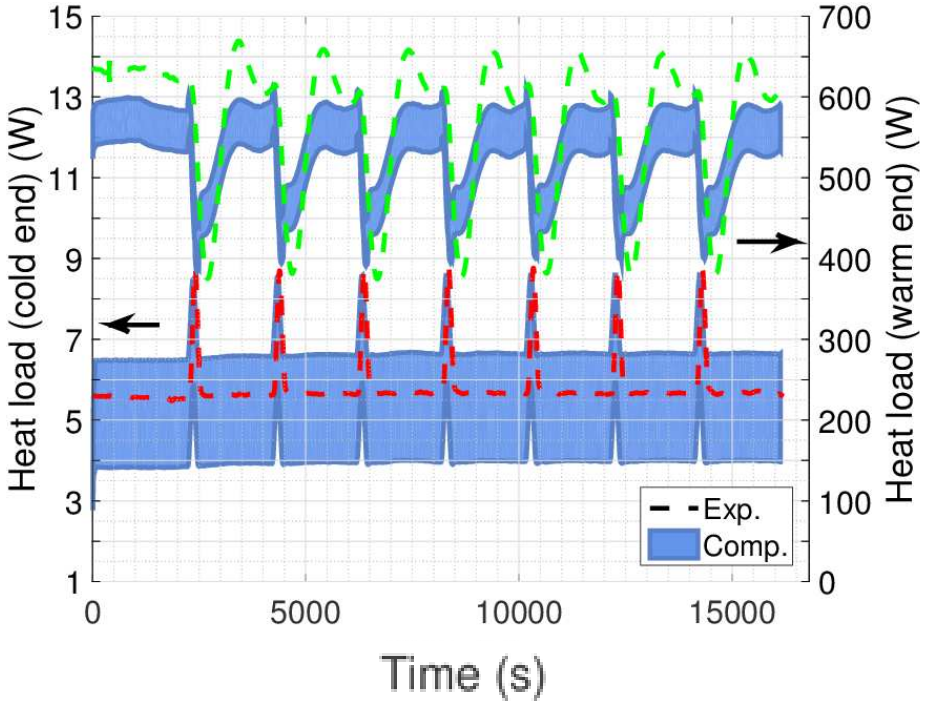
- The calibration obtained from the CL2 has been used to compute also the solution on the CL1;
- Band of computed results obtained considering the experimental uncertainty on the He mass flow rate and He inlet temperature;
- Exp.1 and Exp.2 are the two redundant sensors of the T_{target} → Agreement within the experimental accuracy.

Results (II): Analysis of pulsed operation (JT-60SA)



Only qualitative agreement possible → the pressure drop is measured not exactly at end of the HX where it is computed

Very good agreement with experimental results.
Note that the heat load at the cold is = $\dot{Q}^{Vac}_{COND,OUT} + \dot{Q}_{COND,OUT}$



Conclusions and perspectives

- The improved version of the CURLEAD code has been presented.
- The new features greatly improve the agreement with experimental data, namely T_{target}, heat loads and pressure drop.
- In perspective: apply the model to other available datasets and/or to a predictive analysis of the envisaged tests in KIT of the REBCO CL.

backup

Energy balance

$$\Delta E_{st} = E_{in} - E_{out} + E_g$$

$$E_{st,end} = E_{st,init} + E_{in} - E_{out} + E_g$$

$$\boldsymbol{E_{in}} = \int_{t_{init}}^{t_{end}} P_{heater} \cdot dt + \int_{t_{init}}^{t_{end}} P_{rad,in} \cdot dt + \int_{t_{init}}^{t_{end}} \dot{m} \cdot c_p(T_{in}) \cdot T_{in} dt$$

$$\boldsymbol{E_{out}} = \int_{t_{init}}^{t_{end}} P_{cold} \cdot dt + \int_{t_{init}}^{t_{end}} P_{rad,out} \cdot dt + \int_{t_{init}}^{t_{end}} \dot{m} \cdot c_p(T_{out}) \cdot T_{out} dt$$

$$\boldsymbol{E_g} = \int_{t_{init}}^{t_{end}} R \cdot I^2 dt$$

$$\boldsymbol{E_{st,init}} = (\rho \cdot c_p \cdot V \cdot \bar{T}_{init})^{high} + (\rho \cdot c_p \cdot V \cdot \bar{T}_{init})^{low}$$

$$\boldsymbol{E_{st,end}} = (\rho \cdot c_p \cdot V \cdot \bar{T}_{end})^{high} + (\rho \cdot c_p \cdot V \cdot \bar{T}_{end})^{low}$$

Energy balance

where $(\rho \cdot c_p \cdot V \cdot \bar{T}_{end})^{high}$ and $(\rho \cdot c_p \cdot V \cdot \bar{T}_{end})^{low}$ are evaluated from RT to half HX (where the T sensors are positioned) and from half HX to the cold temperature end.

The integrals are evaluated as:

$$\int_{t_{init}}^{t_{end}} P(t) \cdot dt \approx \sum_{i=1}^{N} P(t_i) \cdot \Delta t_i$$

Results:

$E_{st,end} = 7.93E5\,J$

$E_{st,init} = 7.12E5\,J$

$E_{in} = \int_{t_{init}}^{t_{end}} P_{heater} \cdot dt + \int_{t_{init}}^{t_{end}} \dot{m} \cdot c_p(T_{in}) \cdot T_{in} dt = 7.27E6 + 2.07E6\,J$

$E_{out} = \int_{t_{init}}^{t_{end}} P_{cold} \cdot dt + \int_{t_{init}}^{t_{end}} \dot{m} \cdot c_p(T_{out}) \cdot T_{out} dt = 8.2E4 + 1.15E7\,J$

$E_g = 4.98E6\,J$

$$E_{st,end} - \left(E_{st,init} + E_{in} - E_{out} + E_g\right) = -2.66E6\,J$$

Equations

$$\rho c_p A \frac{\partial T_{Cu}}{\partial t} =$$
$$= \frac{\partial Q_{cond,x}}{\partial x} + P'_{el} + P'_{ext} - hP(T_{Cu} - T_{He})$$
$$hP(T_{Cu} - T_{He}) = \dot{m} \cdot c_{p,He} \cdot \frac{dT_{He}}{dx}$$
$$\frac{dp}{dx} = f \cdot \frac{\dot{m}^2}{2\rho_{He} A_c^2 d_H}$$

$$\rho_{SS} c_{p,SS} A \frac{\partial T_{HX}}{\partial t} = \frac{\partial Q_{cond,x}}{\partial x}$$

$$\begin{cases} 1 & \text{if } x \in \text{target region} \\ 0 & \text{otherwise} \end{cases}$$

$$\rho_{SS} c_{p,SS} A \frac{\partial T_{Vac}}{\partial t} = \frac{\partial Q_{cond,x}}{\partial x} - \frac{T_{Vac} - T_{Cu}}{R_c} \cdot f(x)$$

$$q_{rad} = \sigma \cdot \varepsilon_{G10} \cdot A \cdot (T_{cryo}^4 - T_{Vac}^4)$$