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Predictive 1-D analysis of the prototype HTS current leads for the ITER Correction Coils

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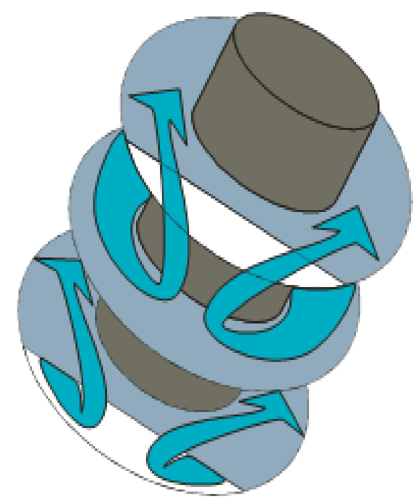
INSTITUTE FOR TECHNICAL PHYSICS, FUSION MAGNETS



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- HTS Current Lead layout
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- CURLEAD model description
- Correlations for pressure drop and heat transfer
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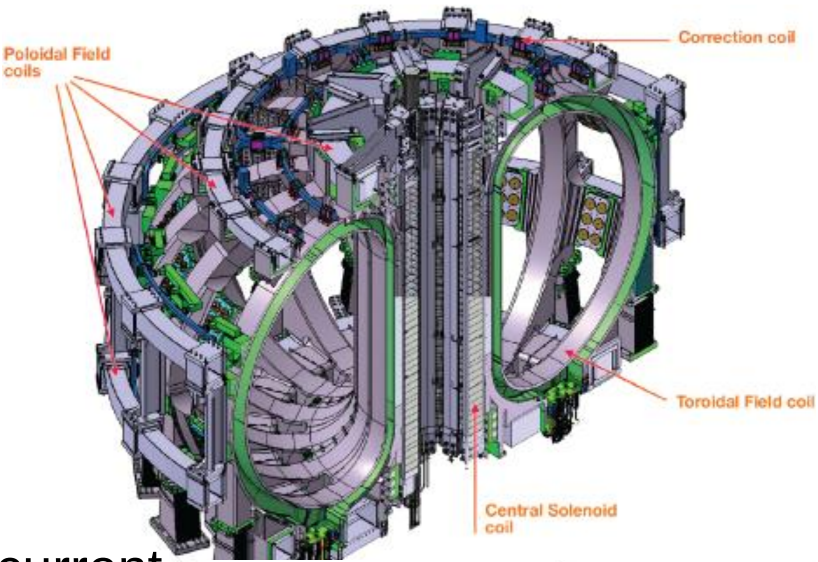
- Conclusions and Perspective

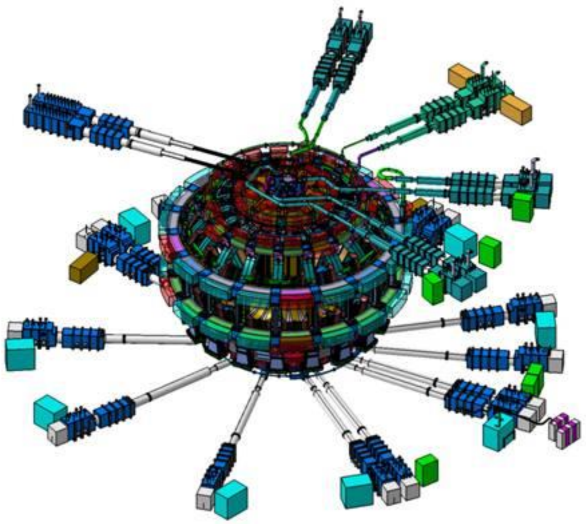
Introduction (I)

- The ITER magnet system consists of
  - 18 Toroidal Field (TF) Coils,
  - 6 Central Solenoid (CS) Modules,
  - 6 Poloidal Field (PF) Coils and
  - 18 Correction Coils (CC)



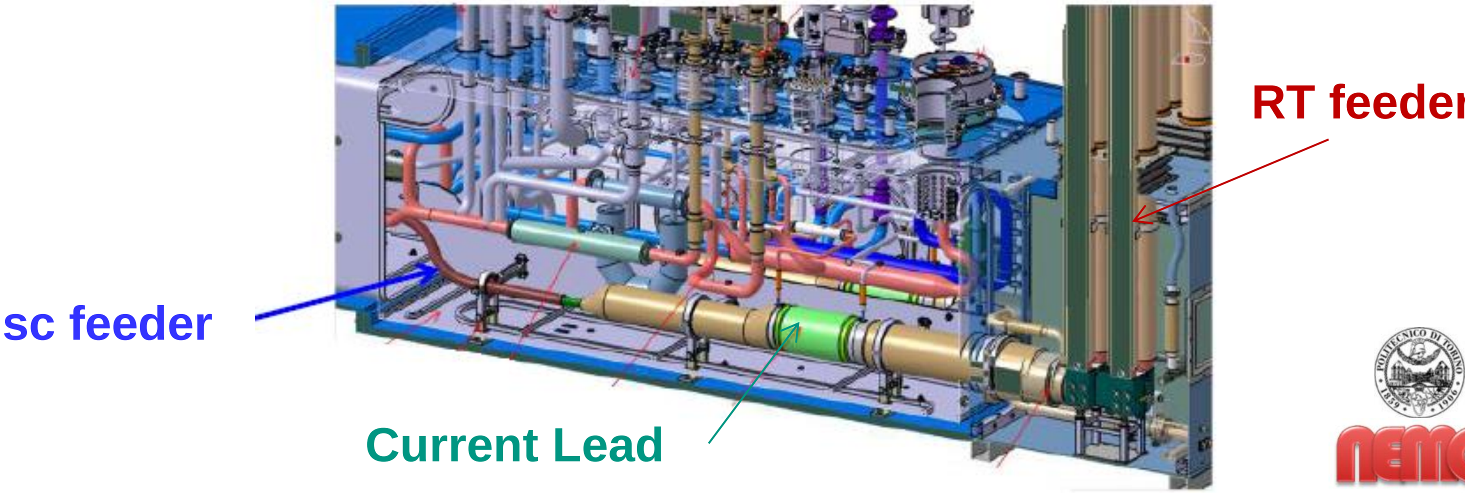
- The ITER magnets are supplied by 26 current feeders which end with current leads

Coils	Number of CL	Maximum current (kA)	Maximum voltage (kV)	Operation
TF	18	68	19	steady state
CS	12	45	29	pulsed
PF	12	52 (57)	25	pulsed
CC	18	10	7	pulsed



Introduction (II)

- ITER has a total of 60 single current leads (CLs)
- By using High Temperature Superconductor (HTS) CLs the heat load at the 4.5 K cold end of the leads can be strongly reduced saving significant power during ITER operations
- Each current lead pair is located horizontally in Coil Terminal Boxes (CTB) and connected
  - to a superconducting feeder by twin box joints and
  - to a room temperature (RT) feeder by water cooled interface bus bars



Aim of the work

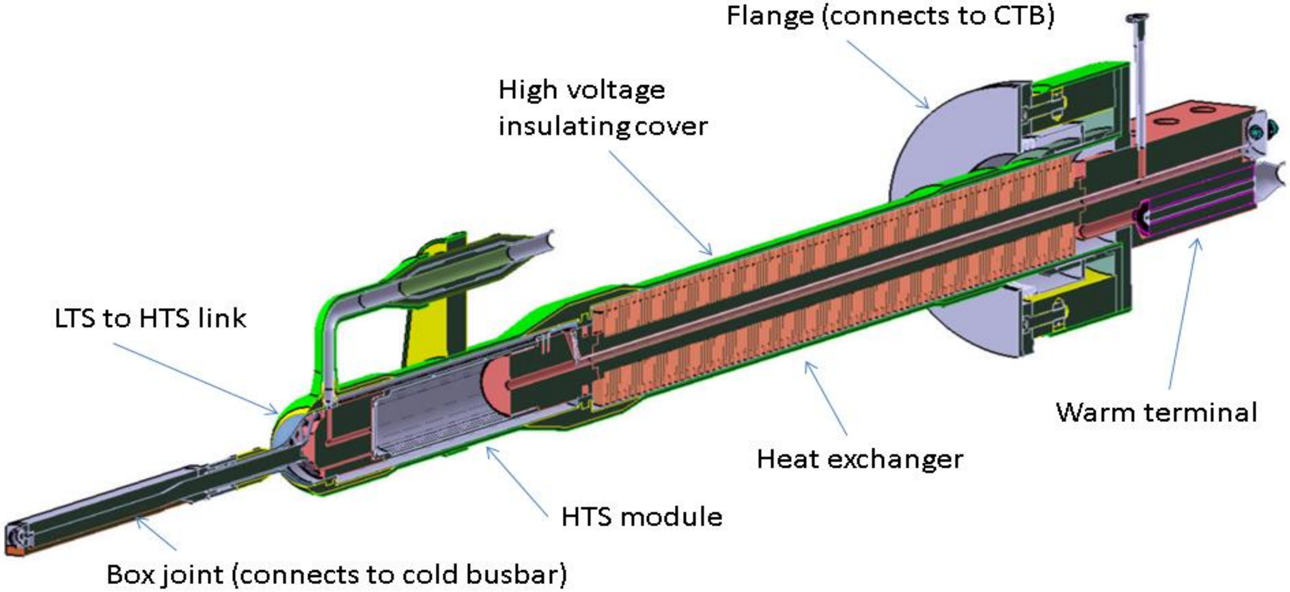
- Prediction of the performance of the HTS CL for the ITER CC, using the CURLEAD code, supplemented by correlations for friction and heat transfer in the MF-HX derived from CFD

- Although the experimental campaign had already been conducted before the simulations were performed, the data were not made available by ITER IO until *after* the simulations

BLIND TEST!

Current Lead Layout (I)

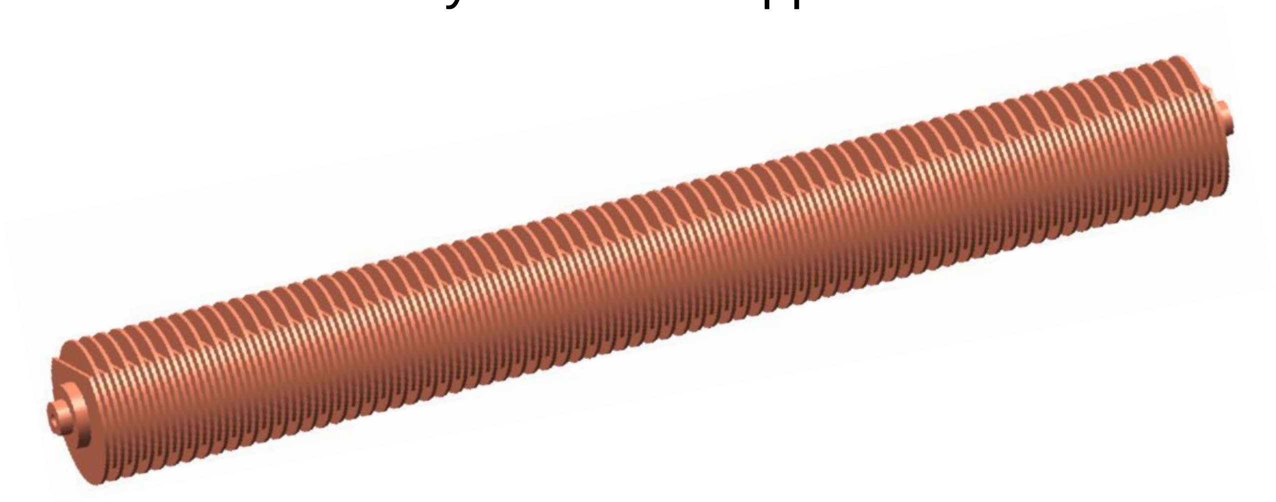
- The HTS CL consists of
  - Meander-flow type heat exchanger (RT → 65 K) including RT-terminal
  - HTS module (65 K → 6 K) made of SS support cylinder with Cu end caps using Bi-2223 Ag/Au HTS tapes
  - LTS-linker including twin box joint connecting HTS module to superconducting feeder



Current Lead Layout (II)

- Meander-flow type heat exchangers (MF-HX) are commonly in operation in big machines (LHC, W7-X) and under construction (JT-60SA, ITER)

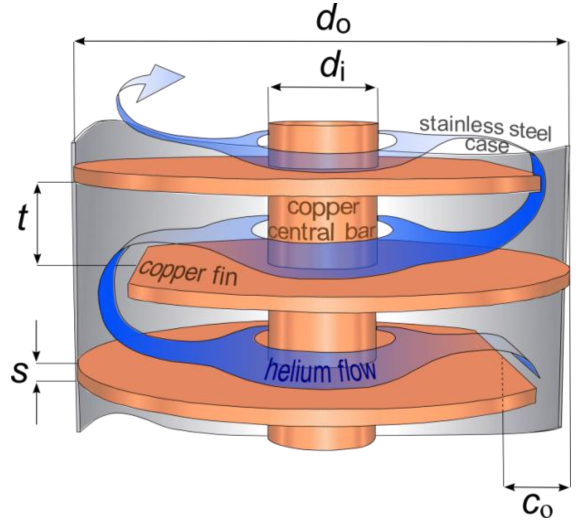
- Consists of central current carrying copper rod and fins around with cut-offs alternatively located at opposite sides.



- Important for the current lead design are heat transfer and pressure drop in the MF-HX.

Current Lead Layout (III)

- MF-HX extensively studied in the frame of a PhD thesis and published in a couple of papers. Basic consideration is the use of a CFD periodic model of the HX which allows the investigation of heat transfer and pressure drop in a wide parameter range:
  - inner and outer diameter, d_i and d_o,
  - fin thickness s,
  - fin distance t, and
  - cut-off c_o



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5. E. Rizzo, R. Heller, L. Savoldi Richard, R. Zanino, Fus. Eng. Des. **88**(11), (2013) 2749–2756
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Experimental campaign (I)

- Experimental set-up
  - 2 prototype HTS CL for ITER CC were manufactured by ASIPP
  - Two HTS CL connected by superconducting short circuit feeder and installed in a test facility at ASIPP. Test performed in March 2015

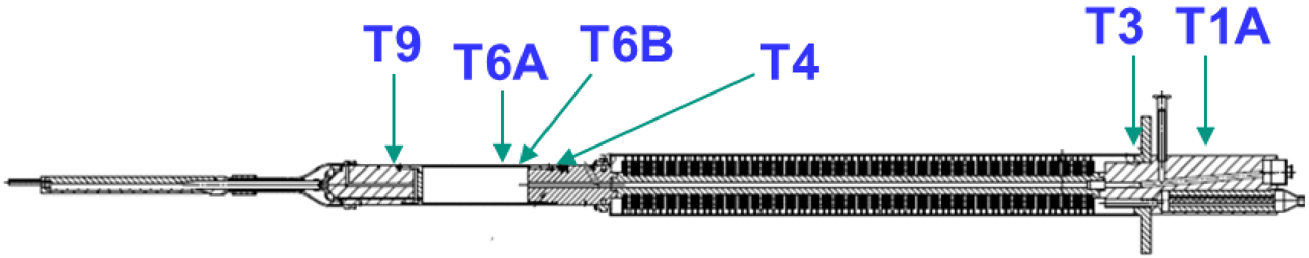
Courtesy of T. Zhou and K. Ding, ASIPP

Experimental campaign (II)

- Definition of cases for analysis:

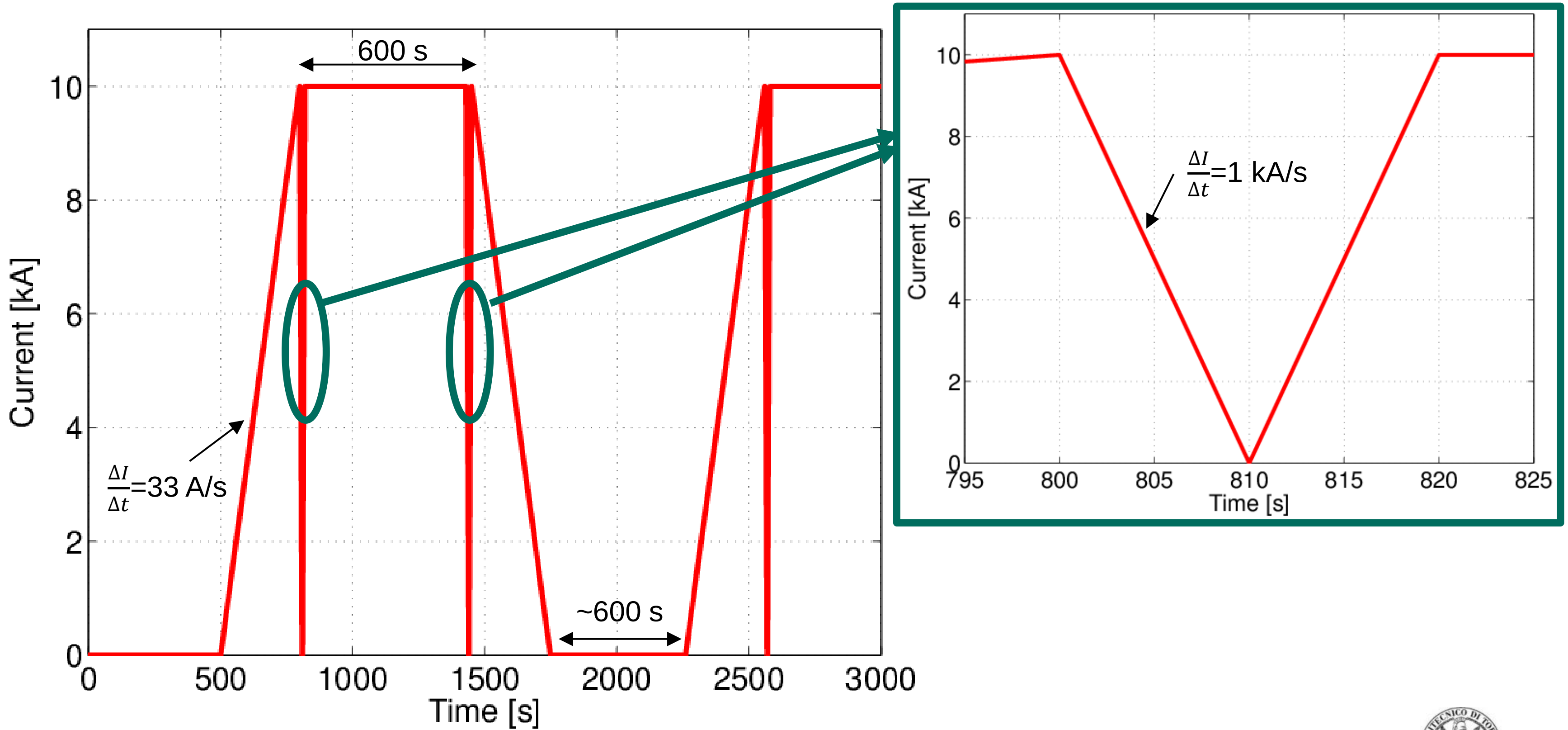
Case	Current (A)	$T_{HTS100\%}$ (K)	Comment
I	0	65	Nominal
II	0	80	
III	10	65	Nominal
IV	12	65	Over-current
V	Pulse	65	7 pulses

- Location of relevant temperature sensors:



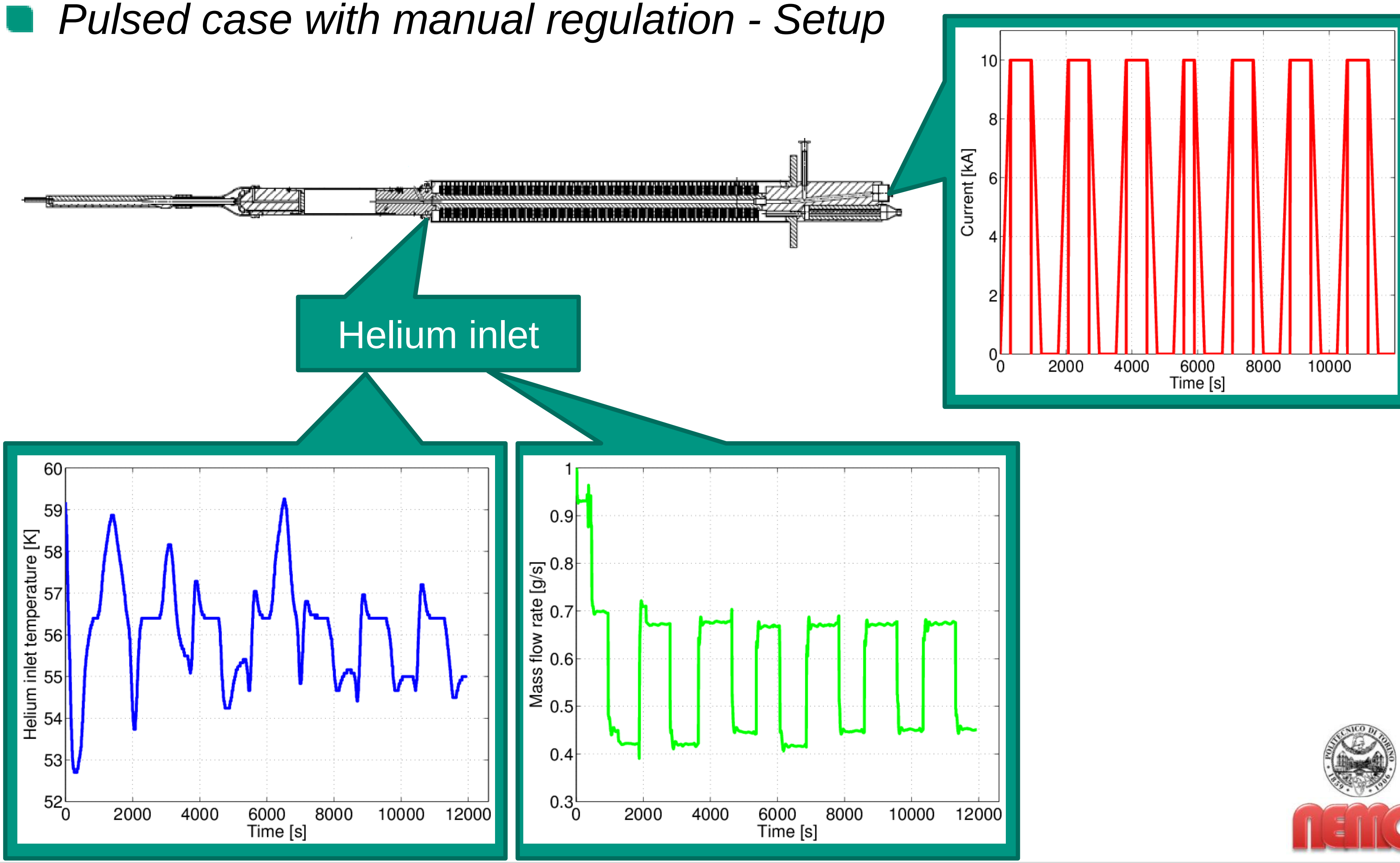
Experimental campaign (III)

- Pulsed scenario (7 pulses, used in prototype test):



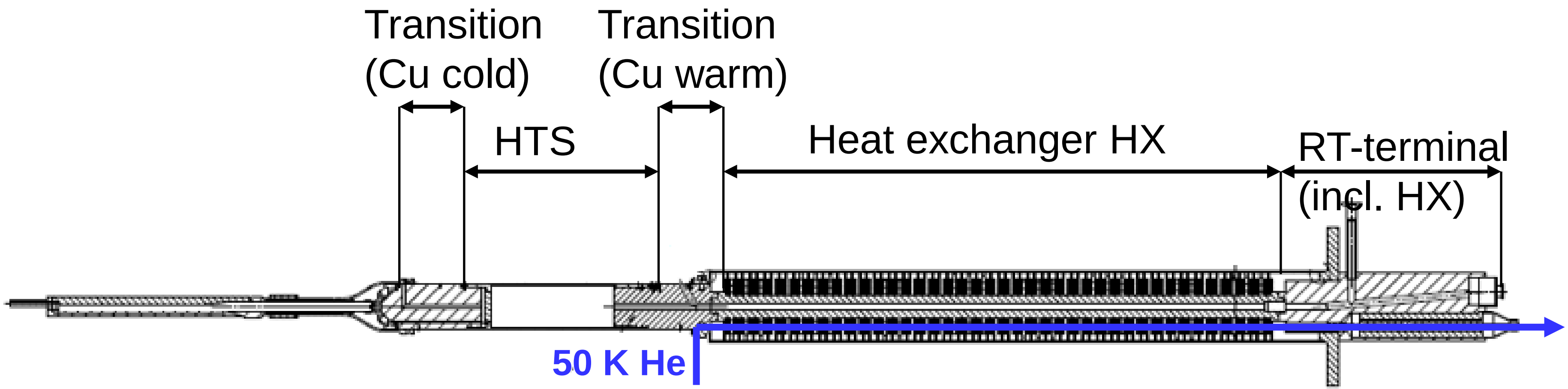
Experimental campaign (IV)

- *Pulsed case with manual regulation - Setup*



CURLEAD model description

- 1-dim FD code solving heat diffusion equation and energy balance in coolant taking into account heat transfer and pressure drop



INPUT

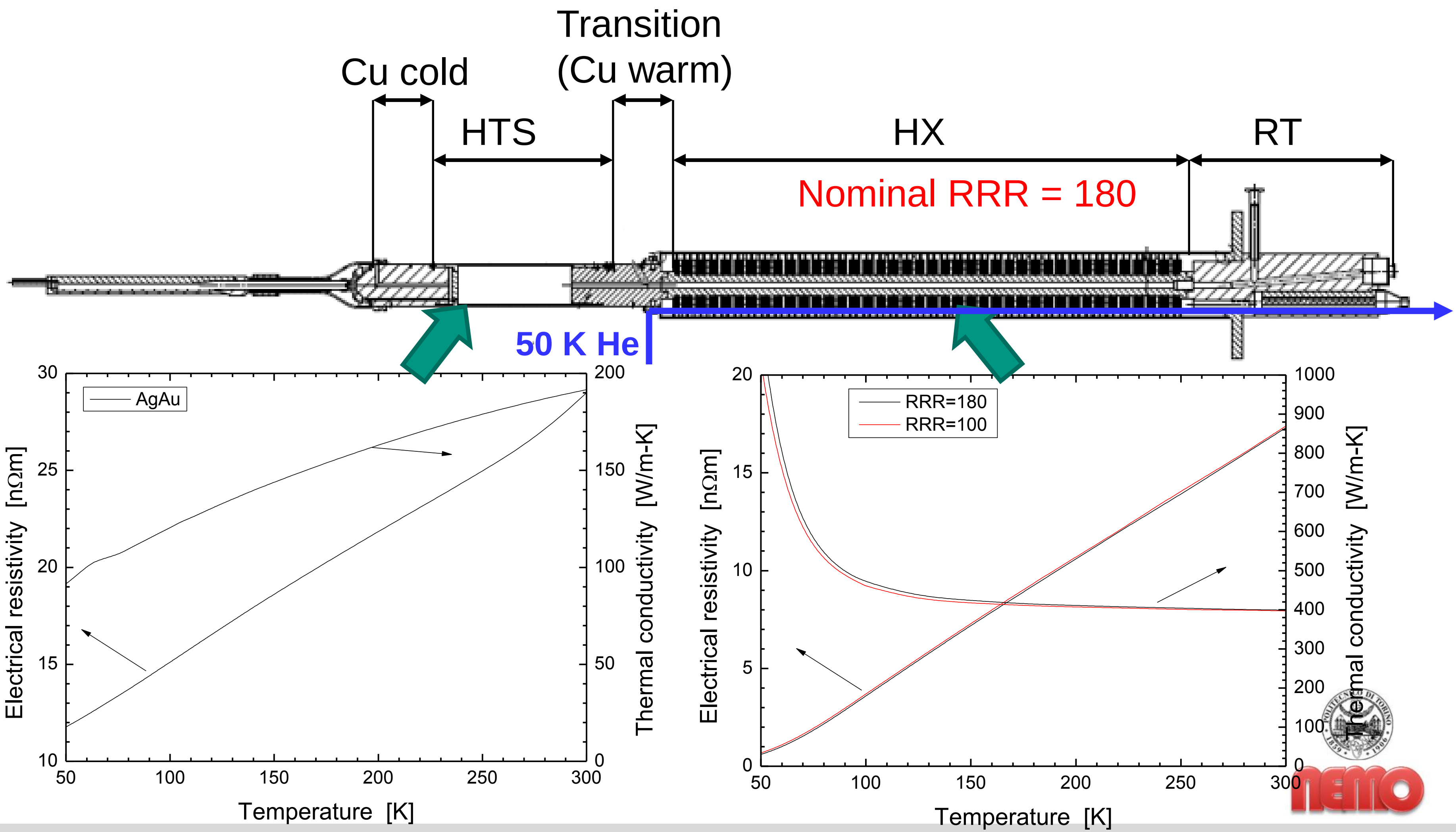
- Geometry
- Material properties
- Mass flow
- Cu and He BCs
- Current

→ **CURLEAD** →

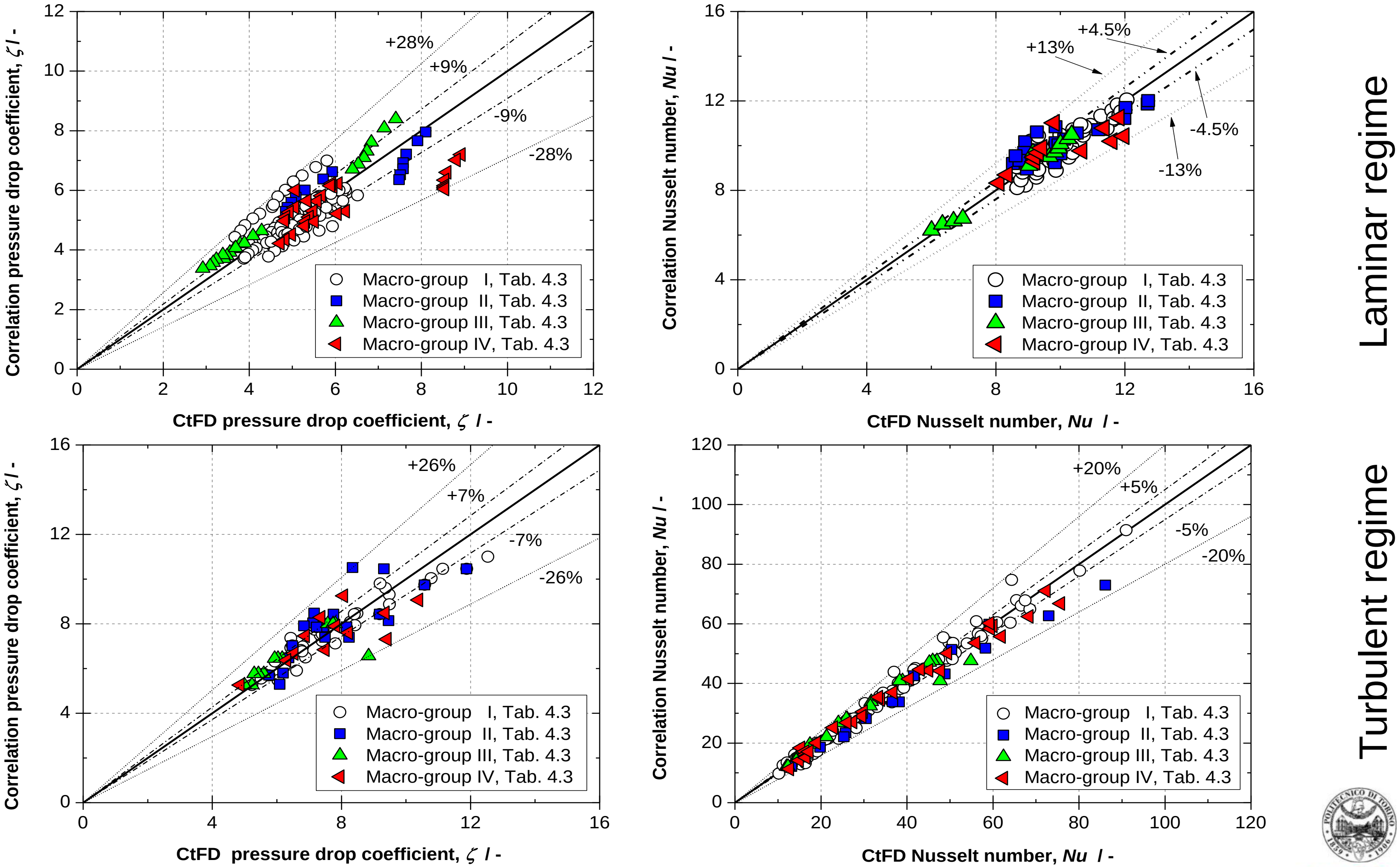
OUTPUT

- Cu and He temperature profile
- Pressure drop
- Voltage drop
- Heat leakage

Material properties



Correlations for pressure drop & heat transfer (I)



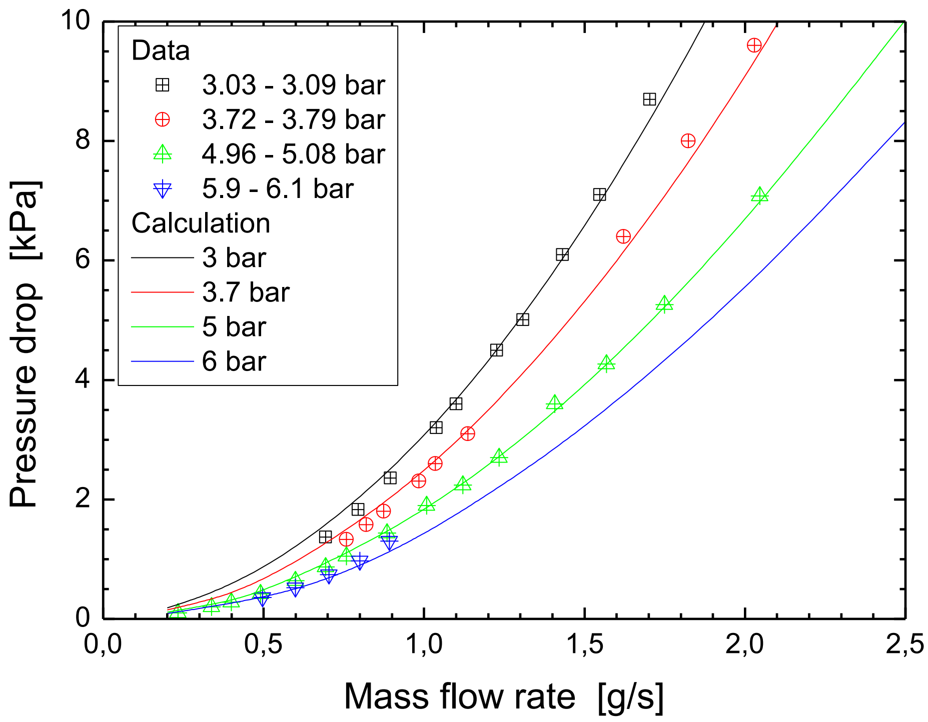
Enrico Rizzo, Simulations for the optimization of High Temperature Superconductor current leads for nuclear fusion applications, (Karlsruher Schriftenreihe zur Supraleitung ; 14)

Correlations for pressure drop & heat transfer (II)

- Laminar regime (E. Rizzo et al, FED 88 (2013) 2749):
  - $\zeta = 143 \cdot Re^{-0.52} \cdot \left(\frac{d_i}{d_o}\right)^{0.49} \cdot \beta^{-0.27} \cdot \left(\frac{c_o}{d_o}\right)^{-0.17} \cdot \left(\frac{s}{d_i}\right)^{-0.07}$
  - $Nu = 20 \cdot Re^{0.10} \cdot \left(\frac{s}{d_o}\right)^{0.15} \cdot \left(\frac{t}{d_i}\right)^{0.08} \cdot \beta^{0.63} \cdot \left(\frac{t}{a}\right)^{0.12}$
- Turbulent regime (E. Rizzo et al, Cryogenics 53 (2013) 51):
  - $\zeta = 13.5 \cdot Re^{-0.12} \cdot \left(\frac{d_i}{d_o}\right)^{0.16} \cdot \left(\frac{c_o}{d_o}\right)^{-0.07} \cdot \left(\frac{s}{t}\right)^{-0.23} \cdot \left(\frac{A_{co}}{A_{He}}\right)^{-0.15}$
  - $Nu = 0.84 \cdot Re^{0.73} \cdot \left(\frac{A_{He}}{A_{HX}}\right)^{0.15} \cdot \left(\frac{d_i}{d_o}\right)^{0.72} \cdot \left(\frac{t}{d_i}\right)^{0.24} \cdot \left(\frac{c_o}{d_o}\right)^{0.12}$
- Correlations validated using results of W7-X prototype current leads (E. Rizzo et al, FED 86 (2011) 1571)

Predictive analysis (I)

- **Simulation of pressure drop in MF-HX at RT with nitrogen gas and comparison to data**



Prediction agrees very well with experimental data

Predictive analysis (II)

- **Simulation strategy**

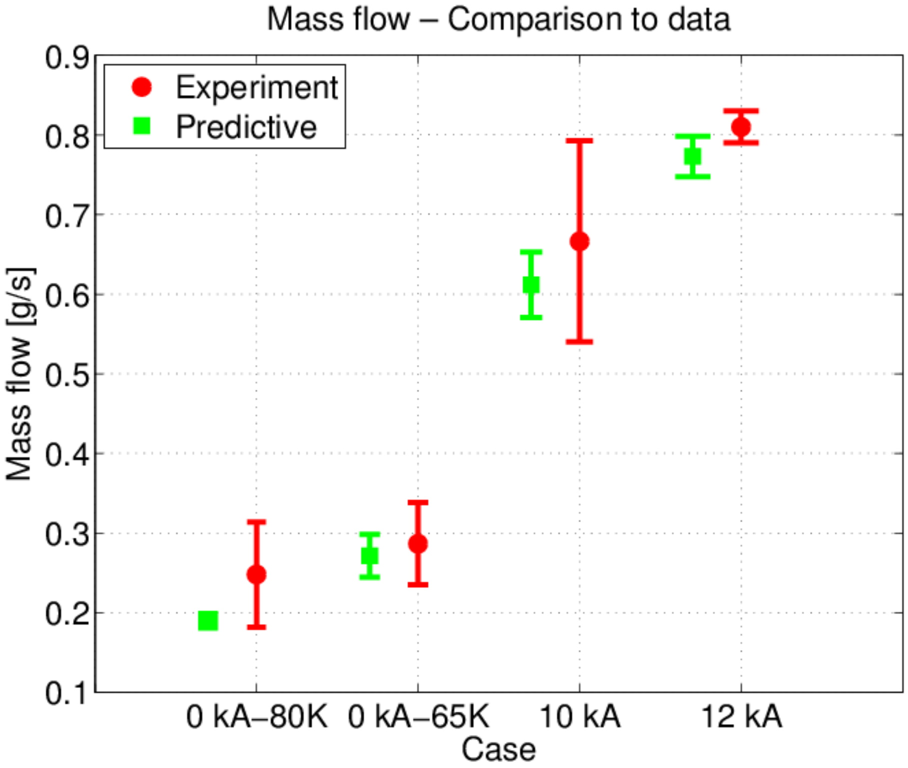
- Adjustment of the He mass flow rate to get $T_{HTS100\%}$ = T6A;
- Perform sensitivity analysis according to the table;
- Post process the results, performing an envelop of the solutions computed

	Nominal	Error considered
T Cu warm	300 K	± 10 K
T Cu cold	5 K	± 0.5 K
T He inlet	50 K	± 3 K
T6A (target temperature)	65 (or 80) K	± 2.5 K
Sensor position (T6A)	375 mm	± 5 mm

Predictive simulation (III)

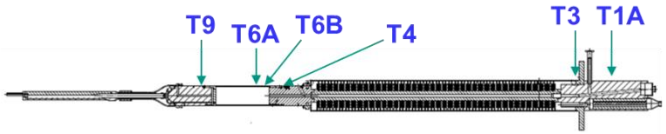
- **Simulation of steady state performance and comparison to data**

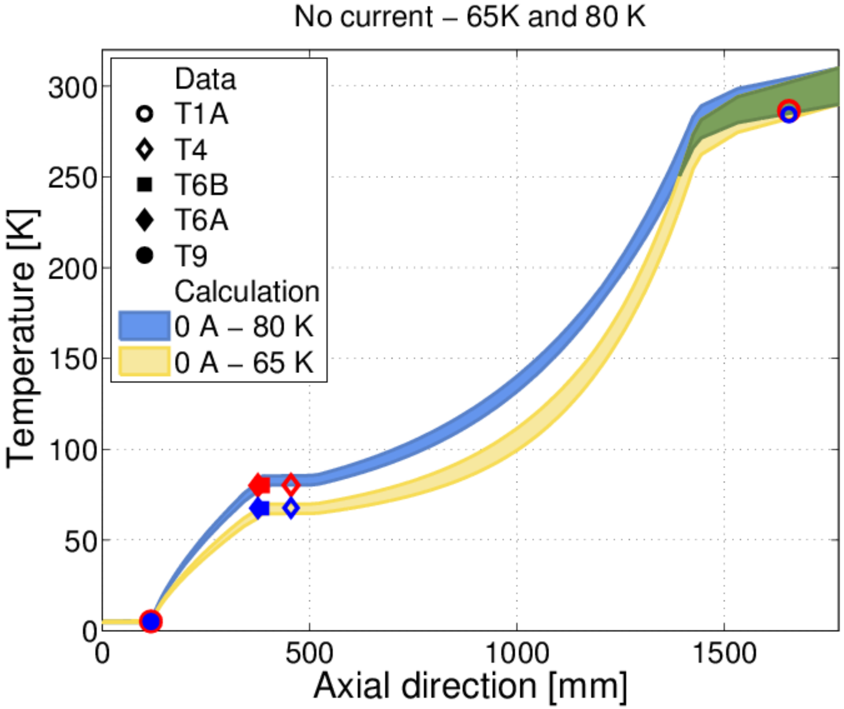
- *Mass flow rate*
  - Predictive results are within the experimental error bars
  - Systematic + statistical error is considered

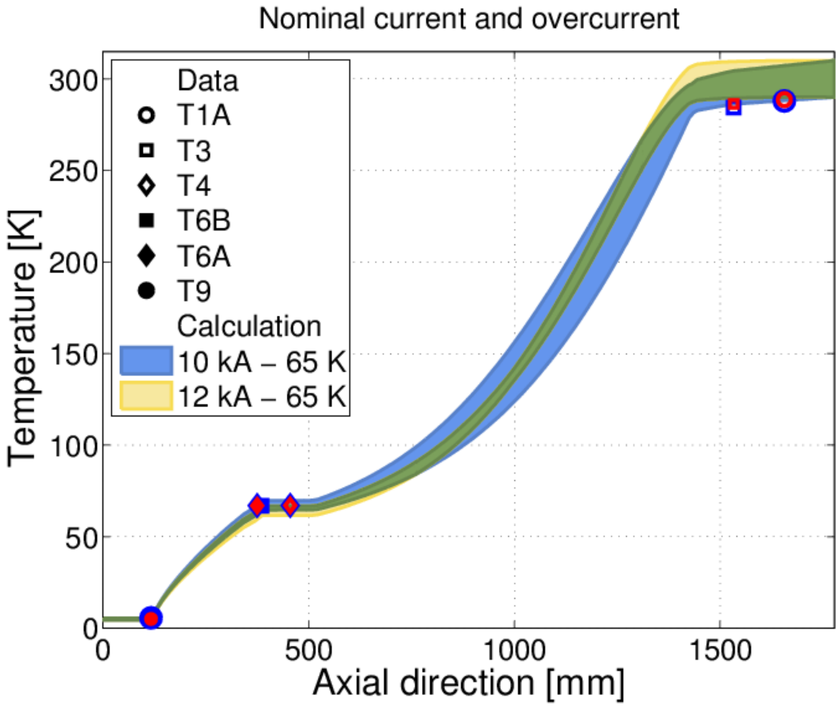


Predictive simulation (IV)

- *Temperature profiles:*





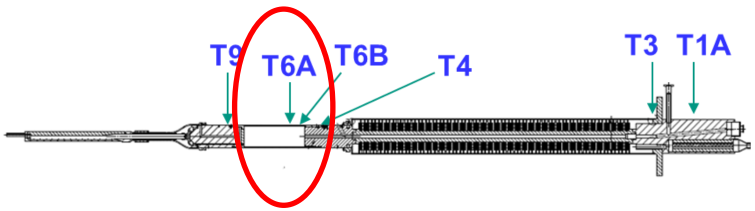


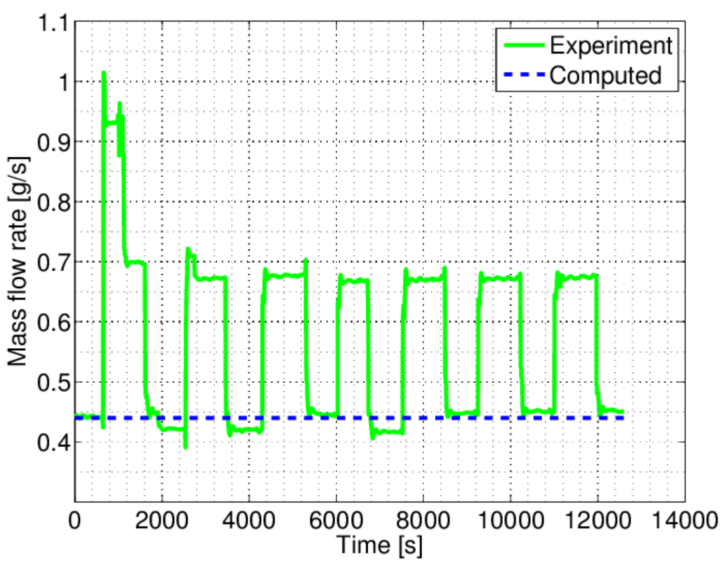
- *Heat loss at cold end (I = 0):*

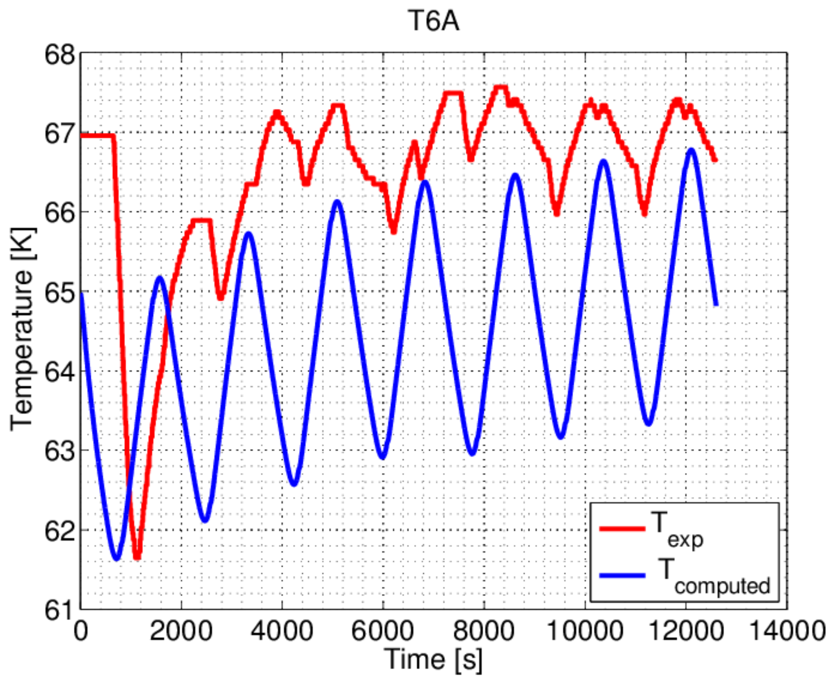
$$P_{cold} = 2.72\ W$$

Predictive simulation (V)

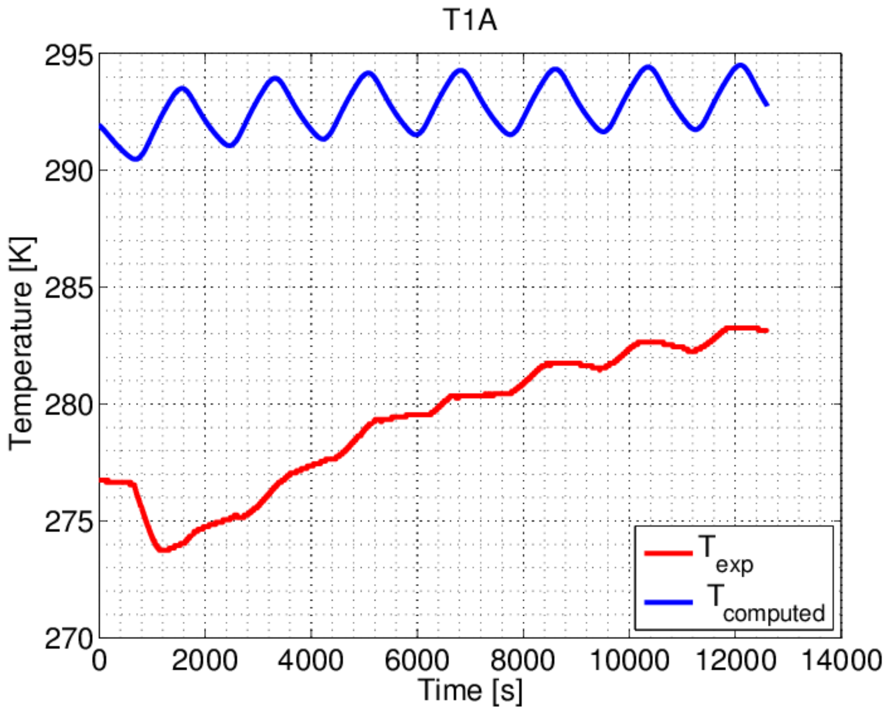
- **Pulsed case – Simulation strategy and results**
  - Current scenario with 7 pulses
  - Constant He mass flow rate of 0.44 g/s averaged over whole pulsed cycle
  - Initial condition: $T_{HTS100\%}$ = 65 K;
  - Nominal BCs.

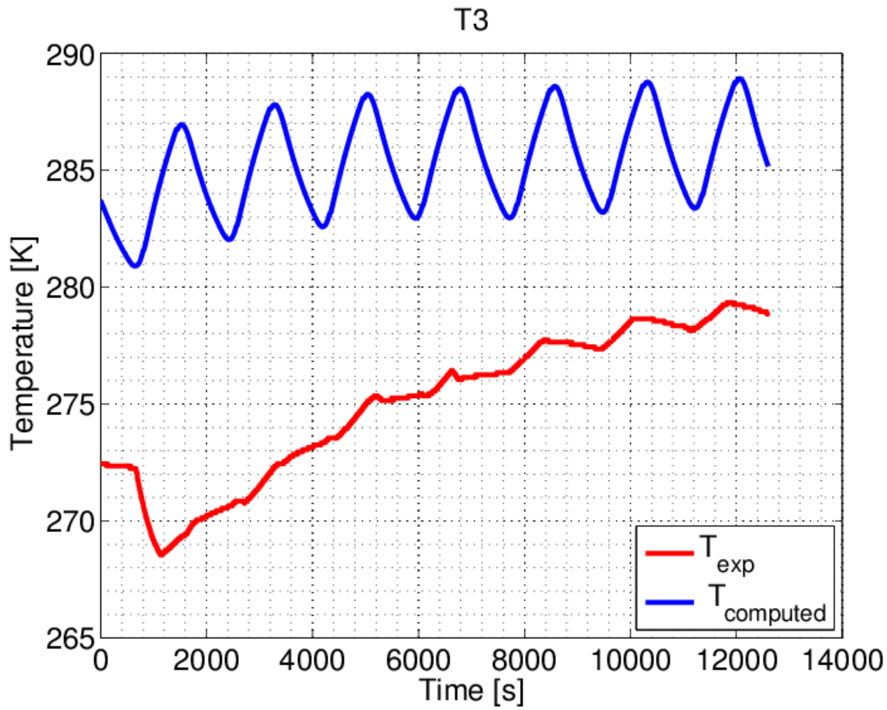


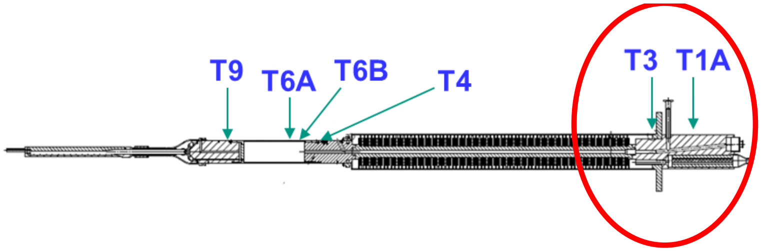




Predictive simulation (VI)





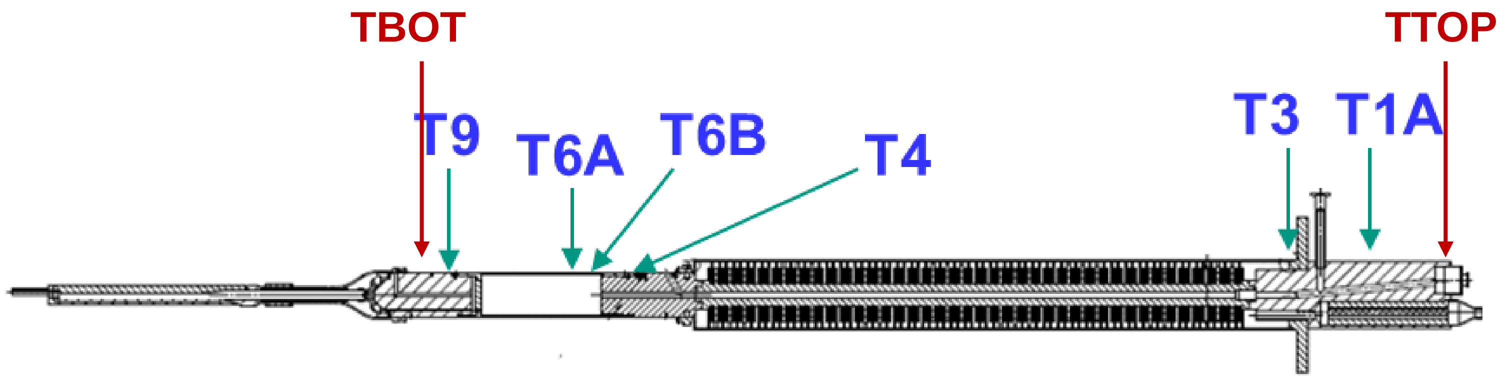


Predictive simulations (VII)

- **Conclusions and lessons learned**
  - The CURLEAD code is able to predict the performance of the lead in terms of temperature profile and He mass flow rate;
  - The uncertainties on the BCs (T6A value and even more $T_{warm\ end}$) cause a large error bar on the computed results;
  - The prediction for the pulsed operation shows the largest deviation: in particular the BC at the RT-end is not correctly simulated

Post blind test simulation results and comparison to experimental data (I)

- WHY: real BCs deviate from the nominal ones → an interpretative analysis performed



- **Steady state cases – Simulation strategy**

1. Adjustment of the Cu BCs TBOT and TTOP such to get T9 and T1A data values;
2. Use the experimental He inlet temperature
3. Adjustment of the He mass flow rate to get $T_{HTS100\%}$ = T6A.

Post blind test simulation results and comparison to experimental data (II)

- **Steady state cases – Comparison with experimental data**
  - CL2 is not considered as it did not reach steady state in the experiment;
  - Heat loss at cold end could not be measured during the CC CL test;
  - Heater power at RT-end was not measured as well;
  - The error bar on the mass flow rate is calculated as statistical + systematic (←10 mg/s);
  - The error bar (band) on the computed results is an envelop of the results with ± 5 mm on the sensor position and ± 1 K on the T_{He} inlet.

Post blind test simulation results and comparison to experimental data (II)

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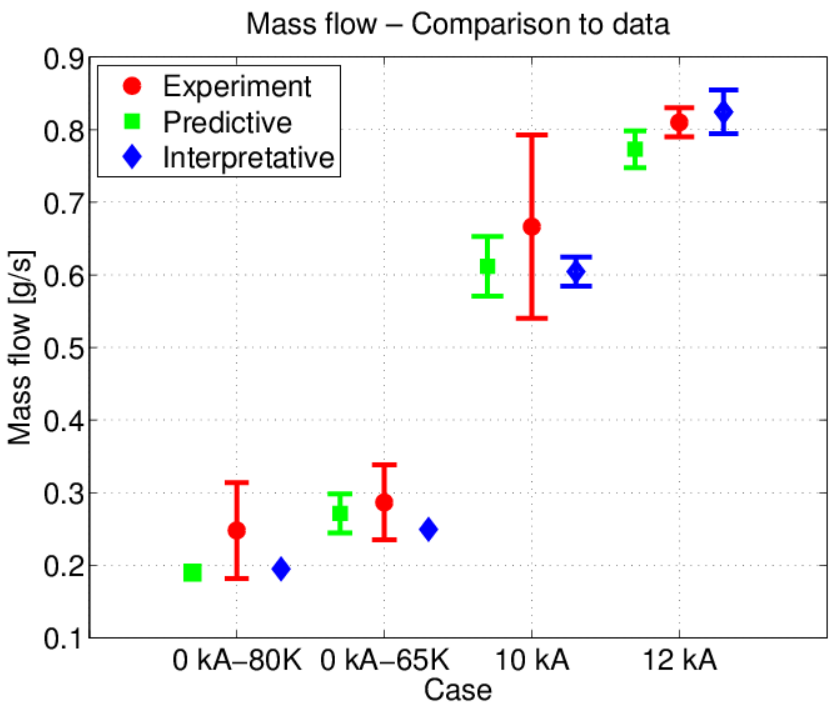
- **Steady state cases – Results**

  Mass flow

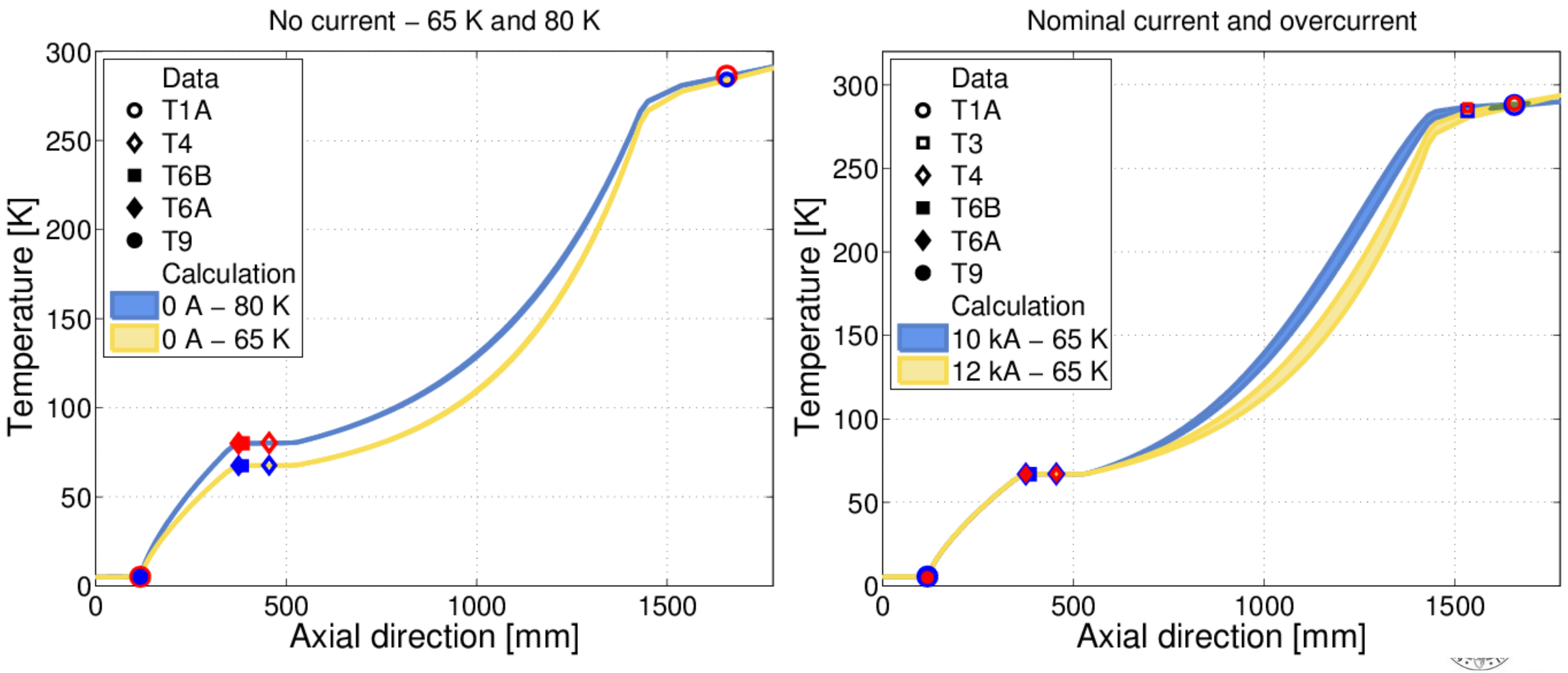
  - The computed mass flow rates are within the experimental error bars;
  - In the 0-kA computed cases, the error bar is negligible;
  - In the 10 kA case, large oscillations in the measured data cause a much larger statistical error bar



Post blind test simulation results and comparison to experimental data (III)

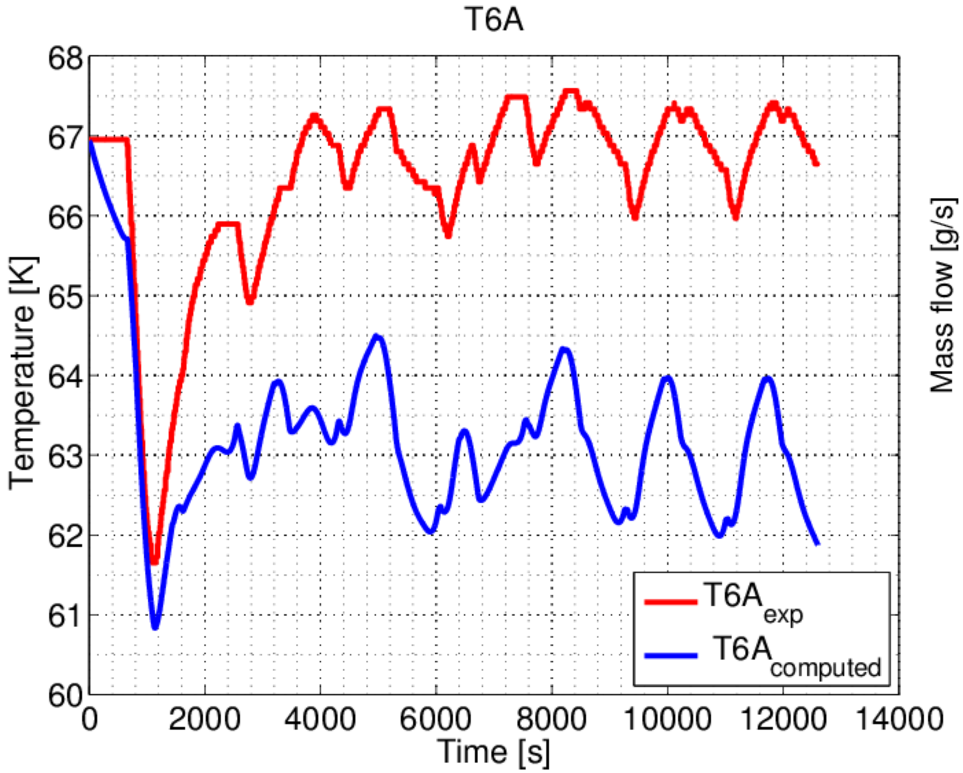
- **Steady state cases – Results**

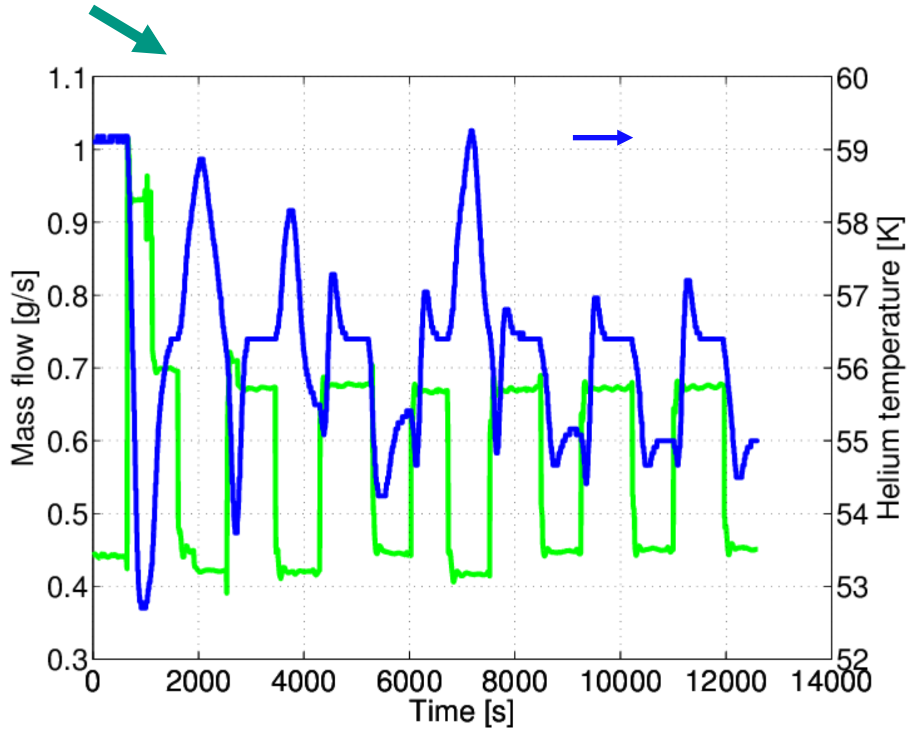
Temperature profile



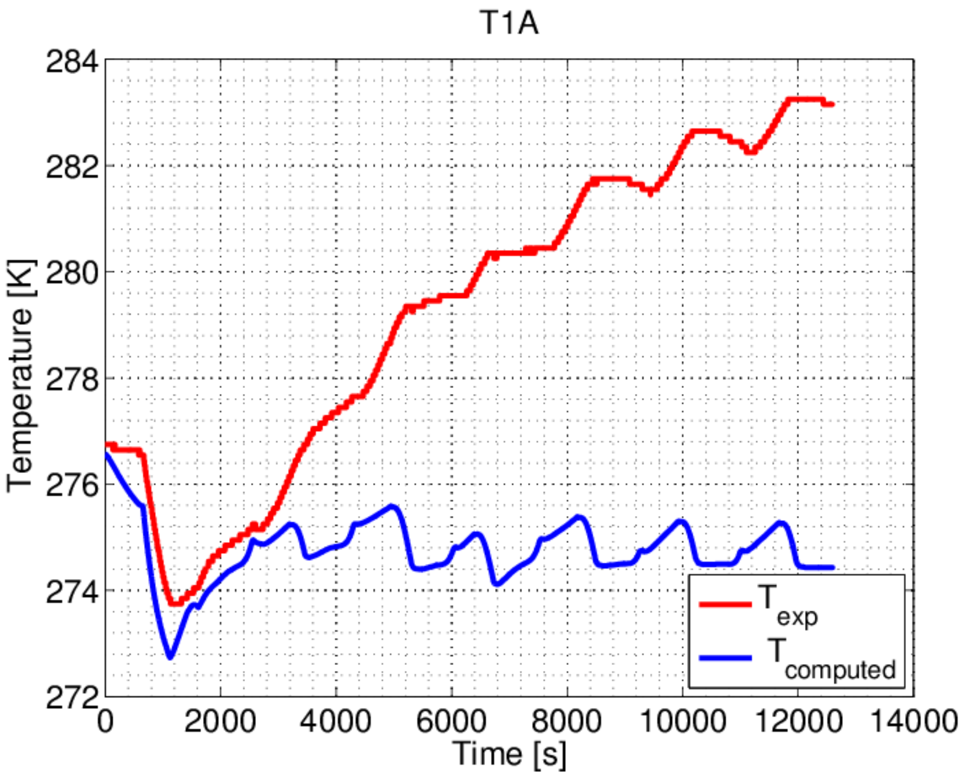
Post blind test simulation results and comparison to experimental data (II)

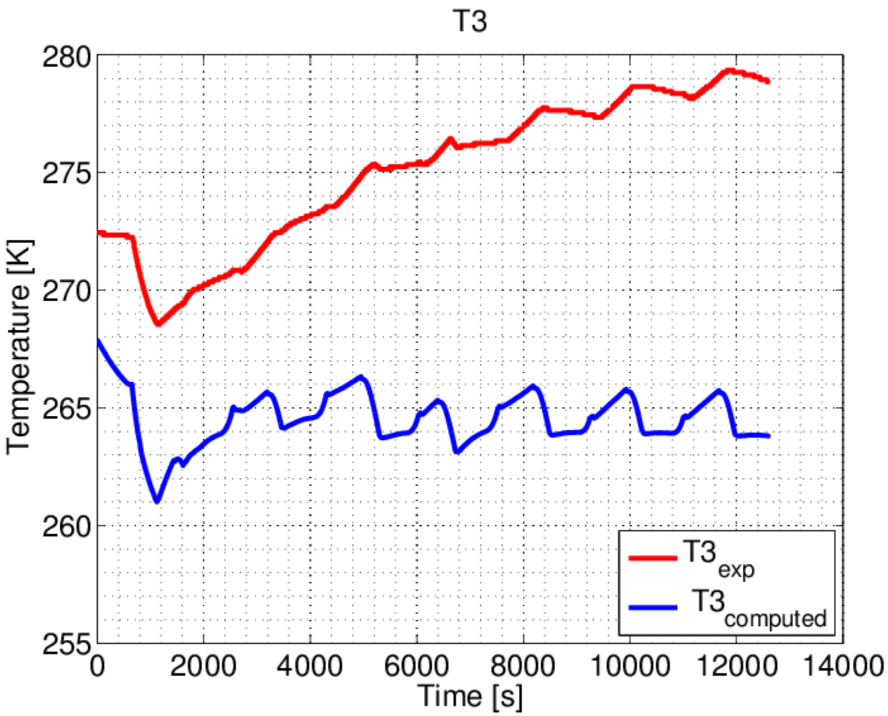
- **Pulsed case – Simulation strategy**
  - Initial condition : same temperature at T6A and T1A
  - Experimental BCs and mass flow rate
- **Pulsed case – Results**





Post blind test simulation results and comparison to experimental data (III)





Conclusions and perspective (I)

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- The correlations for heat transfer and pressure drop developed can be used to predict the performance of the ITER CC prototype current leads
- The He mass flow rates needed in the simulations are in the order of 10% lower than performed in the experiment but still within the statistic + systematic error bars
- The simulation results support the effectiveness of the HX installed in the RT-terminal of the CL to heat up the helium gas up to ambient temperature. No problem of icing should occur during normal operation
- The error bars on the T-profiles in the interpretative analysis are much smaller than those of the predictive analysis, as a consequence of the smaller uncertainties

Conclusions and perspective (II)

- The simulation of the pulsed operation leads to a qualitatively reasonable agreement if taken into consideration the time dependent boundary conditions which come from the influence of the RT feeder and of the heat capacity of parts of the CL which were not modeled. In addition in the post blind simulations both the experimental He inlet temperature and mass flow have been used. As in all steady state runs the simulated mass flow rate is lower than the one used in the experiments this leads to an additional over-cooling of he CL in the simulations.

The End

Current Lead Layout

Parameters	TF	PF	CS	CC
Design Parameters				
Max heat load at full current per lead at 4.5 K end (W)[1]	15	12	12	3
Max 50 K flow rate in HEX section (g/s)	5.5	3.5	3.5	1
Max pressure drop in HEX section (MPa)	0.1			
HX to HTS joint max resistance / HTS to LTS joint max resistance (nΩ)	10 / 1			25 / 5
LTS to busbar joint max resistance (nΩ)	2			5
Max AC losses (W/m)	<1			
Max length end-to-end (m)	<3			
Protection Parameters for HTS				
Max HTS hot spot temperature (K)	200			
Max. HTS quench detection delay. (s)	2			
HTS burnout time[2] (s)	15	18	11.5	18
Test pressure 4.5 K circuit (MPa)	1.25 × 3			
Protection Parameters for HEX				
LOFA time[3] (s)	350	250	250	120
HEX helium test pressure (MPa)	1.25 × 0.6			
High voltage insulation				
Design voltage to ground (kV)	30			10
Paschen resistant	Y			
Ground screen	Y			

[1] = excluding the HTS to busbar joint resistance,

[2] = burnout time = time at full current after a quench to reach hot spot temperature (excludes $t_{QD\text{-}det}$),

[3] = LOFA time = time at full current after a loss of flow accident to reach T_{CS} in HTS