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INSTITUT NANOSCIENCES ET CRYOGÉNIE

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Using the HELIOS facility for assessment of bundle-jacket thermal coupling in a CICC

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2 – Measurement method and mock-up design

3 – Manufacturing and integration in HELIOS facility

4 – Experimental results analysis

5 – Conclusion

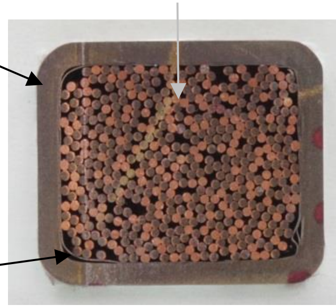
1 – Impact of Heat Transfer Coefficient in CICC thermo-hydraulics

2 typical Cable In Conduit Conductors (CICC) for fusion magnets

Cable: 324 NbTi strands
+ 162 Cu strands
Ø = 0.81 mm
Wetted Perimeter ≃ 1,3 m

Stainless steel jacket 22×26 mm

Cable wrapping
0.1 mm thickness
50 % overlap



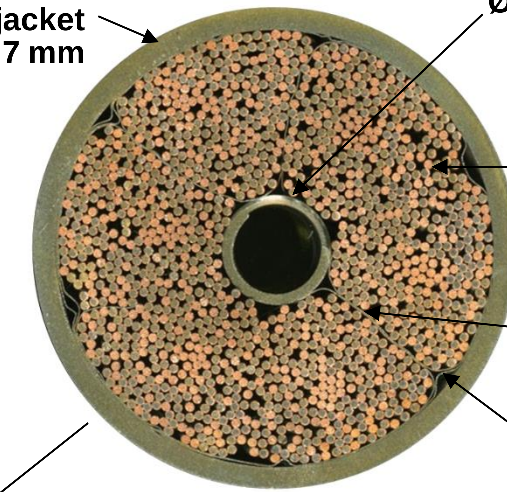
Stainless steel jacket
Ø 39.7×43.7 mm

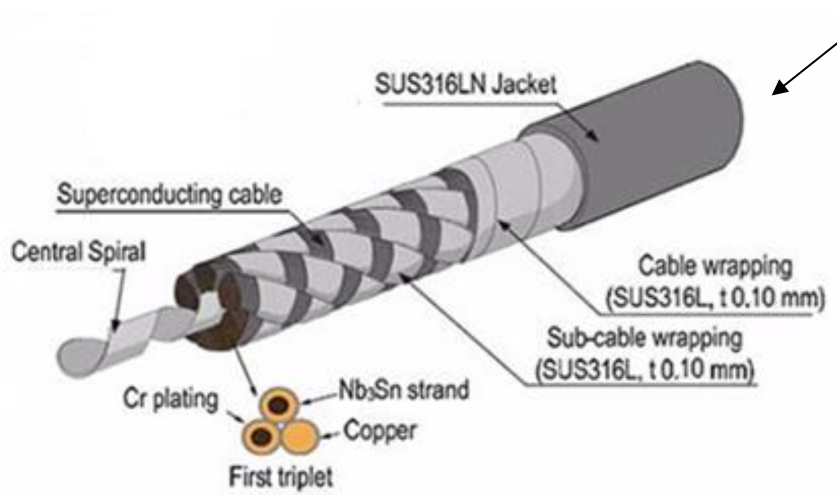
Central spiral
Ø 8×10 mm

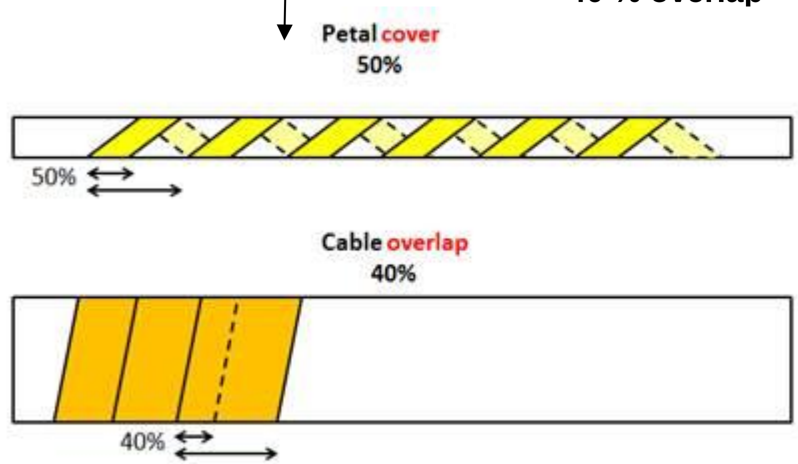
Cable:
900 Nb_3Sn strands
+ 522 Cu strands
Ø = 0.816 mm
WP ≃ 3.8 m

Petal wrapping
0.1 mm thickness
50 % cover

Cable wrapping
0.1 mm thickness
40 % overlap

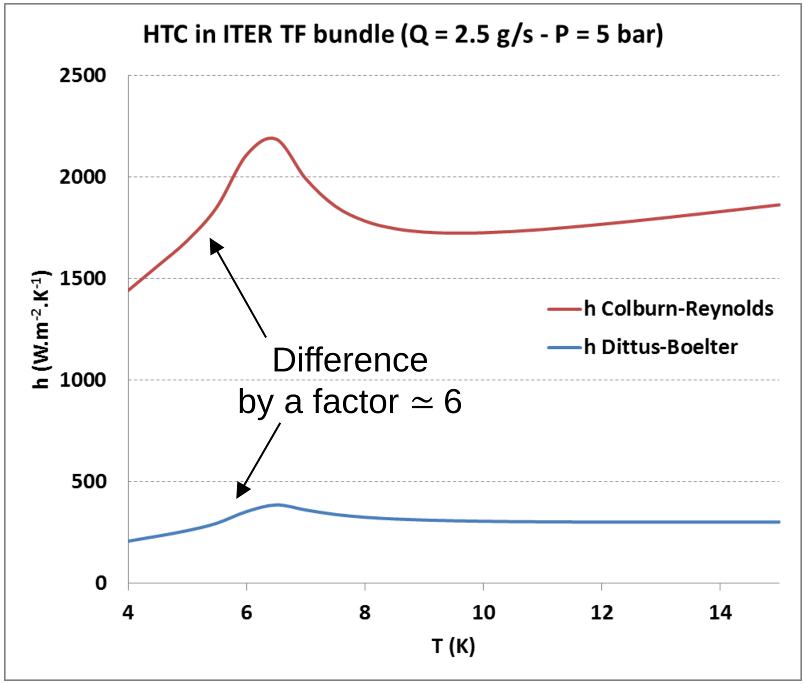






1 – Impact of Heat Transfer Coefficient in CICC thermo-hydraulics

- 2 Heat Transfer Coefficients (HTC) to assess in strands channel:
  - h He/strands (h_{bundle})
  - h He/jacket (h_{jacket})



- 2 correlations are usually applied:
  - Dittus-Boelter **$Nu = 0{,}023\, Re^{0.8}\, Pr^{0.4}$**
  - Colburn-Reynolds (Chilton-Colburn) analogy between heat transfer and friction

    $Nu = f_{EU}/8\ Re\ Pr^{1/3}$

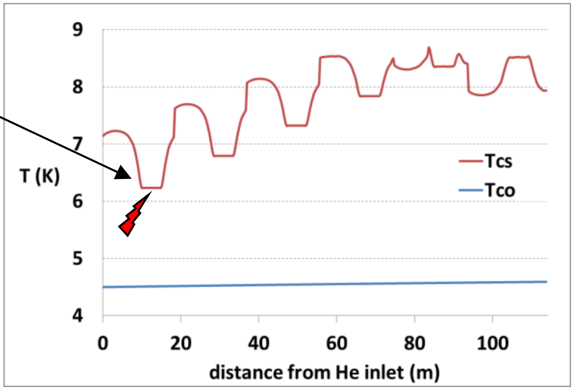
- He/bundle and He/jacket HTC may impact CICC thermo-hydraulic behaviour and thus CICC design:
  - conductor **thermal stability**
  - **quench propagation** velocity
  - **hot spot temperature** (maximum conductor temperature reached during Fast Safety Discharge of current in case of quench detection) – Usual criterion: **$T_{hot\ spot} < 150$ K**

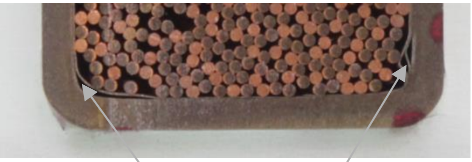
→ These effects were assessed by **Gandalf calculations on JT-60SA TF conductor** (easier interpretation in the **absence of central channel**)

Remark : Operating temperature T_{op} and thus $\Delta T_{ma} = T_{cs} - T_{op}$ are not affected by h value, because $T_{He} - T_{strands} \simeq 0$ due to the large He/strands wetted perimeter

1 – Impact of Heat Transfer Coefficient in CICC thermo-hydraulics

- Simulations on JT-60SA TF conductor with Q = **3.5 g/s**, P_{inlet} = **5 bar**, T_{inlet} = **4.5 K** and without thermal load
- Disturbance of 100 ms and 1 m applied at middle of high field region (between 12 and 13 m from He inlet)





- By default, h_{jacket} integrates **thermal resistance $R_{th\ wraps}$ due to He layer** (estimated average thickness e = 26 µm) trapped between wrappings and jacket (conduction through SS wrappings integrated in jacket thickness)

$$h_{jacket} = \frac{1}{\frac{1}{h_{conv}} + R_{th\ wraps}} \quad with \quad R_{th\ wraps} = \frac{e_{He\ layer}}{\lambda_{He\ layer}}$$

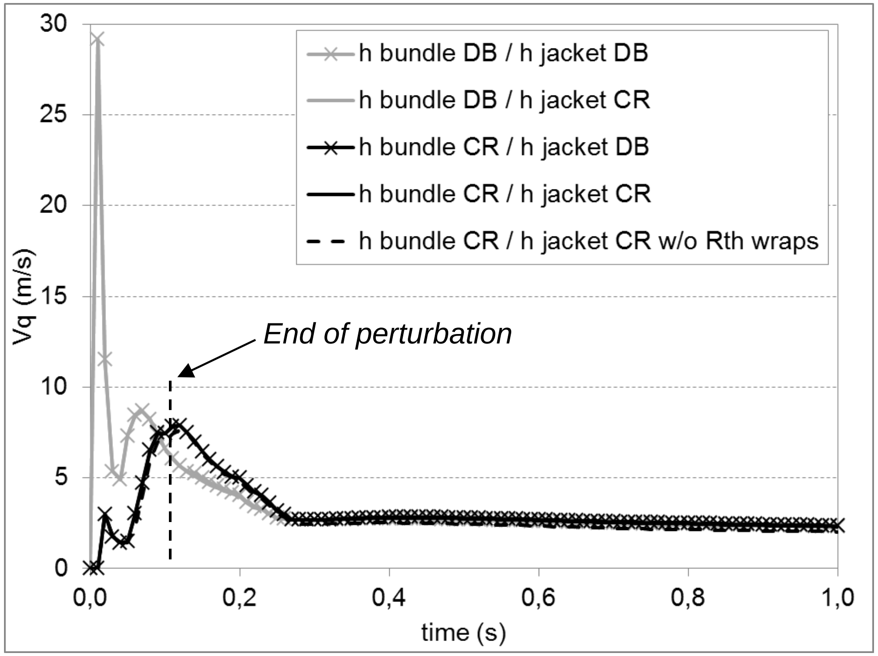
✓ Impact of HTC correlations on **thermal stability** (Minimum Quench Energy) and on $\mathbf{T_{hot\ spot}}$:

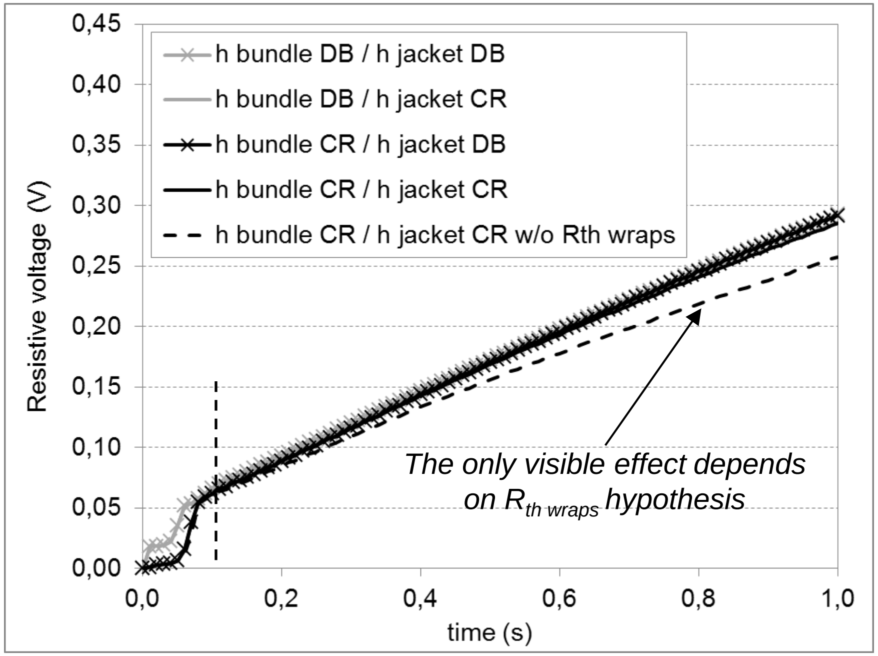
h_{bundle}	h_{jacket}	MQE (W/m)	$T_{hot\ spot}$ (K)
DB	DB with $R_{th\ wraps}$	460	187
DB	CR with $R_{th\ wraps}$	460	156.5
CR	DB with $R_{th\ wraps}$	850	183
CR	CR with $R_{th\ wraps}$	850	152.5
CR	CR w/o $R_{th\ wraps}$	870	134

- ✓ **MQE** is mainly sensitive to $\mathbf{h_{bundle}}$
- ✓ $\mathbf{T_{hot\ spot}}$ is mainly sensitive to $\mathbf{h_{jacket}}$

1 – Impact of Heat Transfer Coefficient in CICC thermo-hydraulics

✓ Limited impact of HTC correlations on early **quench propagation**





✓ $\mathbf{h_{bundle}}$ may impact **thermal stability**

✓ $\mathbf{h_{jacket}}$ impact $T_{hot\ spot}$ calculation, and to a lesser extent early quench propagation, so $\mathbf{h_{jacket}}$ may impact the parameterization of the **quench detection system**

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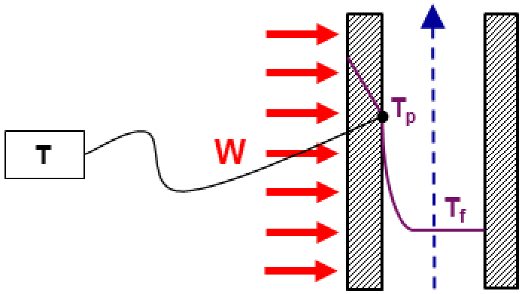
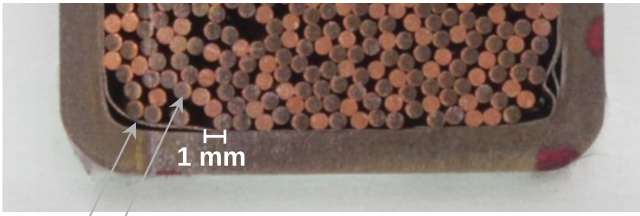
2 – Measurement method and mock-up design

- **Usual method for measuring a Heat Transfer Coefficient requires Tp measurement at inner wall**

$$h = \frac{W}{T_p - T_f}$$

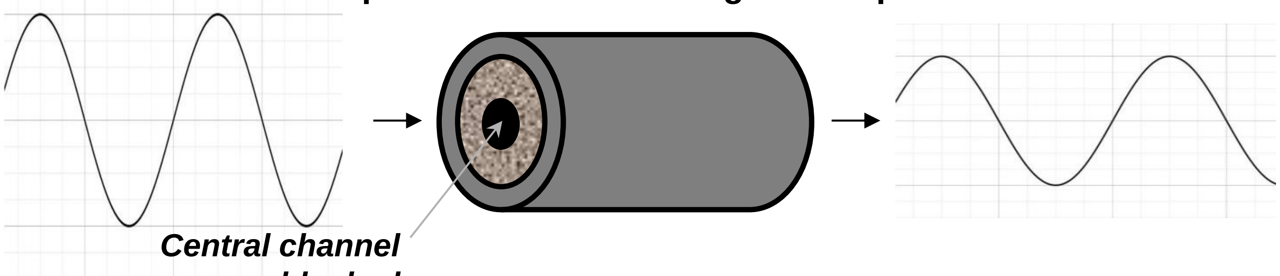




But T_p? **Wall temperature measurement is not possible for inner jacket nor for strands**

- **Possible alternative = technique used for measuring HTC in porous media**

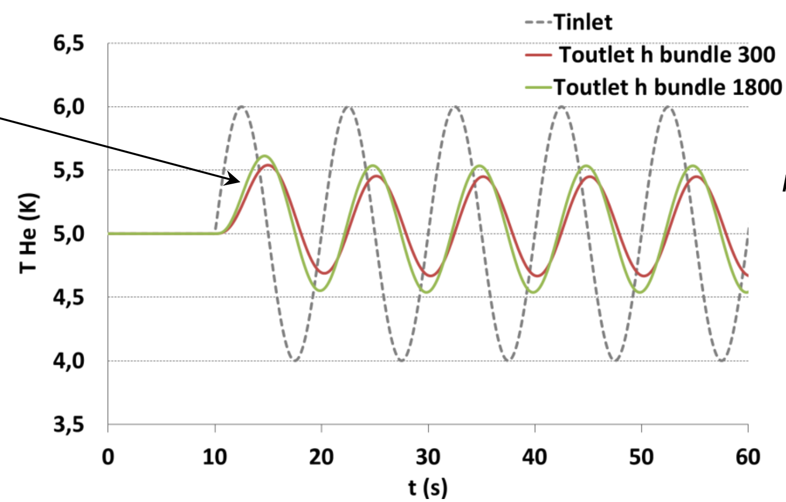
Sinusoidal $T_{He\ inlet}$



Central channel blocked

Phase and/or amplitude transformation depends on HTC in bundle

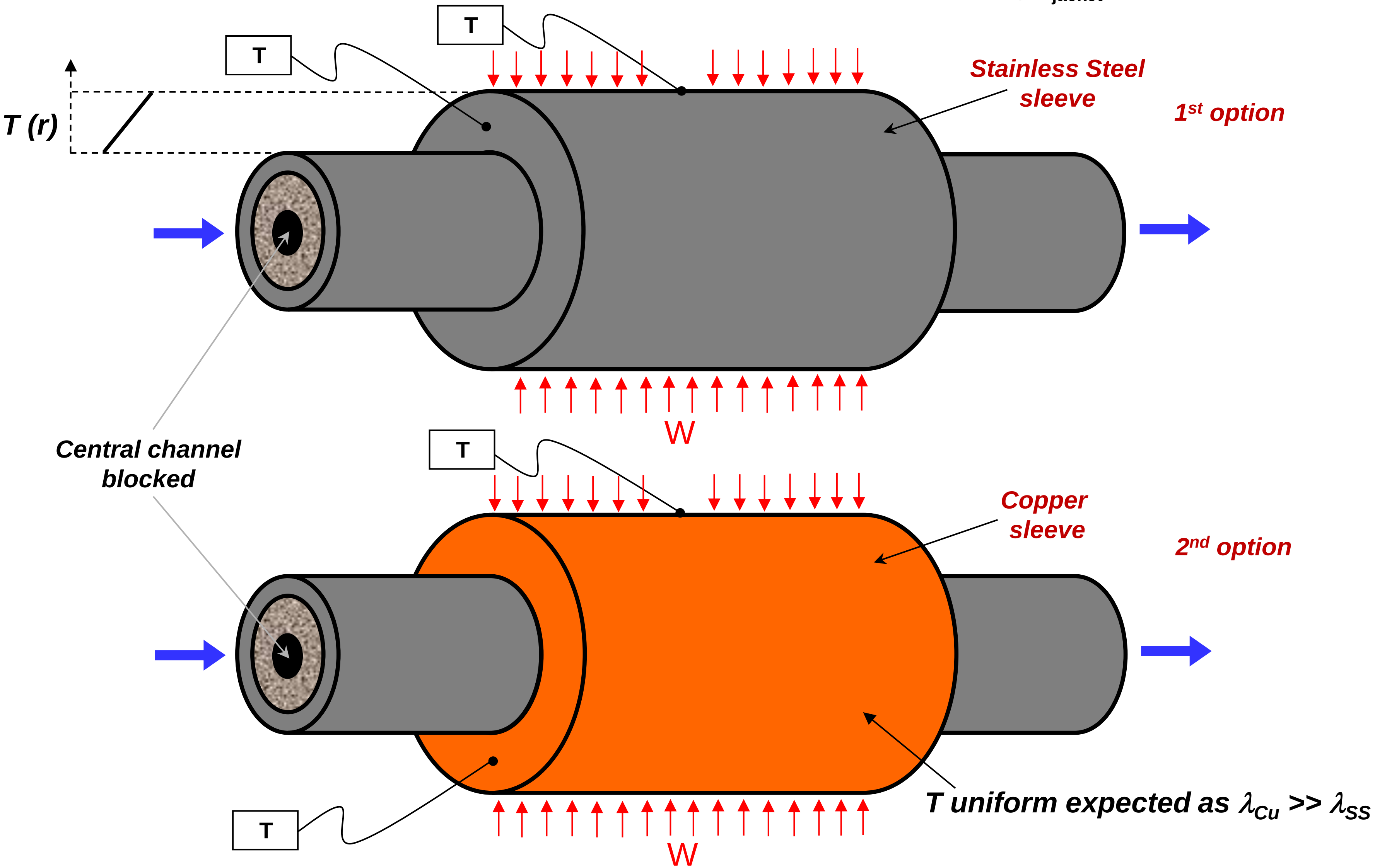
But
- **simulations showed little impact of h_{bundle} on T_{outlet} shape**
- **Method seems inadequate at cryogenic operating conditions probably due to ratio of materials / He enthalpies**



Gandalf simulation of response to sinusoidal T_{inlet}

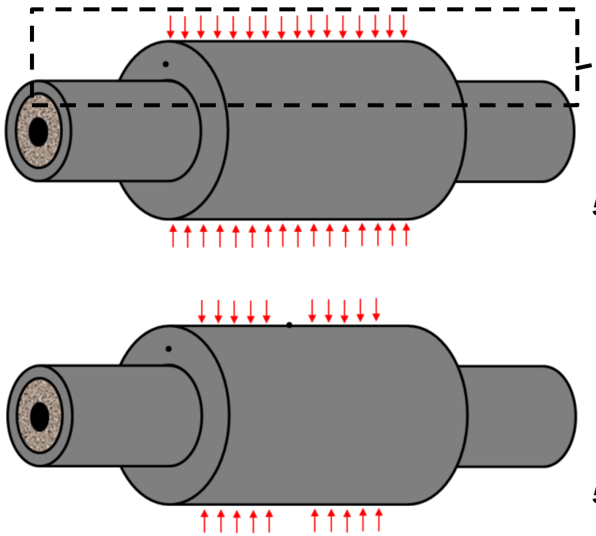
(ITER TF conductor sample of 10 cm with Q = 1 g/s)

- **Possible solution : externalize wall temperature measurement for assessing h_{jacket}**

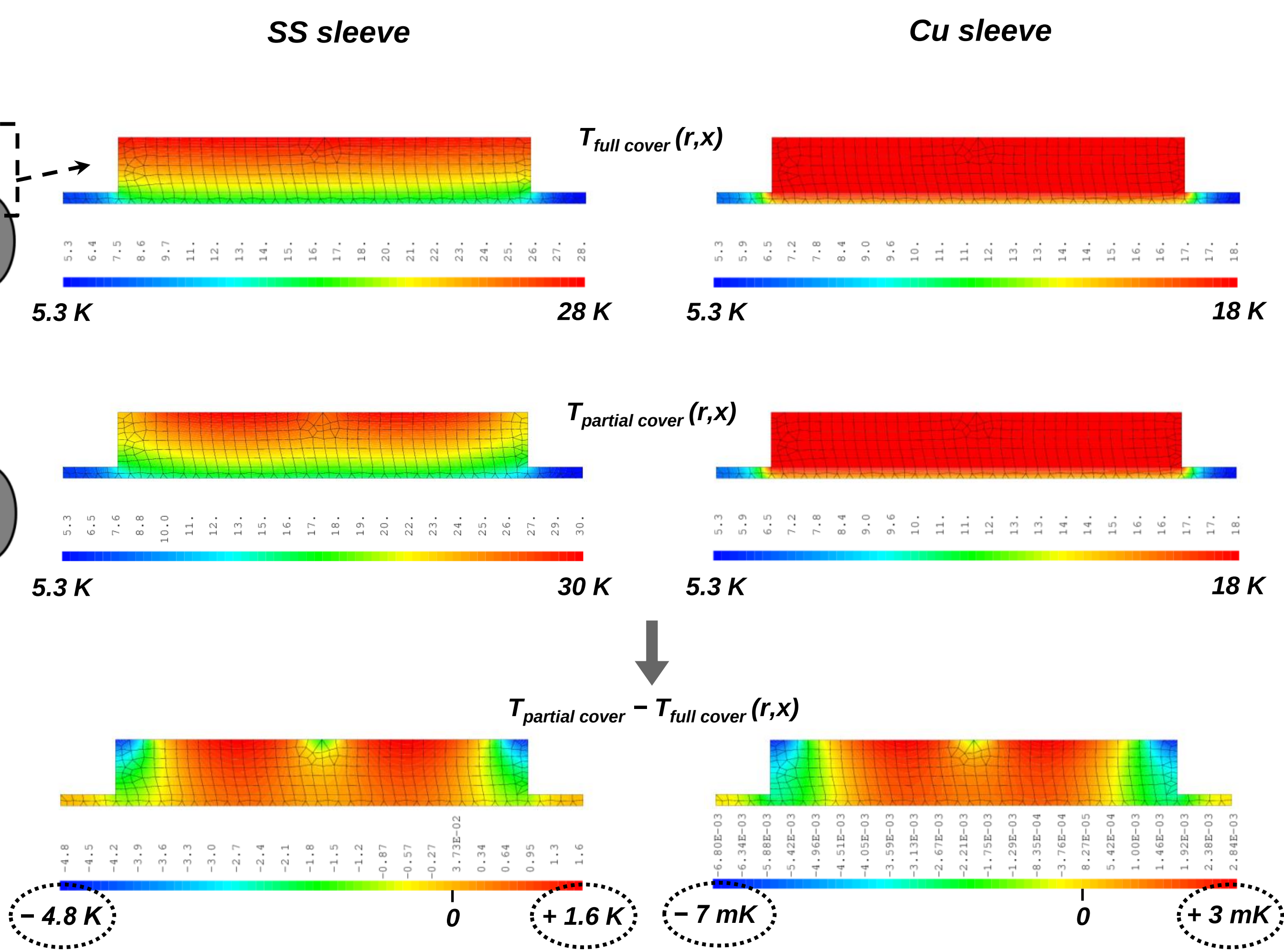


- First reason why Cu sleeve option is more adequate

Ribbon heaters __fully__ cover sleeve external wall



Ribbon heaters __partially__ cover sleeve external wall
(extremities uncovered & space reserved at mid length for thermometer)



✓ With **Cu sleeve**, external wall T^re **do not depend on sensor location**, allowing an easier manufacturing, whereas **analysis of SS sleeve mock-up** would require taking into account **detailed geometry**

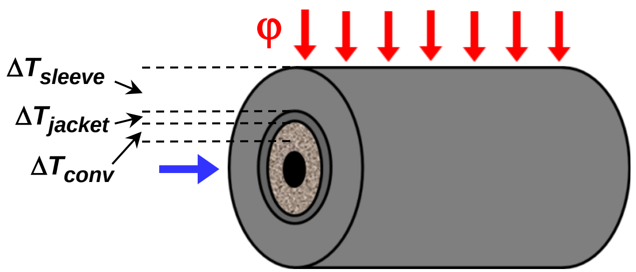
➢ **Second reason why Cu sleeve option is more adequate**

Radial T^re gradient: $T_{outer\ sleeve} - T_{fluid} = (T_{inner\ jacket} - T_{fluid}) + (T_{outer\ jacket} - T_{inner\ jacket}) + (T_{outer\ sleeve} - T_{outer\ jacket})$

$$= \Delta T_{conv} + \Delta T_{jacket} + \Delta T_{sleeve} \quad (1)$$

measured ($T_{outer\ sleeve}$, T_{fluid}) — *calculated* (ΔT_{jacket}, ΔT_{sleeve})

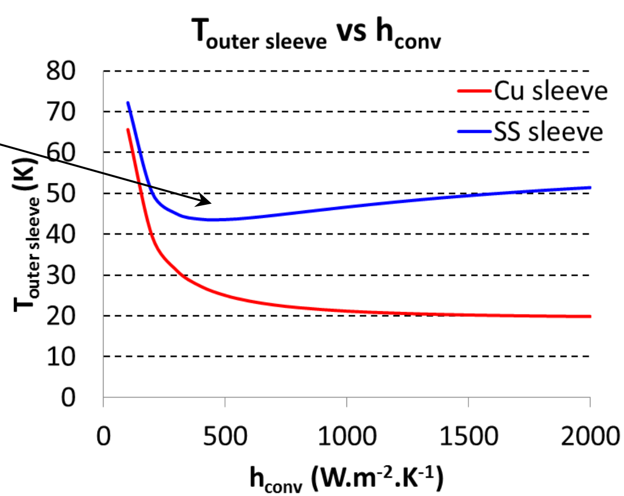
$\Delta T_{conv} = \dfrac{\varphi}{h_{conv}}$ *where φ is imposed and h_{conv} is tuned for balancing the equality*



✓ **With Cu sleeve, $\Delta T_{sleeve} \simeq 0$ → lower uncertainty & better sensitivity to h_{conv} (ΔT_{conv} has higher relative weight)**

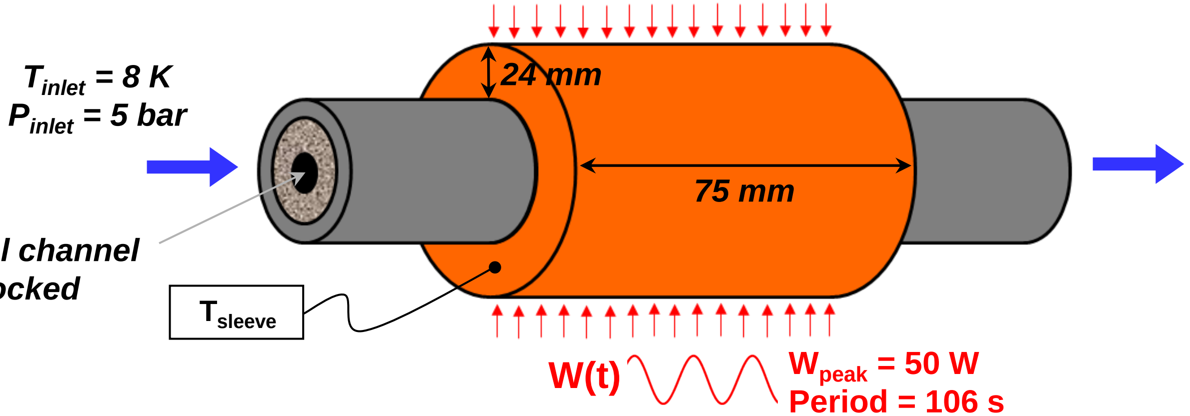
✓ **If h_{conv} ↗ →**
- **ΔT_{conv} ↘**
- **in case of SS sleeve, as λ_{SS} ↘ when T ↘, ΔT_{sleeve} ↗**

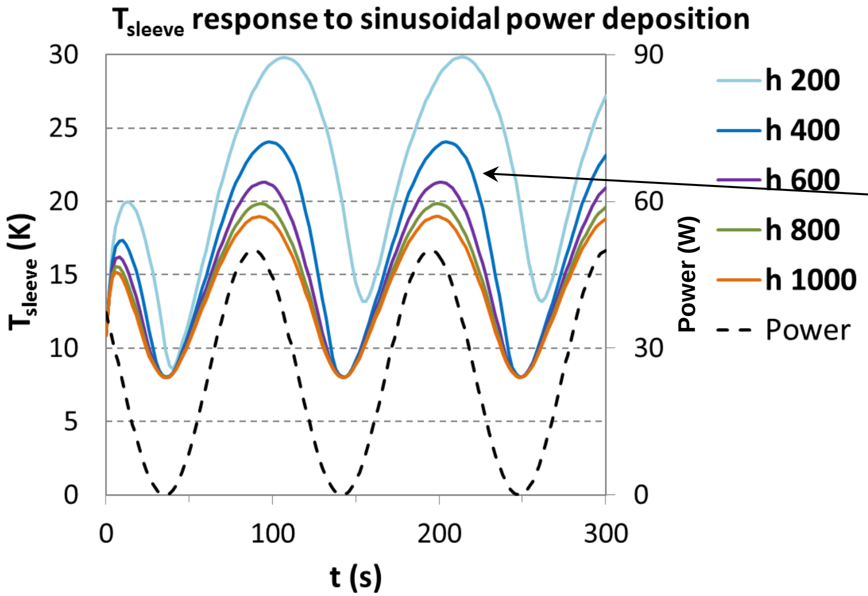
Thus, if SS sleeve thickness is large enough, equation *(1)* can have 2 solutions on h_{conv}



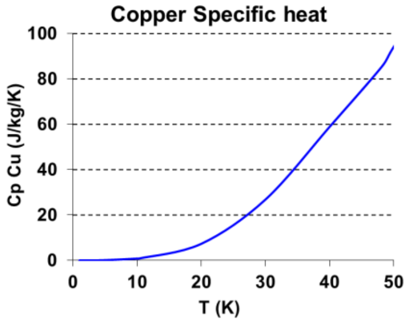
Computation with:
- *P = 50 W*
- *Tfluid = 10 K*
- *Sleeve thickness = 10 mm*
- *length = 75 mm*

- Retained mock-up could allow an alternative h_{jacket} **measurement** by applying **sinusoidal power deposition** instead of constant heating
- **Sensitivity of $T_{sleeve}(t)$ to h_{jacket}** was assessed by simulating the following case:





- ✓ Sensitivity to h_{conv} seems **workable**
- ✓ The asymmetric shape of $T_{sleeve}(t)$ is due to large dependence of Cu specific heat on T



- **Cu sleeve** option is **chosen**
- Mock-up allows h_{jacket} **assessment only,** but **by 2 methods:** with **stationary** or **sinusoidal** power deposition

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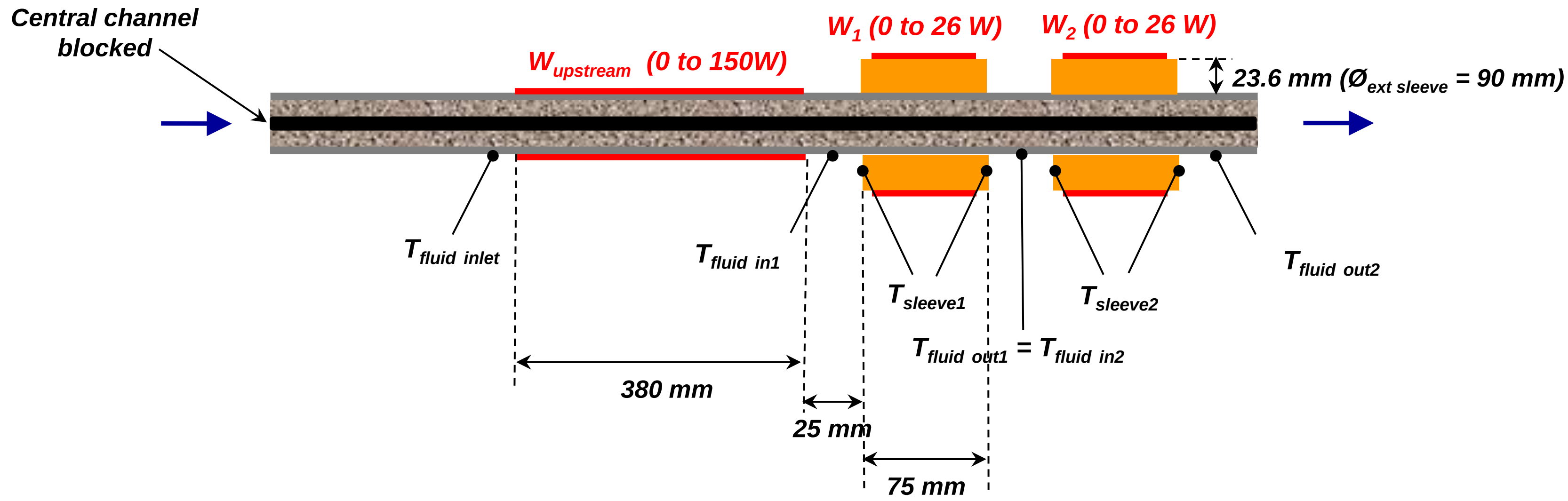
3 – Manufacturing and integration in HELIOS facility

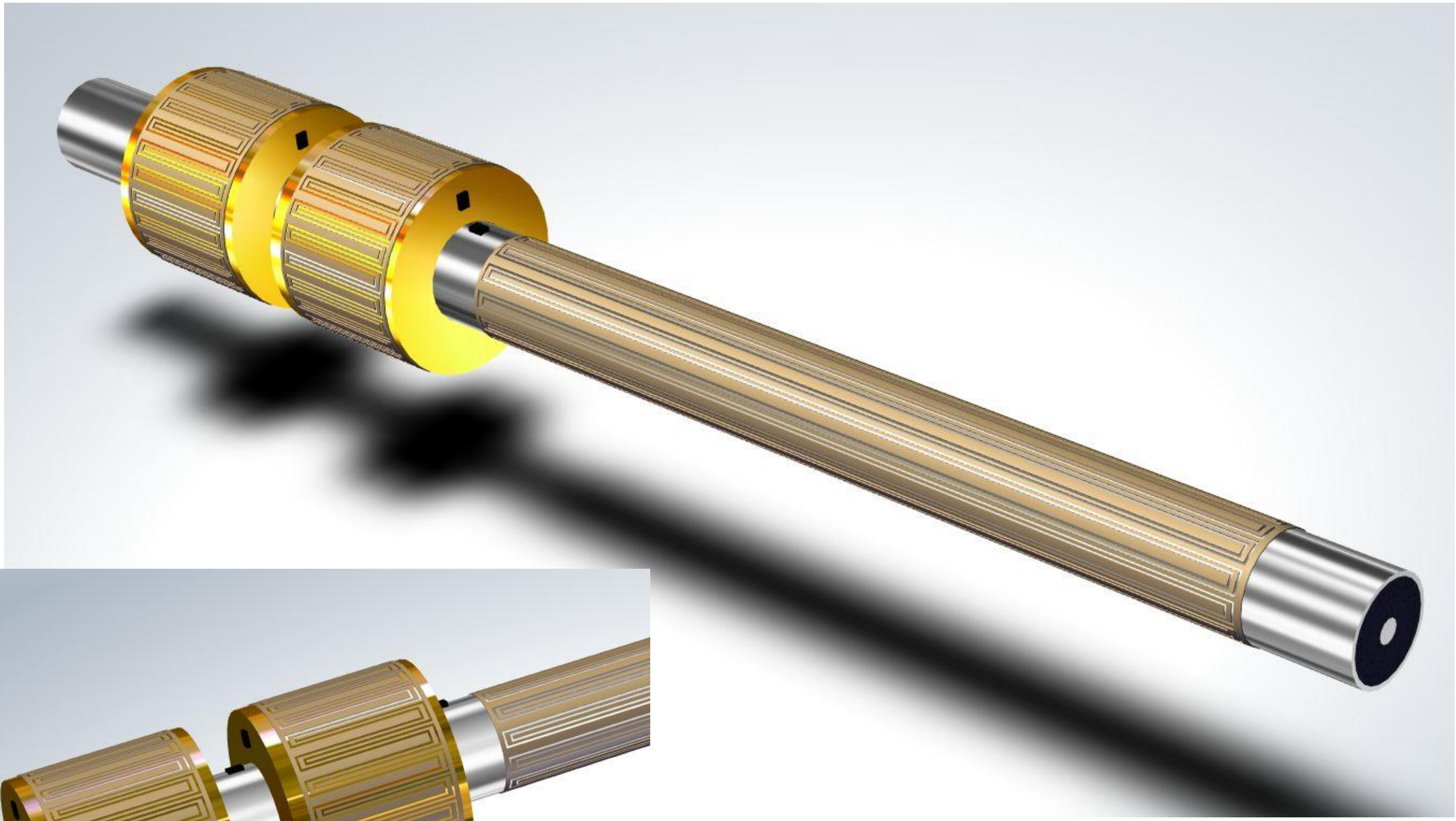
- The mock-up was manufactured from a **1.2 m sample of ITER TF <u>dummy</u> conductor (<u>SC strands replaced by Cu strands</u>)**

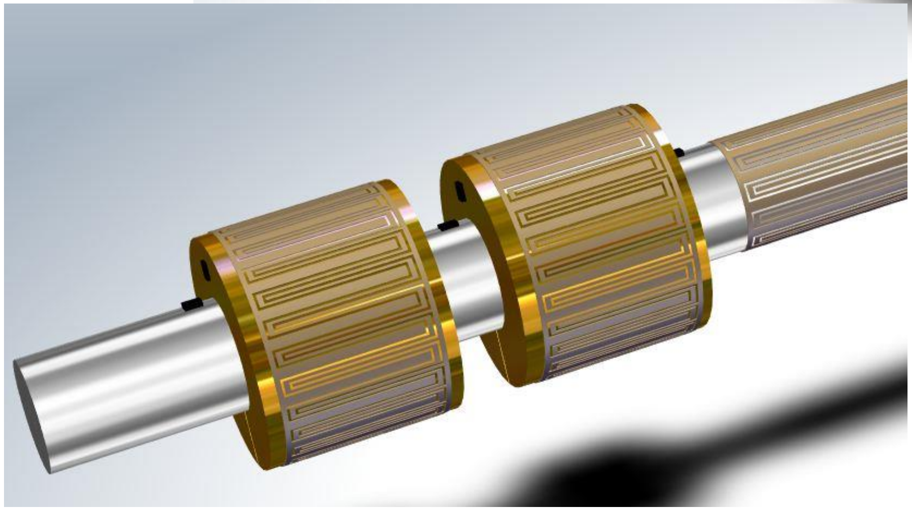
- **2 sleeves of OFHC Cu** (for a high thermal conductivity) were **soldered** on SS jacket (SnAg brazing) for the **best thermal coupling jacket/sleeve**

- **3 ribbon heaters** were installed, **2 on both sleeves** outer face and **one upstream** of sleeves for accessing a wider range of temperature

- **7 Cernox T^re^ sensors** were installed on sleeves zone, **3 on jacket around sleeves** for measuring fluid temperature and **4 on sleeves lateral sides** for measuring Cu temperature (2 sensors per sleeve for checking T^re^ uniformity)



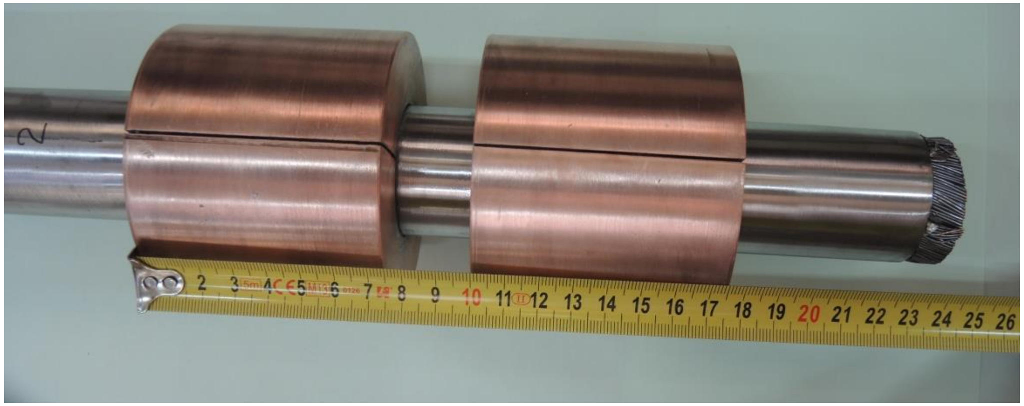


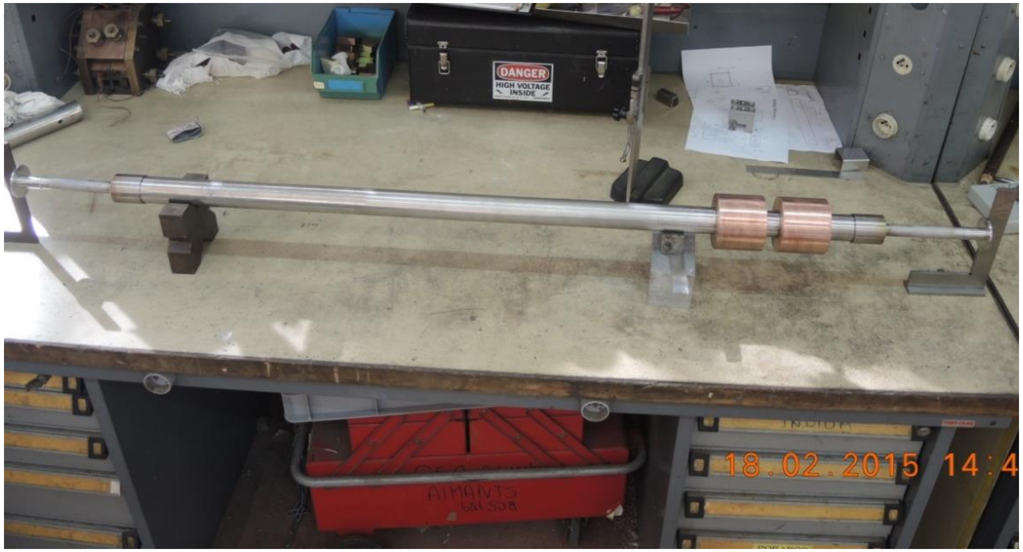


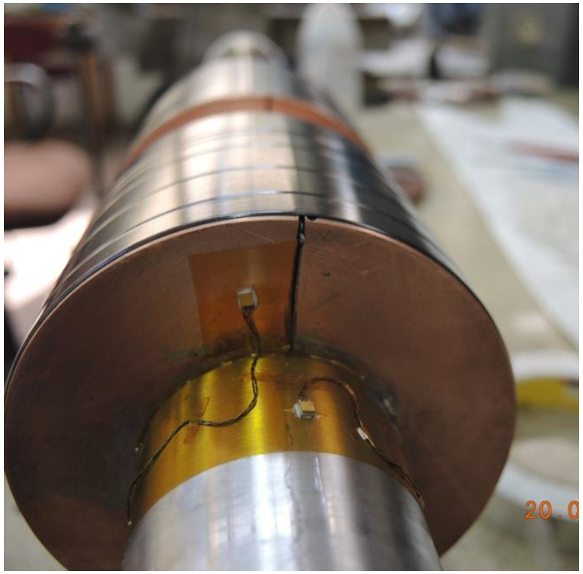
CAD view of sleeves, heaters and instrumented zone

3 – Manufacturing and integration in HELIOS facility

First manufacturing stage at IRFM Cadarache

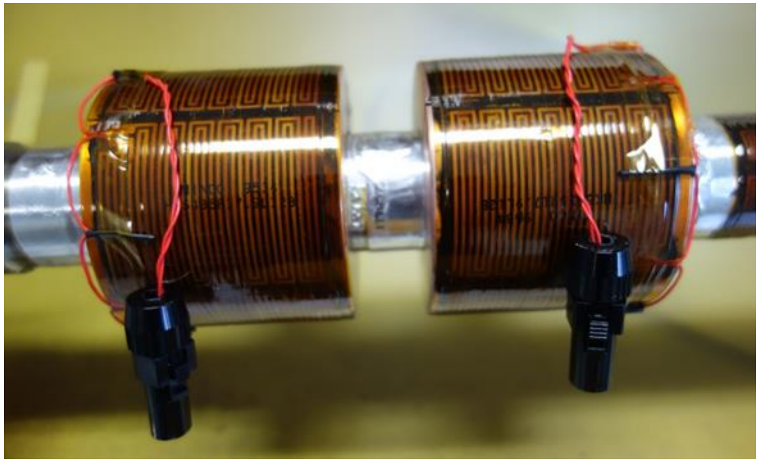


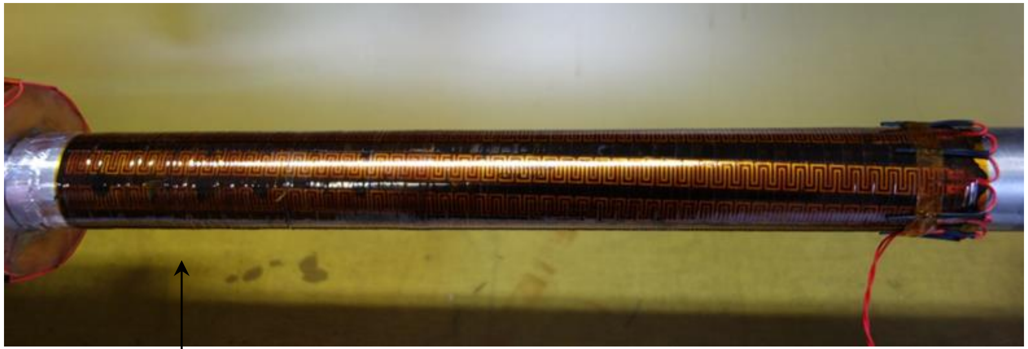




3 – Manufacturing and integration in HELIOS facility

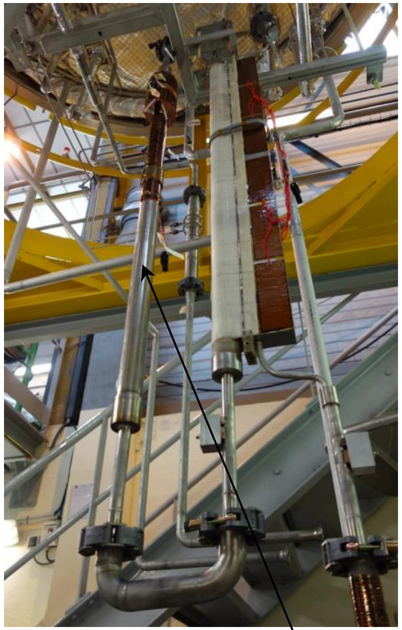
2nd manufacturing stage at INAC/SBT Grenoble





MINCO heaters glued with Stycast

INAC/SBT refrigerator – 400 W at 4 K



Installing in HELIOS facility

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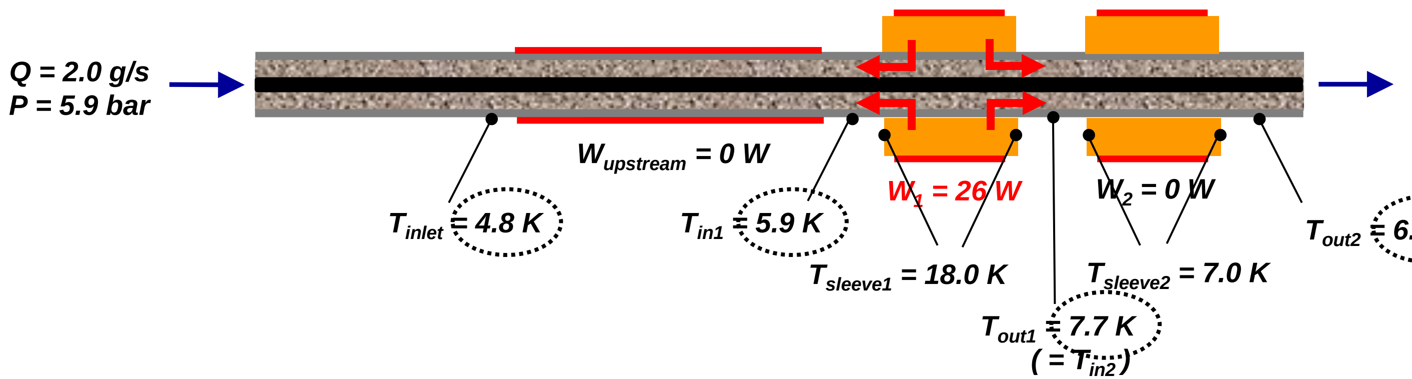
4 – Experimental results analysis

- Steady state power runs allowed exploring the following ranges:
  - **T_{fluid}** from **6.0** to **38.4 K**
  - **Pressure** from **4.9** to **8.8 bar**
  - **$Q_{He\ bundle}$** from **1.0** to **6.1 g/s**
  - **Re_{bundle}** from **180** to **2350**

- **Unexpected thermohydraulic behaviour** was systematically observed. One case is reported hereafter:

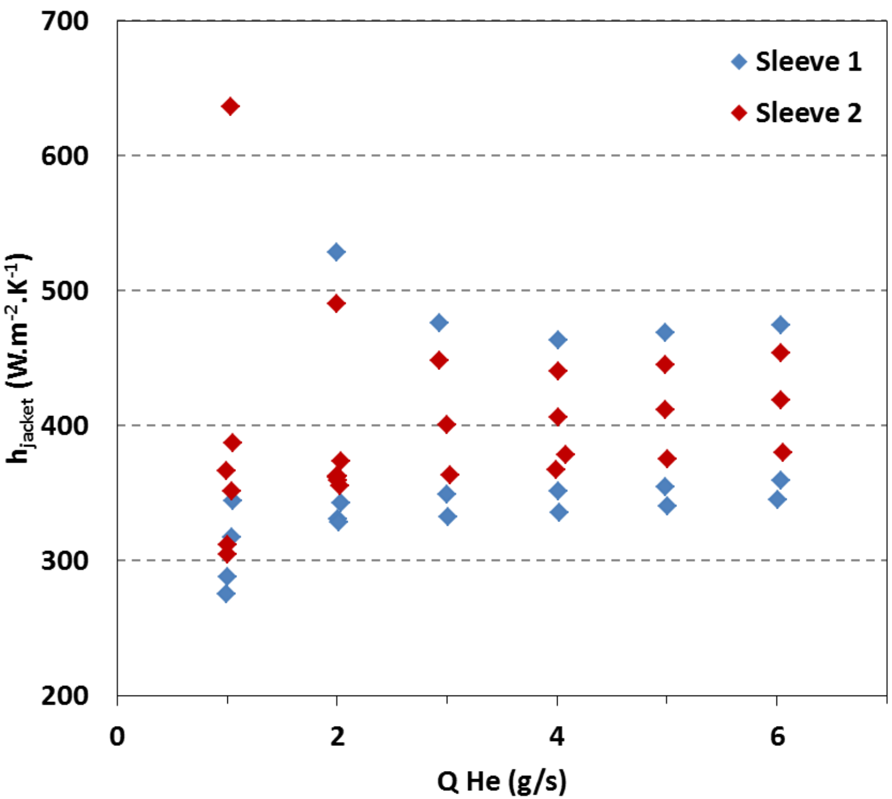


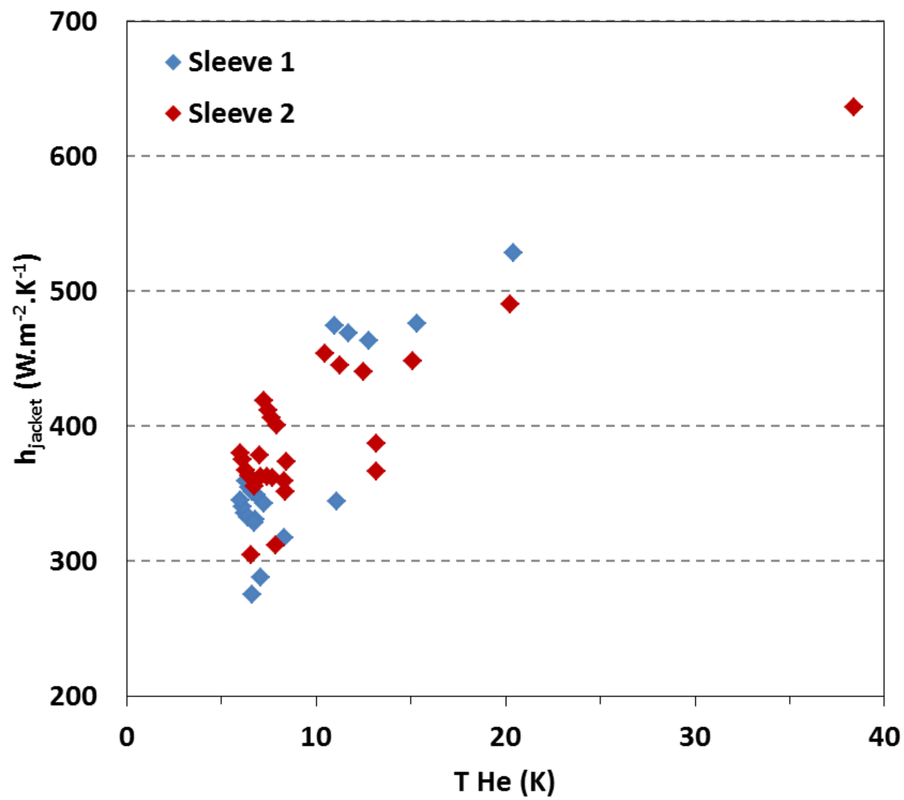
✓ **T_{in1} > T_{inlet}** : **upstream T^{re} is affected by heat applied downstream → heat is « backflowing »**, certainly due to **conduction in strands** (cooling fin effect), this phenomenon being emphasized by the fact that all strands are in Cu (sample was made from dummy Cu conductor)

✓ **T_{out1} > T_{out2}** : downstream the heated zone, T[re] should remain constant (no heat load, no significant P decrease). As **cooling without cold source is impossible**, one explanation can be a mixing between a **cold** (not heated) **central flow** and a **warm flow in the vicinity of inner jacket**

➡ As heat exchange process takes place close to the wall, all runs were analyzed considering **$T_{fluid\ i}$ = ($T_{in\ i}$ + $T_{out\ i}$) / 2** , with i = 1 or 2 for sleeve 1 or 2

Analysis of steady state runs



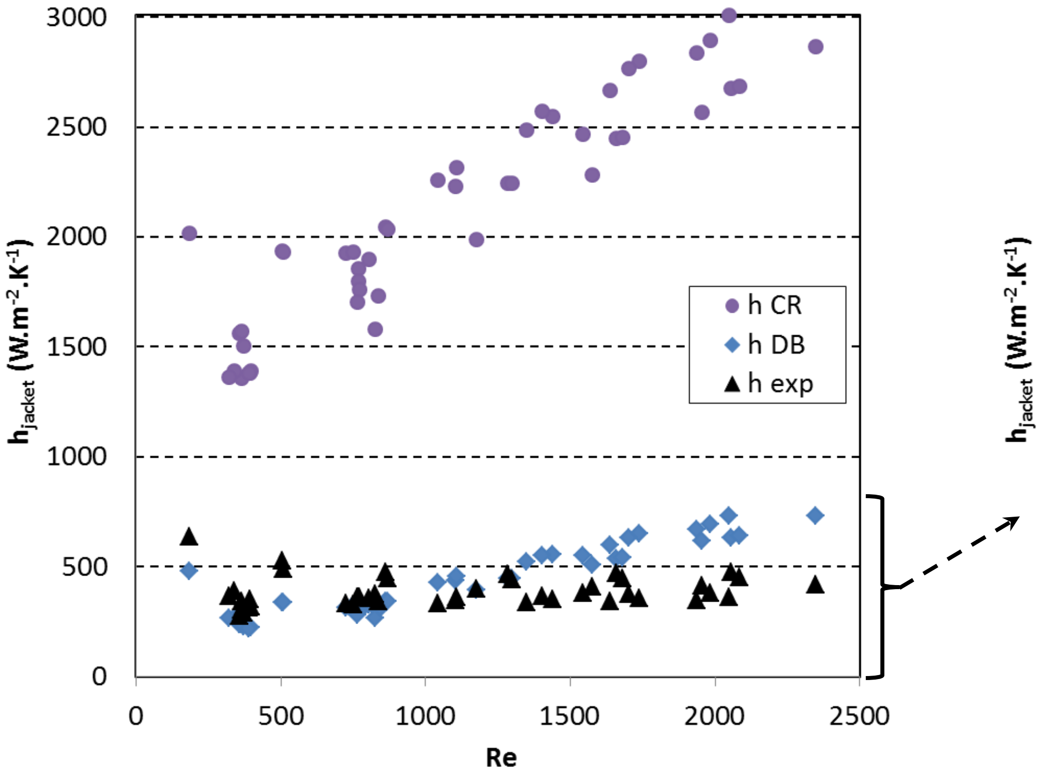


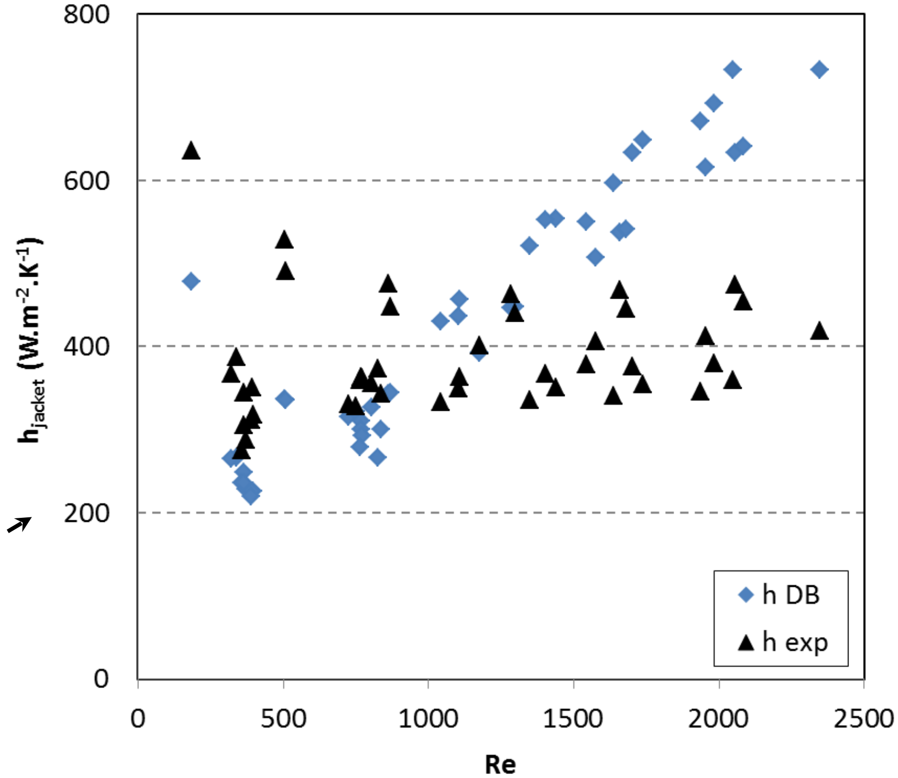
➢ **Good agreement** between experimental h_{jacket} values assessed with **both sleeves**

4 – Experimental results analysis

Analysis of steady state runs

Comparison with Dittus-Boelter and Colburn-Reynolds correlations





- h_{jacket} order of magnitude is **closer to Dittus-Boelter** than to Colburn-Reynolds
- But a **discrepancy** exists between experimental and computed Dittus-Boelter values

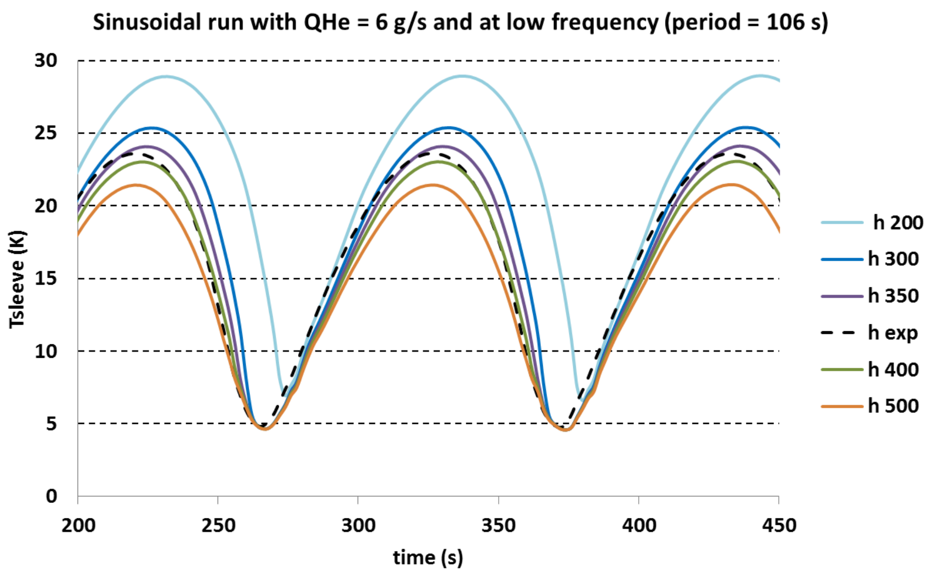
4 – Experimental results analysis

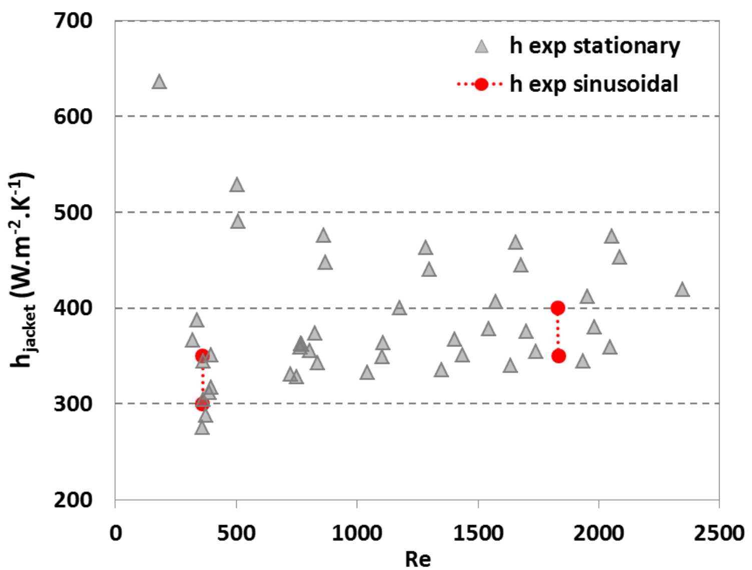
Analysis of sinusoidal runs

- **4 sinusoidal** power deposition **runs** were performed, varying **QHe** (**1 g/s and 6 g/s**) and at **2 frequencies** (**period = 38 s and 106 s**)
- Experimental response of **sleeve T^re^** had the **expected asymmetric shape**, but h_{jacket} assessment was less obvious than for stationary power runs

QHe	Frequency	Tfluid (average)	Re (average)	h_{jacket} ($W.m^{-2}.K^{-1}$)
1 g/s	Low	8.86 K	360	300 – 350
1 g/s	High	8.05 K	360	Idem
6 g/s	Low	5.82 K	1833	350 – 400
6 g/s	High	5.82 K	1829	Idem

h_{jacket} assessed with sinusoidal heat deposition is in good agreement with stationary approach, bringing confidence in the analyses





4 – Experimental results analysis

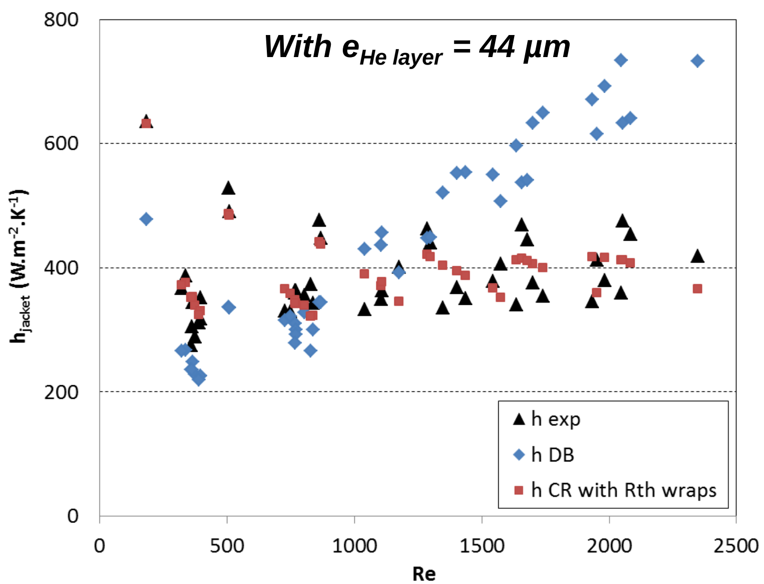
Attempt to fit experimental values

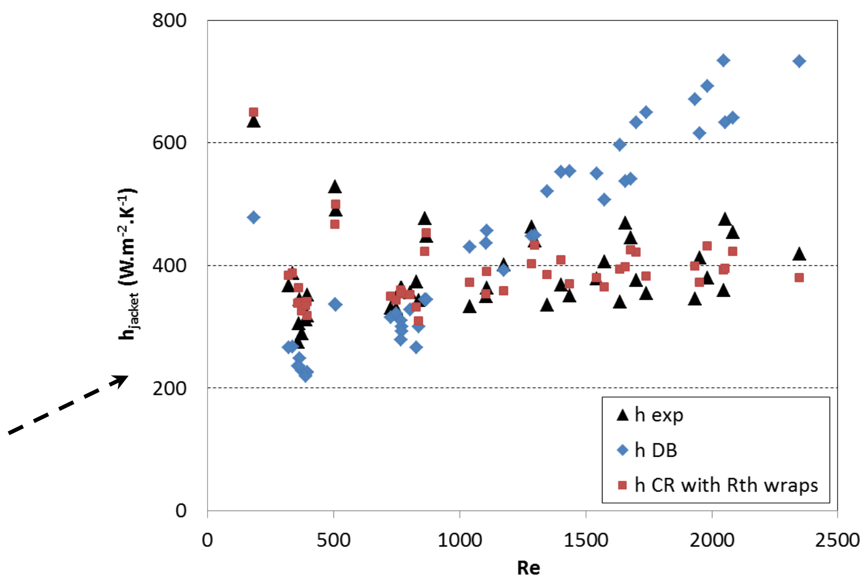
- Considering the He layer trapped between wraps and jacket, $h_{jacket} = \dfrac{1}{\dfrac{1}{h_{conv}} + R_{th\,wraps}}$ (1) $with\ R_{th\,wraps} = \dfrac{e_{He\,layer}}{\lambda_{He\,layer}}$

- Even if h_{jacket} order of magnitude is close to Dittus-Boelter, **h_{conv} cannot be approached by DB** correlation since **$h_{DB} < h_{exp}$ at low Re values**

- The model based on (1) was applied, considering **Colburn-Reynolds analogy for h_{conv}** and **tuning $e_{He\ layer}$ in each sleeve** in order to fit exprimental values of h_{jacket}

- The best consistence was found with **$e_{He\ layer}$ = 47 and 43 µm in sleeves 1 and 2** respectively
  - These orders of magnitude are consistent with the value of **26 µm** estimated for **JT-60SA TF conductor**
  - This analysis suggests that **Colburn-Reynolds analogy** is applicable for **convective HTC** between He and wraps or thus between He and strands too (h_{bundle})





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5 – Conclusion

- Due to **complex geometry, Heat Transfer Coefficient in a CICC** is a **not well documented parameter**

- An **experiment** was designed and carried out **in HELIOS** facility (CEA Grenoble – spring 2015) **for estimating He/jacket thermal coupling** in a sample of **ITER TF conductor**

- Experimental results suggest that **Colburn-Reynolds** analogy could be applied for both **He/strands and He/wraps** Heat Transfer Coefficients

- Regarding the **overall He/jacket HTC**, the thermal resistance induced by **cable wraps can limit** strongly **the thermal coupling** between the He and the conduit.
  If this thermal resistance cannot be assessed, Dittus-Boelter correlation should give a good order of magnitude for He/jacket HTC.

- An **additional experiment** based on **HTC measurement method in porous media** could help **confirming these results**. But such an experiment seems incompatible with cryogenic operating conditions (to be confirmed) and could require similitude conditions.

Courtesy of ITER Organization

Thank you

for your attention