Fully 3D model of TF coil structures in the 4C code

R. Bonifetto, L. Savoldi, R. Zanino

NEMO Group, Dipartimento Energia, Politecnico di Torino, Torino, Italy

Szczecin, July 9-12, 2019

Outline

- Introduction and background: the 4C code
- Motivation and aim of the work
- Test cases definition
- Results and discussion
- Conclusions and perspective

Background: the 4C code

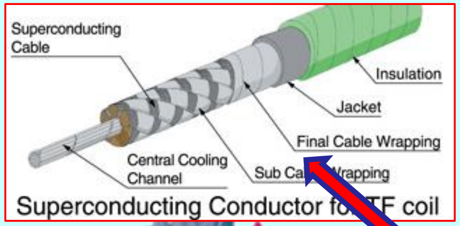
L. Savoldi et al., *Cryogenics*, 50, 2010, pp. 167-176

Circuit module [Modelica]
0D pumps, thermal buffers, manifolds, valves, 1D pipes

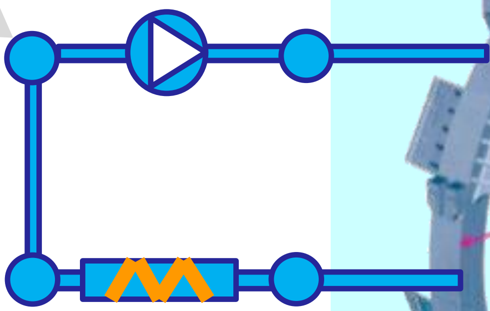
T, p

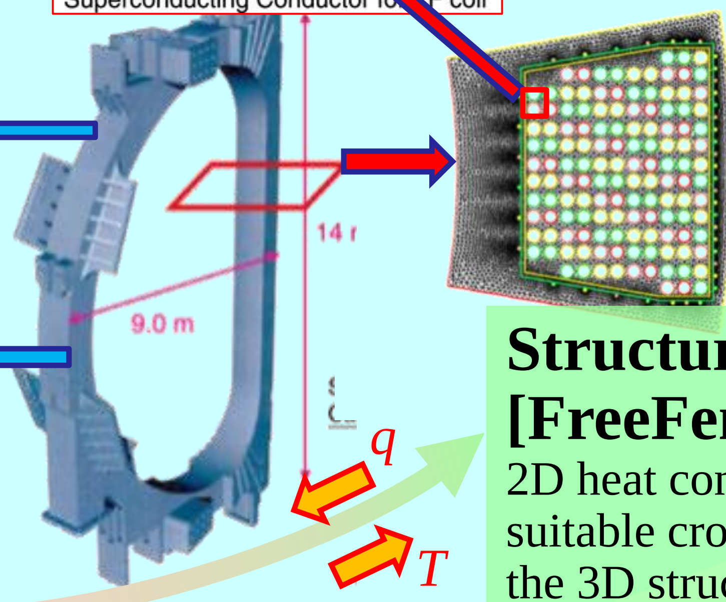
T, dm/dt

Winding module [FORTRAN]
1D conductors (two-fluid + solids), thermally coupled in transverse 2D



Synchronization and coupling
via TISC environment





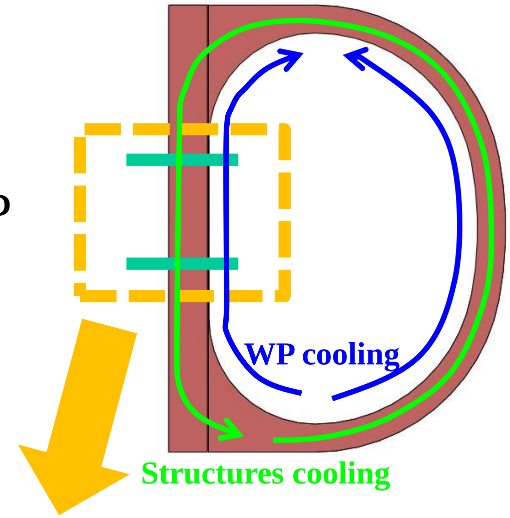
T *q*

Structure module [FreeFem++]
2D heat conduction in suitable cross-section of the 3D structures

Structure cooling module [FORTRAN]

Focus: the 2D(+1D) structures model

- **ASSUMPTIONS:**
  - All the He flow paths are in the poloidal direction
  - Forced flow cooling
  - Major polidally non-uniform driver located in the WP

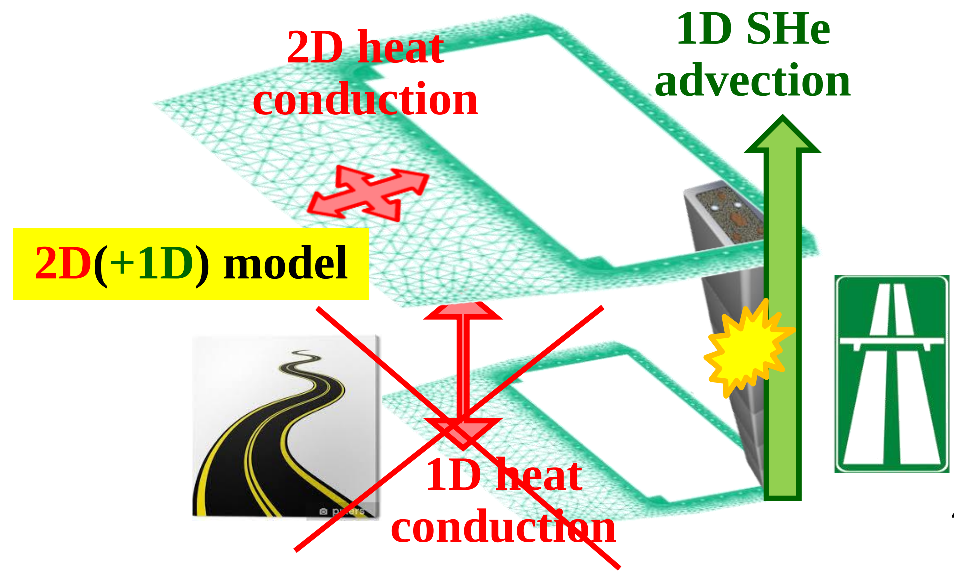


- <u>Peclet number</u> (in the ***poloidal*** direction):

$$\frac{conduction\ time}{advection\ time} \sim 100\text{-}1000 \rightarrow \text{neglect poloidal heat conduction}$$

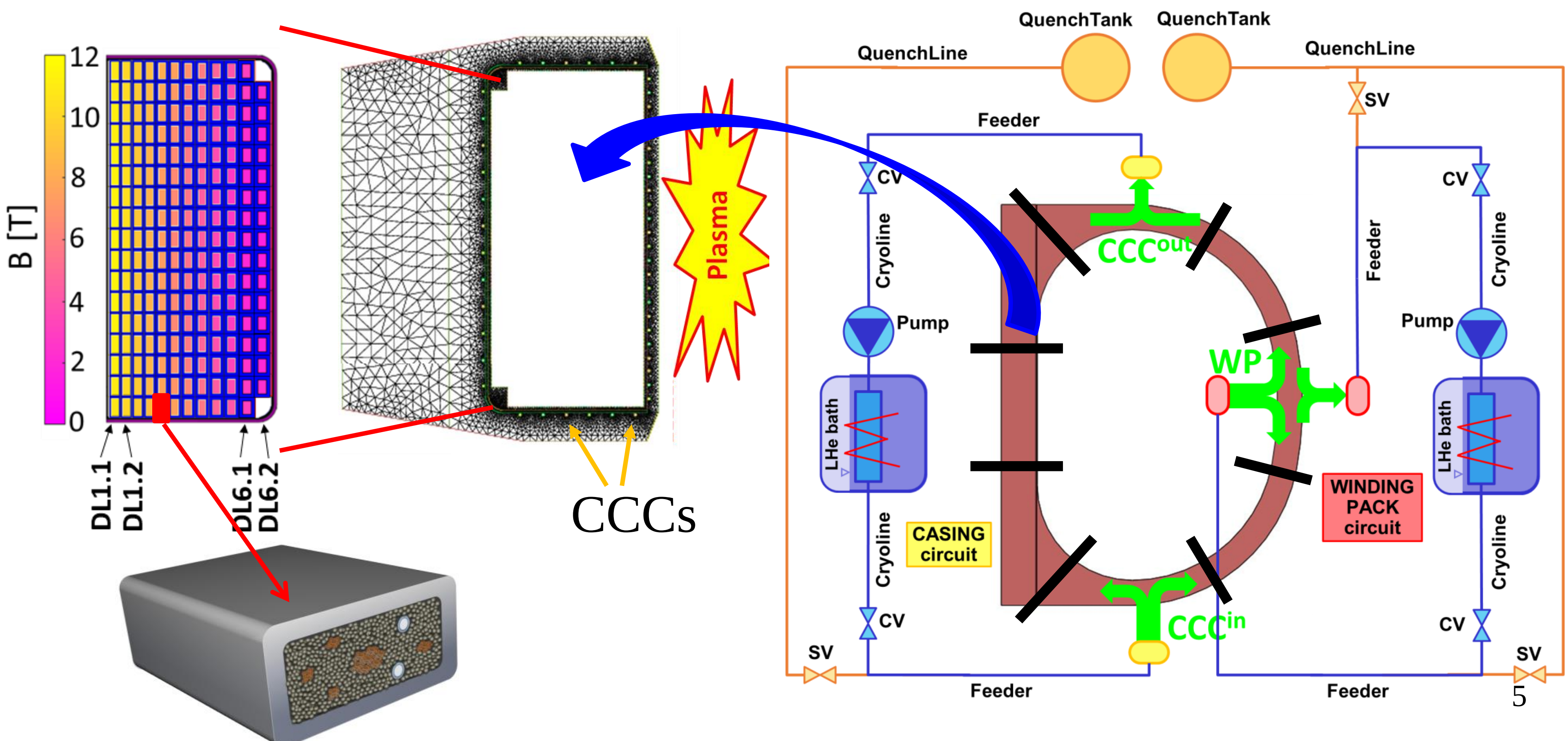
➔ most of the heat is advected by SHe between poloidal cuts (<u>1D poloidal heat transfer</u>)

➔ the most important T gradient in structures is *across* SHe flow direction (<u>2D radial-toroidal conduction</u>)



The 4C model of the EU DEMO TF coils

- **WP** with inter-turn and inter-layer thermal coupling
- **Steel casing** (thermally coupled with WP)
- **Casing cooling channels** (CCCs)
- **External cryogenic circuits**



4C Verification&Validation including structures

[RZ.and L. Savoldi., Multi-scale approach and role of validation in the thermal-hydraulic modelling of the ITER superconducting magnets, IEEE TAS 2013]

ITER CSI CD

ITER TFMC FD

W7-X NPC CD

Development

Interpretive validation

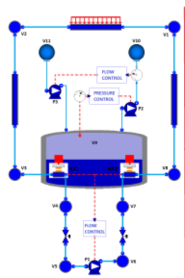
INCLUDES PARAMETER ESTIMATION AND CALIBRATION

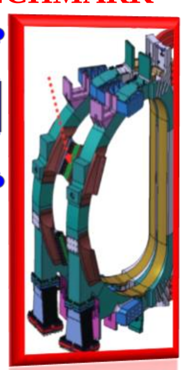
Solution verification

Predictive validation

BLIND TESTS: EXPERIMENTAL EVALUATION OF PREDICTIVE ACCURACY

BENCHMARK





ITER TF CD

ORDER OF ACCURACY CHECK

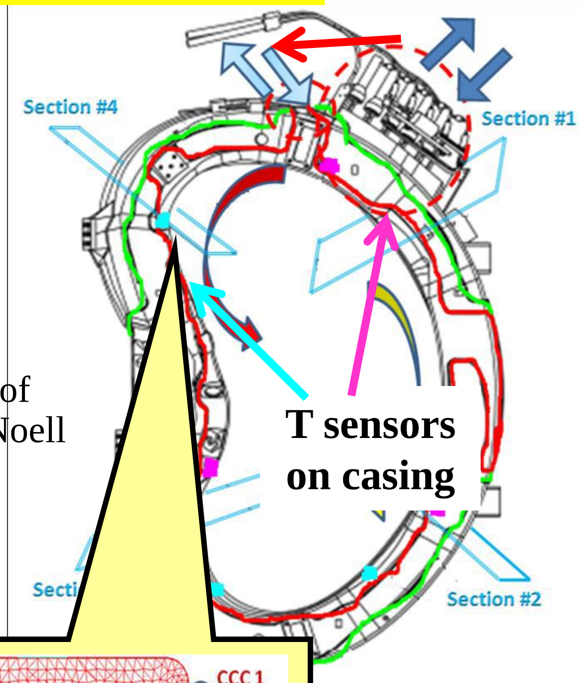
Terminology from [W.L.Oberkampf and C.L.Roy, V&V in scientific computing, Cambridge UP 2012]

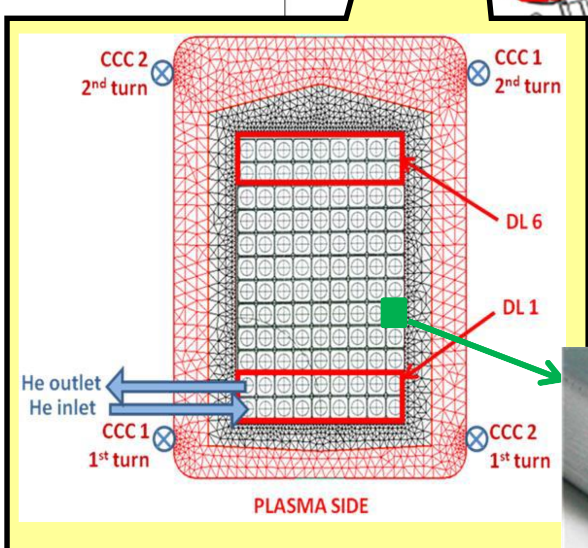
Slow/fast transients

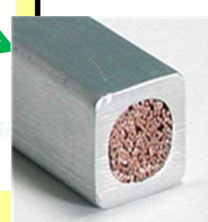
VALIDATION

Cooldown of a W7-X non planar coil

(Courtesy of Babcock Noell GmbH)



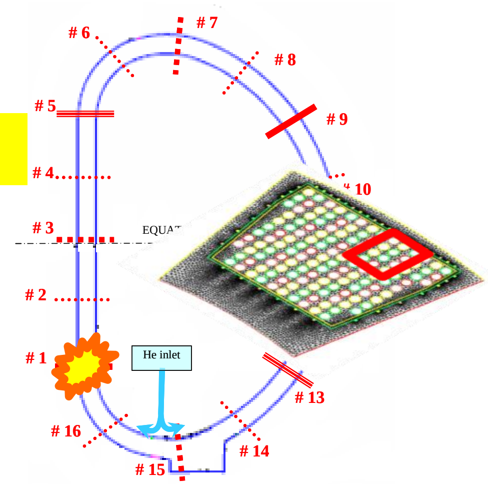


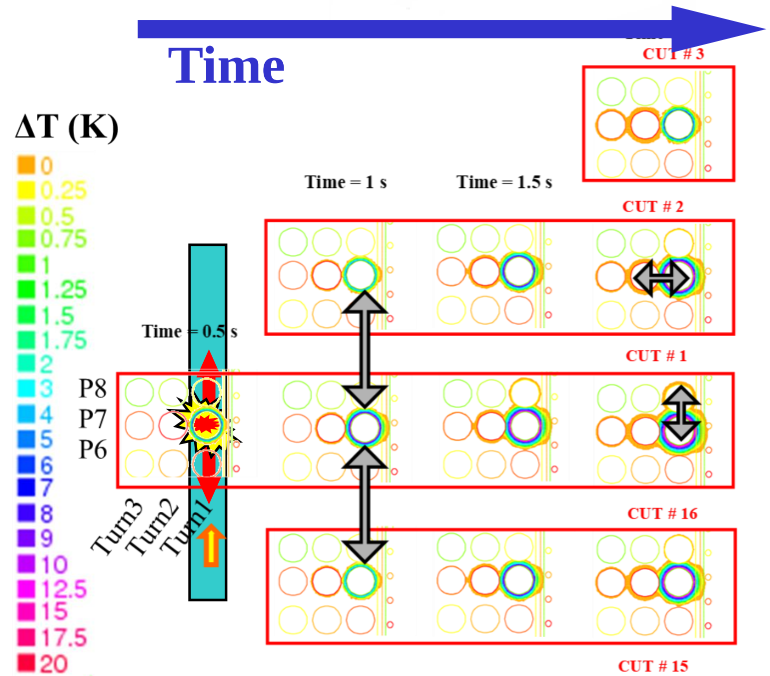


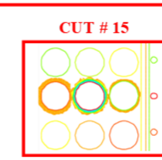
DRIVER: cooling of the (passive) structures by WP/CCCs

APPLICATION

Quench in an ITER TF coil







DRIVER: resistive heating in the CICC normal zone

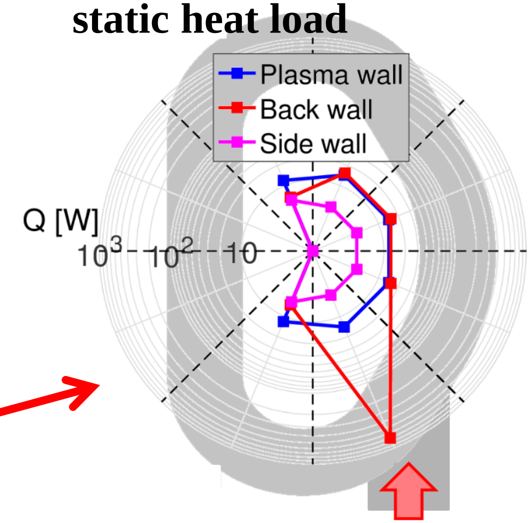
Motivation

- The 4C code is now used in the <u>*design*</u> phase of forthcoming tokamaks (EU DEMO, DTT, …)

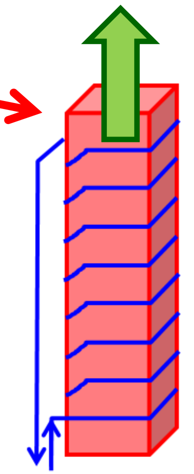
→ **new needs**:

– Investigate transients driven by a strongly *non-uniform* power deposition <u>*in the casing*</u> (e.g. localized conductive heat load)

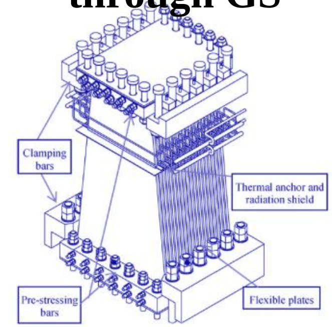
EU DEMO static heat load



– Analyze <u>*new designs*</u> with non-(only-)poloidal cooling paths

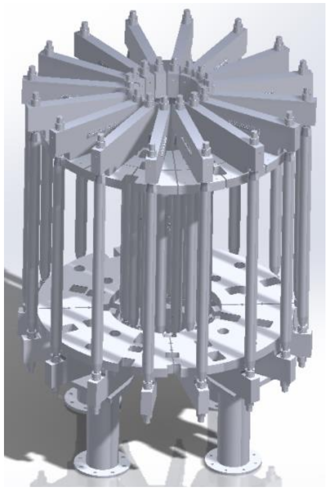


Conduction through GS



– Simulate operation/accident at <u>*reduced/no He flow*</u> (LOFA, baking, …)

– Investigate <u>*complex 3D features*</u> of the structures

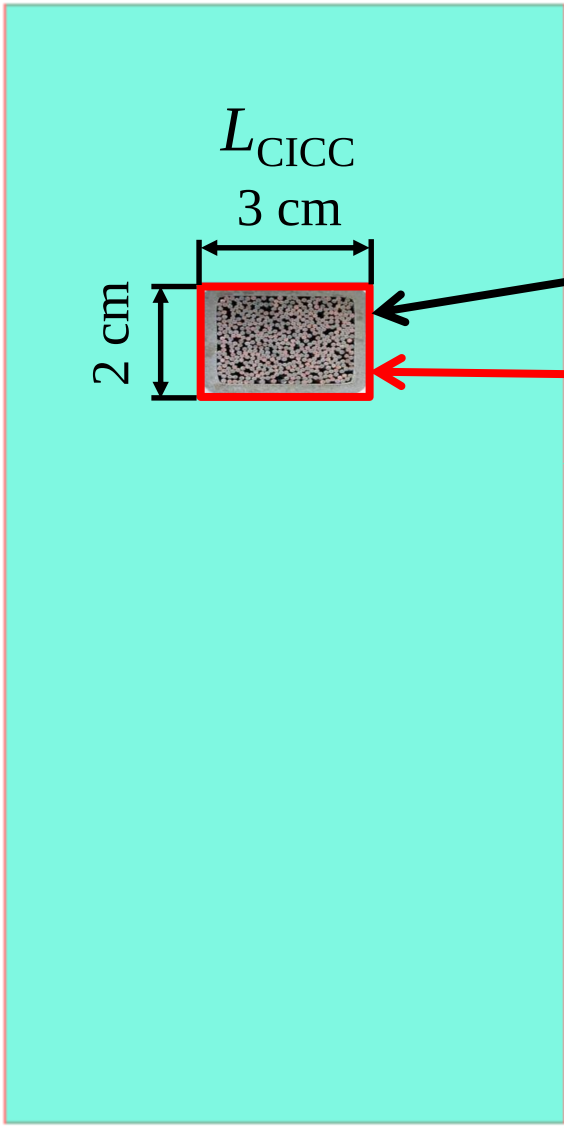


ITER CSMC structures

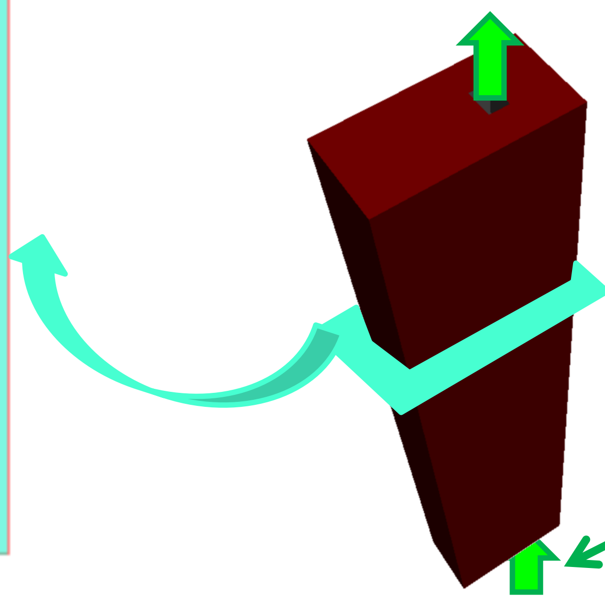
Aim of the work

- Develop and test a first (simplified) 3D model of the coil structures
  - Demonstrate the full 3D model feasibility with the same tool (FreeFEM++) already used to model the 2D heat conduction in the structures cuts
    - → straightforward integration in the 4C architecture
  - Assess the difference/improvement in the simulation results

Test geometry



- AIM: suitable simplification of a TF coil
  - WP made of a single, 1-region CICC
  - (1-mm) ground insulation = turn insulation
  - Bulky SS structures

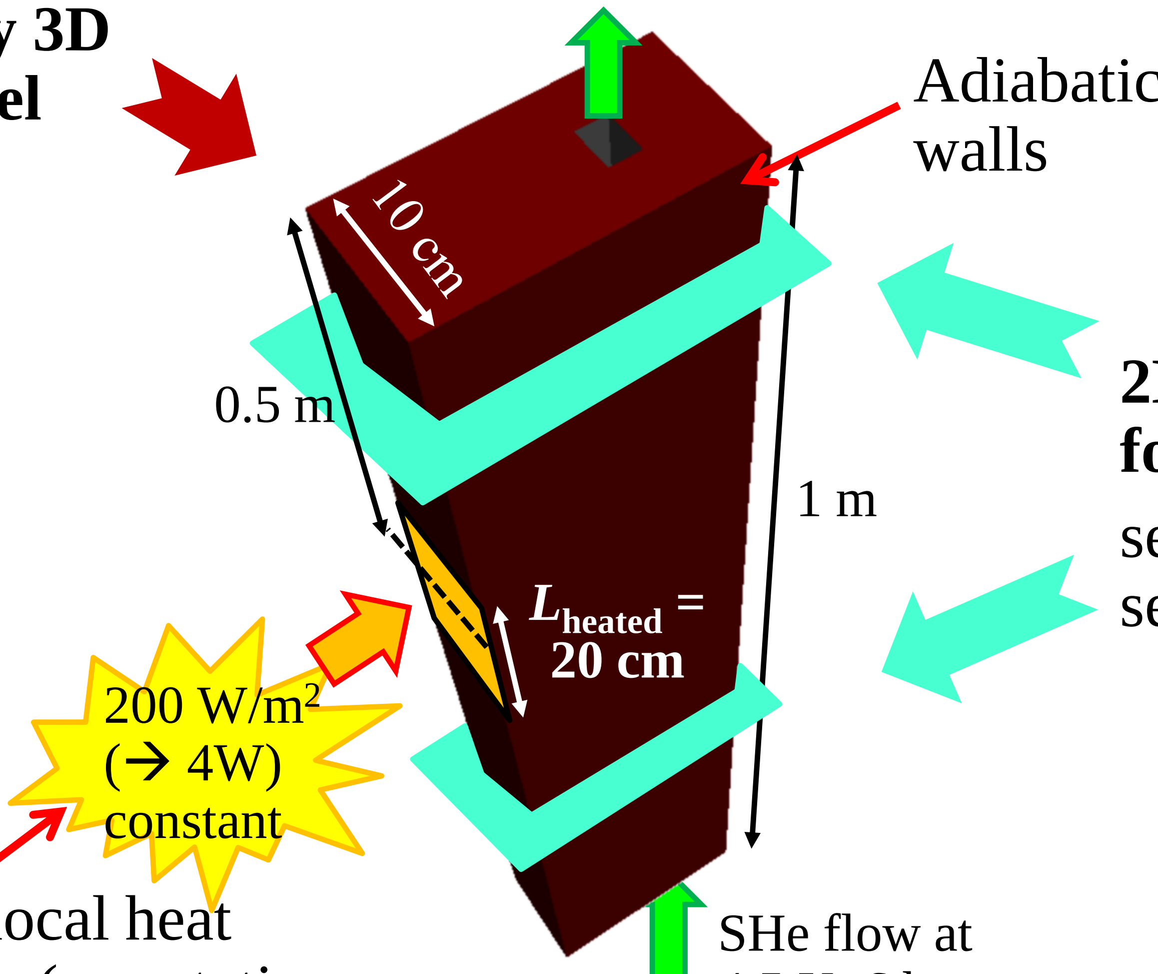


Cooling provided only by 4.5 K, 6 bar SHe flow in the CICC

POLITECNICO DI TORINO
Dipartimento Energia "Galileo Ferraris"

Simulation setup

Fully 3D model



2D(+1D) model for comparison:
set of 2D cross sections

Mimic a local heat deposition (e.g. static heat conduction from the gravity support)

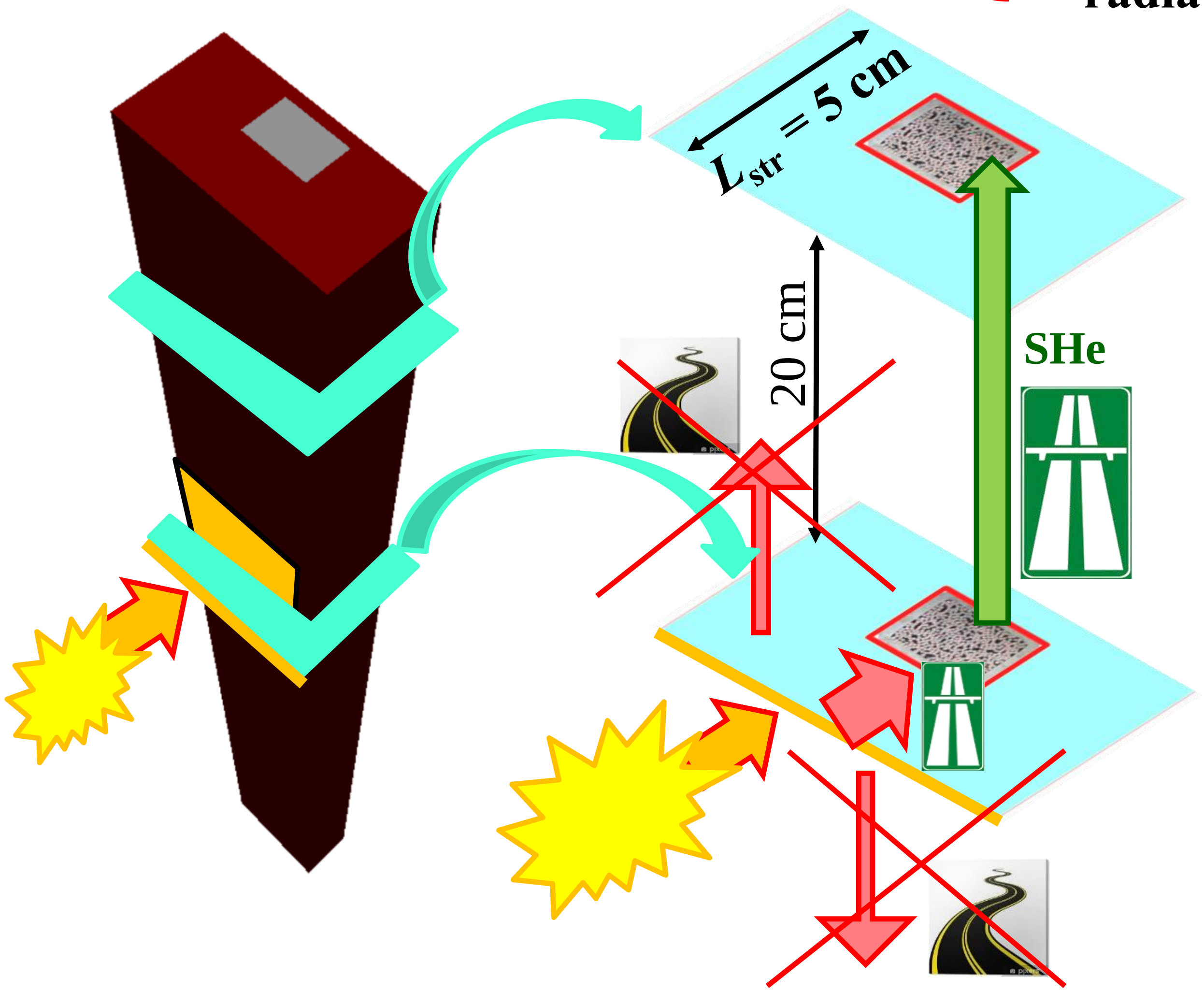
SHe flow at 4.5 K, 6 bar nominal
dm/dt ~2 g/s

<u>Simulation is run up to steady state temperature distribution</u>

Test case 1: "thin" structures

$L_{heated} >> L_{str}$ ($\sim L_{CICC}$)

Poloidally distributed heating (nuclear, eddy, radiative, …)



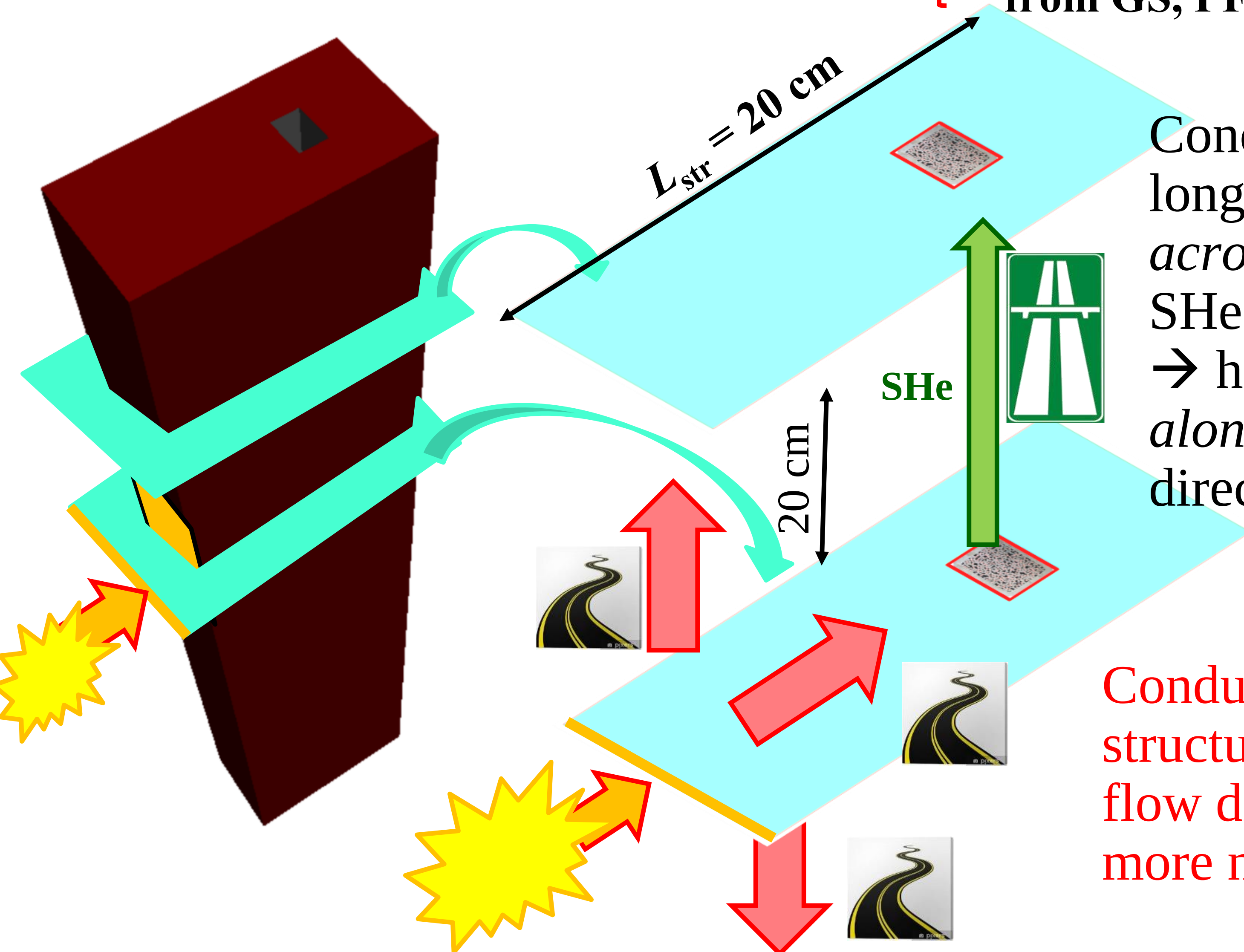
Conduction time among cuts (*along* SHe flow direction) is long (~1000 s)

Conduction in the structures *across* SHe flow direction is predominant! (conduction time ~10 s)

Test case 2: "thick" structures

$L_{str} \sim L_{heated}$ ($\gg L_{CICC}$)

Poloidally localized heating from GS, PF coil supports, …

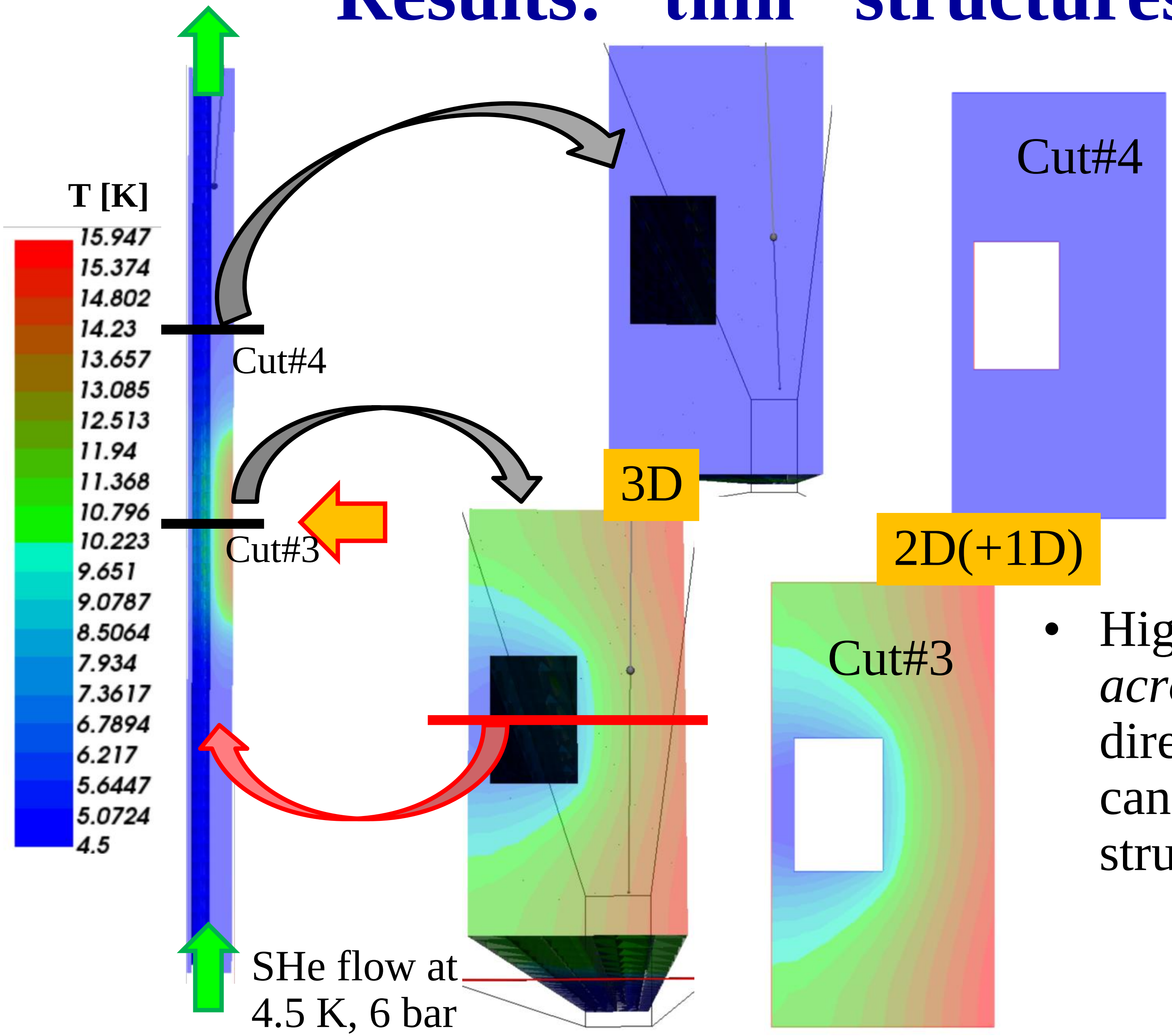


Conduction time still long (~1000 s) both *across* and *along* SHe flow direction
→ heat will flow also *along* SHe flow direction

Conduction in the structures *along* SHe flow direction no more negligible!

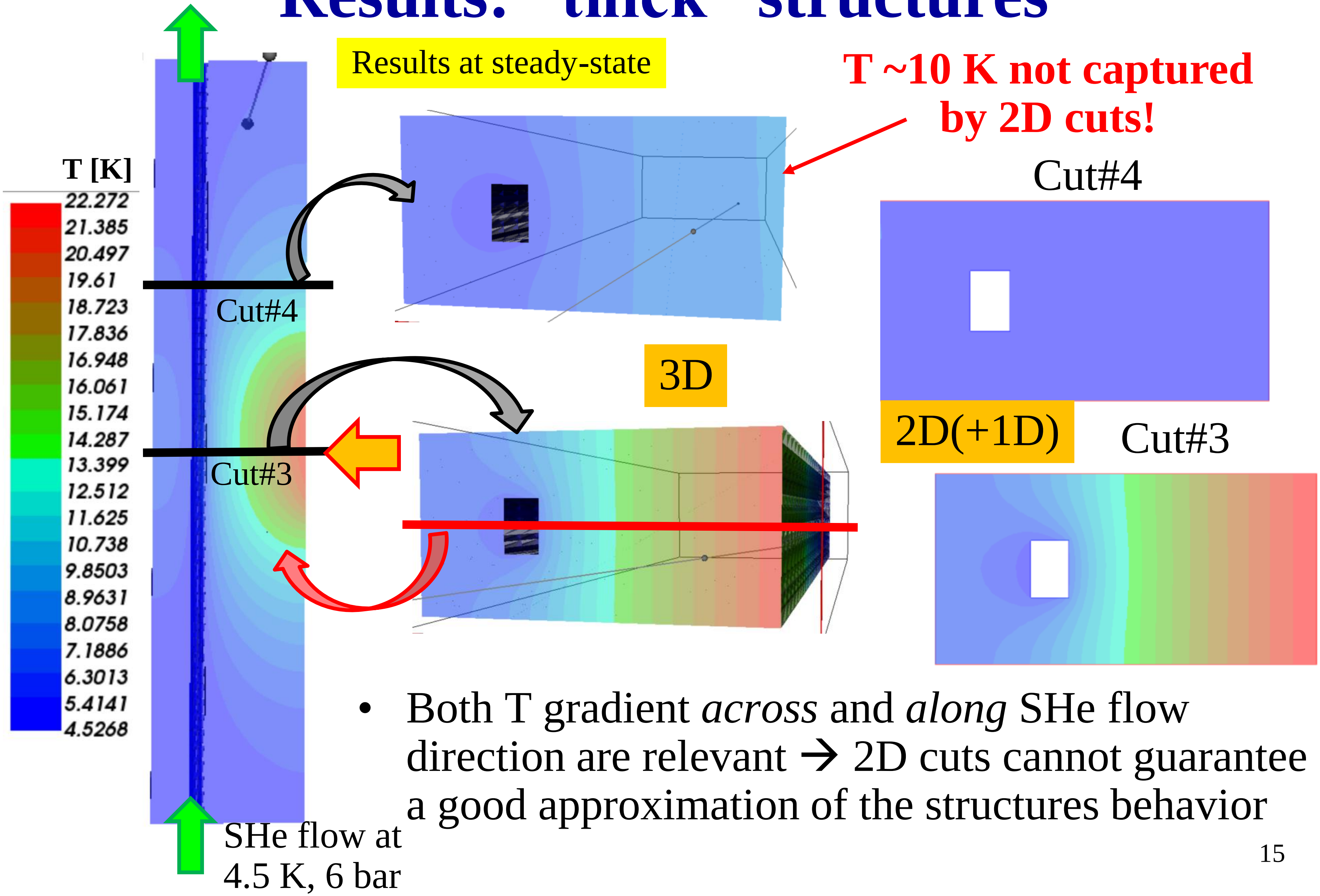
Results: "thin" structures

Results at steady-state



- Highest T gradient *across* SHe flow direction → 2D cuts can approximate the structures behavior

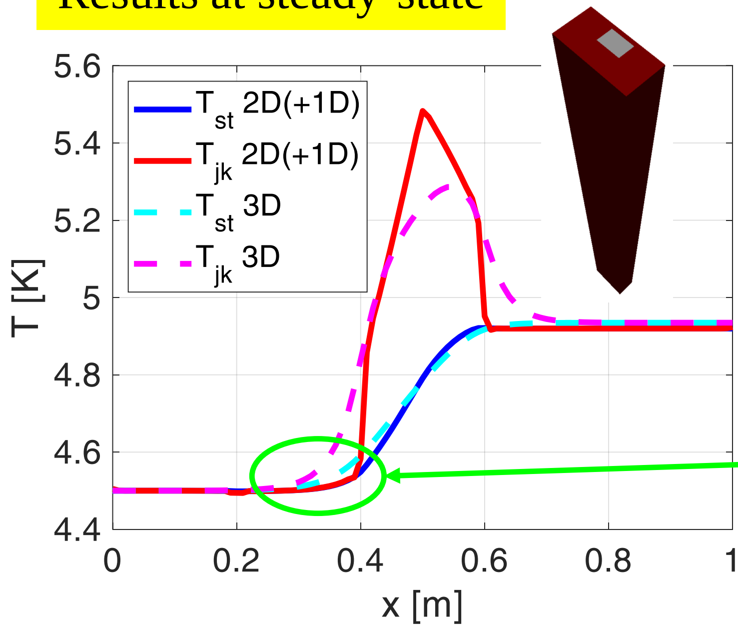
Results: "thick" structures



- Both T gradient *across* and *along* SHe flow direction are relevant → 2D cuts cannot guarantee a good approximation of the structures behavior

Results: CICC (I)

Results at steady-state

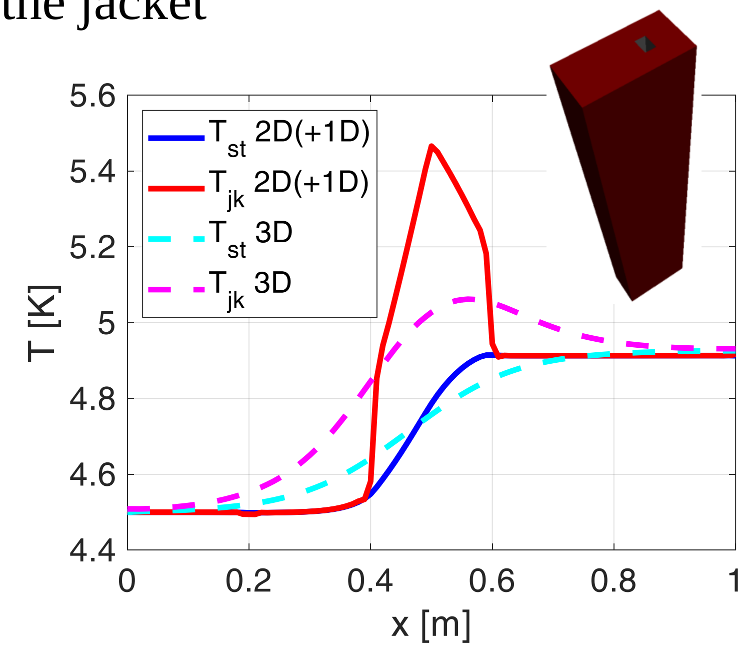


- The “thinner” the structures, the more similar the CICC temperature profiles for both 2D+(1D) and 3D structure models

Effect of heat conduction in the jacket

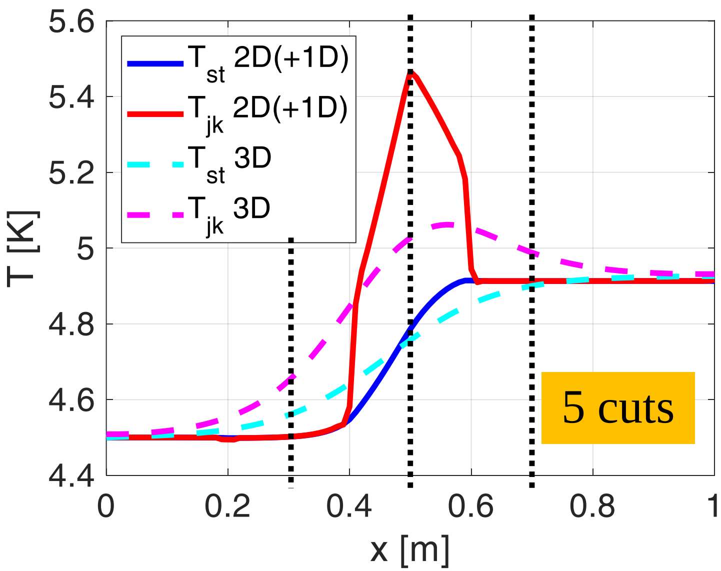
For **“thick” structures**:

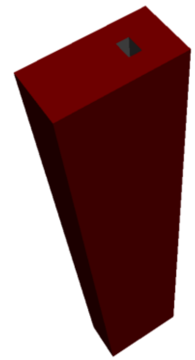
- The peak jacket T can be overestimated by ~0.4 K
- The cable temperature can be locally underestimated by ~0.1 K

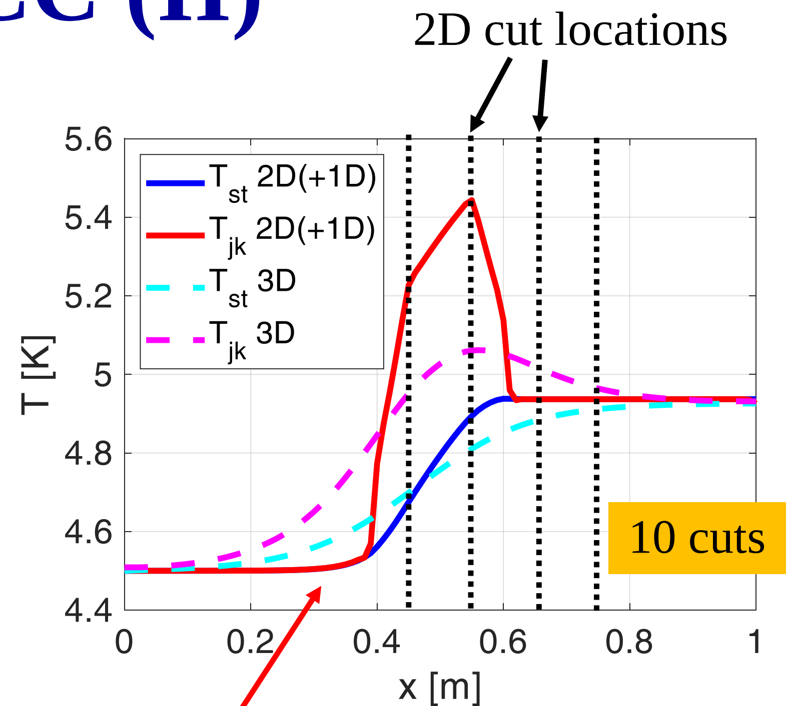


Results: CICC (II)

Results at steady-state





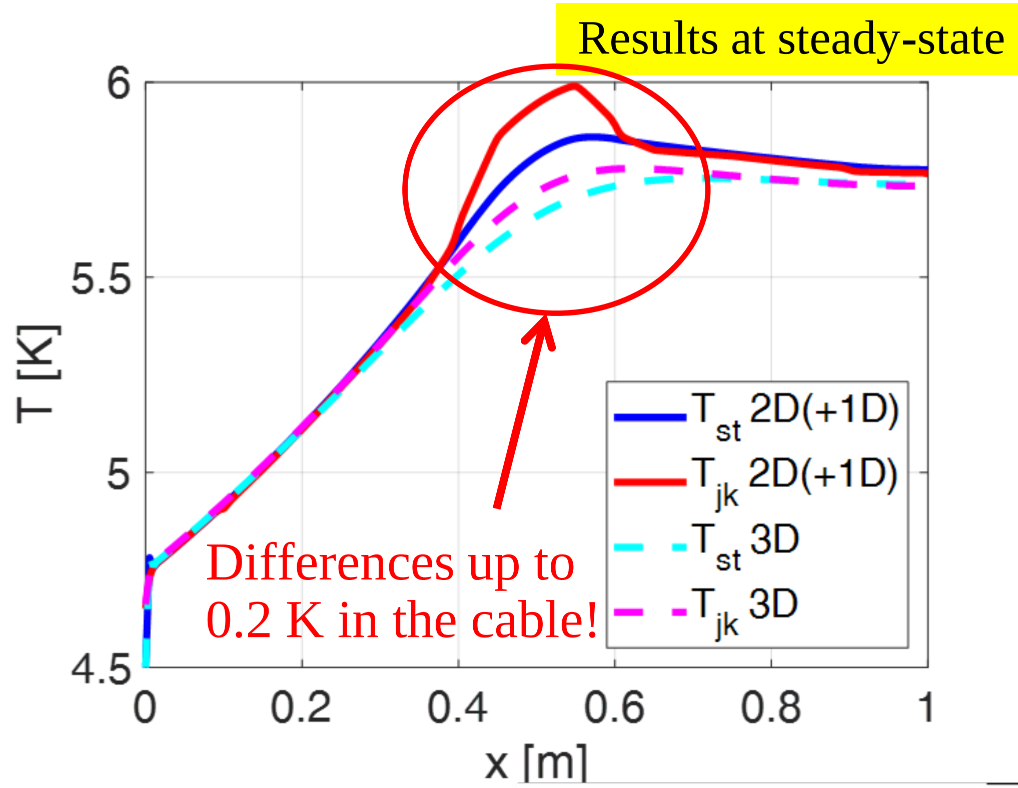


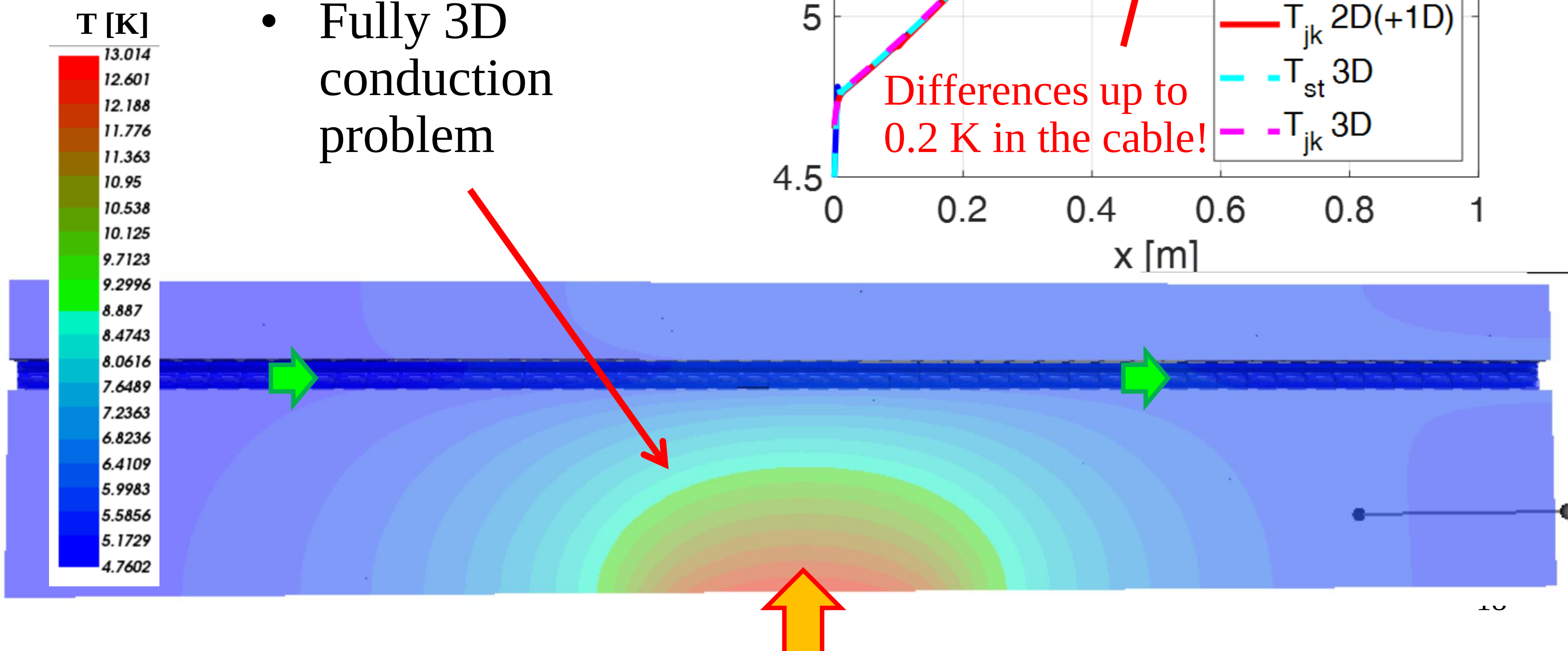
Only the jacket T is (locally) affected by the increase of the cut number

- No effect on the cable T distribution
- Conduction along the SHe flow direction neglected → the pre-heating effect of the conduction in the structures is not captured even for increasing cut numbers

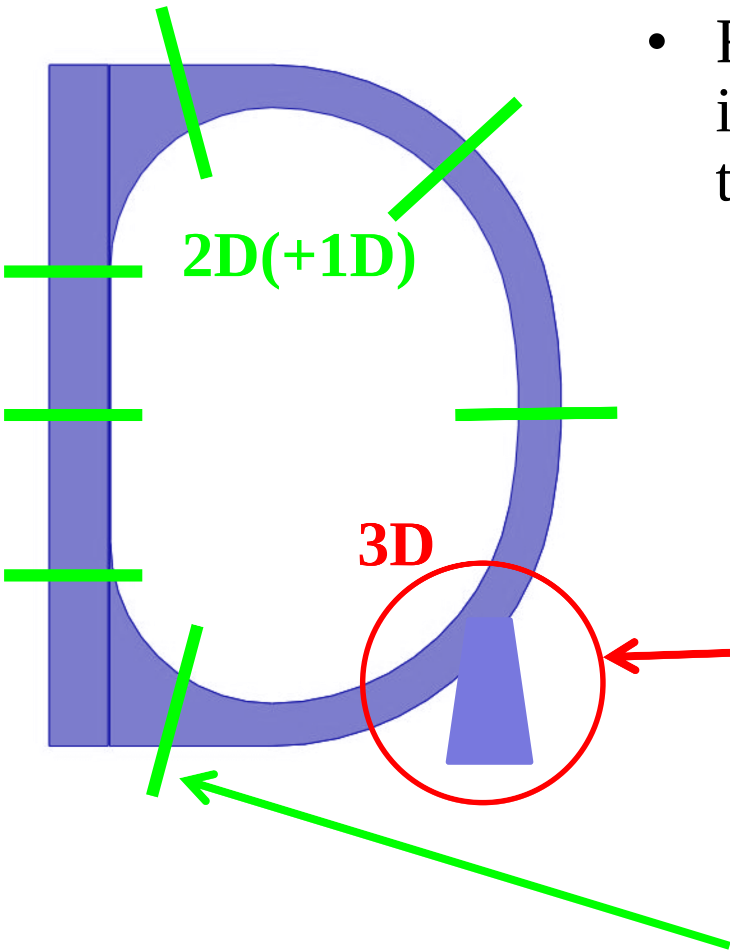
Reduced Peclet number case

- Mimic a partial LOFA (~no flow in WP): advection time increases → Peclet ~1-10
- "Thick" structures case
  - Fully 3D conduction problem





Drawback and workaround



- Full 3D model of the structures → increased computational cost (~10 times longer!)

  - full 3D model only in the coil sections where it is necessary (e.g. gravity support region, …)
  - set of 2D cuts in the other regions (2D+1D model)

Conclusions and perspective

- The new, design-oriented applications of the 4C code ask for a more detailed modeling of the TF structures
- The possibility to build the full 3D model of the structures within the 4C code has been demonstrated
- The full 3D model has been benchmarked against the validated 2D(+1D) model highlighting:
  - Limited (but not negligible) impact on the cable temperature
  - Relevant impact on the structures temperature

In perspective:

- The (full or partial) 3D model can be adopted to describe complex geometries / cooling solutions or to investigate transients involving reduced-cooling conditions
- The full 3D model can be extended to
  - Include other piece of physics (e.g. thermo-mechanics)
  - Develop electromagnetic models to compute eddy currents in the casing

Thank you for your attention!