Predictive analyses to support test programs for BEST: 4C code validation against data from the cooldown of the EAST TF magnets

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EU-CN collaboration meeting

October 28, 2026

Preliminary results presented at CHATS-AS workshop, Saariselkä, Finland (March 2026)

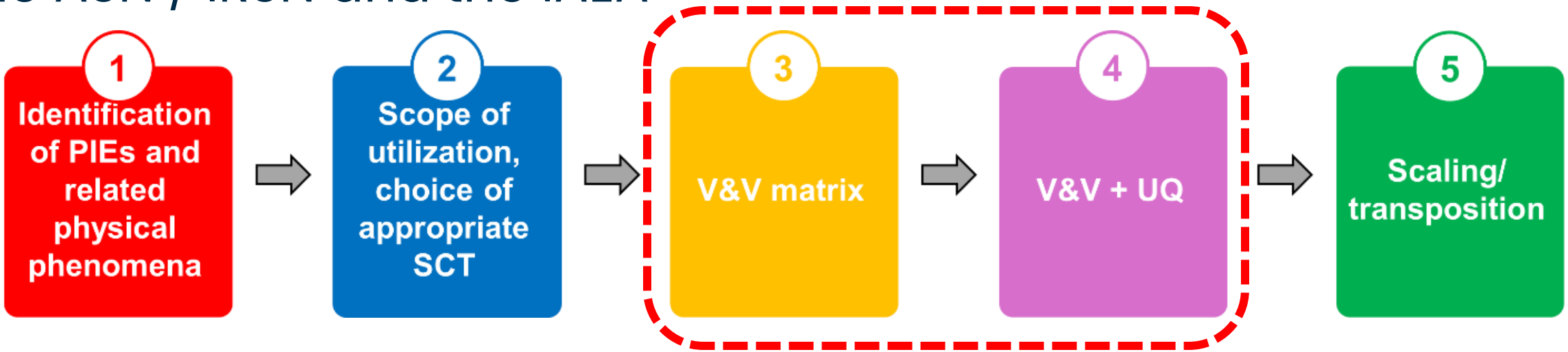
Outline

- Motivation: qualification of scientific computing tools
- EAST TF coil
- Experimental data: winding pack and casing
- 4C code model of an EAST TF coil
- Comparison of cooldown simulation results with measurements
- Conclusions

Motivation: qualification of scientific computing tools used in nuclear safety analyses

Guidelines described by both the ASN / IRSN and the IAEA

[Bonifetto, Zanino, Zappatore, "The 4C code as a candidate tool for the qualified analysis of superconducting magnets towards the licensing of nuclear fusion reactors," presented at IAEA FEC, 2025]



[HERER, ASN/IRSN guide 28: Qualification of scientific computing tools used in the nuclear safety case – 1st barrier, NED 2023]

[IAEA, Deterministic Safety Analysis for Nuclear Power Plants, SSG-2, 2017; https://www.iaea.org/publications/12335/deterministic-safety-analysis-for-nuclear-power-plants]

4C Verification&Validation roadmap


Cryogenics 50 (2010) 167–176

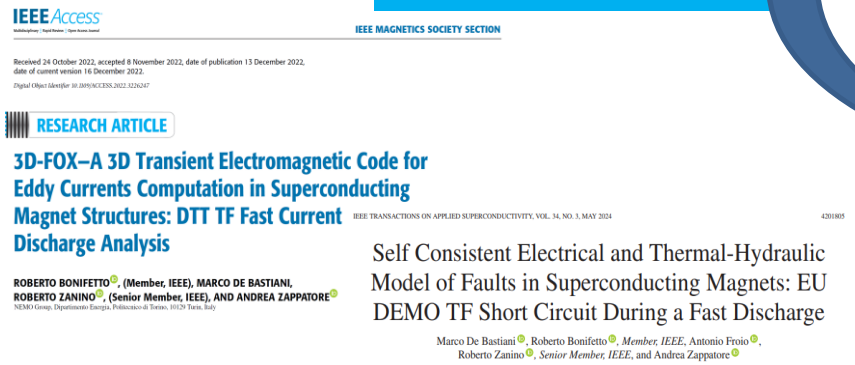
Contents lists available at ScienceDirect

Cryogenics

journal homepage: www.elsevier.com/locate/cryogenics

The 4C code for the cryogenic circuit conductor and coil modeling in ITER

L. Savoldi Richard [a], F. Casella [b], B. Fiori [a], R. Zanino [a,*]


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RESEARCH ARTICLE

3D-FOX–A 3D Transient Electromagnetic Code for Eddy Currents Computation in Superconducting Magnet Structures: DTT TF Fast Current Discharge Analysis

ROBERTO BONIFETTO, (Member, IEEE), MARCO DE BASTIANI, ROBERTO ZANINO, (Senior Member, IEEE), AND ANDREA ZAPPATORE

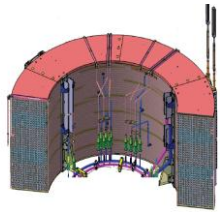
IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 34, NO. 3, MAY 2024 4201805

Self Consistent Electrical and Thermal-Hydraulic Model of Faults in Superconducting Magnets: EU DEMO TF Short Circuit During a Fast Discharge

Marco De Bastiani, Roberto Bonifetto, *Member, IEEE*, Antonio Froio, Roberto Zanino, *Senior Member, IEEE*, and Andrea Zappatore











Development

Interpretive validation

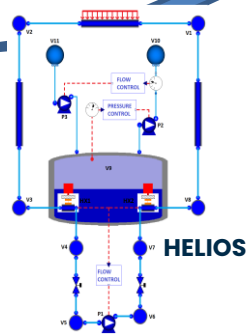
Predictive validation

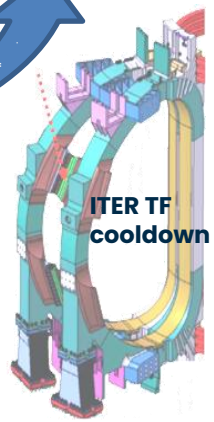
INCLUDES PARAMETER ESTIMATION AND CALIBRATION

Solution verification

BENCHMARK

ORDER OF ACCURACY CHECK







EXPERIMENTAL EVALUATION OF PREDICTIVE ACCURACY

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

Terminology from [Oberkampf and Roy, V&V in scientific computing, Cambridge up 2012]

Validation matrix

Based on data collected in different facilities and in different conditions, including:

— **Basic tests**: simple experiments which might not be directly related to PIE (e.g.: hydraulic characterization)

— **Separate effect tests**: the driver, the instrumentation and the diagnostics allow to turn on or off or to isolate the different physical phenomena (e.g.: full scale component tests)

— **Integral effect tests**: the different physical phenomena are simultaneously present, but the boundary conditions are different from the operational ones (e.g.: system during commissioning)

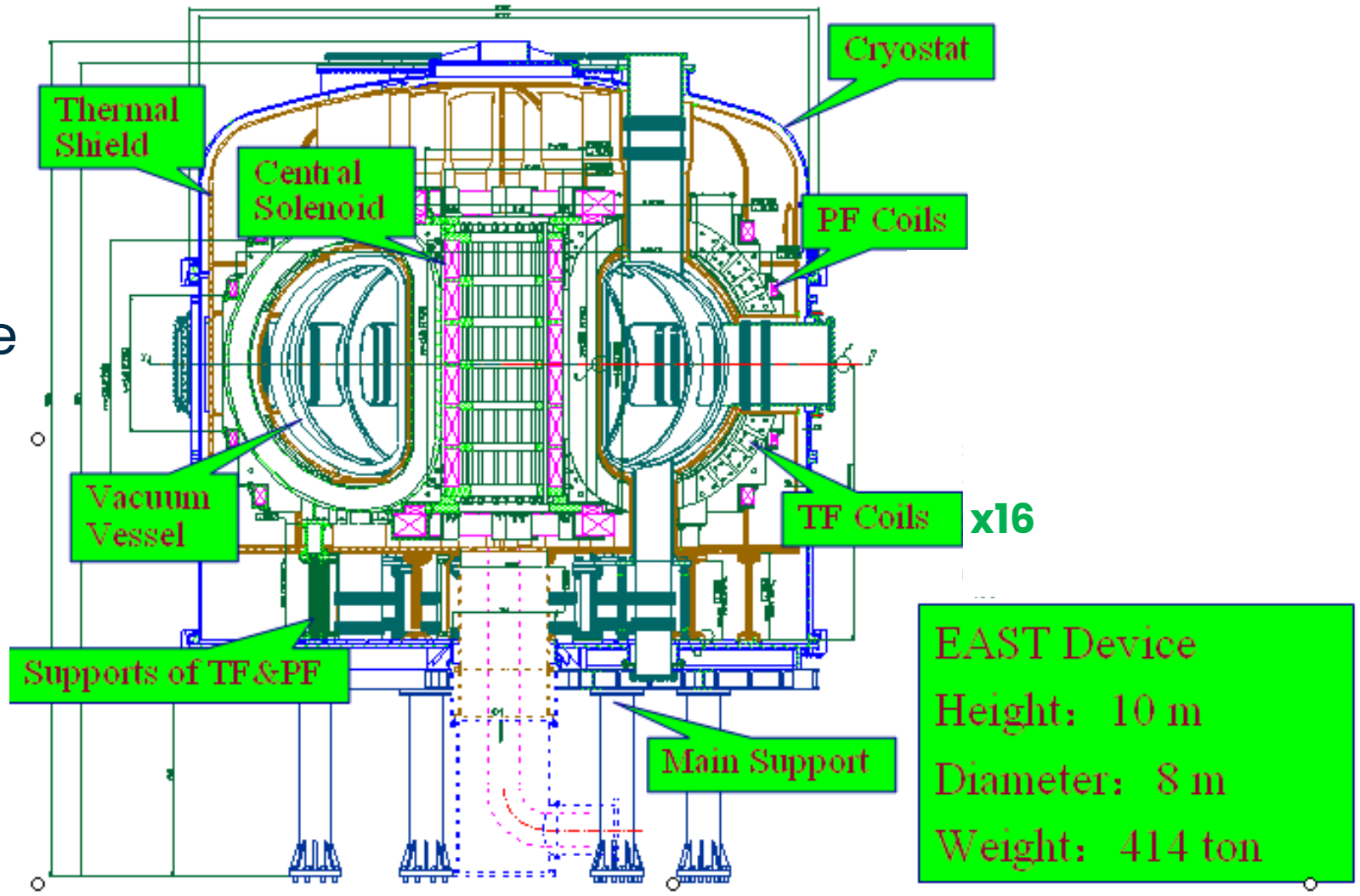
— **Plant level tests**: operation of the entire plant, with all the possible feedbacks and/or control loops (e.g.: system during operation)

[IAEA, Deterministic Safety Analysis for Nuclear Power Plants, SSG-2, 2017; https://www.iaea.org/publications/12335/deterministic-safety-analysis-for-nuclear-power-plants]

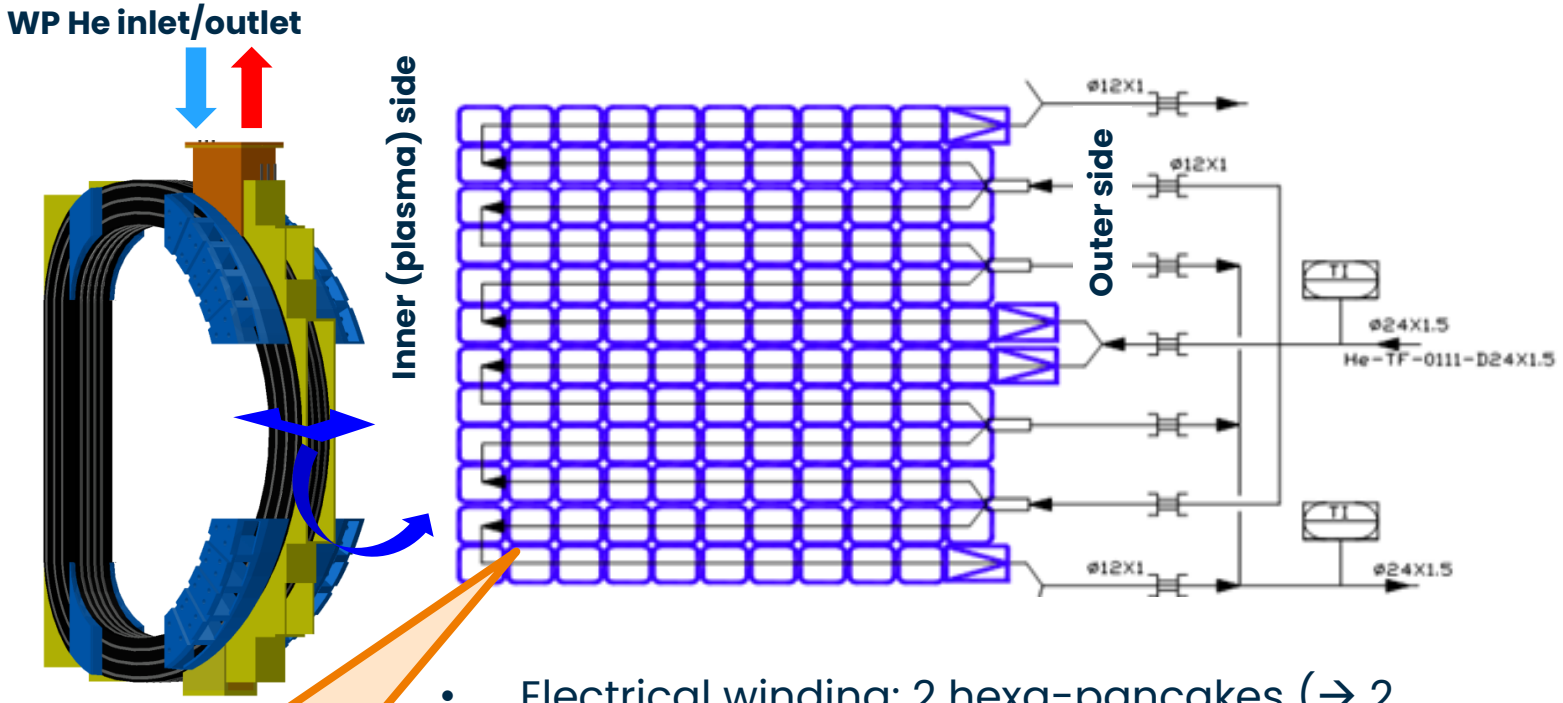
Aim of the work

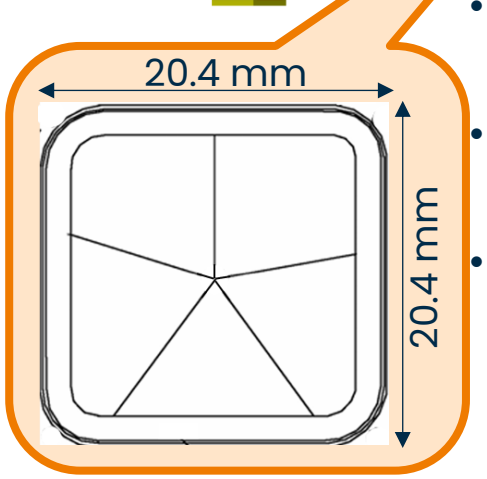
- Past (fruitful) collaborations between PoliTo and ASIPP
- 4C code being adopted to support design and operation of future Chinese tokamaks (**e.g. BEST**)
- V&V is a never-ending exercise

→ **<u>Plant level validation</u> of 4C on experimental data from the EAST TF coils cooldown**



The EAST TF coils: winding pack (WP)

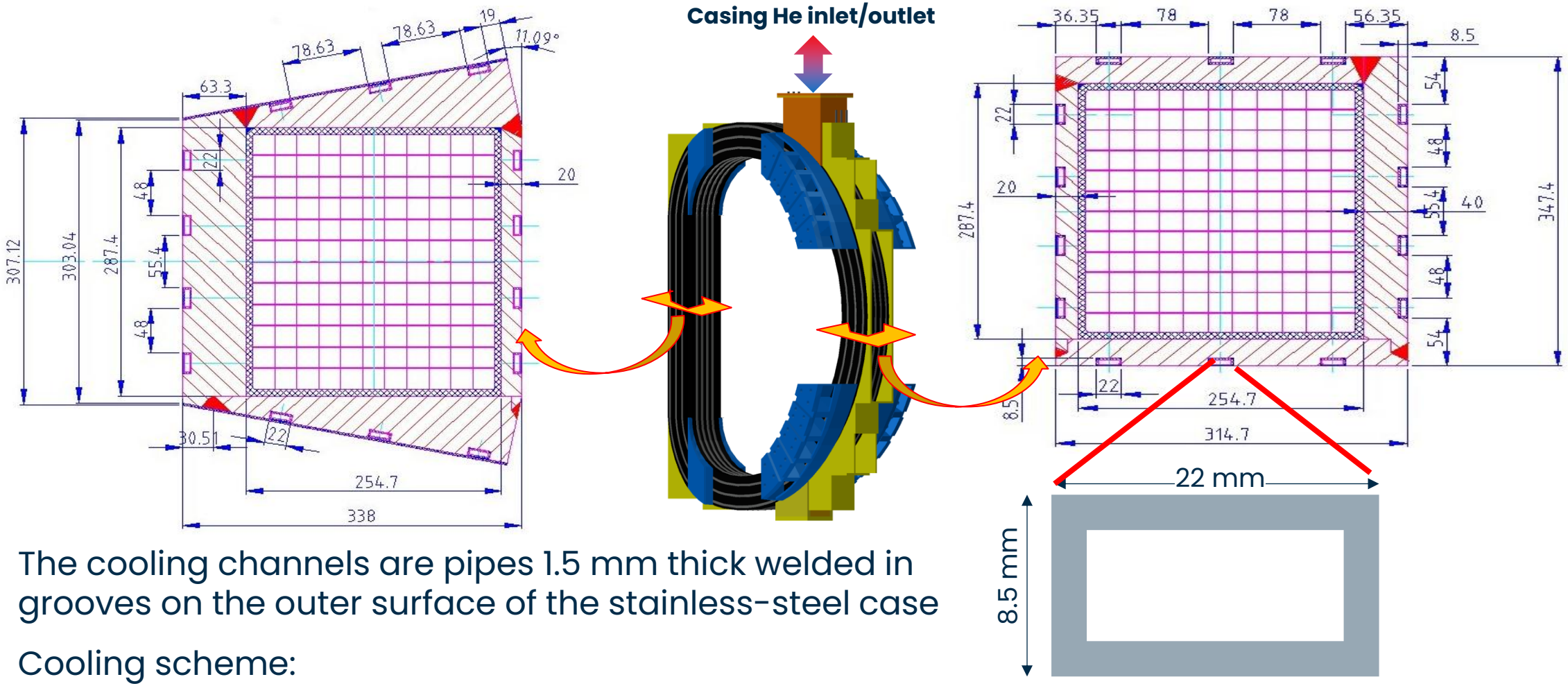




- Electrical winding: 2 hexa-pancakes (→ 2 terminations, 1 internal joint)
- Hydraulic scheme: 6 double-pancakes (→ 3 inlets, 4 outlets)
- Number of turns:
  - first and last pancake: 10
  - other pancakes: 11

Cable configuration	(2SC+2Cu)×3×4×5 +1 copper cable core
Diameter of SC strands	0.87 mm
Diameter of Cu strands	0.98 mm
Cu / non-Cu	1.38
RRR of Cu strands	>100
316LN conduit thickness	1.5 mm
Size of CICC	20.4×20.4 mm^2
Void fraction	35.0%
Cooling channel length	200 m
Peak field (after upgrade)	6.72 T
Operating current (after upgrade)	16 kA

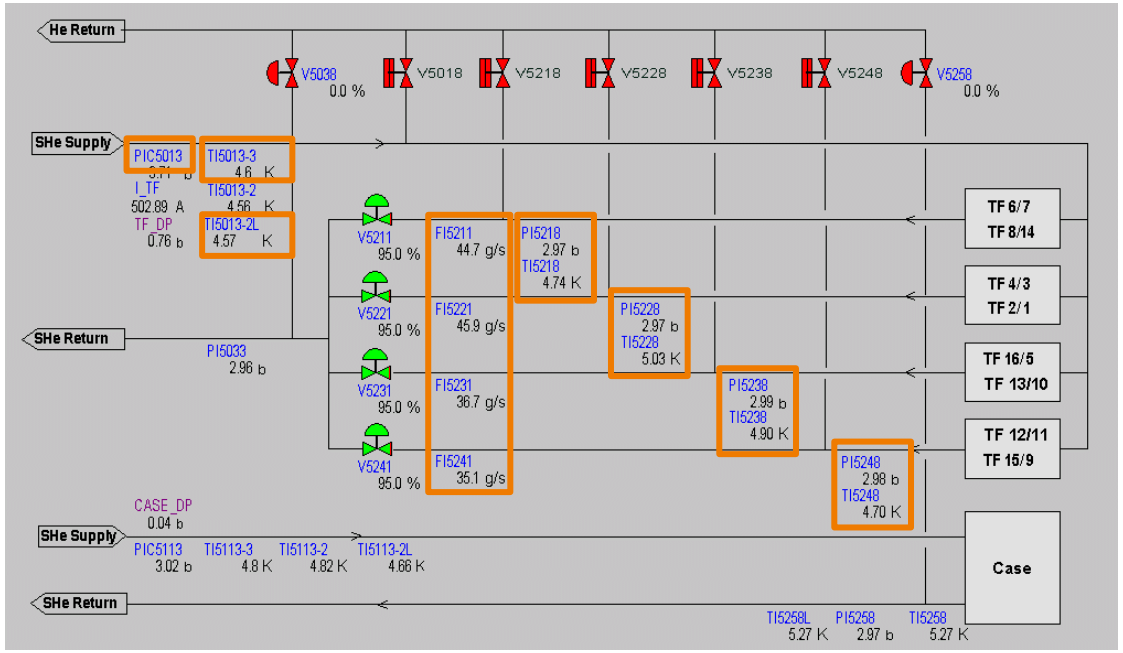
The EAST TF coils: casing



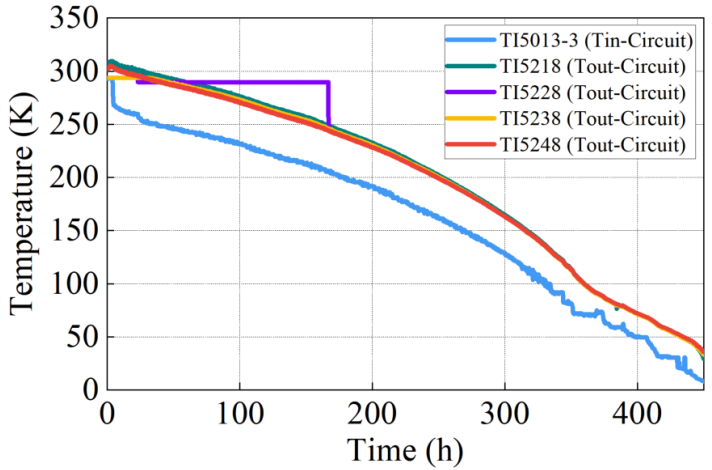
- The cooling channels are pipes 1.5 mm thick welded in grooves on the outer surface of the stainless-steel case
- Cooling scheme:

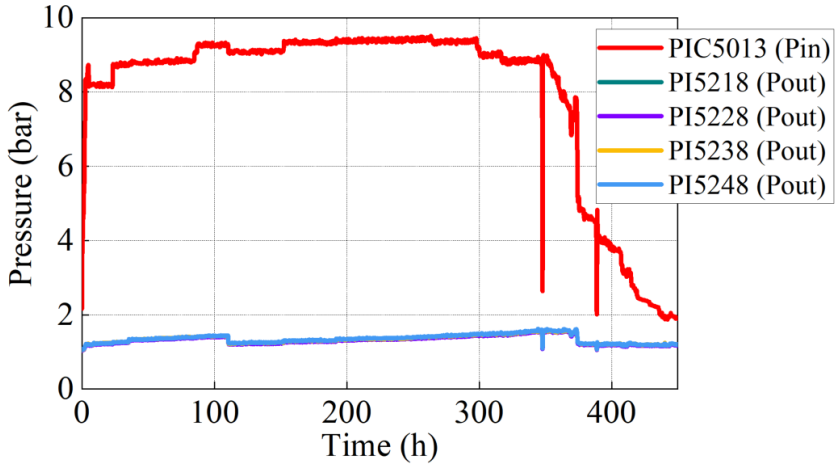
INNER channels (4 in parallel) → SIDE channels (3 in parallel) → SIDE channels (3 in parallel) → OUTER channels (4 in parallel)

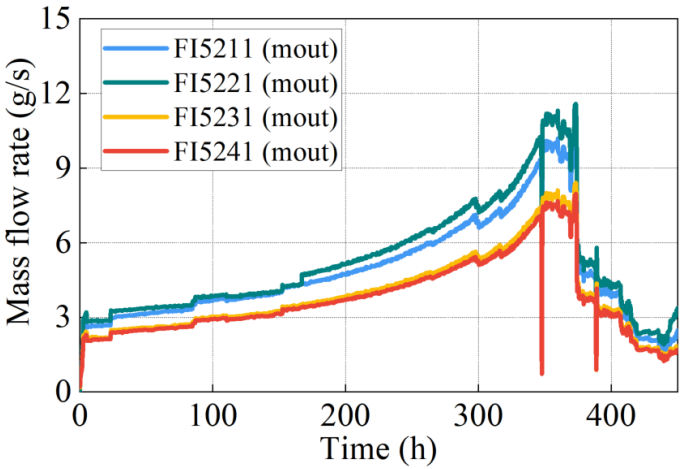
Experimental data: winding



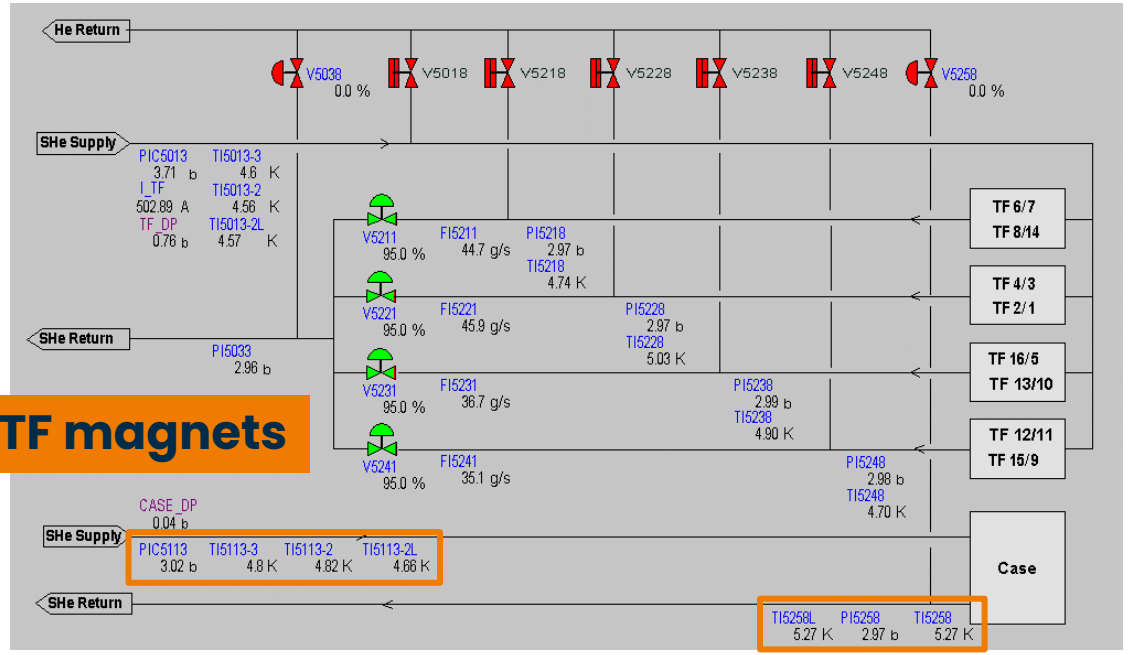
T_in	T_out	P_in	P_out	m_out
TI5013-3	TI5218	PIC5013	PI5218	FI5218
TI5013-2L	TI5228		PI5228	FI5228
	TI5238		PI5238	FI5238
	TI5248		PI5248	FI5248



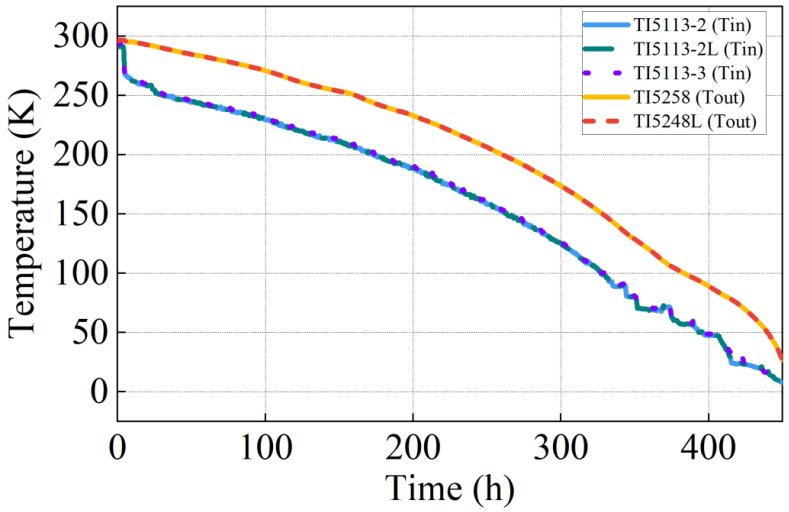




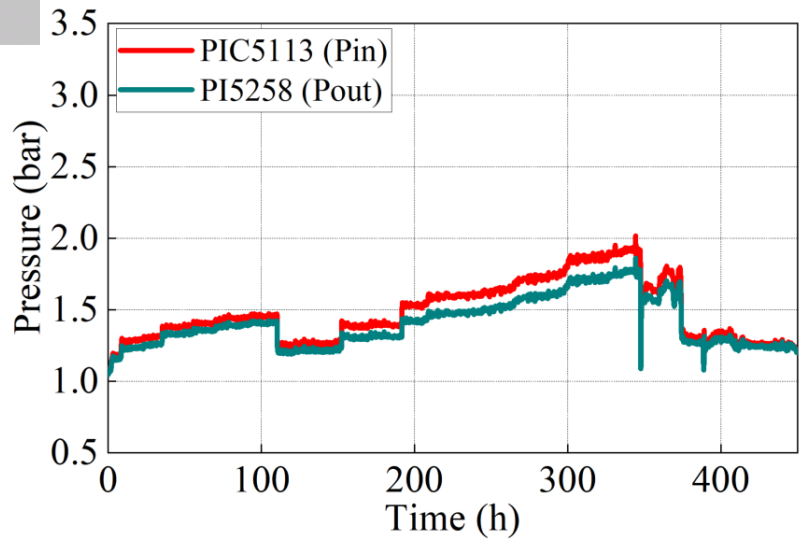
Experimental data: casing (I)



TF magnets

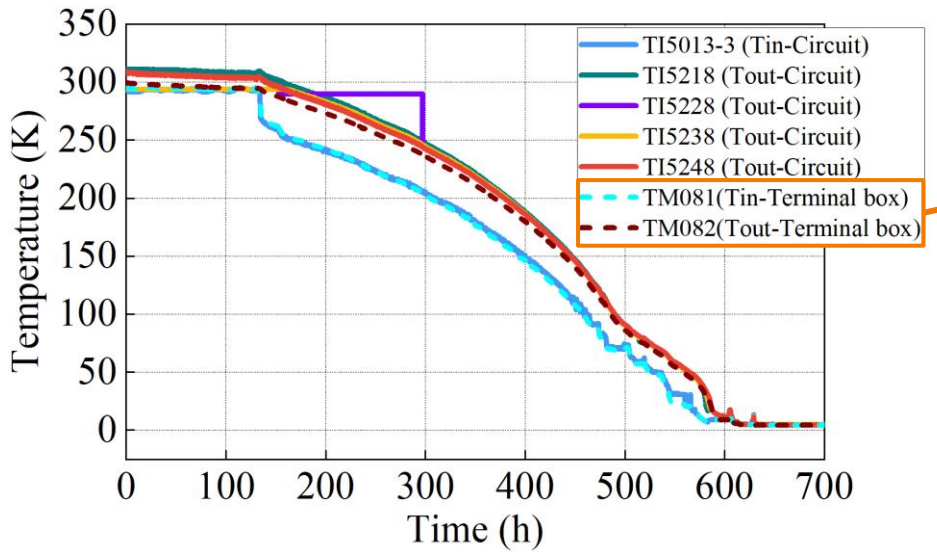


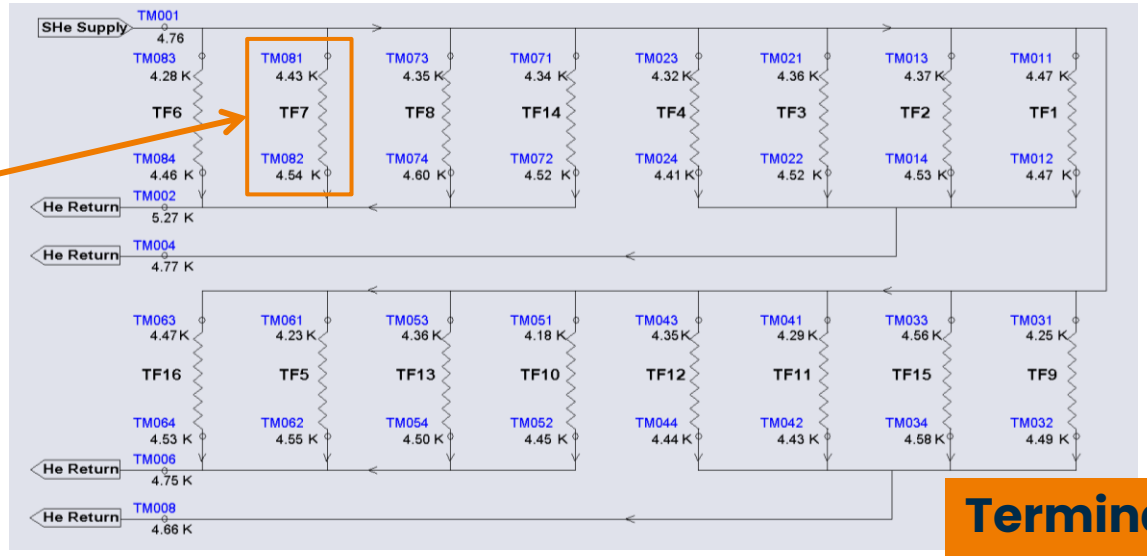
T_in	T_out	P_in	P_out
TI5113-2L	TI5258L	PIC5113	PI5258
TI5113-2	TI5258		
TI5113-3			



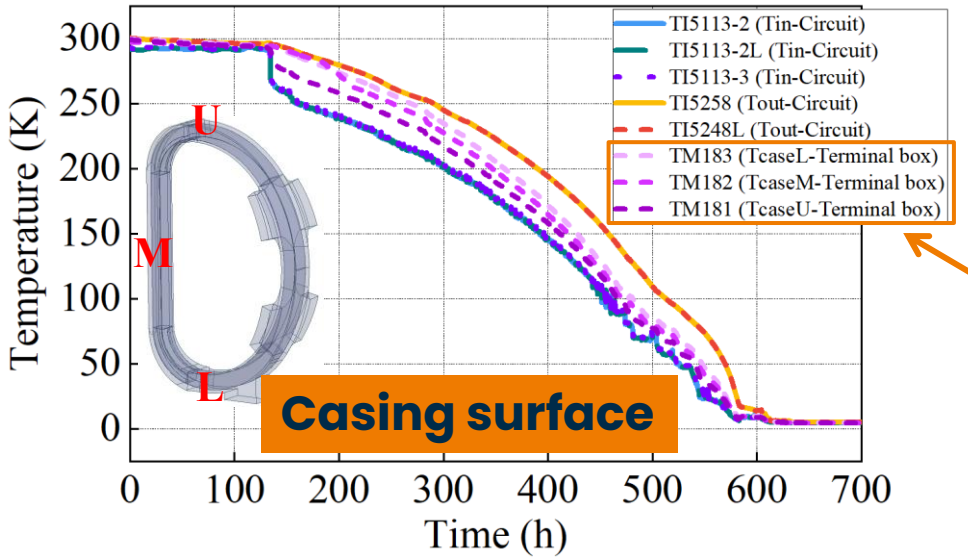
m_in measured only in the distribution valve box but reliability at T < room T under investigation

Experimental data: additional sensors





Terminal box

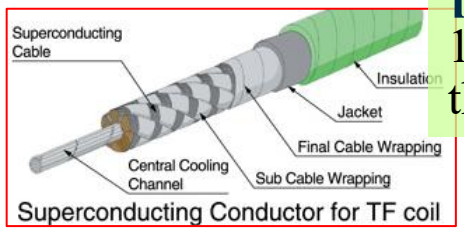


Casing surface

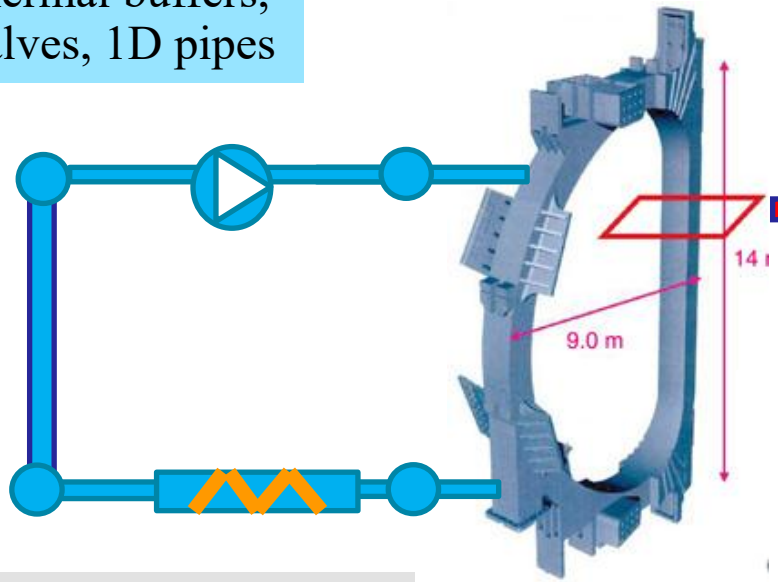
- At the beginning of the CD, the T_{out} in the low-temperature system is significantly higher than the T_{in}, but the T_{out} in the terminal box is close to the T_{in} → terminal box temperature more reliable, *possibly* due to less radiative heat loads?!
- The temperature at different positions on the casing surface is significantly different (*detailed location of the thermometer unknown*)

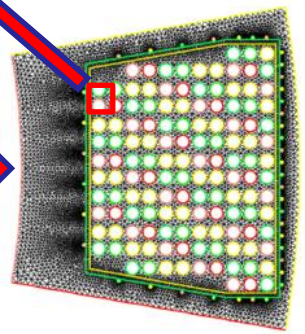
Architecture of the 4C code

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



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



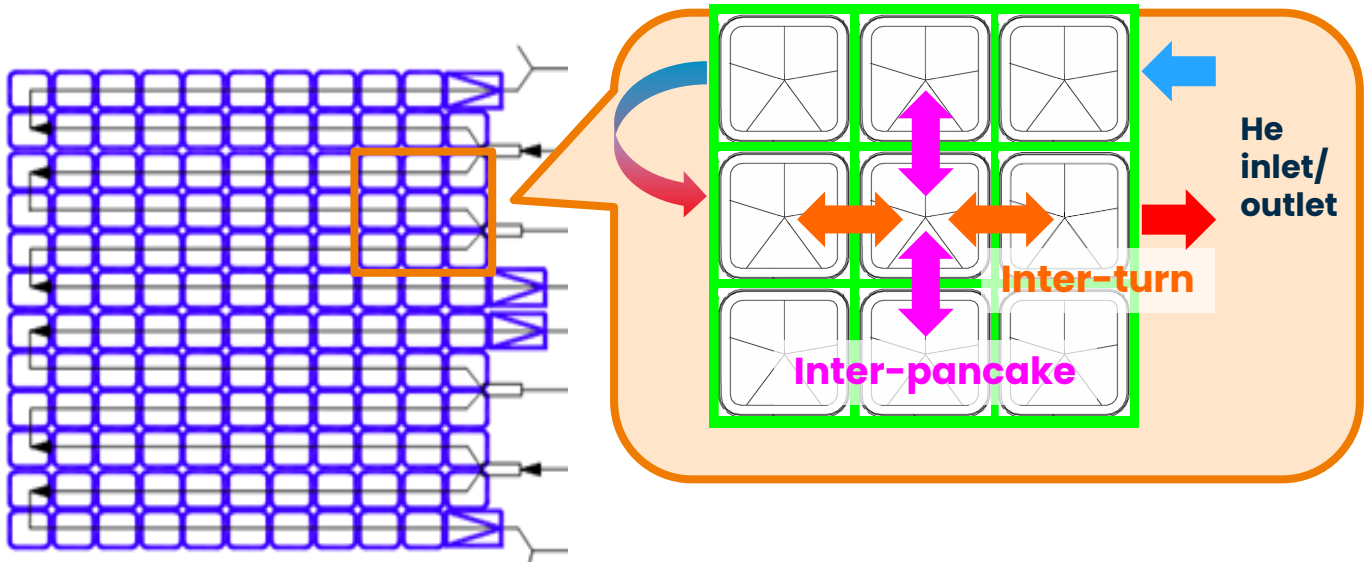


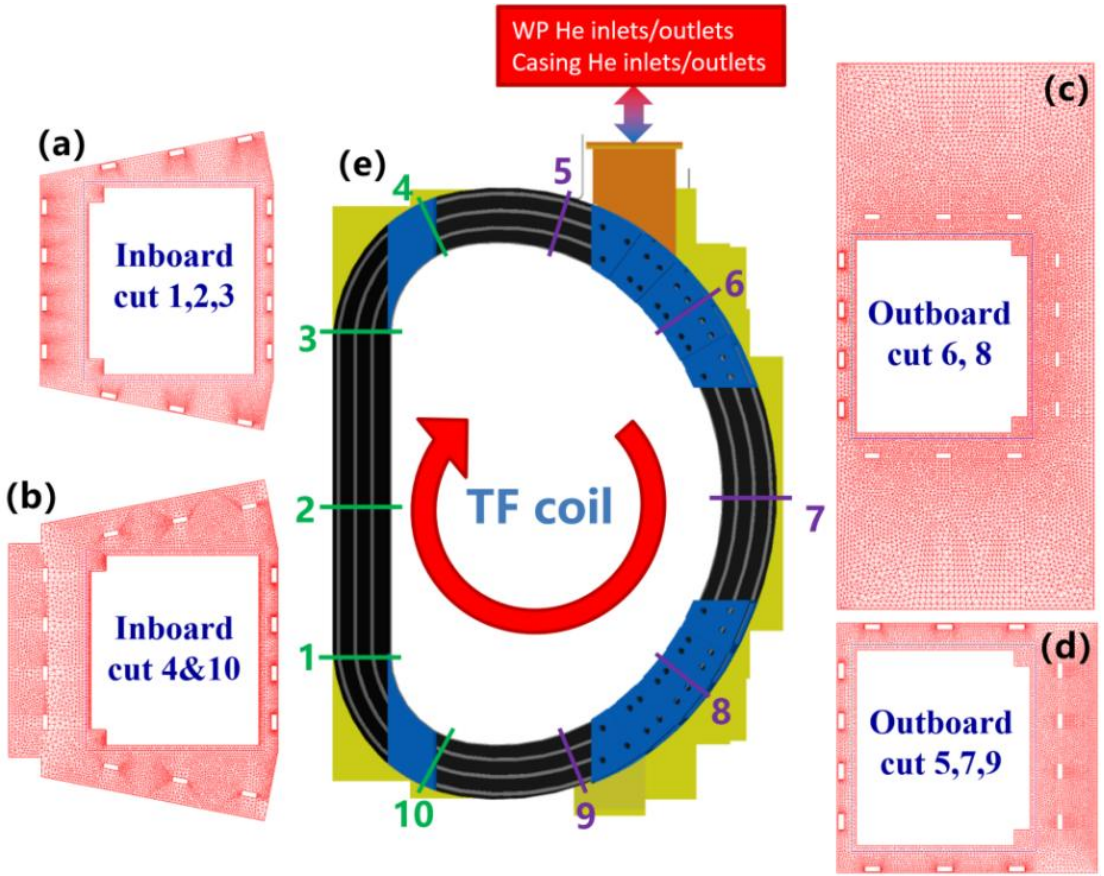
Structure module [FreeFem++]
2D-3D heat conduction

Structure cooling module [FORTRAN]

[Savoldi et al., *Cryogenics* 2010]

4C code model of an EAST TF coil



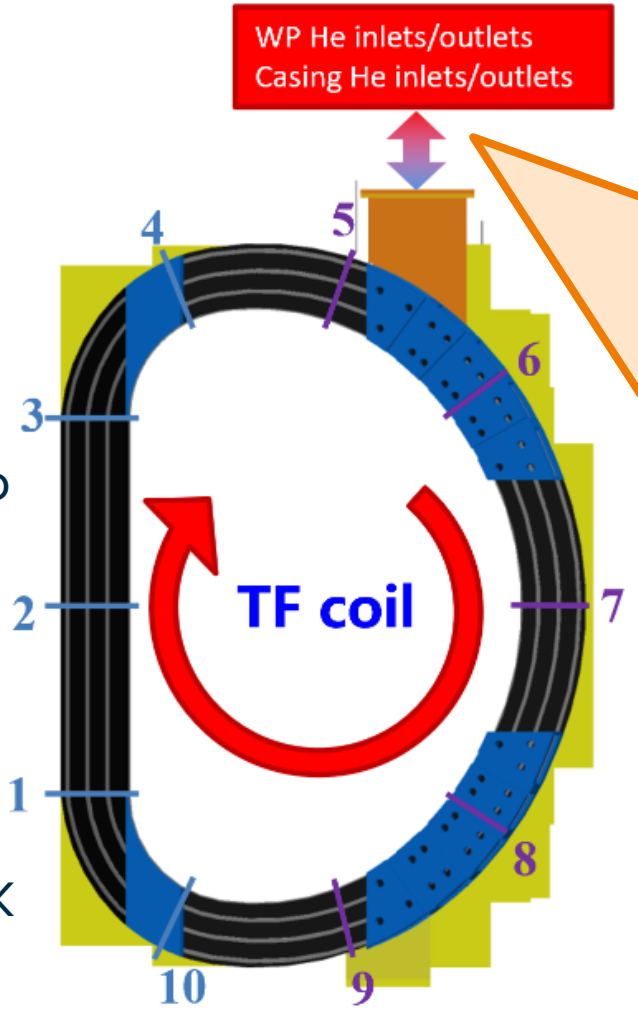


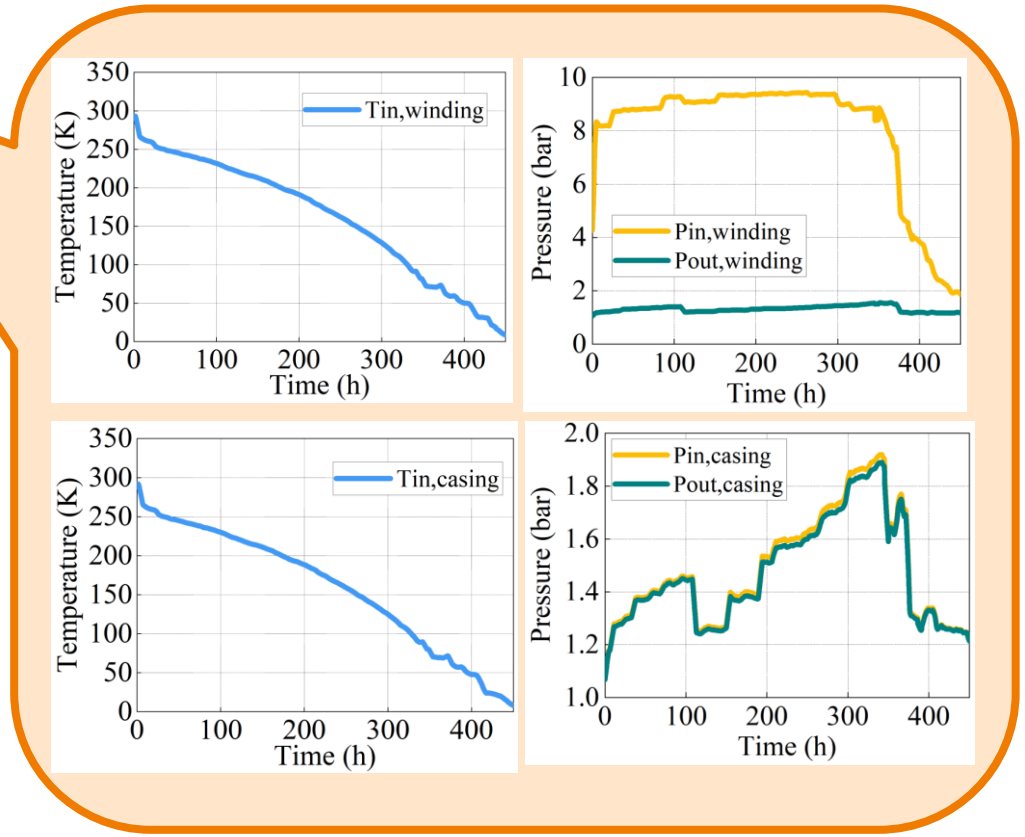
Model of TF coil for cool-down simulation:

- Inter-turn and inter-pancake thermal coupling are considered
- Thermal coupling between winding and structures is modelled
- CICC bundle friction factor: Katheder

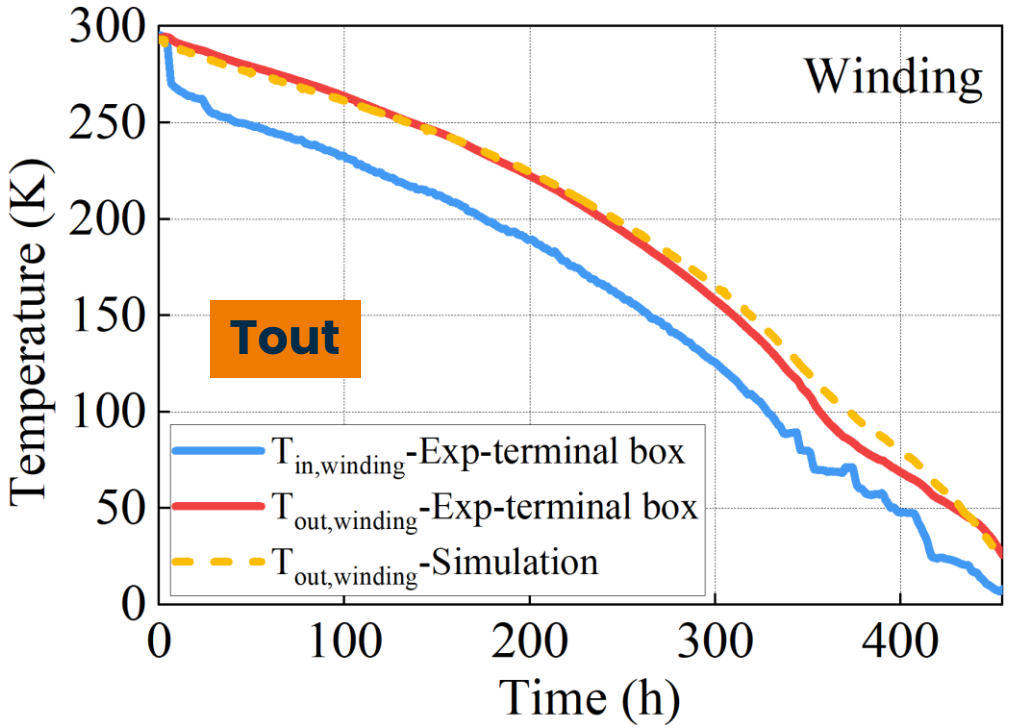
4C code model of an EAST TF coil cooldown: driver

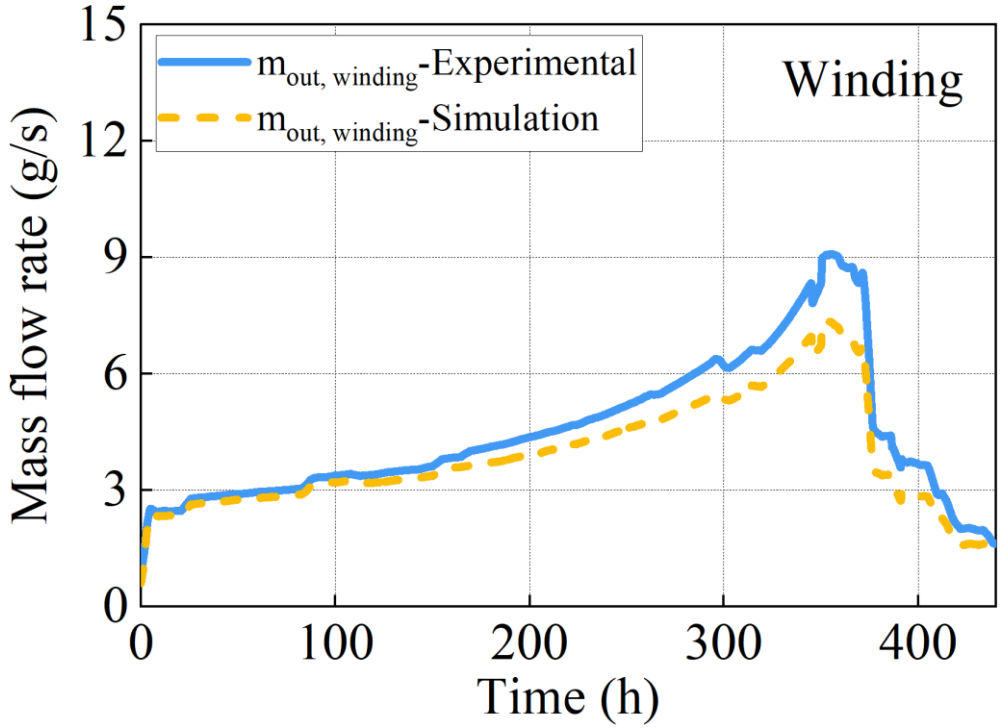
- During the CD the TF coils are directly connected to the refrigerator → cryogenic circuit not included in the model → use experimental boundary conditions
- Friction factor: smooth pipe x 5 to match mass flow rate; bundle x 0.7 to match mass flow rate
- Thermal coupling to the casing reduced by a factor 2000 for the welding discontinuity
- The thermal shield is cooled in parallel to the coils: same Tin → ~adiabatic conditions above 80 K





Results: winding pack



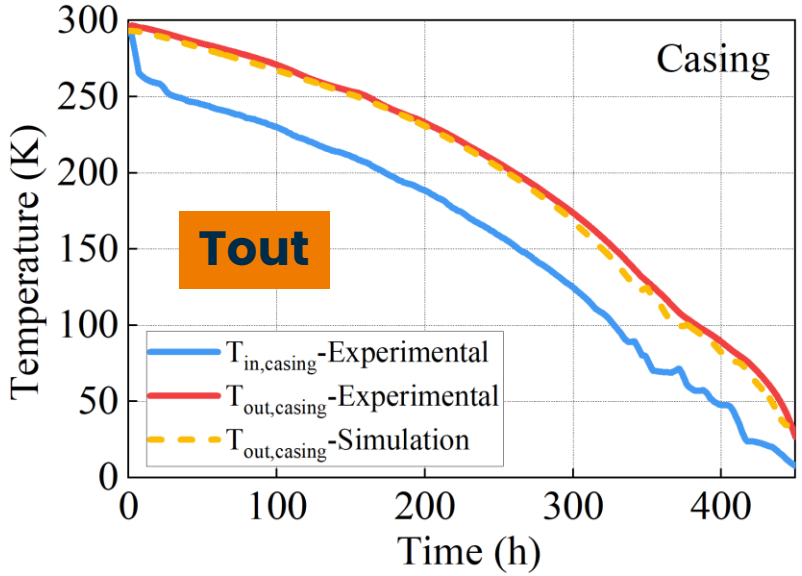


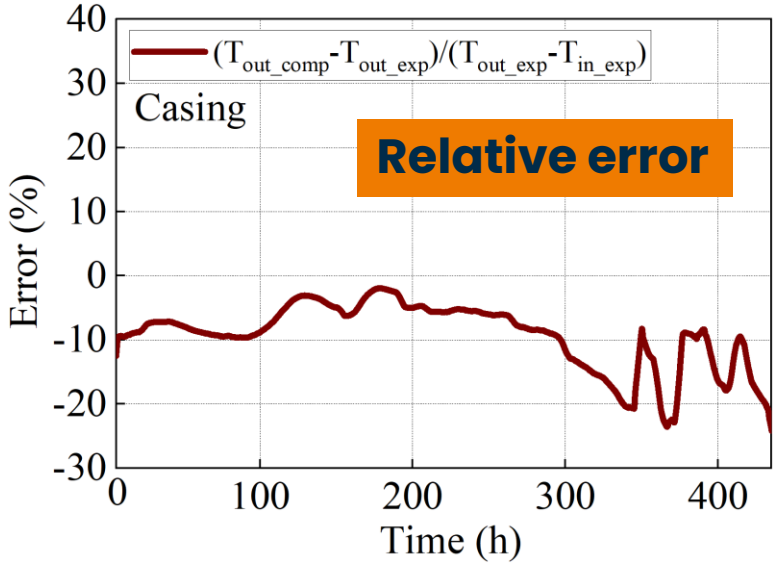
T_out He slightly overestimated by the model. Possible reason being assessed (*uncertainty quantification*): thermal coupling within WP and between the casing and the WP across the ground insulation

m_out underestimated by the model, given the experimental pressure head. Possible reasons being assessed:

- Uncertainty in the mass flow rate repartition among the 4 coils in parallel (*uncertainty quantification*)
- Mass flow meter accuracy

Results: casing (He) (error quantification)





T_out He slightly underestimated by the model in the second part of the CD.

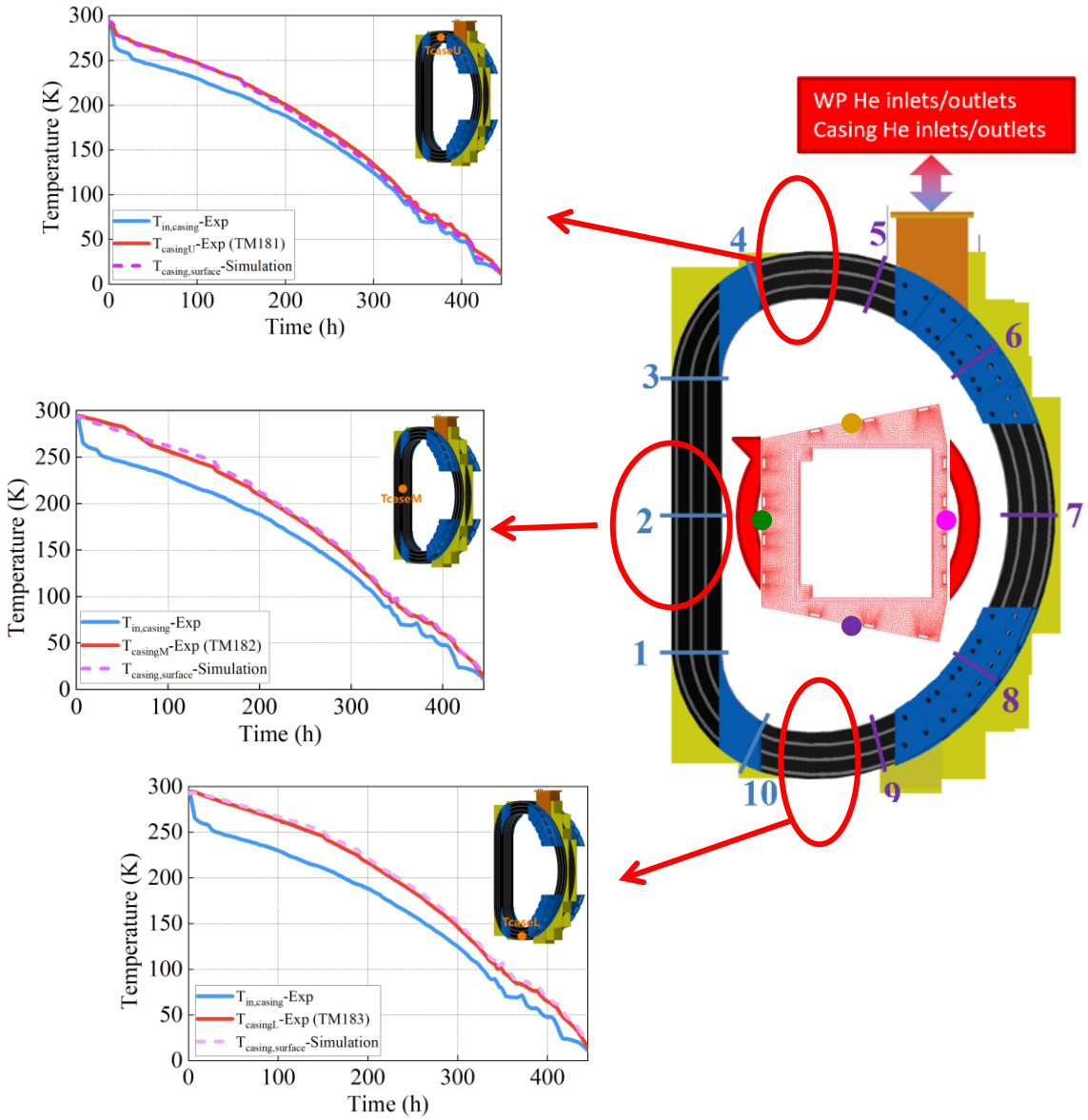
Possible reason being assessed (*uncertainty quantification*): casing-WP and casing-pipes thermal coupling

Try to assess the model accuracy

- Relative error on the computed temperature difference <20%

during the whole CD

Results: casing (structures)



- The simulated profiles (purple dashed lines) show excellent agreement with the measured outlet temperatures (red solid lines)
- The observed vertical temperature gradient (highest at the bottom, lowest at the top) is consistent with the top-inlet configuration
- The strong agreement between simulation and experiment confirms the model's fidelity and provides a reliable tool for thermal analysis and system optimization

Conclusions and perspective

- The full qualification of the 4C code as a scientific tool for nuclear safety analyses requires additional V&V at the plant level
- The model of the EAST TF cooldown has been implemented in the 4C
- The successful comparison with experimental data have been reported
- Challenges / next steps:
  - Uncertainty quantification
  - Use 4C code to support the definition of BEST test program

Thank you for your kind attention



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