Modelization of the thermal coupling between the ITER TF Coil conductor and the structure cooling circuit

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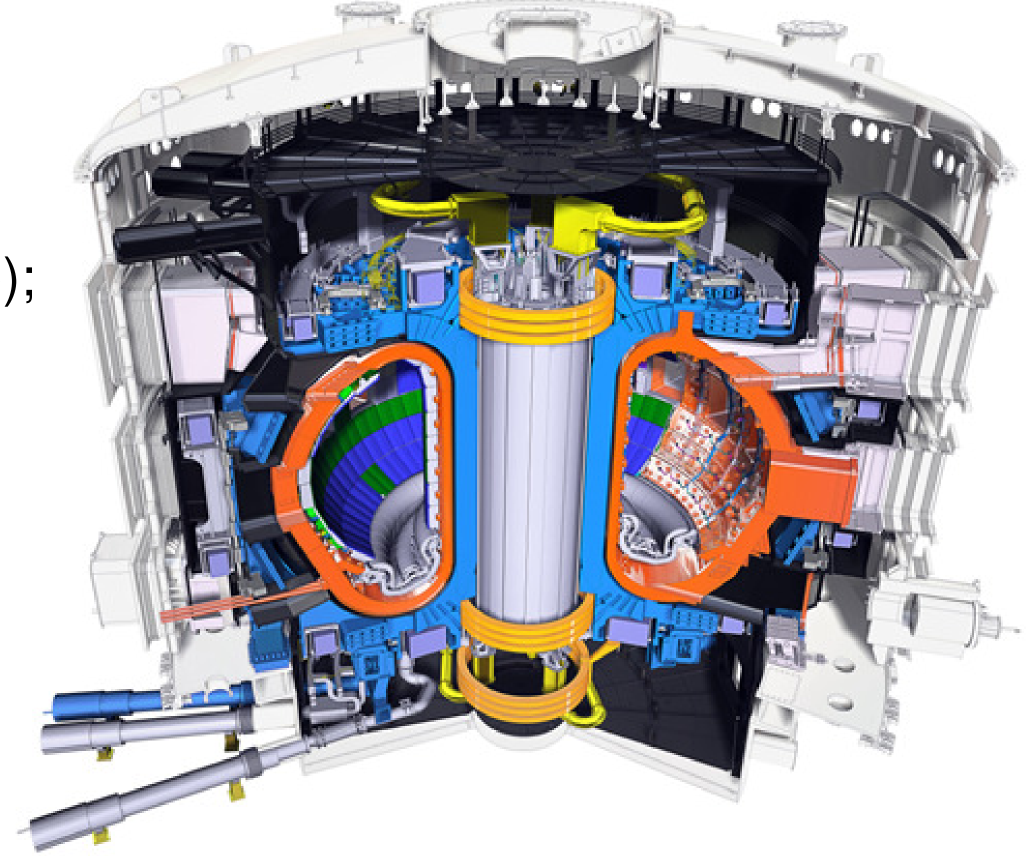
Layout

- Introduction:
  - IO requirement
  - Global modelization / Local modelization
  - Objective of the analyses;
- Global / local approach;
- Investigated cooling pipe design;
- Codes
- Analysis results:
  - Steady state results: CAST3M simulations;
  - Transient (pulse) results: VENECIA / SuperMagnet simulations
- Conclusions
- Perspectives

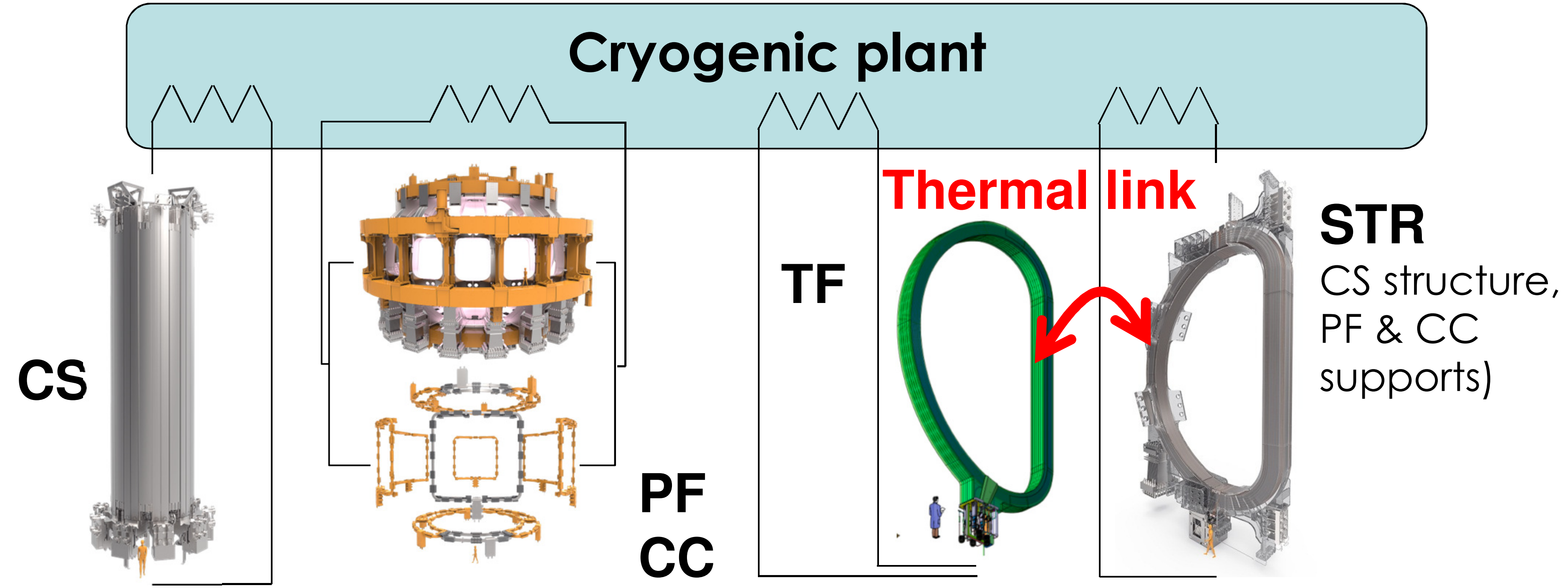
Introduction (1/7)

- ITER magnet system mainly composed by:
  - Central solenoid (CS);
  - Poloidal Field (PF) coils;
  - Correction Coils (CC);
  - Toroidal Field Coils (TFC);



Introduction (2/7)

- The various magnets are cooled by supercritical helium (SHe) by four independent cooling loops:



Cryogenic plant

CS

PF

CC

TF

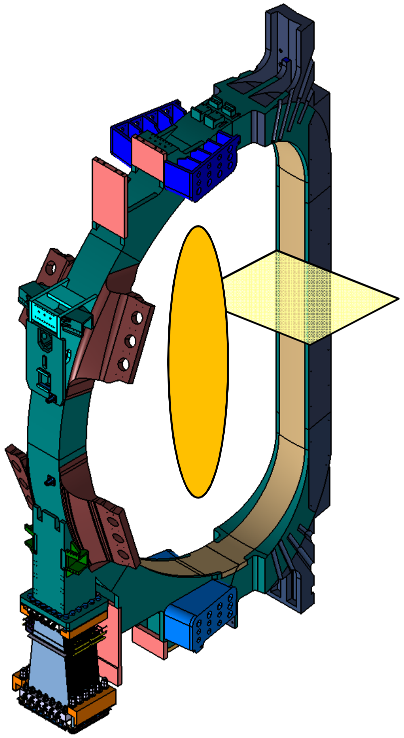
Thermal link

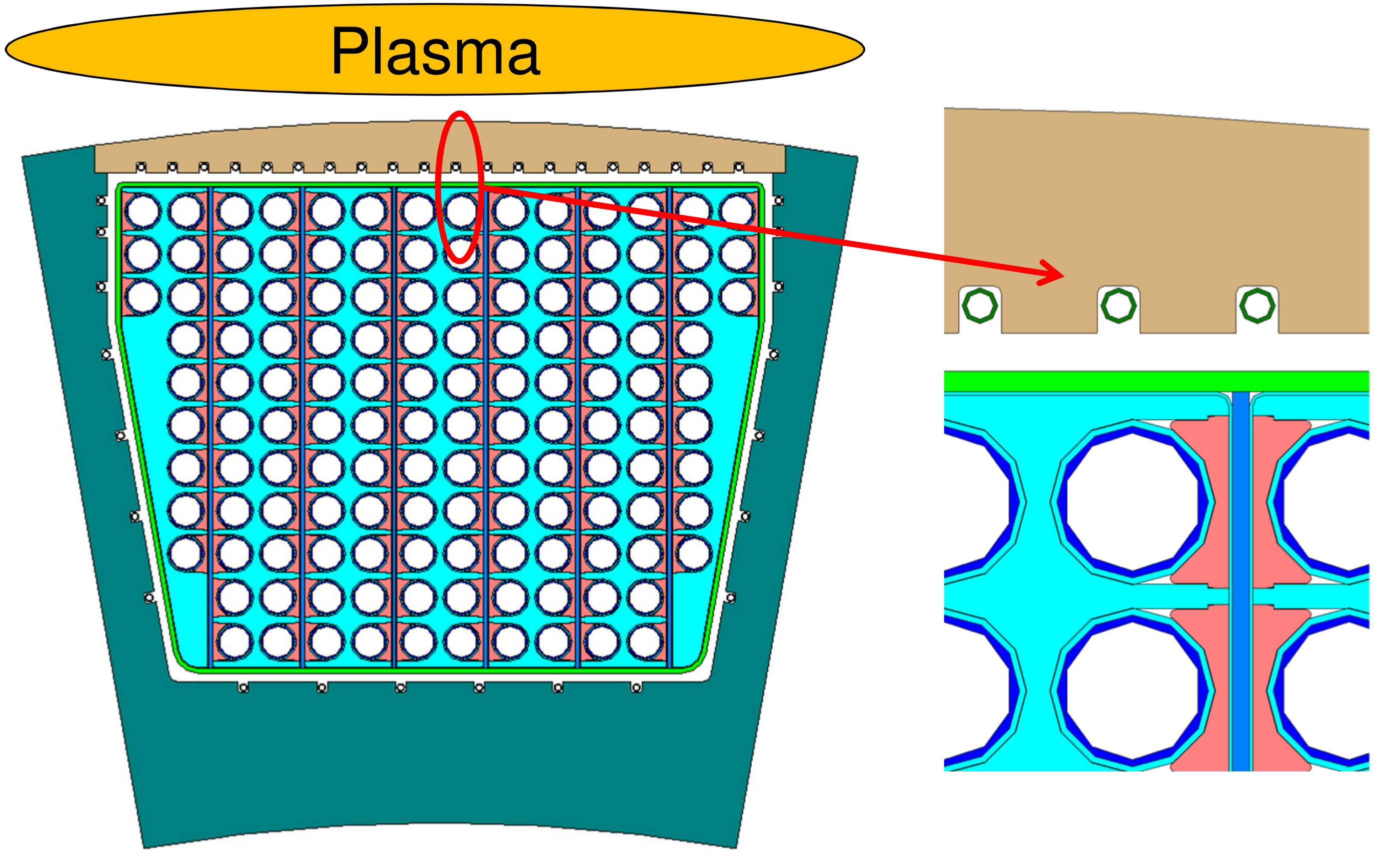
STR

CS structure, PF & CC supports)

Introduction (3/7)

- 2D cross section of the TFC:



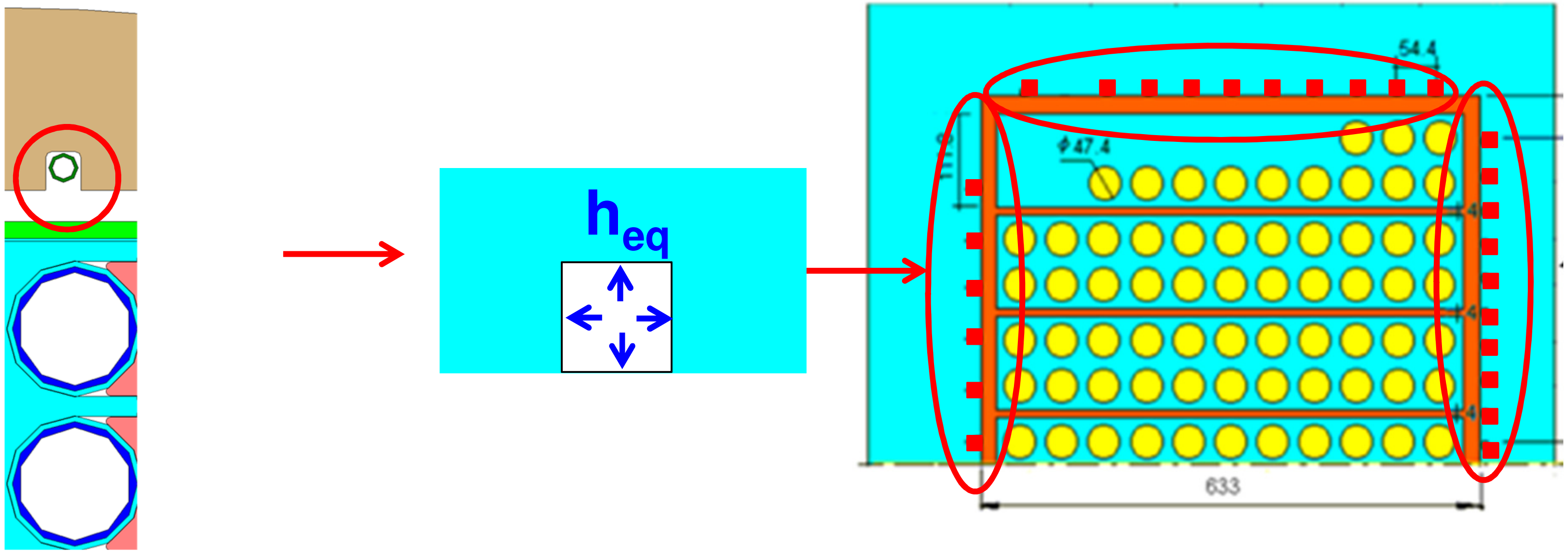


Introduction (4/7)

- IO requirements:
  - Plasma disruption followed by the CS, PF and CC fast discharge shall not trigger a TF fast discharge **[1]**;
  - Plasma disruption and fast discharge of all coils (except TFC) create additional heat deposition in the TFC conductor (AC losses) but also in the various steel components (eddy current losses), in particular in the TF casing;
  - The heat flux from the TF casing to the TF winding pack (mainly innermost turn) has to be limited during this transient event to reduce the impact on the conductor temperature, thus avoiding the risk to trigger the fast discharge of the TFC;
  - Consequently, the local efficiency of the cooling pipe to extract the heat deposited in the TF casing is a key parameter;

Introduction (5/7)

- Global modelization:
  - Past analyses **[2]** have been carried out with complex model in which no details of the cooling pipe design were included;
  - A equivalent heat transfer coefficient (HTC) was implemented to model the local cooling efficiency as described below:



Introduction (6/7)

- Local modelization:
  - Analyze the local efficiency separately has many advantages:
    - Light model;
    - Dedicated analyzes;
    - Simplification;
  - Dedicated mockup can be manufactured and tested [3]:
    - Representative mock-up of the TF casing-TF winding pack thermal coupling has been tested in HELIOS facility (CEA Grenoble – FRANCE);

Introduction (7/7)

- Objectives of the analyses:
  - Demonstrate that a general approach can be applied as followed to support design verification:
    - Analysis of the heat flux sharing (local model);
    - Simplification of the local behavior of the thermal coupling (local model);
    - Implementation of the simplification into global model;
    - Confirm that the proposed design fits the IO requirement;

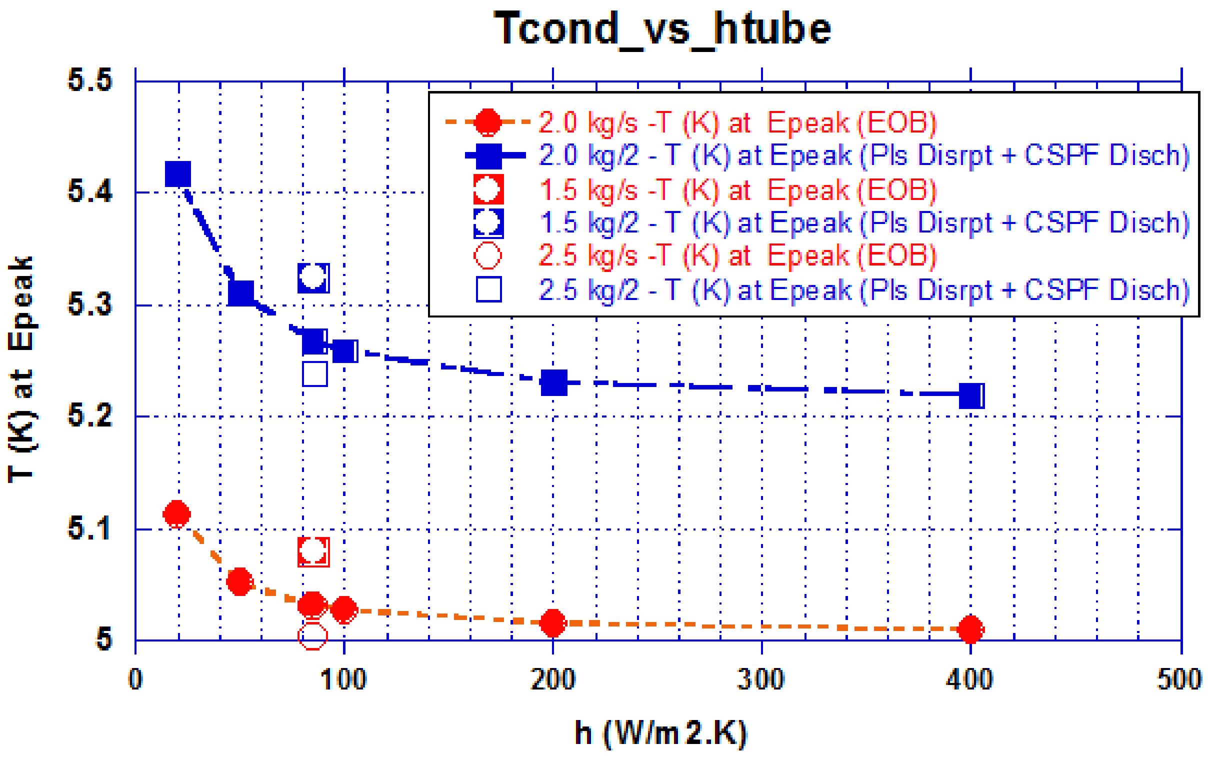
Global / local modelization (1/2)

- Global modelization:
  - For ITER reference scenario, i.e. 15 MA scenario, this approach was sufficient since the time scale of the heat deposition, then the heat diffusion was such that the cooling pipe efficiency was not a limiting parameter;
  - For the limiting load case (i.e., plasma disruption followed by fast discharge), early parametric study showed the sensitivity of the conductor temperature to the HTC for ground insulation made out of G10:
    - HTC > 90 W/m^2/K: the conductor temperature is quasi independent of the HTC
    - HTC < 90 W/m^2/K: the impact on the conductor temperature is more important as the HTC decreases;

Note that the 90 W/m^2/K boundary is expected to reduce for less conductive material in ground insulation (GKG)

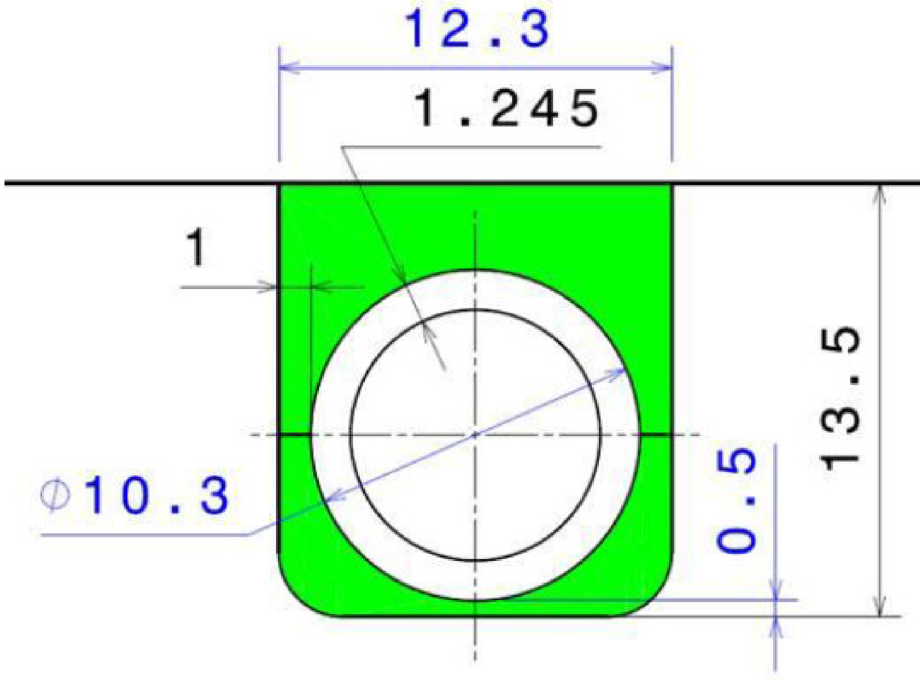
Global / local modelization (2/2)

- Conductor temperature at innermost turn, lower temperature margin



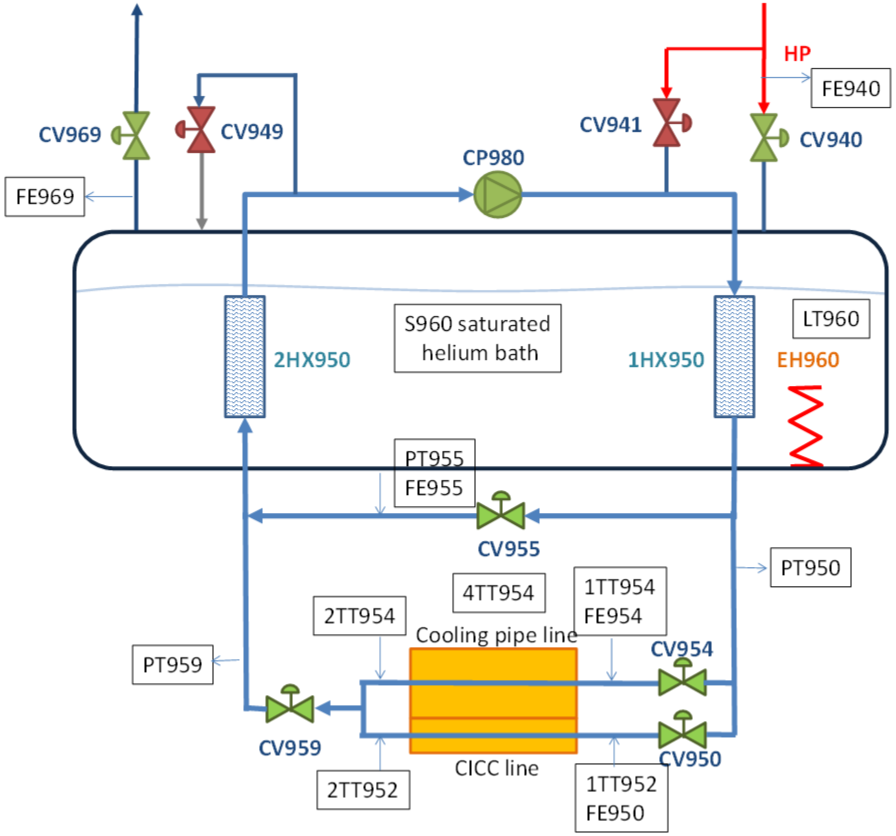
Investigated cooling pipe design

- Cooling pipe embedded in a conductive resin [4]



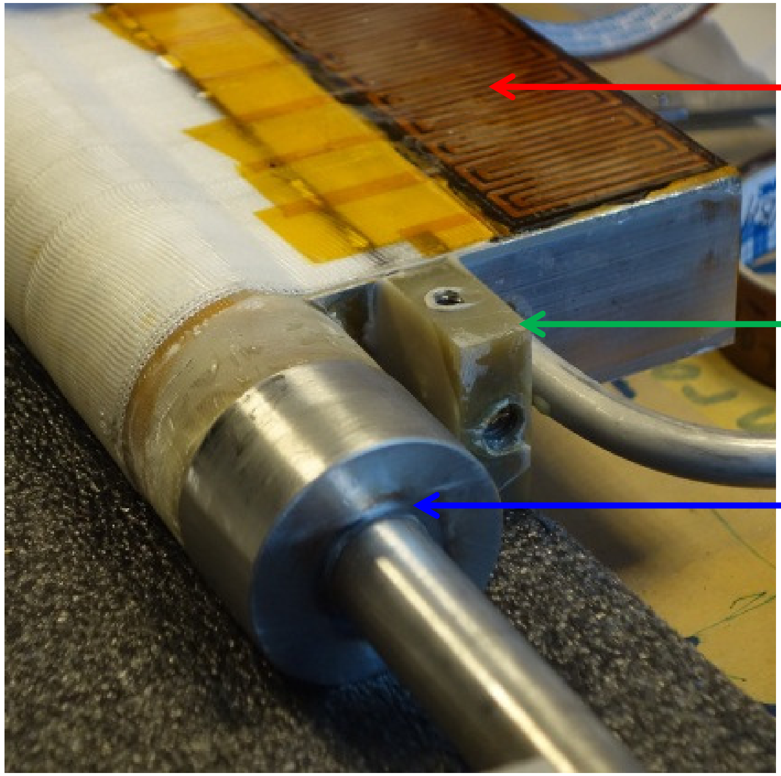
Experimental test (1/2)

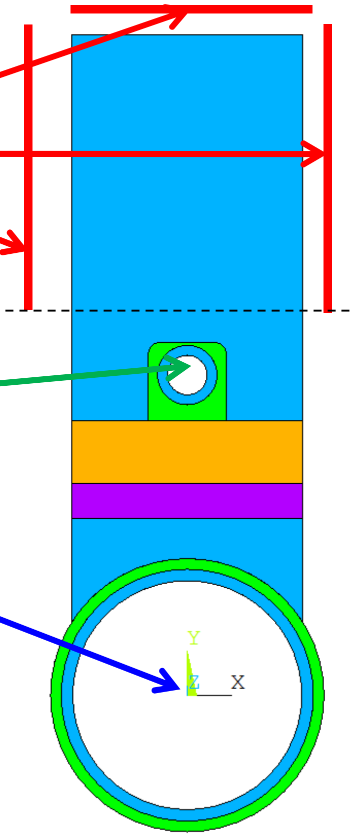
- HELIOS test facility



Experimental test (2/2)

- Mock-up: first time that a TFC+STR integrated sample has been tested;





Heaters

Cooling pipe

Conductor

Codes

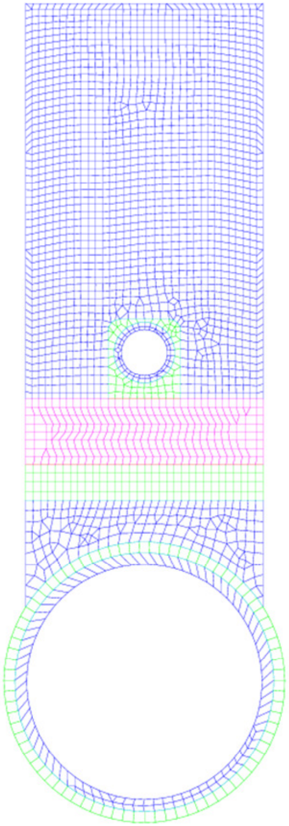
- Three different codes have been used:
  - CAST3M:
  - VENECIA;
  - SuperMagnet (CryoSoft suite of codes):
    - THEA;
    - FLOWER;
    - HEATER;

Analyses (1/12)

- CAST3M: thermal diffusion modelling:
  - From steady state experimental data:
    - Maximum temperature of the casing;
    - Heat flux sharing between the CICC and the cooling pipe;
  - From simulation:
    - Compute the average thermal conductivity of the resin around the cooling pipe to fit the maximum temperature on the casing;
    - Compute the average insulation conductivity to fit the heat flux repartition;

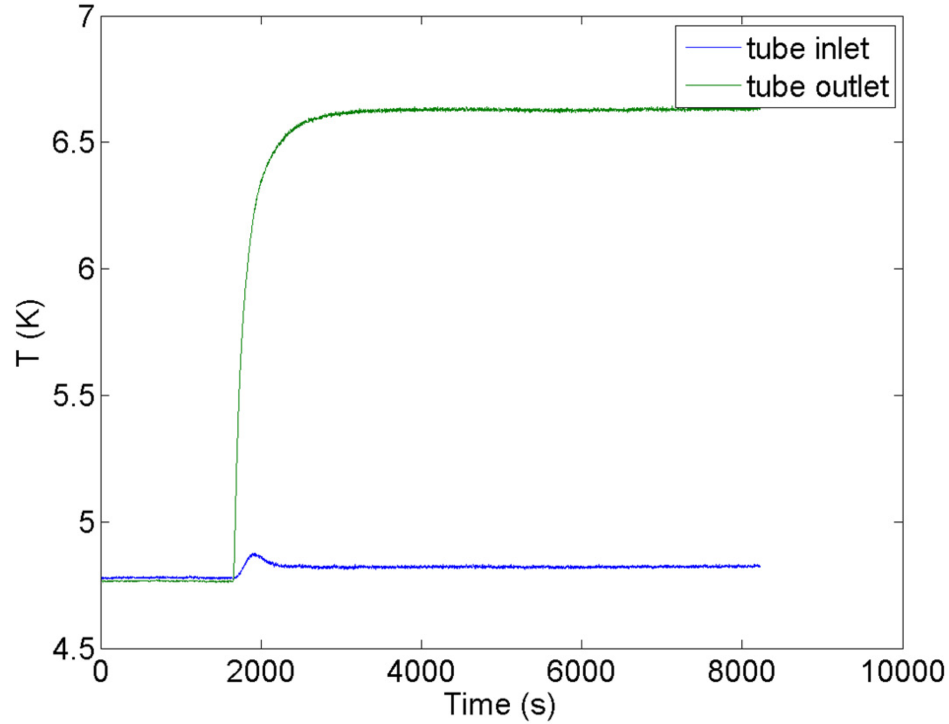
Analyses (2/12)

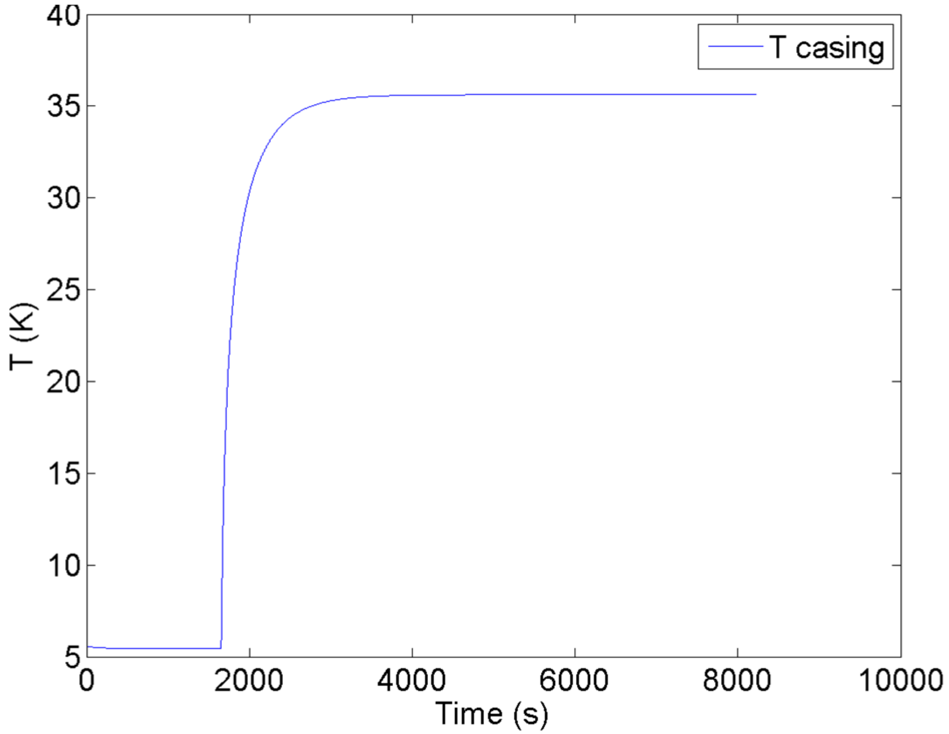
- CAST3M: 2D thermal diffusion modelling:
  - Model:



Analyses (3/12)

- CAST3M: 2D thermal diffusion modelling:
  - Experimental data: steady state under 30 W heating



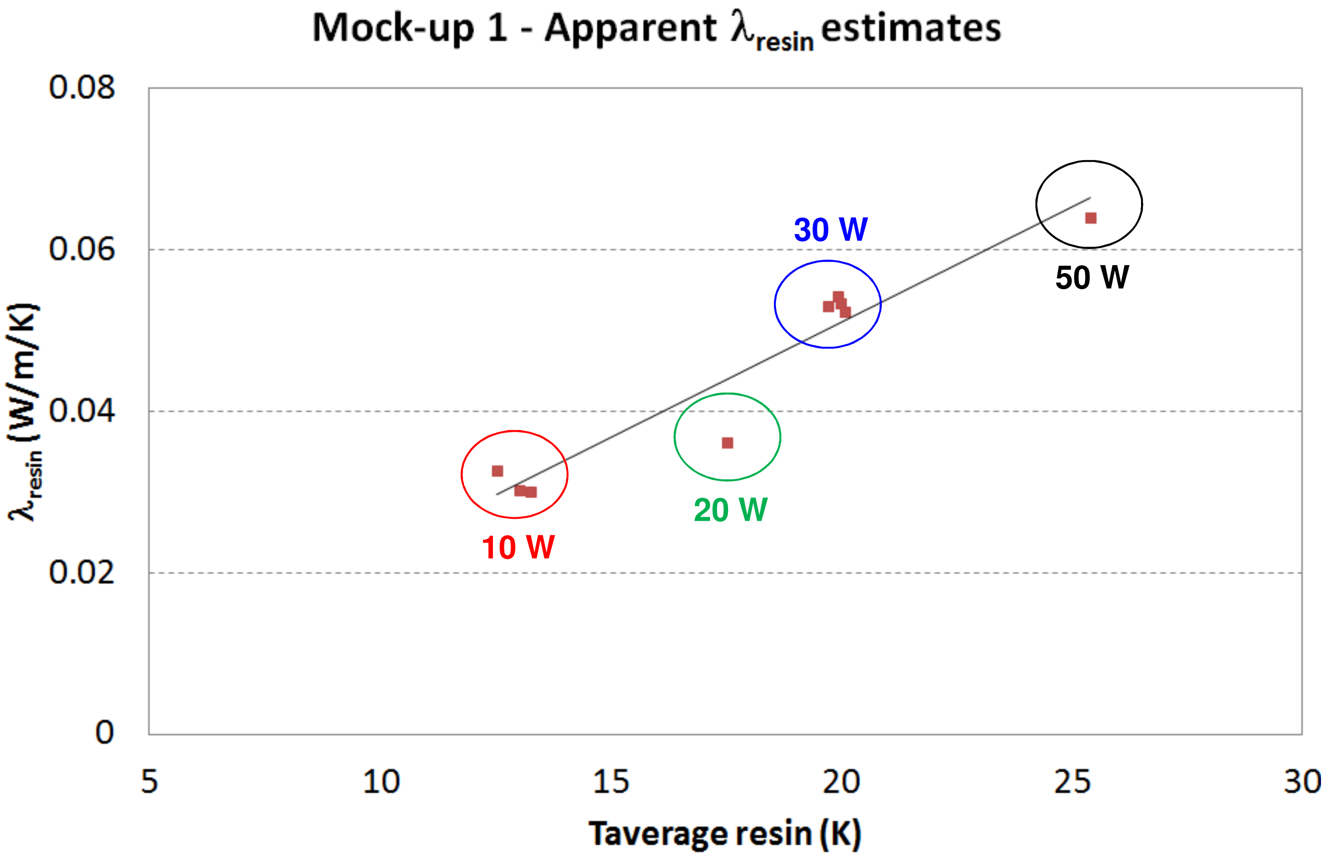


Analyses (4/12)

- CAST3M: 2D thermal diffusion modelling:
  - Experimental data: steady state:
    - Very clean data have been measured [3];
    - Various heating steady state have been considered (from 10 W to 50 W);
    - From casing temperature measurements, estimates of the thermal efficiency (given in the next slides as an “apparent” thermal conductivity of the resin around the cooling pipe) have been done;
    - It results a temperature-dependent function that can be extrapolated at 5 K;
    - This estimate suggest that “apparent” thermal conductivity is around 0.015 W/m/K;

Analyses (5/12)

- CAST3M: 2D thermal diffusion modelling:

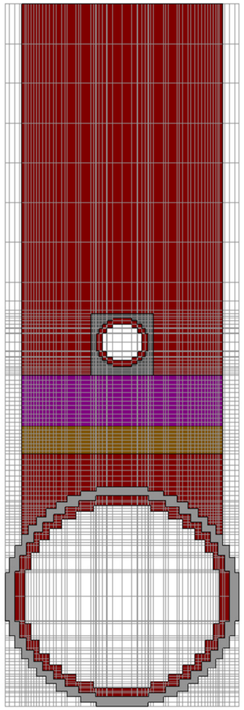


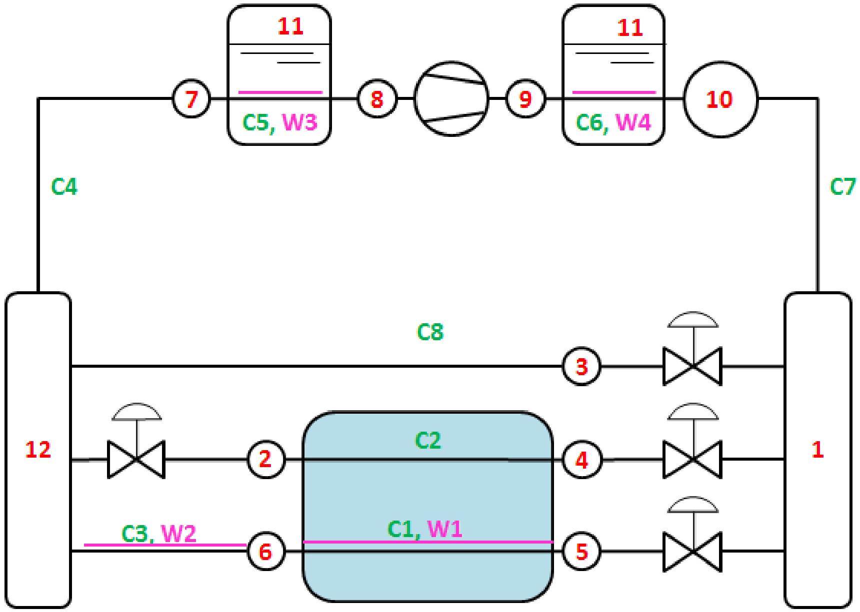
Analyses (6/12)

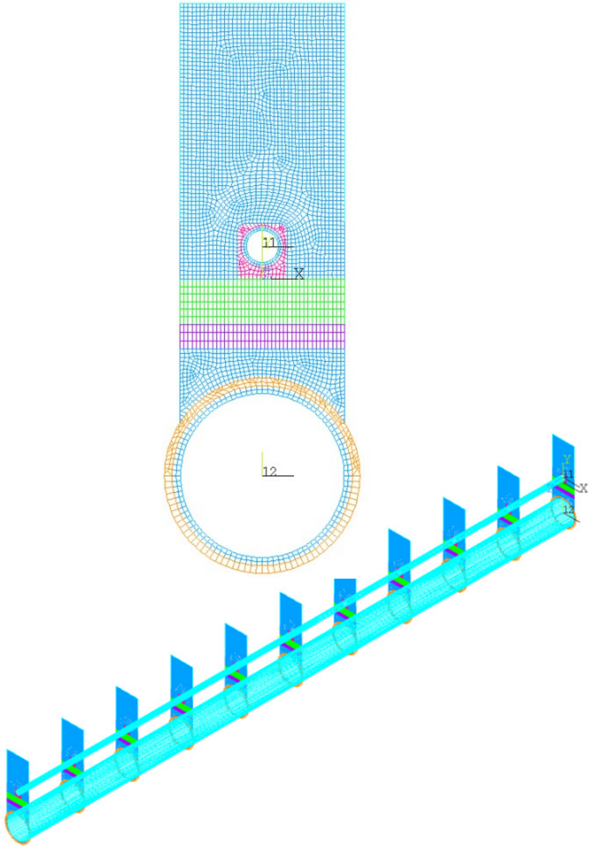
- VENECIA / SuperMagnet: thermal hydraulic:
  - Transient event (PD+FD like):
    - Compute the thermal hydraulic response under pulsed heat load;
    - Fitting with equivalent heat transfer method

Analyses (7/12)

- VENECIA / SuperMagnet: thermal hydraulic:
  - Models:





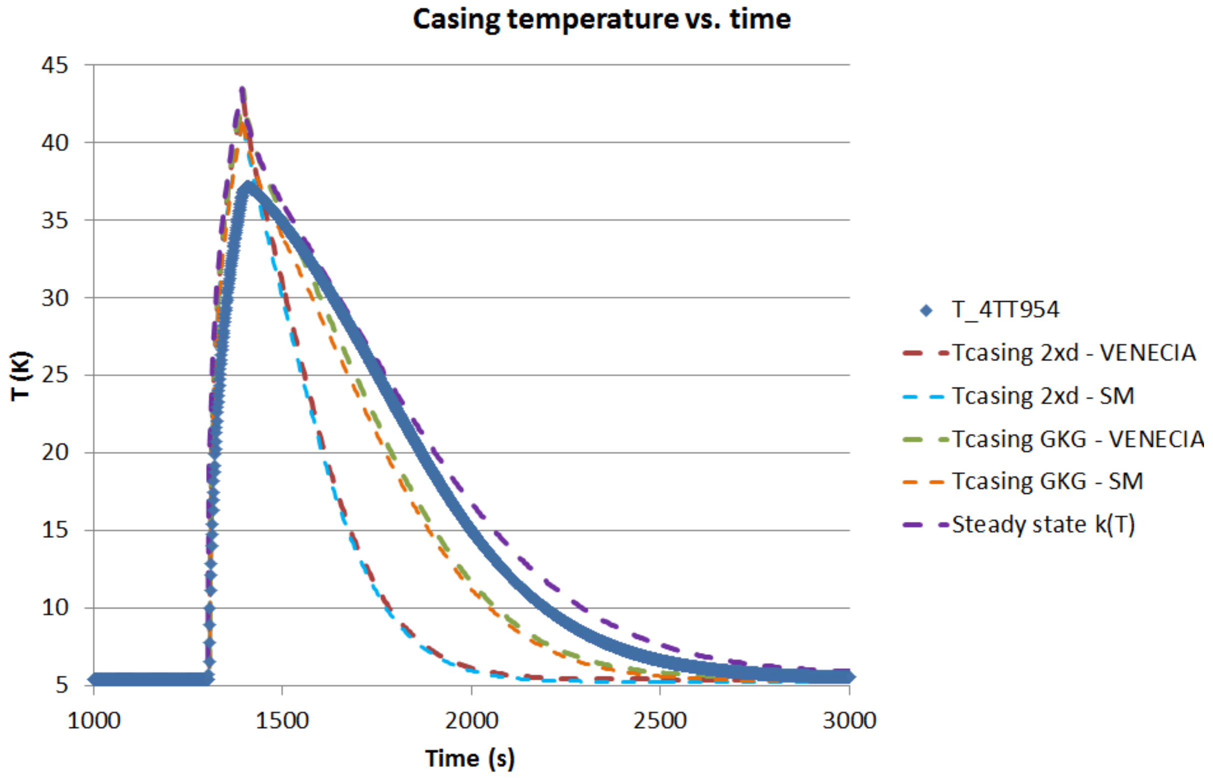


Analyses (8/12)

- VENECIA / SuperMagnet: thermal hydraulic:
  - Models:
    - Mock-up:
      - 11 cross sections (2D model);
      - Special resin with two extreme thermal conductivity:
        - » 2 × dolomite: λ (5 K) = 0.194 W/m/K;
        - » GKG: λ (5 K) = 0.032 W/m/K;
      - Mock-up length: 1 m;
    - HELIOS loop volume: ~28 L;

Analyses (9/12)

- VENECIA / SuperMagnet: thermal hydraulic:
  - Time response: 150 W during 90 s heat pulse:

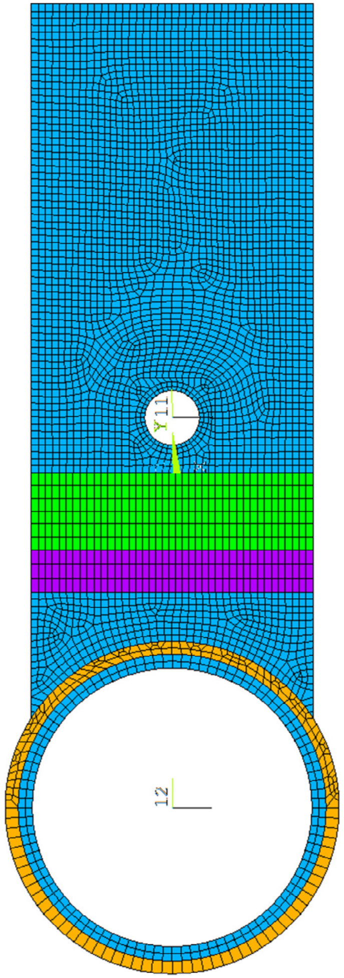


Analyses (10/12)

- VENECIA / SuperMagnet: thermal hydraulic:
  - Time response: 150 W during 90 s heat pulse:
    - Comparison between simulations and experiments show that the casing cooling once the heater is turn off takes more time than what we consider as the slower case, i.e. the special resin with low thermal conductivity (GKG like);
    - The experimental results suggests, as in the steady state measurements, the “apparent” thermal conductivity should be lower than expected;
    - The simulation with the $\lambda(T)$ estimated from steady state measurements is closed to the pulsed heat load experimental results;

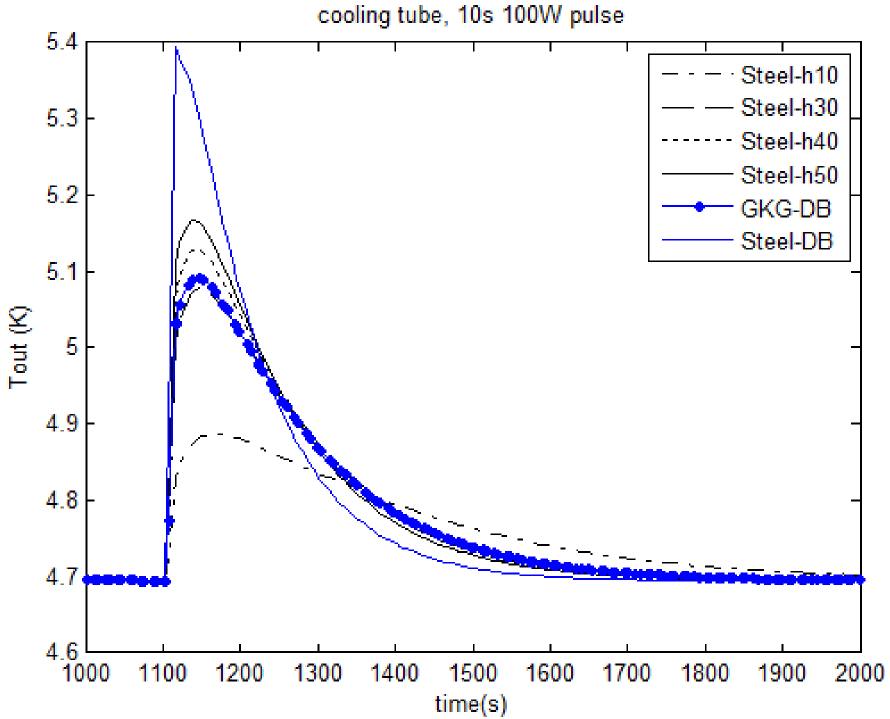
Analyses (11/12)

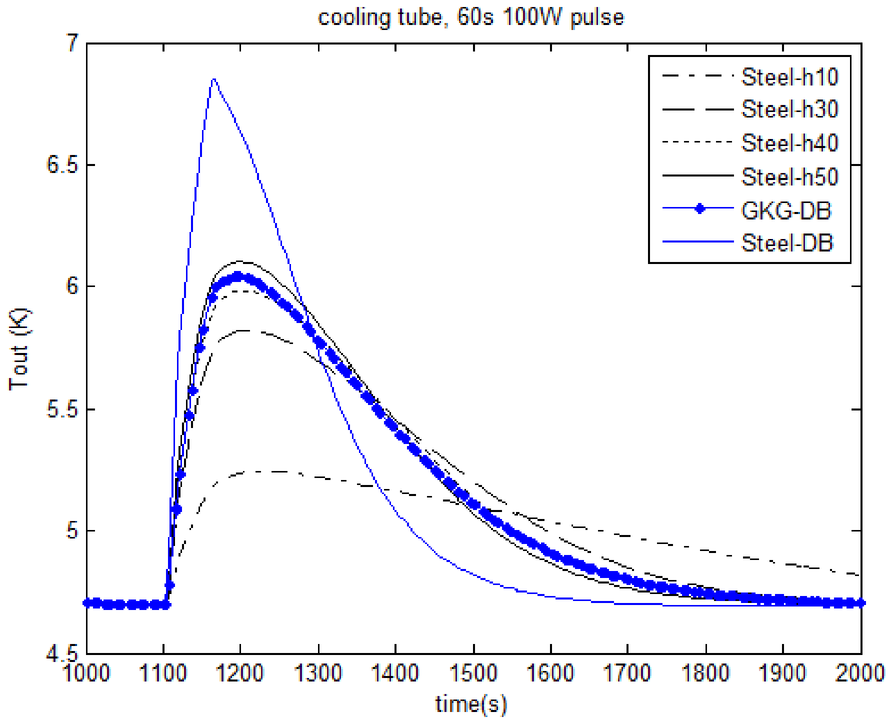
- VENECIA / SuperMagnet: thermal hydraulic:
  - Equivalent heat transfer coefficient:
    - Model change: special resin assumed to have steel properties;
    - Parametric study on the HTC applied on the inner surface of the tube;
    - Comparison between previous simulation (special resin) and equivalent HTC under pulsed heat load (100 W, 10 s & 100 W, 60 s) have been done;
    - Equivalent HTC around 40 W/m²/K can be used to model the thermal behavior of the mock-up;



Analyses (12/12)

- VENECIA / SuperMagnet: thermal hydraulic:
  - Equivalent heat transfer coefficient: reference special resin as GKG and HTC computed with Dittus-Boelter correlation (DB)





Conclusion

- Thermal diffusion analyses were used to determine a “apparent” resin thermal conductivity as a function of temperature from experimental data;
- Qualitative comparisons between experimental data and steady state and transient simulations suggest that the local cooling efficiency is lower than expected;
- Thermal hydraulic analyses show that the behavior of the local model of TF coil can be simplified as an equivalent heat transfer model;
- Using equivalent HTC saves CPU time since there is no need to compute HTC for every single channel (fixed parameter);

Perspectives

- Further analyze of the experimental test results are on going;
- Non destructive and destructive examination of the mock-up are on-going;
- Analyze alternative cooling pipe design proposal and cross check if they agree with the IO requirements;

References (1/2)

- [1]: Project Requirements (PR), v 5.3, IDM: 27ZRW8
- [2]: D. Arslanova and al., “Advanced thermal-hydraulic analysis of the ITER TF magnets performed with VENECIA code for 15 MA reference scenario”, Fusion Engineering and Design 88 (2013) 1486–1490
- [3]: C. Hoa and al, “Experimental characterization of the ITER TF structure cooling in HELIOS test facility”, Proceedings of the CEC-ICMC conference, Tuscon, Arizona, 28th June- 2nd July 2015, under review

References (2/2)

- [4]: ITER IO DEVIATION REQUEST on TFC Structures No. 22: Test program for confirmation of revised cooling pipe groove design and replacement of arc-brazing with resin bonding for TFCC sub-assemblies, v 1.3, NBWRAE