FROM RESEARCH TO INDUSTRY

THERMO-HYDRAULIC ANALYSES ASSOCIATED TO CEA DESIGN PROPOSAL FOR DEMO TF CONDUCTOR

R. Vallcorba, B. Lacroix, D. Ciazynski, A. Torre, F. Nunio, L. Zani,
Q. Le Coz, M. Lewandowska, M. Coleman

Zachodniopomorski Uniwersytet Technologiczny w Szczecinie

EUROfusion

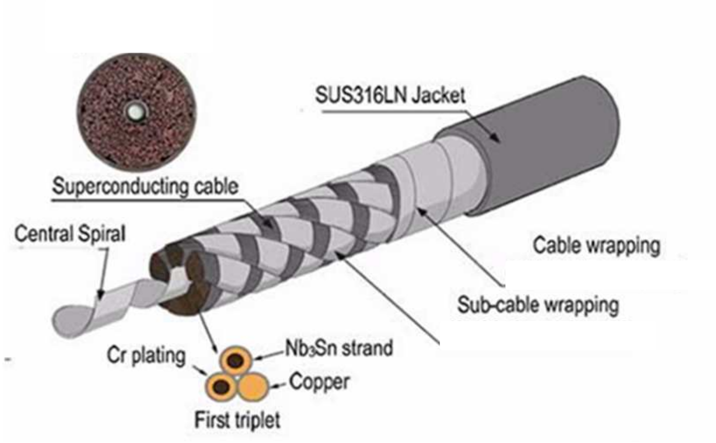
This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission."

www.cea.fr

Chats on Applied Superconductivity   Bologna, 14-16 September 2015

OUTLINE

- Context
- CEA design proposal
  - Conductor features
  - Magnetic field
  - Nuclear heating
- Thermohydraulic tools
  - Cryosoft THEA code
  - Simplified thermohydraulic code
- Thermohydraulic analysis
  - Main hydraulic parameters
  - Burn scenario
    - ✓ Influence of cooling channel in casing
    - ✓ ΔT margin
  - Quench scenario
    - ✓ Quench initiation, detection and protection
    - ✓ Hot spot assessment
- Conclusion and outlook



Sketch of the CICC' conductor, Courtesy of ITER

CONTEXT

EUROfusion supports programs to develop concepts for the fusion power demonstrator plant DEMO. In this framework, design activities are led at CEA for providing a Toroidal Field (**TF**) winding pack compatible with DEMO plant requirements.

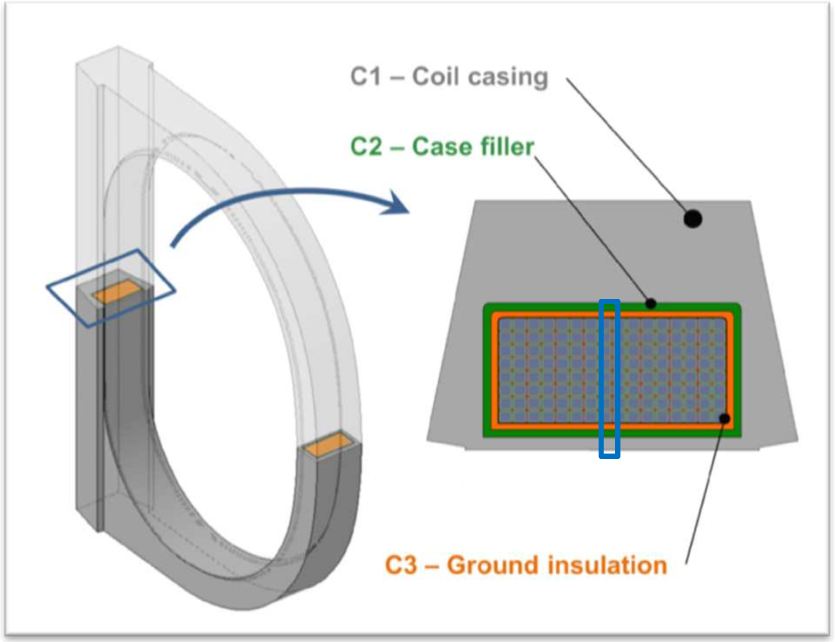
The CEA proposal design is mainly based on the ITER experience regarding design and qualification tests.

Main criteria

$\Delta T_{CS}=T_{CS}-T_{op} > 1.5$ K

$T_{\text{Hot Spot}} < 150$ K

From the specifications of the winding pack given by Process system code.



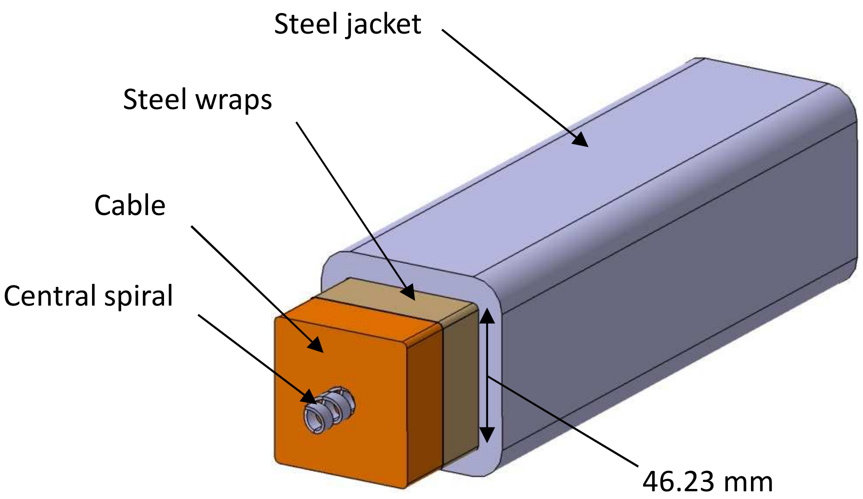
View of **TF** coil and its associate winding pack cross section

The future DEMO magnets proposed by CEA are likely to feature cable-in-conduit conductors (CICC) (the most successful from the stability point of view) cooled by forced flow of supercritical helium.

For each of the 16 D-shaped winding (2x392 m long), 10 double-pancakes wound in 10 turns with hydraulic length of 392 m.

Thermo-hydraulic analyses contributes to asses the conceptual conductor design and focuses the study on the most critical pancake, the central where the maximum magnetic field is reached

CEA CONDUCTOR: CABLE MAIN FEATURES



The conductor is a square-shaped Nb_3Sn double channel with a central spiral

TFEU4 OST Nb_3Sn strand

1392 SC + 294 pure Cu strands

Nominal current Iop = 95.5 kA

B_{eff} = 13.09 T → **T_{cs} = 6.25 K**

void fraction = 29 %

Double pancake design

→ hydraulic length = 392 m per pancake

Electrical model

(ε_{eff} , n_{eff}) = (-0.66 %,6)

Annular bundle region

$\Phi_{strands}$ = 1.024 mm

$Area_{He}$ = 594 mm^2

Φh = 0.48 mm

Central spiral

$\Phi in/\Phi out$ = 8x10

All conductors will be cooled by supercritical helium that will flow in the central channel at high speed and at lower speed in the bundle region.

In the normal operation, the central channel increase the heat removal rate

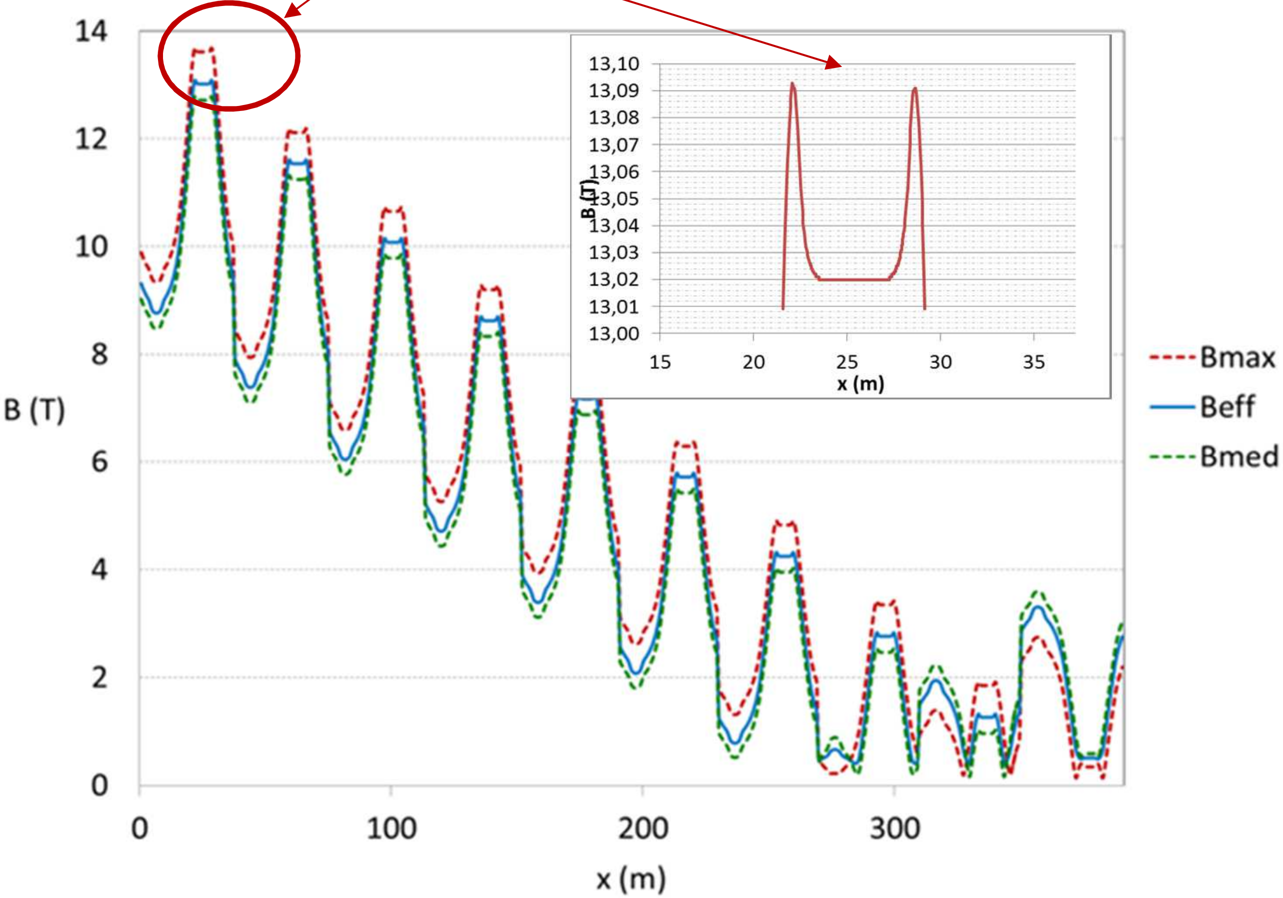
During the quench, it prevents over high pressure raise.

SIMULATION of one conductor on median pancake that is the most critical one

MAGNETIC FIELD

The conductor is subjected to the Effective Magnetic Field calculated with TRAPS code

B_{eff} max = 13.09 T



Courtesy of A. Torre et al.

$B(x) \longrightarrow T_{cs}(x)$

T_{cs} min = 6.25 K

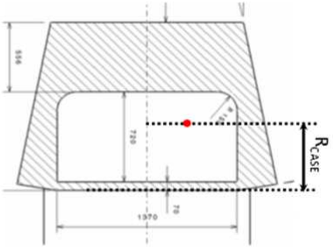
NUCLEAR HEATING MODEL 1/2

Neutron Heat (NH) load distribution

380 W per coil

Neutrons heating contribution (W/m^3)

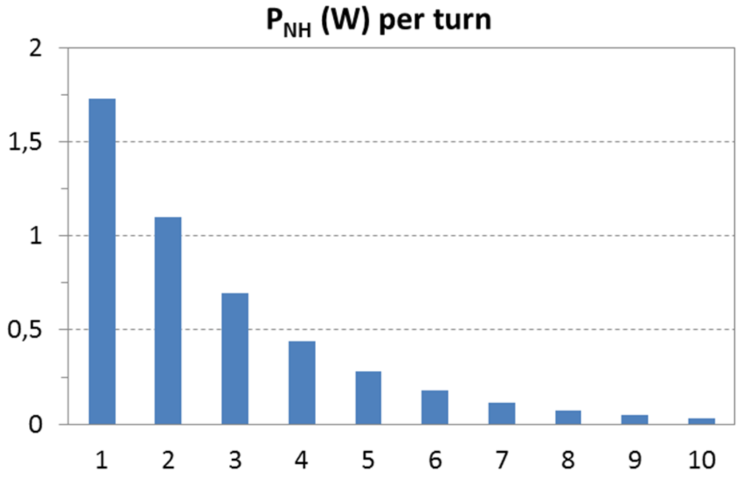
$$P_{NH} = 50 . e^{\left(-R_{CASE}/140\right)} \quad W/m^3$$



NH map in TF coil section across radial section

Conservative approach : P_{NH} constant in poloidal direction

Nuclear power deposited directly in cable + Nuclear power deposited in casing

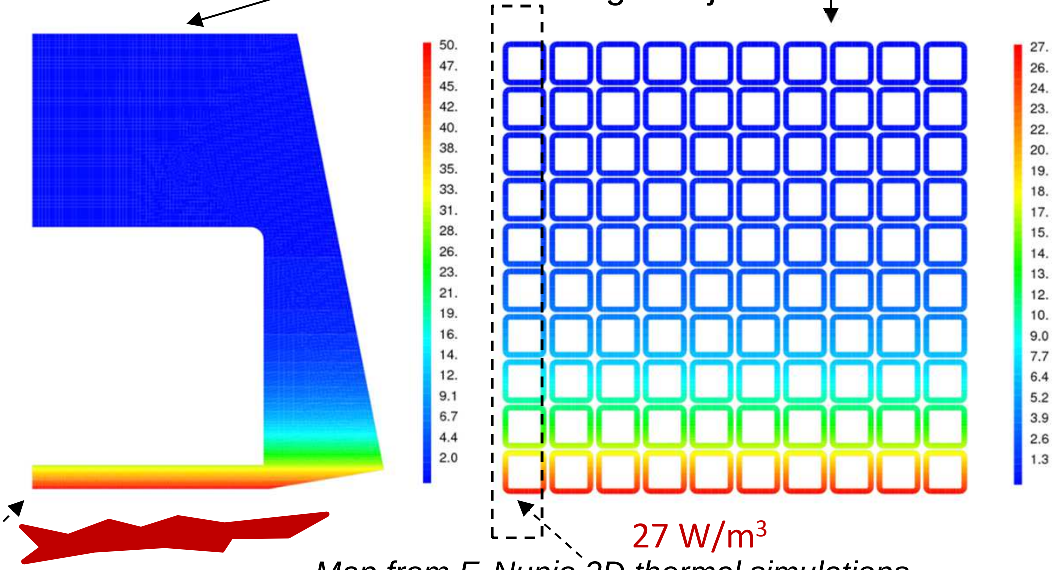


TF front case, 1st turn, 2nd turn …

Gradient over TF, radial decay

Courtesy of L.Zani et al.

2D heat diffusion from casing and jacket



50 W/m^3

27 W/m^3

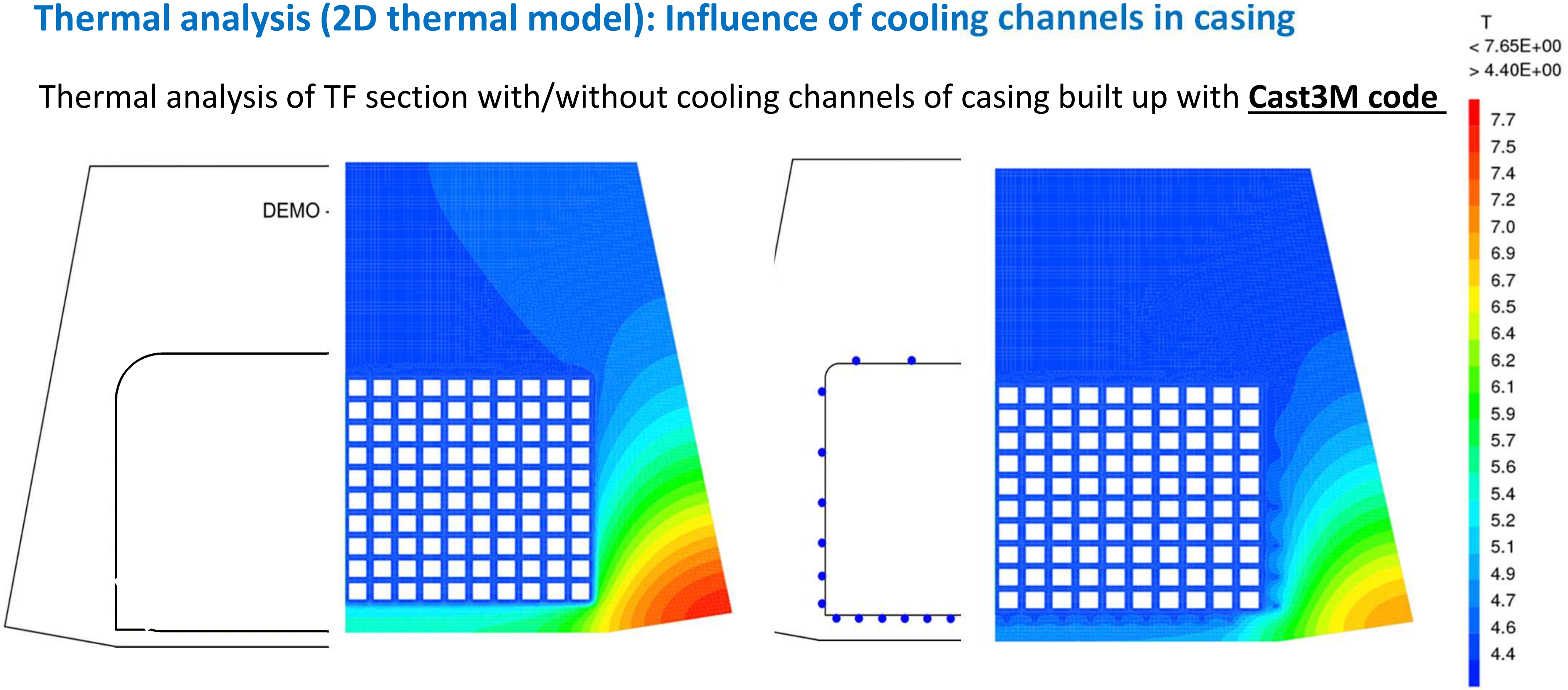
Plasma

Map from F. Nunio 2D thermal simulations

NUCLEAR HEATING MODEL 2/2

Thermal analysis (2D thermal model): Influence of cooling channels in casing

Thermal analysis of TF section with/without cooling channels of casing built up with **Cast3M code**



nominal case (reference scenario)

Max T = 7.65K

Nominal case with **cooling of casing**

Max T = 7.02K

Output data: Temperature, average heat load variation with time on all individual conductors
This cooling effect is included in the **thermohydraulic analysis** as an input data

Improvement:

ΔT = 0.63 K

THERMAL-HYDRAULIC CODES

Cryosoft **THEA** is computer program for the **T**hermal, **H**ydraulic and **E**lectric **A**nalysis of superconducting cables that computes the evolution of **the temperature**, **coolant flow** and **current distribution** in a cable **[1]** both in steady state (**BURN**) scenario and transient (**QUENCH**) modes.

1D model:

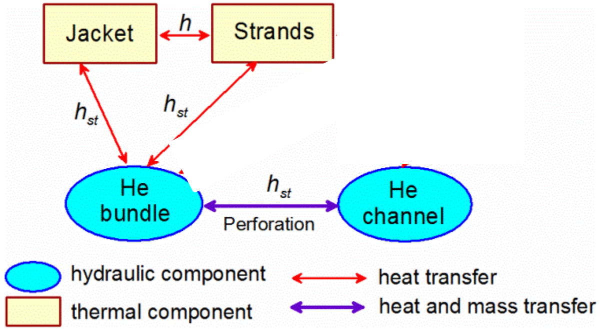
- Thermal components as **strands and jacket**
- Hydraulic components: **compressible flow (P, T, v)** in a channel
  - Heat exchange with the wall
  - Mass, momentum and heat exchange with other channels
- Electrical components, current diffusion among resistive and inductive current carrying materials **(I)**

Implicit coupled analysis
User controlled configuration

Simplified 1D **steady state model** [2]:

- Assumed heat deposition profile along a cable
- Instantaneous transverse heat transfer between the cable components
- Steady state energy and momentum balance equations for compressible flow

mass flow rates and temperature profile along a cable



[1] L. Bottura et al. , A numerical model for simulation of quench in the ITER magnets, Journal of Computational Physics 125, 26-41, N°0077
[2] M. Lewandowska, K. Sedlak, Thermal-Hydraulic Analysis of LTS Cables for the DEMO TF Coil, IEEE Transactions on Applied Superconductivity 24 (2014) 4200305

THERMAL-HYDRAULIC PARAMETERS AND LAWS

Main thermal-hydraulic parameters:

- **T_{inlet} = 4.5 K**
- **ΔP** = 6 – 5 = **1 bar**
- Friction factor correlations
  - Annular bundle region:
    - Darcy-Forchheimer in bundle (conservative with void fraction = 29 %, geometry of the cable)

    or
    - Katheder correlation
  - Central channel:
    - $f_{EU\ spiral} = 0.42 / Re^{0.1}$ (from measurements on 8/10 mm spiral)
- Heat transfer coefficients
  - $Nu_{turbulent} = 0.023\ Re^{0.8}\ Pr^{0.4}$ (Dittus-Boelter correlation)
  - $Nu_{laminar} = 4$

New neutron heating load map presented previously

Normal (burn) and off-normal (quench) simulations:

Burn reference : Simulation of 2 h burn + 4 h dwell

Quench reference: Simulation of 60 s

BURN SCENARIO – FRICTION LAWS 1/2

The choice of a reliable correlation for the flow in the bundle region is not obvious:

One possibility is the Katheder correlation (fKath) that is based on the Katheder's experimental data base for the **void fraction φ from 0.37 to 0.47.**

DEMO conductor
void fraction **φ =29 %**

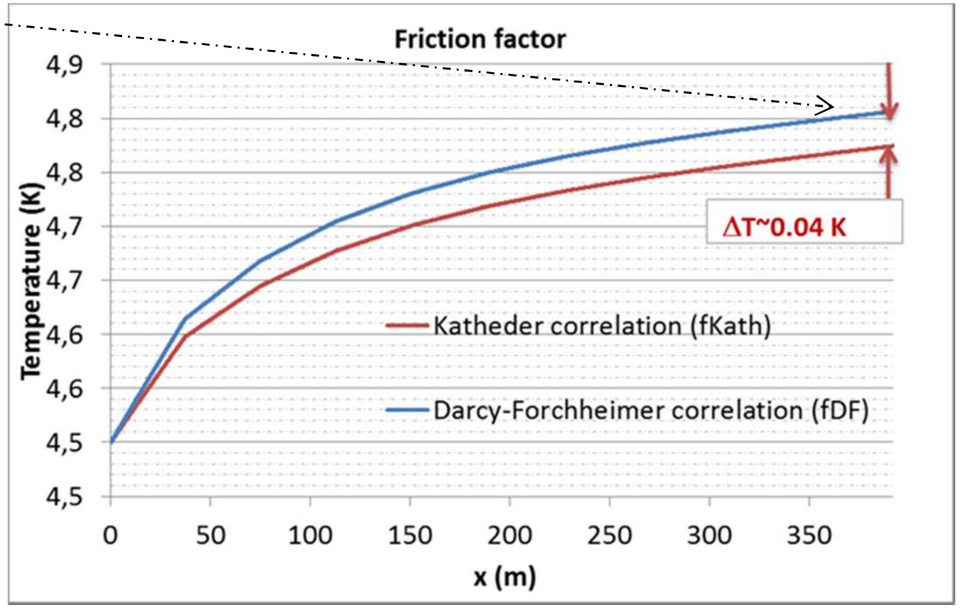
One other is, the Darcy-Forchheimer correlation (**fDF**) based on the porous medium analogy model with an extensive database that included the results of pressure drop measurements in 23 CICCs with the **void fraction ranging from 0.25 to 0.365**

fKath correlation predicts much smaller friction factors than the fDF correlation which proposes a more conservative approach for the DEMO conductor.

fKath $$f(\mathrm{Re},\varphi)=\frac{1}{\varphi^{\alpha}}\left[\frac{\beta}{\mathrm{Re}^{\gamma}}+\delta\right]$$

fDF $$f=\frac{D_h^2\varphi}{2K}\frac{1}{\mathrm{Re}}+\frac{D_h\varphi^2}{2}\frac{C_F}{\sqrt{K}}$$

φ	void fraction
Re	Reynolds number
K	permeability
CF	drag factor
Dh	hydraulic diameter

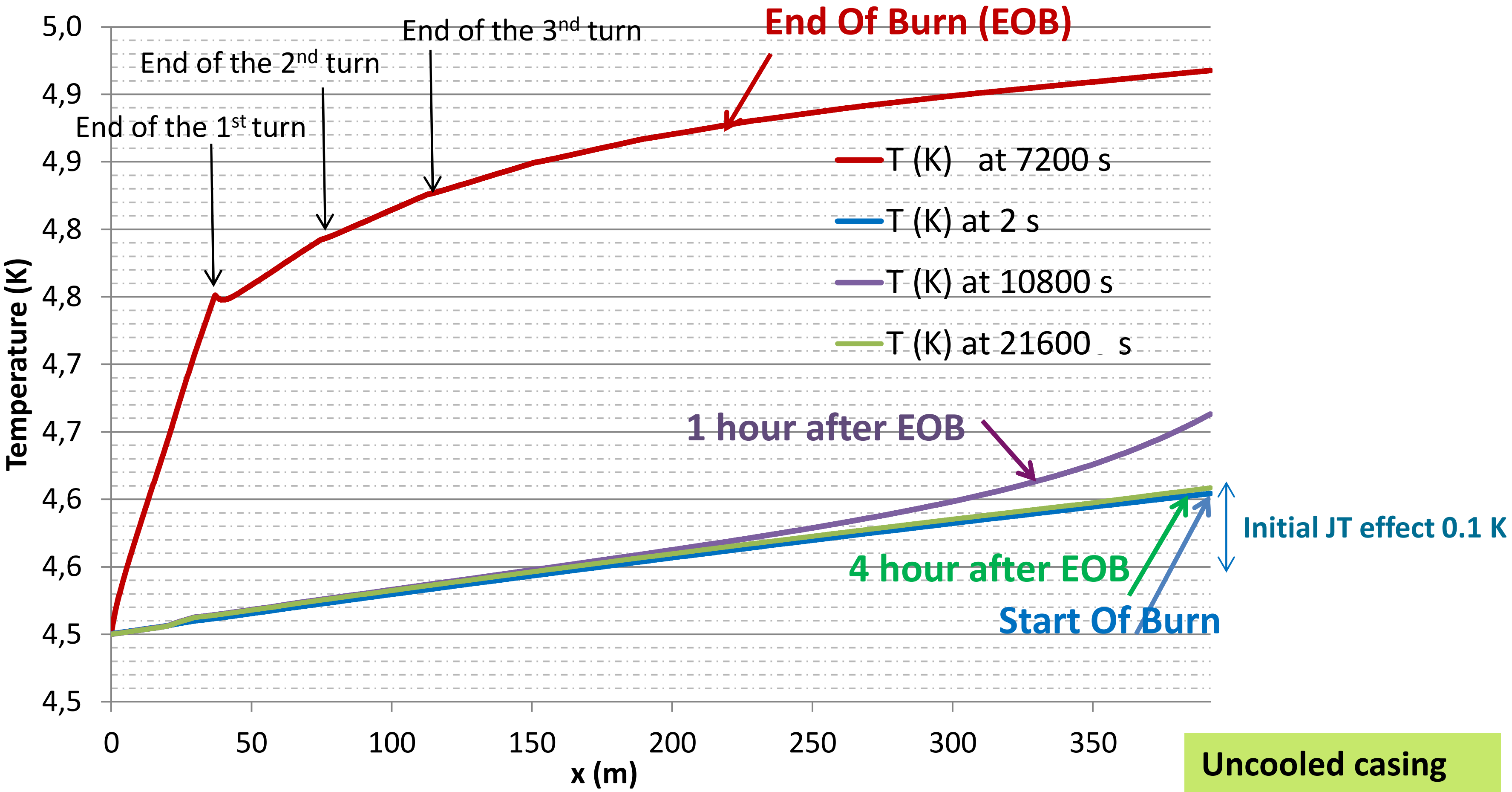


BURN SCENARIO – FRICTION LAWS 2/2

Mass flow (g/s) with	Bundle region		Central channel
f Kath ~ 28,4% greater	f Darcy-Forchheimer	f Katheder	
	5.57	7.77	5.85

Mass flow (g/s)	Bundle region		Central channel	
f DF	THEA at the outlet of conductor	Simplified model	THEA at the outlet of conductor	Simplified model
with cooling channels in casing	5.57	5.57	5.82	5.85

BURN SCENARIO – STEADY STATE TEMPERATURE

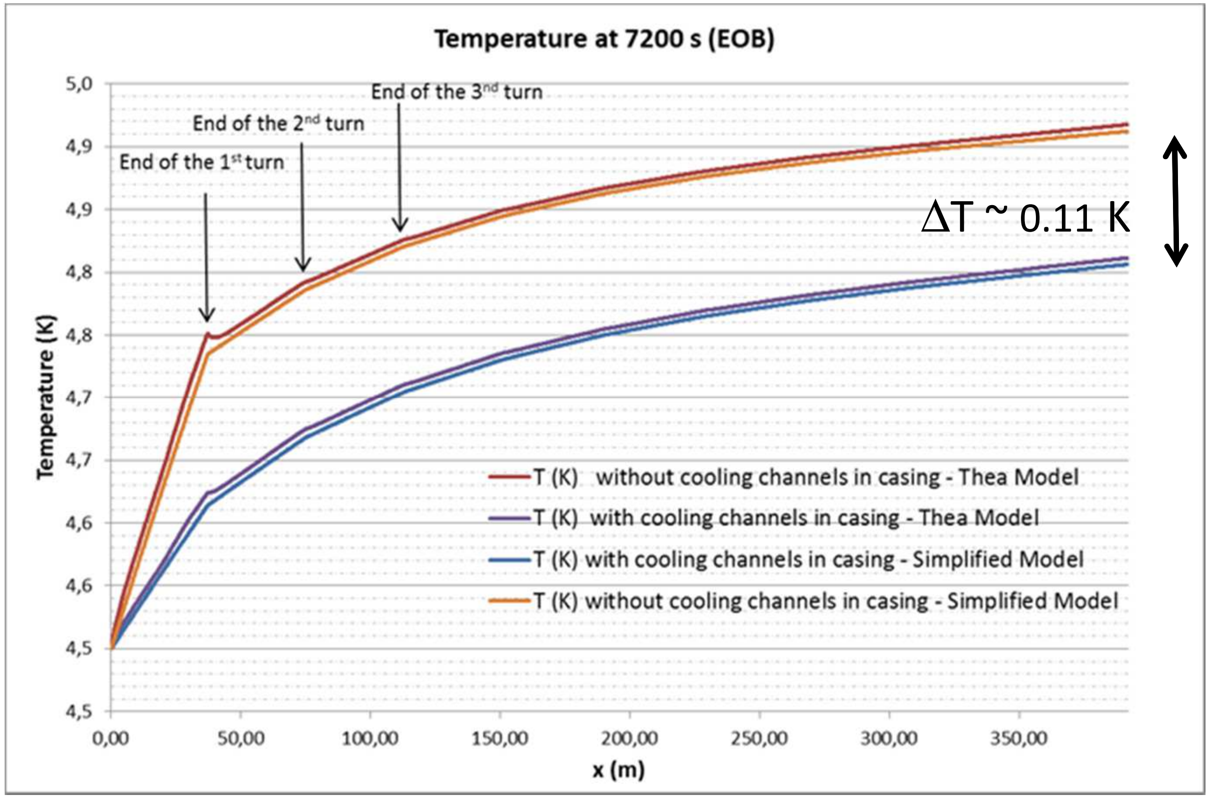


Uncooled casing
THEA code

Conductor temperature as function of space and time

BURN SCENARIO – CASING

improvement due to the cooling channels in casing



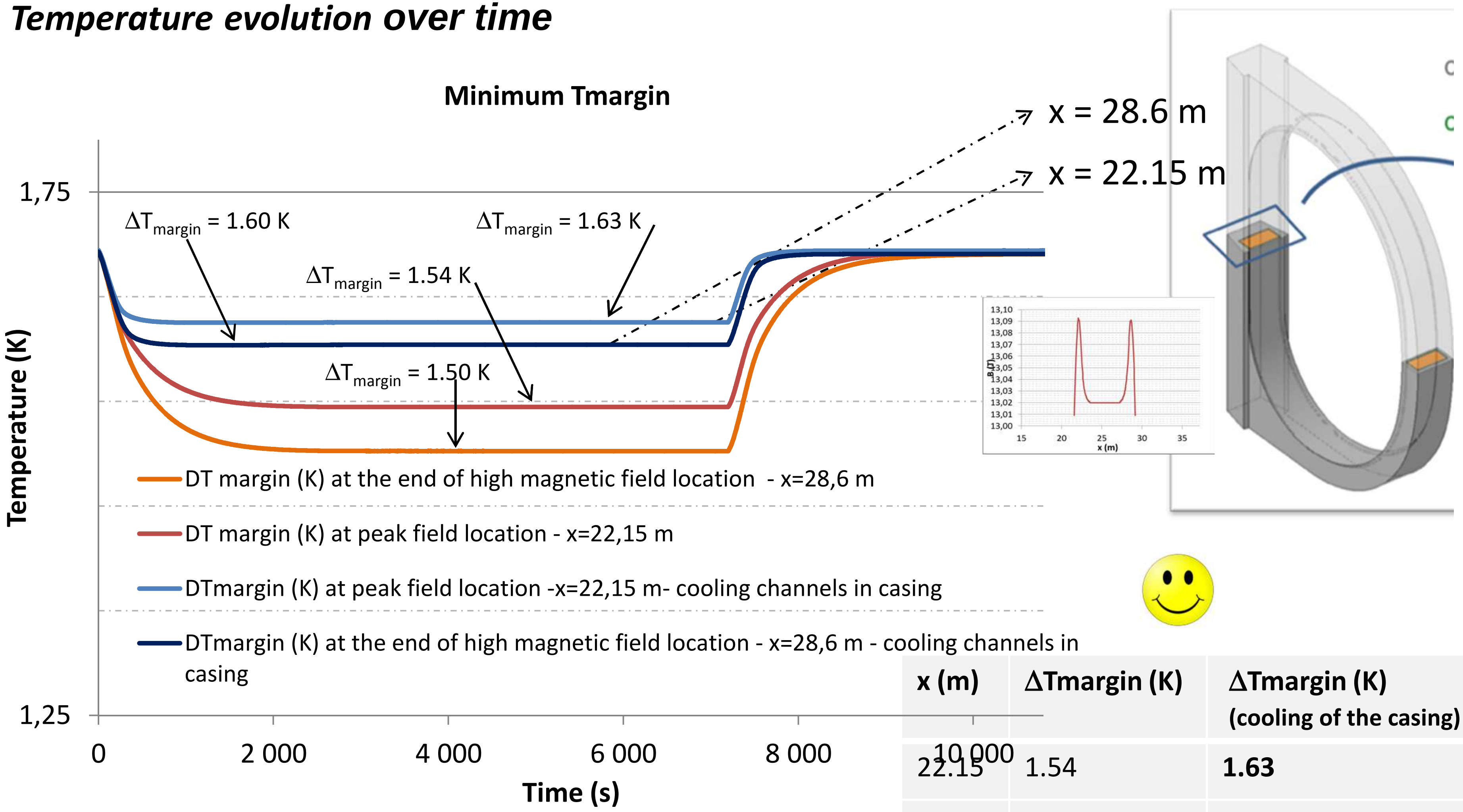
ΔT ~ 0.11 K

THEA and
Simplified model
Friction factor fDF

Temperature at end of burn (K) (EOB)	Without cooling	With cooling	Cooling improvement
x=392 m			
Thea Model	**4.918**	**4.811**	**0.11**
Simplified Model	**4.912**	**4.806**	**0.11**

BURN SCENARIO – ΔT MARGIN

Temperature evolution over time



x (m)	ΔTmargin (K)	ΔTmargin (K) (cooling of the casing)
22.15	1.54	**1.63**
28.60	1.50	**1.60**

SUMMARY OF THE BURN SCENARIO ANALYSIS

Related to the temperature …

- Steady state simulation (burn scenario) -> good agreement between THEA and simplified model **ΔT ~ 0.008 K**
- Friction factor -> f Darcy-Forchheimr correlation is a conservative approach **ΔT ~ 0.04 K**
- Cooled casing
  - ✓ Temperature gain on casing **ΔT ~ 0.63K**
  - ✓ And at the end of hydraulic length (x=392 m) **ΔT ~ 0.11K**
- Gain on ΔTmargin (with/without casing cooling) **ΔT ~ 0.03K**

☺

Max. Tmargin = **1.63 K** while,
under the most pessimistic scenario
Min. Tmargin = **1.50 K**

QUENCH SCENARIO

Objective:

Analysis of quench behavior along the conductor and hydraulic circuit in one of the most realistic scenarios:

- ✓ Local heat deposition at the peak field where the margin in temperature is minimal and the internal layer exposition on plasma maximal

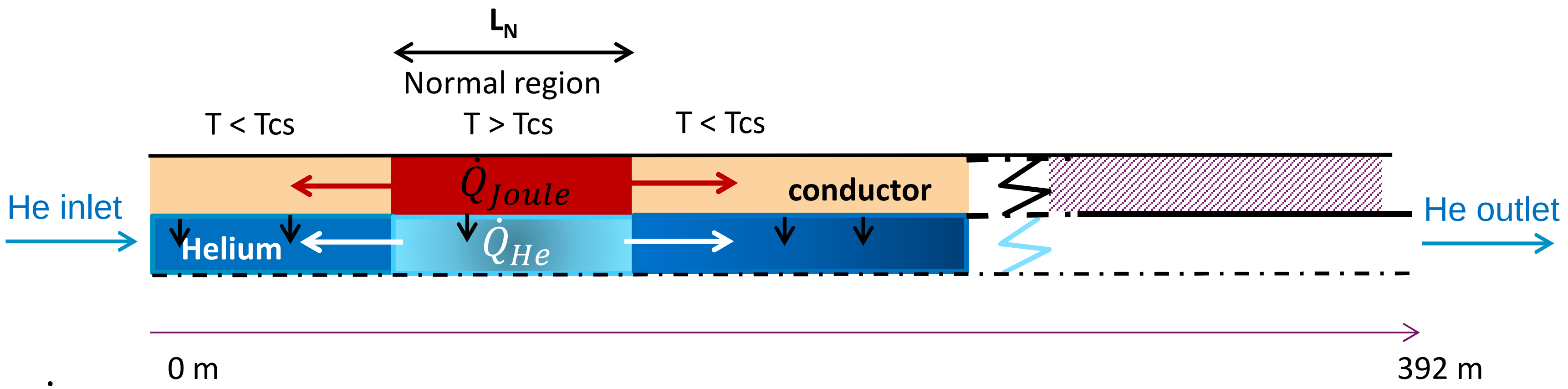
This scenario assess the hot spot temperature in conservative way.

QUENCH SEQUENCES AND HEAT TRANSFERT MODE

Main numerical quench sequences:

Quench initiation	-> Research of the MQE
Quench detection	-> Voltage threshold, holding time
Quench propagation	-> Fast Discharge Method

Main heat tranfert between conductor and Helium



$\dot{Q}_{Joule}$ Joule heat flux per length in the conductor (W/m) due to the current into the copper if T > Tcs

$\dot{Q}_{He}=hP(T-T_{He})$ Thermal power exchange by convection between the conductor and helium

Temperature front between the normal and superconducting region:

Vn: velocity of the normal zone

VHe: velocity of spelling induced by the warmed helium due to $\dot{Q}_{He}$

QUENCH: INITIATION AND DETECTION PARAMETERS

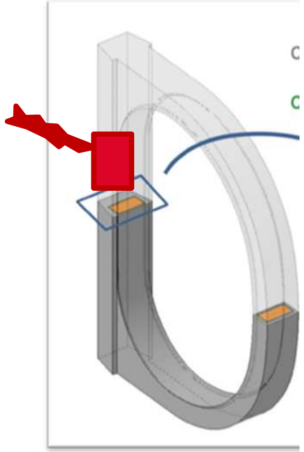
Quench is initiated locally at the peak field region by a minimum quench energy
This scenario is conservative for T hot spot assessment:

Minimun Quench Energy Power:

Perturbation of **100 ms** applied over **1 m** length (from 25 to 26 m) at **B = 13.02 T** →

MQE computed at 2700 W/m (12.07 mJ/cc of SC strand)

inboard leg

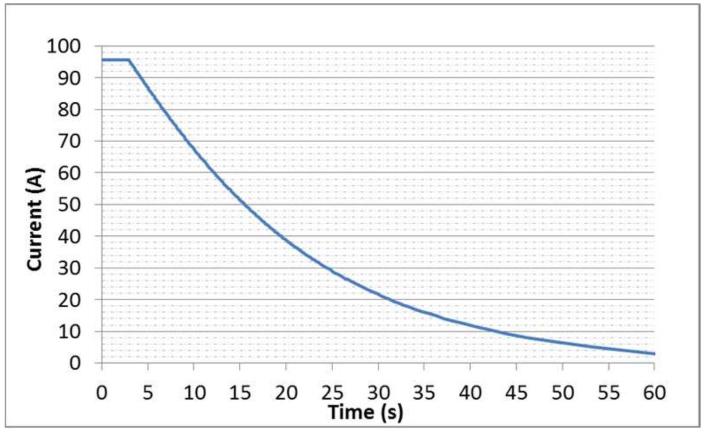


The quench detection is based on a resistive voltage threshold

- ✓ Voltage threshold $\mathbf{U_t = 0.5\ V}$
- ✓ Delay time $\boldsymbol{\tau_{delay} = 1.5\ s}$
- ✓ The Fast Safety Discharge (FSD)

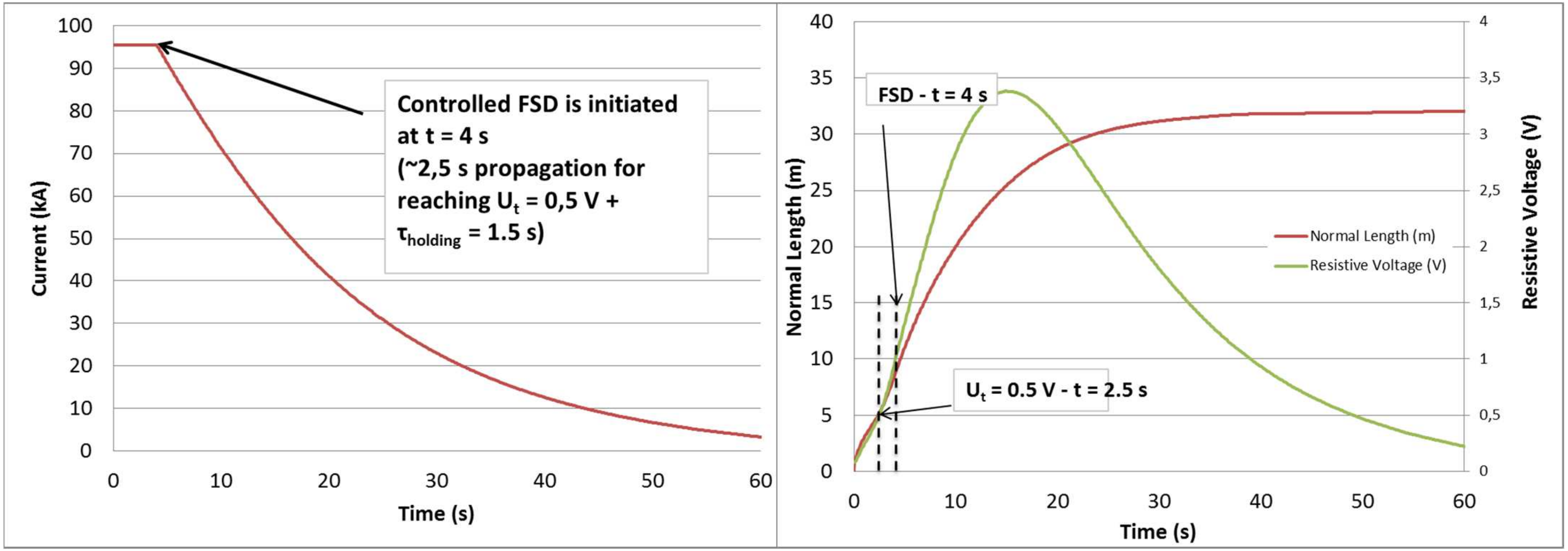
is triggered after 4 s and the current decrease is

controlled taking into account the heating of the dump resistor.



Normal zone is established by a 2x minimum energy input
over limited length in the superconductor
and propagate then.

DETECTION AND PROPAGATION PHASES


Controlled FSD is initiated at t = 4 s (~2,5 s propagation for reaching U_t = 0,5 V + $\tau_{holding}$ = 1.5 s)

FSD - t = 4 s

U_t = 0.5 V - t = 2.5 s

Current evolution during detection and propagation phases

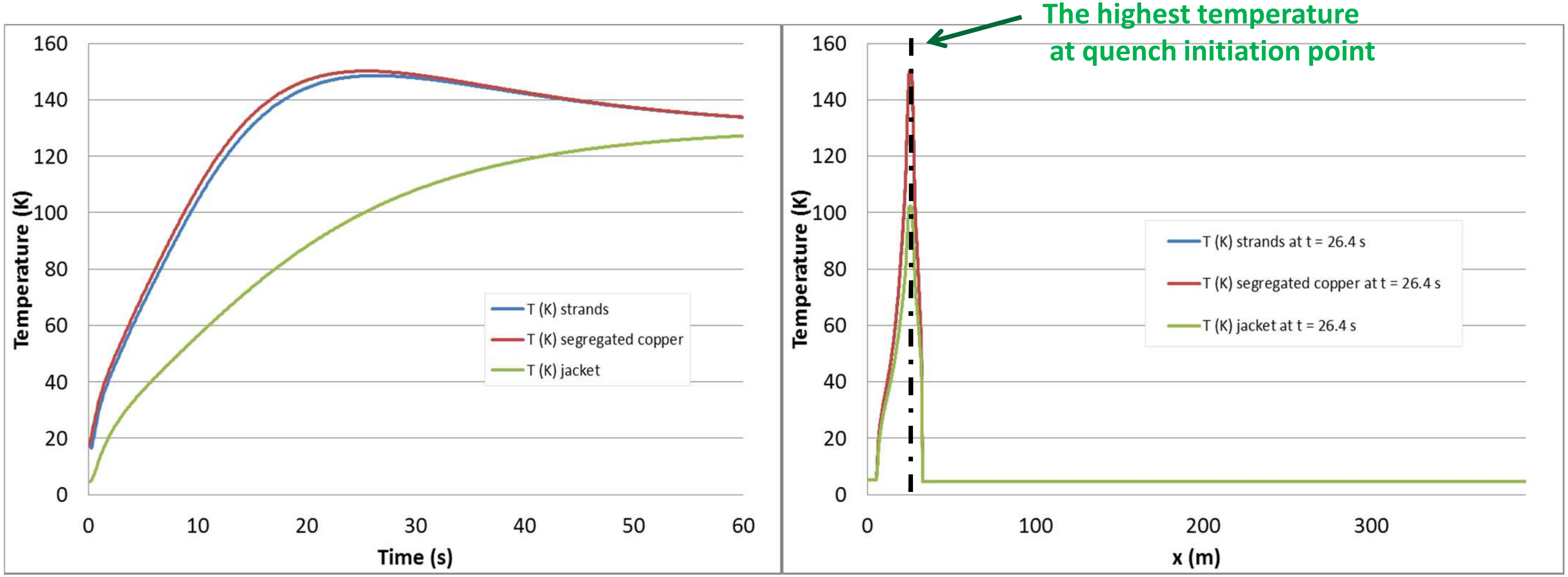
Normal zone starts to grow, it will continue to expand under combined actions of Heat conduction and ohmic heating

~5.22 m of quenched length at t=2.5 s for reaching Ut = 0.5 V

~8.56 m of quenched length at t=4 s for FSD

~32 m of quenched length at t=60 s

T HOT SPOT



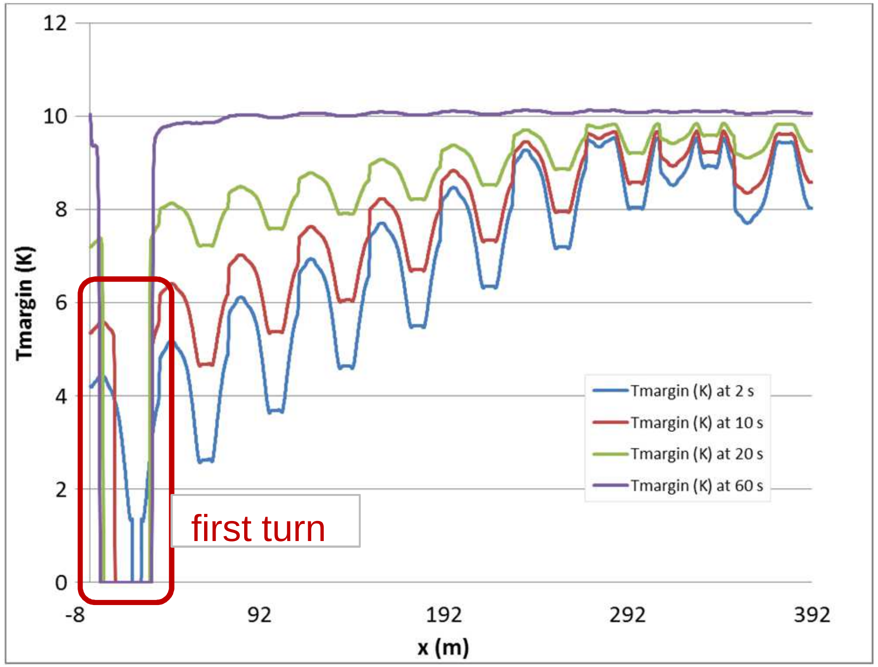
The highest temperature at quench initiation point

Temperature vs space and time

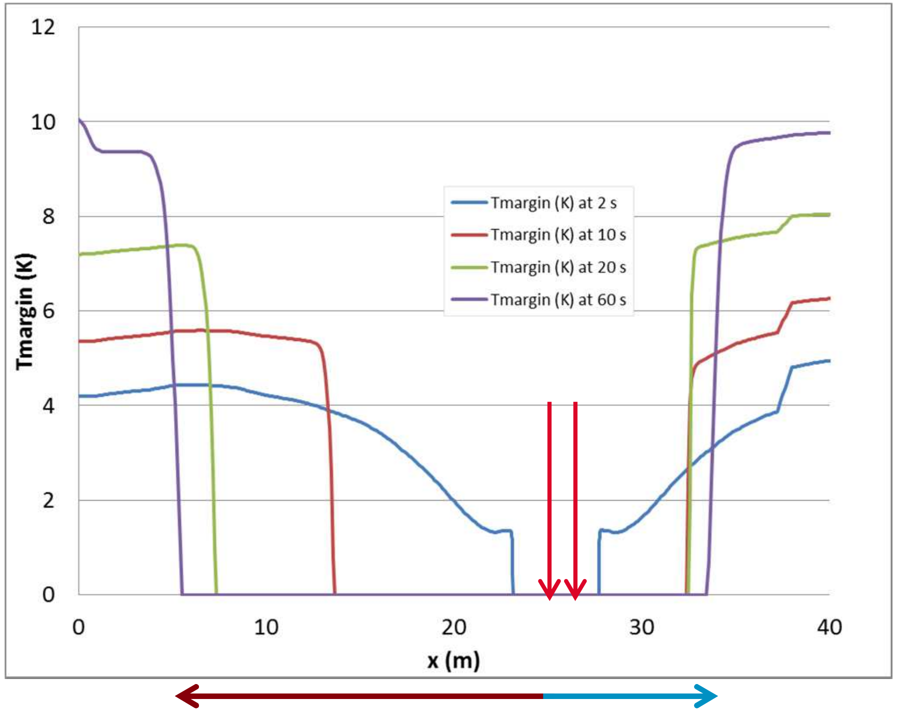
T hot spot = 148.6 K

Requirement is met

NORMAL REGION



ΔT margin illustrates the Normal zone advancing along the conductor



Normal region at 60 s

Velocity from disturbed area is higher towards He inlet than towards He outlet. The disturbance location is closer to He inlet

CONCLUSION AND OUTLOOK

- ☐ Transient thermo-hydraulic studies are performed on CEA conductor proposal for winding pack of DEMO TF magnet in the currently allocated space proposed by the PROCESS system code.
- ☐ Two models (THEA code and simplified model) are used, in complementary approach, to investigate the temperature behavior.
- ☐ Currently plasma **burn reference scenario** and one of the **realistic quench scenario** are analyzed for the most critical pancake, i.e. median one.
- ☐ **Burn scenario:**

The long pulse operation of 2 hours plasma burn and 4 hour Dwell is analyzed under proposed operating values and criteria. For this, it is used detailed electromagnetic and a new neutron heating load maps diffusing on the casing and falling directly to the conductor. In addition to that, analyses are led in order to assess the sensitivity of cooling channels in casing. In all cases the temperature margin criteria of 1.5 K is respected, in particular in cooled casing case with ΔTmargin equal to 1.63 K.

- ☐ **Quench scenario:**

The requirement for $T_{\text{hot spot}}$ is met (149.2 K < 150 K)

- ☐ In this first assessment of the thermo-hydraulic efficiency of the CEA conductor, the analysis shows than the thermohydraulic operating values can operate correctly.
- ☐ In spite of the fact that the design conductor proposes an acceptable thermohydraulic solution, the mechanical analysis ongoing could validate in a future the more realistic winding pack area.