A 3D electromagnetic model for eddy currents analysis in superconducting magnets for fusion applications

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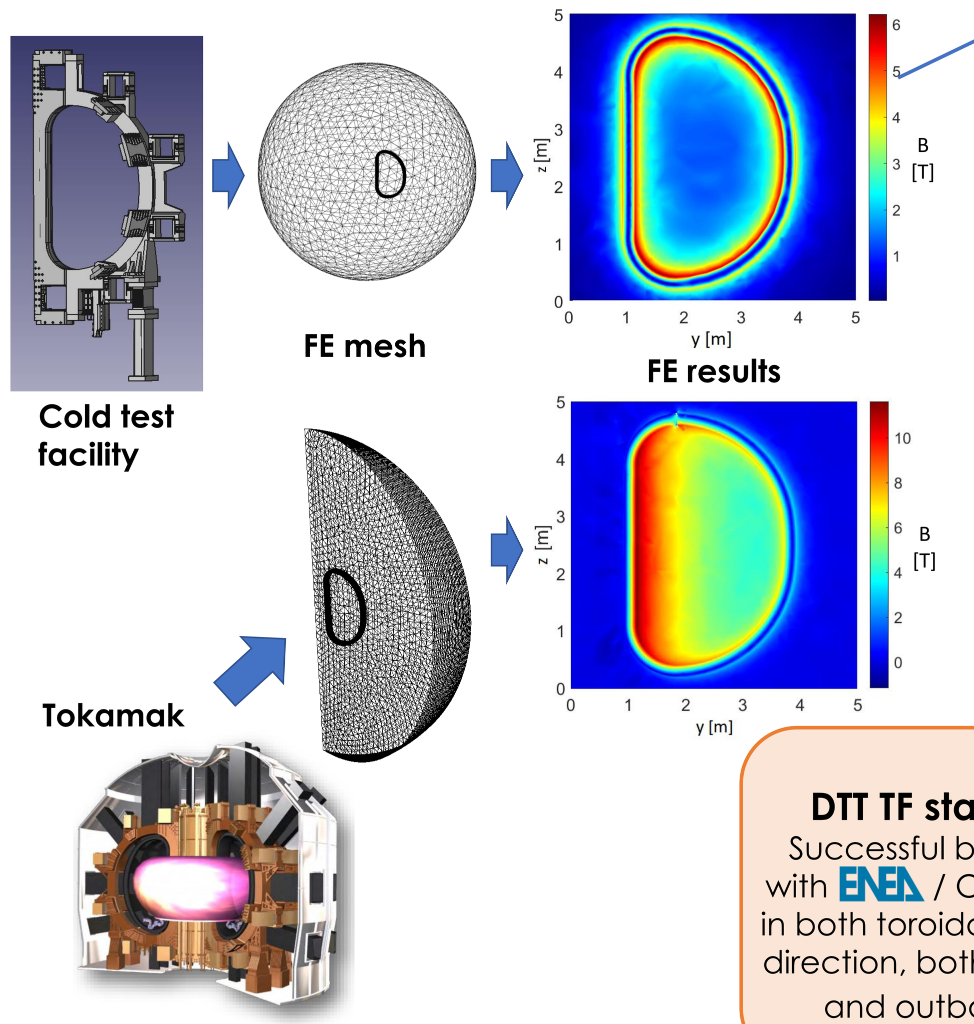
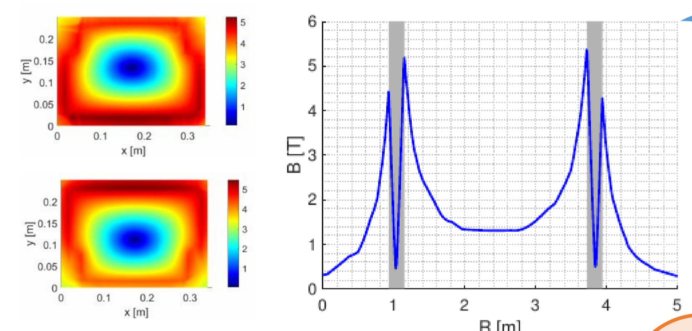
Introduction

The magnetic confinement of the plasma in a tokamak fusion reactor is guaranteed by three different sets of coils
Strong Lorentz forces arise due to high currents and magnetic fields → bulky metallic structures are needed
In tokamak machines the magnetic field is time dependent → eddy currents in the structures → power deposition close to the WP → erosion of the temperature margin
An open source, 3D transient FE tool has been developed to evaluate this power deposition, then used as input to the 4C code (TH simulation of SC magnets)
Application: fast current discharge in a Divertor Tokamak Test (DTT) TF coil [R. Albanese, et al., Fusion Eng. Des. 146 (2019) 194–197]

3D magnetostatic model





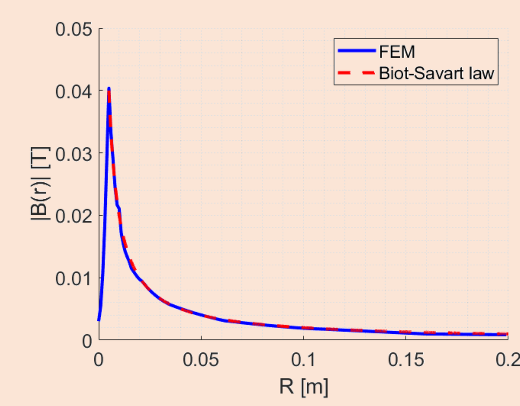
Benchmark

- Biot – Savart law
- Static field at DTT TF (results from ENEA)

Simulation of the steady state operation of the coil both in stand alone and in tokamak configuration

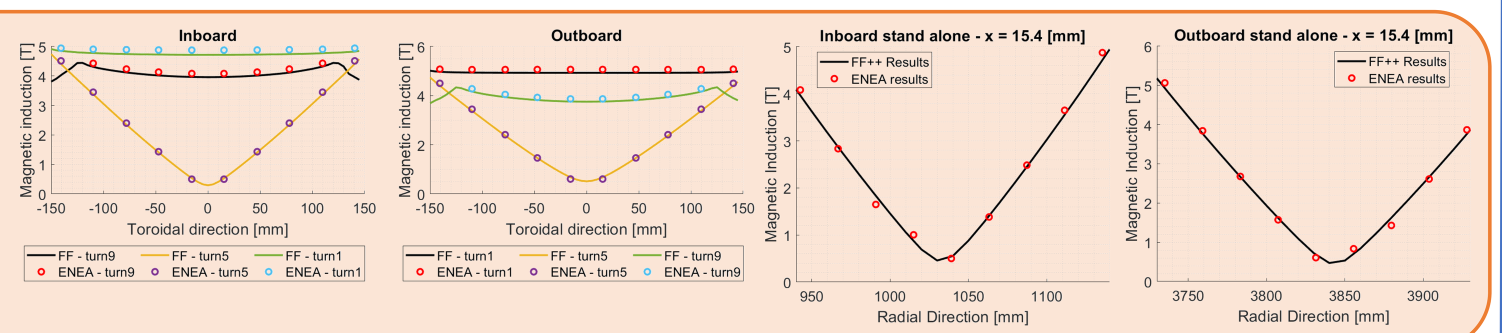
Biot – Savart

1 [m] long cable with diameter of 1 [cm] has been modeled.
Good agreement between FE and theory outside the conductor



DTT TF static field

Successful benchmark with ENEA / Opera results in both toroidal and radial direction, both at inboard and outboard leg



Electro-dynamic model

- Time dependent driver (transport current)
- The generated time dependent electrical field induces in conductive materials eddy currents that must be considered in the equation solution and deposit power

Faraday law → $\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$

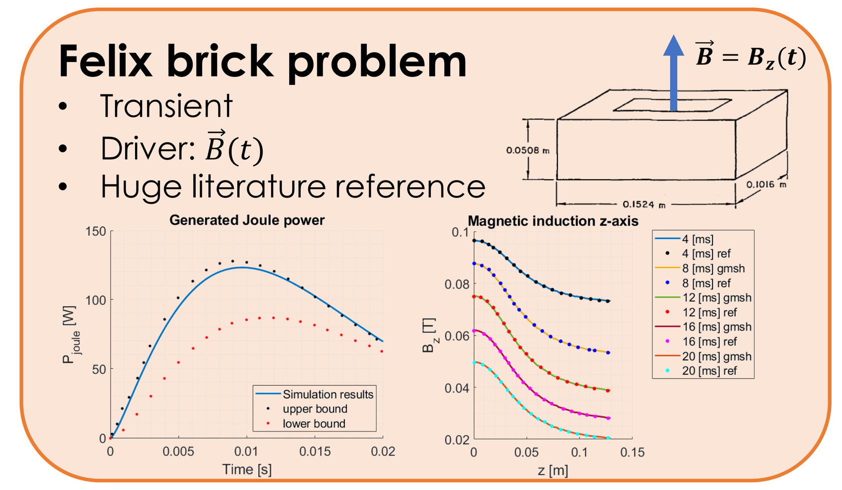
Eddy current equation → $\nabla \times \vec{B} = \mu(\vec{J} + \vec{J}_{eddy})$

Benchmark

- The Felix brick problem
- Simplified coil model

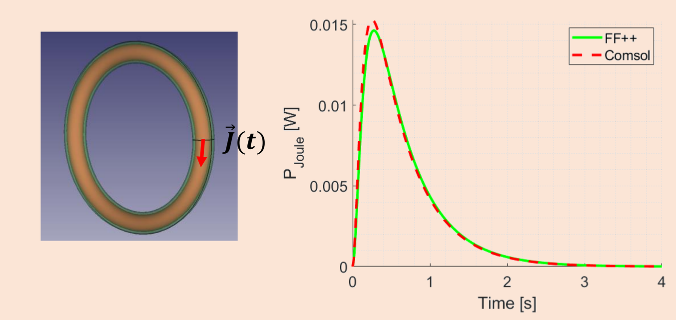
Felix brick problem

- Transient
- Driver: $\vec{B}(t)$
- Huge literature reference

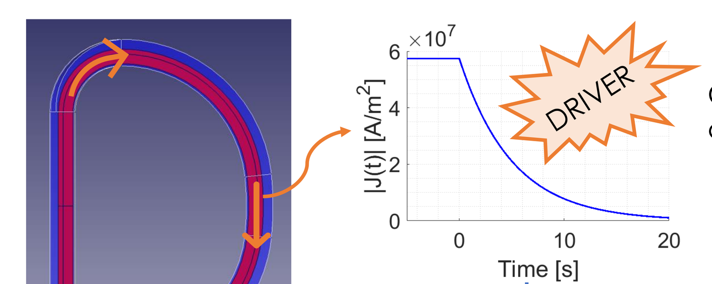


Simplified coil model

- Transient
- Driver: $\vec{J}(t)$
- Benchmarked against commercial FE software



Simulation of a fast current discharge in a single DTT TF

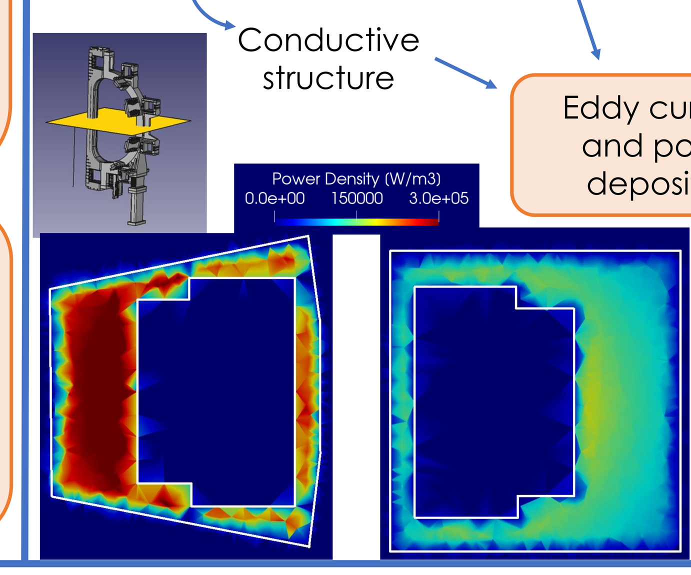


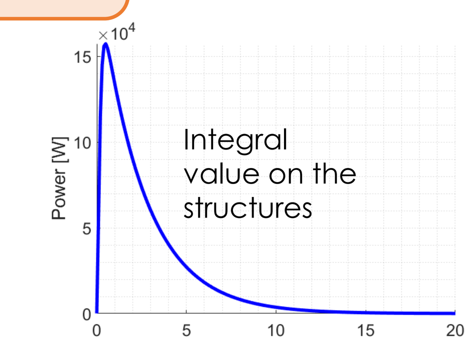
Characteristic time constant = 5 s

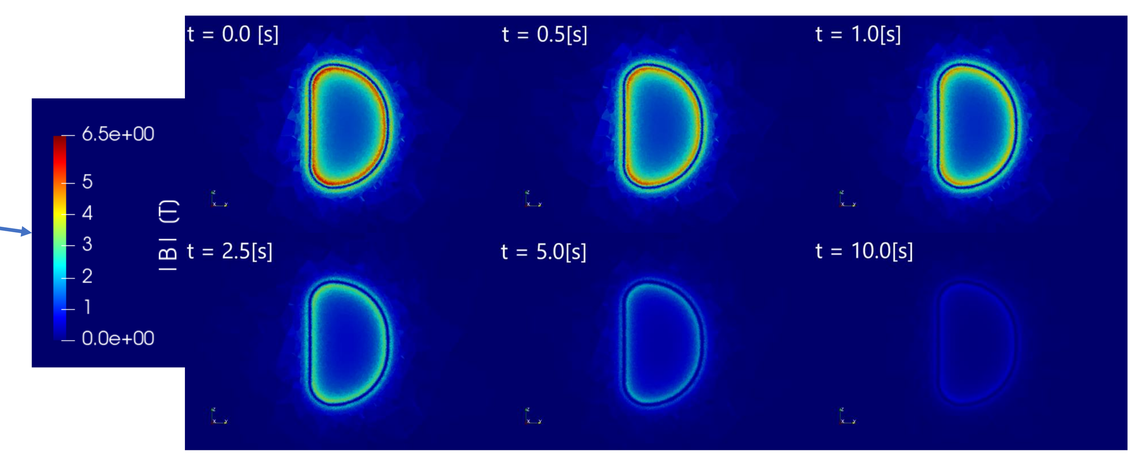
$\vec{B}(t)$

Conductive structure

Eddy currents and power deposition



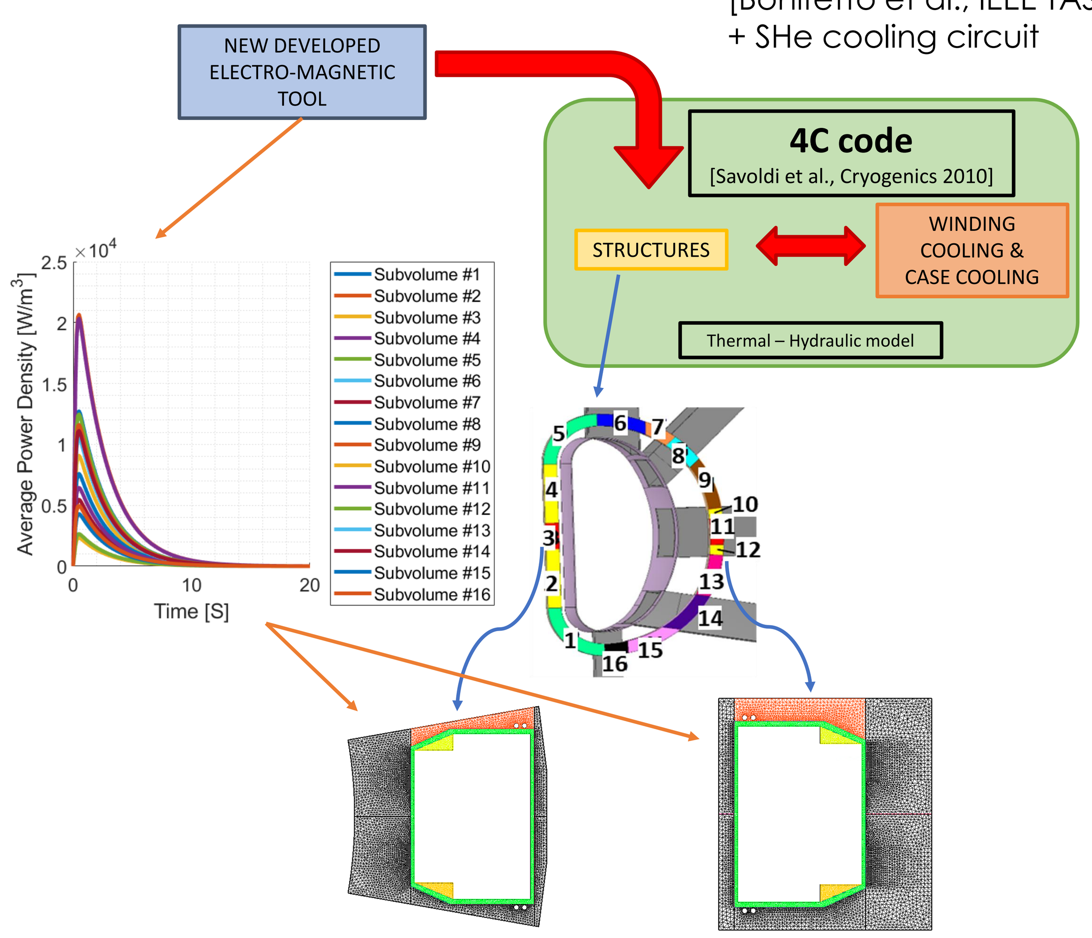




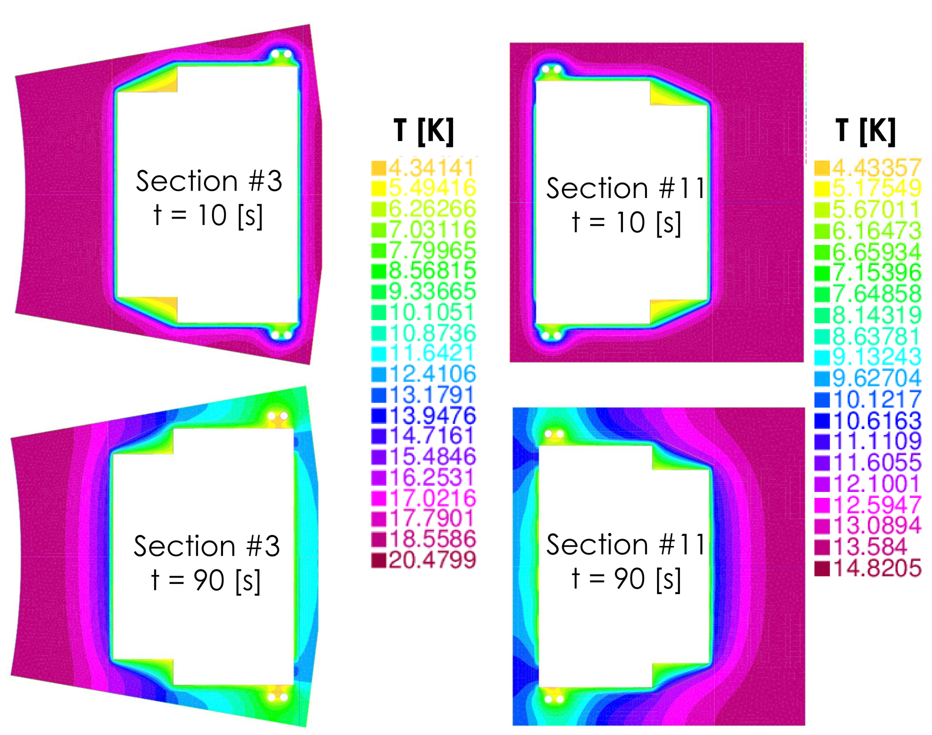
- Magnetic induction evolves following the driver
- 3D nature of the tool allows
  - computing a detailed distribution
  - detect non-uniformities in the power deposition, due to the different geometry of the inboard and outboard cross sections (→ different electrical resistences depending on the thickness of the solid structure)

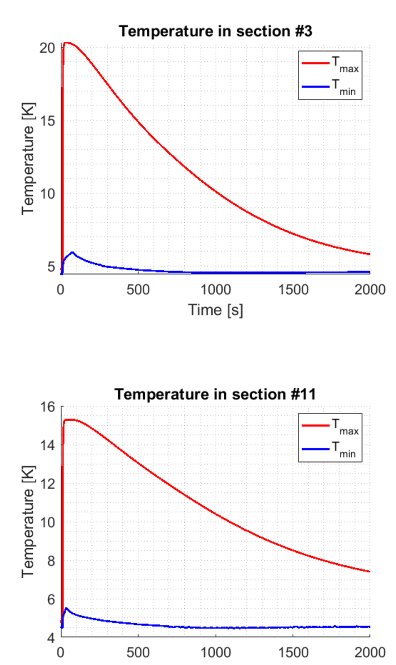
EM + TH model of DTT TF

TH model of DTT TF described in [Bonifetto et al., IEEE TAS 2020] + SHe cooling circuit

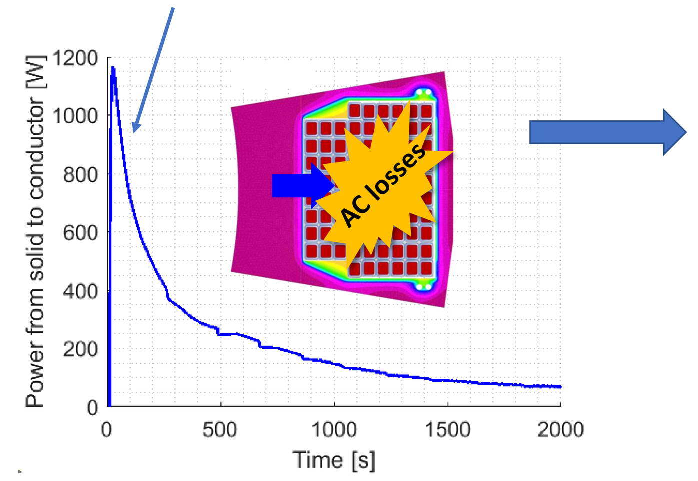


- Due to the power deposition, a substantial temperature increase within the structures is computed
- After the end of the power deposition, the magnets cools down below 7 [K] again in ~1 [h]



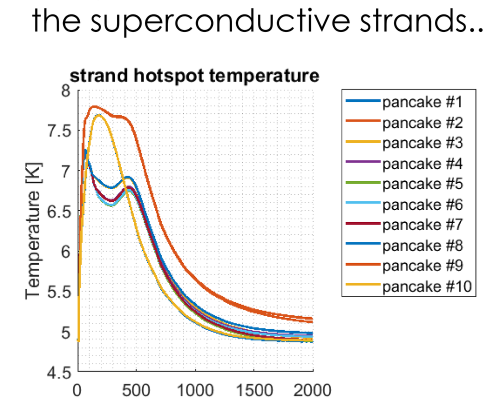


Power deposited by eddy currents in the structures
→ removed by the casing cooling channels
→ transferred to the WP through the ground insulation

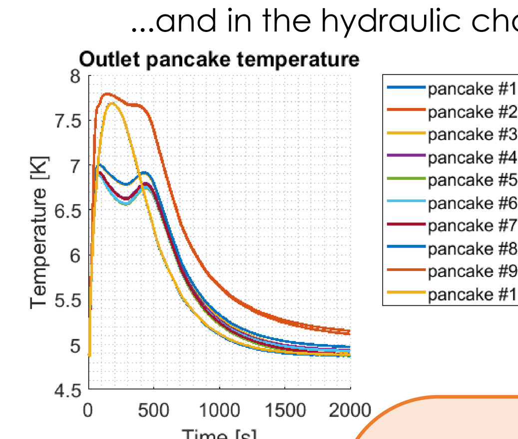


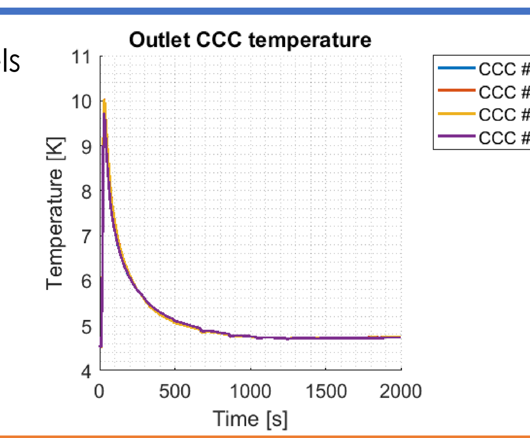
AC losses also deposit power directly in the WP:
Eddy currents in casing + AC losses in WP → strand temperature increase

Temperature increase is detected in the superconductive strands...

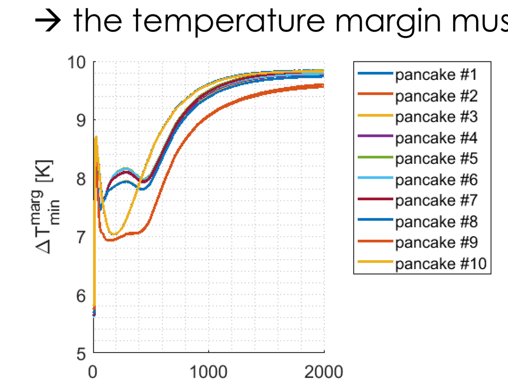


...and in the hydraulic channels





Strand temperature increase could cause a loss of superconductive properties
→ the temperature margin must be evaluated



$\Delta T_{min}^{marg} > 1.4\ [K]$

Conclusions & perspective

- A first-of-a-kind 3D transient electro-dynamic model for eddy current computation in SC magnets for fusion has been developed, using open-source tool FreeFEM++
- The tool has been successfully benchmarked against literature and state of the art software results
- Results used as input to the 4C code to assess the temperature margin evolution during the DTT TF coil fast current discharge → no quench is expected during cold tests

NEXT STEPS:

- Improvement of the coupling (EM + TH) strategy to include thermal feedback on EM model
- Application of the model to different transients / magnets