# EU-CN: Model and analysis of HTS performance degradation after quench

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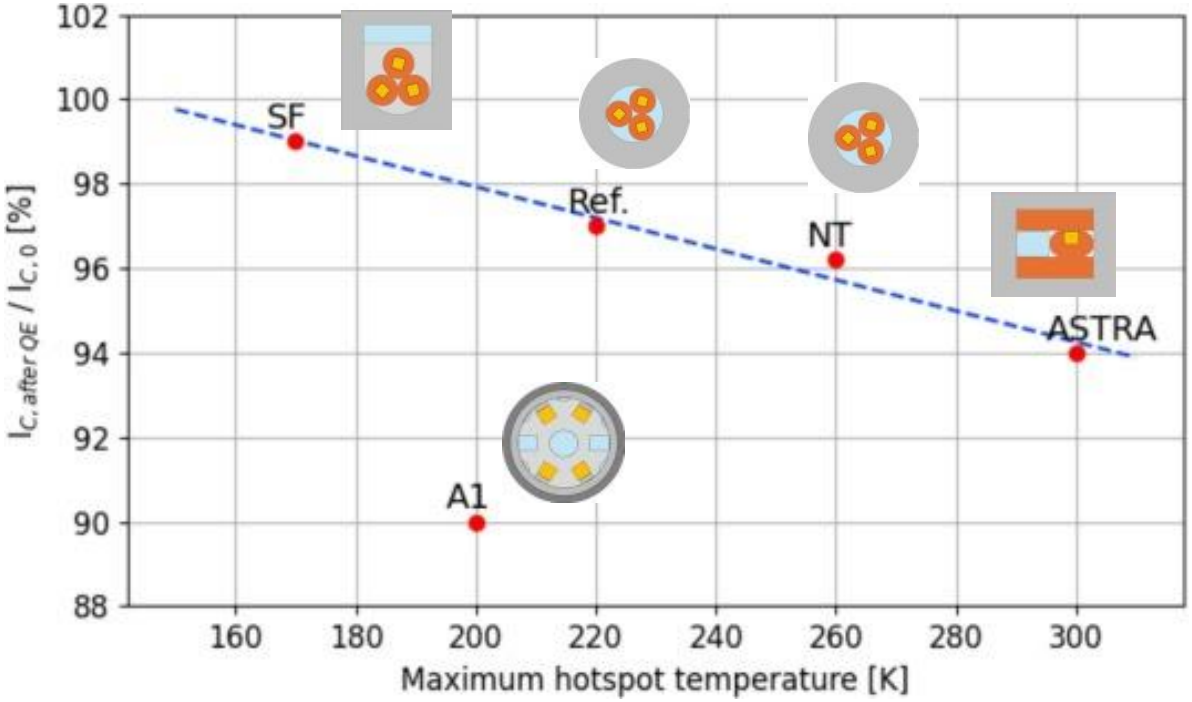
# Outline

- Background & aim
- Full 3D thermal-hydraulic + electric model
- Full 3D thermo-mechanical model
- Conclusions

# Background & aim

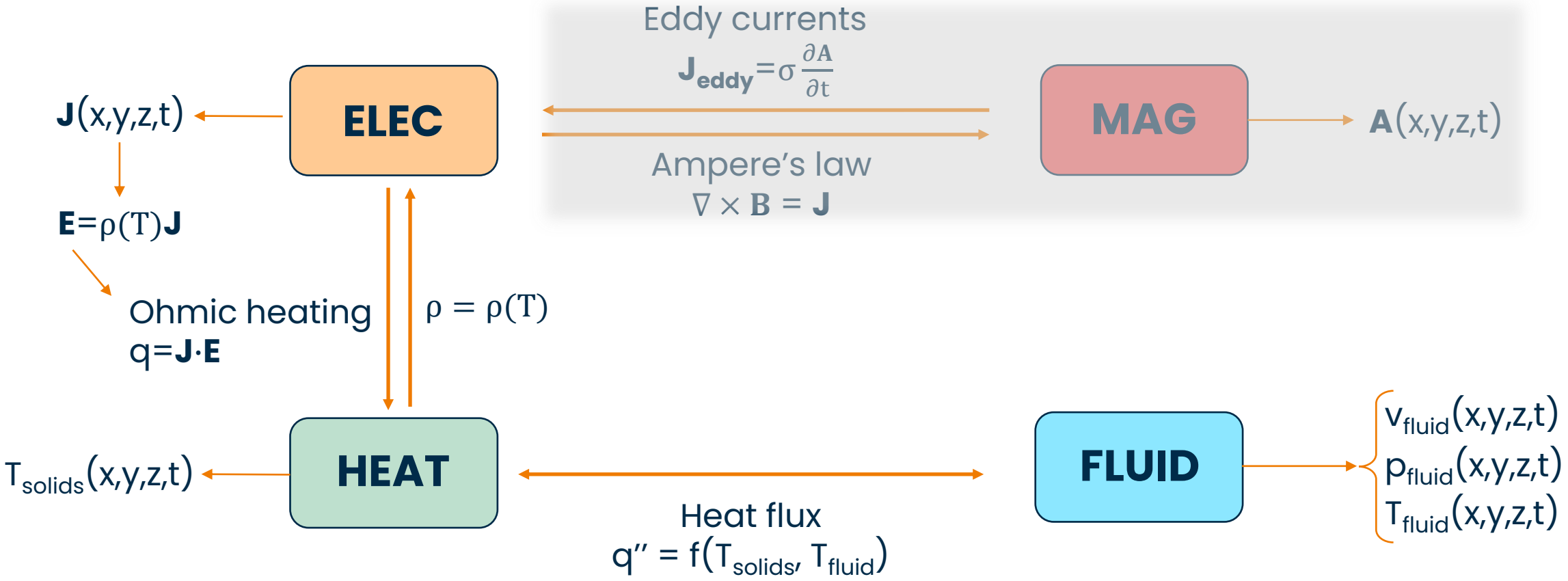
- Quench propagation tests in HTS conductors (EU-CN collaboration within EUROfusion Consortium) started in 2020 in SULTAN
- Degradation was found for all conductors tested so far, likely due to hotspot temperature reached during quench




Aim of the deliverable:

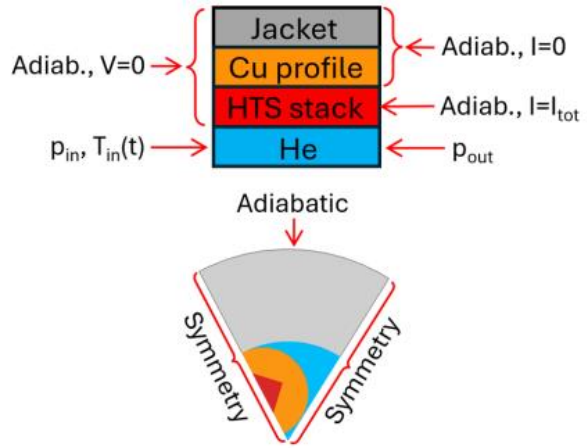
- Compute temperature distribution during quench
- Develop and apply a thermo-mechanical model to compute strain state

# Full 3D model for quench simulation
# Model equations

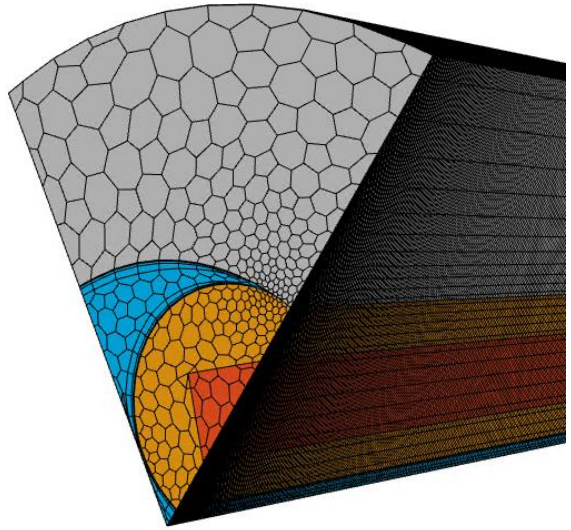


# Full 3D model for quench simulation: Boundary conditions and mesh

- V=0 on the opposite boundary
- P=0 (gauge) at the outlet



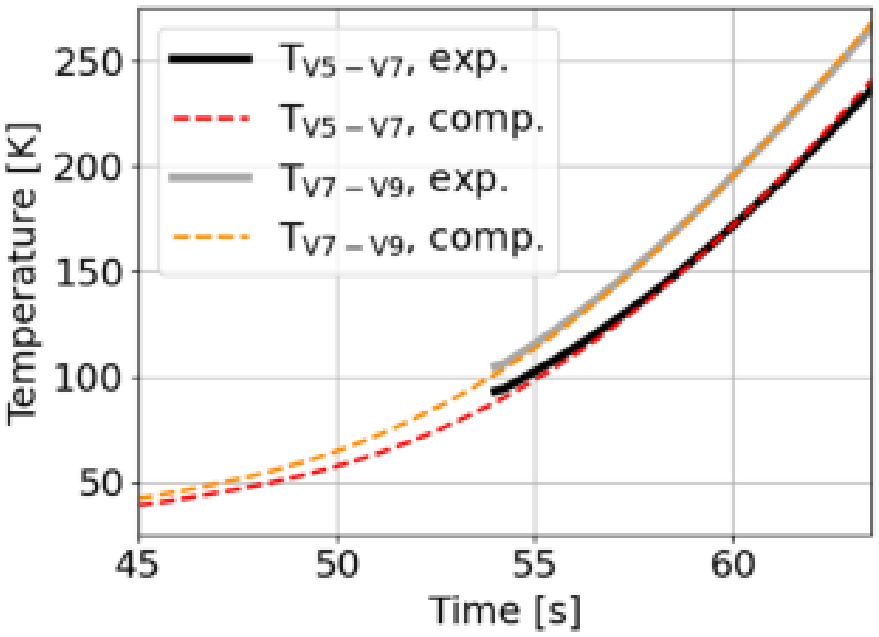

- Imposed transport current ($I_{tot}$ = 15 kA) at SC boundary, $I_{tot}$ = 0 kA elsewhere
- Experimental inlet temperature and mass flow rate for the He
- Adiabatic/insulation on the other (external) boundaries

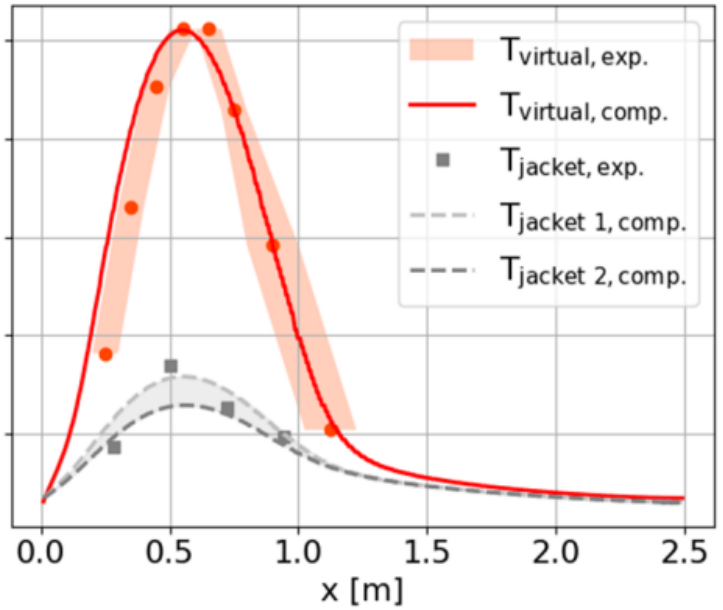


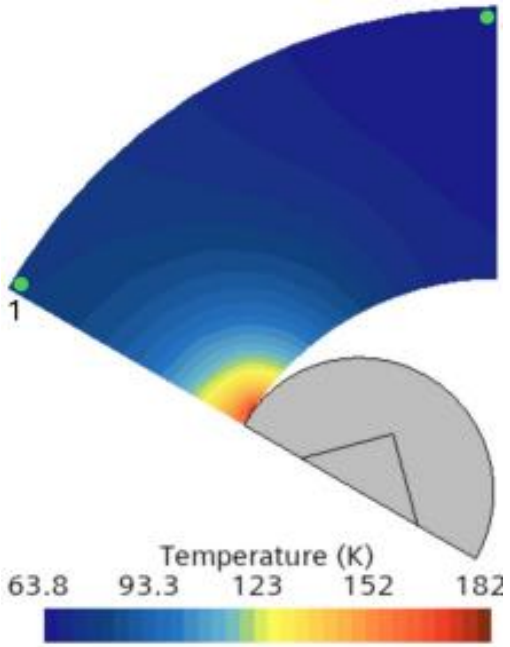
- Finite Volume polyhedral mesh
- 0.5 mm characteristic size in High Field Zone
- Exploiting symmetry → ~2 Mcells
- Adaptive time step based on rate of change in the current density

[A Zappatore 2024 Supercond. Sci. Technol. 37 125012]

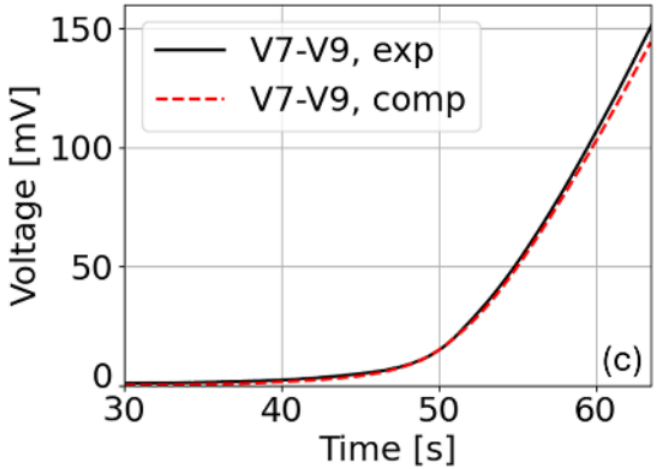
# Full 3D model validation & results




Computed results (temperature distribution, temperature and local voltage evolutions) agree well with measured results

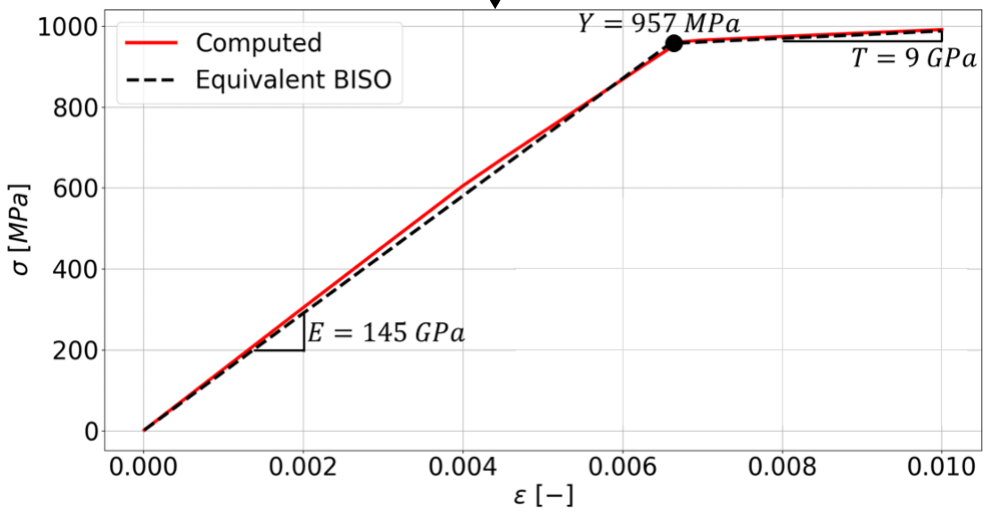



Temperature in the jacket is confirmed to be non-uniform in the radial-azimuthal directions

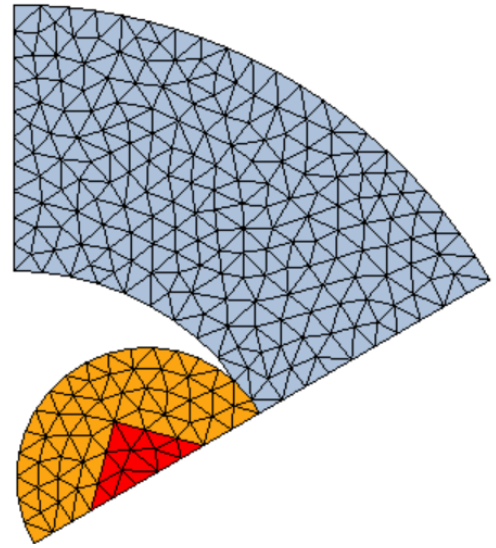
# 3D thermo-mechanical model

Tape model to evaluate equivalent mechanical properties (including plastic behavior) → Bilinear isotropic hardening

| Material | E [GPa] | Y [MPa] | T [GPa] |
|---|---|---|---|
| Copper | 85 | 350 | 4 |
| Hastelloy | 180 | 1225 | 7.5 |
| Silver | 90 | 225 | 22 |
| HTS layer | 150 | - | - |




Homogeneous model of the stack → lighter conductor model (main assumption: temperature distribution uniform across the stack)



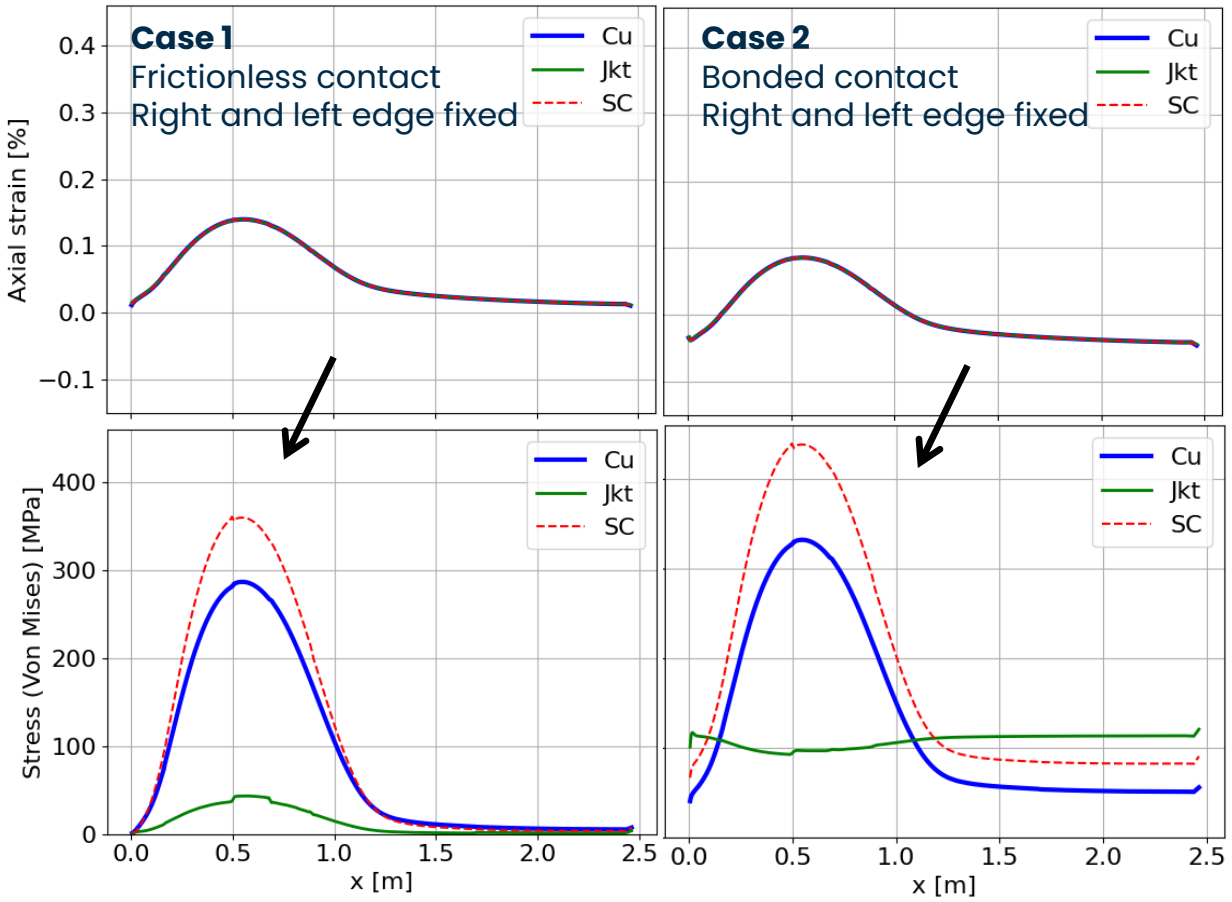
| Material | E [GPa] | Y [MPa] | T [GPa] | α [K⁻¹] |
|---|---|---|---|---|
| Copper | 85 | 350 | 4 | $1.67 \cdot 10^{-5}$ |
| Steel | 210 | - | - | $1.35 \cdot 10^{-5}$ |
| Stack | 145 | 957 | 9 | $1.37 \cdot 10^{-5}$ |

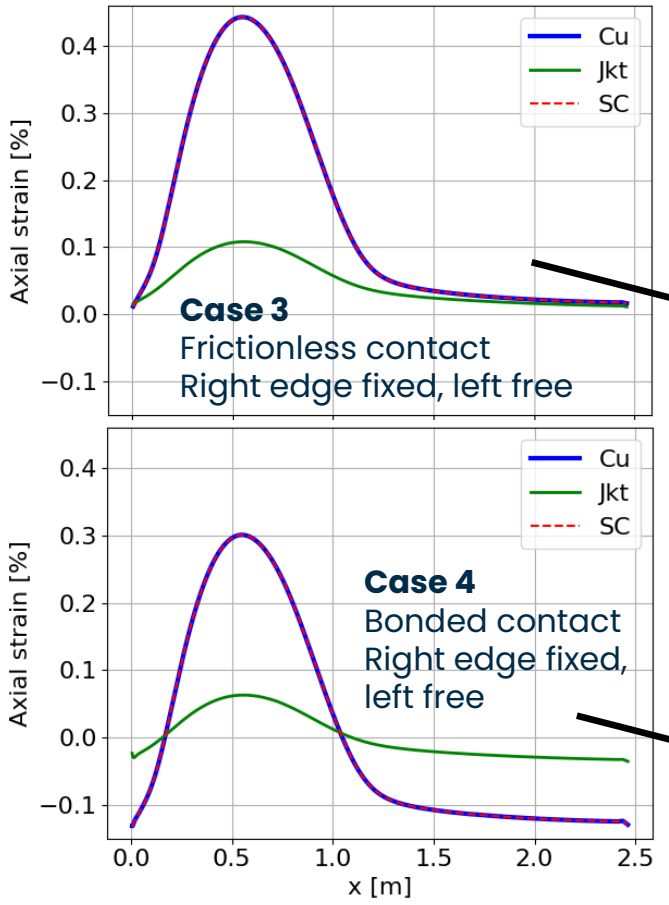
| Case simulated | Boundary condition | Contact type (Jkt-Copper) |
|---|---|---|
| 1 | Fully bonded | Frictionless |
| 2 | | Bonded |
| 3 | One bonded edge, one free | Frictionless |
| 4 | | Bonded |

Extreme cases considered for boundary conditions (bottom joint) and contact type

[M De Bastiani et al 2024 IEEE Trans. Appl. Supercond. 35 4600205]

# Results



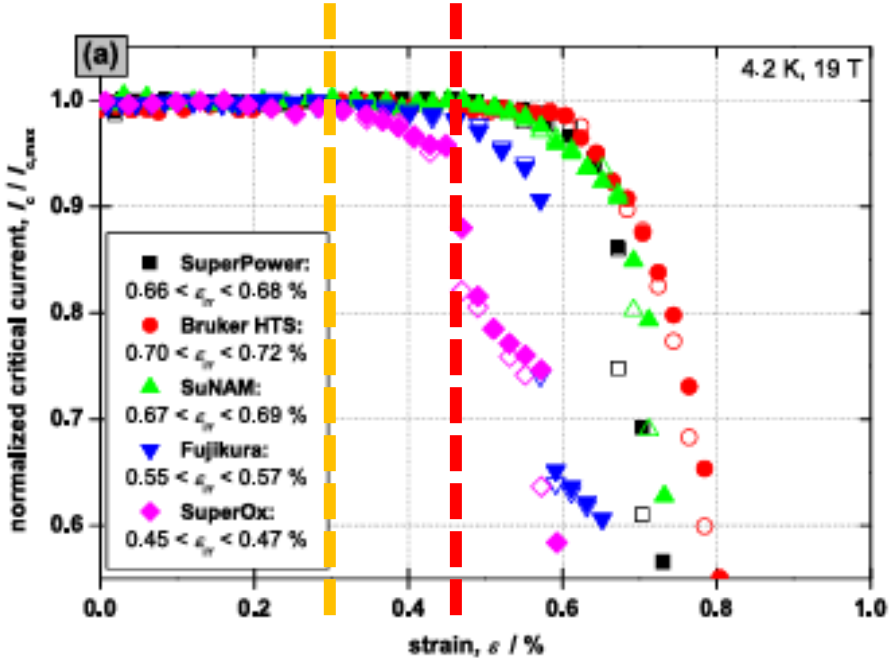

- If conductor is assumed to be fully bonded → stress is maximum (~430 MPa)
- If conductor can expand, strain is maximum (~0.44%)
- If bonded, colder jacket limits the expansion of the strands → lower strain

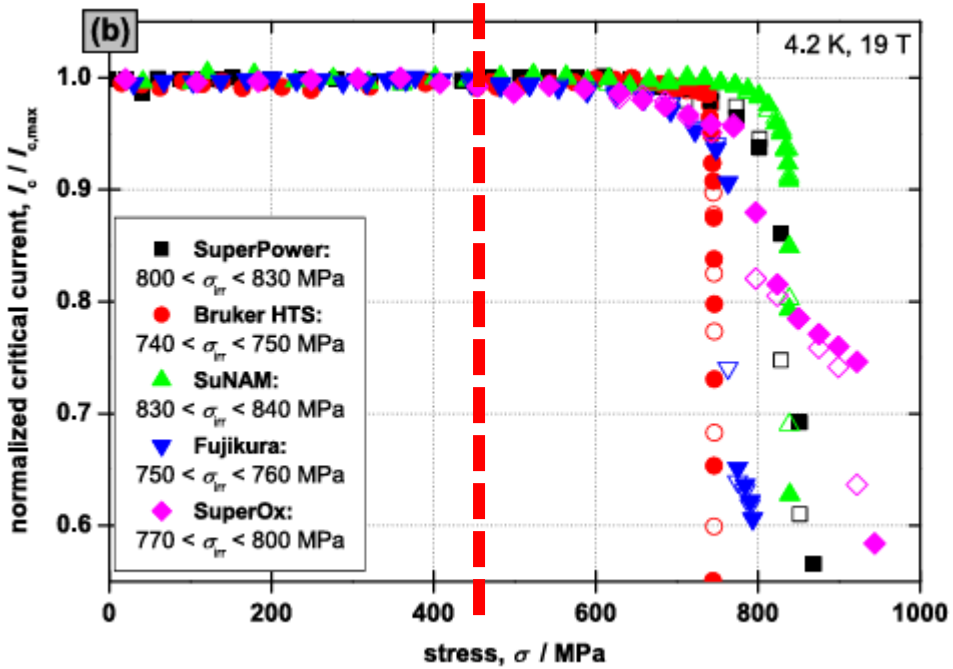
# Discussion

Strain computed in ENEA A1

0.44 % axial strain looks compatible with few % irreversible degradation

Stress <600 MPa should not lead to permanent degradation




[C Barth et al 2015 Supercond. Sci. Technol. 28 045011]

# Conclusions

- Fully 3D multi-physics (thermal-hydraulic and electro-magnetic) model has been developed validated against quench test results
- 3D thermo-mechanical model has been developed and applied in the case of the largest hotspot reached during quench
- In case of frictionless contact between strand and jacket + one free edge, axial strain overcomes 0.4% which could be compatible with few % degradation

Thank you for your attention!

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# Full 3D model for quench simulation Models and solvers

**Electric (SC, Cu, SS) model**:
- Transient
- 3D
- Electric current density → **J**(x,y,z,t)
- Ohmic heating
- (T,B)-dependent material properties
- Power-law for SC

- Hypre solver
- Adaptive time step to cope with strong non-linearity of power law

**Heat diffusion (SC, Cu, SS) model**:
- Transient
- 3D
- Heat conduction → T(x,y,z,t)
- Ohmic heating
- (T,B)-dependent material properties

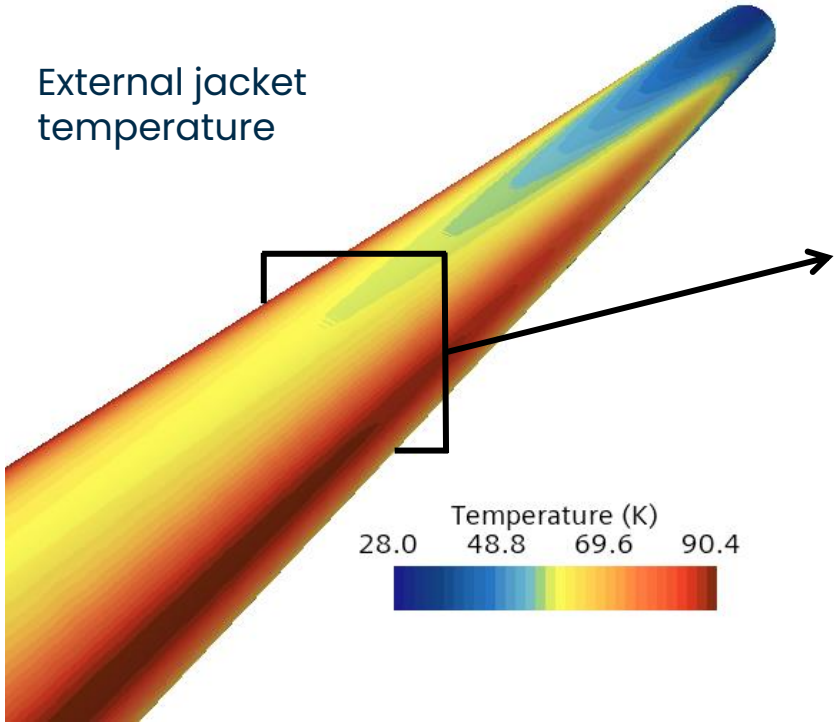
**Magnetic (SC, Cu, SS, He, Air) model**:
- Transient
- 3D
- A-formulation → **A**(x,y,z,t)

- Coupled implicit solver to cope with strong non-linearity of the supercritical helium

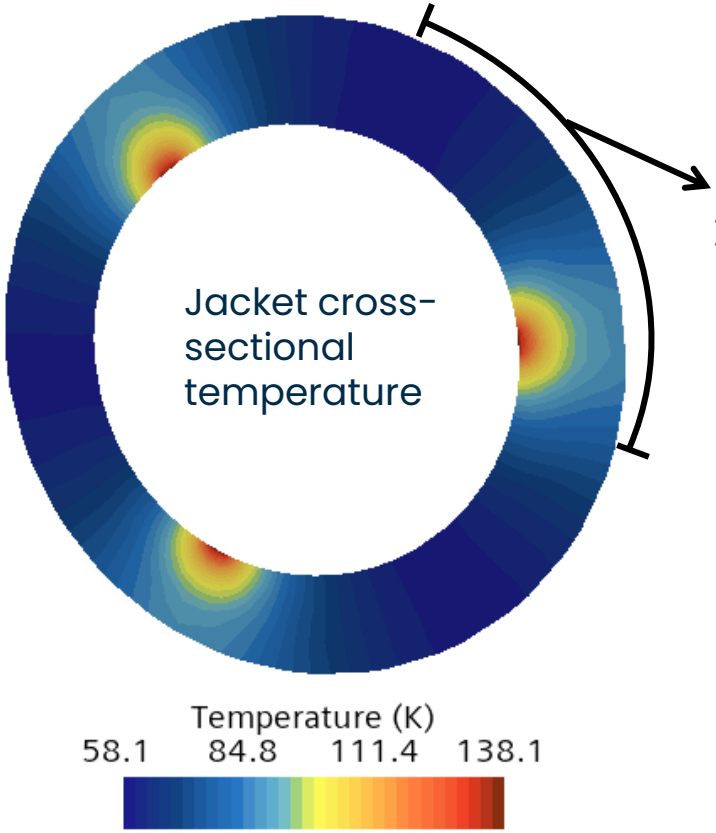
**Fluid (He) model**:
- Transient
- 3D
- N-S equations → v(x,y,z,t), p(x,y,z,t), T(x,y,z,t)
- Turbulence
- (T, p)-dependent material properties

# Full 3D model results

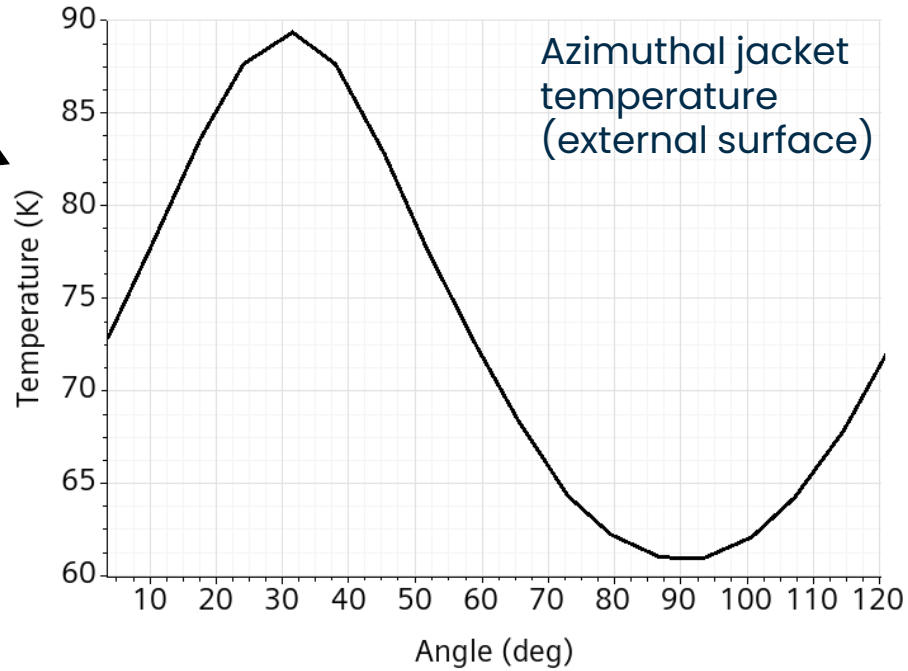
External jacket temperature




Jacket cross-sectional temperature

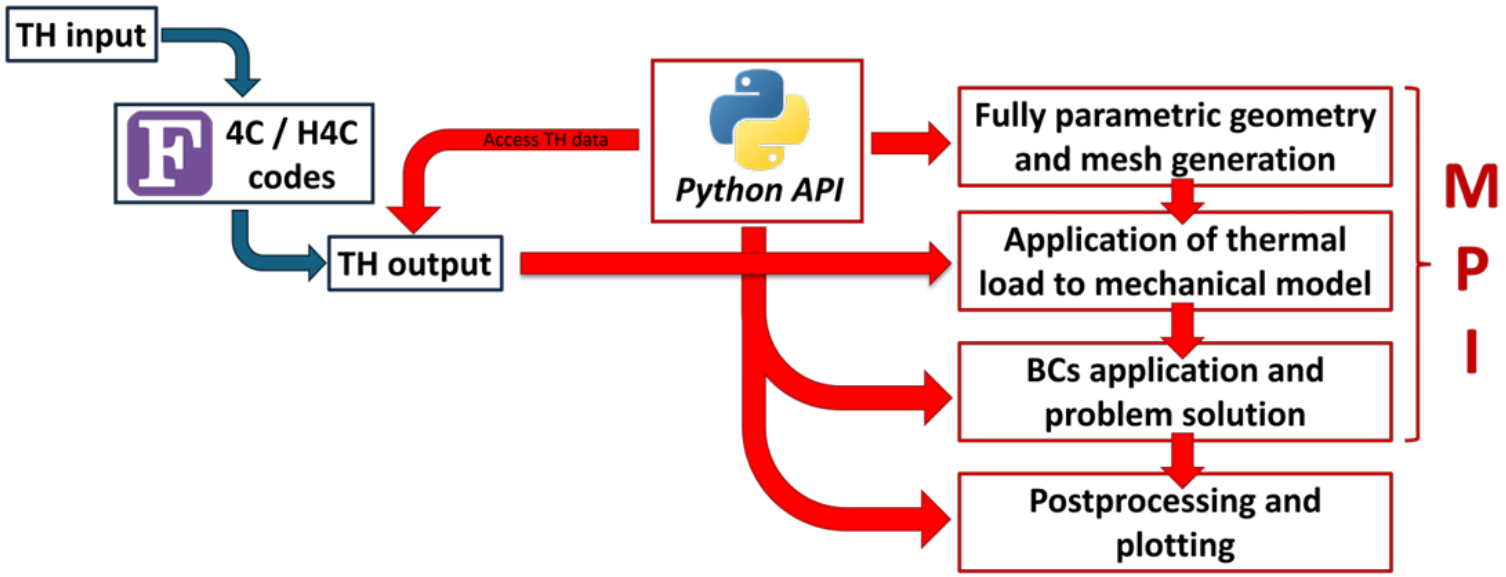



Azimuthal jacket temperature (external surface)



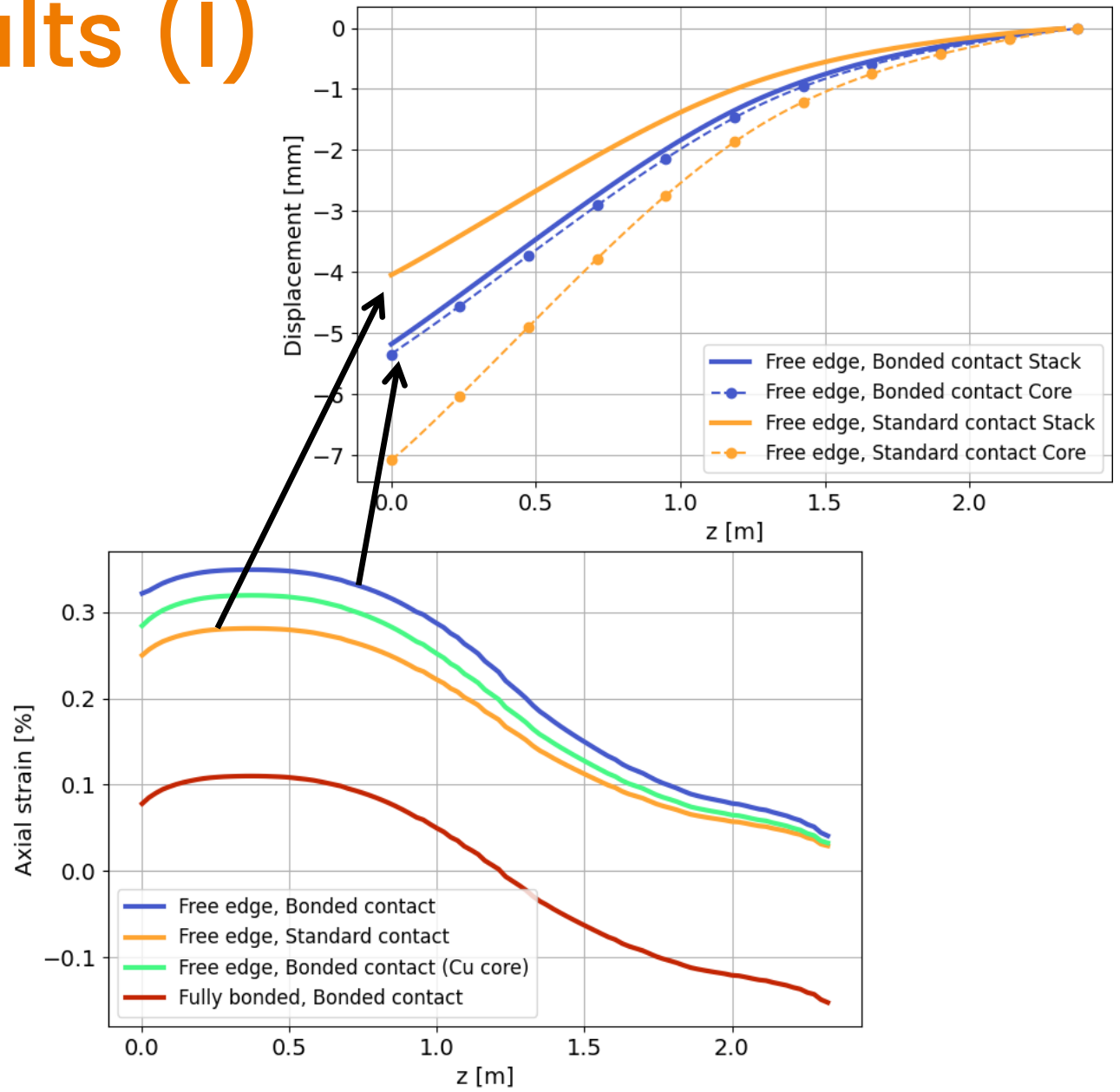

- Local contact of SC+Cu strands with stainless lead to 3D distribution (axial, azimuthal, radial directions) on jacket temperature throughout the transient
- This maybe useful for QD using SC wires or fibers (either due to temperature or, indirectly, due to secondary stresses → TH-MEC analysis)

# Coupling the TH and T-MEC models




- Mechanical model (geometry, mesh, boundary conditions, solution) is developed in ANSYS APDL
- The python package PyMAPDL allows the communication between a python script and the ANSYS kernel
- Main advantages:
  - flexibility of python high level scripting
  - Pre-processing of TH results before sending them of the mechanical model
  - Mech. model is parametric → different analysis can be performed directly from the python master
  - Same API can be used to solve different problems (from cable to coils)
- Quench with hotspot = 210 K is considered here

[M. De Bastiani et al 2024 IEEE Trans. Appl. Supercond. 35 4600205]

# Results (I)

- Fully bonded conductor → much lower (axial) strain
- If one edge is free → larger axial displacement → larger strain
- Core expands more than the stack:
  - If stack is bonded to the core → it pulls the stack → larger strain
  - Otherwise (standard) → they can expand freely → smaller strain on the stack
- Copper core expands similarly to the stack → smaller strain in case of bonded contact