PAUL SCHERRER INSTITUT

COMSOL CONFERENCE
2017 ROTTERDAM

WIR SCHAFFEN WISSEN – HEUTE FÜR MORGEN

Paul Scherrer Institut

Multiphysics Simulations for the design of a Superconducting magnet for proton therapy

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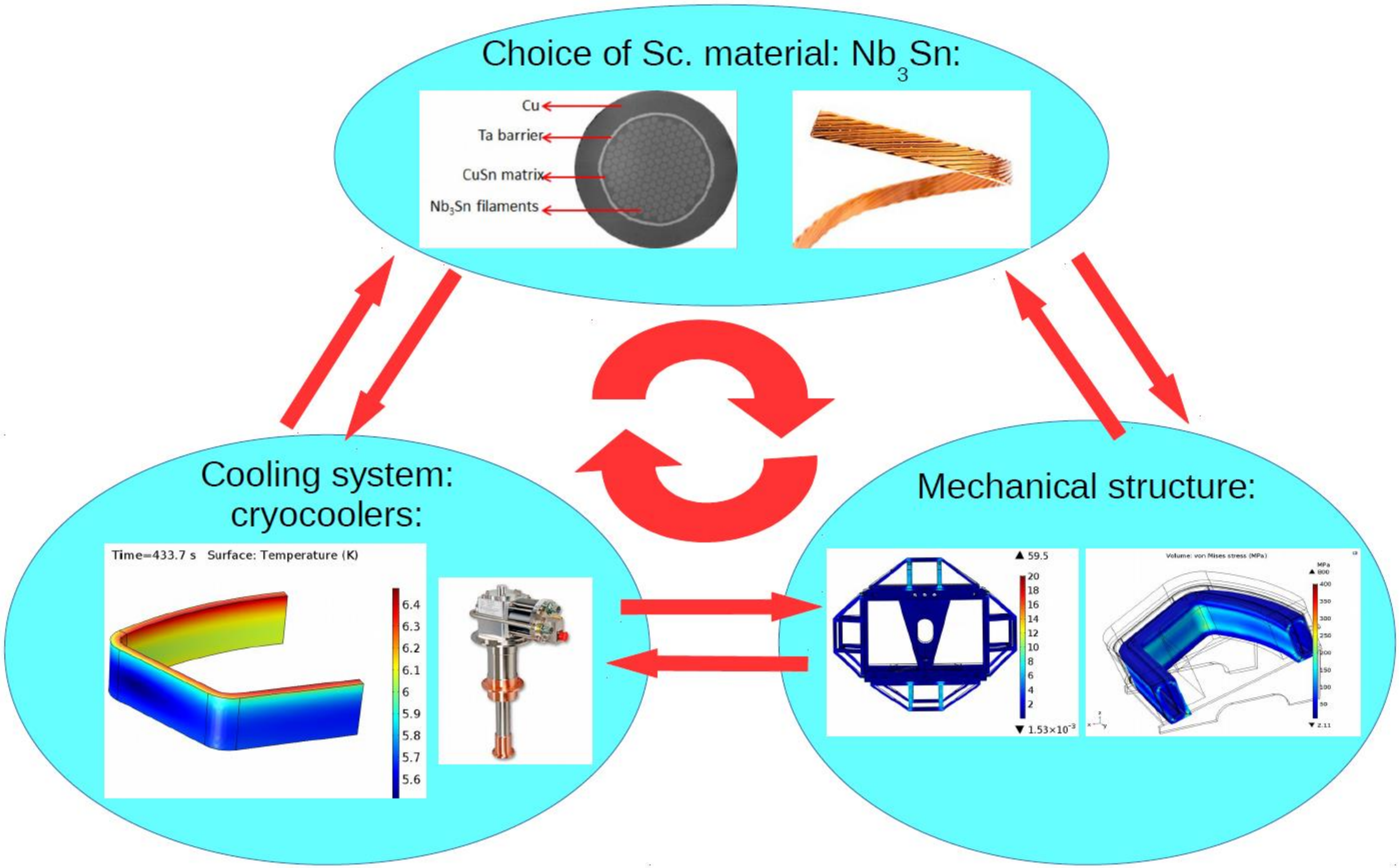
OUTLINE

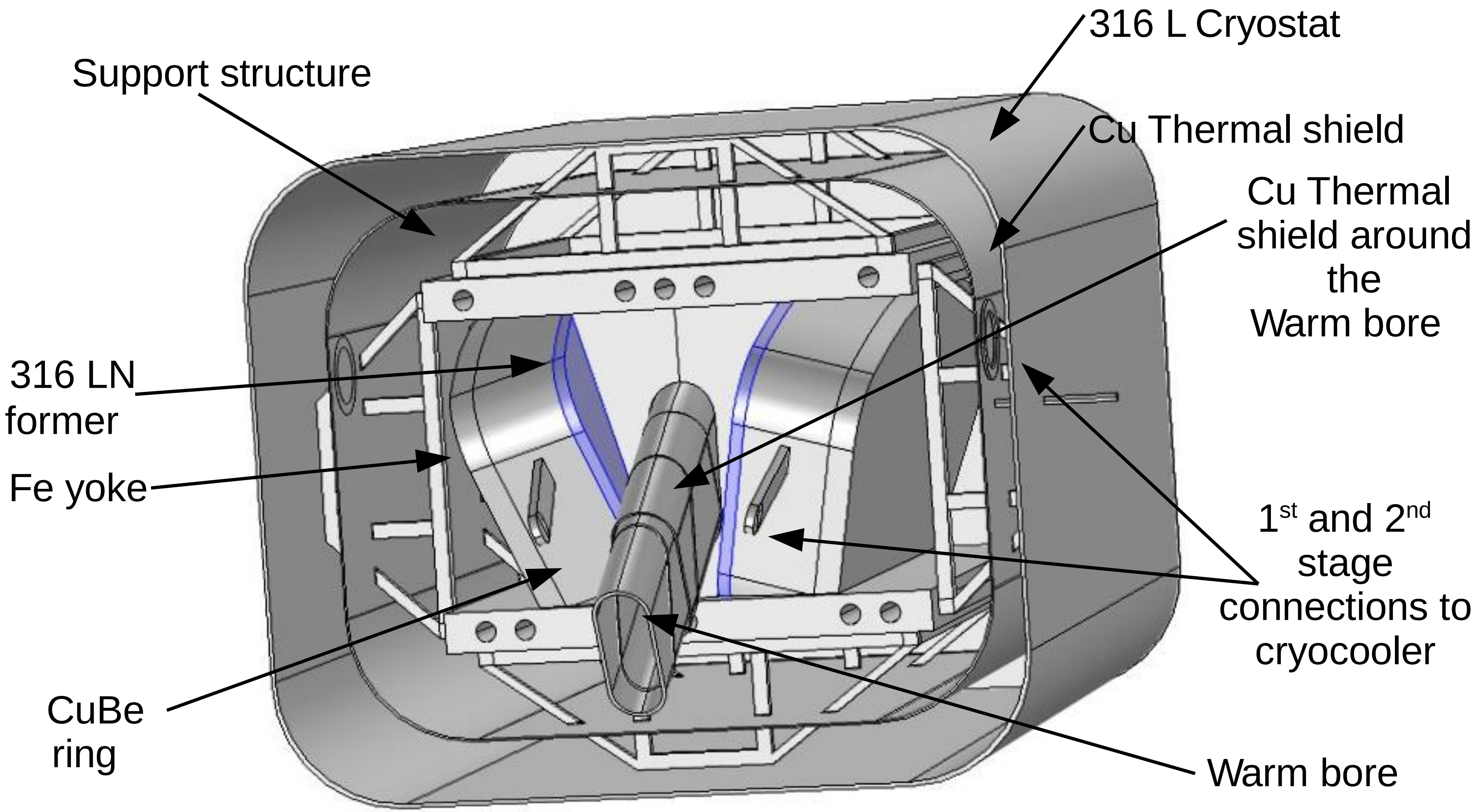
- ✓ Superconducting magnets: a Multiphysics approach
- ✓ CAD drawing;
- ✓ Cool-down analysis;
- ✓ Operation
  - ✓ AC losses calculation;
  - ✓ Mechanical analysis.
- ✓ Further steps: Quench analysis

Superconducting magnets: a Multiphysics approach



CAD drawings

Support structure



Fully parametric CAD used during the optimization phase.

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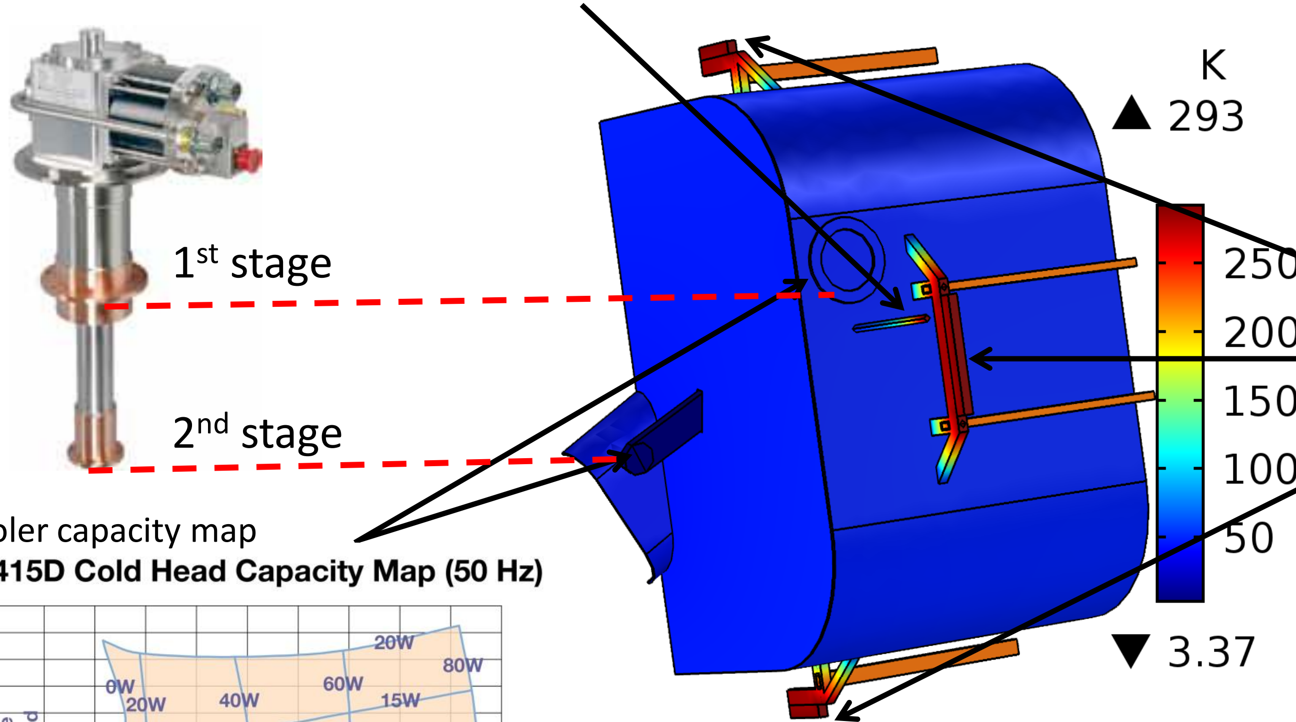
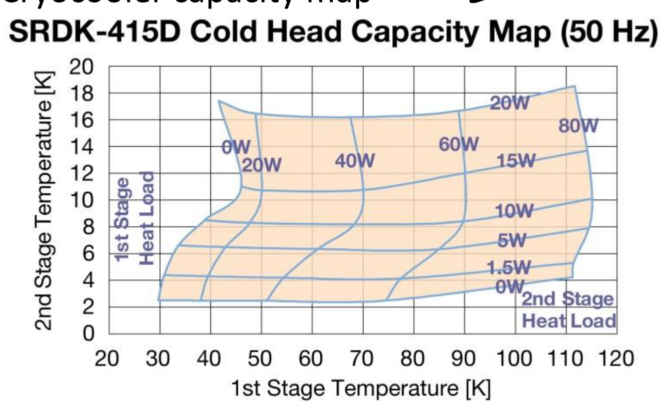
Cool-down

Cool-down



Cryocooler capacity map



Capacity map implemented as two arguments interpolating function.

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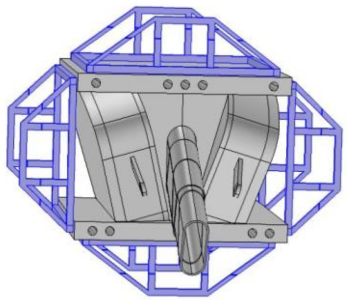
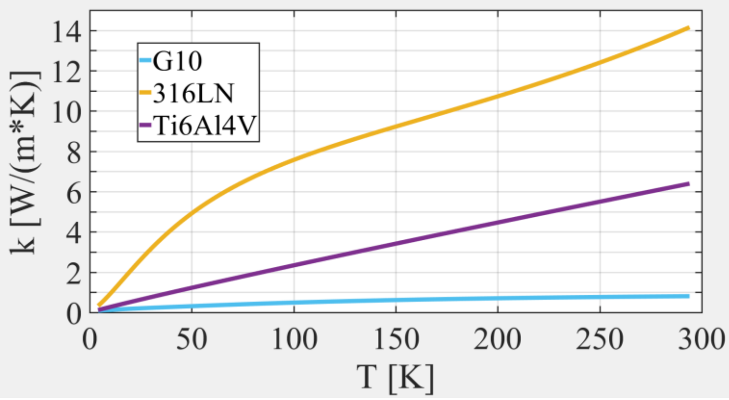
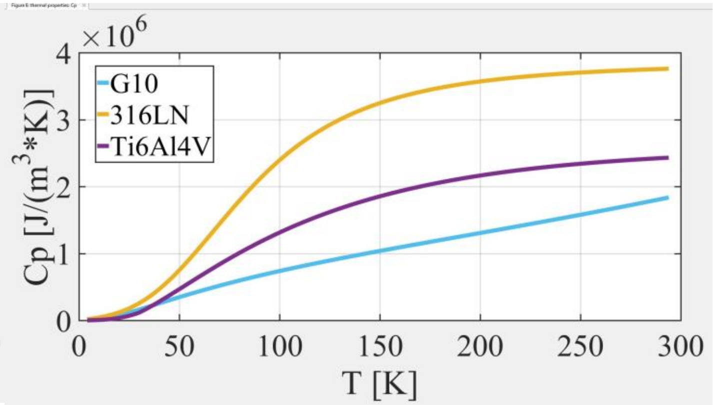
Support structure: materials choice

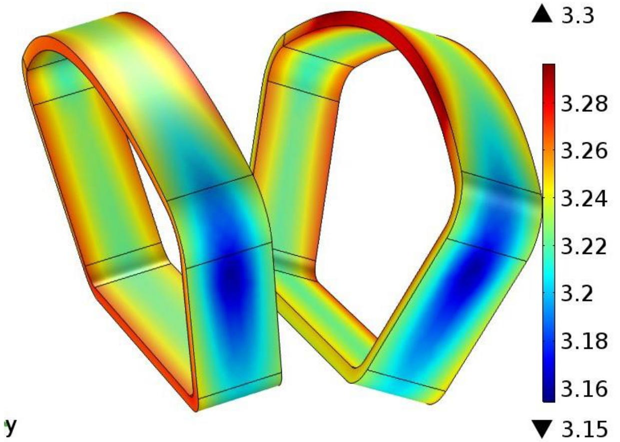






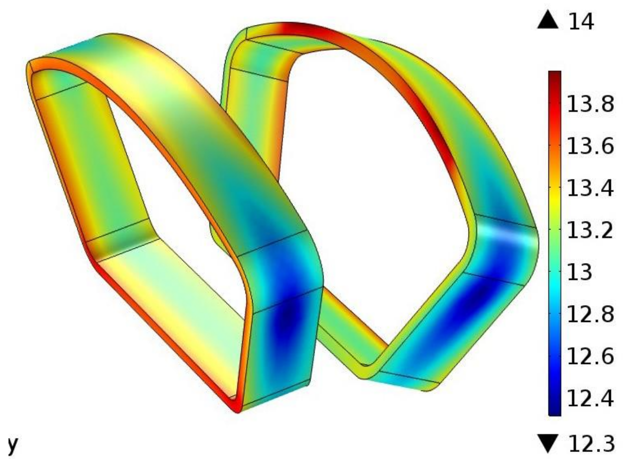
G10

Surface: Temperature (K)



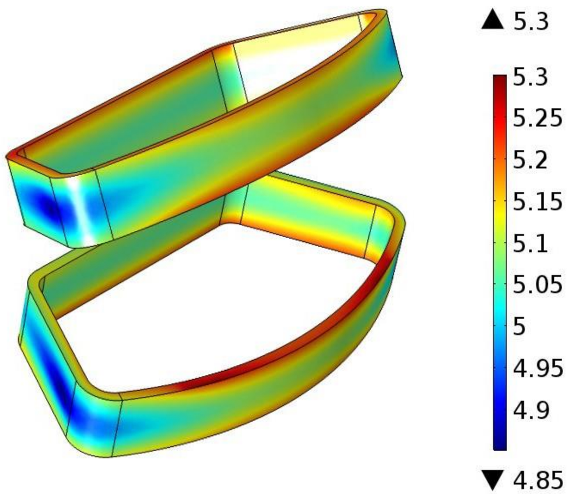
316LN

Surface: Temperature (K)



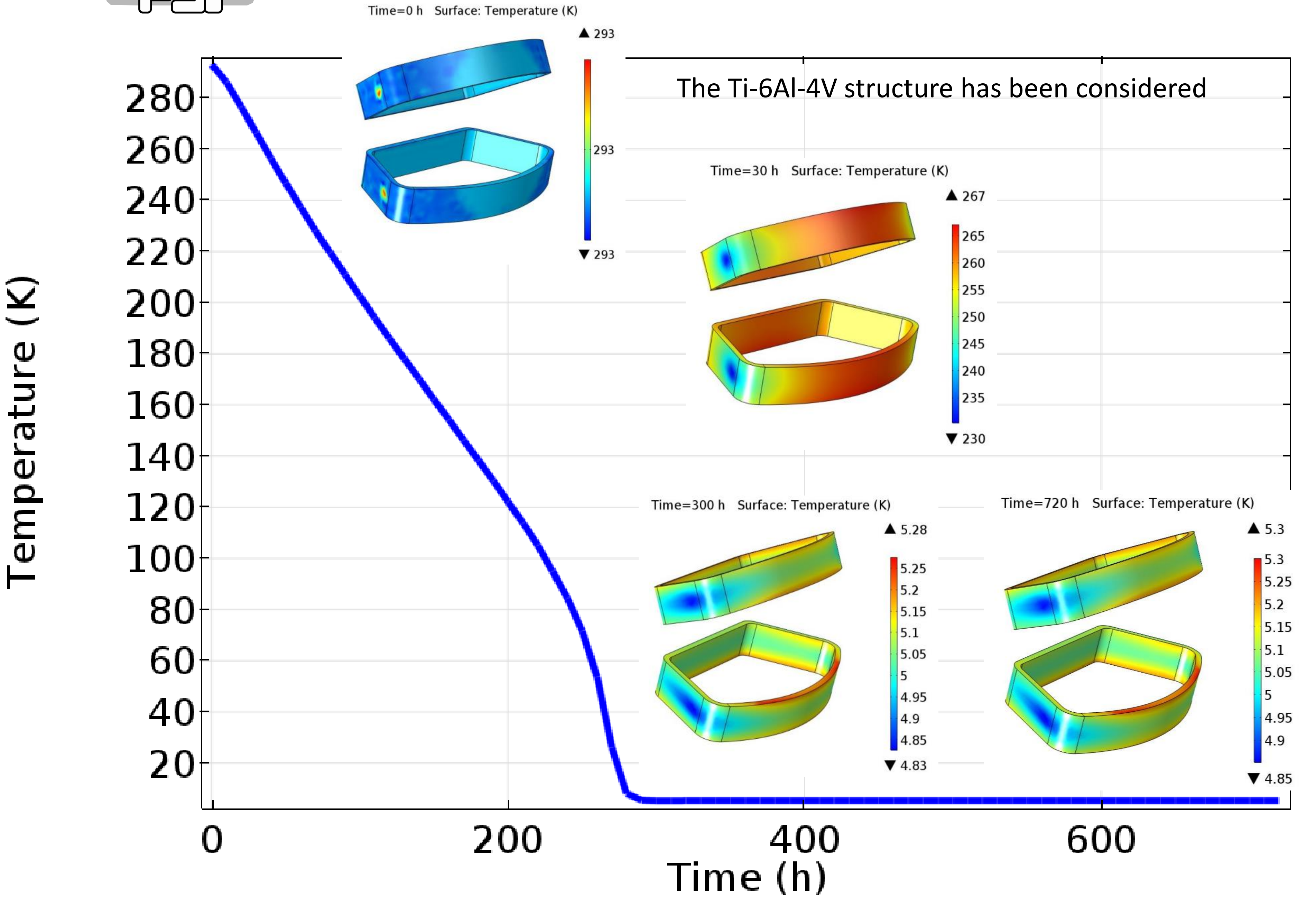
Ti-6Al-4V

Surface: Temperature (K)



	G10	316LN	Ti-6Al-4V
Mechanic			
thermal			

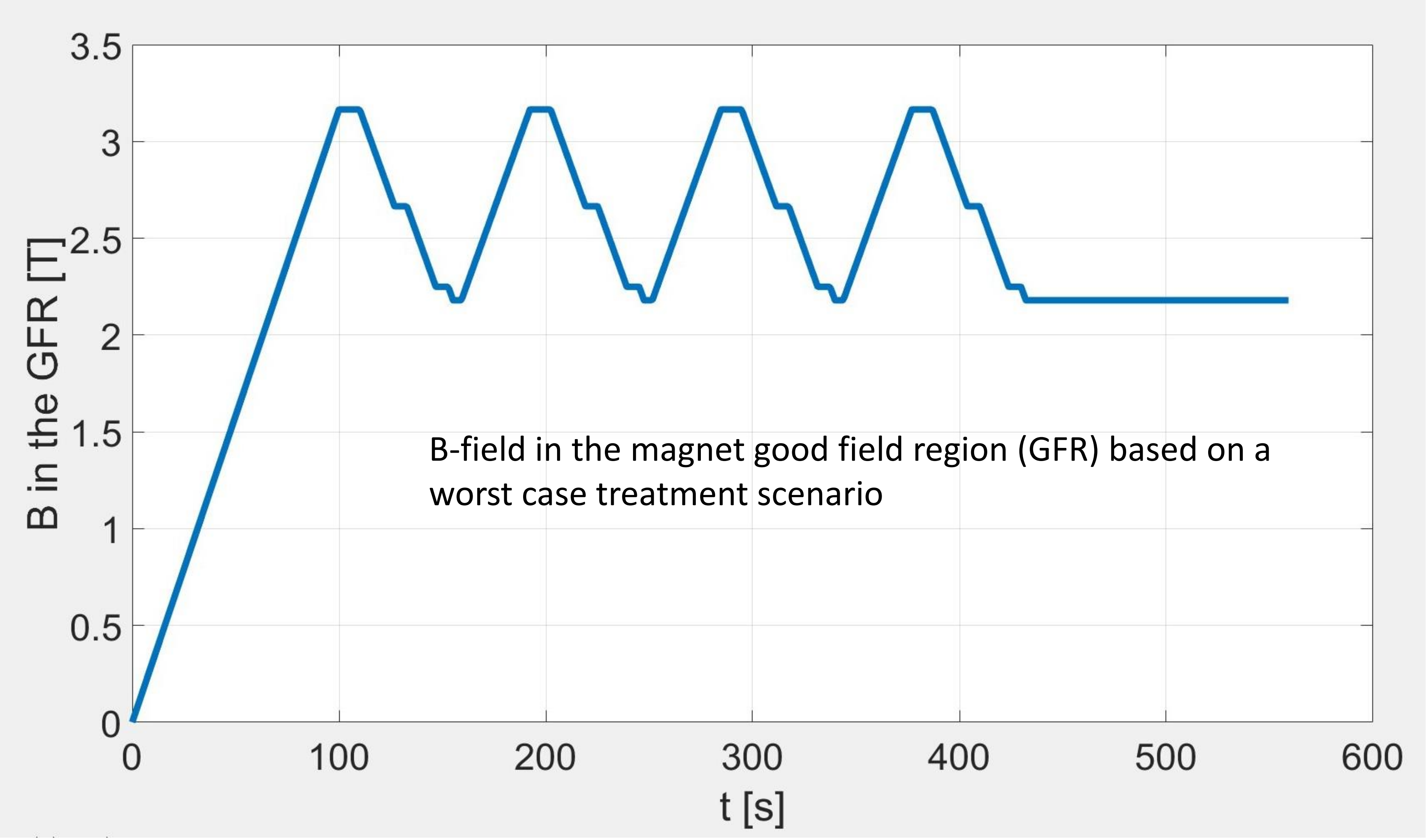
Thermal Analysis: cool-down



Operation
AC-losses

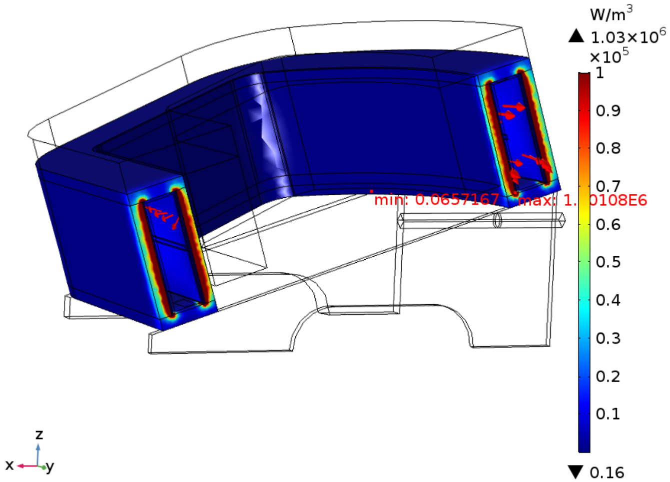
AC losses

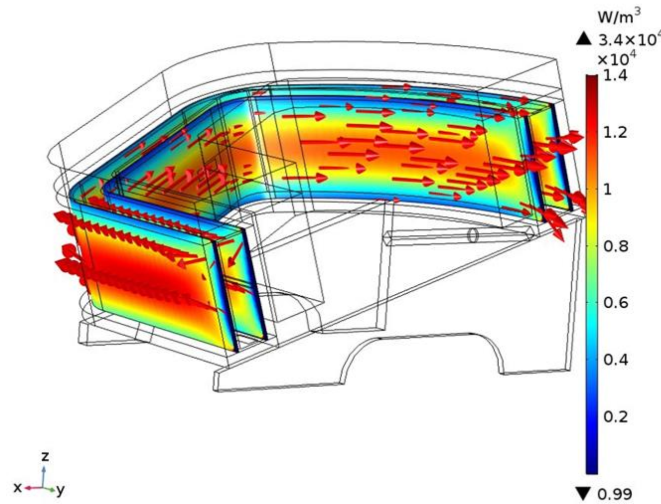
To change the protons penetration depth it is necessary to change their energy → the bending field has to change accordingly.



316Ln coil structure: eddy currents

AC losses in the structure



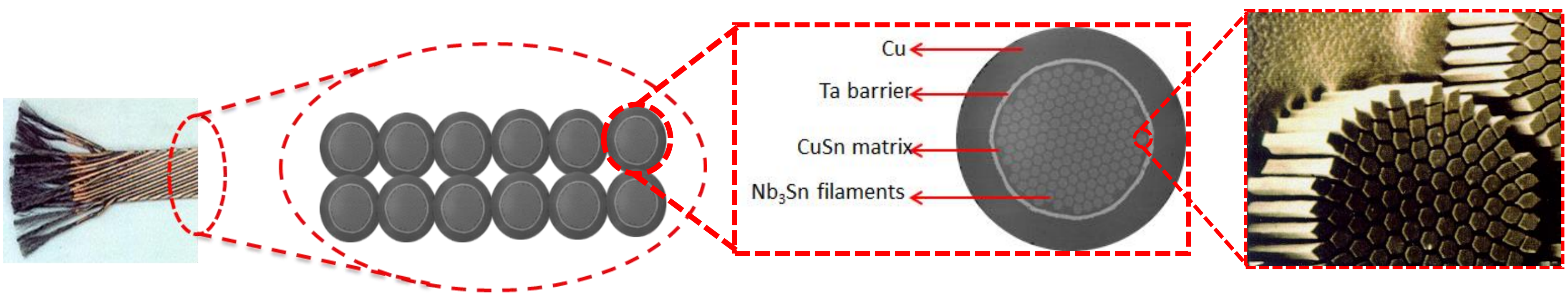


AC losses in the coils

Cable: 4.9 mm x 1.5 mm x 1100 m

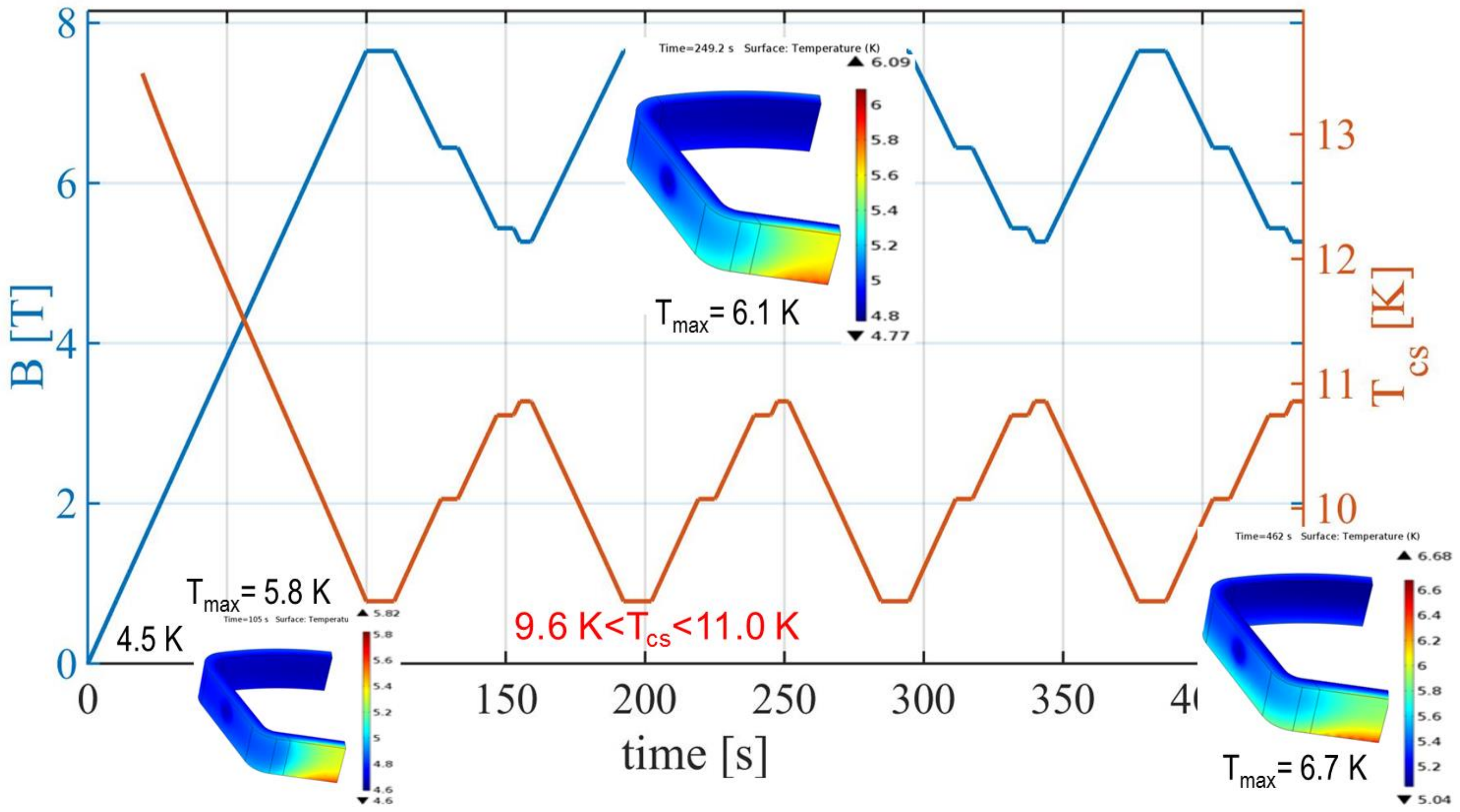
Strand: ϕ = 0.82 mm

Nb_3Sn Filaments: ϕ ~ 4-5 μm



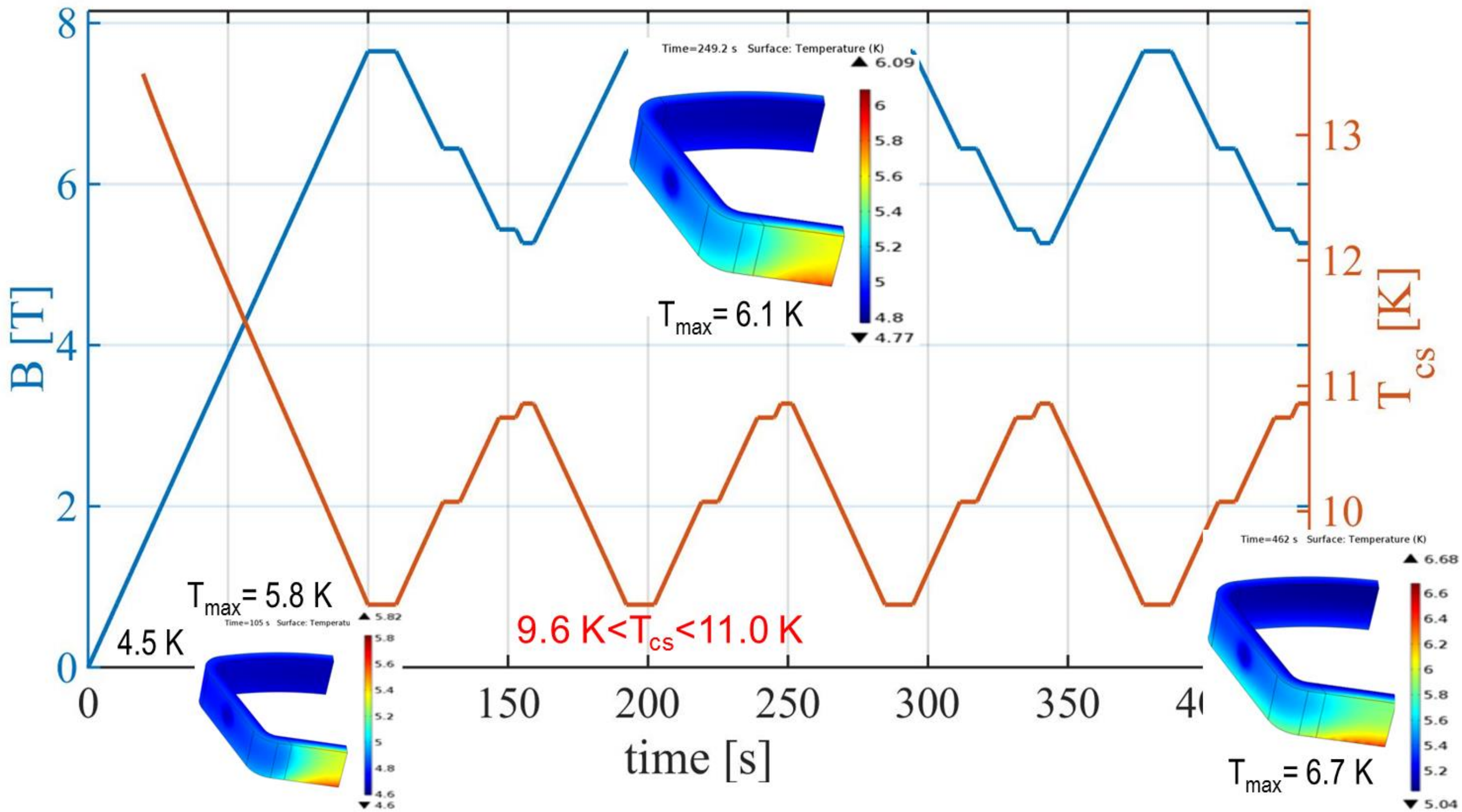
AC losses in the coils (inter-strands + inter-filaments + hysteresis) evaluated analytically

AC losses



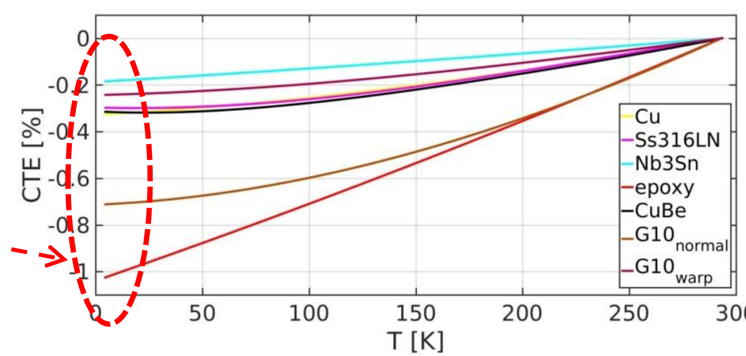
B [T]
T_{cs} [K]
time [s]
0
2
4
6
8
10
11
12
13
150
200
250
300
350
4.5 K
T_{max}= 5.8 K
T_{max}= 6.1 K
T_{max}= 6.7 K
9.6 K<T_{cs}<11.0 K
Time=249.2 s Surface: Temperature (K)
Time=462 s Surface: Temperature (K)
6.09
4.77
6.68
5.04
5.82
4.6

AC losses



It is important to prove that the coils temperature stays below T_{cs} (current sharing temperature) to avoid Joule heating.

In operation the $\Delta\varepsilon_{thermal}$ is negligible



Operation mechanics

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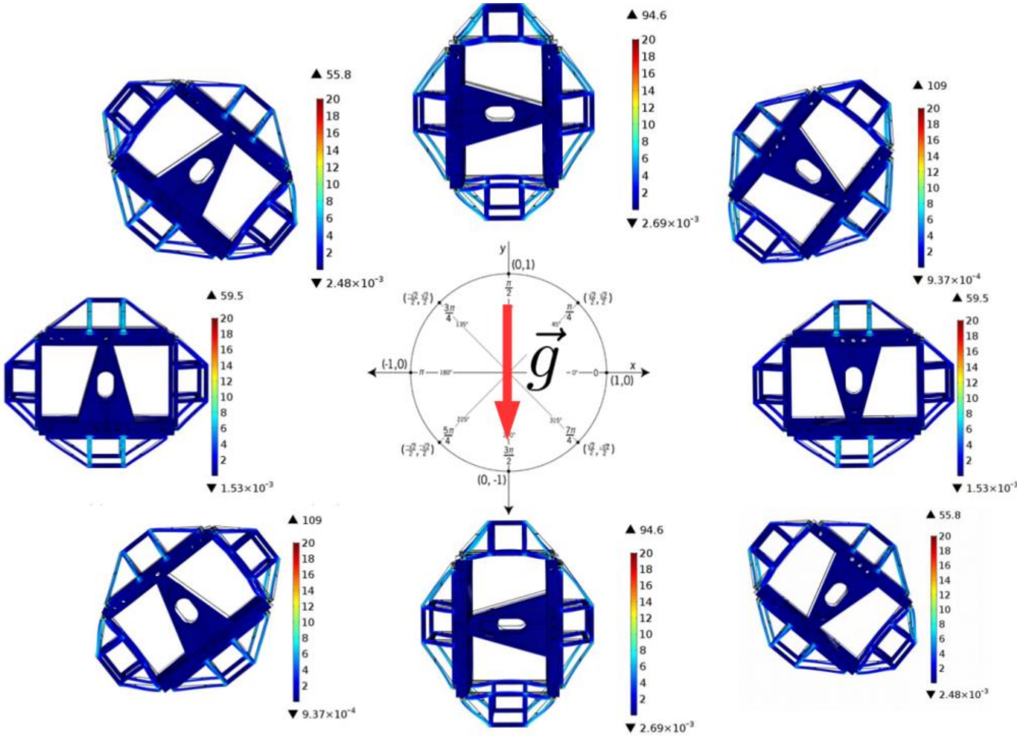
Support structure cryostat verification

1) σ_{Mises} < 110 MPa upon rotation < σ_{yield}



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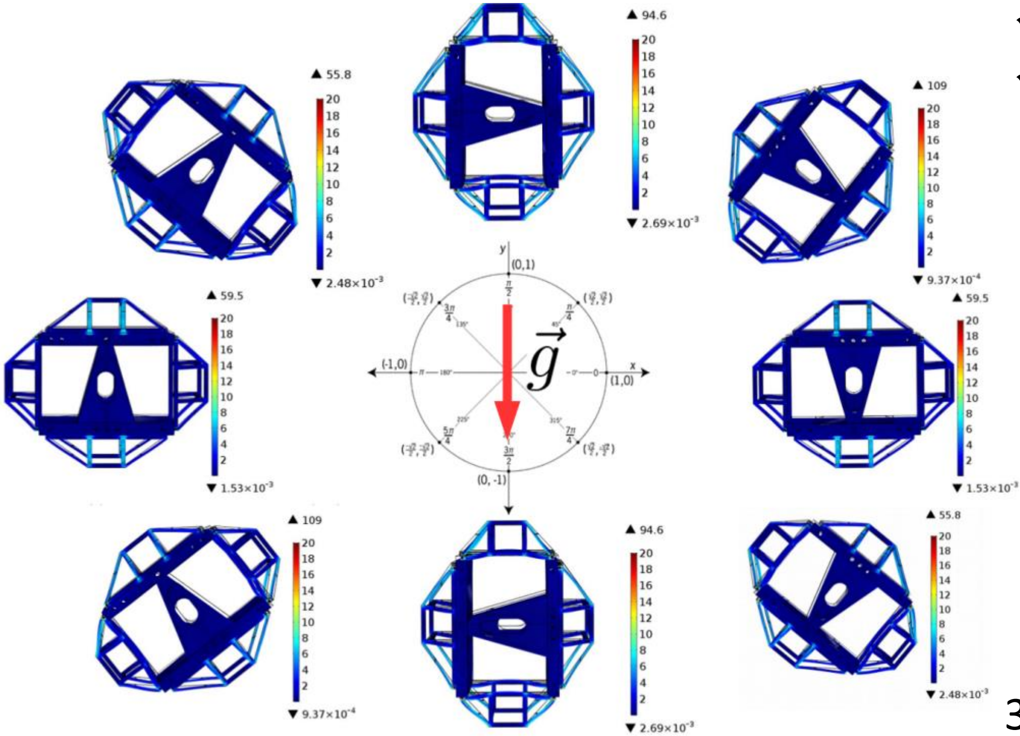
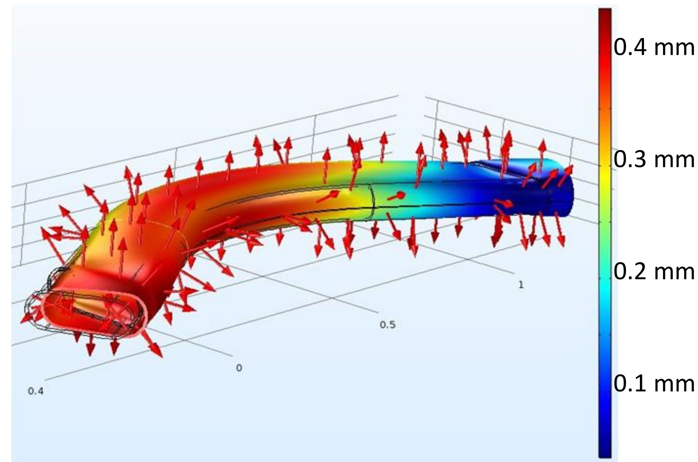


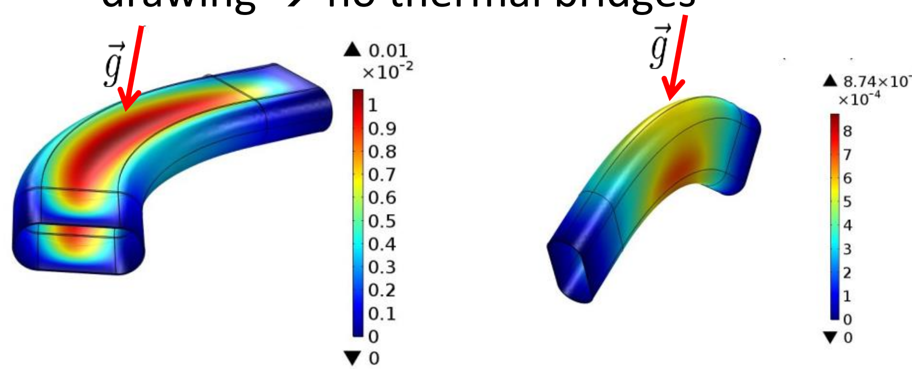
2) Warm bore

- ✓ load < critical load → no buckling
- ✓ total displacement < clearances in CAD drawing → no thermal bridges



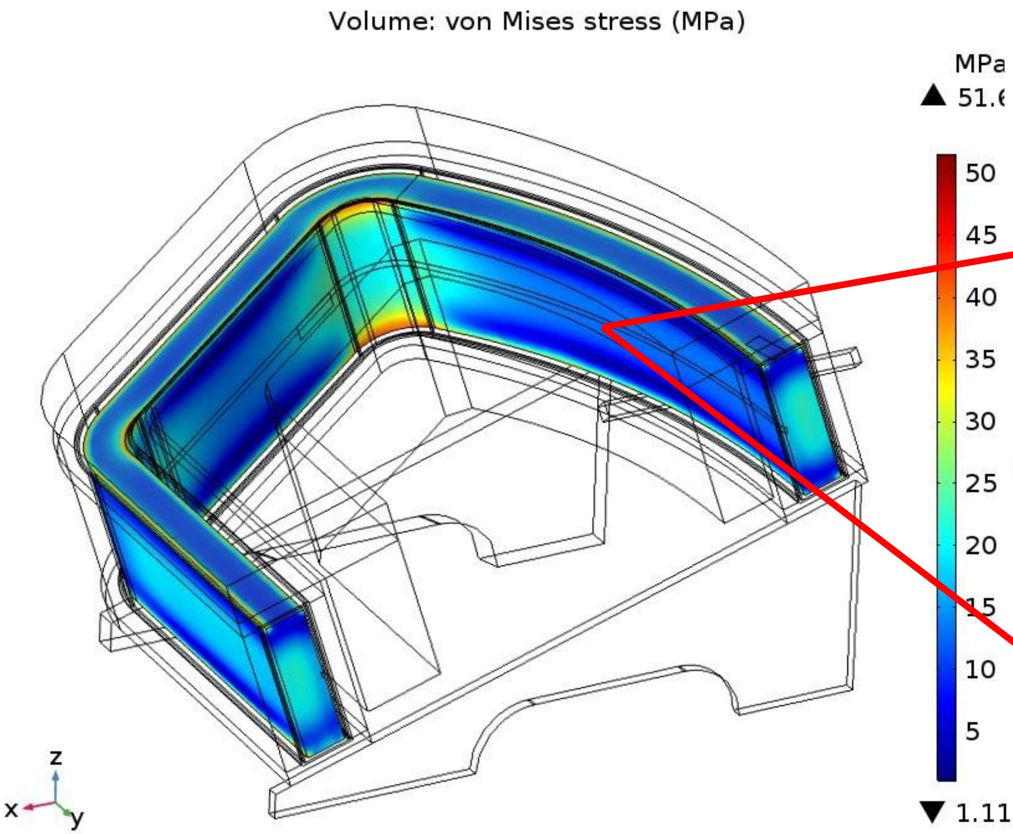
3) Thermal shield

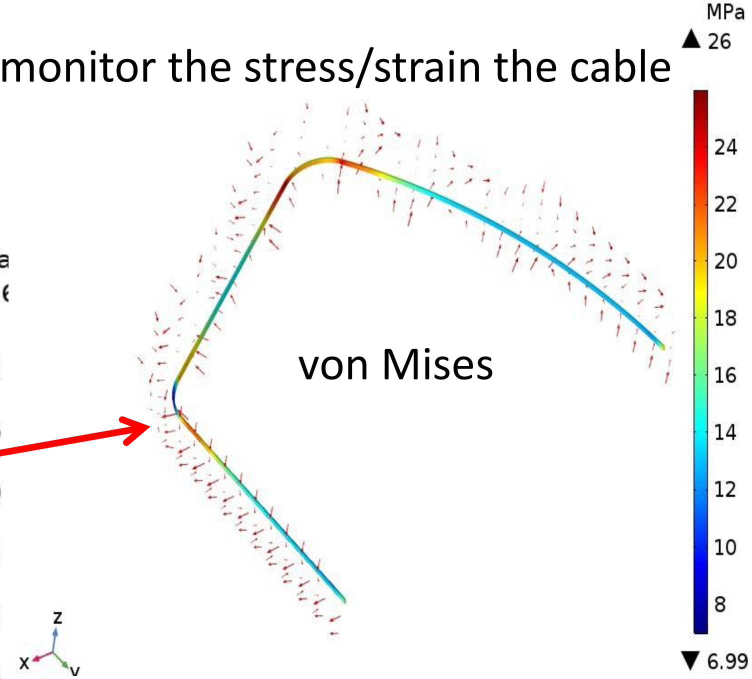
- ✓ total displacement < clearances in CAD drawing → no thermal bridges

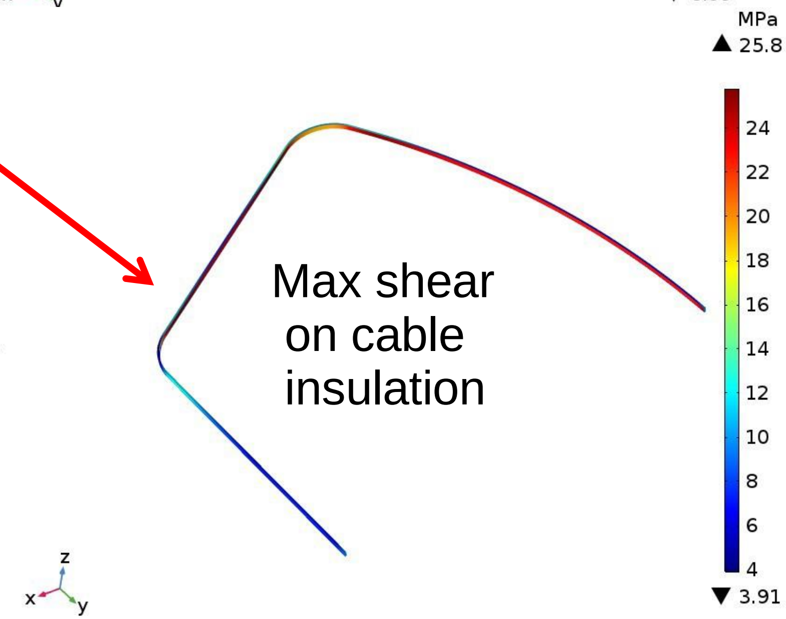


Stress on the conductor

Nb_3Sn is brittle + strain sensitive → it is crucial to monitor the stress/strain the cable
Lorentz forces + thermal strain were considered.





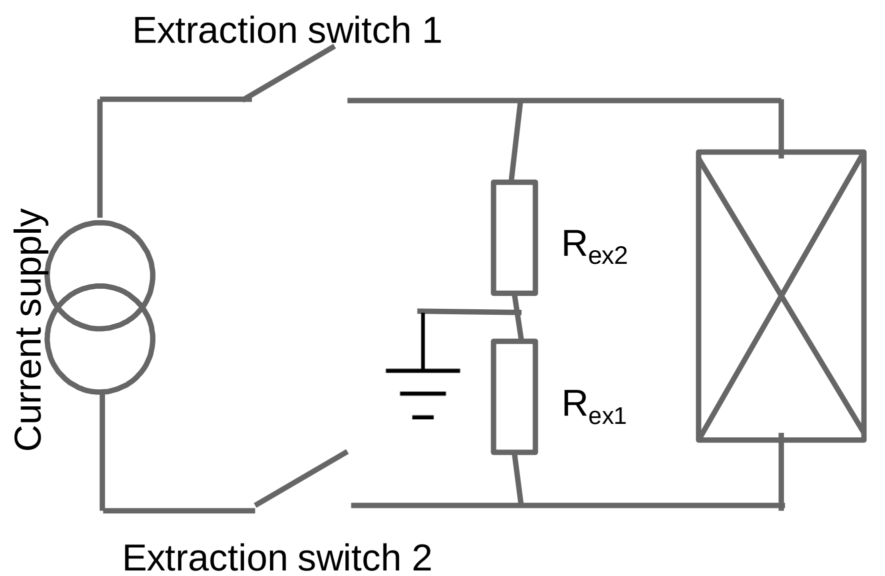


A moderate performance degradation is expected

Further steps:
Quench analysis

Quench scenario

Despite the efforts during the design phase, a perturbation in the coils my trigger a transition from the superconducting to the normal state, namely a quench.
In this case it is necessary to extract the magnet energy and to dump it into an external resistor.



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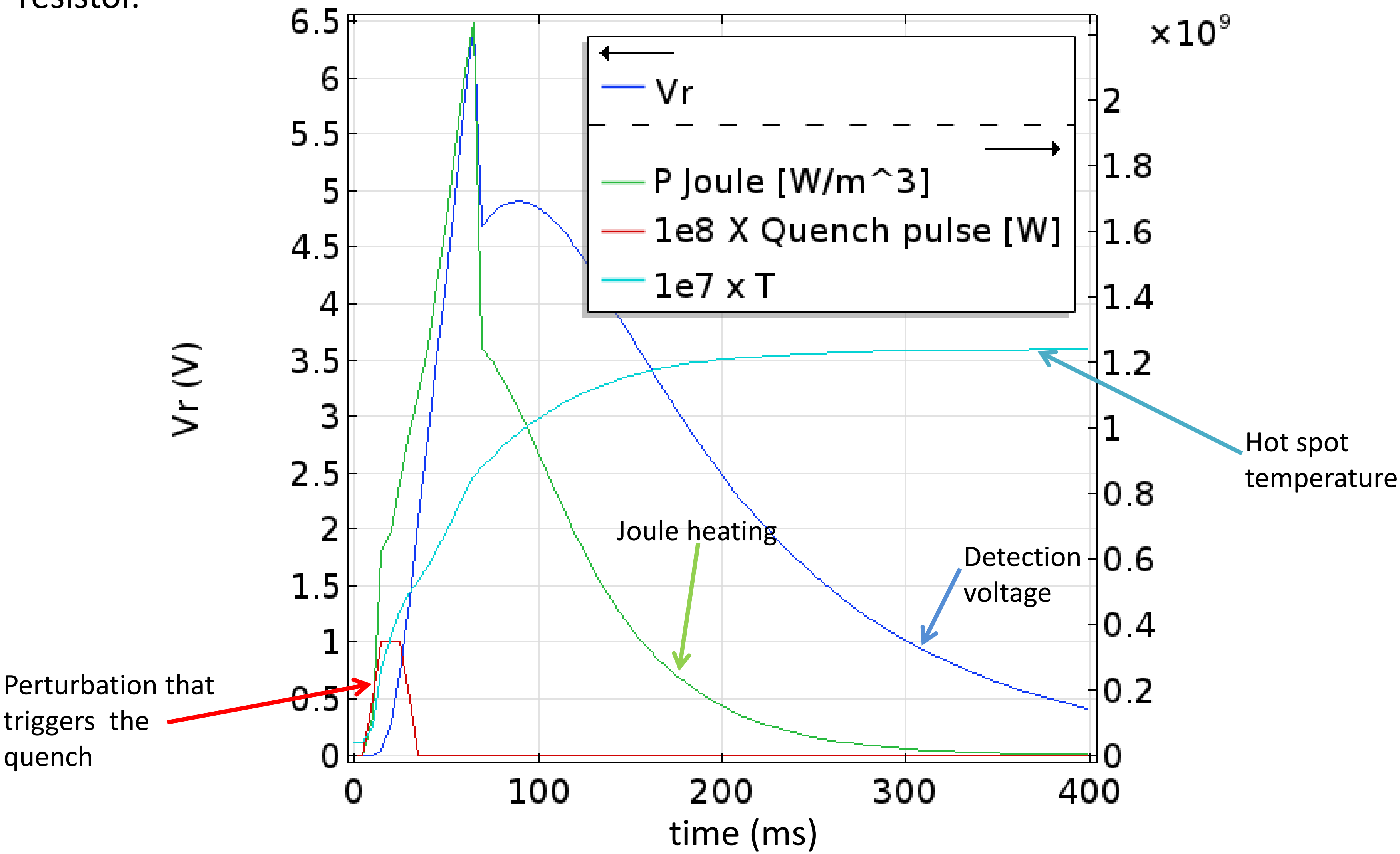

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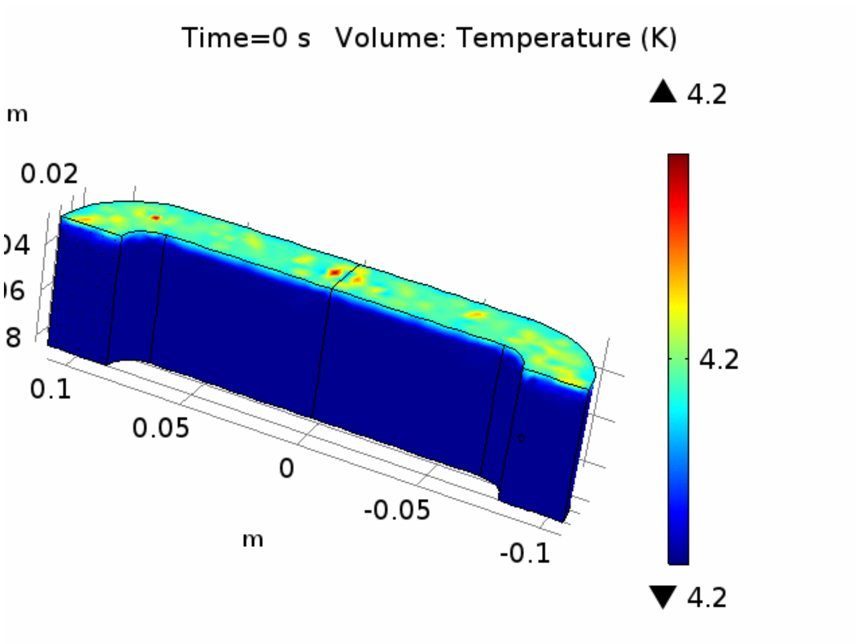

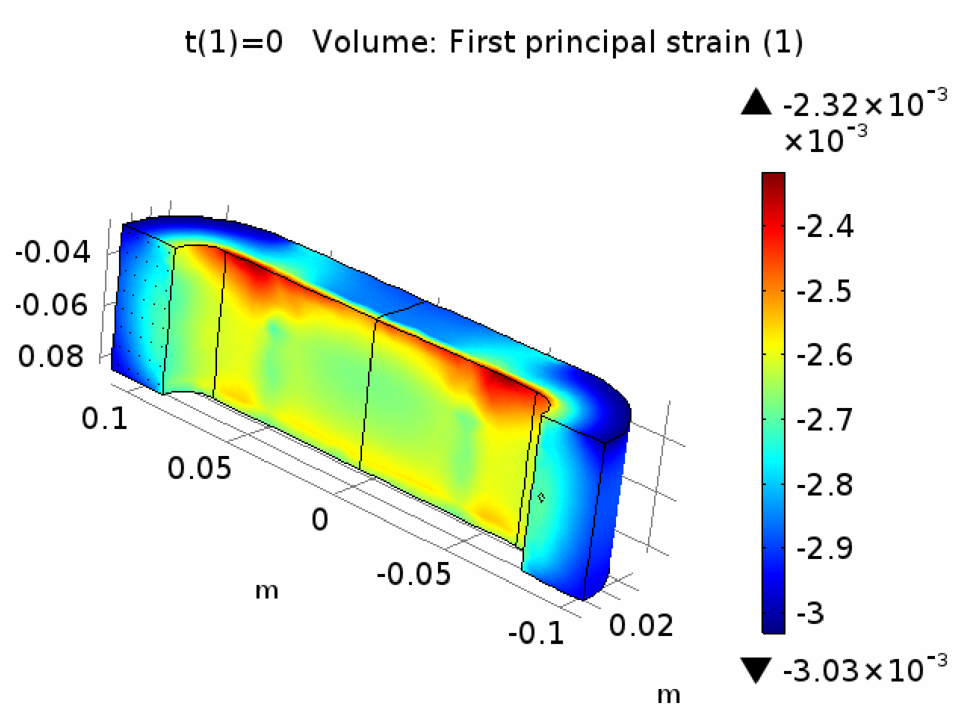

Summary

- ✓ Modelling a superconducting coil implies dealing with Multiphysics problems.
- ✓ COMSOL Multiphysics has been used to
  - ✓ Produce a parametric CAD of the magnet;
  - ✓ Analyze the cooldown time and the achievable temperature;
  - ✓ Estimate the AC losses in the magnet in operation;
  - ✓ Check the stress in the structure and in the coils due to the Lorentz forces and the thermal strain;
- ✓ In operation it is possible to have perturbations that leads to a quench of the superconducting magnet. In this case
  - ✓ A fast heating of the coils takes place;
  - ✓ If the energy is not safely extracted, the fast heating may even destroy the coils.

APPENDIX

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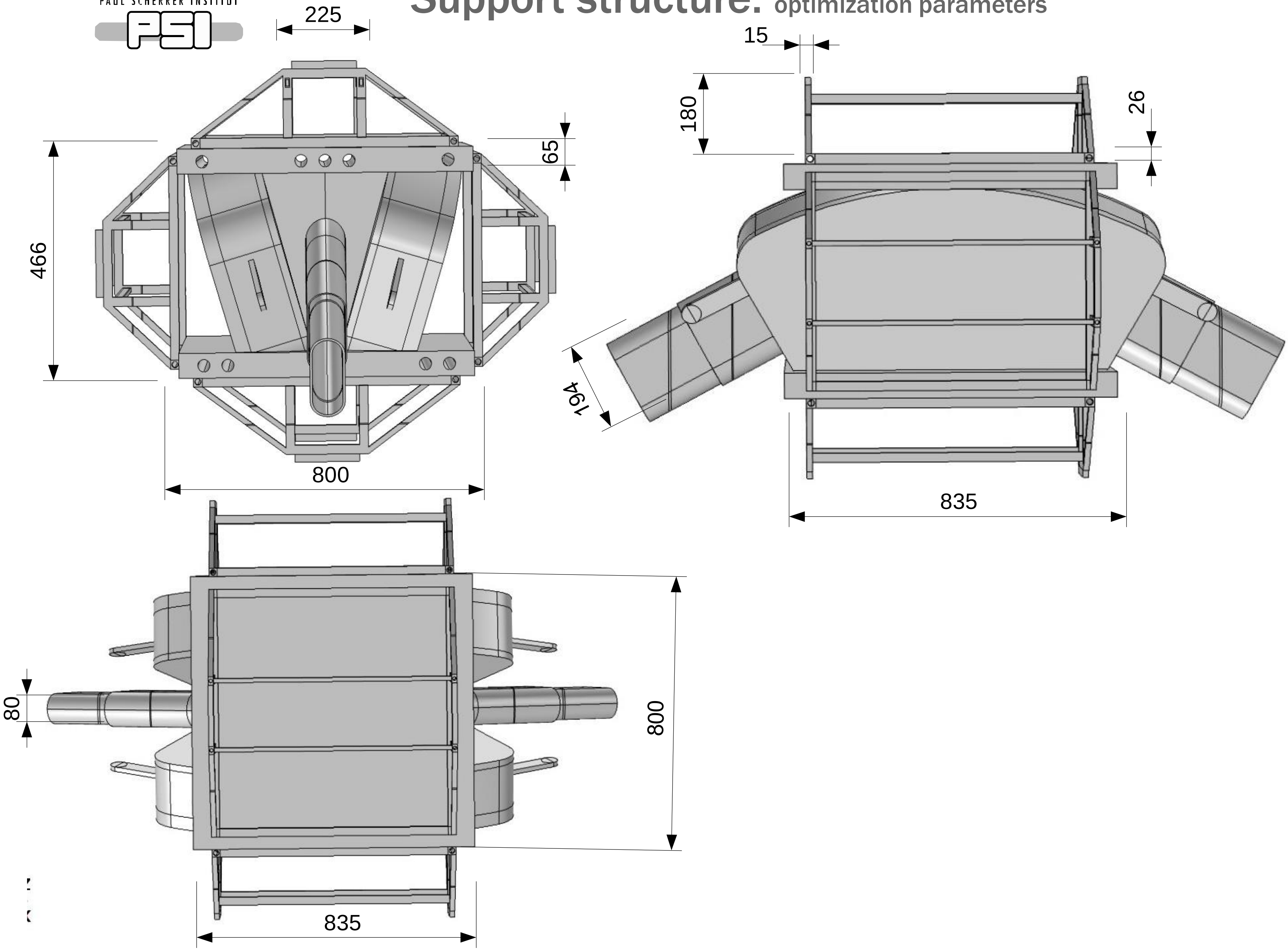
Support structure: optimization parameters



Thermal Analysis

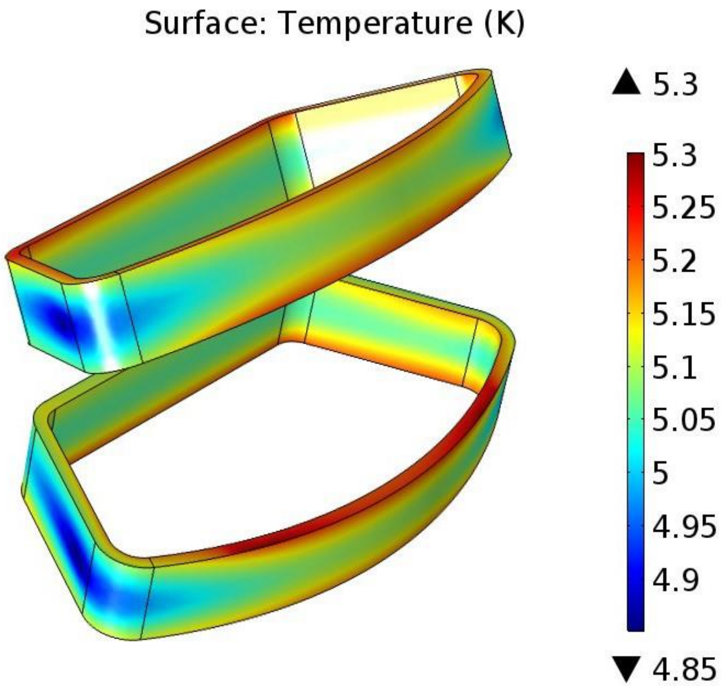
Heat capacity

Joule heating

AC losses coils

Eddy currents

Magnetization Fe



Cryocoolers

Conduction

AC losses

AC losses in the structure

$$\begin{cases} J = \nabla \times \mathcal{H} \\ B = \nabla \times \mathcal{A} \\ E = -\dfrac{\partial \mathcal{A}}{\partial t} \\ J = \sigma E + J_e \end{cases} \implies \nabla \times \nabla \times \mathcal{A} = \mu_0 \sigma \frac{\partial \mathcal{A}}{\partial t}$$

AC losses in the coils

$$\text{qH} = \frac{2}{3\pi} J_c(T, B, \epsilon) d_f \frac{dB}{dt}$$

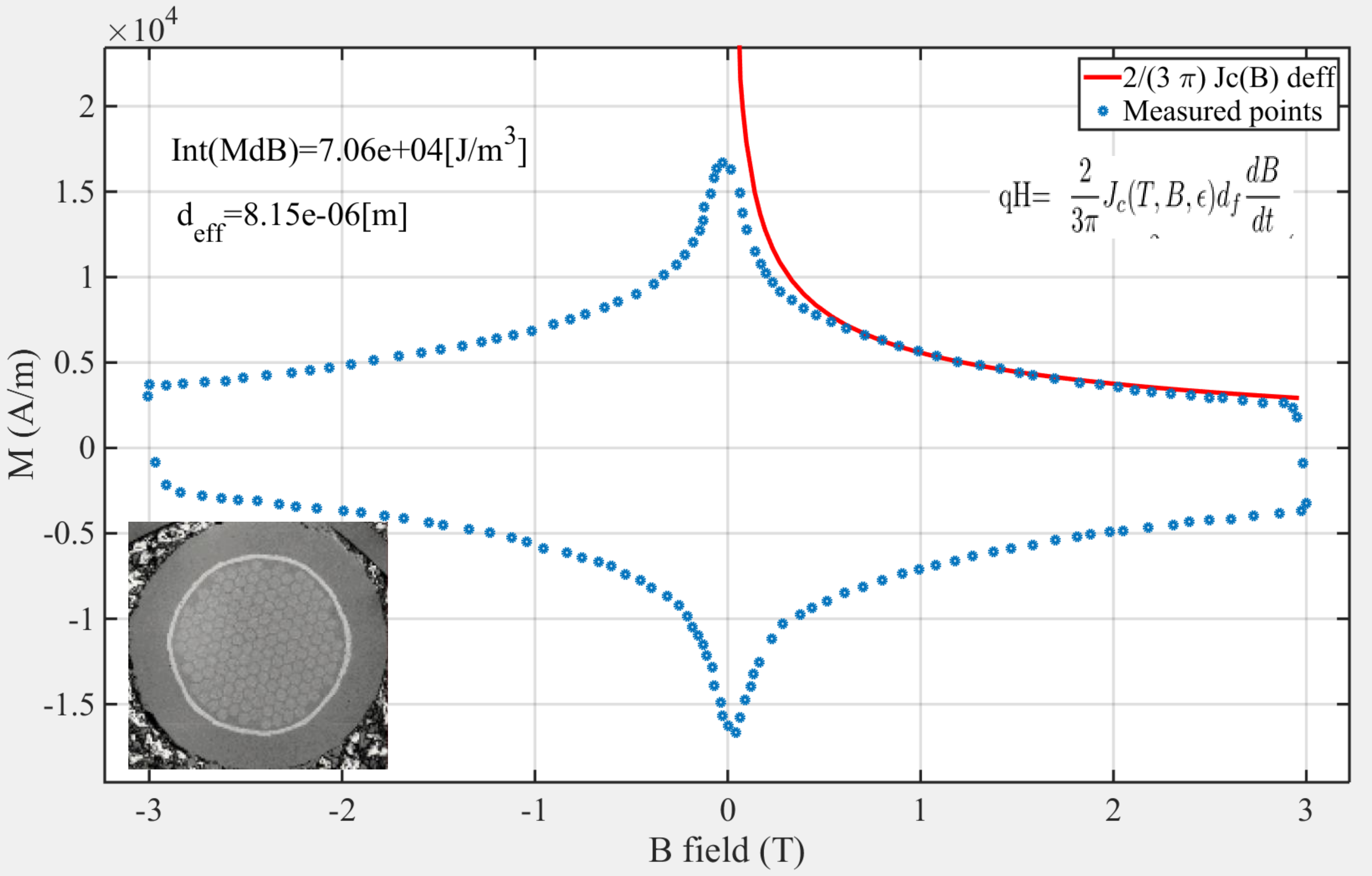
$$qiF = \frac{2}{\mu_0} \left(\frac{dB}{dt}\right)^2 \frac{\mu_0}{2\rho_t} \left(\frac{tp_f}{2\pi}\right)^2$$

$$qiS = \frac{1}{6} \left(\frac{dB}{dt}\right)^2 \frac{1}{R_a} tp_s \frac{c}{b} + \frac{1}{120} \left(\frac{dB}{dt}\right)^2 \frac{1}{R_c} \frac{c}{b} tp_s Ns(Ns - 1)$$

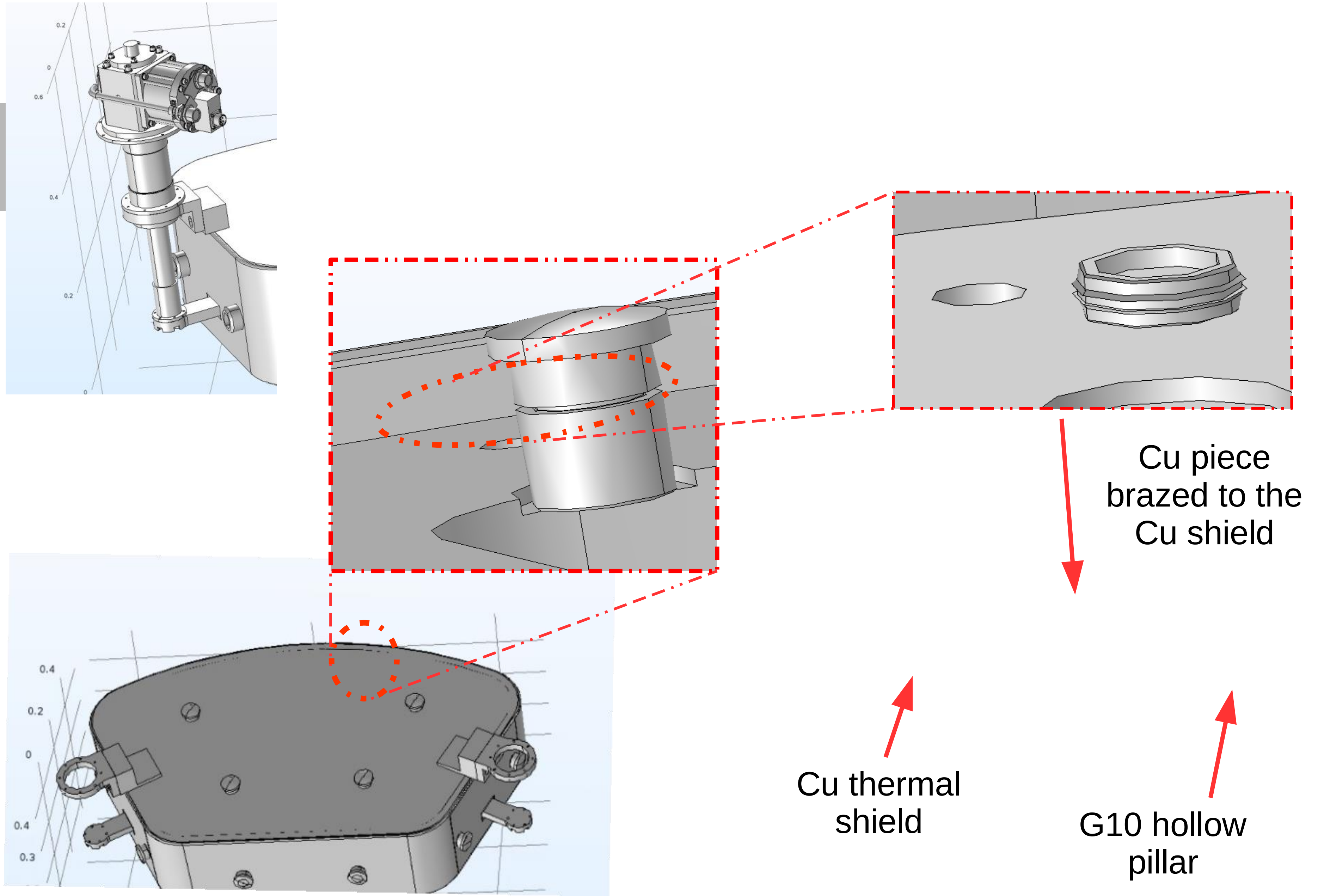
Temperature profile

$$\rho C_p \frac{\partial T}{\partial t} + \nabla \cdot (-k \nabla T) = \rho_{el} J^2 + qH + qiF + qiS$$

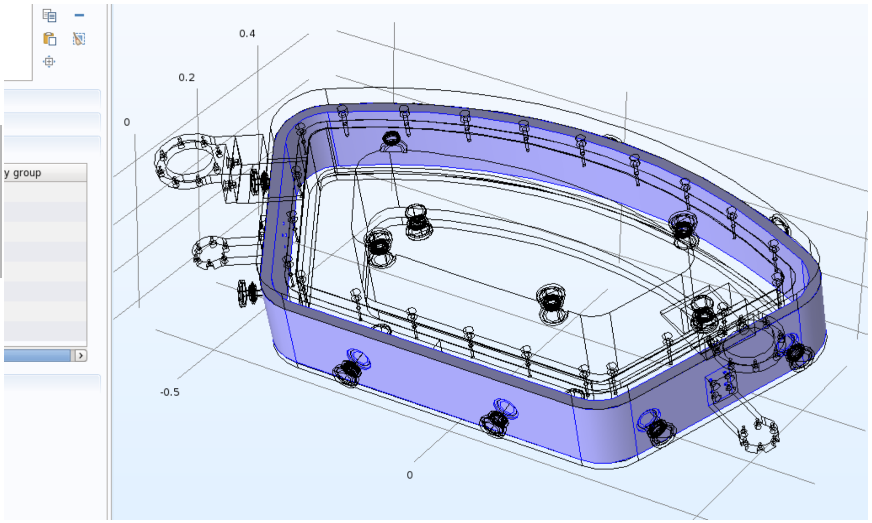
AC losses - hysteresis



DQS structure: 1st stage thermal shield



DQS structure



Cu support around the coil.

316 L former

Fe yoke