Recent developments in the thermal modeling of superconducting magnets

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Outline

- Motivation
- Simplified model of He II
- Validation of simplified model

Steady state modeling

- Modeling of thermal – flow process during AC losses in Nb_3Sn magnet
  - Description of *Fresca 2* magnet;
  - 3D computational region, assumptions and boundary conditions;
  - Mesh;
  - Numerical results.

Unsteady state modeling

- Modeling of thermal process during quench heating
  - Geometry and mesh;
  - Numerical results.

- Conclusions

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Motivation

- □ Within a framework of the European project EuCARD, a Nb_3Sn high field accelerator magnet is under design to serve as a test bed for future high field magnets and to upgrade the vertical CERN cable test facility, *Fresca 2*.
- □ Calculation of the maximum temperature rise in the magnet during AC losses.
- □ Calculation of magnet`s thermal – flow behavior during the quench detection event.
- □ Implementation of superfluid helium in commercial software - ANSYS CFX.

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Two - fluid model for He II

- Density of superfluid helium $\rho = \rho_n + \rho_s$ (1)
- Density flux $\rho\, u = \rho_n u_n + \rho_s u_s$ (2)
- Continuity equation $\frac{\partial \rho}{\partial \tau} + \nabla \cdot (\rho_n u_n + \rho_s u_s) = 0$ (3)
- Momentum equations for the total fluid

$$\frac{\partial}{\partial \tau}(\rho_n u_n + \rho_s u_s) = -\nabla \cdot (\rho_n u_n u_n + \rho_s u_s u_s) - \nabla p + \eta\left[\nabla^2 u_n + \tfrac{1}{3}\nabla(\nabla \cdot u_n)\right] + \rho g \quad (4)$$

- Momentum equations for the superfluid component

$$\frac{\partial u_s}{\partial \tau} = -(u_s \cdot \nabla) u_s + s\nabla T - \frac{1}{\rho}\nabla p + \frac{\rho_n}{2\rho}\nabla |u_n - u_s|^2 + A\rho_n |u_n - u_s|^2 (u_n - u_s) + g \quad (5)$$

- Entropy equation

$$\frac{\partial}{\partial \tau}(\rho s) = -\nabla \cdot (\rho s u_n) + \frac{A\rho_n \rho_s |u_n - u_s|^4}{T} \quad (6)$$

Simplified model of He II (Kitamura et al.)

- The momentum equation for the superfluid component is simplified to the form

$$\frac{\partial u_s}{\partial \tau} = -(u_s \cdot \nabla)u_s + s\nabla T - \frac{1}{\rho}\nabla p + \frac{\rho_n}{2\rho}\nabla|u_n - u_s|^2 + A\rho_n|u_n - u_s|^2(u_n - u_s) + g$$

$$s\nabla T = -A\rho_n|u_n - u_s|^2(u_n - u_s)$$

(the thermomechanical effect term and the Gorter-Mellink mutual friction term are larger than the other)

Superfluid component:

$$u_s = u - \frac{\rho_n}{\rho}(u_n - u_s) = u + \left(\frac{\rho_n^3 s}{A\,\rho^3 \rho_n |\nabla T|^2}\right)^{1/3} \nabla T$$

Normal component:

$$u_n = u + \frac{\rho_s}{\rho}(u_n - u_s) = u - \left(\frac{\rho_s^3 s}{A\,\rho^3 \rho_n |\nabla T|^2}\right)^{1/3} \nabla T$$

Momentum equation

$$\rho\frac{\partial u}{\partial \tau} = -\rho(u \cdot \nabla)u - \nabla p - \nabla \cdot \left[\frac{\rho_n\,\rho_s}{\rho}\left(\frac{s}{A\rho_n|\nabla T|^2}\right)^{2/3} \nabla T \nabla T\right] + \eta\left[\nabla^2 u + \left\{\nabla^2(\nabla T) + \frac{1}{3}\nabla(\nabla \cdot \nabla)T\right\}\right] + \rho g$$

The system of equation for He II simplified model

- Continuity equation

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho\, u) = 0 \qquad (1)$$

- Momentum equation:

$$\rho \frac{\partial u}{\partial \tau} = -\rho(u \cdot \nabla)u - \nabla p - \nabla \cdot \left[\frac{\rho_n\, \rho_s}{\rho}\left(\frac{s}{A\rho_n |\nabla T|^2}\right)^{2/3} \nabla T \nabla T\right] +$$

$$\eta\left[\nabla^2 u + \frac{1}{3}\nabla(\nabla \cdot u) - \left(\frac{\rho_s^3 s}{A\rho^3 \rho_n |\nabla T|^2}\right)^{1/3}\left\{\nabla^2(\nabla T) + \frac{1}{3}\nabla(\nabla \cdot \nabla)T\right\}\right] + \rho g \qquad (2)$$

where:

$\nabla \cdot \left[\frac{\rho_n\, \rho_s}{\rho}\left(\frac{s}{A\rho_n |\nabla T|^2}\right)^{2/3} \nabla T \nabla T\right]$ - the convectional acceleration;

$\left(\frac{\rho_s^3 s}{A\rho^3 \rho_n |\nabla T|^2}\right)^{1/3}\left\{\nabla^2(\nabla T) + \frac{1}{3}\nabla(\nabla \cdot \nabla)T\right\}$ - the viscous effect.

- Energy equation:

$$\rho c_p \frac{\partial T}{\partial \tau} = -\rho c_p (u \cdot \nabla)T - \nabla \cdot \left\{\left(\frac{1}{f(T)|\nabla T|^2}\right)^{1/3} \nabla T\right\} \qquad (3)$$

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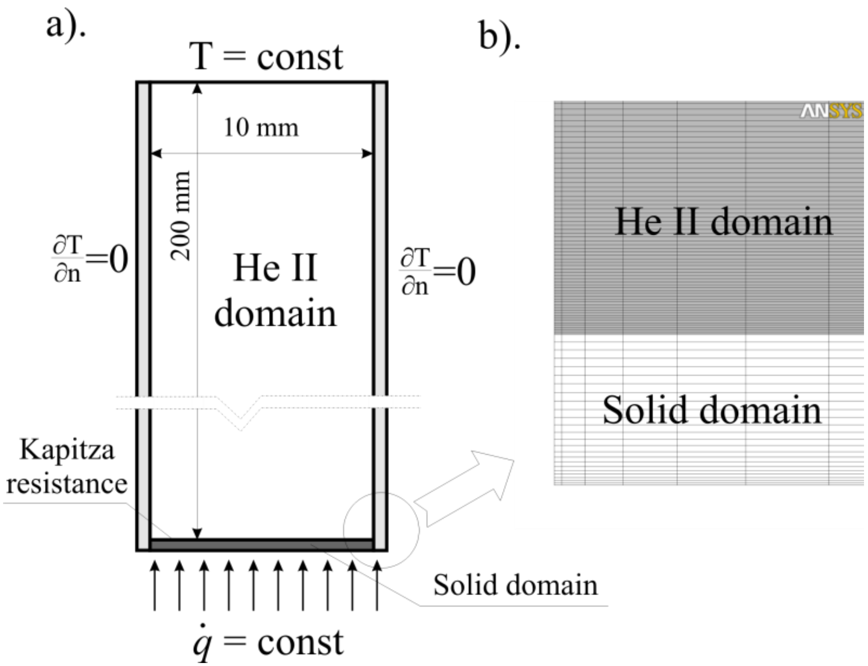
Validation of the simplified model



1. For He II domain (fluid domain)

- $$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho\, u) = 0$$
- $$\rho \frac{\partial u}{\partial \tau} = -\rho (u \cdot \nabla) u - \nabla p - \nabla \cdot \left[\frac{\rho_n \rho_s}{\rho} \left(\frac{s}{A \rho_n |\nabla T|^2} \right)^{2/3} \nabla T \nabla T \right] + \eta \left[\nabla^2 u + \frac{1}{3} \nabla (\nabla \cdot u) - \left(\frac{\rho_s^3 s}{A \rho^3 \rho_n |\nabla T|^2} \right)^{1/3} \left\{ \nabla^2 (\nabla T) + \frac{1}{3} \nabla (\nabla \cdot \nabla) T \right\} \right] + \rho g$$
- $$\rho c_p \frac{\partial T}{\partial \tau} = -\rho c_p (u \cdot \nabla) T - \nabla \cdot \left\{ \left(\frac{1}{f(T) |\nabla T|^2} \right)^{1/3} \nabla T \right\}$$

2. Insulation (solid domain)

- $$\rho_{solid}\, c_p(T) \frac{\partial T}{\partial \tau} = \left[\frac{\partial}{\partial x} \left(k(T) \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left(k(T) \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left(k(T) \frac{\partial T}{\partial z} \right) \right]$$

3. Kapitza resistance R_k is a function of temperature

With boundary conditions

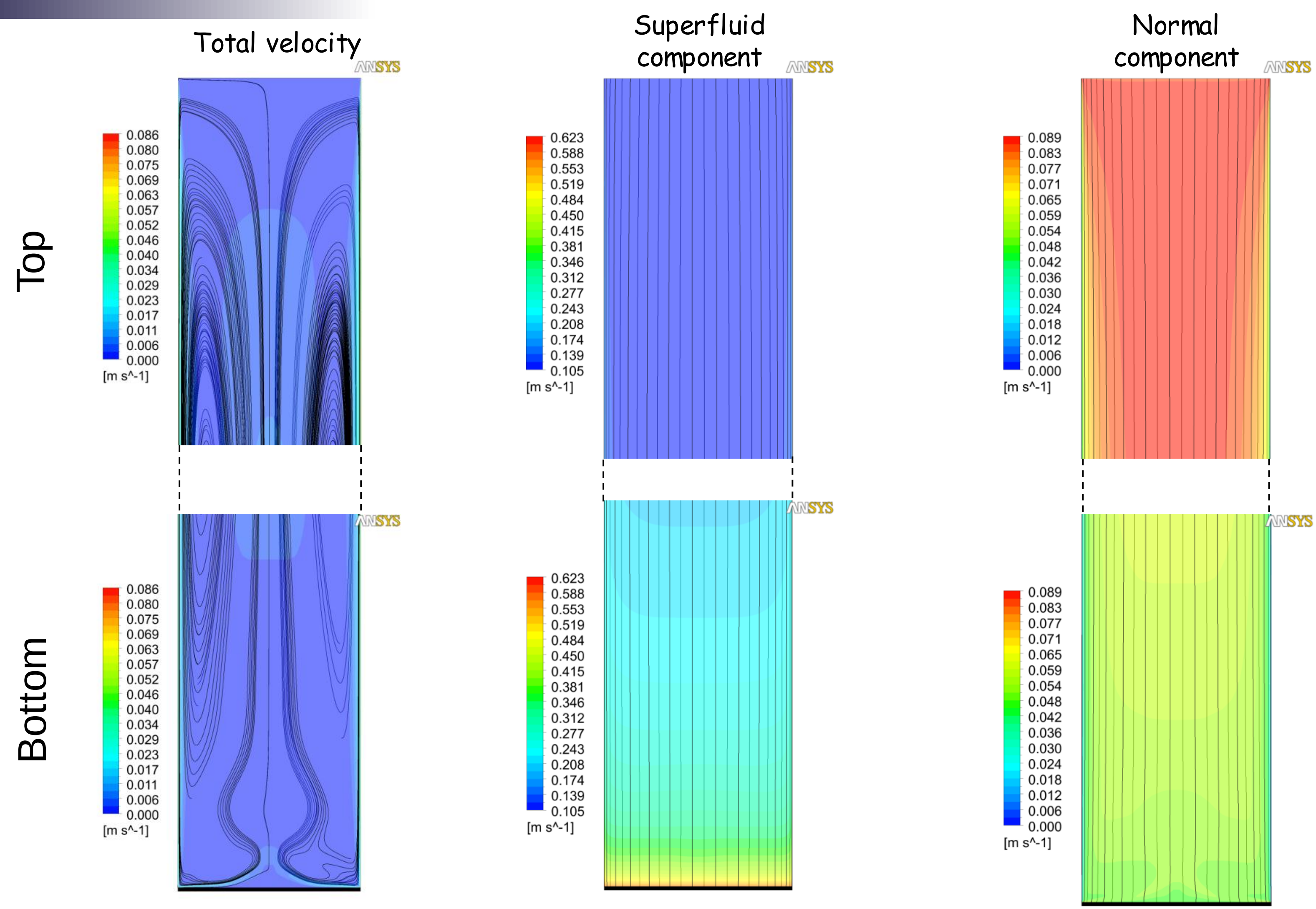
on left and right – adiabatic condition $\frac{\partial T}{\partial n} = 0$

on the top – constant temperature T_b=1.95 K

on the bottom – constant heat flux q=const

on all walls $u_\perp = 0$ and $u_\parallel = \left(\frac{\rho_s^3 s}{A\, \rho^3 \rho_n |\nabla T|^2} \right)^{1/3} (\nabla T)_\parallel$

Validation of the simplified model

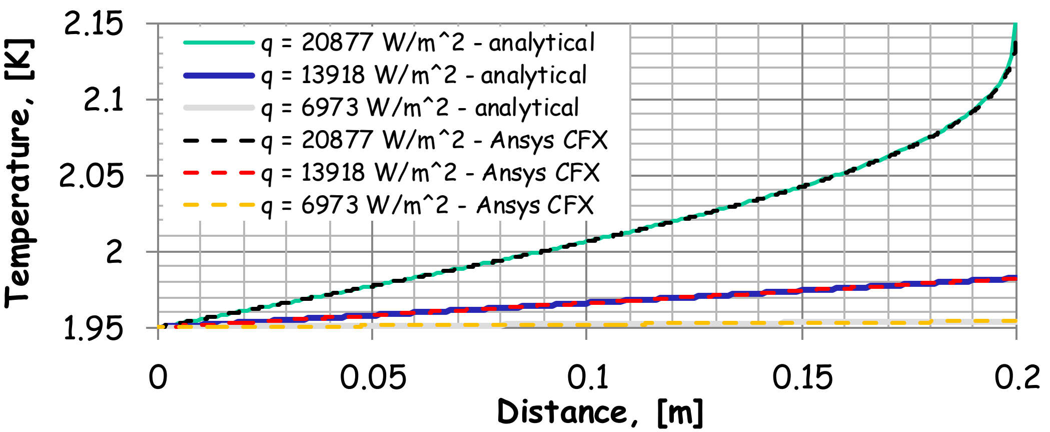


General view of velocity distribution with the streamlines of the total velocity the superfluid, and the normal components in the region near the bottom and the top of He II domain for the heat flux of 20877 W/m^2

Validation of the simplified model

The comparison between analytical and numerical maximum temperature for applied heat flux at the bottom of solid domain and the temperature profiles along symmetry axis obtained from analytical solution and ANSYS CFX

Applied heat flux	Maximum temperature		*Error*
	Analytical	Numerical	
W/m²	K	K	%
20877	2,1500	2,1371	0,602
13918	1,9823	1,9823	0,002
6959	1,9540	1,9540	0,000



The comparison between applied and calculated (from difference between normal and superfluid components) heat fluxes at the bottom and top of He II domain

Applied heat flux	$(u_n - u_s)$		$q=\rho_s sT(u_n-u_s)$		*Error*	
	at bottom	at top	at bottom	at top	at bottom	at top
W/m²	m/s	m/s	W/m²	W/m²	%	%
20877	0,624	0,193	20826	20877	0,25	0,000
13918	0,132	0,129	13935	13918	0,12	0,000
6959	0,066	0,065	7078	7011	1,71	0,007

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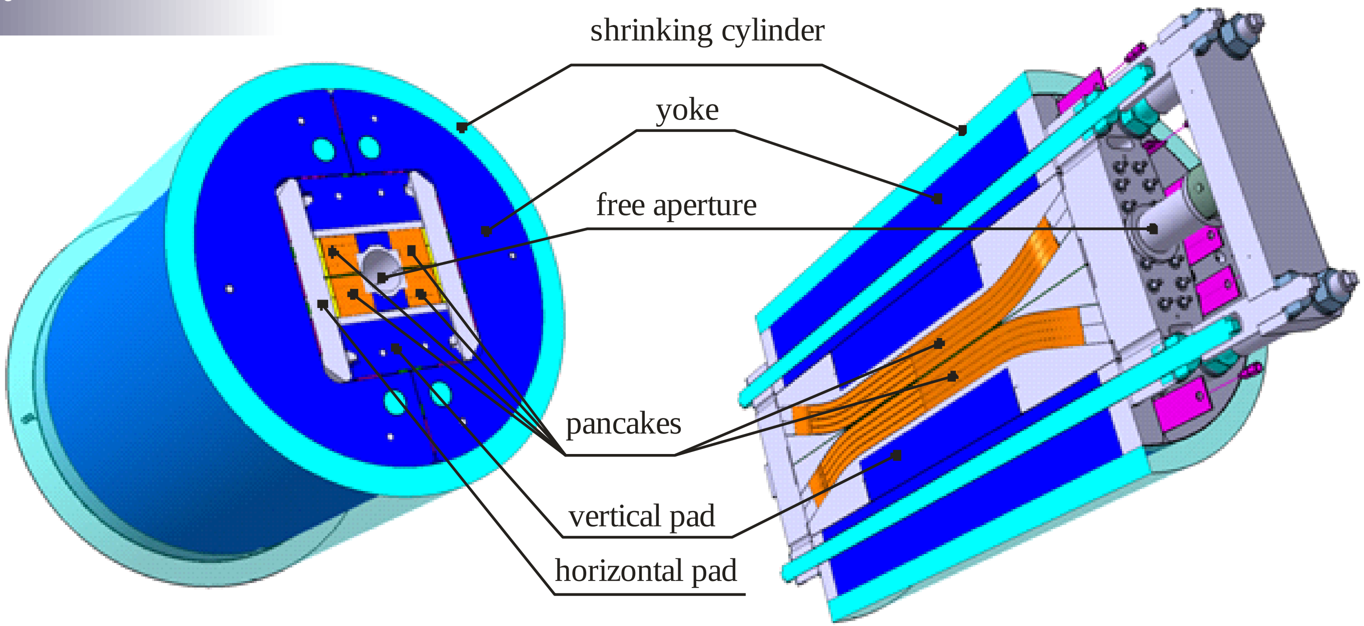
Description of *Fresca 2* magnet



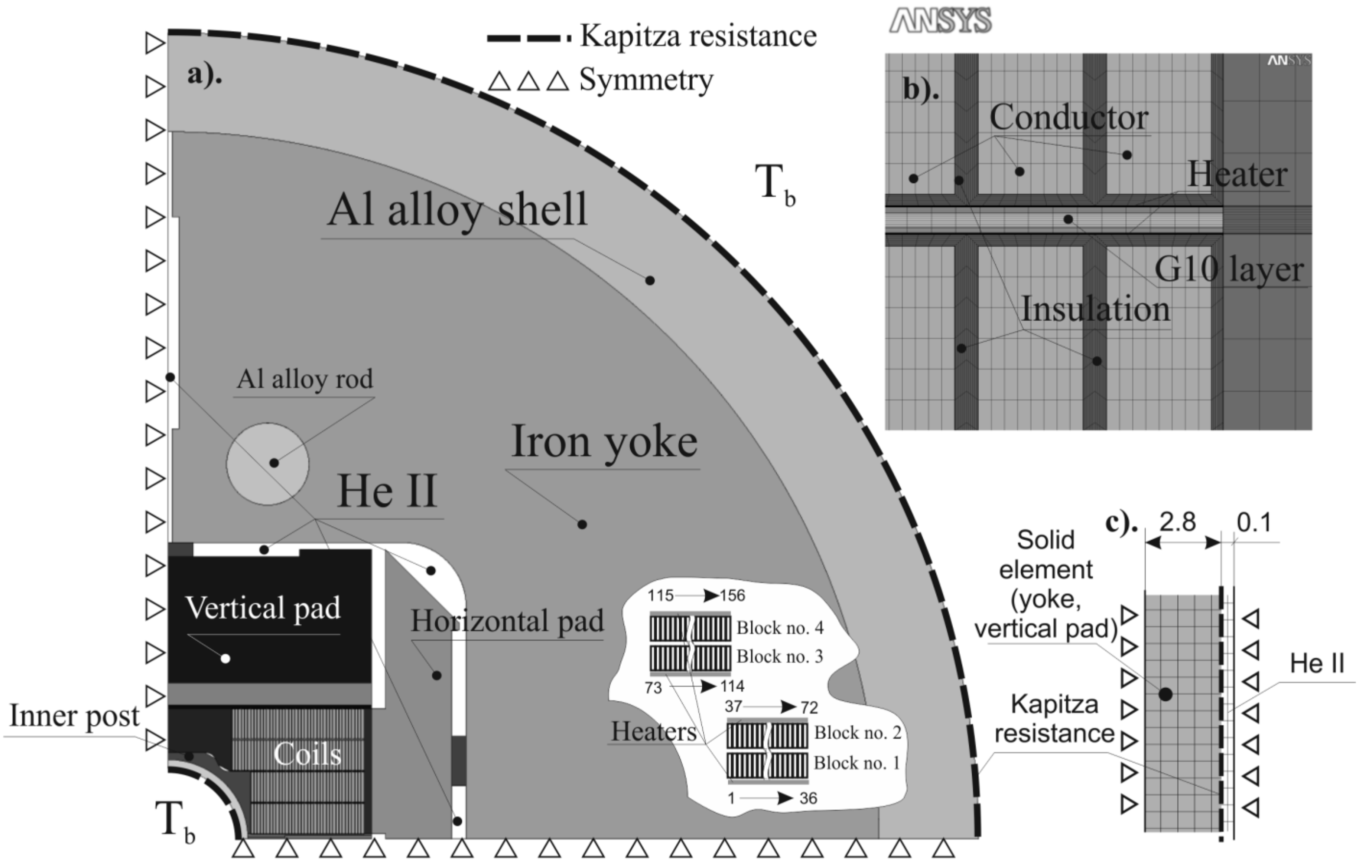
MAGNET SPECIFICATION

- type: block coil, 156 conductors in one pole;
- free aperture: 100 mm;
- total length: 1600 mm;
- outside diameter: 1030 mm;
- magnetic field: 13 T;

OPERATING PARAMETERS

- coolant: superfluid and/or saturated helium;
- temperature: 1.9 K and/or 4.2 K;
- temperature operating margin: 5.84 at 1.9 K and 3.54 K at 4.2 K

3D computational region, assumptions and boundary conditions

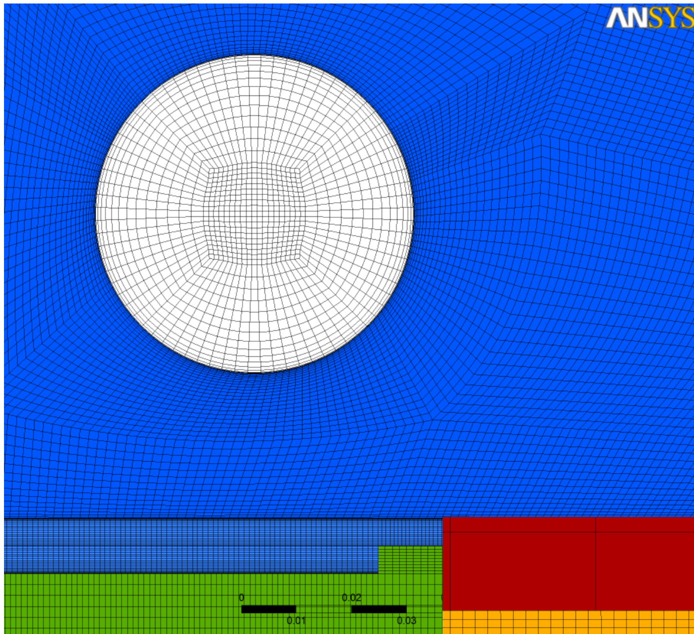


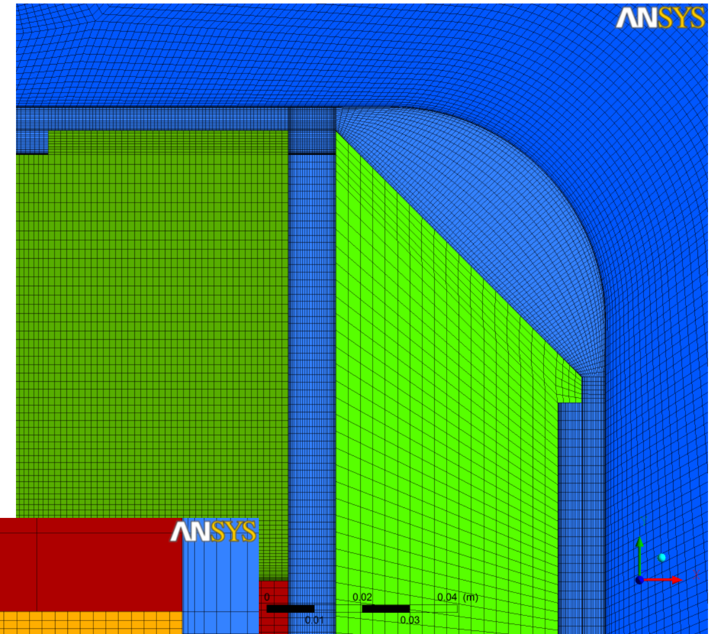
The simplified geometry of the Fresca 2 magnet a) general view with applied external boundary conditions, localization of the heaters and numbering of double-pancakes b) the details of geometry and mesh, c) the cross-section along the z-direction through solid and helium domains.

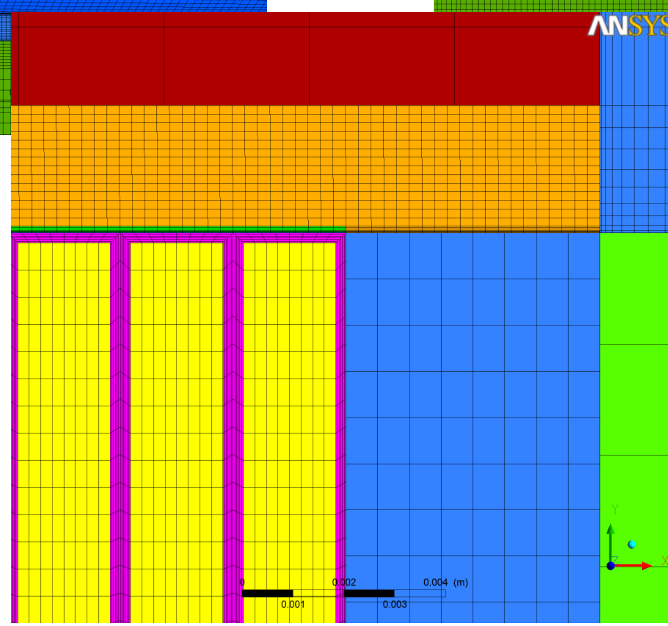
Assumptions

- Two types of boundary conditions at external sides:
  1. Constant bath temperature of 1.9 K and Kapitza resistance;
  2. Symmetry;
- Thermal conductivity as function of temperature;
- Perfect contact between solid elements;
- Calculations are carried out for CUDI model (AC loss due to ISCC losses, non-homogenous spreads)
- He II between yokes and pad laminations (200 μm)

Mesh

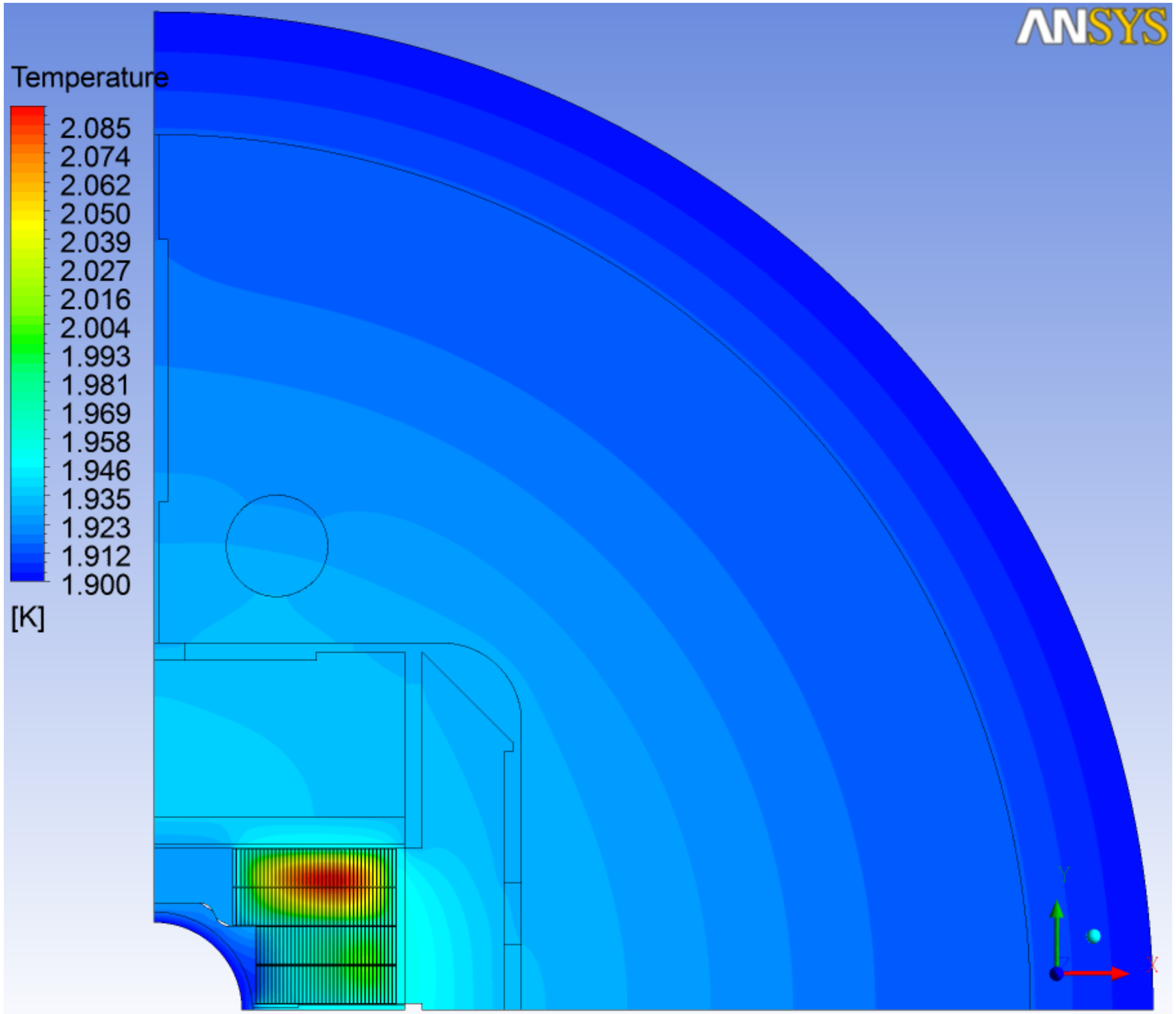




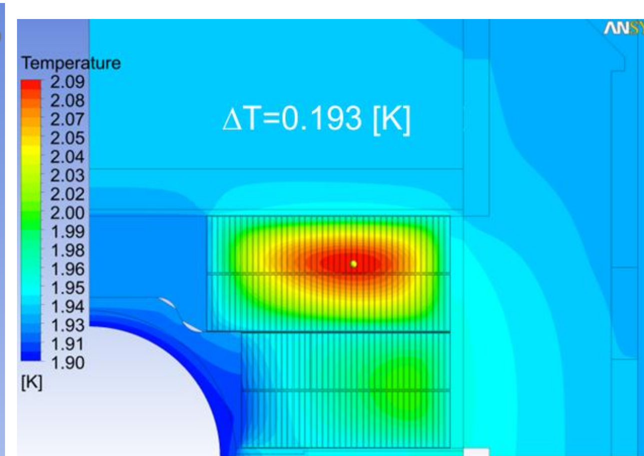


About 2 mln of structural elements
2.5 mln of nodes

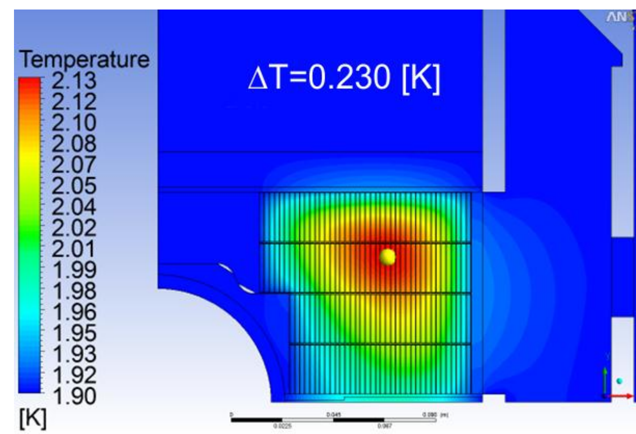
Numerical results



The contour of temperature field for the bath temperature of 1.9 K



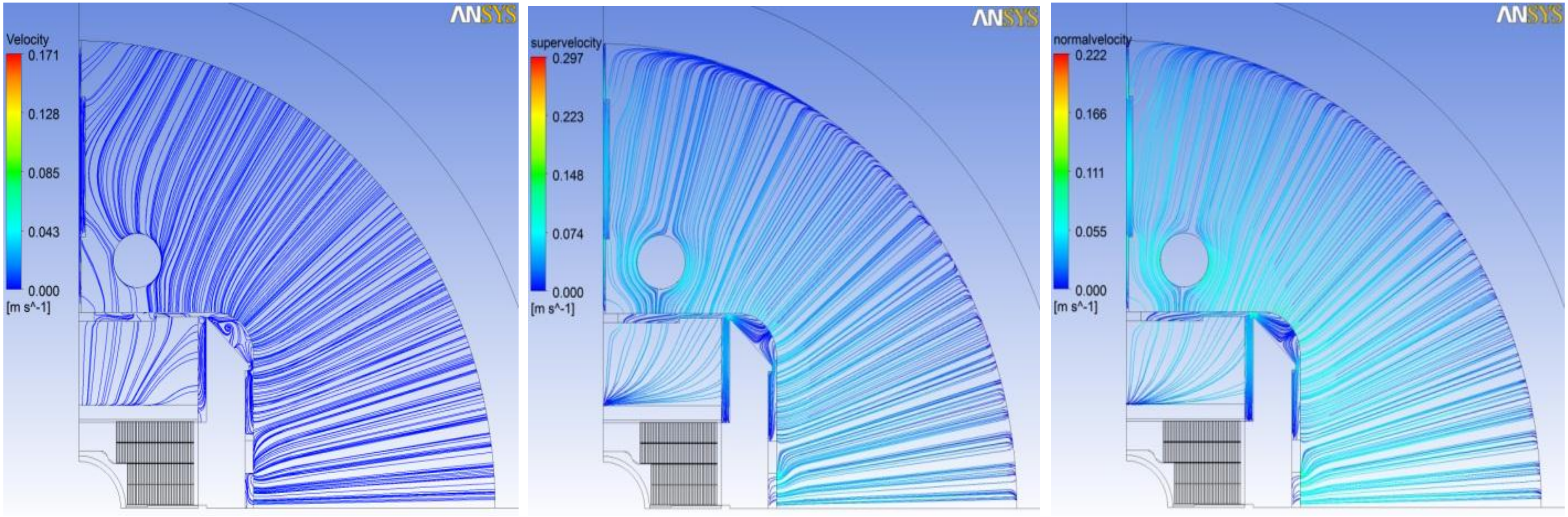
Details of temperature map in the conductors



Details of temperature map in the conductors for solid model (S. Pietrowicz, B. Baudouy, *Thermal design of an Nb_3Sn high field accelerator magnet, CEC Conference, 2011, Spokane, USA*)

de Rapper, W. M., "Estimation of AC loss due to ISCC losses in the HFM conductor and coil", CERN TE-Note-2010-004, 2010;

Numerical results



The streamlines and the velocity field for a) the total velocity, b) the superfluid and c) the normal-fluid components.

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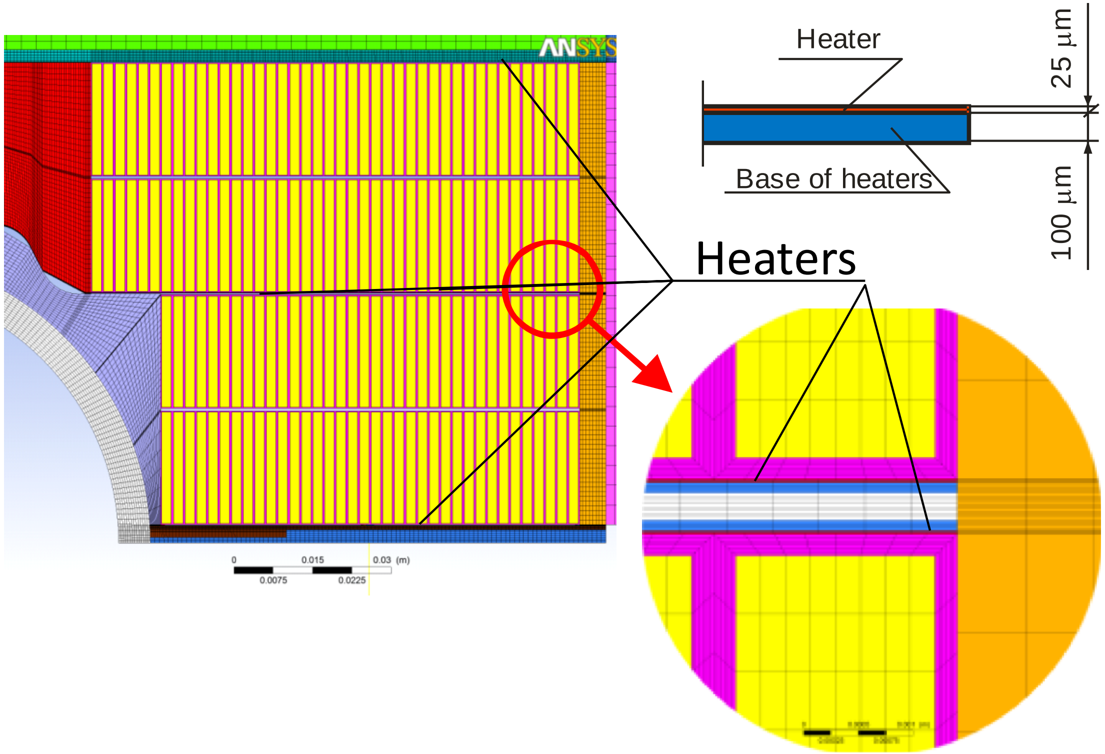
Modeling of thermal process during quench heating – unsteady state model

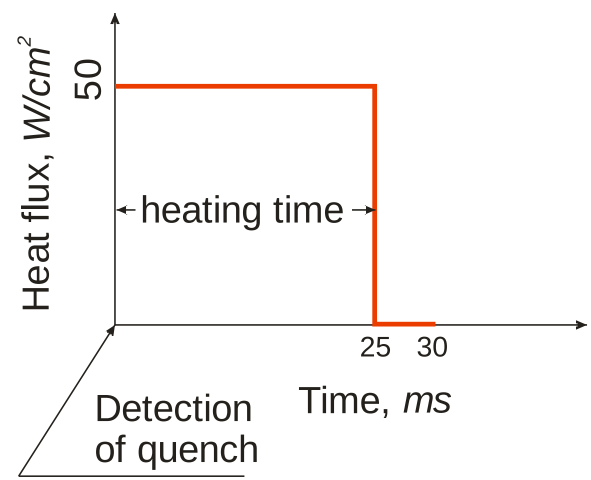


The details of applied quench heaters and their localization

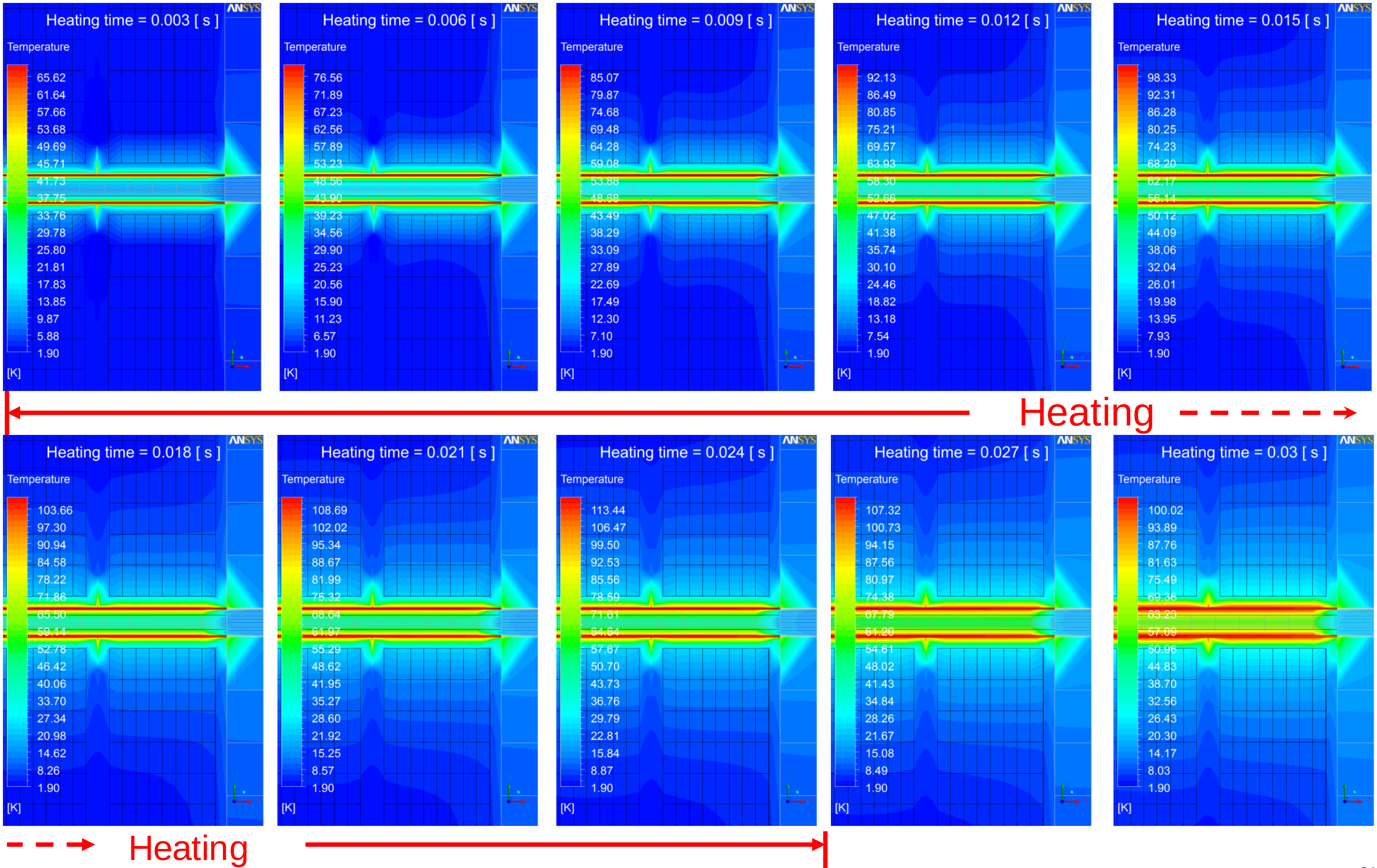
Assumptions

- Two types of boundary conditions:
  1. Constant temperature of the bath and Kapitza resistance on walls;
  2. Symmetry;

- Thermal conductivity and capacity as a function of temperature;
- Perfect contact between solid elements;
- Bath temperature 1.9 K
- Heating power of quench heaters **50 W/cm²** (the magnet is heated 25 ms after quench detection)



Modeling of thermal process during quench heating – unsteady state model



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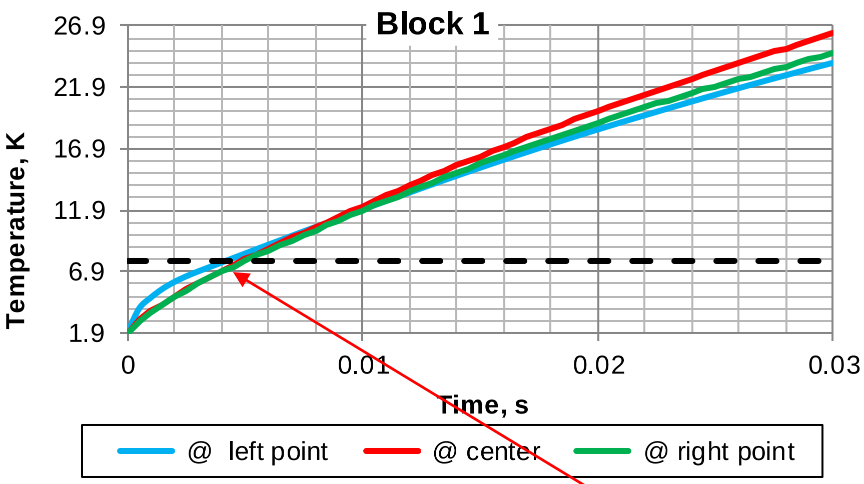
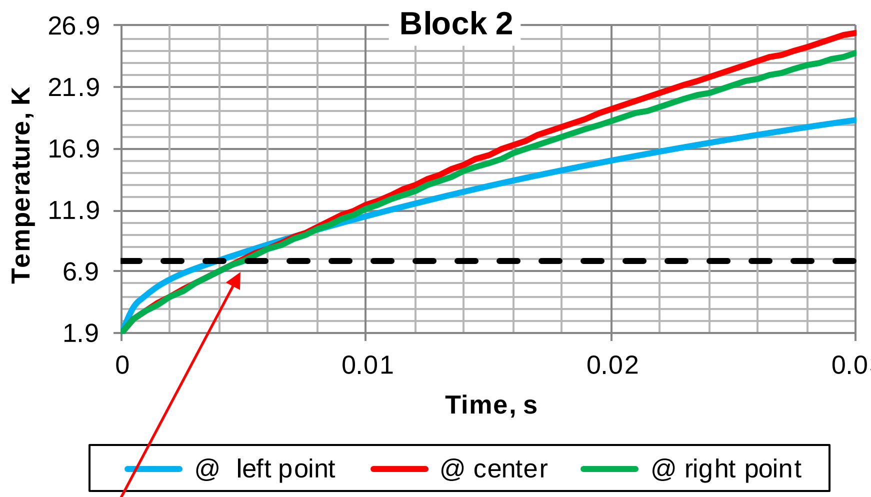
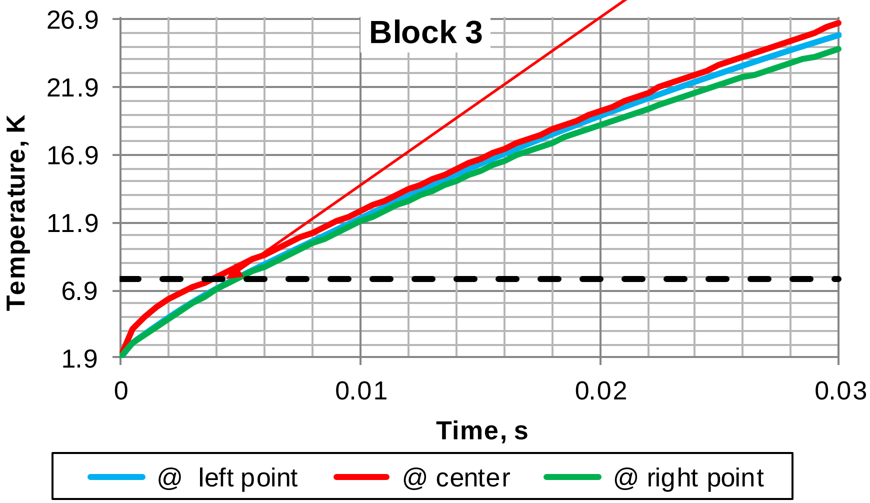


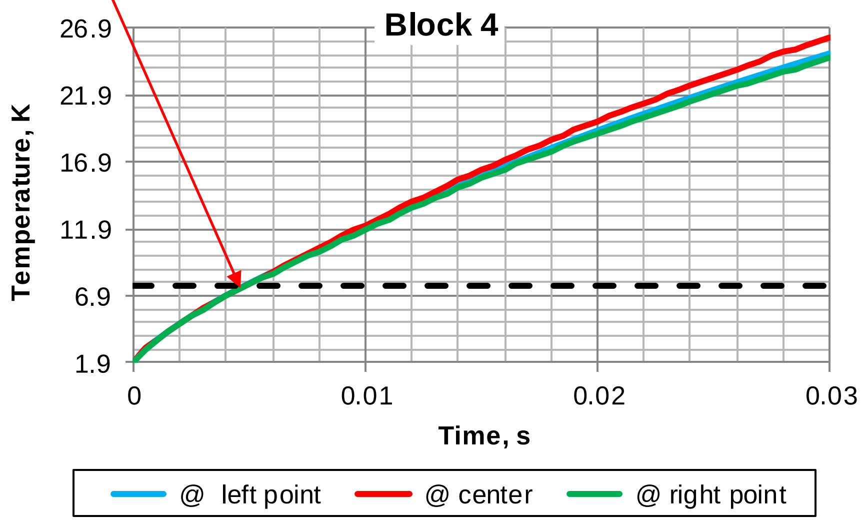


Has to be validated

4 – 5 *ms*

Temperature evolution at selected points





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Conclusions

- A He II simplified model is running under ANSYS CFX software
  - Steady state and transient calculation implementations
  - Model benchmarked against analytical solution within few percent
  - Improvement of the model during 2012

- Thermal modeling of Fresca 2
  - ΔT=193 mK for the AC losses given by the CUDI model
  - The transient code is operational
  - *Calculations on newer versions in 2012*