

Simulation of magnetization and heating processes in HTS tapes stacks

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In this work it is presented a computational model for a magnetic levitation system based on high-temperature superconducting (HTS) tapes stacks GdBa₂Cu₃O_{7-x} of the second generation. In the model it was used the features of the stacks properties. The experimental measurements were performed on the 12x12 mm superconducting tapes produced by SuperOx (Russia) with the thickness of the superconducting layer GdBa₂Cu₃O_{7-x} is 1 μ, the thickness of the silver layer is 3 μ, the critical current (at 77 K, own field) - 300 A (criterion 1 μV / cm). Gradient magnetic field is produced using a permanent Nd-Fe-B magnet, 30 mm in diameter, 10 mm thickness, class n42 (residual induction on the surface in the range 0.30 - 0.35 T).

Distribution of the magnetic field throughout the space and the current in every tape of the stack was calculated for two cases: the cryocooler-cooling mode and the liquid nitrogen cooling mode (zero-field cooling). The magnetization curves of the stacks in the external field of a permanent NdFeB magnet and the levitation force dependence on the gap between the magnet and the HTS tapes stack were obtained. Simulation results were compared with the experimental data.

Partial Differential Equations (PDE)

$$e_a \frac{\partial^2 \mathbf{u}}{\partial t^2} + d_a \frac{\partial \mathbf{u}}{\partial t} + \nabla \times \Gamma = \mathbf{F}$$

Dependent variable:

$$\mathbf{u} = \mathbf{H} = \begin{bmatrix} H_x \\ H_y \\ H_z \end{bmatrix}$$

$$e_a = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \quad d_a = \begin{bmatrix} \mu & 0 & 0 \\ 0 & \mu & 0 \\ 0 & 0 & \mu \end{bmatrix} \quad \mathbf{F} = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}$$

$$\Gamma = \rho^* \mathbf{J}^* \quad \mathbf{J} = \begin{cases} J_x = \frac{dH_z}{dy} - \frac{dH_y}{dz} \\ J_y = -\frac{dH_z}{dx} + \frac{dH_x}{dz} \\ J_z = \frac{dH_y}{dx} - \frac{dH_x}{dy} \end{cases}$$

$$\nabla \times \mathbf{E} + \frac{d\mathbf{B}}{dt} = \nabla \times \mathbf{E} + \frac{d(\mu_0 \mu_r \mathbf{H})}{dt} = 0$$

$$\nabla \times \mathbf{H} = \mathbf{J}$$

The resistance nonlinear dependence on the current is given by the power law $\rho = \frac{E_c}{J_c} \cdot \left(\frac{|J|}{J_c}\right)^{n-1}$ (n=21, $E_c = 1 \mu\text{V/cm}$), the current-voltage characteristic is given by formula $\mathbf{E} = \rho \times \mathbf{J}$. The critical current density J_c is set based on the transport measurements of the HTS tapes.

• Dirichlet boundary conditions: $\mathbf{H}|_{\partial\Omega} = \begin{bmatrix} H_{sx} + H_{ex} \\ H_{sy} + H_{ey} \\ H_{sz} + H_{ez} \end{bmatrix}$

• Levitation force calculation: $\mathbf{F} = \int_V \mathbf{J} \times \mathbf{B} dv$

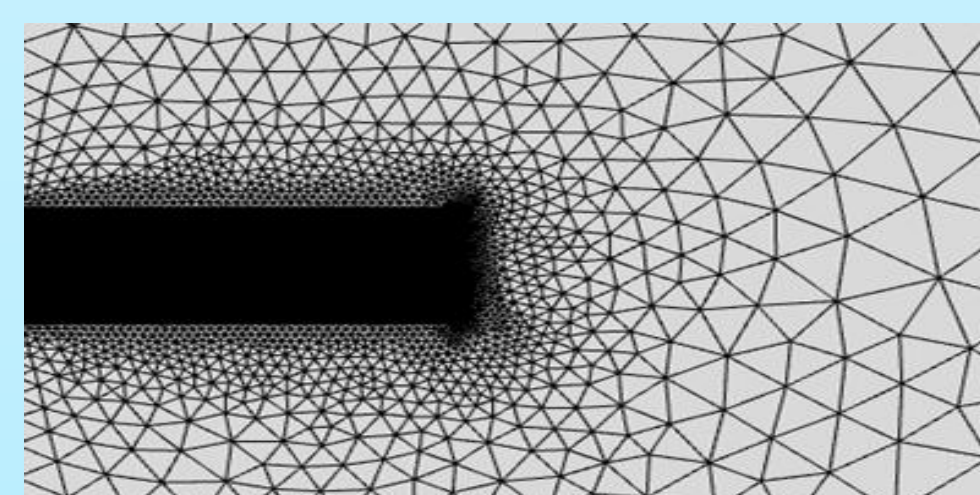
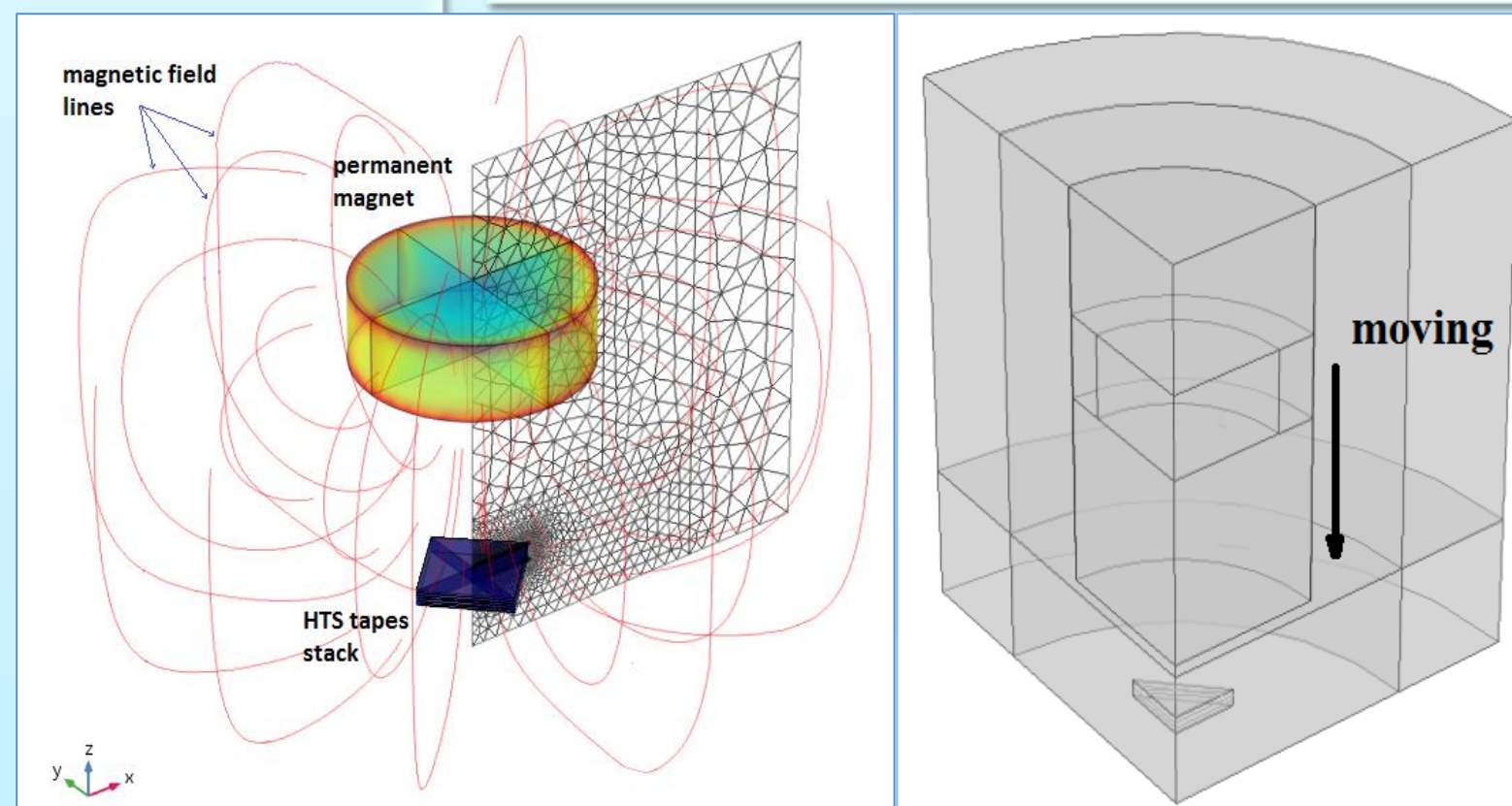
• Kim's dependence of the critical current density:

$$J_c = \frac{J_{c0}}{(1 + H/H_0)}$$

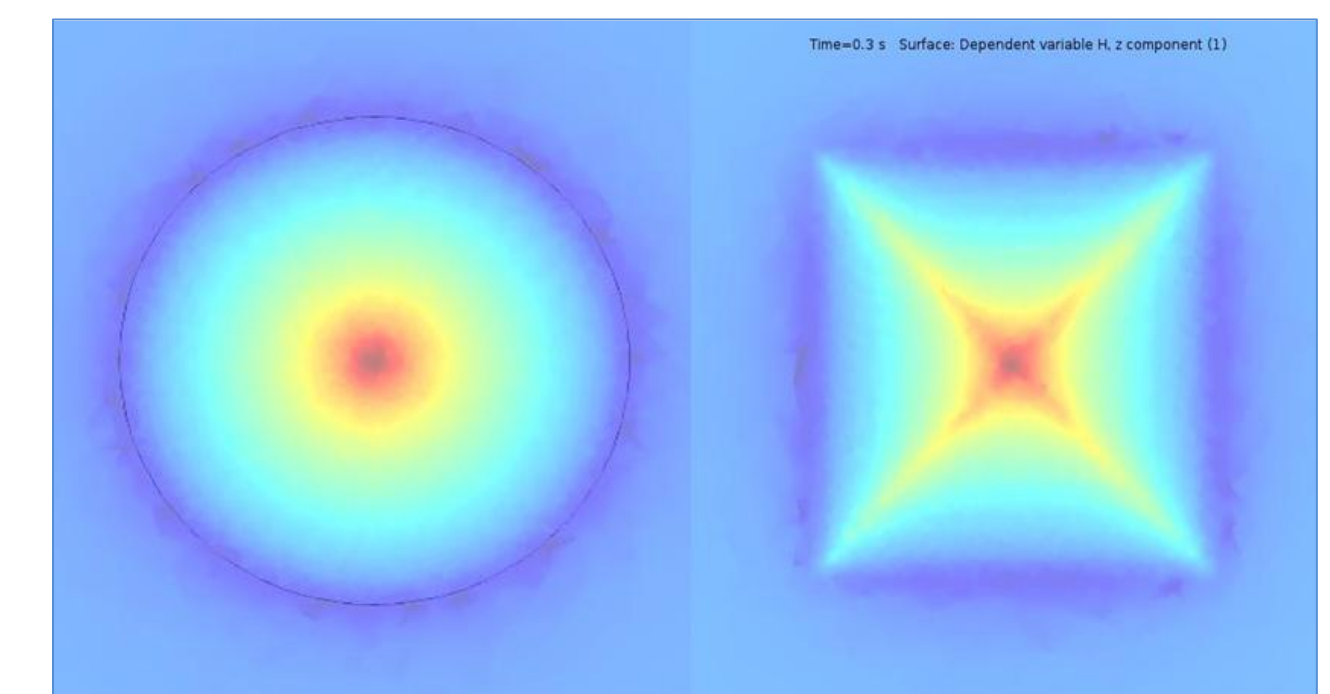
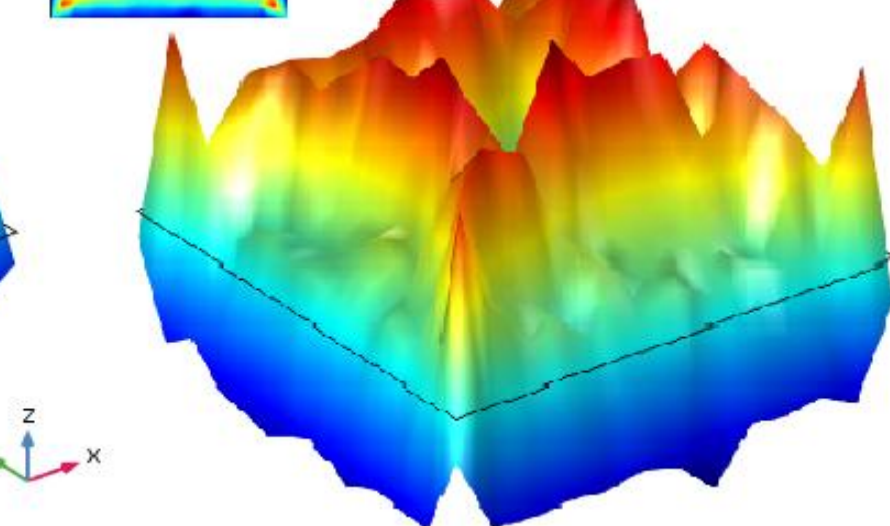
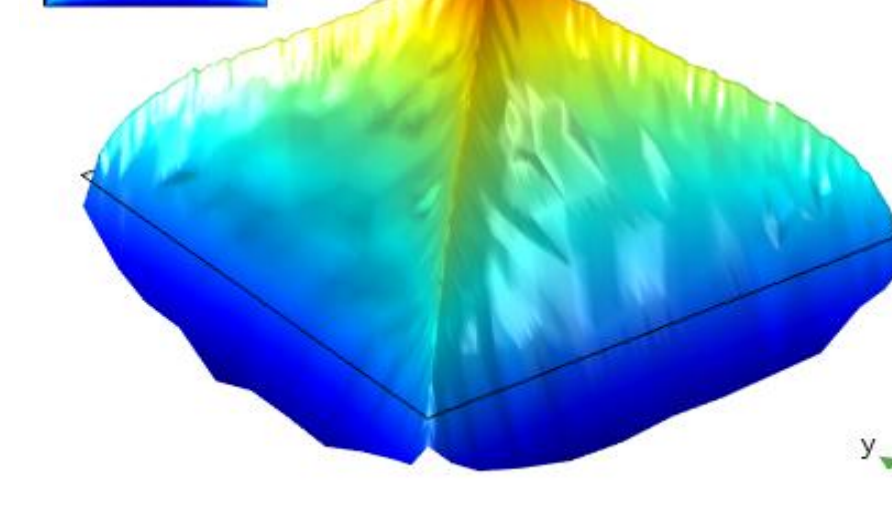
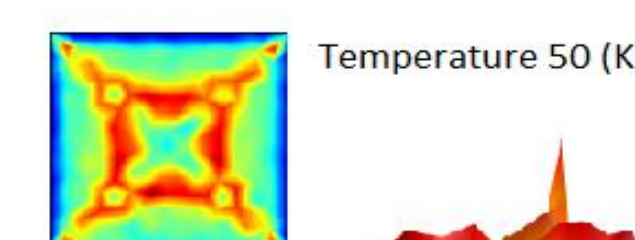
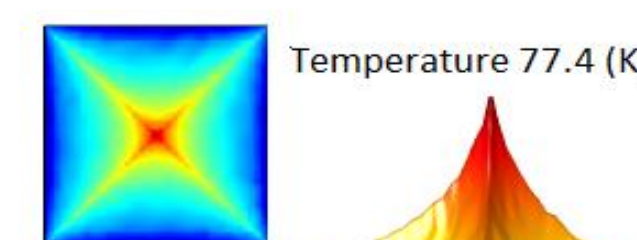
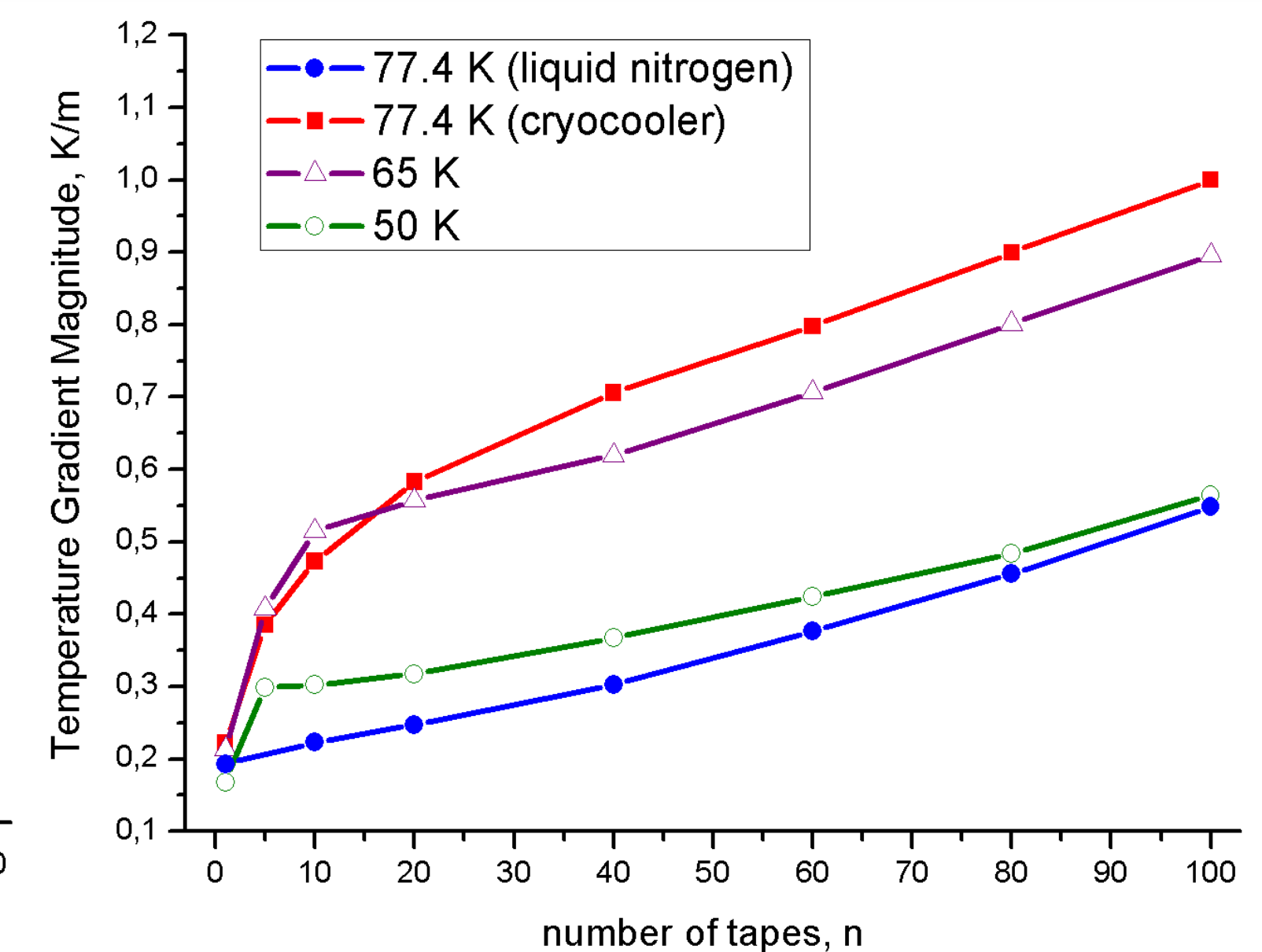
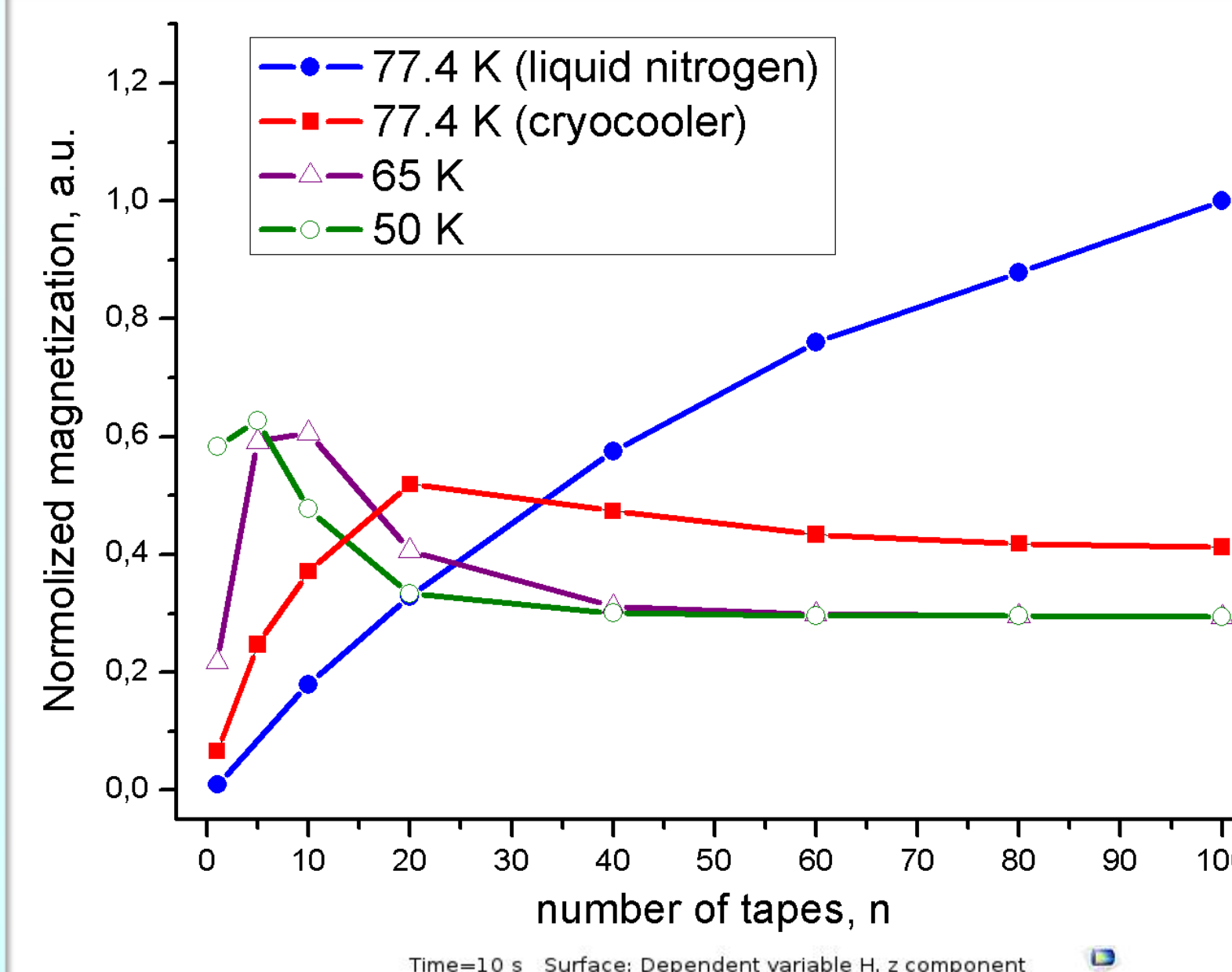
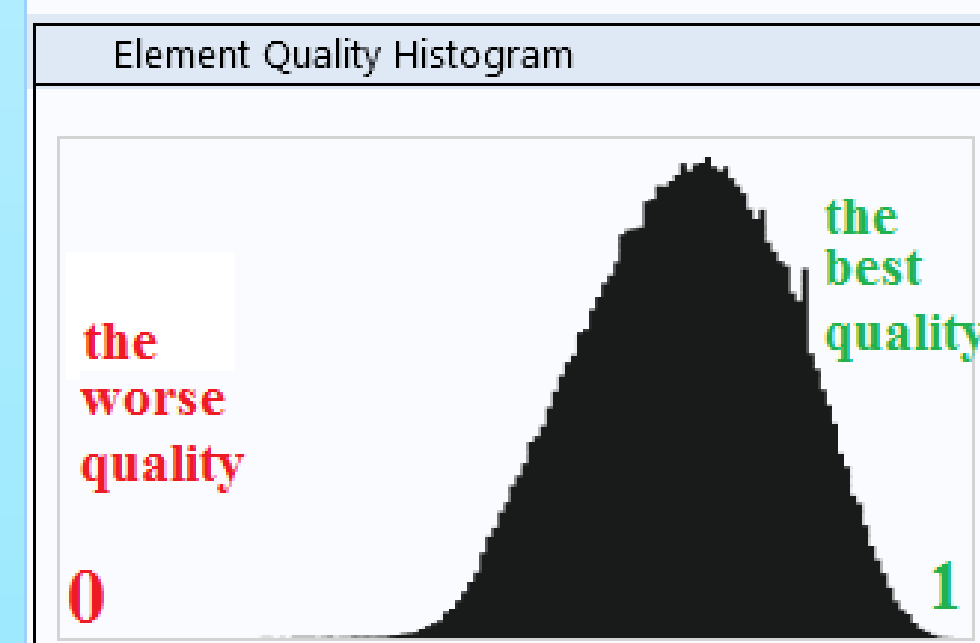
COMSOL

Finite element method (FEM)

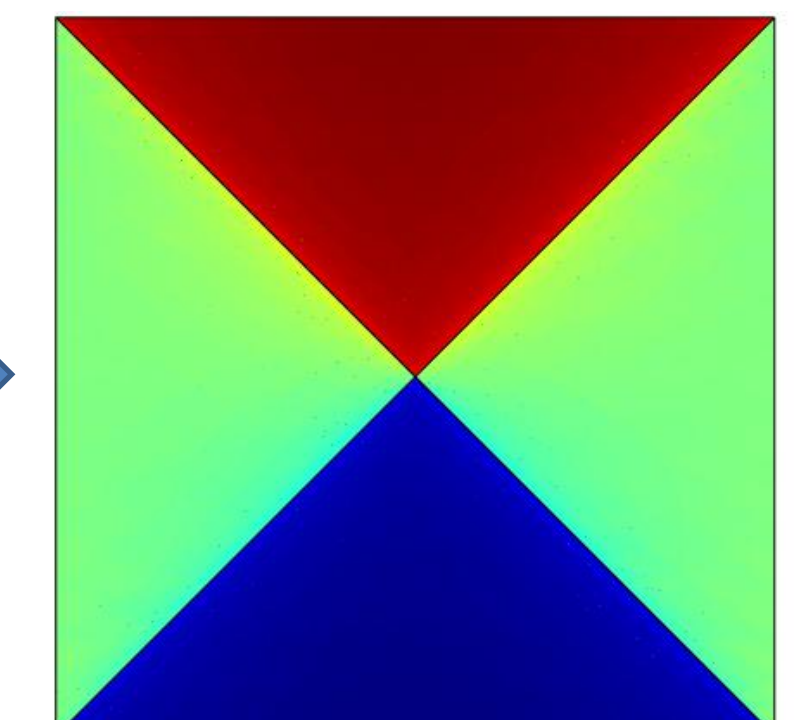
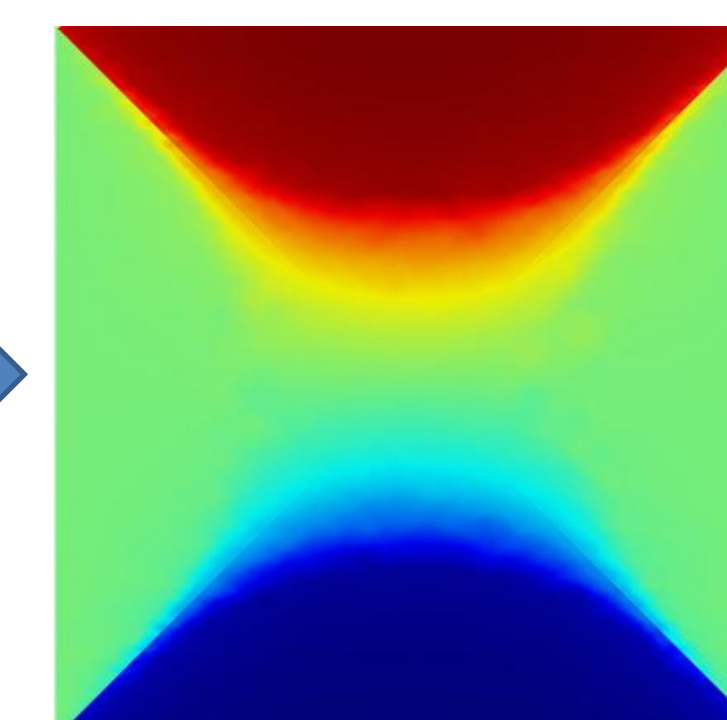
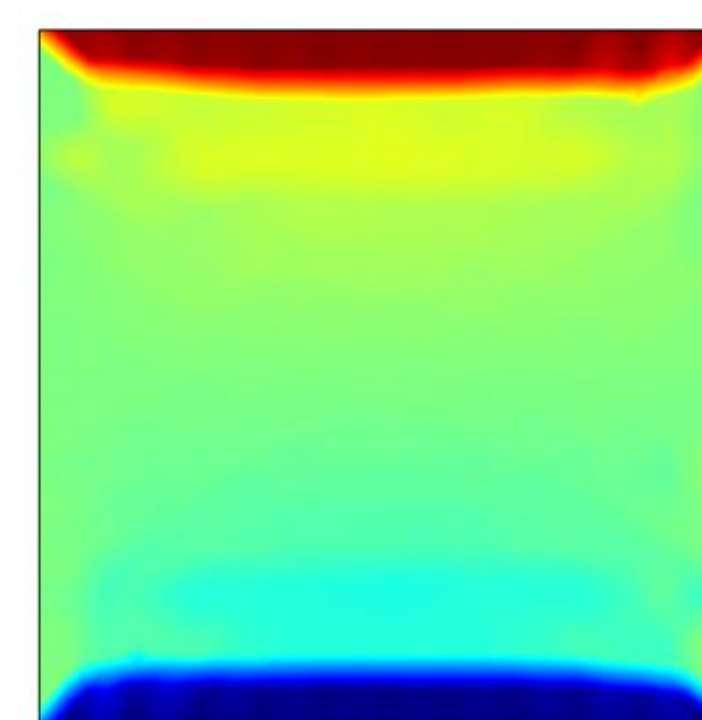
- Multiscale-structuring
- Moving Mesh
- Axial symmetry
- 2D and 3D Modeling



Domain element statistics	
Number of elements:	296654
Minimum element quality:	0.2523
Average element quality:	0.6868
Element volume ratio:	9.212E-7
Mesh volume:	127500.0 mm ³



Current dynamics: surface J, x-component



• Heat transfer

$$\rho C_p \frac{\partial T}{\partial t} + \nabla \cdot (-k \nabla T) = Q - \rho C_p \mathbf{u} \cdot \nabla T$$

Conduction

Convection

Accumulation

Heat sources

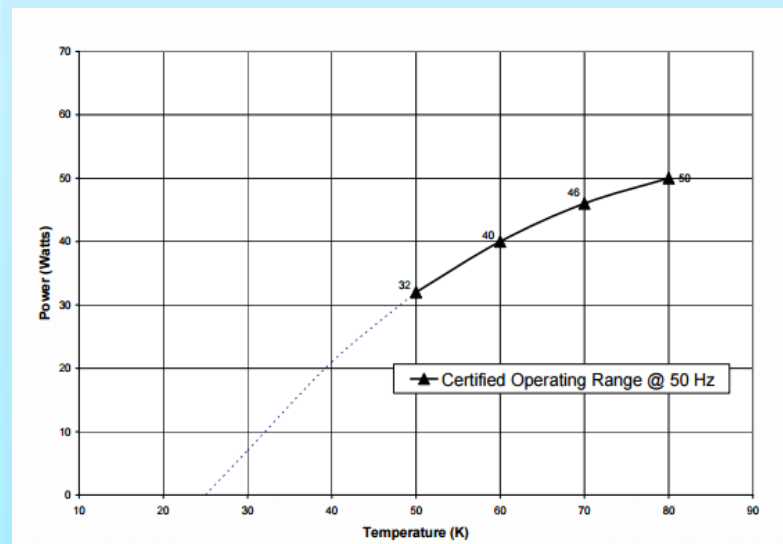
• The dependence of the critical current on the temperature:
 $I_{c0} = \alpha \left(1 - \left(\frac{T}{T_c}\right)^2\right)^{1.5}$
 α - fitting parameter

• Local heat generation in the system:
 $Q = E \cdot J$

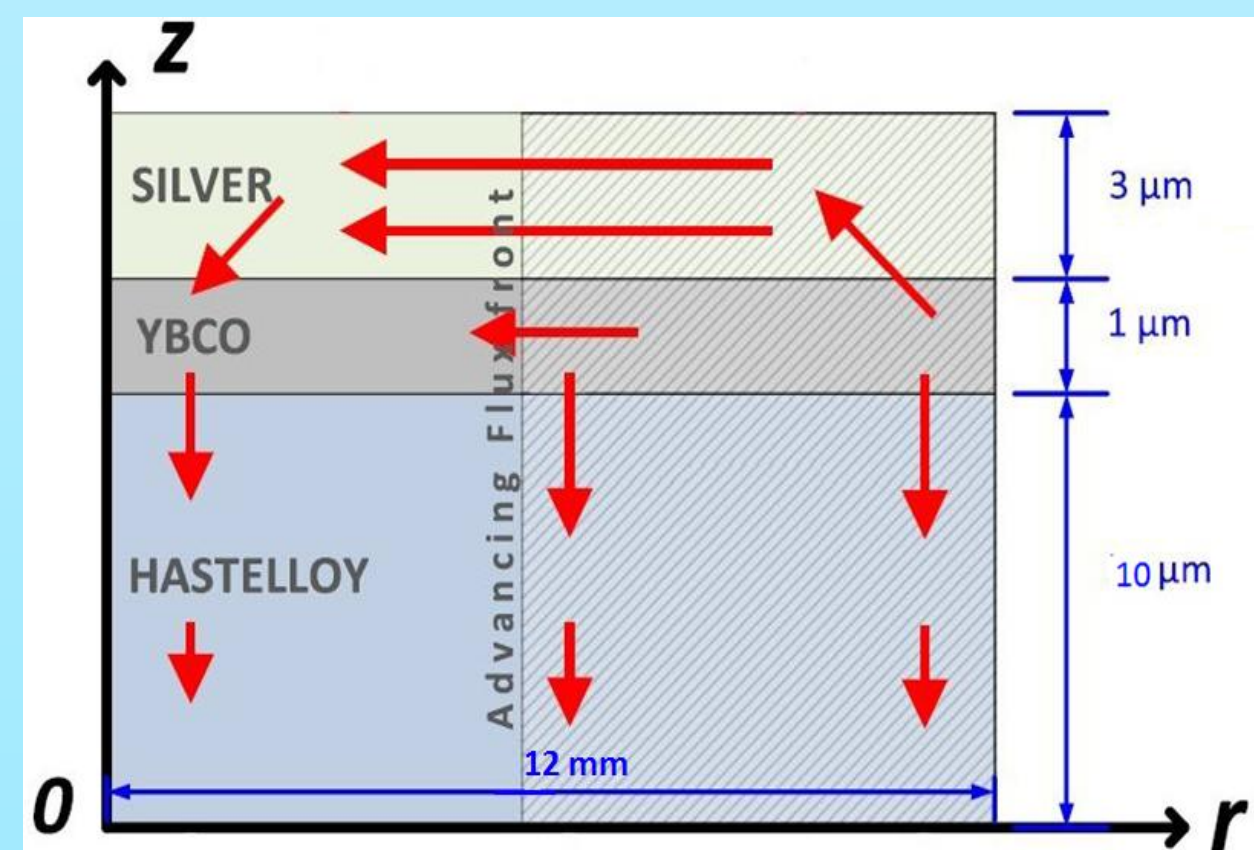
The current distribution J of the superconductor is determined by the conditions of magnetization and is calculated as the solution of the Maxwell equations, realized in the PDE form.

• Cryocooler

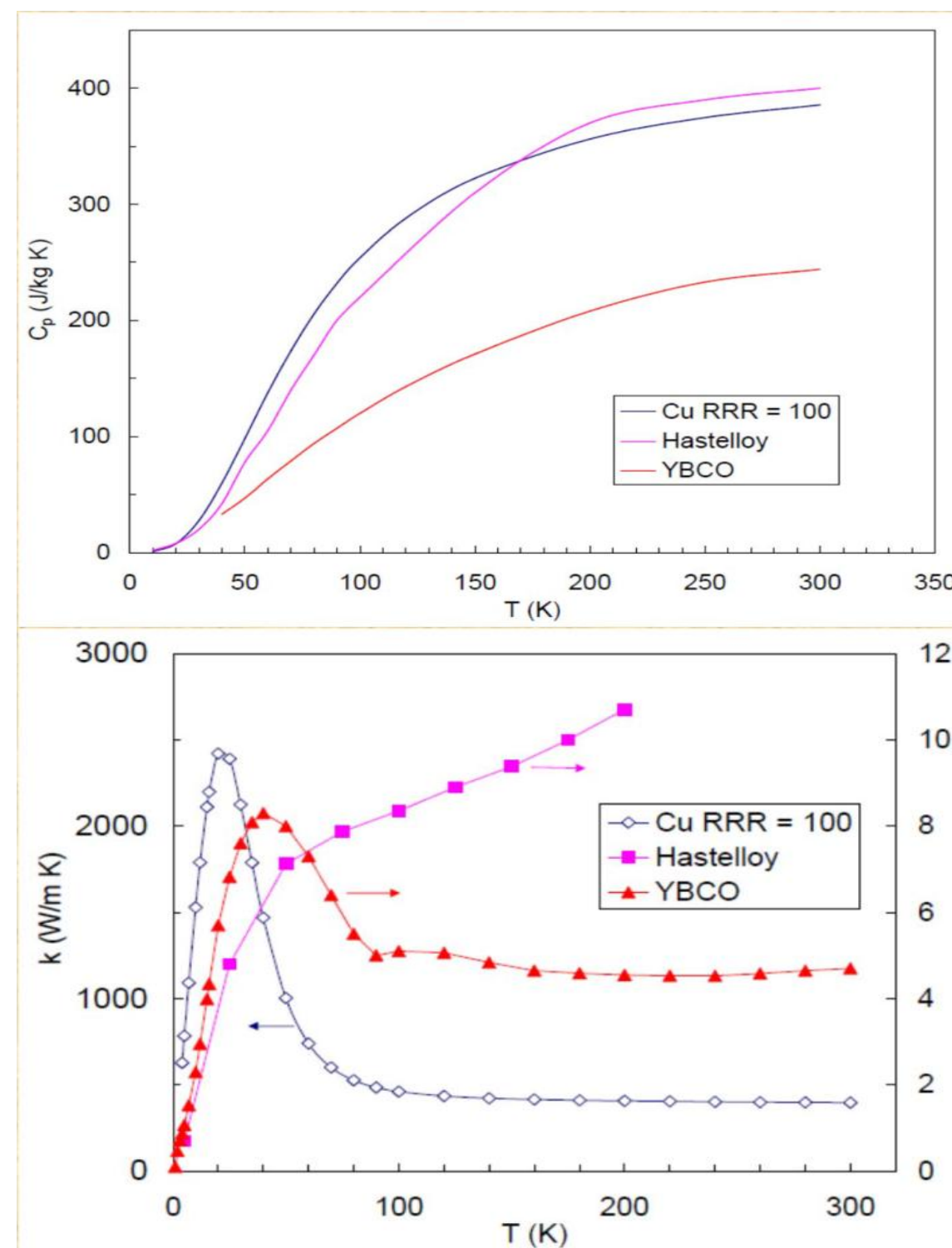
- Constant temperature at the lower boundary (77.4K, 65K, 50K)
- Radiation $-\mathbf{n} \cdot \mathbf{q} = \varepsilon \sigma (T_{amb}^4 - T^4)$
 ε - surface emissivity,
 σ - Stefan–Boltzmann constant,
 $T_{amb}=293.15$ (K)



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A G Page, A Pate, A Baskys, S C Hopkins, V Kalitka, A Molodyk B A, Glowacki. The effect of stabilizer on the trapped field of stacks of superconducting tape magnetized by a pulsed field, Supercond. Sci. Technol. 28 (2015) 085009 (7pp)



Zhang M., Matsuda K., Coombs T. A. New application of temperature-dependent modelling of high temperature superconductors: Quench propagation and pulse magnetization//Journal of Applied Physics. 2012. V.112 Issue 4

• Liquid Nitrogen

• Natural convection

$$\alpha_{conv} = C_{conv} \Delta T^{1/3}, \quad C_{conv} - \text{coefficient}$$

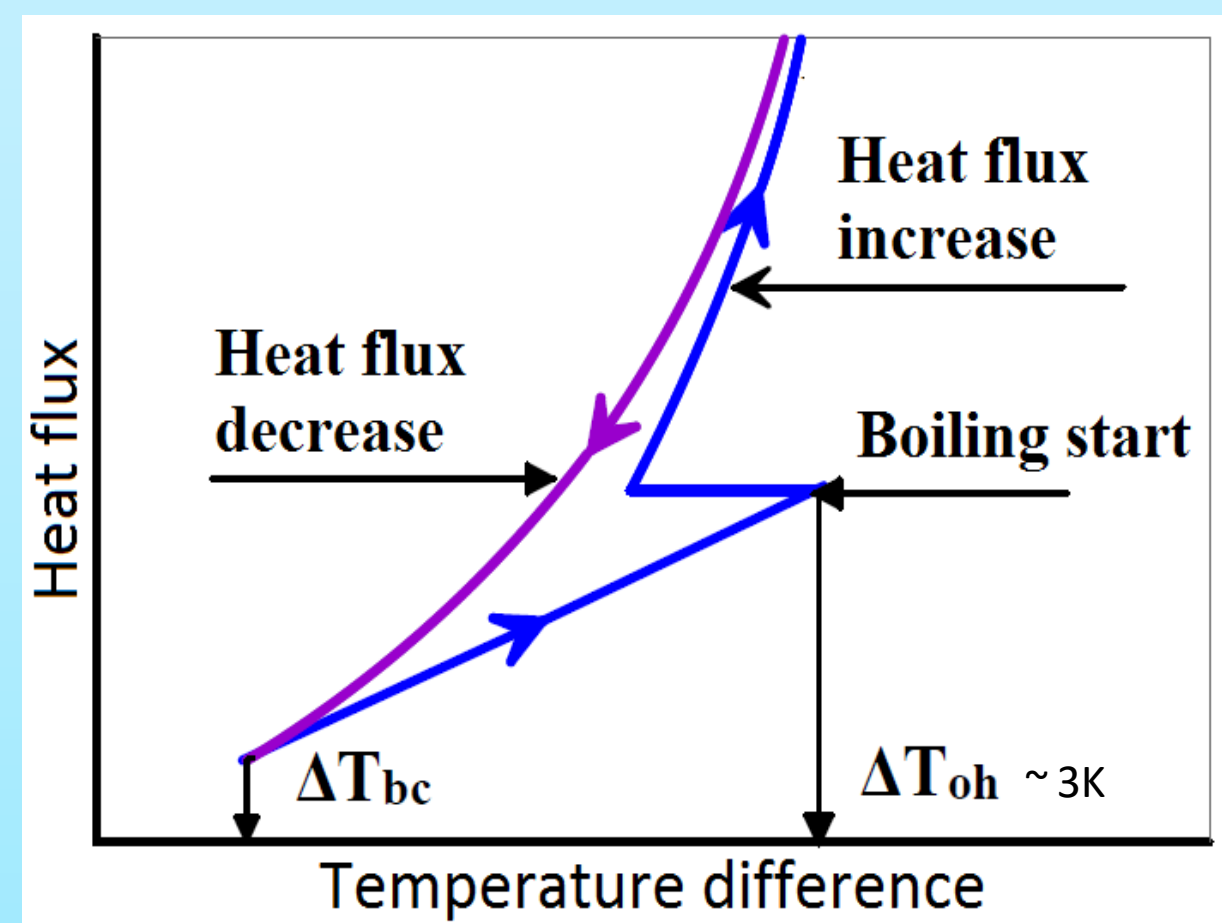
S.S. Fetisov; V. S. Vysotsky; V. V. Zubko. HTS Tapes Cooled by Liquid Nitrogen at Current Overloads// IEEE Transactions on applied superconductivity, v. 21, №. 3, JUNE 2011

• Nucleate boiling

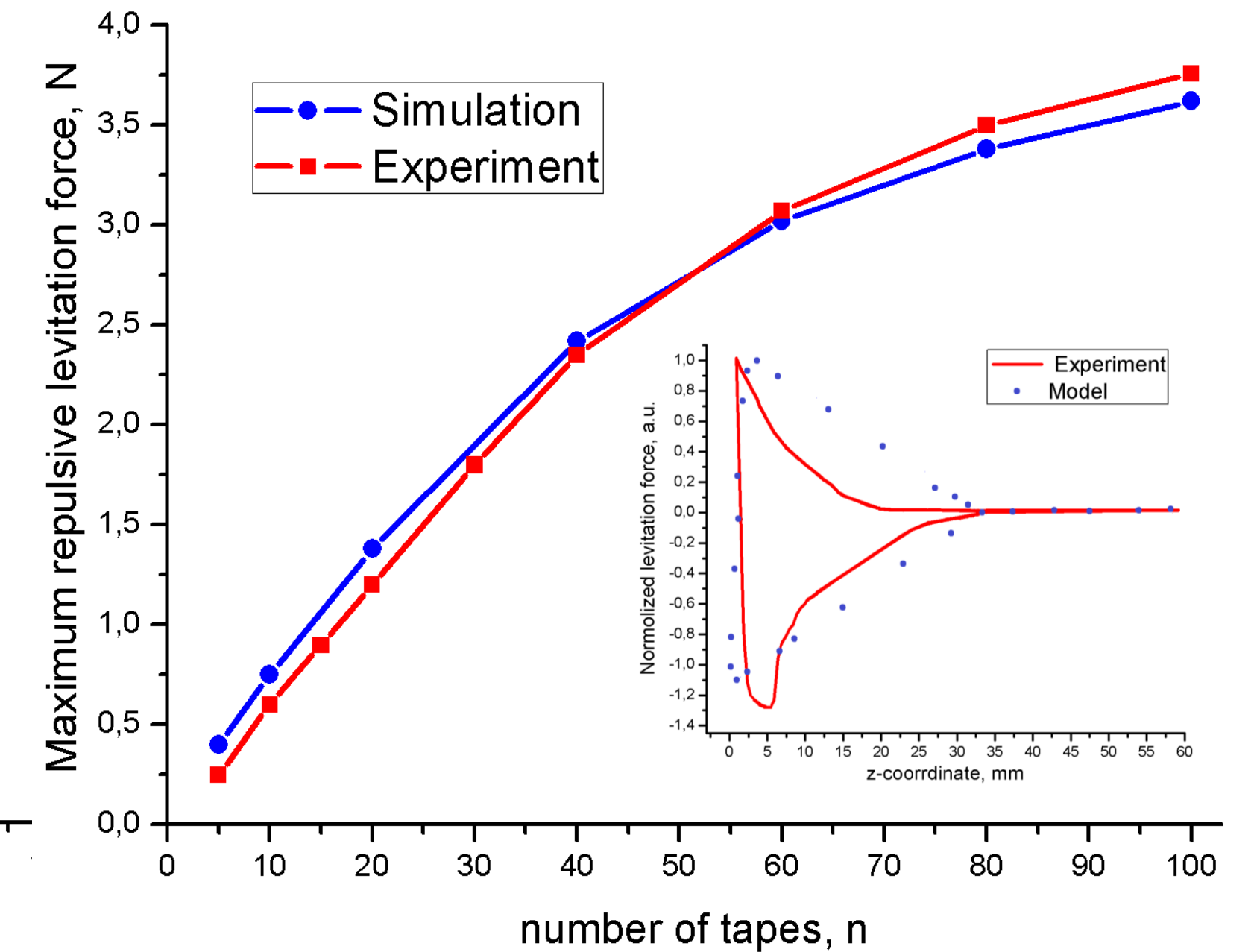
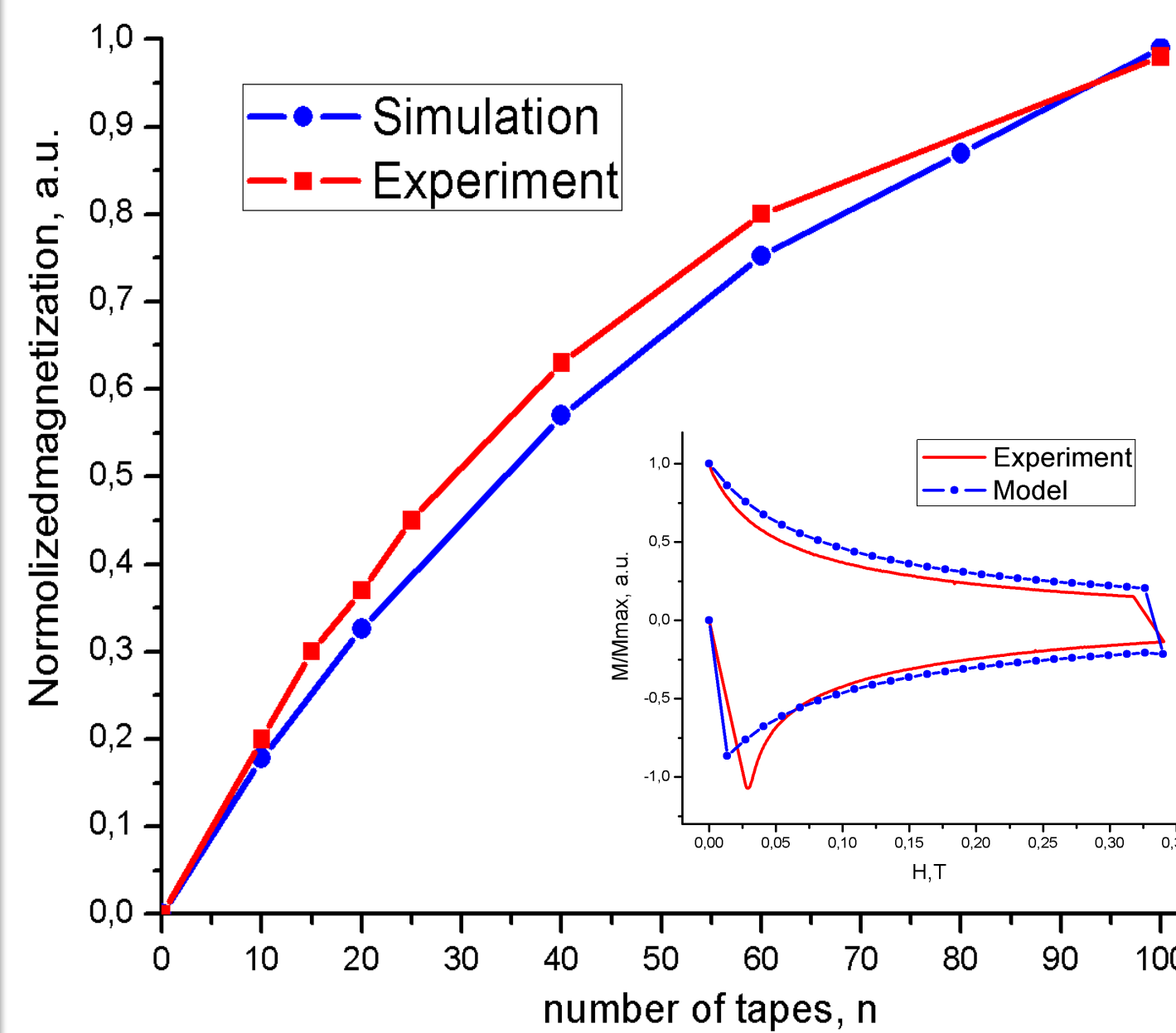
$$\alpha_{boil} = C_h q^{0.624} (\rho \cdot c_p \lambda)^{0.117}$$

q – heat flux, ρ –nitrogen density, c_p - heat capacity at constant pressure, λ - thermal conductivity , C_h - coefficient

Stephan K., Abdelsalam M. Heat-transfer correlations for natural convection boiling // Int. J. Heat Mass Transfer. – 1980. Vol. 23. – P. 73–87.)



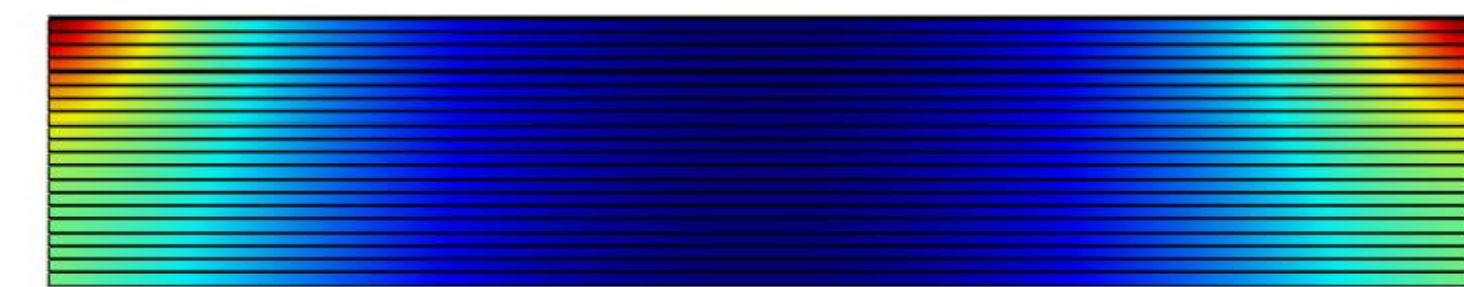
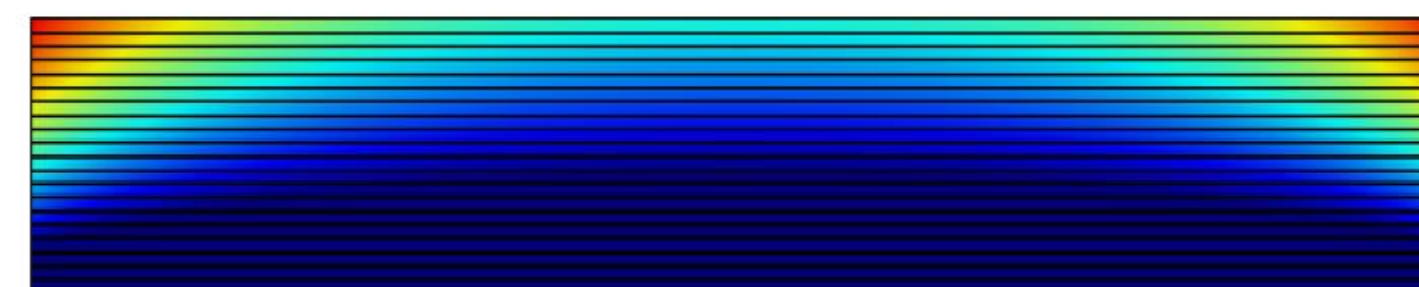
In our case $\Delta T_{max} < 3$ (K)



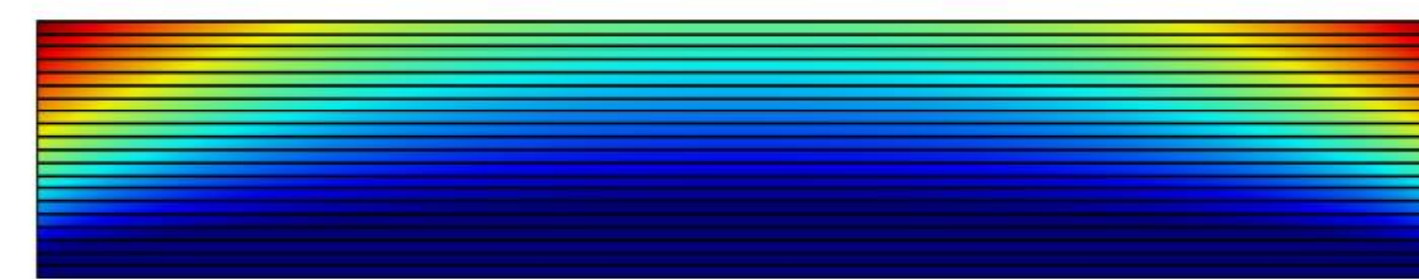
Surface: Temperature

cryocooler

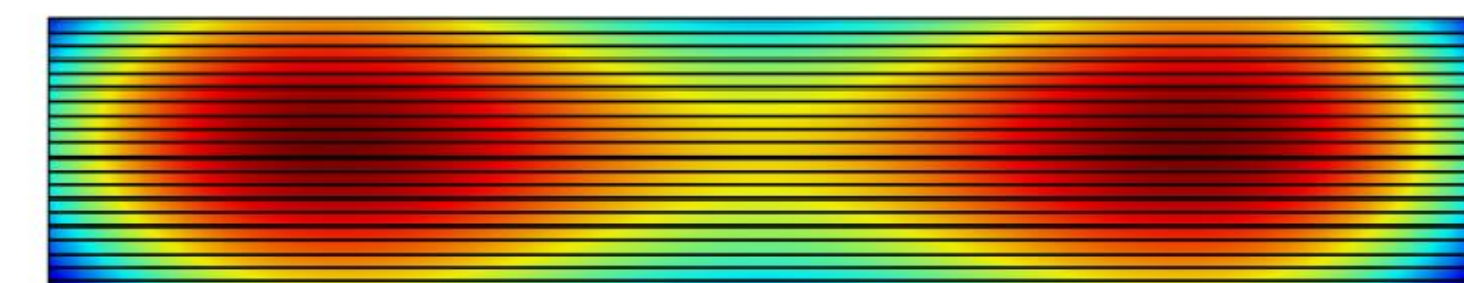
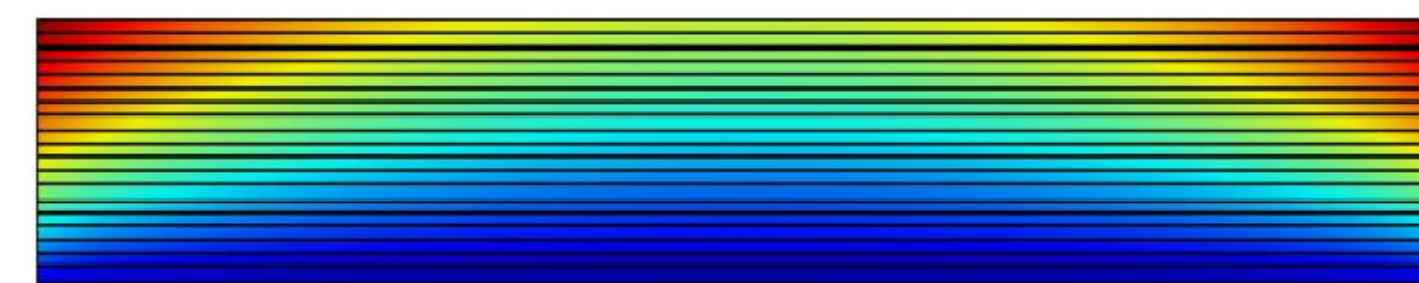
liquid nitrogen



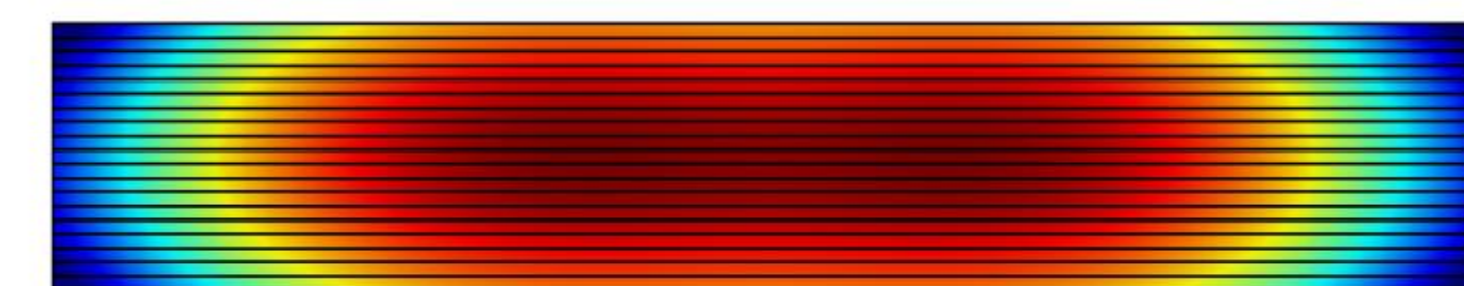
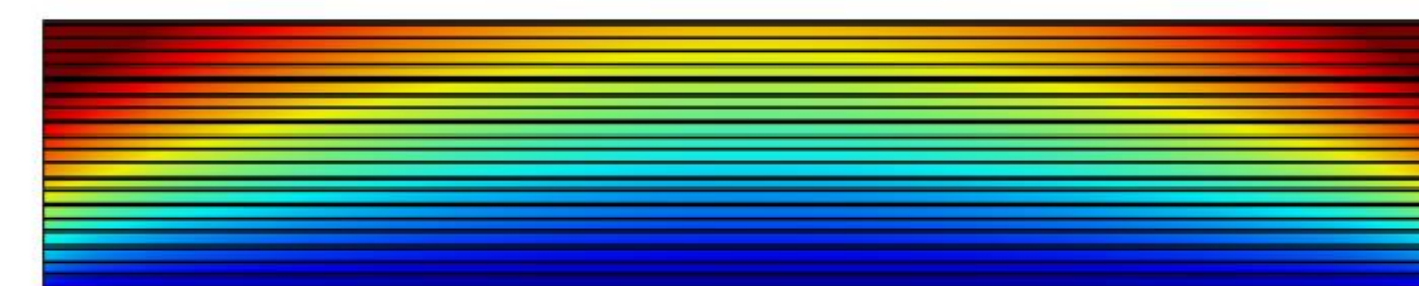
t = 0,1 s



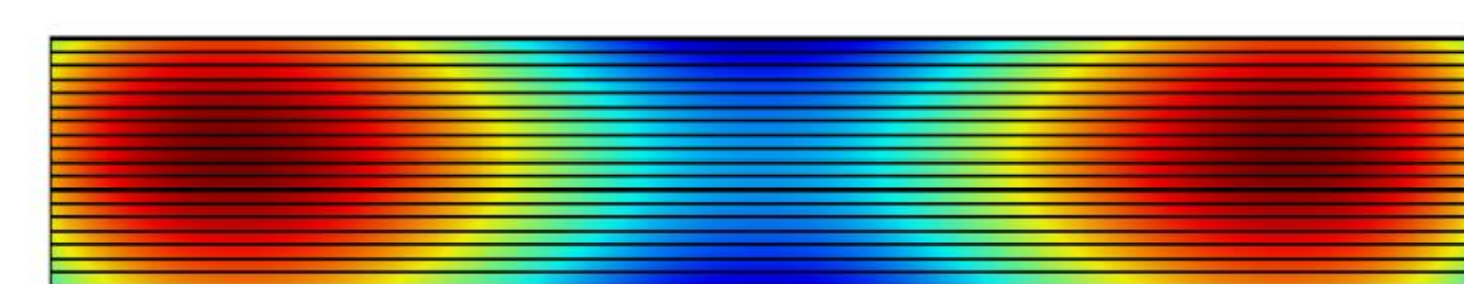
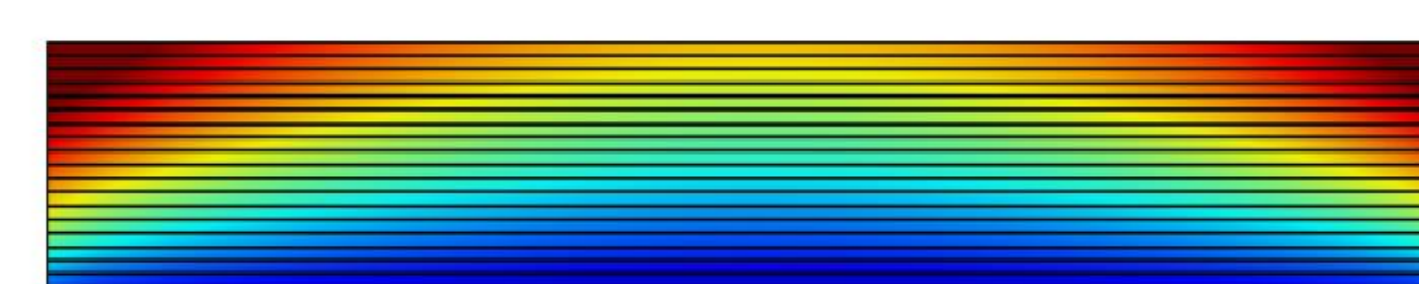
t = 1 s



t = 4 s



t = 5 s



t = 10 s

Based on the use of the finite element method the computational model of the magnetic levitation system based on the HTS stacks tapes was developed.

The advantage of developed model is the possibility of changing all input parameters of the system, as well as changes in the geometry and properties of HTS samples, which makes the model applicable to the calculation and optimization of magnetic and levitation systems of various configurations (in the fields of building of new transport systems of various scales, electrical rotating machines, energy and wind generators).

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