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Improvements in modelling of HTS properties

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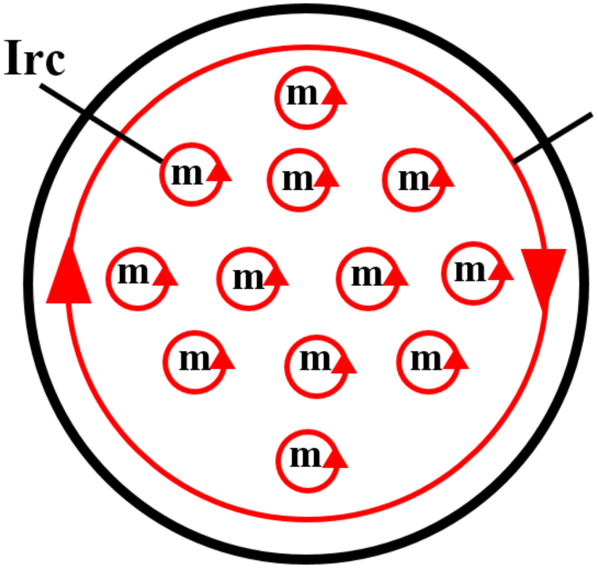
Content

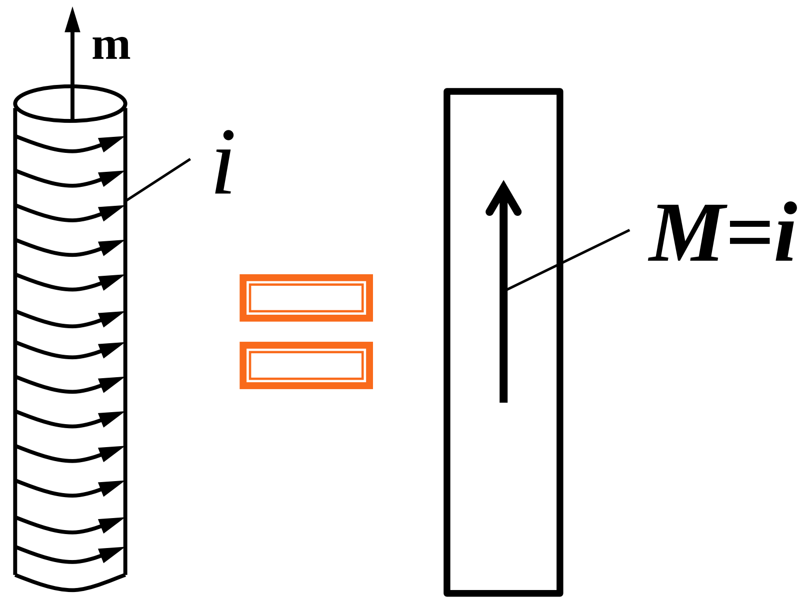
- Introduction
- Model of HTS properties with transport currents and magnetization
- Distribution of electromagnetic field sources in HTS
- Comparison of calculation results with experiments

Introduction

- Calculations of HTS bearings with small gaps show, that there are difference between experiments and calculations using critical-state models.
- The critical state models do not describe the partial Meissner effect at FC modes.
- It is proposed to expand existing models of HTS properties with the addition type of electromagnetic field source.

Combined model of HTS properties





For ideal superconductor:

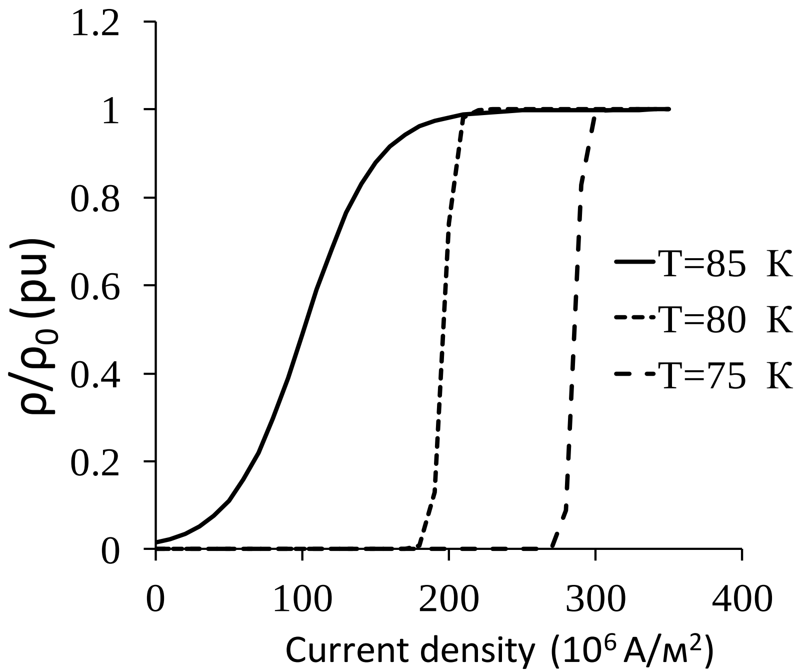
$$B=B_0=\mu_0(M+H)=const$$

$$M=B_0/\mu_0-H$$

Model of transport current

Mathematical model of the transport current is approximation of the critical state model. It connects the nonlinear resistivity of HTS material with current density, magnetic field strength and temperature.

$$\rho(|\mathbf{H}|,|\mathbf{J}|,T)=0.5\rho_{\max}\cdot\left\{1+\mathrm{th}\left[-\left(1-T/T_C\right)\cdot\left(1-|\mathbf{H}|/H_C(T)\right)\cdot\left(1-|\mathbf{J}|/J_C(T,|\mathbf{H}|)\right)/\delta_J\right]\right\}$$



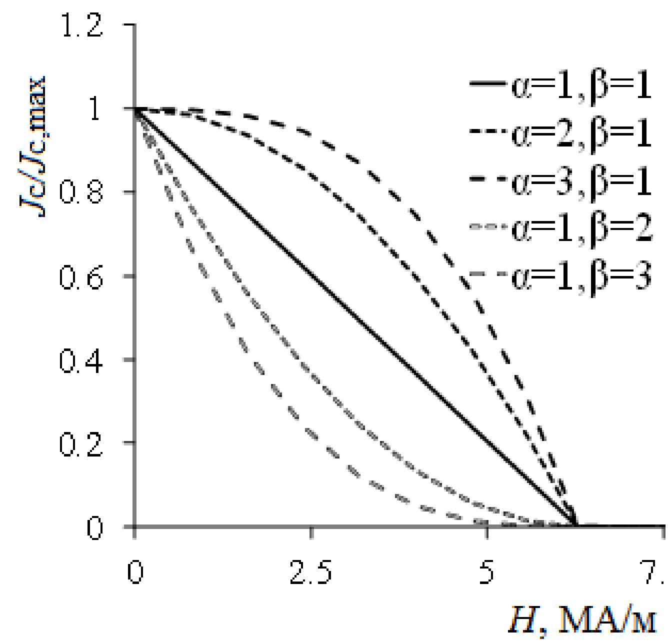
Model of transport current

Nonlinear dependence of the critical current density on the magnetic field is one of the main characteristic of HTS material. To obtain accurate calculation results this dependence should be determined.

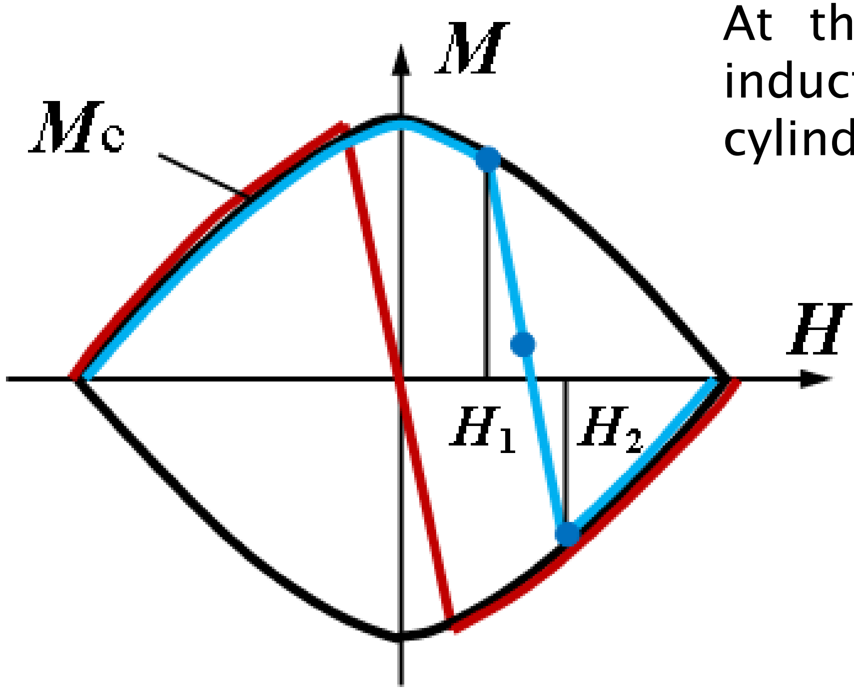
$$J_C(T,|\mathbf{H}|) = J_{C,\max}(T)\cdot[1-(|\mathbf{H}|/H_C(T))^{\alpha}]^{\beta}, |\mathbf{H}| \le H_c$$

$$J_C(T,|\mathbf{H}|) = 0, \quad |\mathbf{H}| > H_c$$

$$H_c(T) = H_{c0}\cdot\left(1-\left(T/T_c\right)^2\right),\ J_{c,\max}(T) = J_{c0}\cdot\left(1-\left(T/T_c\right)^2\right),$$



Magnetization model



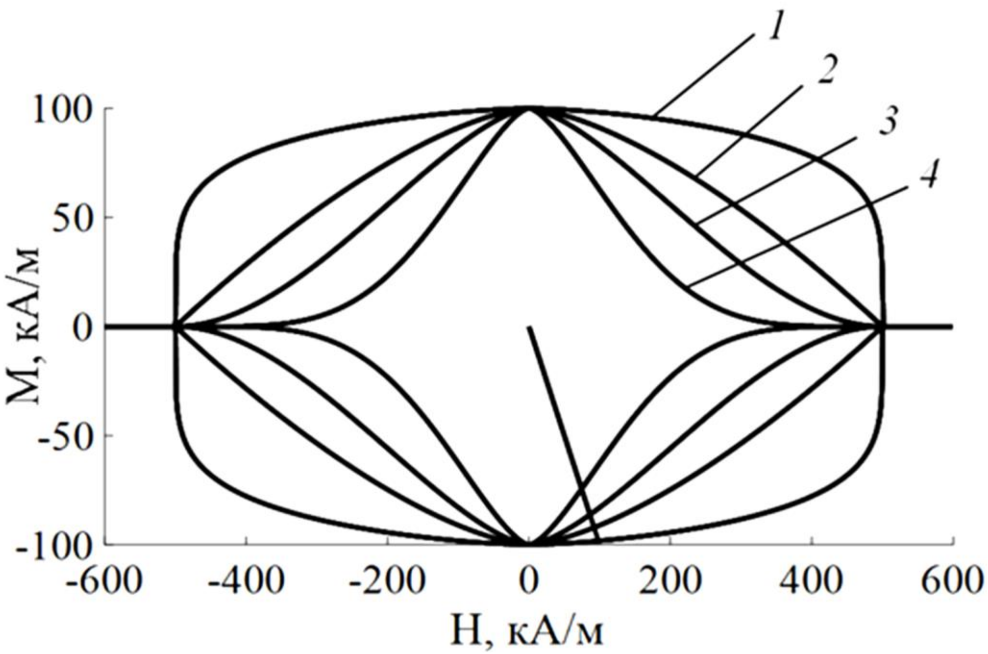
At the linear part of the model magnetic induction is constant. Superconducting cylinder saves the trapped magnetic field.

Linear sections are limited by the critical magnetization line Mc. In this case the magnetic field is higher, than superconducting cylinder can compensate.

For blue line in the picture:

$B=B_0$ =const, $dM/dH=-1$, if $H_1<H<H_2$,
else $M=Mc$

Magnetization model



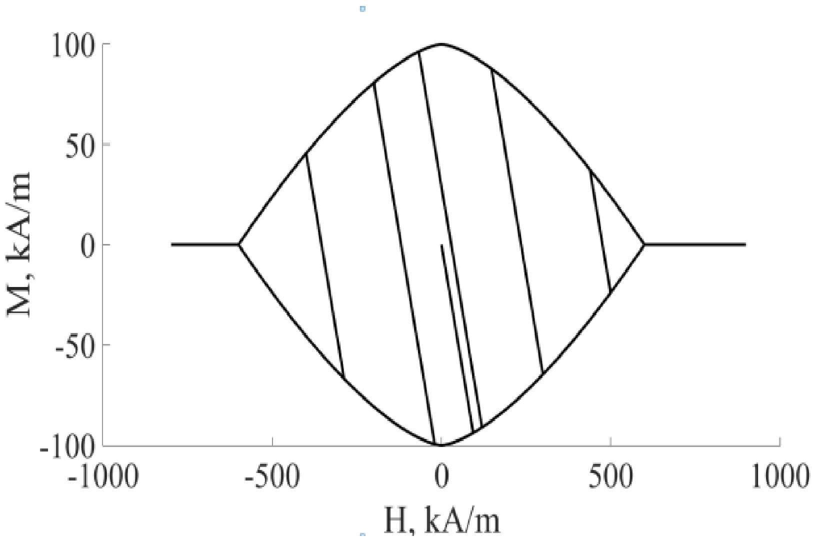
1 – α=1.5, β = 0.2
2 – α=1.5, β = 1.0
3 – α=1.5, β = 2.0
4 – α=1.5, β = 5.0

$$M_C(T,H) = M_{\mathrm{C,max}}(T)\cdot[1-(|\mathbf{H}|/H_{\mathrm{CM}}(T))^{\alpha}]^{\beta},\quad |\mathbf{H}|\le H_{\mathrm{CM}}(T)$$

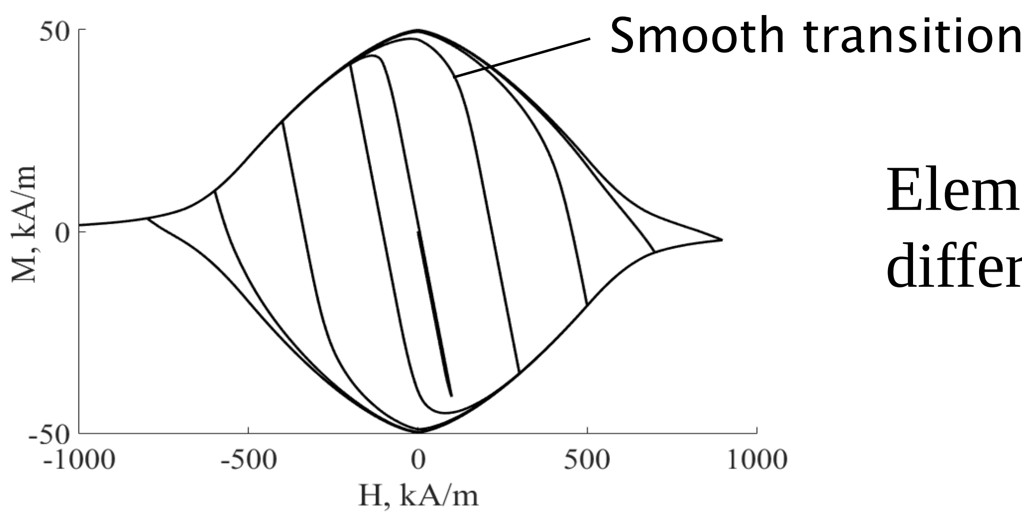
$$M_C(T,H) = 0,\quad |\mathbf{H}| > H_{\mathrm{CM}}(T)$$

$$H_{\mathrm{CM}}(T) = H_{\mathrm{CM0}}\cdot\left(1-\left(T/T_c\right)^2\right),\ M_{\mathrm{C,max}}(T) = M_{\mathrm{C0}}\cdot\left(1-\left(T/T_c\right)^2\right),$$

Magnetization model



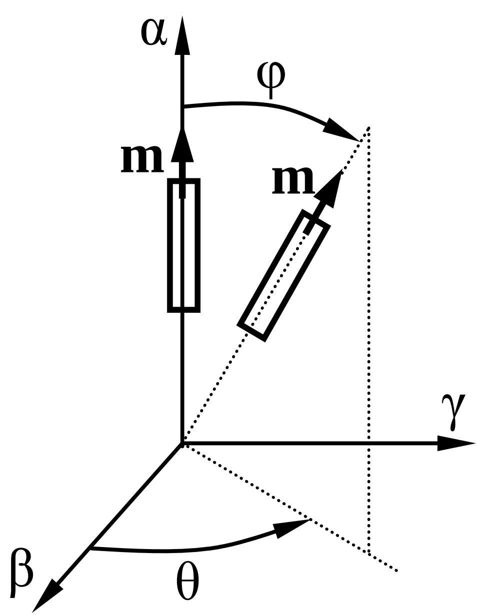
Elementary cylinders are identical

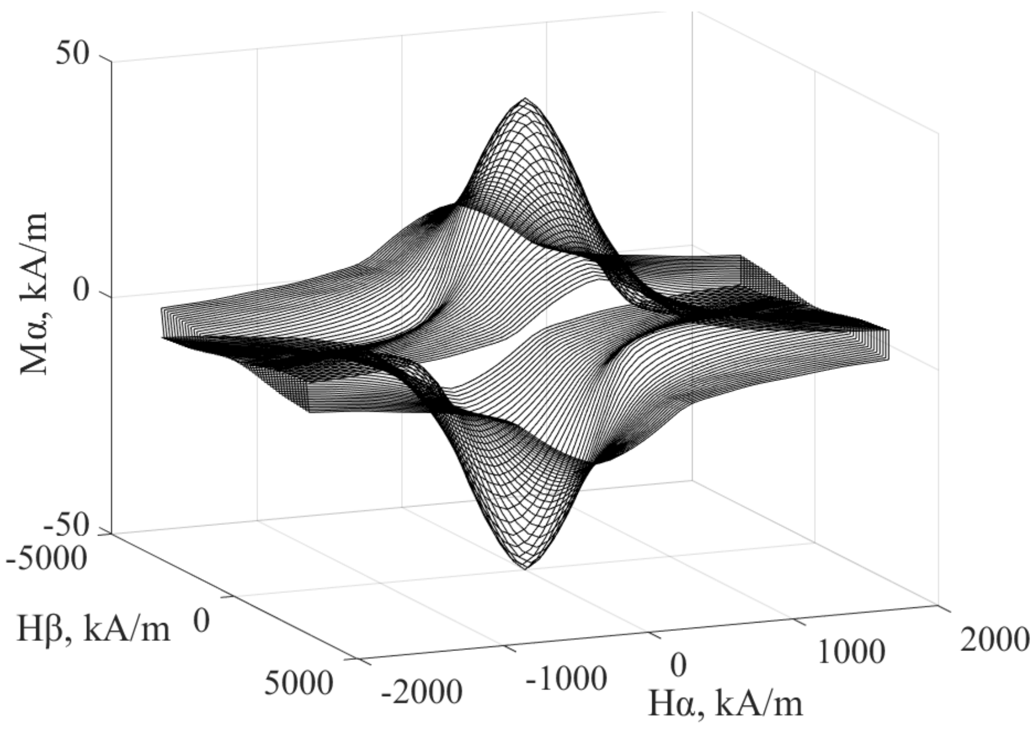


Elementary cylinders with different *M*c and *H*c

Magnetization model

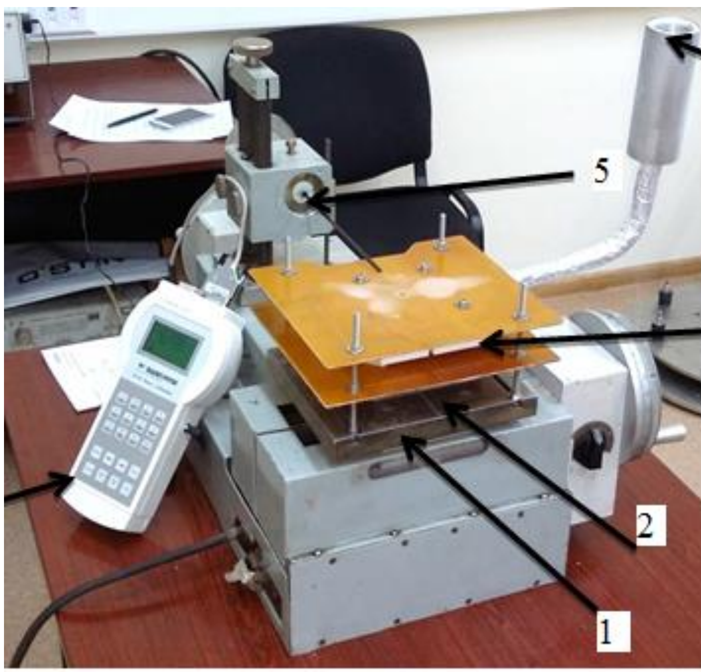
Elementary cylinders with different *M*c, *H*c, φ. Anisotropy

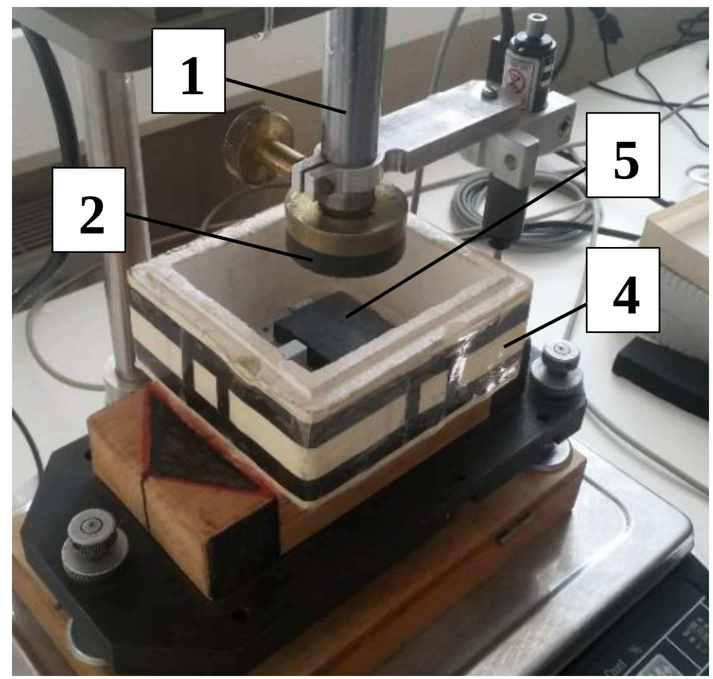




Model parameters

Model parameters may be defined from the experimental measurements or chosen from the comparison of calculation with data from some simple experiments with HTS sample (measurements of magnetic field near the surface of superconductor, force interaction between permanent magnet and superconductor).



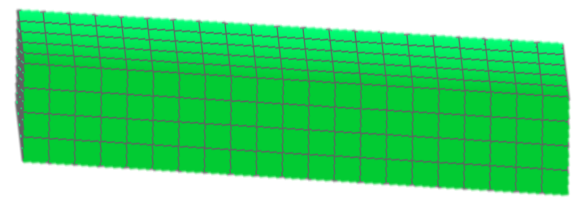


Calculation of electromagnetic field sources

The model was realized in home-made software *EasyMag3D*, which is based on the spatial integral equations method.

$$\mathbf{A}(t_k) = \frac{\mu_0}{4\pi}\sum_{j=1}^{N_1}\mathbf{J}_j(t_k)\sum_{\nu=1}^{l_j}\int_{\Delta S_{\nu j}}\frac{\mathbf{n}_{\nu j}\mathbf{r}}{2r}dS - \frac{\mu_0}{4\pi}\sum_{j=1}^{N_2}\sum_{\nu=1}^{lj}\left[\mathbf{n}_{\nu j}\times\mathbf{M}_j(t_k)\right]\int_{\Delta S_{\nu j}}\frac{1}{r}dS + \mathbf{A}^{cm}(t_k);$$

$$\varphi_e(t_k) = \frac{1}{4\pi\varepsilon_0}\sum_{j=1}^{N_3}\zeta_j(t_k)\int_{\Delta S_{\mathbf{j}}}\frac{1}{r}dS;$$



The calculation of **J** is performed using equations of a nonstationary magnetic field

B=∇×**A**

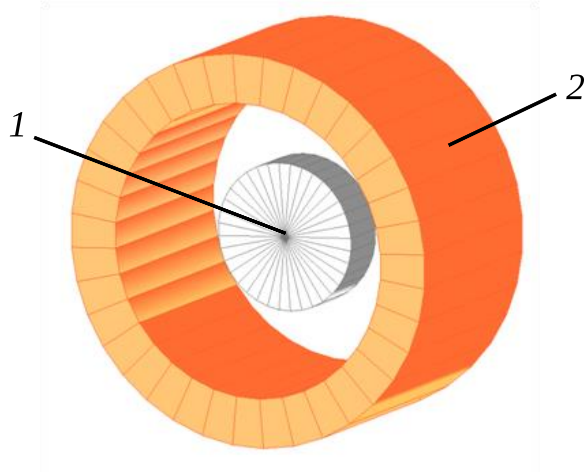
J = **E**/ρ = -d**A**/dt - ∇φ

Calculation **M** is made similarly to the stationary magnetic field

B = ∇×**A**, **B** = μ_0(**M**+**H**)

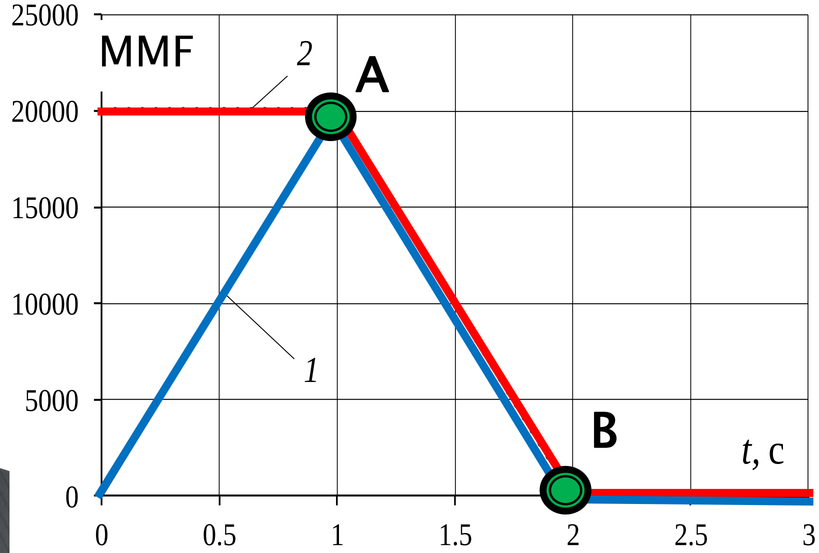
M = f(**H**)

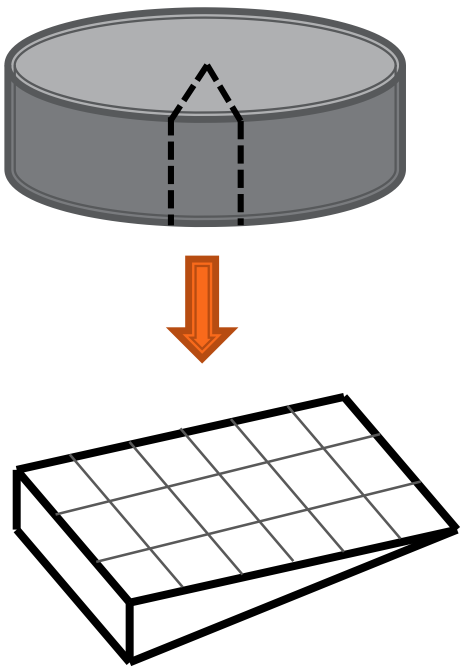
Calculation of magnetization of HTS disk



***1* – disk HTS, *2* – inductor coil**

Diameter of HTS	30 mm
Thickness of HTS	10 mm
Inner diameter of coil	80 mm
Outer diameter of coil	60 mm
Length of coil	40 mm



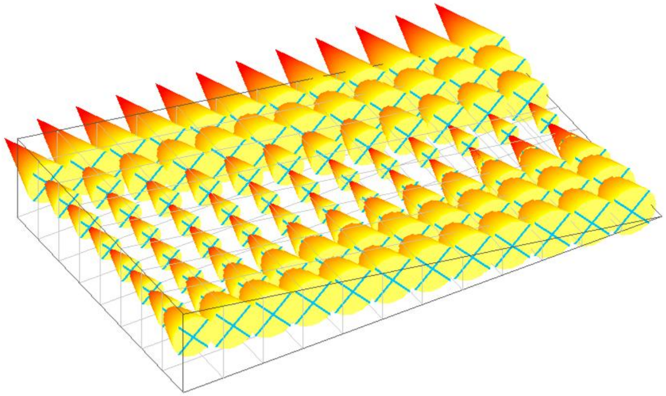


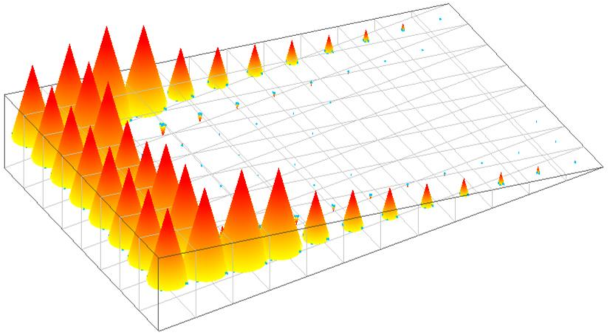
Distribution of electromagnetic field sources inside HTS disk at ZFC

Model for magnetization

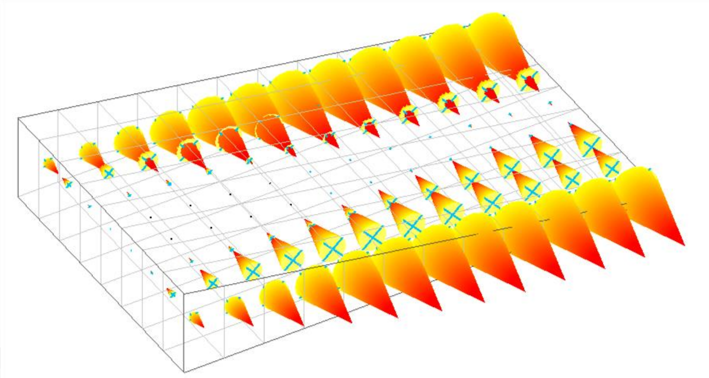
Model for current density

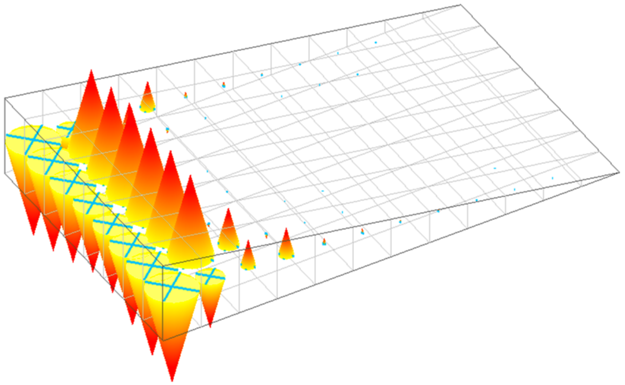
Point A





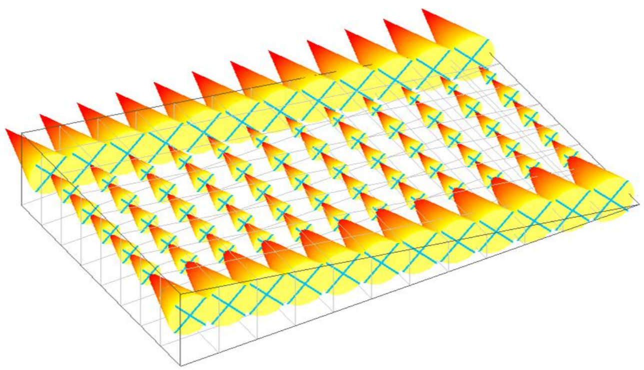
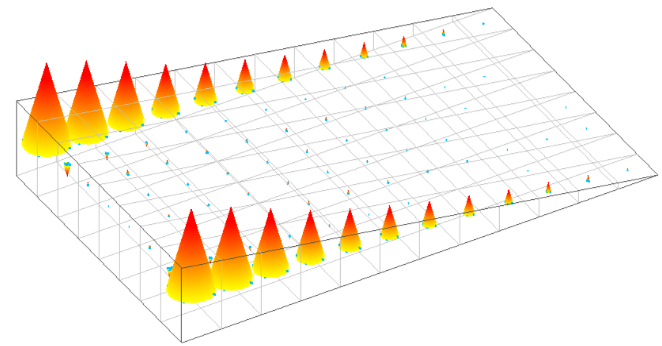
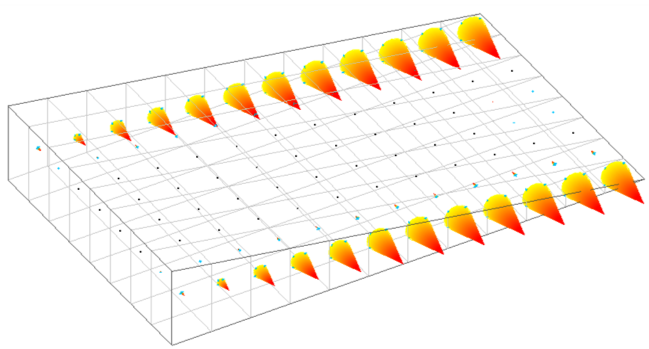
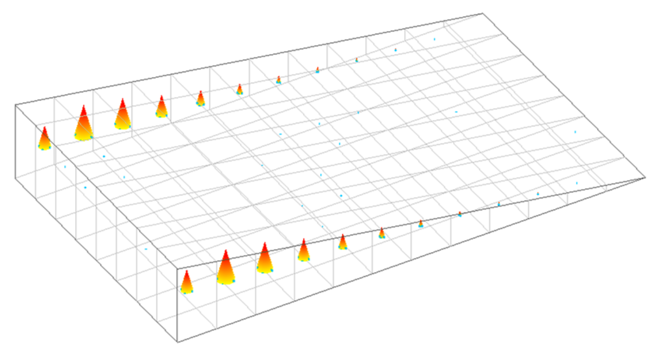
Point B





Distribution of electromagnetic field sources inside HTS disk at ZFC

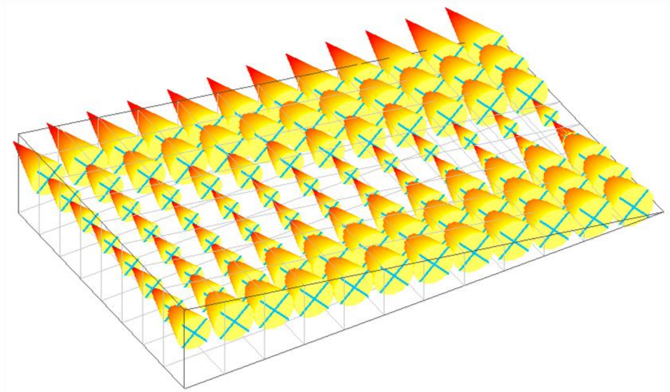
Combined model

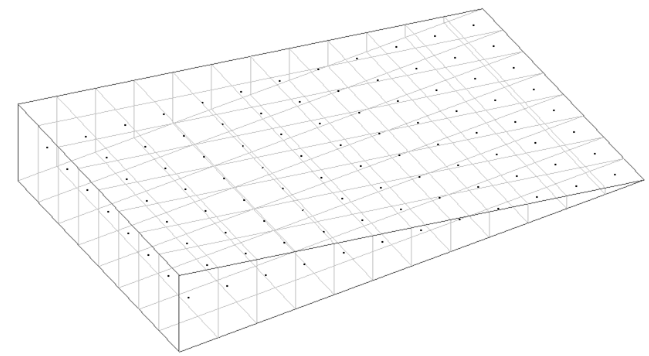
	Magnetization	Transport current
Point A		
Point B		

Distribution of electromagnetic field sources inside HTS disk at FC

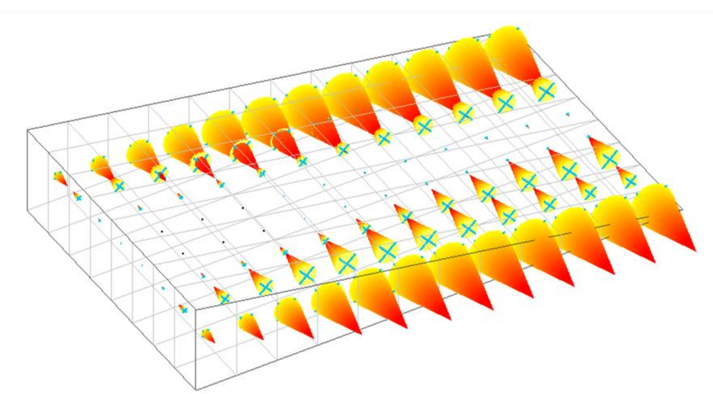
Model for magnetization | Model for current density

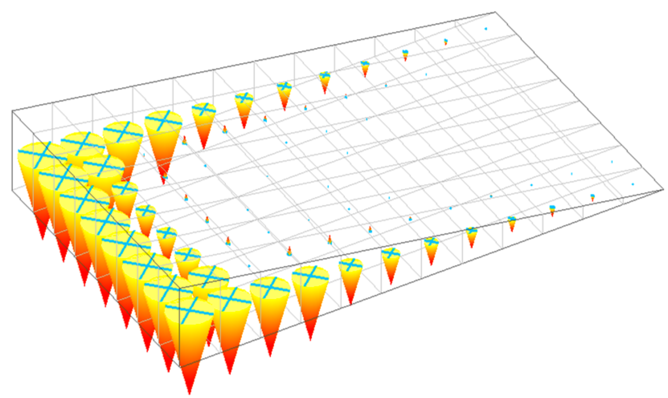
Point A





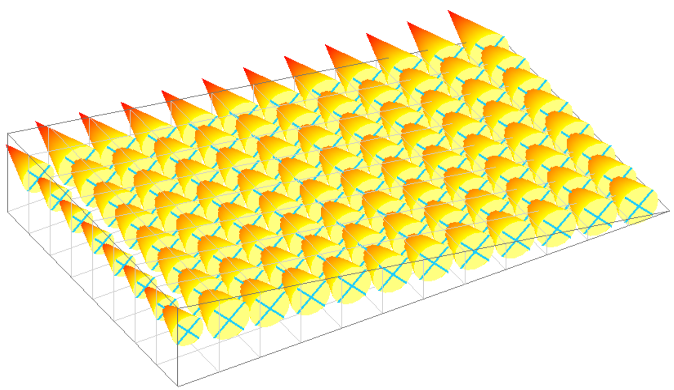
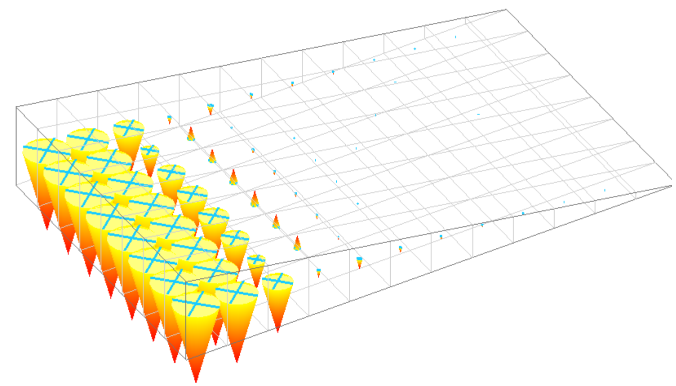
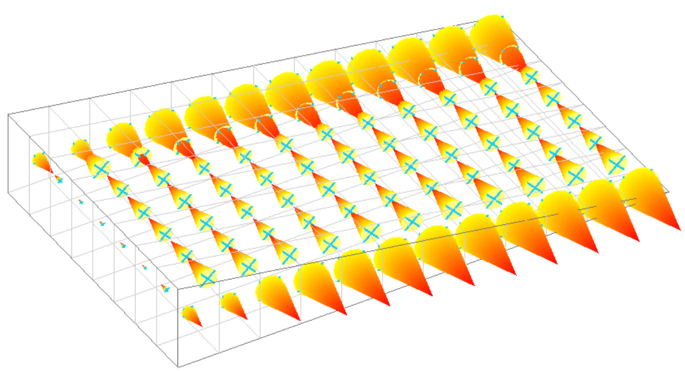
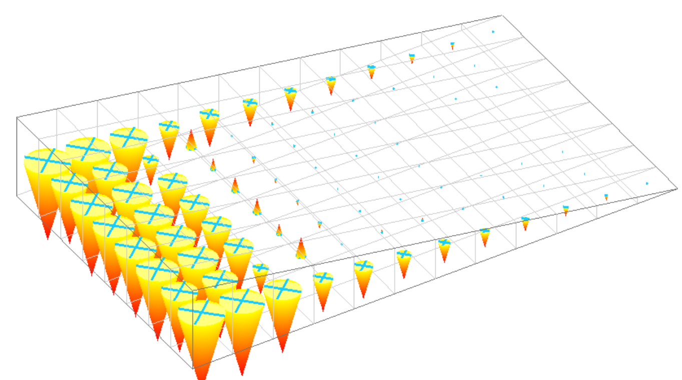
Point B



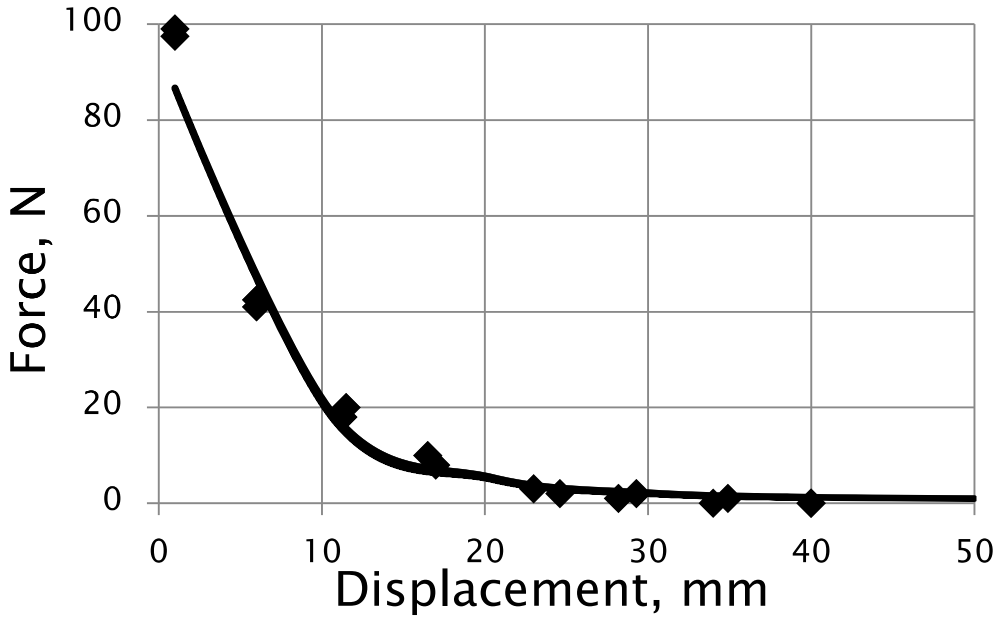


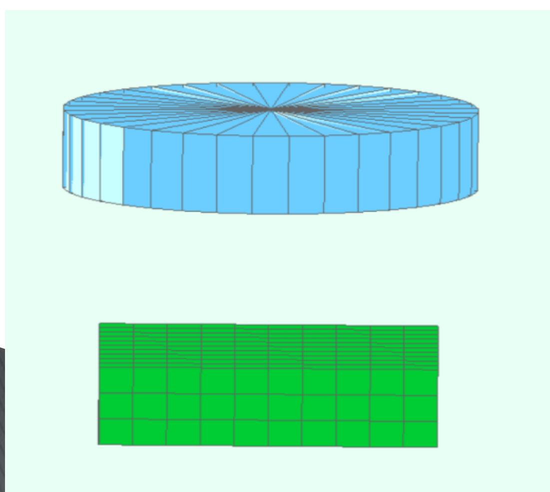
Distribution of electromagnetic field sources inside HTS disk at FC

Combined model

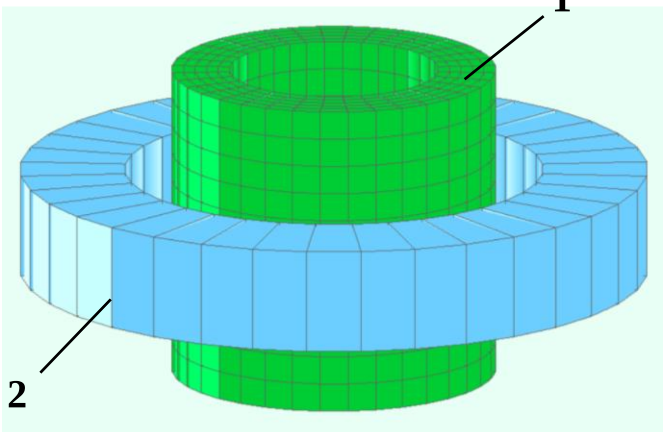
	Magnetization	Transport current
Point A		
Point B		

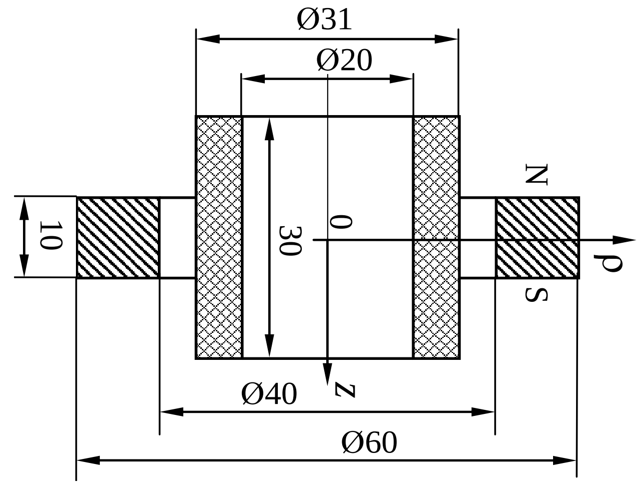
Comparison with experiment (ZFC)

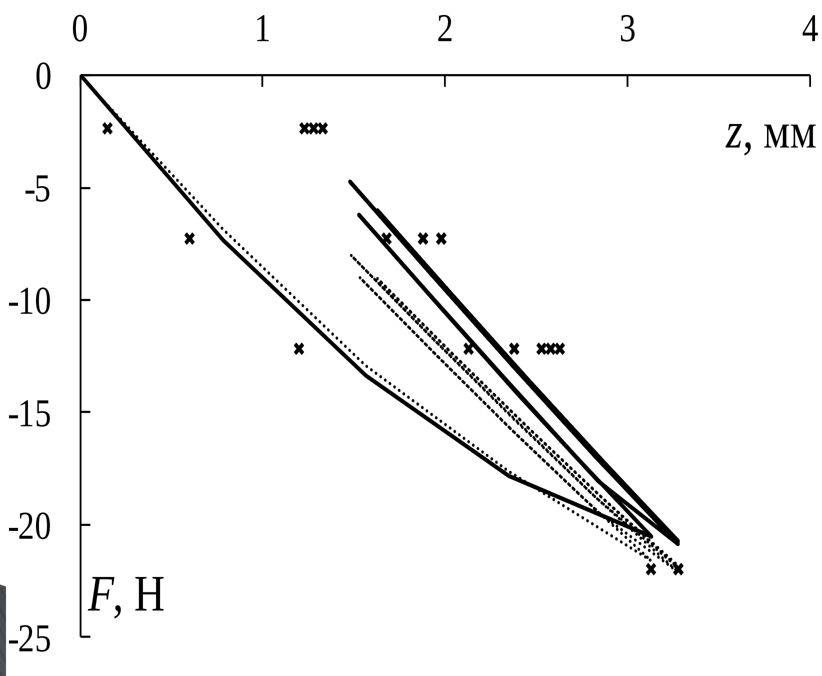




Comparison with experiment (FC)







Conclusion

- It is proposed to expand the model of the critical state by additional sources of a magnetic field-related currents. These sources are modeled by the distribution of magnetization.
- The performed calculations and experiments showed that the developed models can modeling the partial Meissner effect at FC mode and have better results in the analysis of magnetic HTS bearing under cyclic loading.
- It is necessary to perform more computational and experimental studies to justify the effectiveness of such models.

Thank you for your attention!

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