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3D Multiphysics Modelling of Bulk High Temperature Superconductors for Use as Trapped Field Magnets

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Superconducting Electrical Engineering Applications

Almost all aspects of electric power systems have a superconducting equivalent:

- Transformers, cables, electric machines (motors & generators)

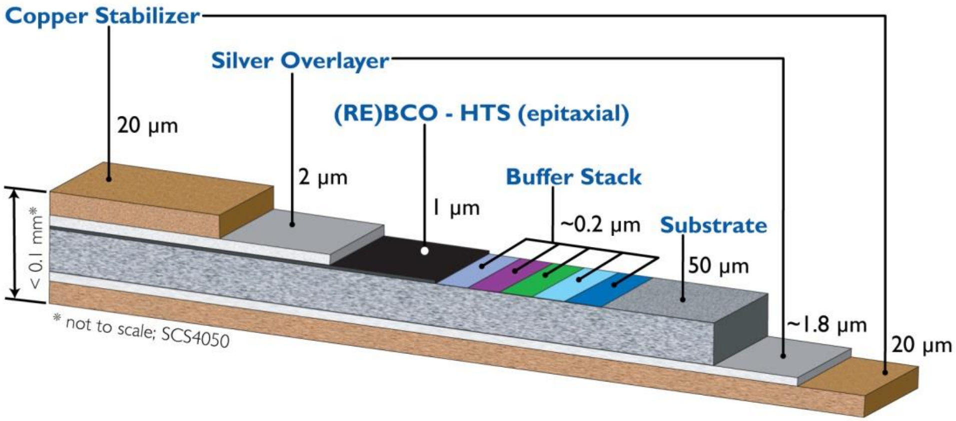
New technologies enabled by superconductors:

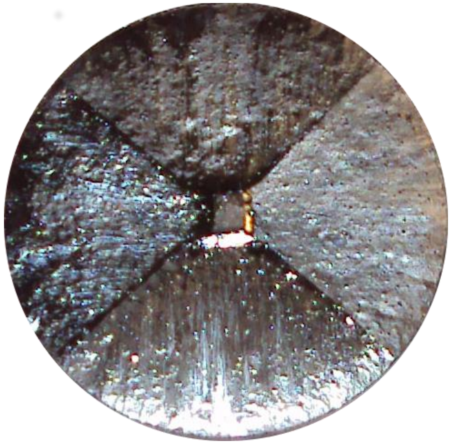
- Superconducting magnetic energy storage
- Superconducting fault current limiters



Superconducting Electric Machine Research

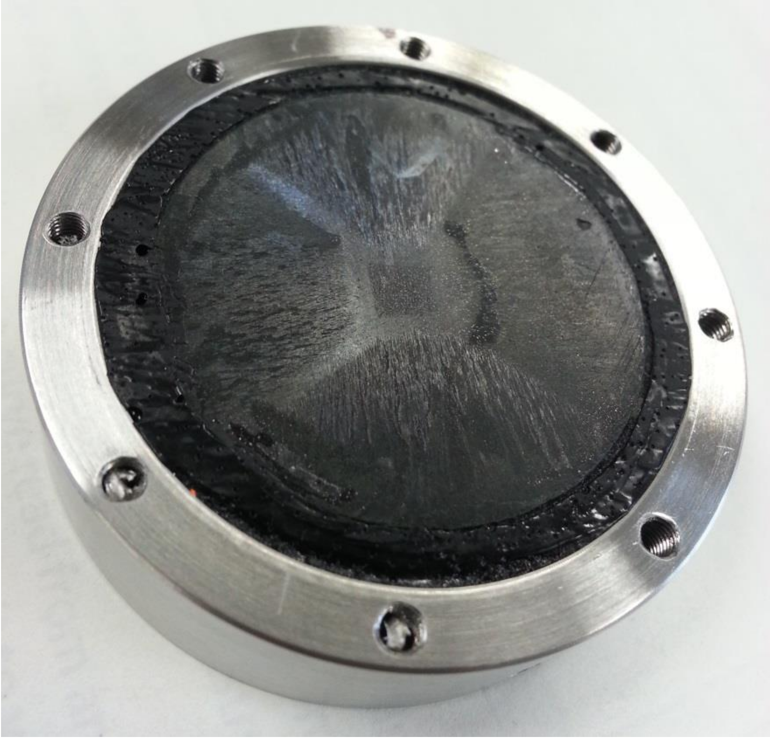
- **Using superconductors can increase electric / magnetic loading of an electric machine**
  - WIRE FORM
    - Higher current density, lower wire resistance
  - BULK FORM
    - Bulk superconductors as trapped field magnets >> permanent magnets





Bulk High Temperature Superconductors

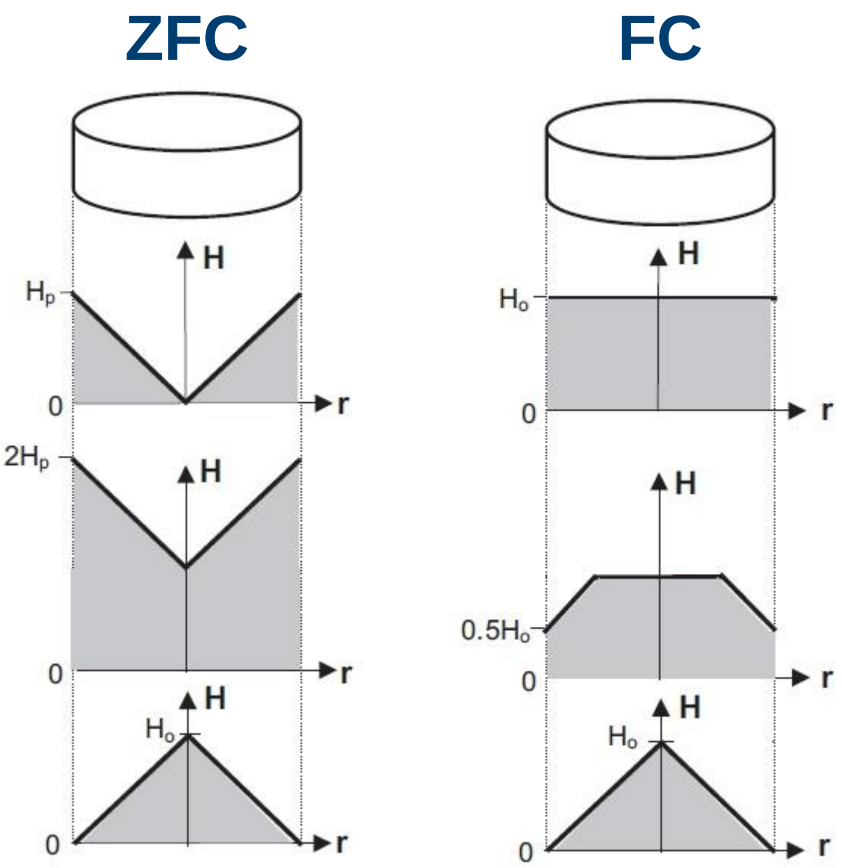
- **Conventional magnets (NdFeB, SmCo) limited by material properties**
  - Magnetization <u>independent</u> of sample volume
- **Bulk HTS trap magnetic flux via macroscopic electrical currents**
  - Magnetization <u>increases</u> with sample volume
- **Magnetization requires application + removal of large magnetic field**



A large, single grain Gd-Ba-Cu-O bulk superconductor

Magnetization of Bulk HTS

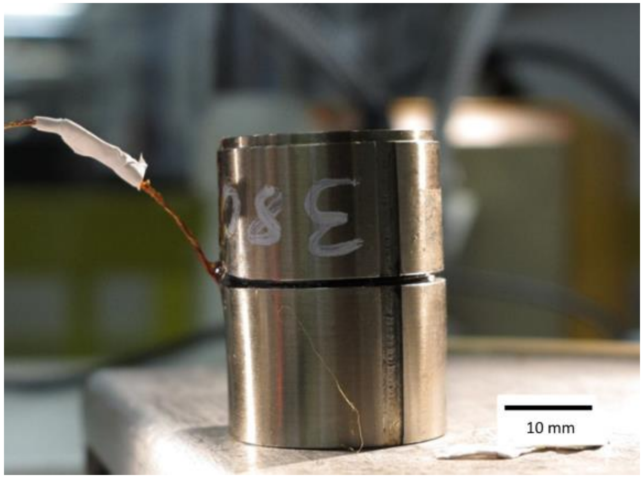
- **Three magnetization techniques:**
  - Field Cooling (FC)
  - Zero Field Cooling (ZFC)
  - Pulse Field Magnetization (PFM)
- **To trap B_{trap}, need at least B_{trap} or higher**
  - FC and ZFC require large magnetizing coils
  - Impractical for applications/devices



Trapped Magnetic Field Potential of Bulk HTS

- **Demonstrated trapped fields over 17 T (field cooling)**
  - 17.6 T at 26 K
  - 2 x 25 mm GdBCO

    Durrell, Dennis, Jaroszynski, Ainslie et al. *Supercond. Sci. Technol.* 2014
- **Significant potential at 77 K**
  - J_c = up to 5 x 10^4 A/cm^2 at 1 T
  - B_{trap} up to 1 ~ 1.5 T for YBCO
  - B_{trap} > 2 T for (RE)-BCO
- **Record trapped field = 3 T at 77 K**
  - 1 x 65 mm GdBCO
  - Nariki, Sakai, Murakami *Supercond. Sci. Technol.* 2005

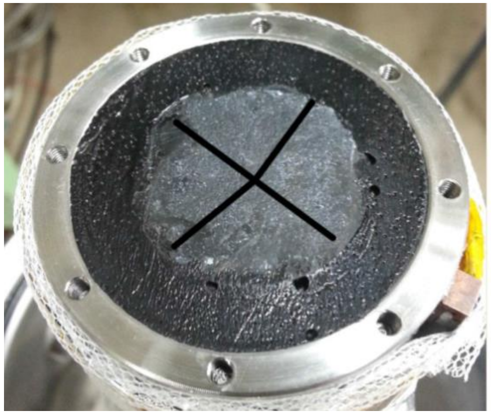


Pulse Field Magnetization

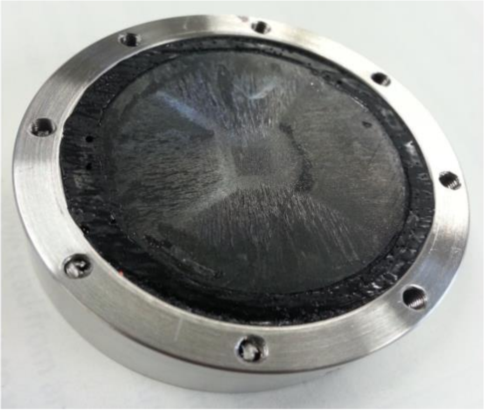
- **PFM technique = compact, mobile, relatively inexpensive**
- **Issues = B_{trap} [PFM] < B_{trap} [FC], [ZFC]**
    - Temperature rise ΔT due to rapid movement of magnetic flux
- **Many considerations:**
    - Pulse magnitude, pulse duration, temperature, number of pulses, shape of magnetising coil(s), sample material properties
- **Record PFM trapped field = 5.2 T at 29 K** (45 mm diameter Gd-BCO) [Fujishiro et al. *Physica C* 2006]

Bulk Modelling in 3D – Pulsed Field Magnetization

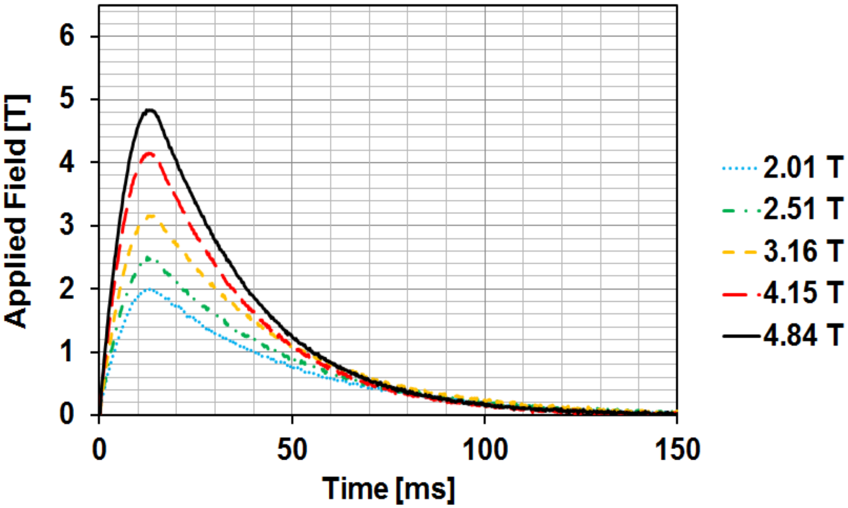
Flux dynamics of (RE)BCO bulk superconductors for pulsed field magnetisation



YBCO
$d = 32$ mm
$t = 15$ mm
$B_{trap} = 0.692$ T



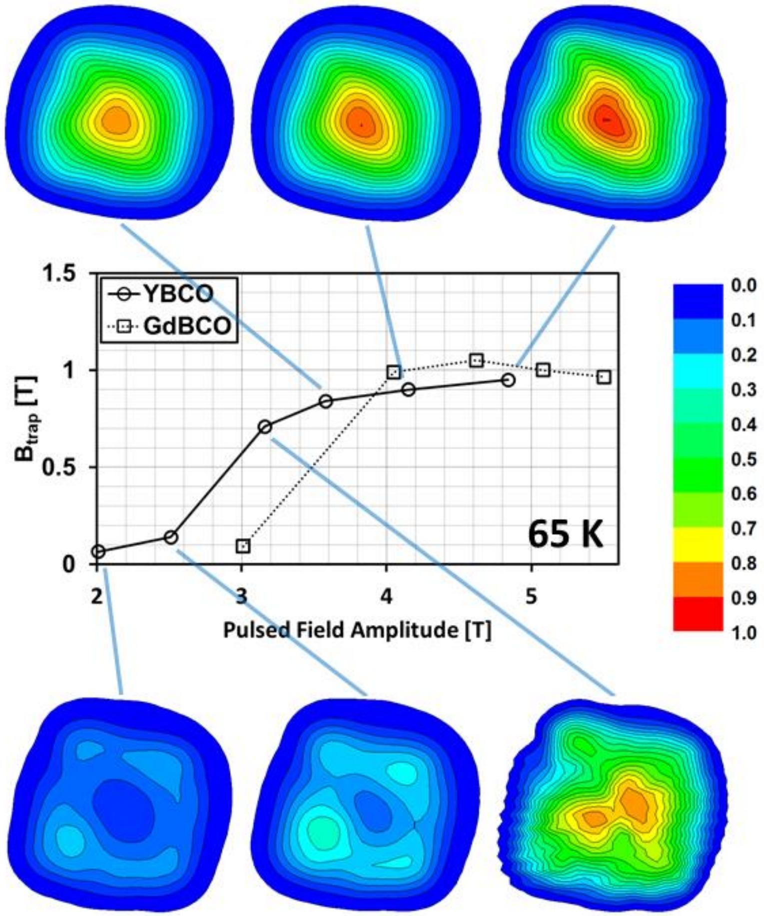
GdBCO
$d = 41$ mm
$t = 16$ mm
$B_{trap} = 1.19$ T

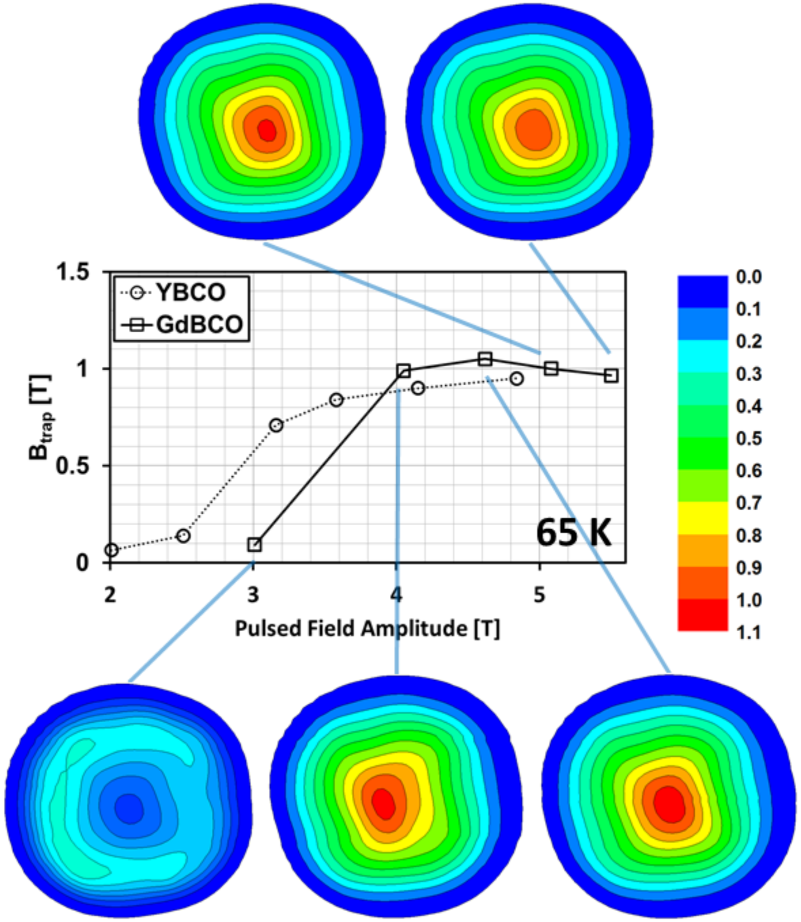


$$B_{\mathrm{ext}}(t) = B_{\mathrm{app}} \frac{t}{\tau} \mathrm{e}^{\left(1-\frac{t}{\tau}\right)}$$

Ainslie et al. *Supercond. Sci. Technol.* **27** (2014) 065008

Bulk Modelling in 3D – Pulsed Field Magnetisation





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Bulk Modelling in 3D – Pulsed Field Magnetisation

- **Finite Element Method (FEM) using Comsol Multiphysics**
- **Governing equations:**

Bulk Modelling in 3D – Pulsed Field Magnetisation

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  - Maxwell's equations (***H*** formulation) + E-J power law
    - AC/DC (or PDE) module

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} = -\frac{\partial(\mu_0 \mu_r \mathbf{H})}{\partial t}$$

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

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$$\rho \cdot C \frac{\mathrm{d}T}{\mathrm{d}t} = \nabla \cdot (k \nabla T) + Q$$

$$Q = E_{\mathrm{norm}} \cdot J_{\mathrm{norm}}$$

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  - $J_c(\boldsymbol{B},T)$

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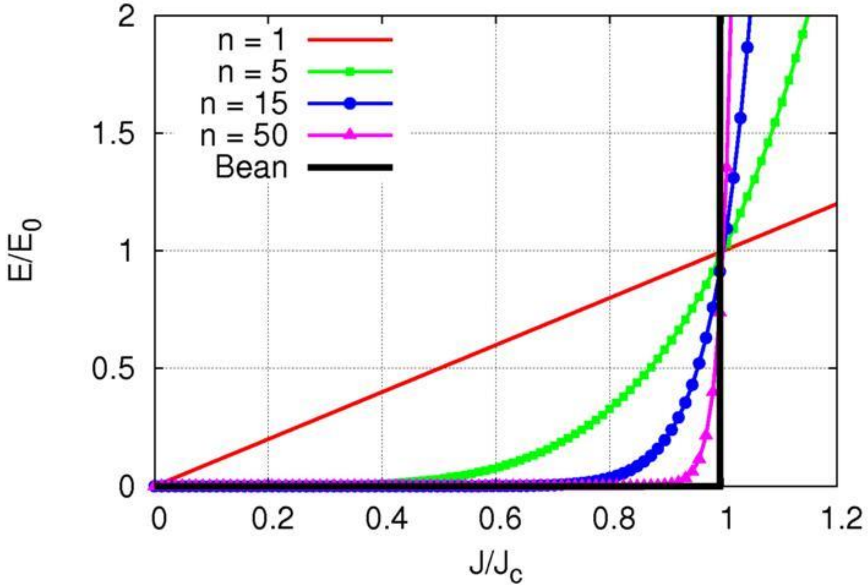
$$J_c = \frac{J_{c0}}{\left(1 + \frac{B}{B_0}\right)^{\alpha}}$$

$$J_{c0}(T) = \alpha \left[1 - \left(\frac{T}{T_c}\right)^2\right]^{1.5}$$

Bulk Modelling in 3D – Pulsed Field Magnetization

- **Why is HTS material modelling difficult?**
  - Conventional materials = non-linear permeability, linear resistivity
  - Superconductors = linear permeability, non-linear resistivity
- **Non-linearity is extreme: power law with n > 20**



$$\mathbf{E} = E_0 \left(\frac{J}{J_c}\right)^{n-1} \frac{\mathbf{J}}{J_c}$$

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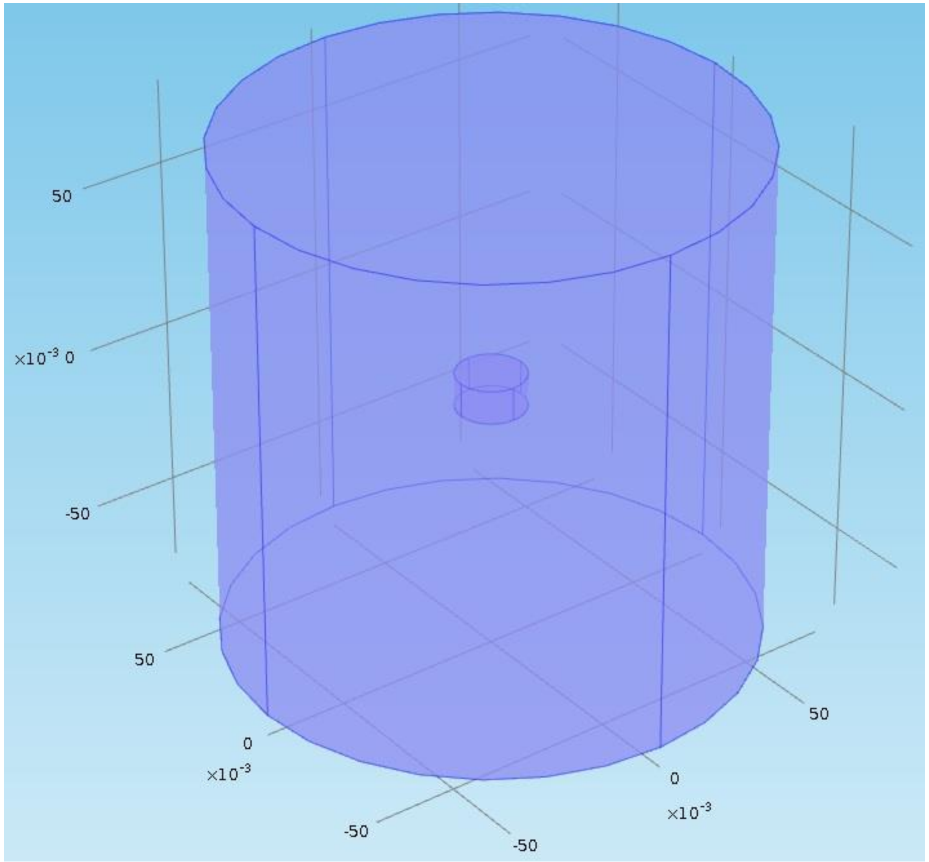

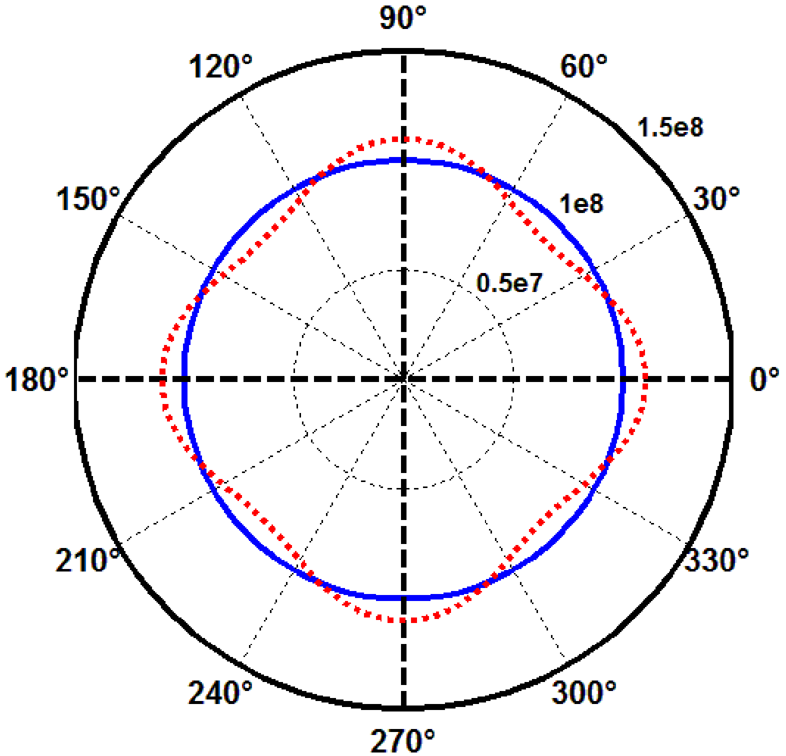

Homogeneous vs. inhomogeneous J_c distribution

Ainslie et al. *Supercond. Sci. Technol.* **27** (2014) 065008

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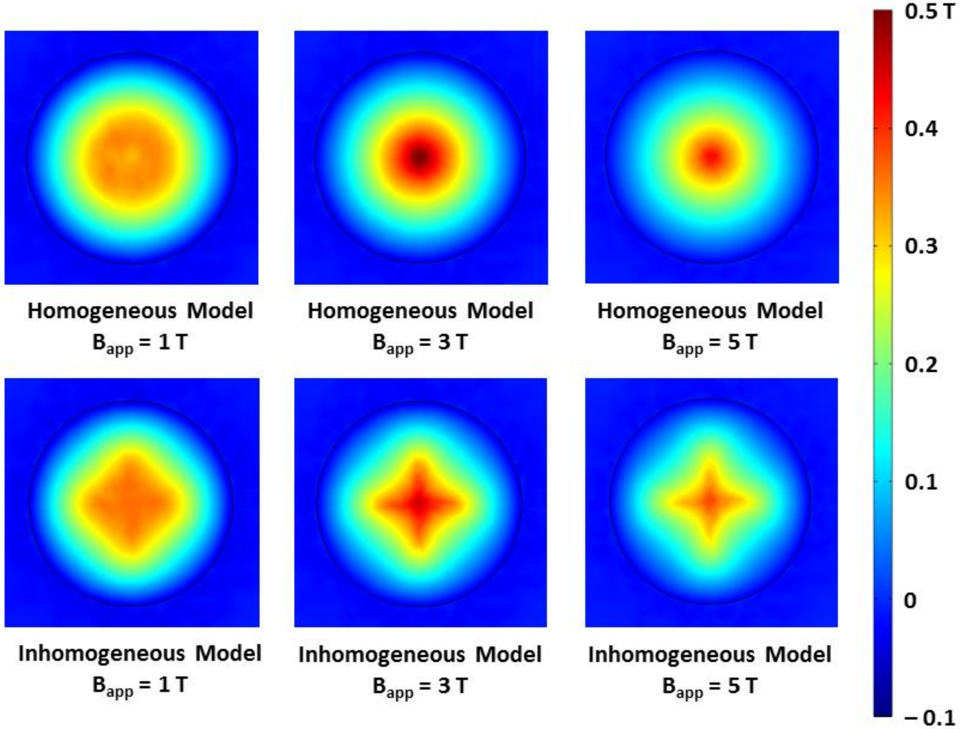

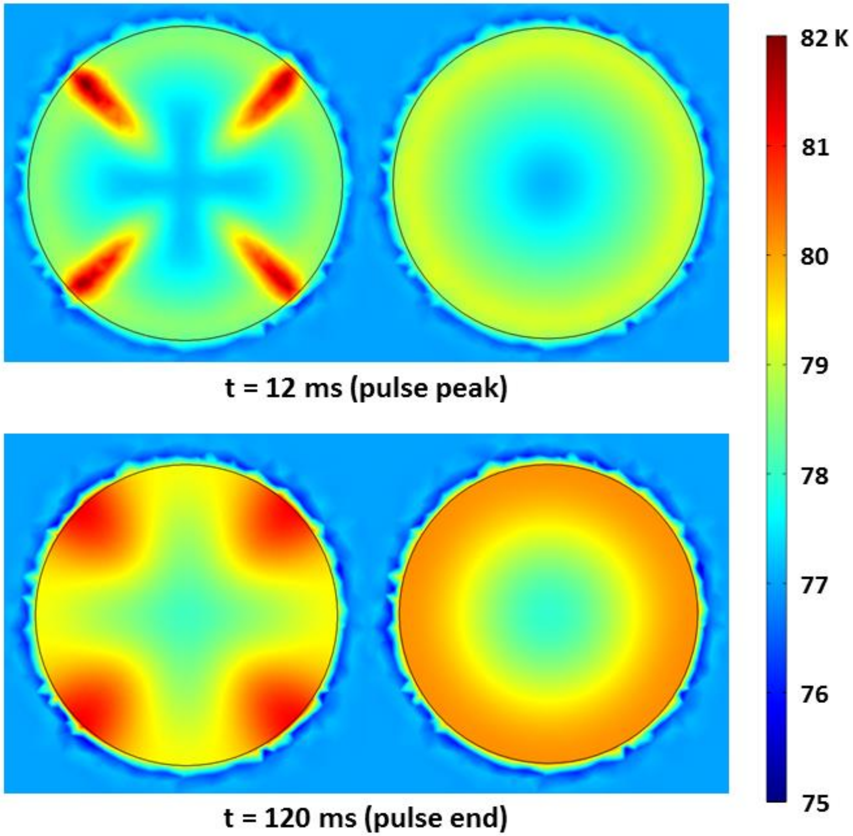

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Thank you for listening

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