UNIVERSITY OF CAMBRIDGE

BSG

Modelling Considerations for Trapped Flux-Type Superconducting Electric Machine Design

Dr Mark Ainslie

Royal Academy of Engineering Research Fellow

Bulk Superconductivity Group, Department of Engineering

Presentation Outline

- **Superconducting Applications for Electric Power Systems**
- **Superconducting Machine Research**
  - Modelling considerations for high temperature superconducting (HTS) tape / bulk materials
    - *<u>Stator:</u> AC loss in superconducting coils*
    - *<u>Rotor:</u> Bulk superconductors as trapped field magnets*

Electrical Engineering Applications

- **Energy security & supply is a crucial 21st century challenge**
- **US DOE estimates > 35 trillion kWh required worldwide by 2035** [1]
  - 1.8 billion middle-class consumers → + 3 billion by 2030 [2]
  - 90% of this growth from Asia-Pacific region
- **Existing methods of electricity supply & usage are unsustainable**
- **Superconductors offer an opportunity for a step change in power system technology**
  - Improved efficiency, lower carbon emissions, increased power-density

[1] http://www.eia.gov/forecasts/ieo/world.cfm
[2] Professor Sir David King, "The Politics of Climate Change"

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 Machine Research

- **Approx. one third of electricity consumed by industry** [1]
  - Approx. two thirds of this consumed by electric motors [2]
- **Using superconductors can increase electric / magnetic loading of an electric machine**
  - Higher current density → increased power density → reduced size & weight
  - Lower wire resistance → lower losses & higher efficiency / better performance
  - Bulk superconductors >> permanent magnets

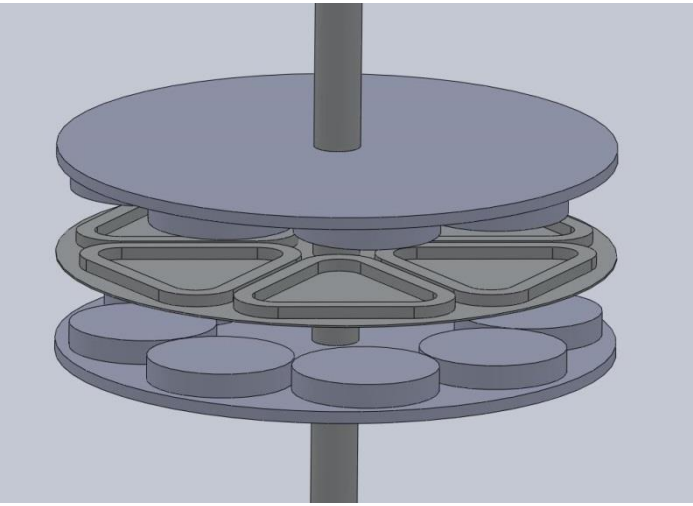
[1] U.S. Energy Information Administration, "Annual Energy Review 2010: Energy Consumption Estimates by Sector Overview"
[2] ABB, "ABB drives and motors for improving energy efficiency," 2010

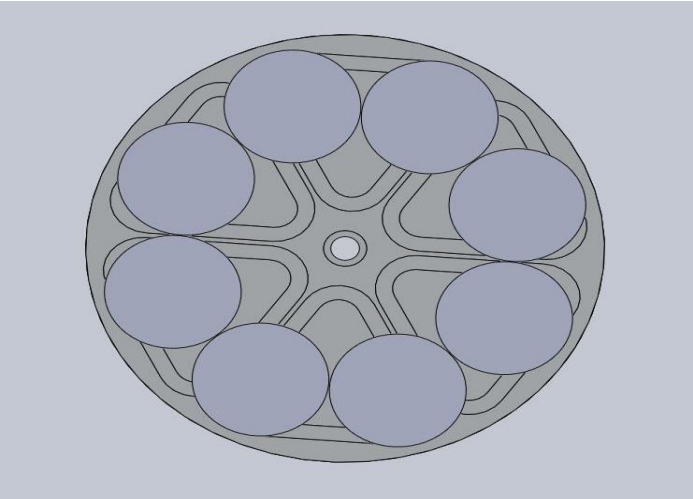
Superconducting Machine Research

- **Five year project funded by Royal Academy of Engineering**
- ***Engineering Interactions of Magnetic & Superconducting Materials for Electrical Applications***
- **Project goals:**
  - Investigate AC loss in superconducting coils & loss reduction methods
  - Investigate practical magnetisation of bulk superconductors & optimisation of trapped field
  - Produce a prototype design of a superconducting electric machine with reduced AC loss (higher efficiency), high torque & reduced weight/size

Superconducting Machine Research – Axial Flux

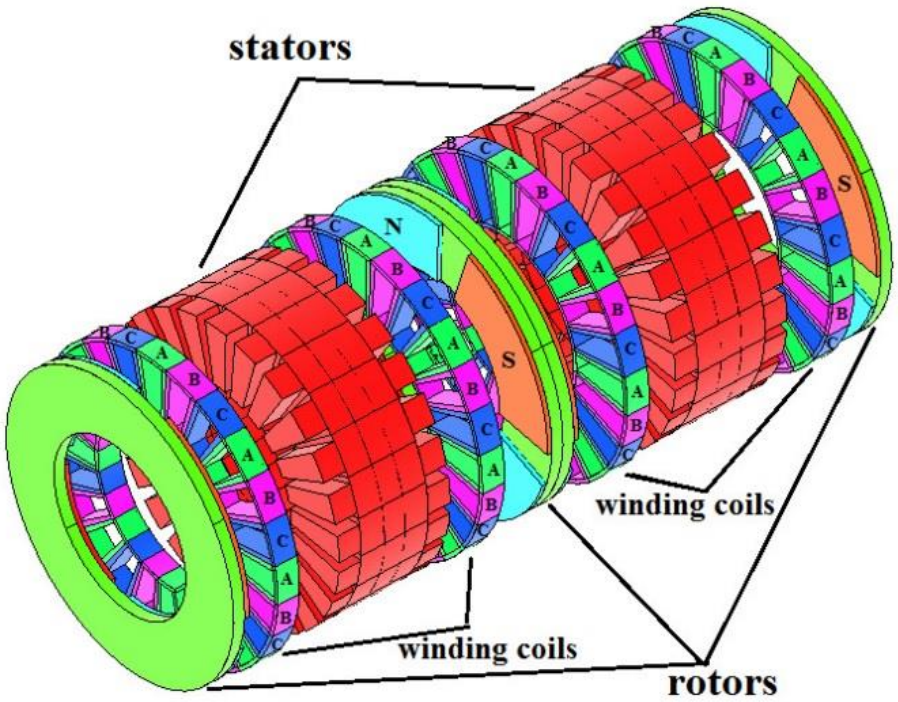
- **Axial flux, trapped flux-type motor**
  - Bulk & wire HTS materials
- **Advantages of axial flux motor**
  - Higher torque/power density & efficiency
  - Compact ‘pancake’ shape
  - Better heat removal
  - Adjustable air gap
  - Multi-stage machines possible





Superconducting Machine Research – Axial Flux

- **Axial flux, trapped flux-type motor**
  - Bulk & wire HTS materials
- **Advantages of axial flux motor**
  - Higher torque/power density & efficiency
  - Compact ‘pancake’ shape
  - Better heat removal
  - Adjustable air gap
  - Multi-stage machines possible



Mahmoudi et al. 2011 Scientific Research and Essays 6(12) 2525-2549

Project Overview

Engineering Interactions of Magnetic and Superconducting Materials for Electrical Applications

SUPERCONDUCTING ELECTRIC MACHINE DESIGN

Rotor
Replacement of permanent magnets with bulk superconductors

Magnetization
Develop in-situ technique for magnetizing bulk superconductors

Modelling
Bulk models (2D axisymmetric, 3D)

Shaping/shimming trapped field using magnetic materials

Large scale pulse magnetization within machine

Pulse magnetization + thermal modelling

Armature/stator
Replacement of conventional copper with superconducting wire

Experiment
Develop transport AC loss measurement rig for superconducting coils

Modelling
Coil models (2D axisymmetric, 3D)

Accurately predict critical current + calculate transport AC loss of coils

AC loss reduction using magnetic materials

Project Overview

Engineering Interactions of Magnetic and Superconducting Materials for Electrical Applications

SUPERCONDUCTING ELECTRIC MACHINE DESIGN

Rotor
Replacement of permanent magnets with bulk superconductors

Magnetization
Develop in-situ technique for magnetizing bulk superconductors

Modelling
Bulk models (2D axisymmetric, 3D)

Shaping/shimming trapped field using magnetic materials

Large scale pulse magnetization within machine

Pulse magnetization + thermal modelling

Armature/stator
Replacement of conventional copper with superconducting wire

Experiment
Develop transport AC loss measurement rig for superconducting coils

Modelling
Coil models (2D axisymmetric, 3D)

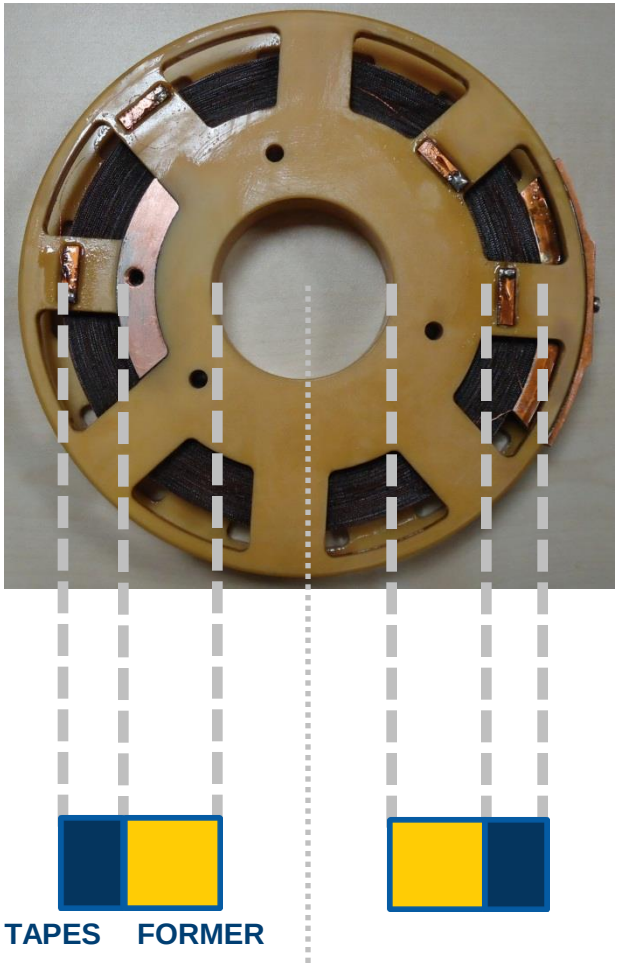
Accurately predict critical current + calculate transport AC loss of coils

AC loss reduction using magnetic materials

Stator – AC Loss in Superconducting Coils

- **Coils found in many electrical engineering applications**
- **Many power applications require AC (alternating current, *time-varying*)**
- **Finite AC loss appears for time-varying current and/or magnetic field**
  - Amplified at low temperatures, e.g., $\mathbf{P_{actual} \approx 20\ P_{77\ K}}$
- **For a superconducting device to be commercially viable**
  - Must have improved performance (size, efficiency, cost) over an existing equivalent/conventional device

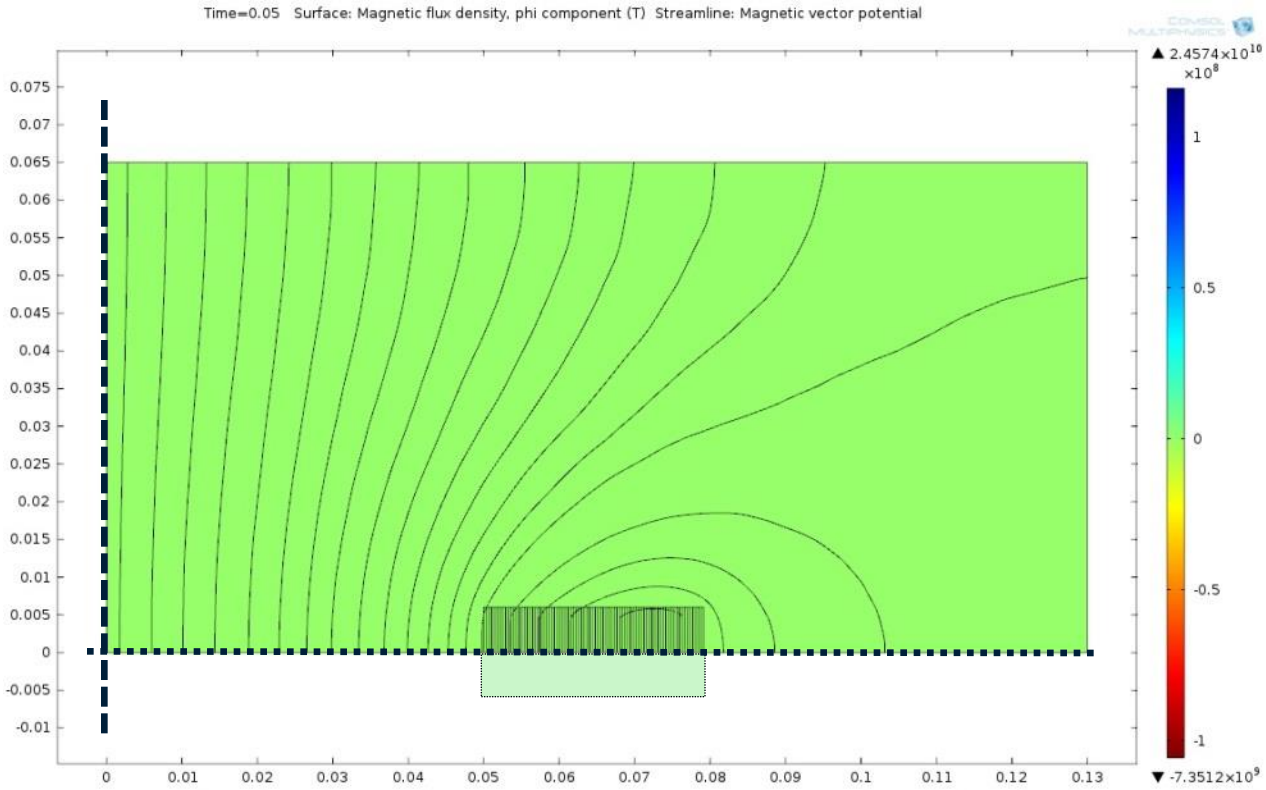
Stator – Coil Modelling



Implemented in COMSOL Multiphysics

*Maxwell's equations (**H** formulation) + E-J power law*

"Multiphysics" = can be coupled with thermal equations

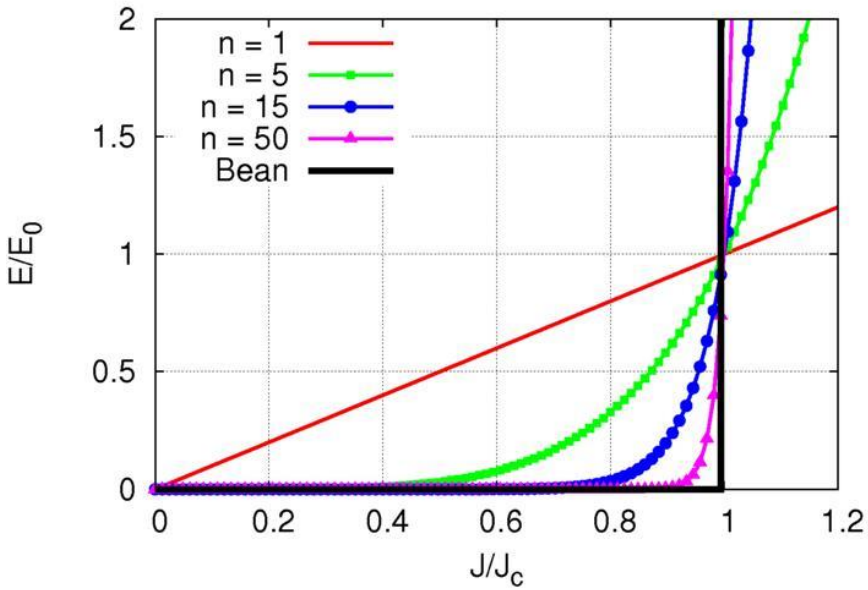


Coil Modelling – What Do We Want To Know?

- DC properties
  - Maximum allowable current / critical current
- AC properties
  - AC loss
- Magnetic field
  - Peak central field
  - I vs B_{centre}
- Effect of critical current density anisotropy $J_c(B,\theta)$
- Effect of inhomogeneities
  - Width, length
- Effect of magnetic materials
  - Magnetic substrates
  - External flux diverters
- Optimisation of coil geometry

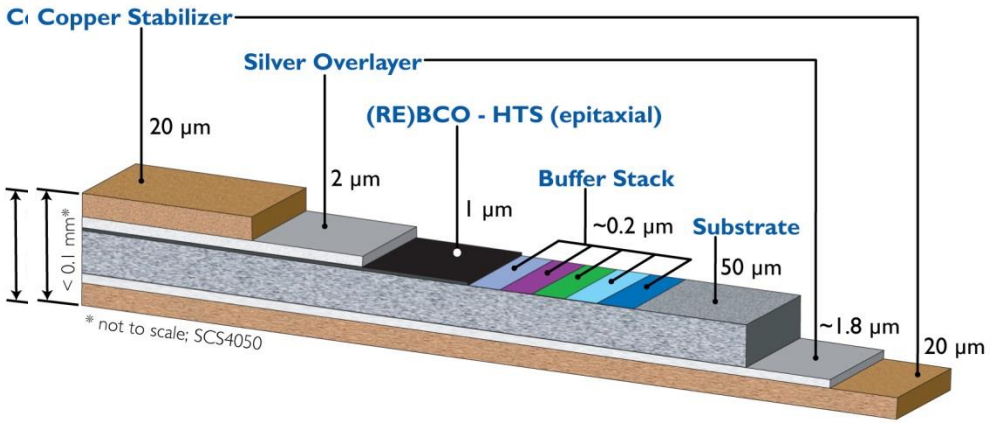
Coil Modelling – Why Is It Difficult?

- **Why is superconducting modelling difficult?**
  - Conventional materials = non-linear permeability, linear resistivity
  - Superconductors = linear permeability, non-linear resistivity
- **Non-linearity is extreme: power law with n > 20**
- **For standard 3D models, 100,000s elements required in FEM**
- **Complicated anisotropy of in-field behaviour $J_c(B,\theta)$**



Critical Current Density J_c

- **Accurate J_c data is crucial for accurate modelling**
  - Can predict coil critical current & AC loss
- **Need engineering equation to represent behaviour**
  - Modified Kim-like models only applicable in some cases



$$J_c(B_\parallel, B_\perp) = \frac{J_{c0}}{\left(1 + \frac{\sqrt{k^2 \cdot B_\parallel^2 + B_\perp^2}}{B_0}\right)^\beta}$$

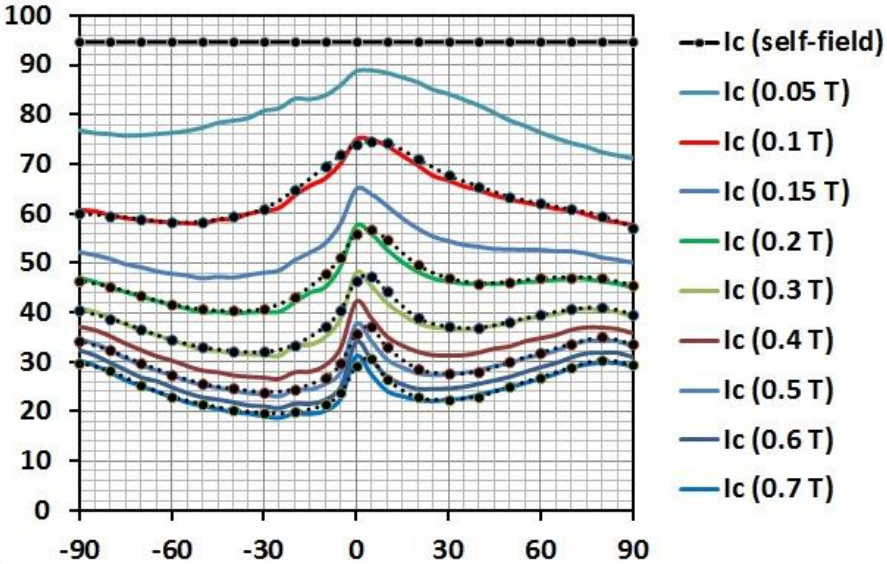
Souc et al. 2009 *SuST* 22 015006

$$J_c(B, \theta) = J_{c,e}[B f_e(\theta)]$$

$$J_{c,e}(B) = \frac{J_{0e}}{(1 + B/B_{0e})^\beta},$$

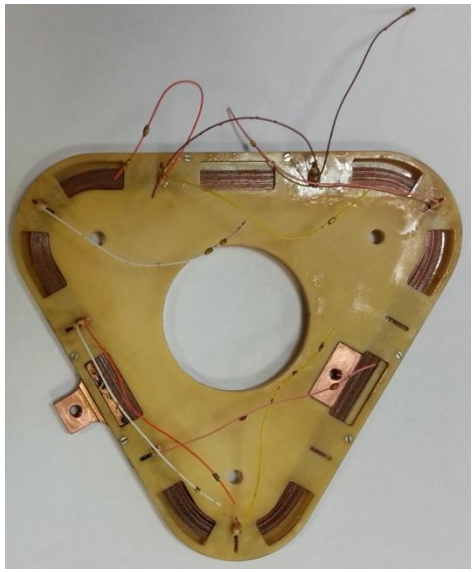
$$f_e(\theta) = \sqrt{\cos^2\theta + u_e^2 \sin^2\theta}.$$

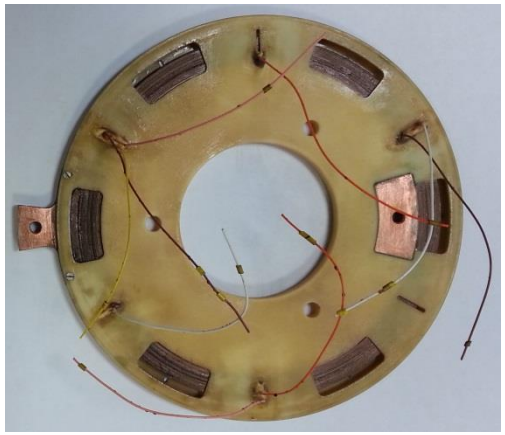
Pardo, Grilli 2012 *SuST* 25 014008



Test Motor Coils

- **Applying these considerations to test motor coils to validate models**
  - Triangular & circular pancake coils
- **Wound by University of Oxford using SuperPower SCS4050 coated conductor**





Project Overview

Engineering Interactions of Magnetic and Superconducting Materials for Electrical Applications

SUPERCONDUCTING ELECTRIC MACHINE DESIGN

Rotor
Replacement of permanent magnets with bulk superconductors

Magnetization
Develop in-situ technique for magnetizing bulk superconductors

Modelling
Bulk models (2D axisymmetric, 3D)

Shaping/shimming trapped field using magnetic materials

Large scale pulse magnetization within machine

Pulse magnetization + thermal modelling

Armature/stator
Replacement of conventional copper with superconducting wire

Experiment
Develop transport AC loss measurement rig for superconducting coils

Modelling
Coil models (2D axisymmetric, 3D)

Accurately predict critical current + calculate transport AC loss of coils

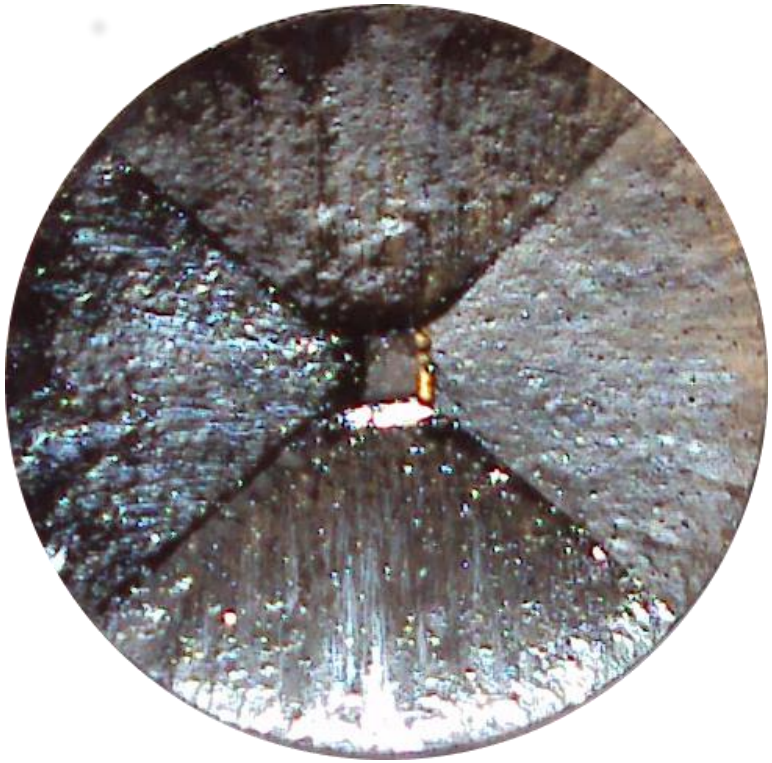
AC loss reduction using magnetic materials

Bulk High Temperature Superconductors

- **Conventional magnets (NdFeB, SmCo) limited by material properties**
  - Magnetisation independent of sample volume
- **Bulk HTS trap magnetic flux via macroscopic electrical currents**
  - Magnetisation increases with sample volume
- **Trapped field given by**

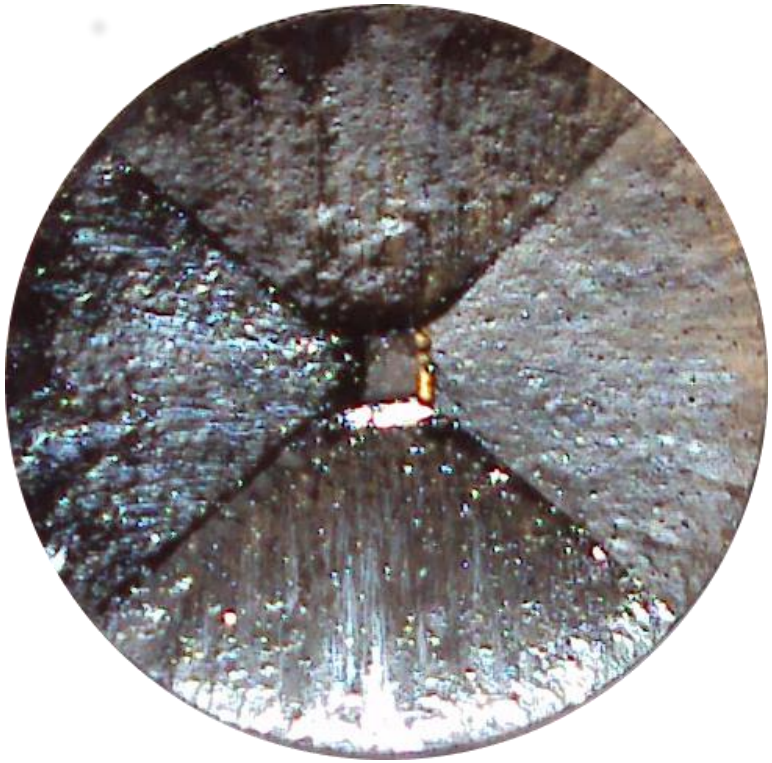
  $B_{trap} = A\ \mu_0\ J_c\ d$

  [Bean approximation]



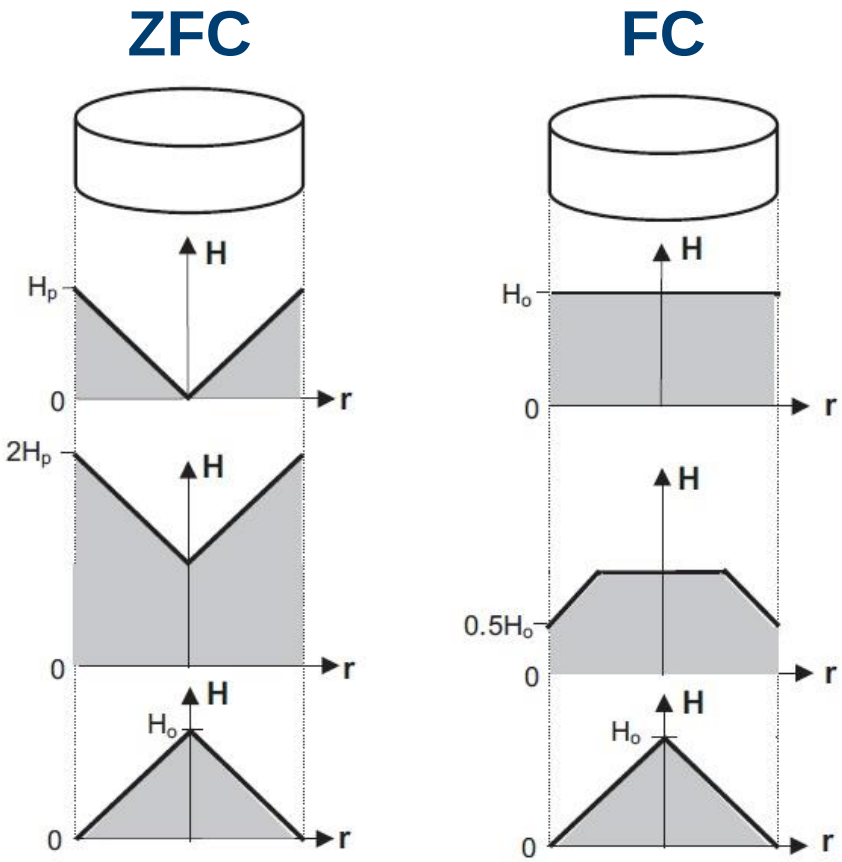
Bulk High Temperature Superconductors

- **Record trapped field = 17 T at 29 K**
  - 2 x 26.5 mm YBCO
  - Tomita, Murakami *Nature* 2003
- **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



Magnetization of Bulk HTS

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

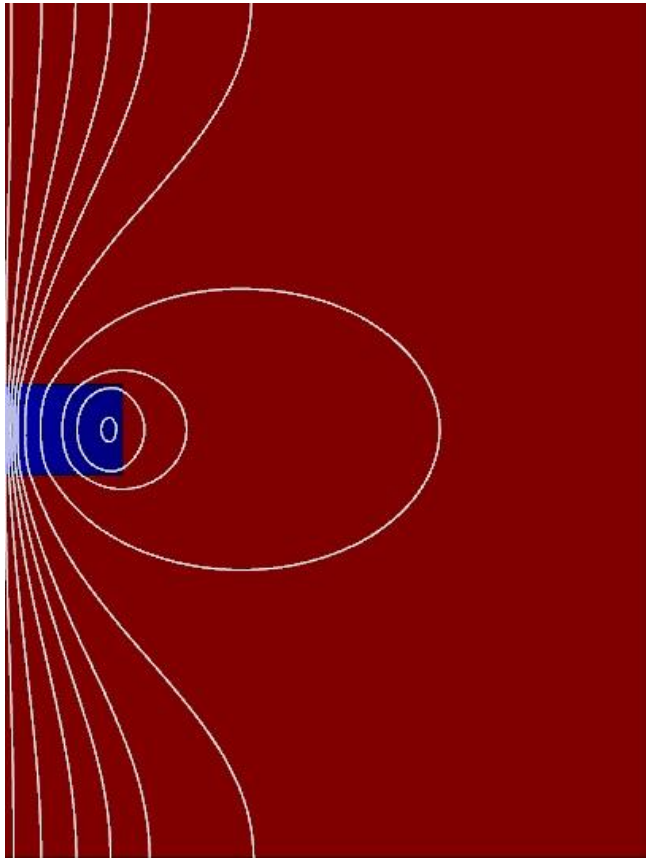


Pulse Field Magnetization

- **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)
- **Record PFM trapped field = 5.2 T at 29 K** (45 mm diameter Gd-BCO) [Fujishiro et al. *Physica C* 2006]

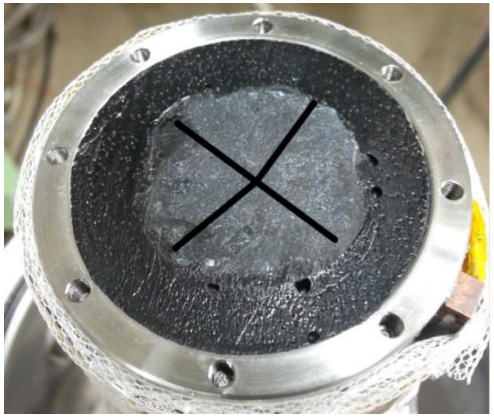
Bulk Modelling

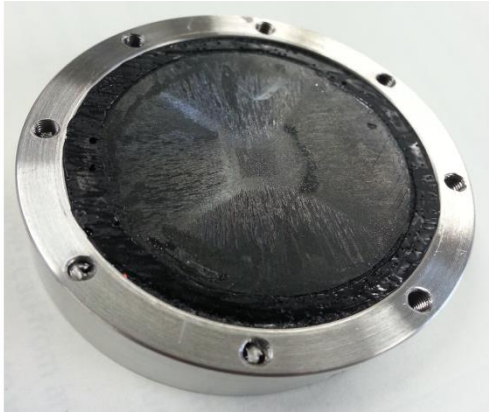
- **Governing equations:**
  - Same ***H*** formulation for EM equations
  - PFM needs to include thermal equations
  - $J_c(B,T) + n(B,T)$
- **2D axisymmetric = simple, okay**
  - 3D models required for arrays of bulks (e.g., motor poles)
  - Inhomogeneities play a significant role in magnetisation



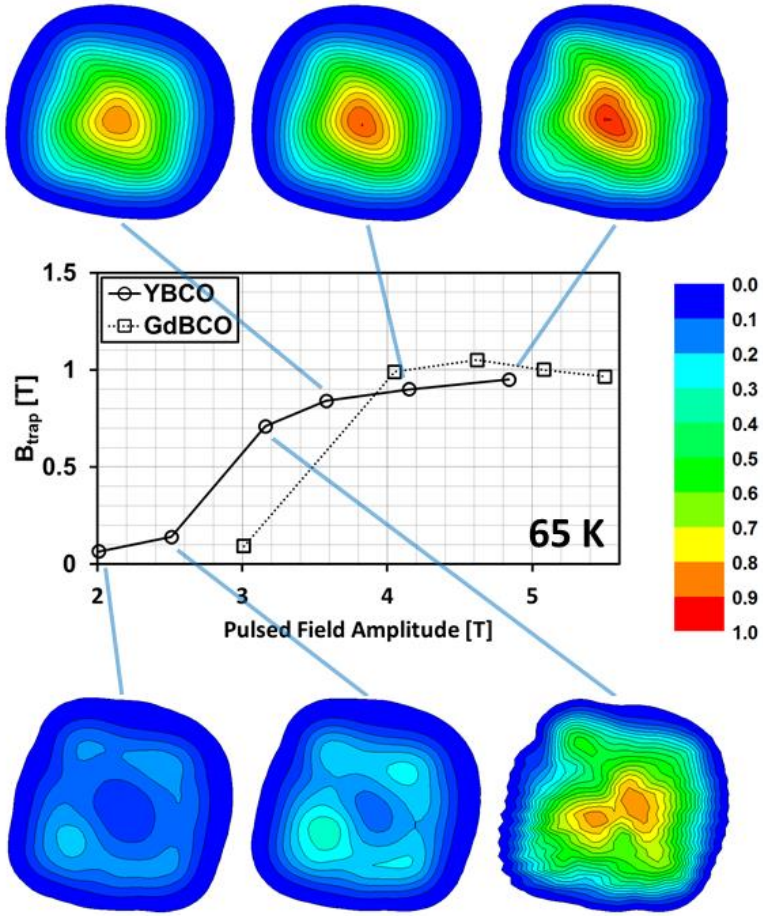
Bulk Modelling in 3D – Pulsed Field Magnetisation

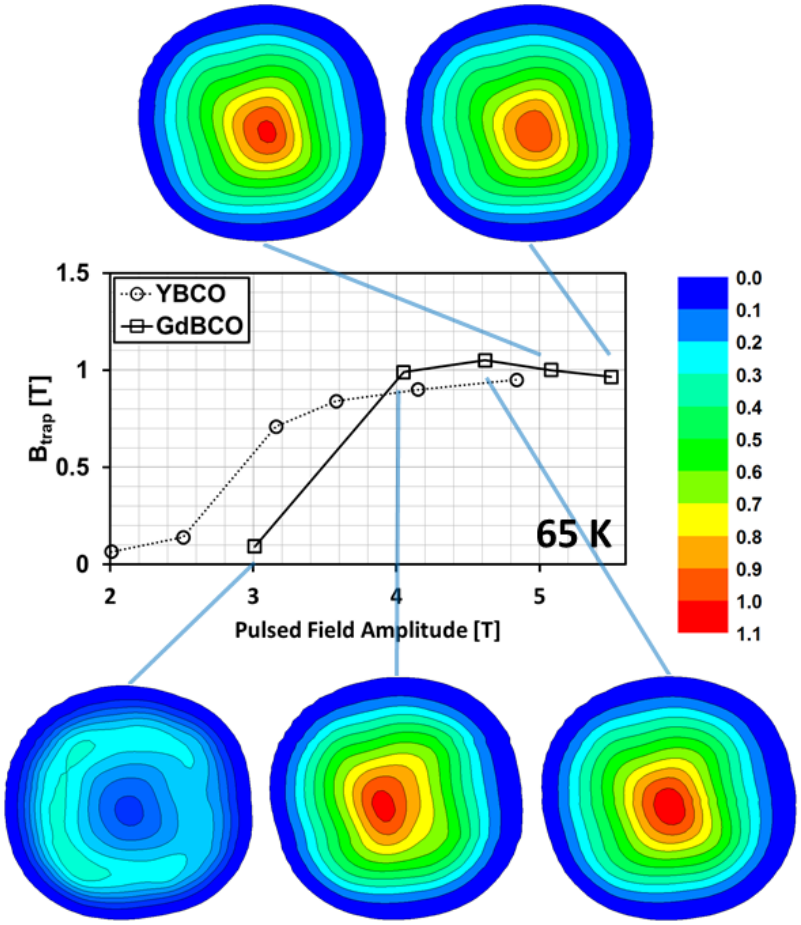
- **Collaboration with Iwate University, Japan**
- **Flux dynamics of (RE)BCO bulk superconductors for pulsed field magnetisation**





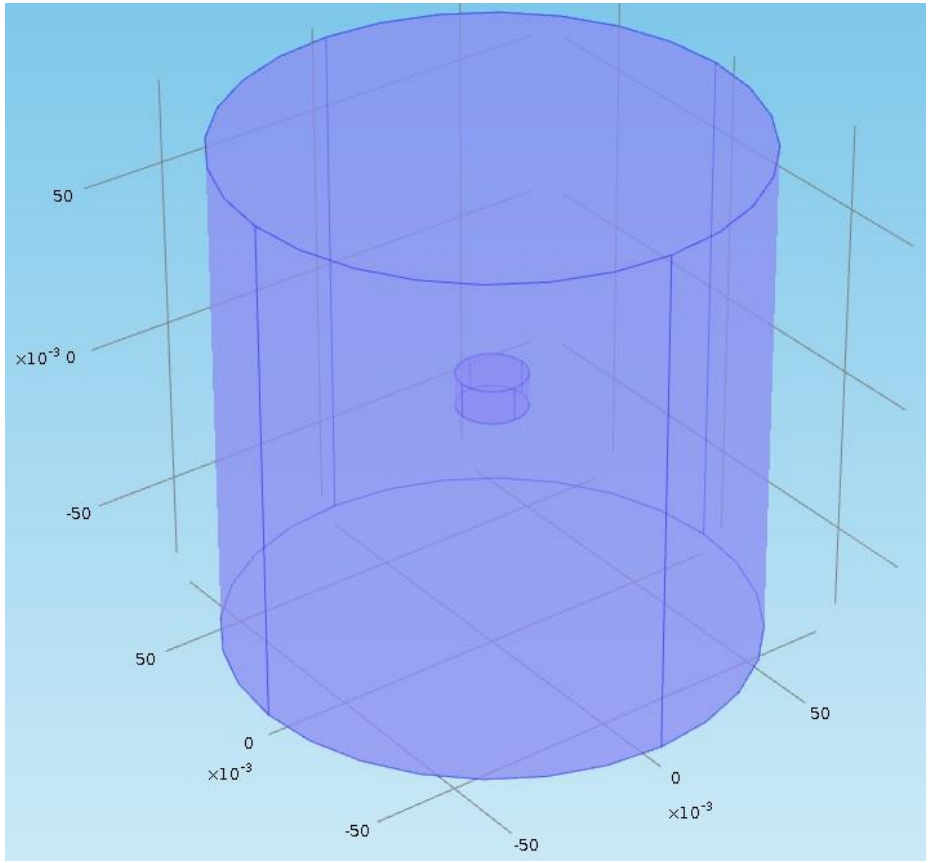
Bulk Modelling In 3D – Pulsed Field Magnetisation

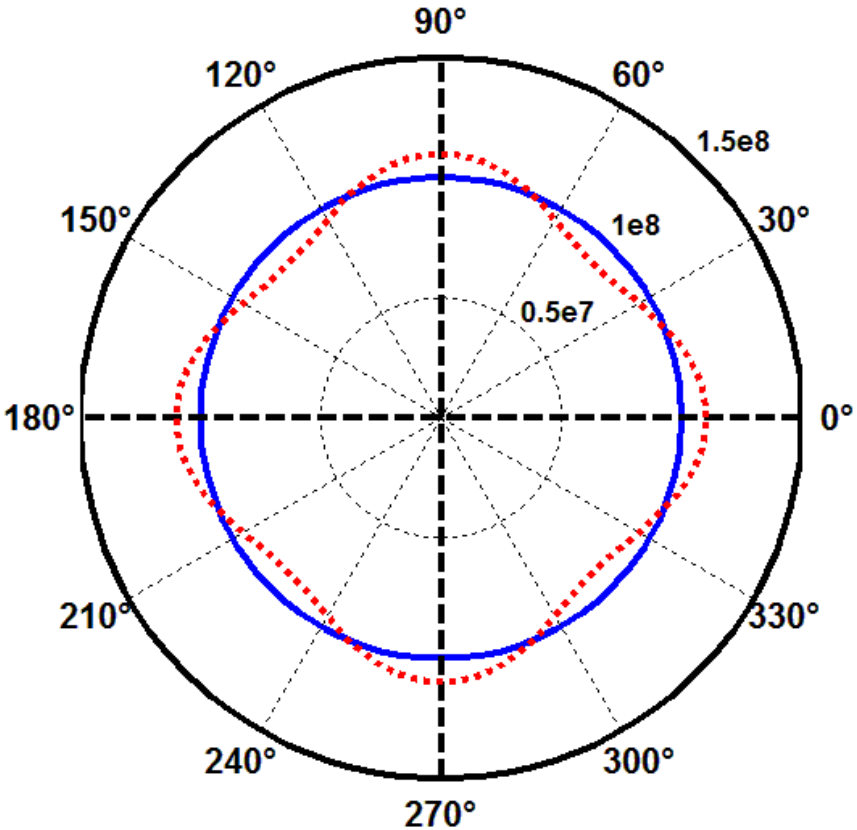




Ainslie et al. *Supercond. Sci. Technol.* **27** (2014) 065008

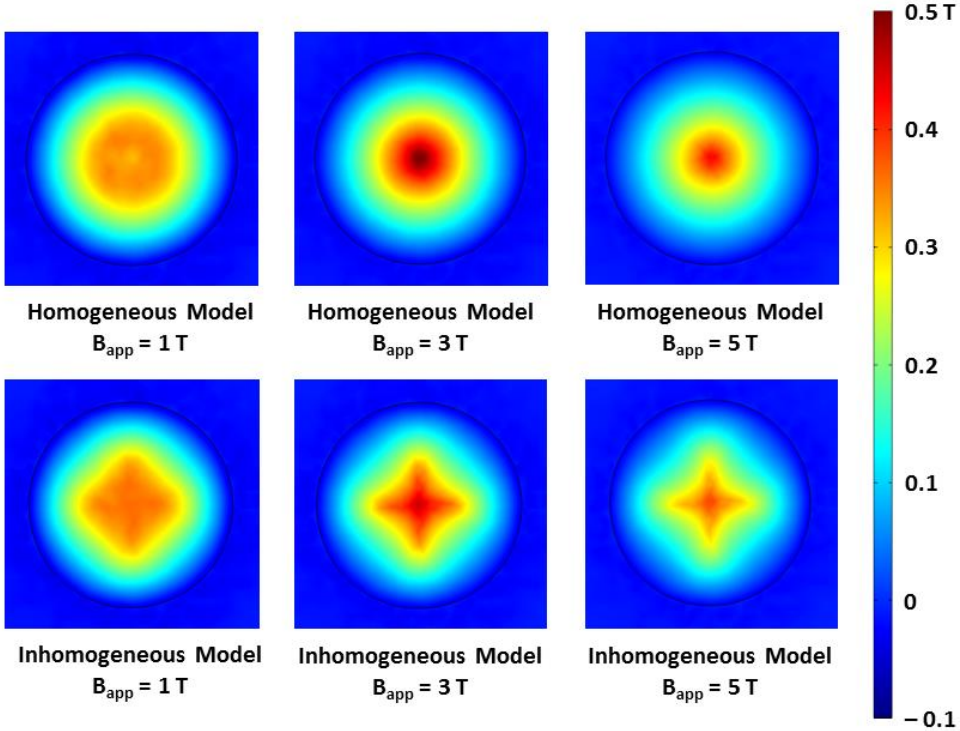
Bulk Modelling in 3D – Pulsed Field Magnetisation

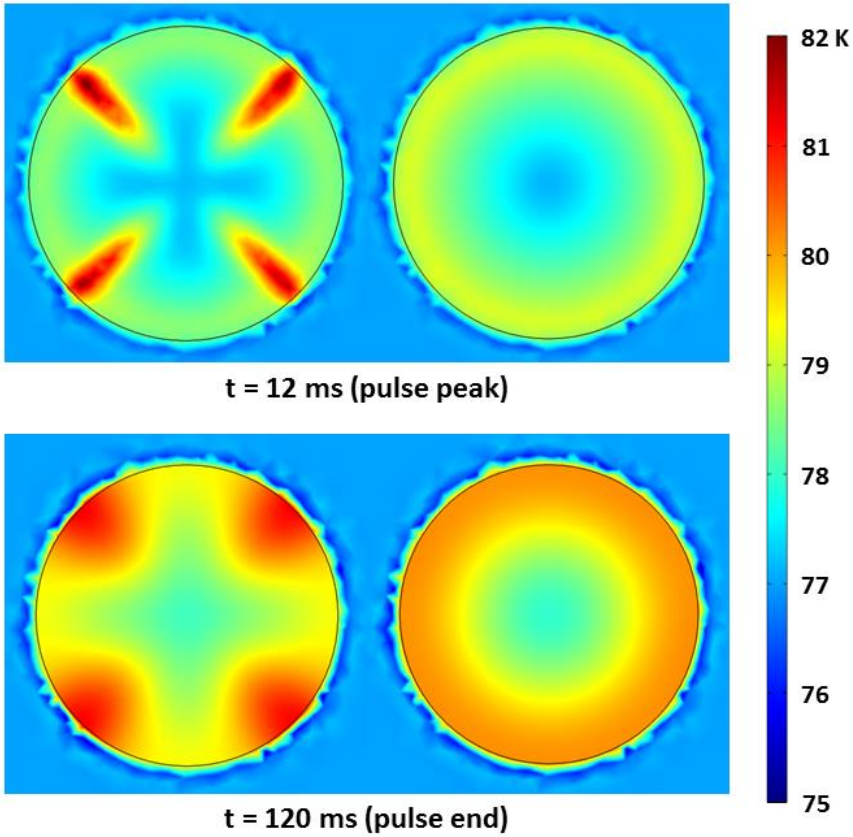




Ainslie et al. *Supercond. Sci. Technol.* **27** (2014) 065008

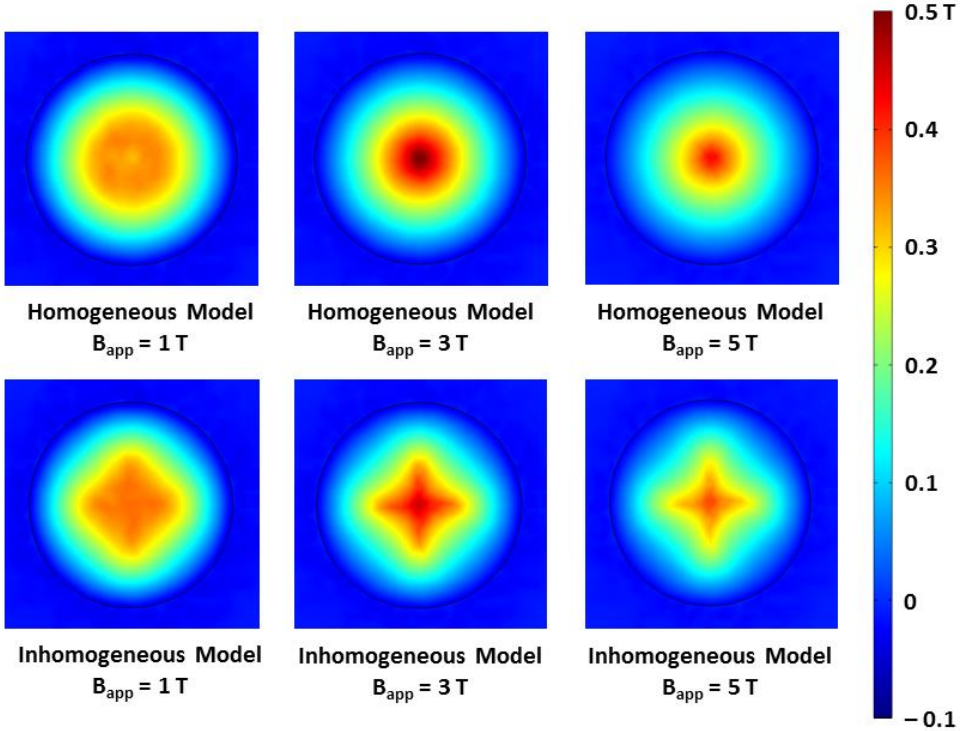
Bulk Modelling in 3D – Pulsed Field Magnetisation

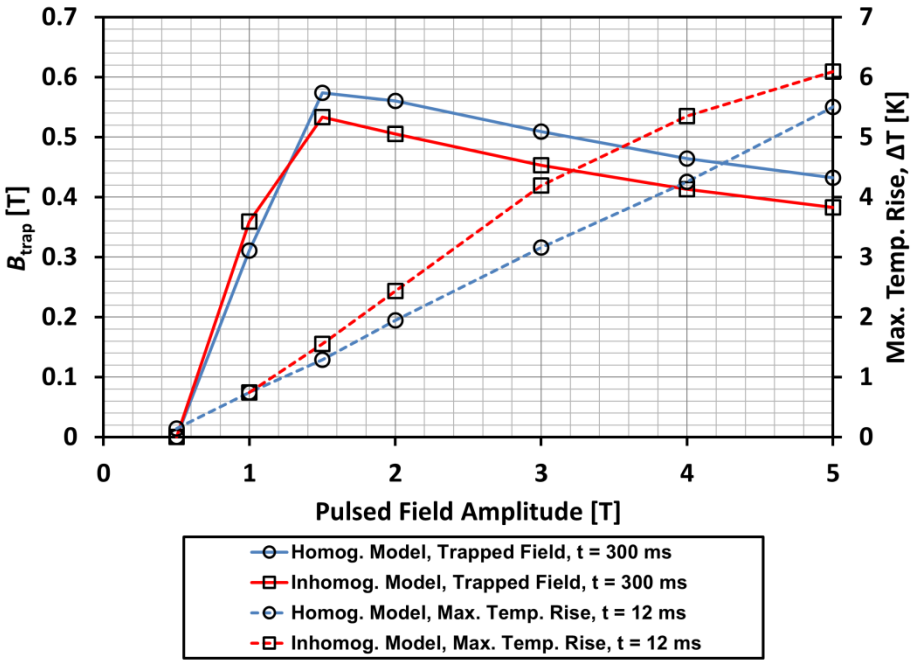




Ainslie et al. *Supercond. Sci. Technol.* **27** (2014) 065008

Bulk Modelling in 3D – Pulsed Field Magnetisation





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

Thank you for listening

ROYAL ACADEMY OF ENGINEERING

IET The Institution of Engineering and Technology

THE ROYAL SOCIETY

Contact email: mark.ainslie@eng.cam.ac.uk
Website: http://www.eng.cam.ac.uk/~mda36/