HTS MODELLING
WORKGROUP

Impact of porosity on trapped magnetic field and mechanical stresses in HTS bulks during PFM

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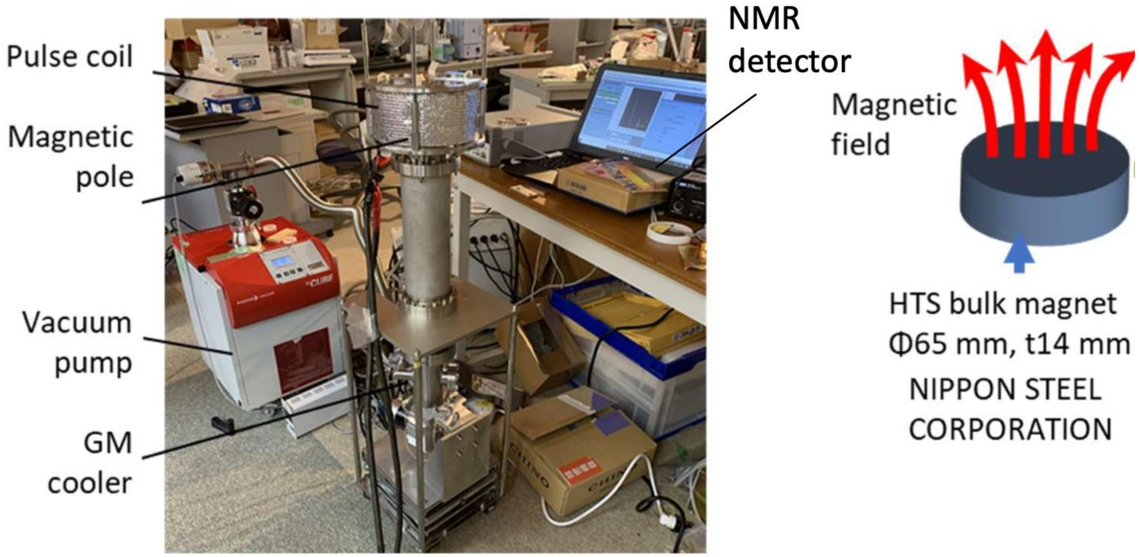
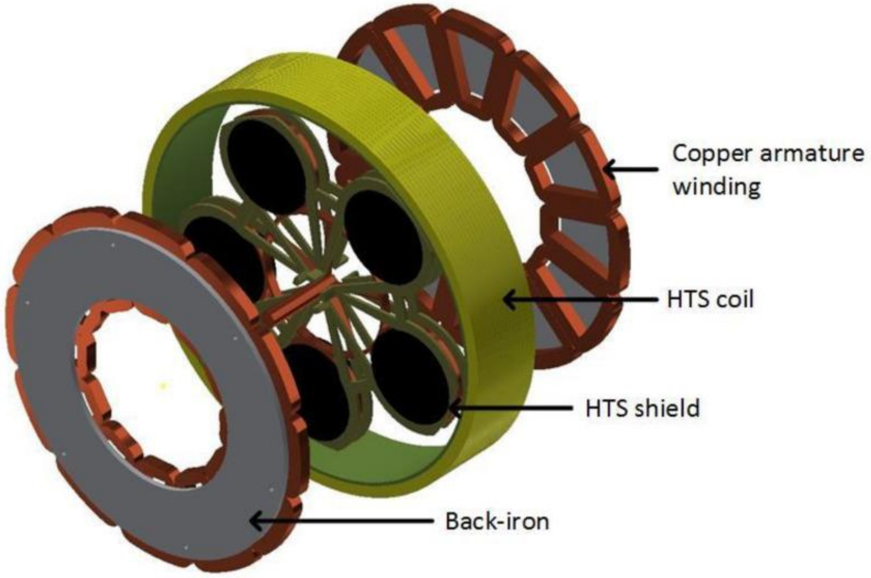
Introduction: HTS bulks as magnets

- HTS bulks can act as cryo-permanent magnets after magnetization.
- The circulation of induced persistent electrical current J_{sc} generates a "trapped" magnetic field $B_z \approx R\,J_c$ ($T_o < T_c$).
- Magnetic fields up to 10 times higher than conventional magnets can be achieved (1-17 T at low temperatures).



NMR Magnet. M. Takahashi *et al*., *IEEE Trans. Appl. Supercond*., 32(6) 2022

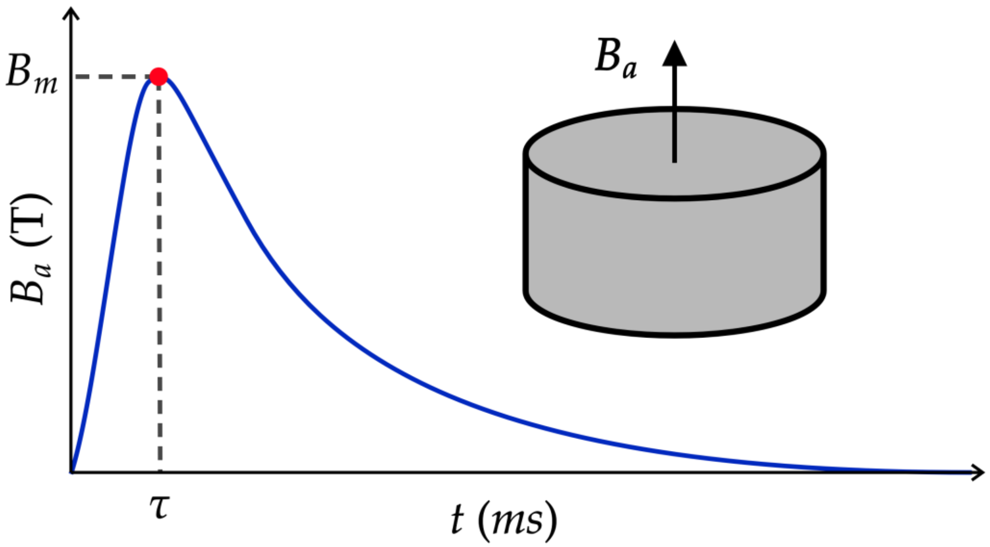


Axial flux HTS motor. Rémi Dorget *et al Materials* 2021, 14, 2847

Pulsed field magnetization (PFM)

- **Pros:**
  - Compact
  - Fast
  - *In situ* magnetization
  - Multi-PFM

T. Oka, K. Yokoyama, Ashikaga University, Japan

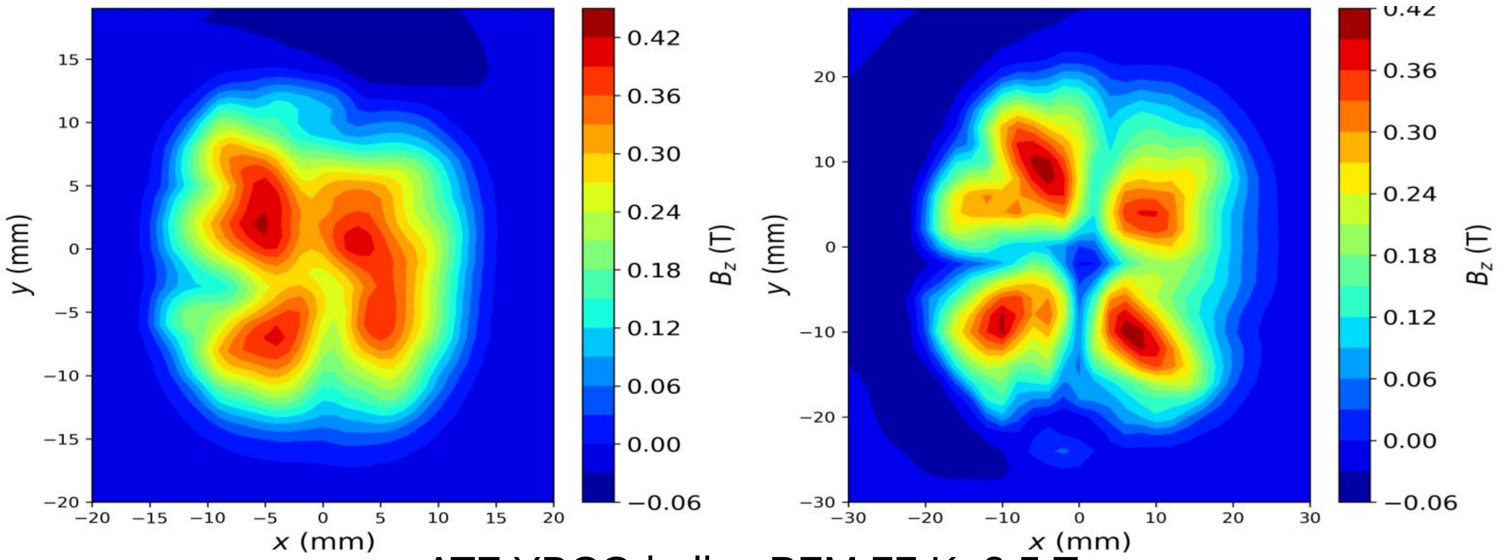


$$B_a(t) = B_m \frac{t}{\tau} \exp\left(1 - \frac{t}{\tau}\right)$$

- **Cons:**
  - Low trapped fields compared to ZFC/FC (Max. ≈ 5 T @ 29K)
  - Large heat generation due to rapid flux motion
  - For larger applied fields or bulks, larger capacitor banks are needed

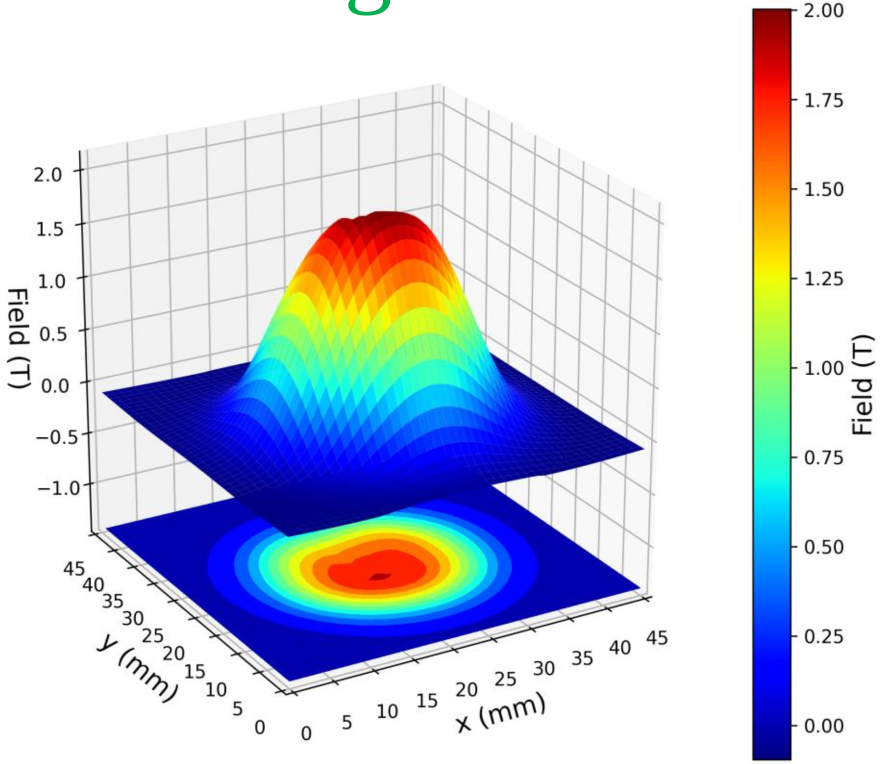
Problems

Inhomogeneous magnetization



ATZ YBCO bulks, PFM 77 K, 2.5 T

Ideal magnetization



Nippon steel GdBCO, PFM 5 T, 40 K

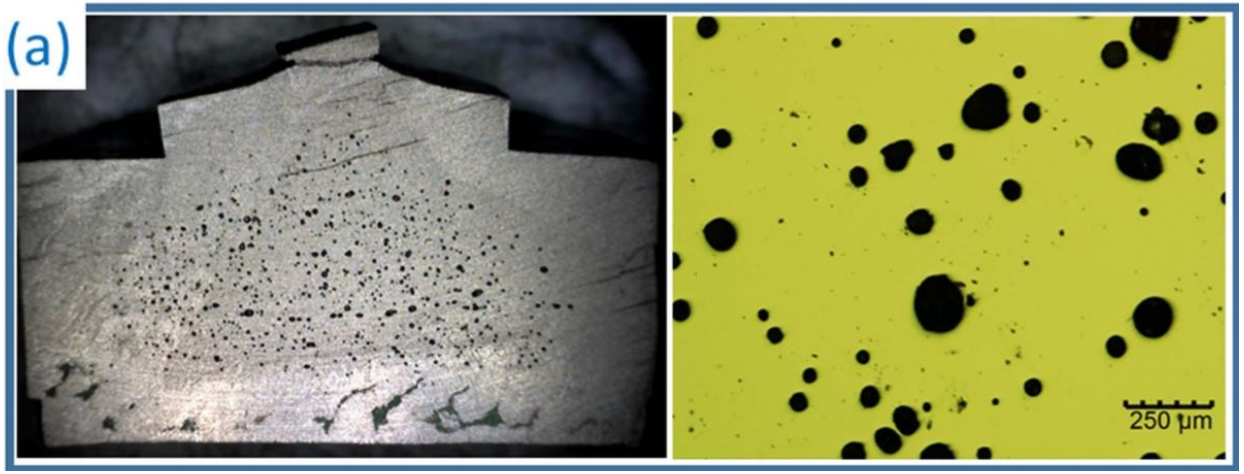
Origins:

- Cracks, pores (addressed here) and inhomogeneous J_c?
- Mechanical crack before and during PFM or influence of Growth Section Boundaries?

Porosity in HTS bulks

- Formed during melt-growth

- Sizes of 50-250 μm ($\gg \xi$)
  - TSMG: 15-30% V_p
  - TSIG: 4-10 % V_p



Devendra K Namburi *et al* 2021 *Supercond. Sci. Technol.* **34** 053002

- Research shows impact on:
  - J_c and trapped field magnitude (Josef Baumann *et al* 2023 *J. Eur. Ceramic Society*)
  - Mechanical properties (N. Sakai *et al* 2000 *Su.S.Tec.***13** 770773, Jasmin V. J. Congreve *et al* 2019 IEEE T.A.S **29-**5)

Multiphysics model in COMSOL

Electromagnetic

$$\mu_0 \frac{\partial \boldsymbol{H}}{\partial t} + \nabla \times (\rho \nabla \times \boldsymbol{H}) = 0 \text{ in } \Omega$$

$$\rho_{sc} = \frac{E_c}{J_c}\left(\frac{|\boldsymbol{J}|}{J_c}\right)^{n-1} \text{ in } \Omega_{sc}$$

$Q = \rho J^2$

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

Thermal

$$\gamma c_p \frac{\partial T}{\partial t} - \nabla \cdot (\kappa \nabla T) = Q \text{ in } \Omega_{sc}$$

$$q_0 = h(T_r - T) \text{ in } \Gamma_{sc}$$

$\boldsymbol{F}_L = \boldsymbol{J} \times \boldsymbol{B}$

ΔT

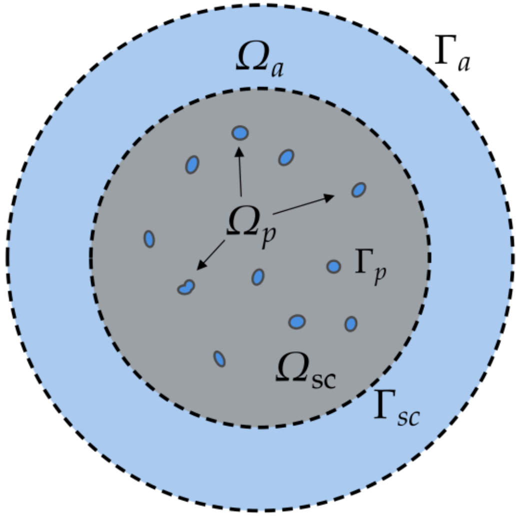
Mechanical

$$\nabla \cdot \boldsymbol{\sigma} + \boldsymbol{F}_L = \gamma \frac{\partial^2 \boldsymbol{u}}{\partial t^2} \text{ in } \Omega_{sc}$$

$$B_a(t) = B_m \frac{t}{\tau} exp\left(1 - \frac{t}{\tau}\right)$$

$$J_c(\boldsymbol{B}, T) = \frac{J_{c0}}{\left(1 + \frac{|\boldsymbol{B}|}{B_0}\right)} \left(1 - \left(\frac{T}{T_c}\right)^2\right)^{3/2}$$

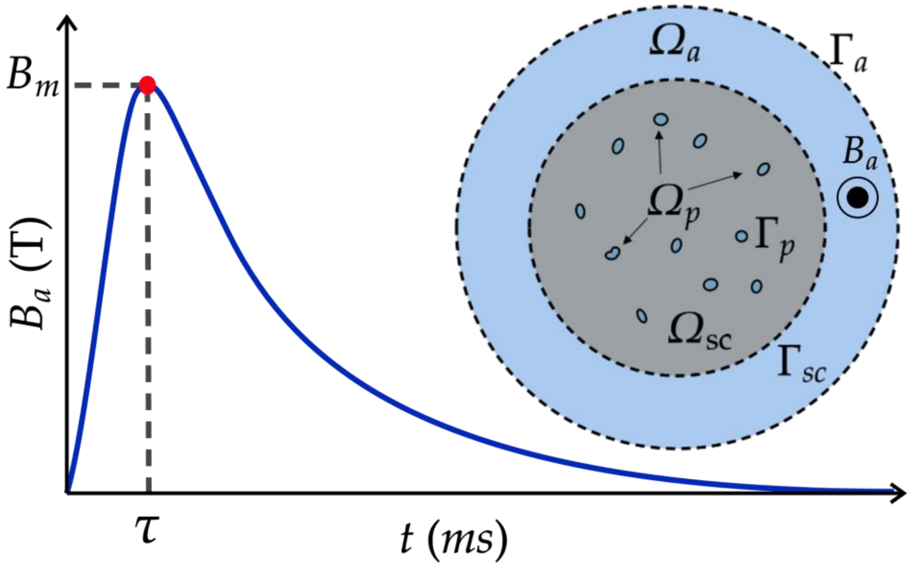
$$\boldsymbol{\sigma} = \boldsymbol{c}\{(\varepsilon_L(\boldsymbol{u}) + \varepsilon_T(\Delta T)\}$$



Schematic drawing of domains and boundaries

Multiphysics model in COMSOL

- Case study:
  - ➢ 2D Infinitely long cylinder approx.
  - ➢ YBCO bulk 1% porosity
- Given porosity surface area (S_p%):
  - Random a-b axis of ellipse [125-250 μm]
  - Randomly distributed inside bulk



Symbol	Parameter (YBCO)	Value
ρ_n	Normal Resistivity	$3.5x10^{-6}$ Ω.m
n	*E-J* power law *n*-value	21
B_0	Fitting parameter Kim	1.3 T
γ_m	Mass density	5900 Kg/m^3
J_{c0}	Critical current density	$5x10^8 A/m^2$
T_o	Operating temperature	65 K
T_c	Critical temperature	92 K
E_c	Electric field criteria	$1x10^{-4}$ V/m
α	Thermal expansion coef.	$1x10^{-5} K^{-1}$
B_{max}	Max. applied magnetic field	4 T
τ	Pulse time constant	13 ms
κ-ab	Thermal conductivity	20 W/m.K
E	Young's modulus	103 MPa
ν	Poisson's ratio	0.33
σ_F	Fracture strength	75 MPa
h	Heat conduction coef.	750 W/(K.m^2)

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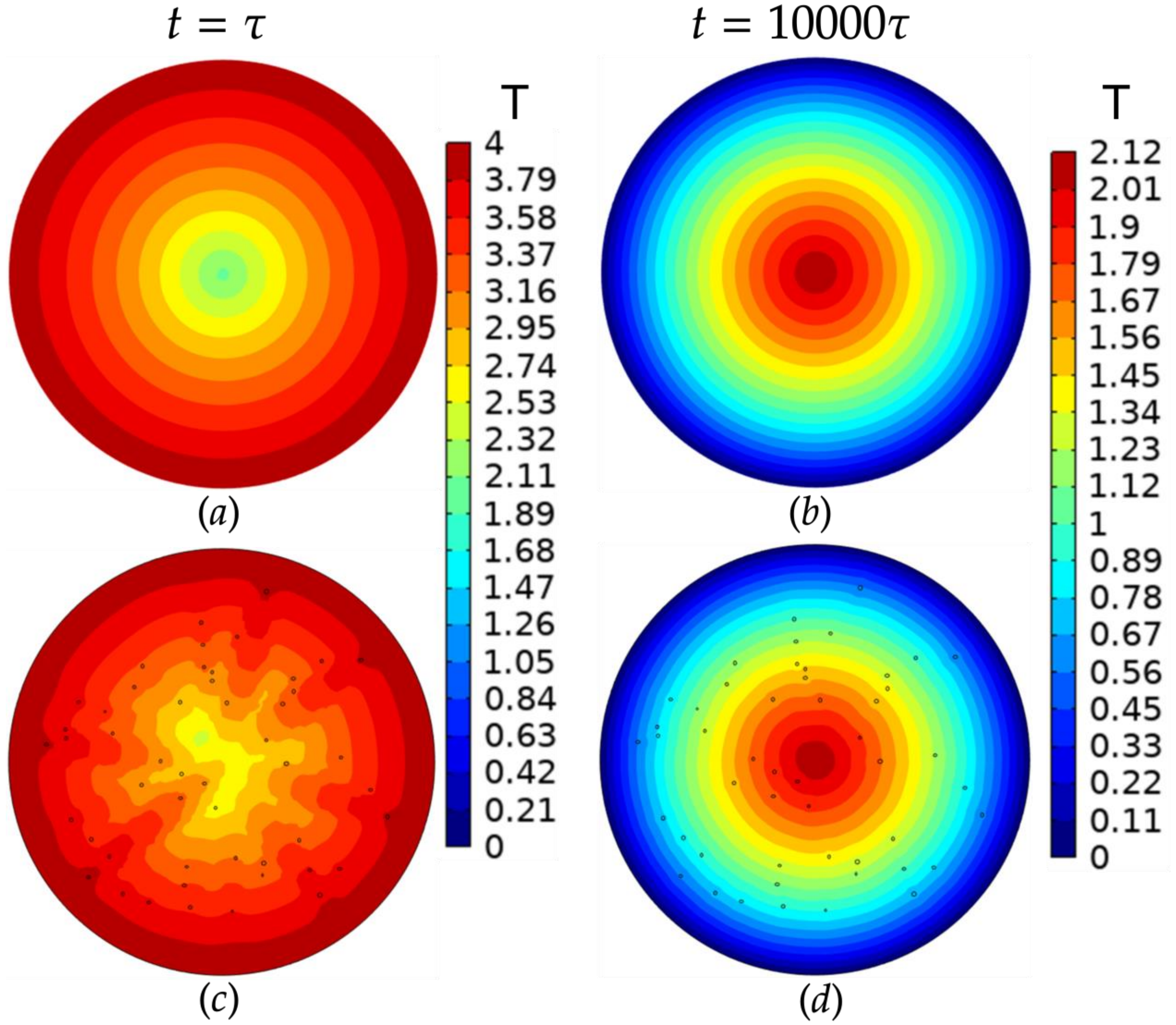
Results: Magnetic flux density

Magnetic flux density distribution



Ideal →

1% Porosity →

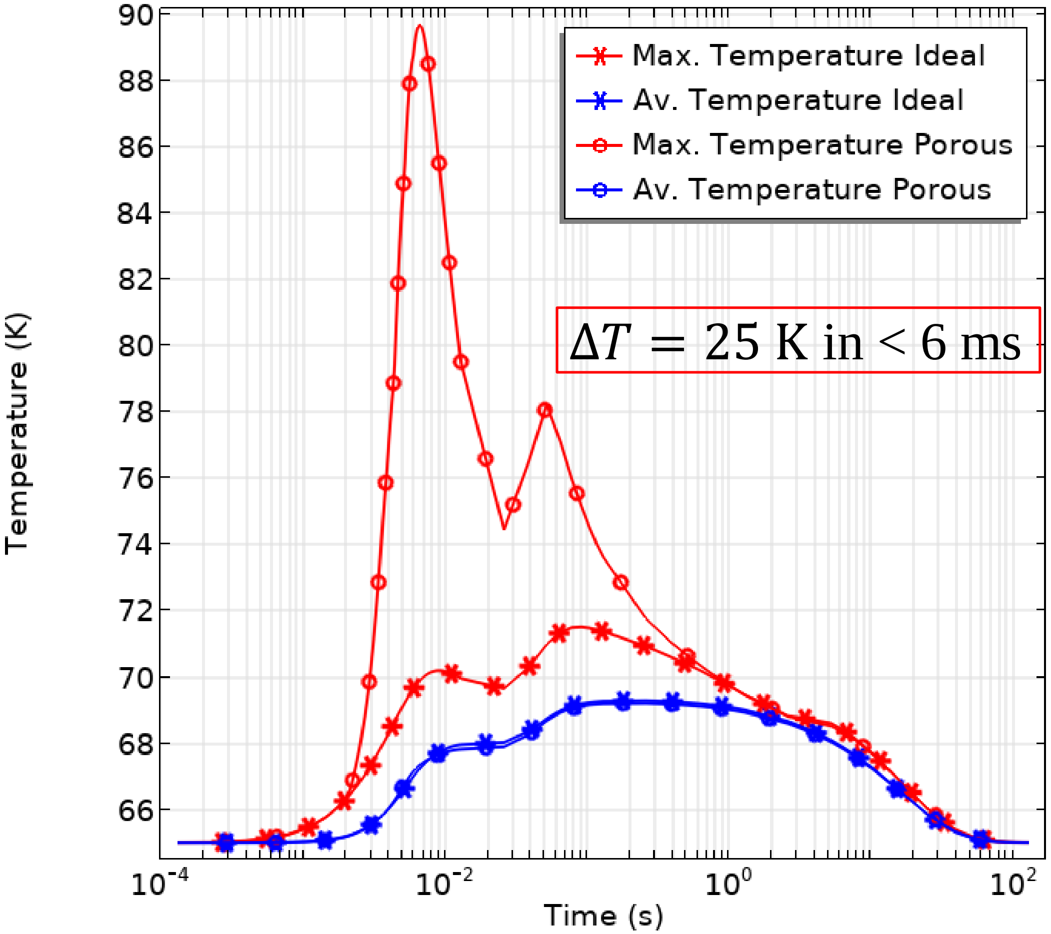
At 130 s center of bulk:

→ $B_z = 2.1180$ T

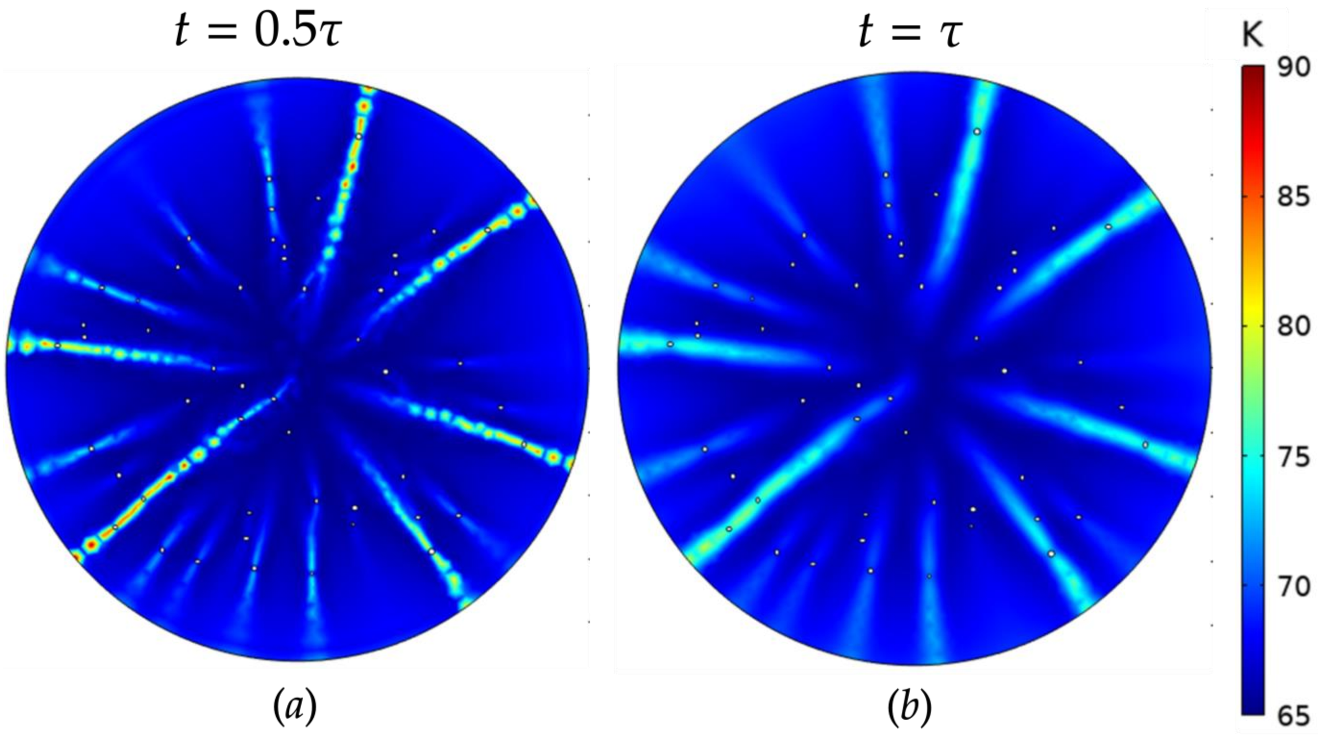
→ $B_z = 2.1078$ T
99.7% Ideal

Results: Thermal impact

Temperature evolution



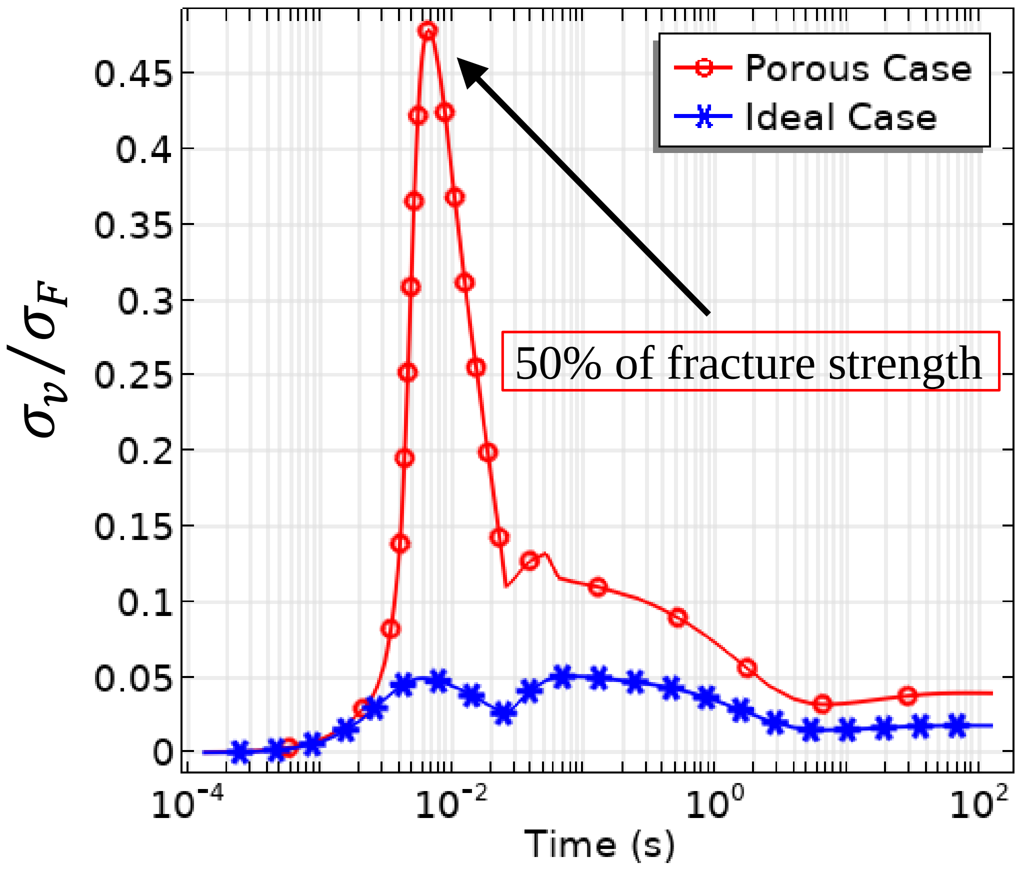
Temperature distribution



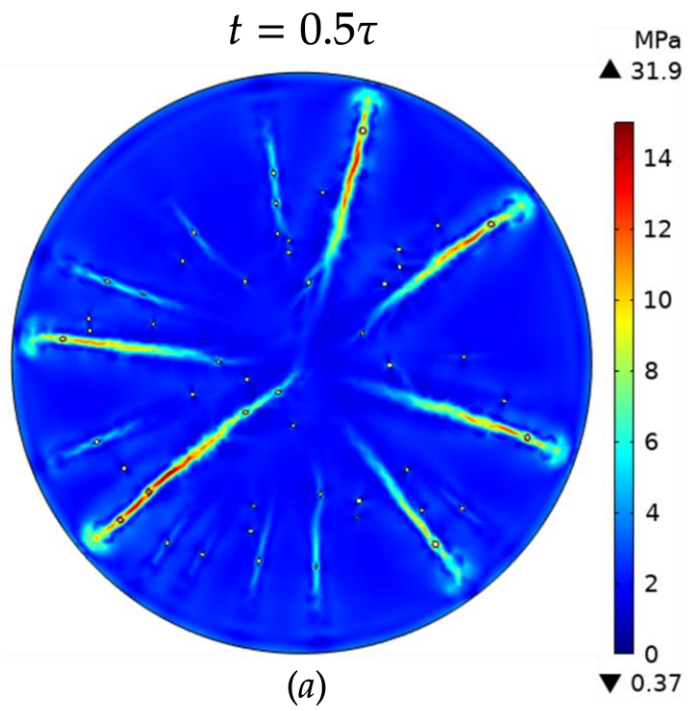
Ze Jing and Mark D Ainslie 2020 *Supercond. Sci. Technol.* **33** 084006

Results: Mechanical impact

Fracture stress comparison



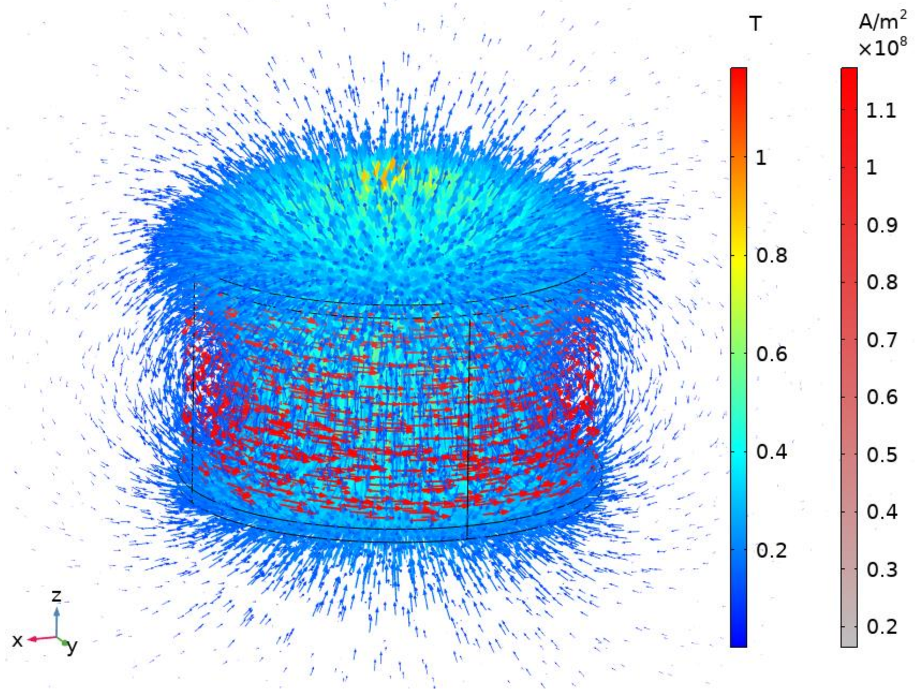
Von mises stress distribution



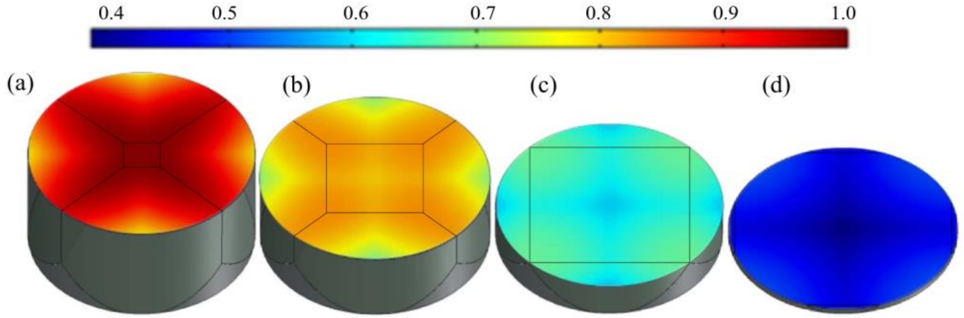
Summary

- A 2D numerical model is proposed as a first approach to study the impact of porosity in the magnetization of bulk HTS by PFM.

- Porosity shows an impact during PFM in:
  - Trapped field distribution
  - Local and abrupt temperature rise
  - High mechanical tensile stresses (possible fracture)



- Future work:
  - Studying the current paths around pores and related rise of temperature
  - 3D model (2D could overestimate the increase in temperature)
  - Investigation on mechanical and thermal stresses contributions



Yanxing Cheng *et al* 2021 *Supercond. Sci. Technol*. **34** 125017

Thank you for your attention!

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