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

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\def\BibTeX{{\rm B\kern-.05em{\sc i\kern-.025em b}\kern-.08em
T\kern-.1667em\lower.7ex\hbox{E}\kern-.125emX}}\begin{document}

\title{Impact of porosity on trapped magnetic field and mechanical stresses in HTS bulks during PFM\\
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\maketitle

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\begin{abstract}
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During pulsed-field magnetization (PFM) processes, high-temperature superconducting (HTS) bulks are subjected to significant mechanical deformations due to rapid changes in magnetic flux (Lorentz force) and temperature (thermal stress), potentially leading to fracture. Furthermore, fabrication-induced defects, such as

cracks, pores, and grain boundaries, can strongly impact the HTS performance, often resulting in non-uniform trapped magnetic fields and promoting mechanical failure. The present study assesses the impact of porosity on the trapped magnetic field, temperature, and mechanical stresses through a 2D multiphysics PFM numerical model using COMSOL Multiphysics. The results show that the porosity highly influences both local stresses and the temperature rise by affecting the distribution of induced currents, which leads to an non-uniform trapped magnetic field.\\ %These results offer valuable insights into poor trapped field distributions of HTS magnets caused by porosity underscore practical and modeling considerations for their magnetization and modeling and highlight key fabrication factors warranting further investigation.
\end{abstract}

\begin{IEEEkeywords}
Electromagnetic analysis, HTS Bulks, porosity, pulsed-field magnetization, coupled thermoelectromagnetic and mechanical analysis.
\end{IEEEkeywords}

%%%
\section{Introduction}
HTS bulks can be used in high-field applications as trapped-field magnets. However, the homogeneity and magnitude of the trapped magnetic field highly depend on the material's fabrication ultimately affecting its quality~\cite{Namburi_2021}. Despite advances in manufacturing processes that enhance flux pinning capabilities and homogeneity, such as the top-seeded melt growth (TSMG) and infiltration growth (TSIG), defects like pores and cracks persist. These defects can impact the thermal, and mechanical properties of the bulk and the magnitude of the trapped field~\cite{CambridgePorosity}.

The mechanical stresses induced during magnetization, notably in pulsed-field magnetization (PFM), originate from the combination of the Lorentz forces and the thermal induced stresses. They can cause fractures within the brittle ceramic materials. Even though there is substantial modeling and research on mechanical failure~\cite{YANG20171,trillaud}, there is a lack of focus on the impact of the pores on the mechanical behavior of the bulk, its temperature rise, and the value and uniformity of its trapped field during PFM. Hence, the present study proposes to fill the gaps by including the presence of pores in a multiphysics model implementing electromagnetic physics via the **H**-formulation coupled to mechanical and thermal physics.

%%%
\section{Modeling framework}
In the proposed 2D plane model shown in Fig.~\ref{figPores}, the HTS bulk domain Ω_{sc} is considered as an infinitely long cylinder encapsulated by an air domain Ω_a. The Ω_{sc} domain includes the presence of pores Ω_p in the shape of small ellipsoids. The external pulsed-field $B_a(t)$, given in~\eqref{eq:magnetic_pulse} is applied along the axial direction of the infinite cylinder at the air boundary Γ_a.
\begin{equation}
B_a(t) = B_m \frac{t}{\tau} \exp\left(1 - \frac{t}{\tau}\right)
\label{eq:magnetic_pulse}
\end{equation}
where \(B_m\) is the peak magnetic flux density and \(\tau\) is the duration required to reach the peak of the pulse.

\begin{figure}[t]
\centerline{\includegraphics[width=0.3\textwidth]{pores.png}}
\vspace{-1em}
\caption{Schematic drawing of the different domains and their boundaries: HTS bulk Ω_{sc}, air Ω_a and pores Ω_p (blue ellipsoidal inclusions). Note that the pores are scaled and appear larger than they are actually in the numerical model.}
\label{figPores}
\end{figure}

%%%%%%%%%%%*%

\subsection{**H**-formulation}
The electromagnetic behavior is modeled by solving for the magnetic field **H** according to:
\begin{equation}
\mu_0 \frac{\partial \mathbf{H}}{\partial t} + \nabla \times \left(\rho \nabla \times \mathbf{H}\right) = 0
\label{eq:maxwell}
\end{equation}
where \(\mu_0\) is the permeability of the vacuum and \(\rho\) the electrical resistivity of the media. The latter is constant equal to \(\rho_{a}\) for both Ω_a and Ω_p, and it follows the power law model for the superconducting domain Ω_{sc}.

%%%%%%%%%%%*%

\subsection{Heat Equation}

To evaluate the temperature changes in the superconductor \(\Omega_{sc}\) caused by the Joule effect \(Q = E \cdot J\), the following equation is solved,
\begin{equation}
\gamma_m c_p \frac{\partial T}{\partial t} - \nabla \cdot \left(\kappa \nabla T\right) = Q.
\label{eq:heat_equation}
\end{equation}
Here, \(\gamma_m\) is the mass density, \(c_p\) is the specific heat capacity at constant pressure, and \(\kappa\) is the thermal conductivity of the bulk.
%%%%%%%%%%%%*%

\subsection{Mechanical Behavior}
Temperature gradients and Lorentz forces ($\mathbf{F}_L = \mathbf{J} \times \mathbf{B}$) emerge during magnetization inducing strain and stresses in the bulk of the superconductor. The resulting displacement field **u** can be solved within the theory of linear elasticity according to,
\begin{equation}
\nabla \cdot \sigma + \mathbf{F}_L = \gamma_m \frac{\partial^2 \mathbf{u}}{\partial t^2}.
\label{eq:mechanical_behavior}
\end{equation}
In this equation, \(\sigma\) symbolizes the 2D stress tensor related to the total strain (mechanical and thermal) via the Hook's law. The thermal induced strain is given by $\alpha \Delta T$, with α the thermal expansion coefficient.

%%

\section{Results and conclusion}
In the present case, the dependence of the critical current density on local magnetic field and temperature $J_c(\mathbf{B}, T)$ is considered. The HTS bulk has a diameter of 29~mm, with 50 ellipsoidal pores dispersed randomly within its structure. In 2D, these pores constitute approximately 1\% of the bulk's surface area, which is less than the fractions commonly observed in real HTS bulks. The diameters of each pore range randomly between 125-250~μm with a proper mesh size. The diameter distribution is consistent with that of actual pores. The peak of the applied field is 4~T, with a time constant τ of 13~ms and parameters corresponding to an operating temperature of 65~K~\cite{TSIG}.

Fig.~\ref{figBDis} shows the magnetic flux density distribution at τ and $10000 \times \tau$ to include the thermal recovery ending the magnetization process. The observed phenomenon of uneven and accelerated penetration of the magnetic field at time τ in the porous case can be explained by the redirection and concentration of current density lines around each pore. This results in a localized increase in both losses and temperature, with a maximum rise of $\Delta T = 25$~K in a few milliseconds. Consequently, in addition to the particular current paths, the presence of pores produces significant magneto-thermal instabilities, which further accentuate the formation of a non-uniform distribution of the trapped magnetic field.

\begin{figure}[t]
\centerline{\includegraphics[width=0.46\textwidth]{BDistv4.png}}
\vspace{-1em}
\caption{Magnetic flux density distributions in the bulk at the peak external magnetic field and at the end of the PFM reaching steady state for the ideal (non-porous) case (a)-(b) and the porous case (c)-(d), respectively.}
\label{figBDis}
\end{figure}

\begin{figure}[t]
\centerline{\includegraphics[width=0.45\textwidth]{Untitled.png}}
\vspace{-1em}
\caption{Maximum hoop and radial stress in the superconductor over time for the ideal and porous case. The porosity leads to a higher tensile stress compared to the ideal case. }
\label{figStress}
\end{figure}

Fig.~\ref{figStress} shows the maximum hoop and radial stresses over time for the porous and ideal (non-porous) simulations. One can see that, for the porous case, the maximum tensile stresses are significantly greater than the ideal case and occur abruptly during the PFM. For higher applied fields and greater number of pores as well as their distribution, stresses could reach the critical tensile stress of the HTS, which is about $\sigma_c \approx 50$~MPa.

In the final version of the paper, we will examine the coupled electromagnetic and thermo-mechanical behavior of the superconductor for different porous scenarios, focusing on the possible reduction of the trapped field and stresses that may break the HTS. Several case studies will be used to better understand the underlying mechanism and predict the situations that can lead to the propagation of cracks.

% \section*{References}
\bibliographystyle{unsrt}

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\bibliography{bib}
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Topic

Coupled and uncoupled multiphysics problems

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