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Annuli of coated conductors with a ferromagnetic substrate: magnetic shielding properties at 77 K and at room temperature

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Abstract—This work deals with the properties of low frequency magnetic shields made of annuli of second generation coated conductor tapes with Ni 5%W alloy ferromagnetic substrate. A stack of tape annuli cut from a 46 mm wide coated conductor acts as an efficient magnetic shield when an axial magnetic field is applied at the liquid nitrogen temperature (77 K). The presence of the ferromagnetic substrate is found to have two important consequences. First, the stack of annuli is able to shield transverse inductions in spite of its layered structure. Second, unlike shields made of bulk superconductors, some shielding effectiveness is demonstrated above the critical temperature of the superconductor. In order to understand the contribution of the ferromagnetic substrate to the shielding process, the field-dependence of its magnetic permeability is determined experimentally from hysteresis loop measurements on the same substrate. A finite-element homogenized model with an h - ϕ formulation reproduces the shielding factor of the stack at room temperature, both under axial and transverse applied fields. In addition, a comparison is performed with the room-temperature shielding factor estimated from analytical formulas used for ferromagnetic shields.

Keywords—Magnetic shielding, coated conductor with ferromagnetic substrate, 3D numerical modelling, ferromagnetic shielding

I. INTRODUCTION

Due to both their large critical current density J_c and thick walls, bulk superconducting cylinders can be used as passive magnetic shields operating at magnetic flux densities well above the saturation of conventional ferromagnets (e.g. for mu-metal $\mu_0 M_{\text{sat}} \sim 0.7$ T) [1,2]. In a superconductor, passive magnetic shielding occurs through persistent current loops that generate a magnetic field opposing the applied magnetic field. The magnetic shielding efficiency can be further improved by combining ferromagnetic and superconducting materials [3]. Recently, our group showed experimentally [4] that a stack of coated conductor annuli can also act as a very efficient magnetic shield. Another recent study [5] reported the 2D axisymmetric modelling of the magnetic shielding behaviour of stacked coated conductors with a non-magnetic substrate; the results demonstrate the significant potential of

such stacks for shielding magnetic fields applied along the axis of the stack.

In the present work, we focus on the shielding properties of a short stack of coated conductor annuli with a Ni5%W ferromagnetic substrate. We explore the magnetic shielding properties when the field is applied in either axial or transverse (i.e. parallel to the tapes planes) directions. Interestingly, the presence of the ferromagnetic substrate allows a conventional shielding mechanism to occur even above the critical temperature T_c of the superconductor. As a consequence, the properties of such a stack also need to be examined at room temperature.

The geometry of the stack of annuli investigated is shown in Fig. 1. In order to model correctly the contribution of the ferromagnetic substrate, low frequency hysteretic loops are first measured experimentally on the same annuli. The first magnetization curve as well as the field dependence of the magnetic permeability at both 77 K and 293 K are shown in Fig. 2. The magnetic shielding efficiency of the stack is then investigated under a uniform magnetic field applied either parallel or perpendicular to its axis. The results are expressed in terms of the shielding factor (SF), i.e. the ratio between the applied field B_{app} and the field inside the shield B_{in} ($SF = B_{\text{app}} / B_{\text{in}}$).

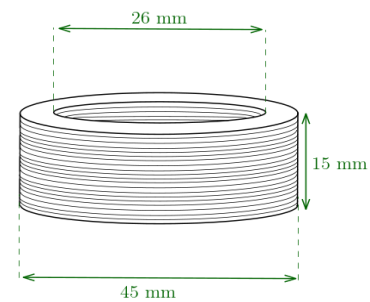


Fig. 1 – Schematic representation of the magnetic shield consisting of tape annuli.

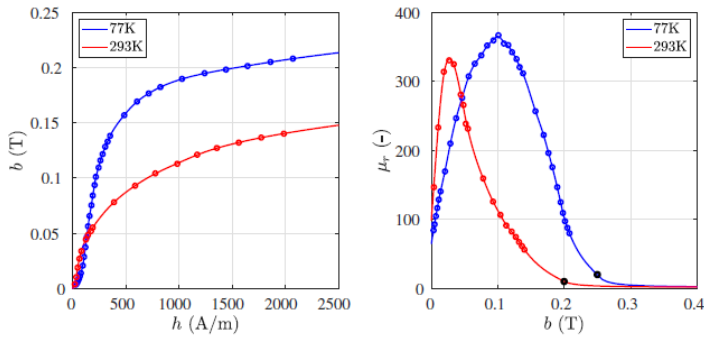


Fig. 2 - Experimental results of the first magnetization curve (left) and the magnetic permeability (right) of the stacked tapes.

Experimental and simulation results are compared with a finite element model solved using the life-HTS toolkit [6]. The 3D numerical results reported here are obtained for an homogenized model with a h - ϕ formulation. The details of the model and the impact of the homogenization procedure on the results are reported in a joint communication by J. Dular [7].

II. RESULTS

Fig. 3 shows the field dependence of the shielding factor of the stack at room temperature. The ferromagnetic substrate allows for a moderate $SF < 2$ under an axial field, almost field independent. In transverse fields, the shielding factor can reach $SF > 8$. The ferromagnetic substrate contributes mainly to shield the magnetic field component which is parallel to the tapes (transverse configuration). In the full communication, we will show that the SF values at low fields are in very good quantitative agreement with the estimations from analytical formulas [8] applicable to a purely ferromagnetic shield, provided a homogenized magnetic permeability is considered. The comparison with 3D numerical modelling results shows an excellent agreement with the experiments. The results give evidence that the knowledge of the magnetic properties of the ferromagnetic substrate (Fig. 2) are important to predict the magnetic shielding properties of the stack. In order to assess the contribution of the superconducting layers on the shielding efficiency, the properties of the stack were measured at 77 K under an axial applied field. Fig. 4 shows the shielding factor in this configuration. The superconducting layers are mainly efficient under an axial field due to the layered structure.

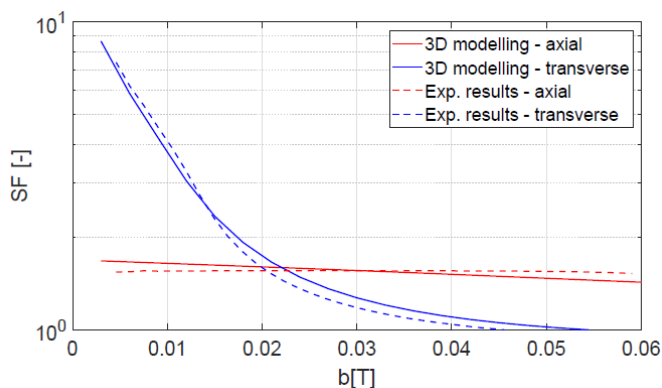


Fig. 3 - Comparison between experimental results and 3D simulation under both axial and transverse applied fields at room temperature.

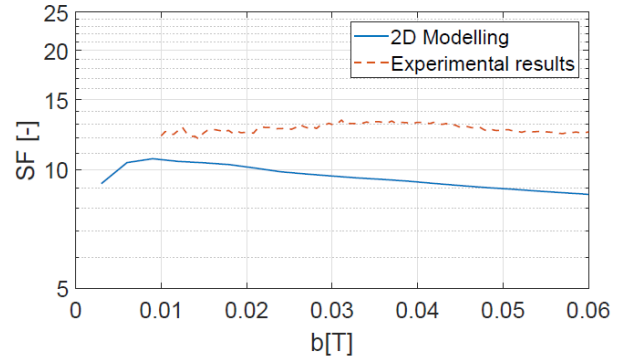


Fig. 4 - Comparison between experimental results and 2D axisymmetric simulation under an axial applied field at 77 K.

Experimental results can be compared to a 2D axisymmetric numerical model, obtained in a reasonable CPU time. In the field range considered here (0 – 60 mT), the shielding factor in the axial configuration remains almost constant $SF \sim 12$, in good agreement with modelling assuming a constant critical current density J_c .

In summary, we examined the magnetic shielding properties of a stack of tapes combining superconducting and ferromagnetic layers. The superconducting layers mostly contribute to the shielding of the axial component of the applied magnetic field whereas the ferromagnetic substrates shield mainly the transverse component. Independent measurements of the magnetic permeability vs. field of the same ferromagnetic substrate are incorporated in the numerical modelling, leading to a very good prediction of the field-dependence of the shielding factor SF of the stack at room temperature. At 77 K, the contribution of the superconductor leads to a substantial increase of the SF in the axial configuration.

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