Numerical modelling of a compact trapped field magnet using an HTSc tape as energizing coil during PFM

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***Abstract*— A compact, trapped field (TF) magnet unit is designed, being energized by pulsed currents in a high-*Tc* superconducting (HTSc) tape wrapped around the YBCO bulk, which is armoured by a stainless-steel ring to reduce cracking effects. The energizing of the unit is due to pulsed currents flowing in the HTSc tape coil, which is cooled together with the bulk to the operating temperature. For the electromagnetic calculation, a new coupling between the A-H and T formulations is used and detailed. The optimum configuration, i.e., maximum trapped field, optimal diameter and height of the (RE)BCO bulk, number of HTSc tape windings, etc., is deduced by numerical simulations using COMSOL multiphysics. Such compact TF magnet may be used in a variety of applications, which will be outlined here as well.**

Keywords—Trapped field magnet, pulsed magnetization, modelling, coupled T-A-H formulations

I. Introduction

In this contribution, we present a design of a compact trapped field (TF) magnet unit. The unit consists of a (RE)BCO bulk (diameter *d*, height *h*), enclosed in a stainless-steel ring (thickness s_0) to minimize cracking effects of the bulk sample like in several other TF-systems already designed in the literature [1]–[5]. A short coil is wound around the bulk sample with *n* layers, which is energized by pulsed currents, and will be cooled together with the bulk sample to the operating temperature. Such a compact TF unit, which we may call PTF magnet hereafter, may be valuable for a variety of applications. The original idea of such a system was described by Koblischka et al. for application in a trapped field – flux pinning docking interface (TF-FPDI) for satellites in space [6]. However, there are many more applications like within robot arms or crane systems to contactlessly attach and release metallic/magnetic parts or also for medical drug-delivery applications [7], [8]. All these applications have in common that the unit will be cooled by cryo-cooling systems to a temperature of 77 K, or lower in case of a space use, in order to be cost-effective and easy to handle. Furthermore, for use in satellites, the unit weight is a crucial point, and for the targeted medical applications, a hand-held system is desirable. In this point of view, it is essential to optimize all system parameters *d*, *h*, *n*, s_0 and the parameters of the required energizing unit and the cryo-cooler to obtain a maximum TF value with minimum material cost, dimensions and weight.

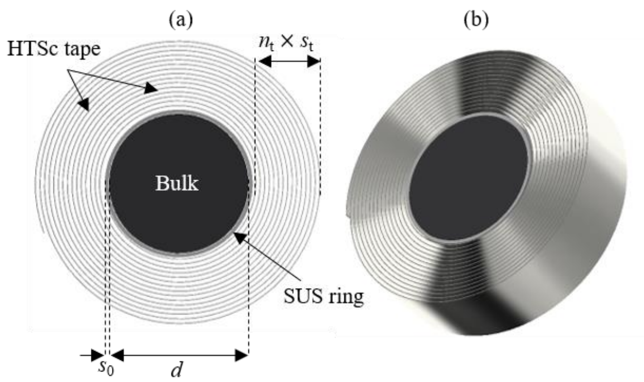

Fig. 1. Illustration of the compact PTF unit, consisting of a (RE)BCO bulk and several layers n_t of superconducting tape wound around it. s_t is the thickness of the superconducting tape.

II. Description and main parameters of the system

As shown in Fig. 1, the diameter of the bulk cannot be too small as the max. TF field depends crucially on this size, and also the bending radius of the tape is not allowed to be too small. Thus, it is clear that a lower limit for *d* exists. On the other hand, an upper limit is given by the magnetic field produced by the HTSc coil which must be reasonably high to allow for proper field trapping. As $d + s_0$ corresponds to the inner diameter of the HTSc coil, the upper limit (= max. TF) is a function of $(d + s_0)$. The stainless-steel ring is required for avoiding cracking of the bulk during energizing, so we must select a proper s_0 and pulse strength and duration for our compact PTF unit. An additional constraint are the required insulation and impregnation layers, shielding the flowing currents as well as protecting the superconducting elements. We make use here of the recent developments of Refs. [9]–[11].

III. Coupled 2D numerical modelling

In this section, we present the axisymmetric model of the complete system implemented on COMSOL Multiphysics. In order to reduce the computation time of the simulation, the solution of the electromagnetic equations is based on the coupling of three formulations, i.e., **T**, **A** and **H**, which is for the first time observed here to the best of the authors' knowledge. As shown in Fig. 2, the three formulations have been implemented in the different domains as follows:

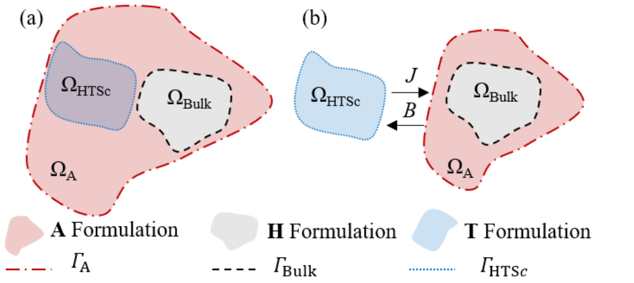

Fig. 2. (a) Representation of the different fields of study: **H** is calculated only in the bulk (gray), **T** is calculated only in the superconducting domain (blue), while **A** is calculated in air (light red). (b) Coupling between **T** and **A-H** formulations in the simulation. **J** and **B** are the two coupling variables.

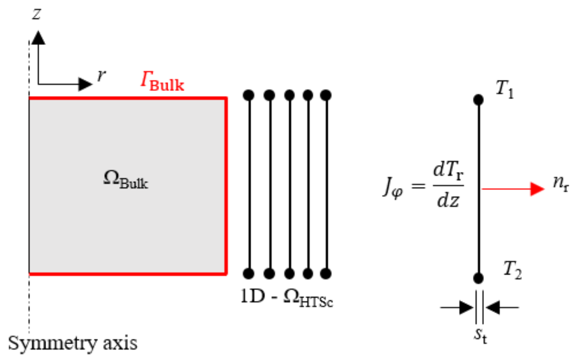

Fig. 3. The thickness of the HTSc tape is reduced to a surface current density (1D element). The current is imposed by boundary conditions at the T_1 and T_2 edges of the tape. Γ_{Bulk} is the boundary between the two regions (Bulk and Air).

- The **A** formulation is solved in air (Ω_A), and the magnetic flux density **B** is obtained by $\mathbf{B} = \nabla \times \mathbf{A}$.
- The **H** formulation is solved in the YBCO bulk (Ω_{Bulk}), and the current density **J** is obtained by the relation $\mathbf{J} = \nabla \times \mathbf{H}$.
- The **T** formulation is solved in the HTSc coil (Ω_{HTSc}), where the determination of the current density **J** is obtained by $\mathbf{J} = \nabla \times \mathbf{T}$.

As shown in Fig. 3, the HTSc tape is described as a surface current density with $I = (T_1 - T_2) / \delta$, where δ is the thickness of the superconducting layer and T_1 and T_2 are the current vector potentials at the tape edges.

The equation to be solved in the different domains are:

$$\nabla \times (\mu_0{}^{-1} \nabla \times \mathbf{A}) = 0 \qquad \Omega_A \qquad (1)$$

$$\mu_0 d_t \mathbf{H} + \nabla \times (\rho_{Bulk} \nabla \times \mathbf{H}) = 0 \qquad \Omega_{Bulk} \qquad (2)$$

$$\mu_0 d_t \mathbf{H} + \nabla \times (\rho_{HTSc} \nabla \times \mathbf{T}) = 0 \qquad \Omega_{HTSc} \qquad (3)$$

with μ_0 the permeability of the air and ρ the resistivity of the considered material. For superconducting materials, the power law $E(J) = E_c(J/J_c)^n$ has been considered. The critical electric field E_c is equal to 1 µV/cm with $n = 25$ and 8 for Ω_{Coil} and Ω_{Bulk} respectively. The critical current density of the bulk depends on the local magnetic field at the operating temperature of the bulk while the critical current of the HTSc tape is equal to 725.6 A/cm with a tape width of 12 mm, which corresponds to SuperOx tape data at 77 K.

The coupling between the **T** and **A** formulation is achieved through the exchange of the current density **J** and the magnetic flux density **B** in the HTSc tape [12]. On the other hand, the coupling between the **A** and **H** formulations is achieved by a vector equality of the magnetic field at the boundary between the two domains Γ_{Bulk} [13].

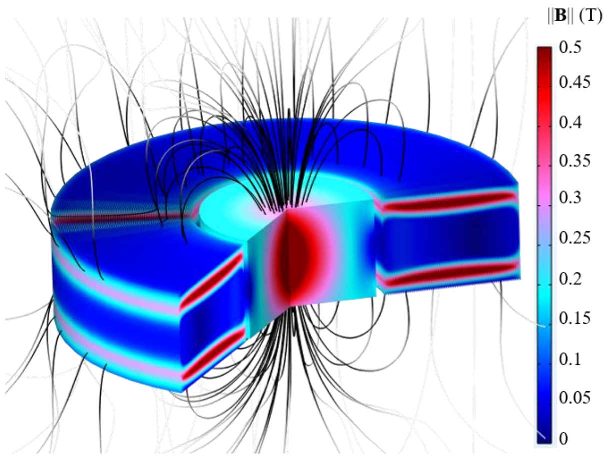

Fig. 4. 3D view of the PTF at the end of the energization process at 77 K, where the norm of the magnetic flux density is presented both in the (RE)BCO bulk and the HTSc tape for $I_{max}/I_c = 0.9$ and 80 turns.

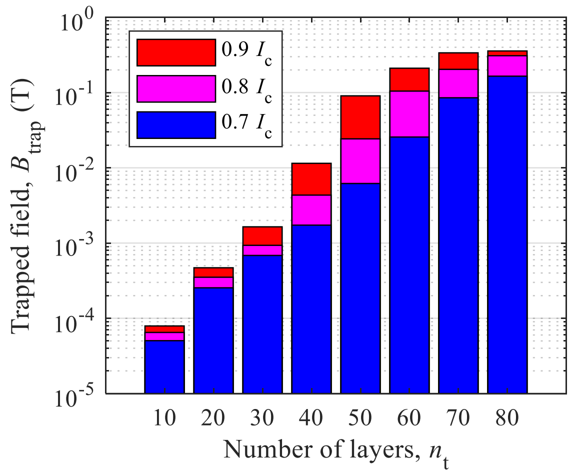

Fig. 5. Trapped field at the center of the top surface of the (RE)BCO bulk at 77 K as a function of the number of layers of the HTSc tape and for different values of I_{max}.

IV. Results and Discussion

Fig. 4 shows a 3D view of the magnetic field trapped in the (RE)BCO bulk and in the different layers of the HTSc tape. In this example, the HTSc coil contains 80 turns with a peak current value equal to 0.9 I_c, i.e., 783.65 A. In Fig. 5, the evolution of the trapped magnetic field at 77 K is plotted as a function of the number of layers of the superconducting tape for $I_{max}/I_c = 0.7$, 0.8 and 0.9. The increase in the number of turns has a significant impact on the value of the trapped field at the center of the top surface, and a compromise must be found between the size of the system and the desired performances.

In the final version of the paper, an optimization of the complete system will be performed. Indeed, the study will aim at maximizing the field trapped in the bulk while minimizing the losses of the magnetization system and its total weight. In our view, the coupling of the **T** and **A–H** formulations may have a strong potential in the electromagnetic simulation of electrical systems with the presence of HTSc bulk and coils such as motors. To that end, we plan to share this COMSOL model as soon as it is accepted on the HTS Modelling Workgroup website.

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REFERENCES

[1] T. Oka, “Processing and applications of bulk HTSC,” *Physica C: Superconductivity and its Applications*, vol. 463–465, pp. 7–13, Oct. 2007, doi: 10.1016/j.physc.2007.03.432.

[2] R. Weinstein, D. Parks, R.-P. Sawh, K. Carpenter, and K. Davey, “A significant advantage for trapped field magnet applications—A failure of the critical state model,” *Appl. Phys. Lett.*, vol. 107, no. 15, Art. no. 152601, Oct. 2015, doi: 10.1063/1.4933313.

[3] F. N. Werfel *et al.*, “Impact of Cryogenics and Superconducting Components for HTS Magnetic Levitation Devices,” *IEEE Trans. Appl. Supercond.*, vol. 27, no. 4, Art. no.3600905, Jun. 2017, doi: 10.1109/TASC.2017.2652332.

[4] J. H. Durrell *et al.*, “Bulk superconductors: a roadmap to applications,” *Supercond. Sci. Technol.*, vol. 31, no. 10, Art. no. 103501, Oct. 2018, doi: 10.1088/1361-6668/aad7ce.

[5] O. Vakaliuk, F. Werfel, J. Jaroszynski, and B. Halbedel, “Trapped field potential of commercial Y-Ba-Cu-O bulk superconductors designed for applications,” *Supercond. Sci. Technol.*, vol. 33, no. 9, Art. no. 095005, Sep. 2020, doi: 10.1088/1361-6668/ab9fc4.

[6] M. R. Koblischka *et al.*, “Flux Pinning Docking Interfaces in Satellites Using Superconducting Foams as Trapped Field Magnets,” *IEEE Trans. Appl. Supercond.y*, vol. 32, no. 4, Art. no.3147734;, Jun. 2022, doi: 10.1109/TASC.2022.3147734.

[7] P. M. Price, W. E. Mahmoud, A. A. Al-Ghamdi, and L. M. Bronstein, “Magnetic Drug Delivery: Where the Field Is Going,” *Frontiers in Chemistry*, vol. 6, Art. no. 619, 2018; doi: 10.3389/fchem.2018.00619.

[8] Y.-L. Liu, D. Chen, P. Shang, and D.-C. Yin, “A review of magnet systems for targeted drug delivery,” *Journal of Controlled Release*, vol. 302, pp. 90–104, May 2019, doi: 10.1016/j.jconrel.2019.03.031.

[9] K. Takahashi, H. Fujishiro, T. Naito, Y. Yanagi, Y. Itoh, and T. Nakamura, “Numerical Simulation of Electromagnetic and Thermal Stress in REBaCuO Superconducting Ring and Disk Bulks Reinforced by Stainless Steel Ring With Various Widths During Field-Cooled Magnetization,” *IEEE Trans. Appl. Supercond.*, vol. 28, no. 3, Art. no. 6800705, Apr. 2018, doi: 10.1109/TASC.2018.2799578.

[10] H. Fujishiro, T. Naito, and S. Awaji, “Proposal of an effective mechanical reinforcement structure for a REBaCuO disk bulk pair by full metal encapsulation to achieve a higher trapped field over 20 T,” *Supercond. Sci. Technol.*, vol. 32, no. 4, Art. no. 045005, Apr. 2019, doi: 10.1088/1361-6668/ab0017.

[11] M. D. Ainslie *et al.*, “Numerical modelling of mechanical stresses in bulk superconductor magnets with and without mechanical reinforcement,” *Supercond. Sci. Technol.*, vol. 32, no. 3, Art. no. 034002, Mar. 2019, doi: 10.1088/1361-6668/aaf851.

[12] H. Zhang, M. Zhang, and W. Yuan, “An efficient 3D finite element method model based on the *T*–*A* formulation for superconducting coated conductors,” *Supercond. Sci. Technol.*, vol. 30, no. 2, Art. no.024005, Feb. 2017, doi: 10.1088/1361-6668/30/2/024005.

[13] J. Dular, M. Harutyunyan, L. Bortot, S. Schöps, B. Vanderheyden, and C. Geuzaine, “On the Stability of Mixed Finite-Element Formulations for High-Temperature Superconductors,” *IEEE Trans. Appl. Supercond.*, vol. 31, no. 6, Art. no. 8200412, Sep. 2021, doi: 10.1109/TASC.2021.3098724.