# Design of a superconducting magnetic shield closed on both ends for a high-sensitivity particle detector


Kevin Hogan,
*Montefiore research unit*
*University of Liege*
Liège, Belgium
kevin.hogan.be@gmail.com

Philippe Vanderbemden
*Montefiore research unit*
*University of Liege*
Liège, Belgium
Philippe.Vanderbemden@uliege.be

Benoît Vanderheyden
*Montefiore research unit*
*University of Liege*
Liège, Belgium
B.Vanderheyden@uliege.be

Alexey Radovinsky
*Plasma Science and Fusion Center,*
*Massachusetts Institute of Technology,*
Cambridge, Massachusets, USA
radovinsky@psfc.mit.edu

Joseph V. Minervini
*Plasma Science and Fusion Center,*
*Massachusetts Institute of Technology,*
Cambridge, Massachusetts, USA
minervini@psfc.mit.edu



***Abstract*—This work deals with the numerical design of a high-efficiency superconducting magnetic shield required for a high-sensitivity particle detector. This research was carried out in the context of the 'ABRACADABRA' project aiming at detecting hypothetical elementary particles called axions. Axions are promising candidates to explain the particle nature of the dark matter. The detector relies on a SQUID for measuring the ultra-small oscillating magnetic field resulting from the interaction between the axions and a toroidal DC field. A magnetic shield is mandatory to reduce the ambient magnetic field noise. Given the operating temperature (~ 1.2 K), the shield is made of type-I superconductor. In this work we use numerical modelling to determine the best topology for the shield and its ability to screen both axial and transverse fields. Amongst the geometries investigated (tubes or 'swiss-rolls' closed on both ends) the best results are obtained with two semi-closed tubes inserted in one another. This geometry is close to the shield of the final prototype, made of two closed Cu tubes, spin-coated with Sn ($T_c$ = 3.72 K) and welded shut.**



***Keywords—Magnetic shielding, axion detector, 2D and 3D numerical modelling, type-I superconductors.***


## I. Introduction

The context of this work is the search for hypothetical elementary particles called axions [1] using an experiment called 'ABRACADABRA', acronym for 'A Broadband/Resonant Approach to Cosmic Axion Detection with an Amplifying B-field Ring Apparatus' [2]. The device is based on the principle that axions interact with static magnetic fields, here generated by a toroidal coil as illustrated in Fig. 1(a). This interaction can be treated as an effective oscillating current $\boldsymbol{J}_{\mathbf{eff}}$ flowing along the static magnetic flux density $\boldsymbol{B}_{\mathbf{0}}$. This current generates its own magnetic field $\boldsymbol{B}_{\mathbf{ind}}$ which can be measured experimentally through a pick-up coil connected to a SQUID. The ultra-low value of $\boldsymbol{B}_{\mathbf{ind}}$ (typically $< 10^{-20}$ T) requires the use of a very efficient magnetic shield to reduce the ambient magnetic field noise below the current shot noise of the SQUID (0.01 fT/sqrt(Hz) for $f > 50$ Hz). To reach such levels, the use of a superconducting shield is the only solution since their Johnson noise is much lower than that of metallic materials.

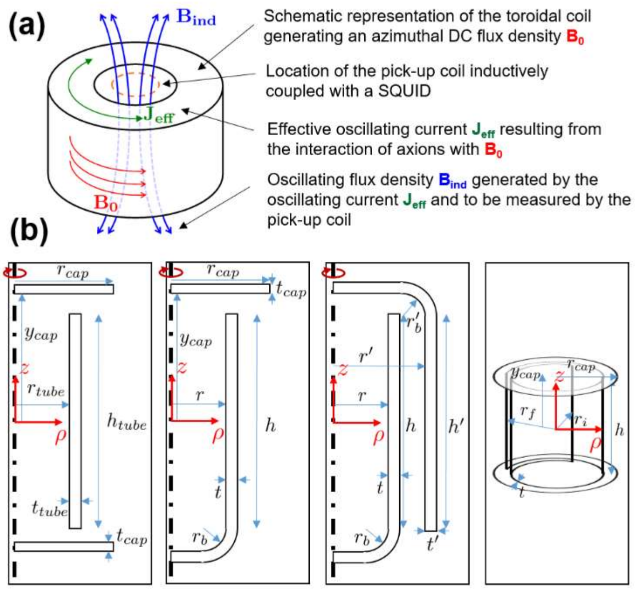


Fig. 1. (a) Schematic representation of the axion detector. (b) Four geometries of superconducting magnetic shields closed on both ends : open tube with two caps, semi-closed tube with one cap, two semi-closed tubes inserted in one another, swiss-roll with two caps.

The shield is made of type-I superconductor. Unlike ferromagnetic materials, however, the magnetic shielding efficiency of superconductors depends on the path of the shielding current loops, hence on the shape of the shield [3,4]. In this work we investigate numerically the best geometry of a shield dedicated to the axion detector. The geometries considered are shown in Fig. 1(b), all closed on both ends. The superconductor is modelled as a perfect conductor with high conductivity ($10^{30}$ S/m), using the OPERA software. The results for two geometries (an open or semi-open tube) are compared to those given by GetDP [5] implementing London equations with an axisymmetric $\mathbf{A}$ formulation, as detailed in [6]. The results are expressed in terms of the shielding factor (*SF*), i.e. the ratio between the applied field $B_{\text{app}}$ and the field inside the shield $B_{\text{in}}$ ($SF = B_{\text{app}} / B_{\text{in}}$).

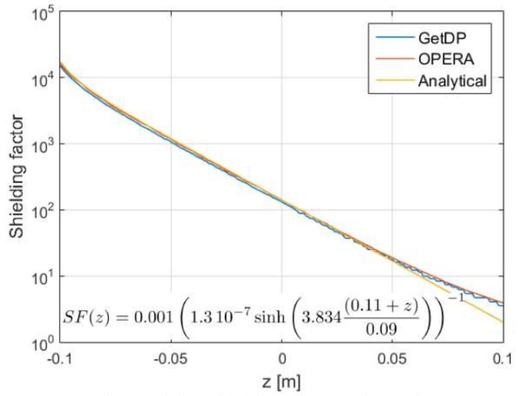


Fig. 2. Comparison of the shielding factor along the symmetry axis of a semi-closed superconducting tube subjected to an axial magnetic field using either GetDP, OPERA, and an analytical formula [7].

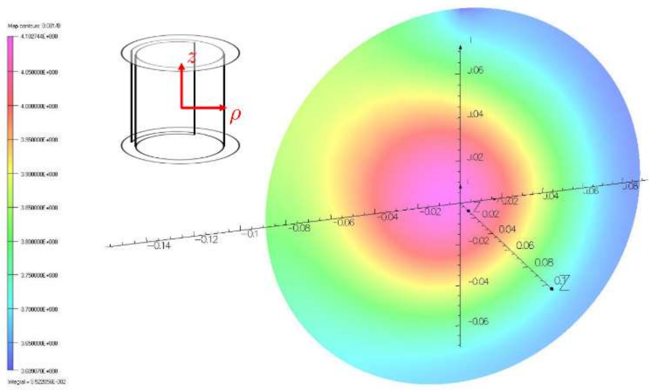


Fig. 4. Shielding factor in the median plane inside a swiss roll shaped superconductor with a cap on each end subjected to an axial field. Results obtained with OPERA.

## II. RESULTS

We first check the numerical results given by OPERA for simple geometries. Figure 2 compares the shielding factor along the axis of a superconducting tube closed on one end subjected to a uniform axial magnetic field, as obtained with OPERA, GetDP and the theoretical *SF* distribution for this geometry [7]. An excellent agreement is found. Similar results are obtained for a transverse field, giving full confidence in the consistency of the results.

Next we investigate the efficiency of the shield geometries shown in Fig. 1(b). The dimensions of the shield are chosen to respect the constraints of the application, i.e. incorporate the toroidal coil (Fig. 1(a)) while being placed in the available space of a dilution cooler (cylinder with a 240 mm diameter and 250 mm height). The thickness of superconductor is 0.5 mm in all cases. Figure 3 shows the results in axial field for an open tube with two caps, a semi-closed tube with one cap and two closed tubes (or cups) inserted in one another. This solution clearly offers the best shielding factor since the flux lines can only penetrate through the gaps between the two cups. As shown in Fig. 4, the swiss-roll configuration, corresponding to the simplest to manufacture from a superconducting film, displays only a weak shielding factor ($SF \sim 4$) in axial field. When the applied field is orthogonal to the axis of the shields, the shielding factors are globally much lower than in the axial configuration. Interestingly the highest shielding factor is still the highest for the two semi-closed concentric tubes, i.e. around $SF \sim 150$ at the center, against $SF < 20$ for the other geometries.

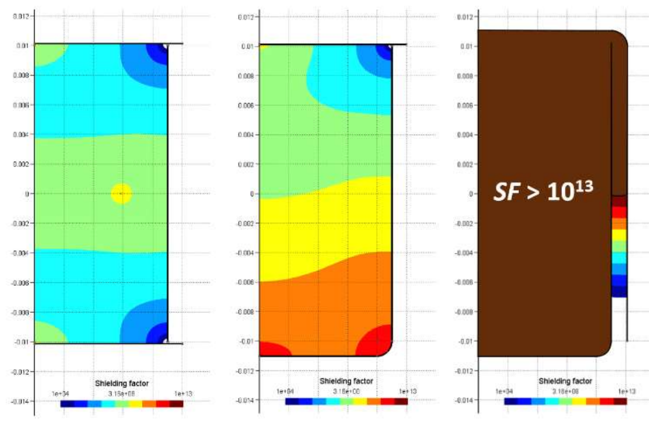


Fig. 3. Distribution of shielding factor (*SF*) in the ρ-z plane for an open tube with two caps, a semi-closed tube with one cap and two closed tubes inserted in one another. Results obtained with GetDP.

In summary, we showed that numerical modelling is well suited to predict the magnetic shielding ability of various shield geometries closed on both ends and with relatively short aspect ratio. The best shielding properties ($SF > 100$) are found with two semi-closed tubes inserted in one another. It has the further advantage to exhibit a gap that can be used as feedthrough for electrical connections. This geometry is close to that of the final prototype [2], made of two closed Cu tubes, spin-coated with Sn ($T_c = 3.72$ K) and welded shut. The results of the present study are relevant to the design magnetic shields of large size using film or bulk superconductors.

## ACKNOWLEDGMENT

K. H. thanks the ‘Fédération Wallonie-Bruxelles’ for a travel grant. K H. was holder of a research grant from the Fonds pour la Formation la Recherche dans l’Industrie et dans l’Agriculture (FRIA). Fruitful scientific discussions with Dr. Makoto Takayasu are also greatly acknowledged.

## REFERENCES

[1] Y. Kahn, B. R. Safdi, and J. Thaler, “Broadband and Resonant Approaches to Axion Dark Matter Detection”, *Phys. Rev. Lett*. vol. 117, Art. no. 141801, 2016

[2] J. L. Ouellet *et al*., “First Results from ABRACADABRA-10 cm: A Search for Sub-μeV Axion Dark Matter”, *Phys. Rev. Lett*. vol. 122, Art no. 121802, 2019.

[3] L. Gozzelino *et al*., “Passive magnetic shielding by machinable MgB2 bulks: measurements and numerical simulations”, *Supercond. Sci. Technol.* vol. 32, no. 3, Art. no. 034004, 2019.

[4] J. F. Fagnard, B. Vanderheyden, E. Pardo and P. Vanderbemden, “Magnetic shielding of various geometries of bulk semi-closed superconducting cylinders subjected to axial and transverse fields”, *Supercond. Sci. Technol.* vol. 32, Art. no. 074007, 2019.

[5] GetDP: A General Environment for the Treatment of Discrete Problems, [Online]. http://getdp.info/

[6] K. Hogan, J. F. Fagnard, L. Wéra, B. Vanderheyden and P. Vanderbemden, “Magnetic shielding of an inhomogenous magnetic field source by a bulk superconducting tube”, *Supercond. Sci. Technol.* vol. 28, Art. no. 035011, 2015.

[7] J. R. Claycomb and J. H. Miller Jr., “Superconducting magnetic shields for SQUID applications”, *Rev. Sci. Instrum*. vol. 70, pp. 4562-4598, 1999.