IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received 31 January 2023, accepted 9 February 2023, date of publication 22 February 2023, date of current version 9 March 2023.

Digital Object Identifier 10.1109/ACCESS.2023.3247749

RESEARCH ARTICLE

Shielding Characteristics of Solenoidal Superconducting Screens Made From HTS Tape, for SFCL Applications

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This work was supported in part by the Government of Extremadura, Spain, under Grant IB18076.

ABSTRACT In the design and prototyping of an Inductive-Resistive Superconductor Fault Current Limiter (IR-SFCL), previously presented by the authors, superconducting screens made from BSCO bulk have been used for shielding the inductive stage of the device. This kind of screens has several problems as rigidity, brittleness, commercial dependence on size and high cost. In order to avoid such issues, replacing the bulk-type superconducting screens by screens made from high temperature superconducting (HTS) tape is proposed. Tapes are more flexible and allow to easily make screens with several sizes and configurations, and better behavior against temperature changes and dynamic effects. To select a suitable configuration for this type of screen, a preliminary study of the shielding capacity of screens with different configurations, made from tape, is presented. This study, as well as literature, led us to select the solenoidal configuration as the most suitable for our application. In this work, we study solenoidal screens built with independent concentric layers, each one made from non-insulated tape, and all in contact just by the Ag external cover of the tape. A test method has been developed, and screens with 1 to 10 solenoid layers have been tested to find out their shielding factor. The shielding mechanism (diamagnetism vs. induced currents) has been studied by measuring of the transport current generated in between the non-insulated solenoids. The low incidence of these currents in the magnetic shielding process of the superconducting tape screens is reported.

INDEX TERMS HTS tape, magnetic shielding, SFCL.

I. INTRODUCTION

The Superconducting Fault Current Limiter (SFCL) is one of the most attractive uses for superconductors in Electrical Engineering. The industrial application of SFCL is as a protection element in power lines, replacing mechanical switches or circuit breakers. This is possible due to the ability to suddenly change the impedance when conditions change.

The SFCL is connected in series with the power line and its impedance is almost zero when the line is working under normal conditions, i.e., delivering power with a current lower than or equal to the rated line current. But the impedance of the SFCL is designed to rise sharply when the current exceeds this value or similar one (the limit current of the line), with the aim of reducing the abnormal current and protecting the line. Now, in this introduction, we present these materials and next we will present the configuration of the limiter where we need to use it.

A. SUPERCONDUCTIVITY AND SUPERCONDUCTORS

Superconductivity [1] is a state of some materials, which appears when their temperature drops below a certain characteristic value called “critical temperature” T_c.

Superconducting state is characterized by two physical properties:

- Null electrical resistivity (ideal conductor)
- Infinite magnetic permeability (ideal diamagnetic)

Materials that can exhibit this behaviour are called *superconductors*.

The associate editor coordinating the review of this manuscript and approving it for publication was Lei Chen.

In addition to temperature, superconductivity disappears when the electrical current density carried by the material exceeds a certain critical value, j_c, or when the magnetic field in the environment of the material exceeds a certain critical value, B_c (or H_c).

Superconductivity was discovered in 1911 by Kamerlingh Onnes (Nobel Prize in 1913) when studying the electrical properties of mercury at 4.2 K.

In the 1970s and 1980s, some special applications, such as magnetic resonance imaging (MRI) or particle accelerators, were developed using mainly Nb-based superconducting alloys (Nb-Ti, Nb_3-Ge or Nb_3-Sn) at 4.2 K, cooled with liquid helium (L-He), but this temperature is not acceptable for practical electrical applications.

In 1986, a new type of superconductor cuprates (copper oxides) was discovered by George Bednorz and Alexander Müler (Nobel Prize in 1987). This advance led to the development of so-called *high critical temperature superconductors* (HTS), which have critical temperatures higher than 77 K and so, can be cooled with liquid nitrogen (L-N_2). This is interesting for electrical applications because L-N_2 is cheap, and the cooling system is simple.

The HTS more used in applications (and used in this work) are:

- $Bi_2Sr_2Ca_2Cu_3O_{10}$ (known in literature as BSCCO)
- $YBa_2Cu_3O_7$ (known in literature as YBCO)

Nevertheless, these HTS are brittle ceramic materials, which initially appear as mass bodies (bulks). In this form, it is not feasible to make wires, or coils for electrical devices. However, nowadays, several companies have developed techniques to manufacture HTS tapes consisting in a substrate, some buffers layers, a superconducting layer and a silver layer to facilitate the electrical contact. Fig. 1 shows this configuration [2].

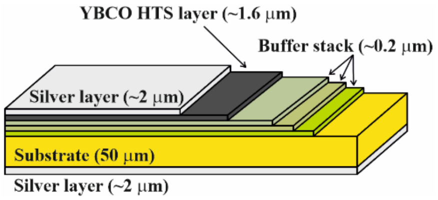

FIGURE 1. **Configuration of the HTS tape used in this study.**

Obviously, in superconducting state, the resistance of the tape is zero (the layers are connected in parallel) and the permeability is infinite in the superconducting layer so, at the scale of the tape, this is a perfect diamagnetic.

B. SFCL UNDER STUDY

There are several SFCL types described in the literature [3], [4], [5] that can be grouped in two categories: resistive (R-SFCL) and inductive (I-SFCL).

The SFCL which use the resistance of a superconductor material as variable impedance are included in the first category. The mechanism is simple: the superconductor, in series with the line, is calculated with a critical current, I_c, equal to the limit current, I_{lim}, and, so, when the current exceeds this value, the element transits from the superconducting state (with virtually null resistance) to the normal state with a high resistance. The main problem of the R-SFCL is that very often the superconductor is destroyed during a transition by current because this is not a homogeneous transition in the whole material and provokes dramatic hot spots in the points where the material first transits.

The second category includes those SFCLs that use, in one way or another, the magnetic properties of the superconductor (perfect diamagnetism) to change the magnetic field in some inductive part of the device in series with the line, thereby increasing the inductance of the element and reducing the current.

The inductive-resistive SFCL (IR-SFCL) proposed by the authors [6] consists of an in-series two-stage limiter in which the resistive stage is located in the magnetic circuit of the inductive stage as it is sketched in Fig. 2.

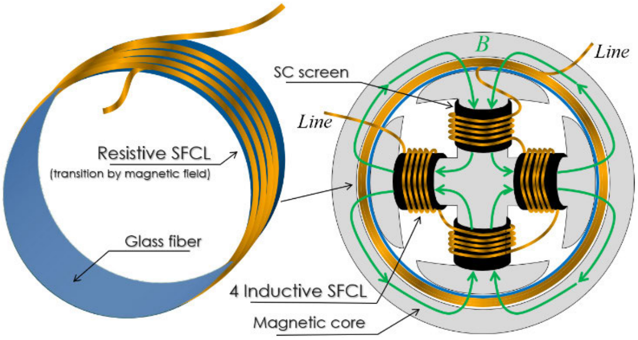

FIGURE 2. **Configuration of the I-R SFCL under study. The transition first occurs in the cylindrical screen (inductive stage) and then in the resistive stage due to the magnetic field in the poles and air-gap.**

The inductive stage is typically a *magnetic-shielded iron-core-type SFCL* [4], [5], where the magnetic field, created by an excitation coil around the ferromagnetic core, is controlled by a superconducting cylindrical screen (initially as the cylindrical bulk in Fig. 4, below): when the screen is in superconducting state (diamagnetic), the magnetic field in the core is almost zero, but when it transits to normal state, the excitation coil magnetizes the core. Note that the purpose of the superconducting screen in this application is quite different from that of the shielding element in electromagnetic compatibility (EMC) scenarios, where the frequency is thousands of times higher, the magnetic field is associated with an electric field (at 50 or 60 Hz the electric field is negligible) and the shielding must be permanent.

In our case [6], the excitation coils are calculated in such a way that the limit line current I_{lim} (which is the same in the excitation coils and the resistive stage, all connected in series) is the current which makes the screens transit. On the other hand, I_{lim} must be slightly lower than the self-field critical current of the tape; otherwise, the whole superconducting tape would transit by current before the screens did it.

The mechanism of transition in our proposal can be clarified by the diagram of Fig. 3, where the transition diagram of the tape (measured in our laboratory) is presented.

In normal operation, the line current I is lower than I_{lim}, (eg. the line rated current, I_{rated}, in Fig. 3). The magnetic field around the screen, B_{ext} is lower than its critical magnetic field B_c. The screen remains in the superconducting state (perfect diamagnetic) and shields the core from the magnetic field. In such a situation, the flux density in the gap, B_g, where the resistive stage is located, is almost zero: $B_g \approx 0$; the magnetic field created by the excitation coil is confined between the coil and the screen.

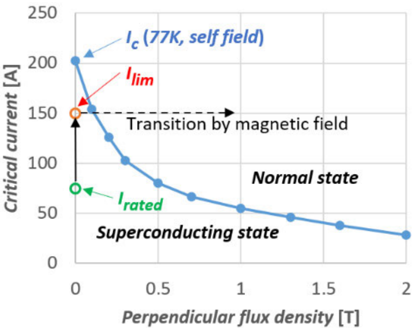

FIGURE 3. Transition diagram to illustrate the magnetic field transition being designed.

But when the line current I increases due to a fault, and reaches the value I_{lim}, then, around the screen, $B_{ext} = B_c$, and the superconducting screen ($\mu_r \rightarrow \infty$) transits to normal state ($\mu_r \approx 1$). At this moment, the magnetic field in the core and the air-gap (B_g) suddenly increases, provoking the transition of the resistive stage. The transition follows a path as the dash arrow in Fig. 3. The difference from other R-SFCLs is that the transition by magnetic field is simultaneous in the whole tape, without hot-spots.

Summarizing, the complete device must be calculated for a limit current I_{lim} verifying two conditions: a) it must be close to but lower than the self-field critical current, and b) it must make the cylindrical screens transit.

Mathematically:

$$I_{lim} \lesssim I_c \tag{1a}$$

$$I_{lim} N_{exc} = F_{c,screen} \tag{1b}$$

where N_{exc} the number of turns of the excitation coils and $F_{c,screen}$ the screen critical magnetomotive force (*mmf*) that produces $B_{\text{ext}} = B_c$, and therefore, the transition.

With these two conditions, the impedance of the I-R SFCL is as follows:

In normal operation, the current in the line, I, is lower than I_{lim}. The screens shield the magnetic field and so, $B_g = 0$. All the superconductor elements are in superconducting state and, therefore, the impedance of the limiter, Z_{SFCL} is virtually zero (2a). But if the line current, I, reaches the limit I_{lim}, the screens transit to normal state and a high magnetic field B_g appears in the gap, making the resistive stage transit. In this case, the limiter exhibits an impedance Z_{SFCL} which is the sum of two components (2b): the resistive impedance of the resistive stage in the gap, Z_R, and the inductive impedance of the coils around the magnetized poles, Z_L:

$$Z_{SFCL} = 0 \quad (I < I_{lim}) \tag{2a}$$

$$Z_{SFCL} = Z_R + Z_L \quad (I \geq I_{lim}) \tag{2b}$$

Both in this I-R SFCL and in a previous single-pole prototype previously studied by the authors (patent at [7]), a hollow cylinder-shaped superconducting bulk, surrounding the central limb of the poles was used as screen. The properties of these screens are excellent [8], [9], but they are brittle, and the electrodynamic stress and the thermal cycles very often degrade their properties [10]. For this reason, we proposed to replace the hollow cylindrical bulk with hollow cylinders made from superconducting tape, having the same dimensions. Other studies have been reported about the protection ability of tapes for various purposes, e.g., the geometrical effects on the shielding quality [11], [12], [13], [14]. the application of a planar magnetic shield [15], or the behavior of multilayer magnetic shields made of HTS tapes [16], [17].

The study that we present, looks for an adequate practical solution in our particular application. First of all, we compare different screens configurations and decide which one is the most suitable for SFCL. This turns out to be the solenoidal configuration. Then, we analyze this configuration studying the influence of the number of layers and the induced transport currents, as well as the ease of construction and adaptation to the prototype. Finally, some conclusions are provided.

II. PRELIMINARY STUDY OF SCREEN CONFIGURATIONS

A. CONFIGURATIONS UNDER STUDY

In order to identify the best solution for SFCL applications, different screens made from YBCO tape have been built and studied, and their properties compared with those of the hollow cylindrical bulk with the same dimensions. Fig. 4 shows all these screens. The first one is the original screen, and its characteristics are summarized in Table 1.

The other 5 screens (screens under study) are made from tape with different structure. All of them are building over a cylindrical support made from polylactide (PLA), by 3D impression, which is later removed (PLA is a common biodegradable thermoplastic, used in 3D printers). The outer radius of the supports is the inner radius of the cylindrical bulk, so that all the screens have the same inner diameter, compatible with the ferromagnetic limb where they are located (see Fig. 2).

To make it easier to understand, the tapes in Fig. 4 have been outlined (continuous line if it is visible and dotted line if hidden).

The structures are:

- Solenoidal structure. Each layer is a continuous solenoidal coil with turns overlapped in a 30%.

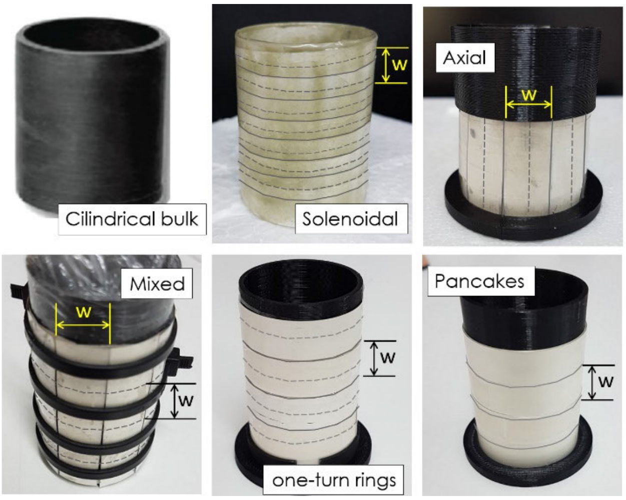

FIGURE 4. Structures studied for this work. The cylindrical bulk is made from BSCCO. The rest are made with YBCO tape. The black supports in the tape screens are made by 3D impression with polylactide (a biodegradable thermoplastic filament commonly known as PLA).

For a multilayer screen, one solenoid is wound over the previous, inside out.

- Axial structure. Each layer is made by strips of tape very close together, not overlapped, along the cylinder generatrix. To reduce the flux penetration between tapes, each layer overlaps the previous one.
- Mixed structure. One axial layer is wound over the previous solenoidal layer, and so on.
- One-turn individual ring structure. Each layer is built with one tape ring over the previous one, very close together, not overlapped, from bottom to top. To reduce the flux penetration between tapes, each layer overlaps the previous one.
- Pancake structure. It is built with pancake coils, one over the previous one, very close together, from bottom to top. In this case, the number of layers is the number of turns in the pancakes.

The characteristics of the tape used in this study are in Table 2.

B. MEASURING EQUIPMENT SETUP

The equipment used to measure the shielding capacity of the screens is sketched in Fig. 5. An AC source feeds the excitation coil, responsible for creating the magnetic field we want to study. The frequency in all measurements is 50 Hz as in the real SFCL. The screens, and so the coil, must work in a liquid nitrogen (l-N2) bath, at 77K, because in all the screens, the material, bulk or tape, is a high temperature superconductor (HTS) which transits to normal state at about 90K.

The coil used in the preliminary study is a 66 turns copper solenoid, 45 mm in diameter and 45 mm high (in subsequent studies this coil was replaced by a superconducting coil). The magnetic flux density, B_Z, is read by a pickup coil and sent to a DAQ (data acquisition board) channel after being adapted by an IA (instrumentation amplifier). On the other hand, a Hall effect current probe reads the current in the coil and sends the reading to another DAQ channel.

TABLE 1. Bulk cylinder main characteristics.

Manufacturer	Can Superconductor
Type	CST-33/48.2
Length	48 mm
Inner diameter	33 mm
Wall thickness	2.5 mm
Self-field critical current density	500 A/cm^2 @ 7K

TABLE 2. Characteristics of the tape.

Manufacturer	SuperPower Inc.
Type	SF12100 (not insulated)
Width	12 mm
Thickness	0.105 mm
Critical bend diameter	25 mm
Self-field critical current	200 A @ 77K

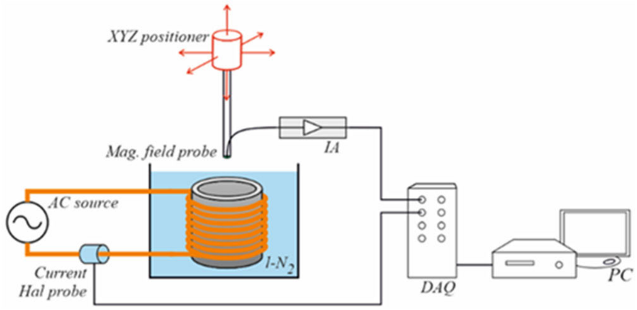

FIGURE 5. Apparatus used to measure the magnetic flux density in any position inside the magnetic shielding, or in the coil without screen.

A computer controls the process by means of a virtual instrument (VI) created with Labview® software. The VI locates the pickup coil in place using an XYZ positioner, then reads the DAQ channels (B_Z and I) and repeats the process for a new position over and over along the internal diameter, in the cylinder hole.

C. RESULTS AND PRELIMINARY CONCLUSIONS

All the tests presented in this paragraph were done with a 5 A (rms) sinusoidal current, corresponding to a *mmf* of 330 A-t. Measurements with other currents were done, but the results are quite linear and not significant for the conclusions we were looking for here.

The first group of measurement were done with the BSCCO bulk hollow cylinders used in previous works in our lab. These tests (see Fig. 6) revealed the degradation suffered by these elements due to the working cycles. This is one of the reasons we need to replace them (the price is another).

It can be observed that the bulk cylinder shows excellent shielding ability when new, but after several thermal cycles and perhaps dynamic forces, the properties degrade.

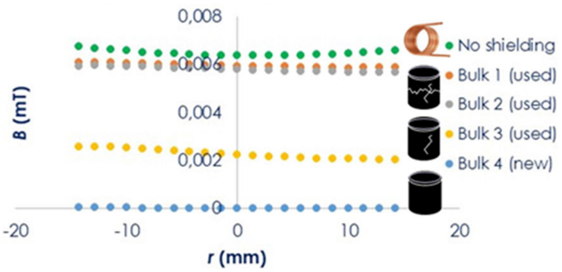

FIGURE 6. **Magnetic field shielded by bulk hollow cylinders in different states of use.**

In the second group of measurements, the BSCCO bulk cylinder is substituted by the different screens made from superconducting tapes and the results presented in Fig. 4. To make an adequate comparison of the shielding capacity, in all the cases the cylinders have 5 layers of superconducting tape. This gives us cylinder wall thickness of between 1 and 2 mm, a little less than the wall of the bulk cylinder. The results are in Fig. 7.

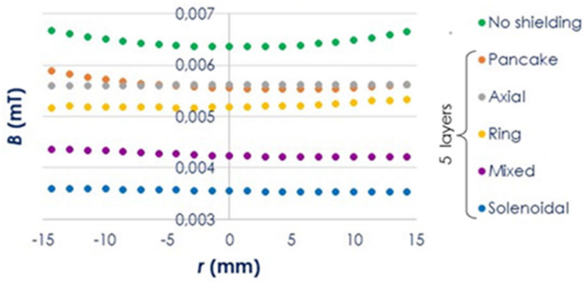

FIGURE 7. **Magnetic field shielded by the superconducting tape cylinders under study. All the structures have 5 layers.**

As expected, a reduction in flux density and a flattening of the curve along the diameter are observed in all cases. The results are worse from those of the unused bulk cylinder. However, one can note significant differences between the structures:

The reduction of the magnetic field inside the pancake, axial, and ring structures, is very low and insufficient for the application we are looking for.

In the case of the mixed structure with three solenoid layers inside and two axial layers outside, the reduction is a little higher than in the previous cases, but still not enough for our application.

Something similar happens with the solenoidal structure, but in this case, we obtained the best results from all of them, with an appreciable difference. This fact and the possibility of increase the number of layers made us decide to study the solenoidal configuration as candidate to substitute the bulk cylinder.

In order to justify the results above, we have to take into account that the penetration of magnetic flux though one tape layer is due to defects in the superconducting lattice and the areas at the edges where the magnetic field is reduced from the external value to zero inside. This is known as ''penetration depth'' [1]. Overlapping tapes and adding tape layers, increase the shielding effect.

It should be noted that in the bulk hollow cylinder the entire wall (approximately 2.5 mm) is superconducting material while in the overlapping 5-layer solenoid the superconducting material occupies an average of 7.5 μm.

As consequence of the preliminary study, the solenoidal structure is selected for the design of the IR-SFCL, and a quantitative study of the shielding capacity carried out.

III. SHIELDING CAPACITY OF SUPERCONDUCTING SOLENOIDAL SCREENS

A. SCREENS UNDER STUDY

For this part of the study, solenoidal screens from 1 to 10 layers have been tested. As said earlier, the coils are made from YBCO tape with the characteristics summarized in Table 2.

To carry out the tests with different numbers of layers, a screen of 10 turns was first used and the test was repeated over and over removing one layer each time. This ensures that the tested structure was present in the previous test.

Fig. 8 shows a 10 layers screen (a) and the screen with 2 layers (b), after removing 8 layers of the previous one. The turns of tapes in each layer overlap each other. Kapton tape is only used at ends of each solenoid layer for holding.

B. MEASUREMENT SETUP

The equipment and procedure for measuring are essentially the same as in section II-B (Fig. 5) but the excitation coil was replaced by a superconducting coil to increase the excitation current and thus the *mmf* on the screen. This coil was made form YBCO tape, and its characteristics are in Table 3.

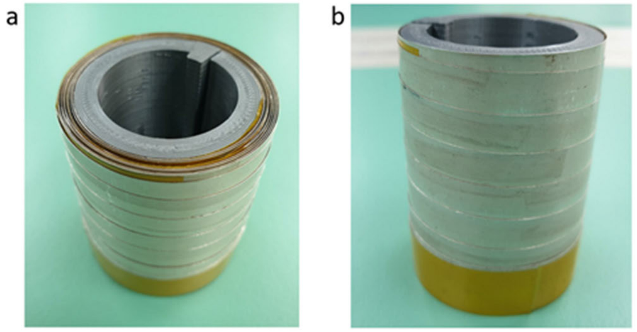

FIGURE 8. **YBCO tape solenoidal coil with (a) 10 layers and (b) 2 layers, after removing 8 of them.**

C. RESULTS AND ANALYSIS. SHIELDING FACTOR

Figs. 9 and 10 shows the axial magnetic flux density, B_Z, inside the screen, along the diameter at the center in height,

TABLE 3. Characteristics of the superconducting coil.

Tape manufacturer	SuperPower Inc.
Tape type	SCS4050I-AP
Tape width	4 mm
Tape self-field critical current	60 A @ 77 K
Coil internal diameter	45 mm
Coil height	45 mm
Coil turns	44

with 25 A (1100 A-t rms *mmf*) and 40 A (1760 A-t rms *mmf*) respectively.

As expected, the higher the number of layers, the greater the reduction of the magnetic field, but it can be observed that the shielding capacity is not proportional to the number of layers. For example, the reduction obtained by adding the 3rd layer is much less than the reduction obtained by adding the 4th layer.

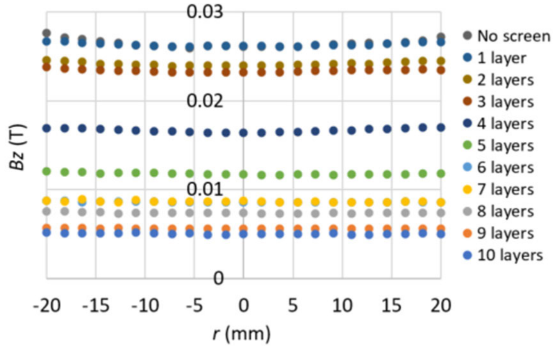

FIGURE 9. Magnetic field inside superconducting solenoidal screens as a function of the number of layers for a mmf of 1100 A-t.

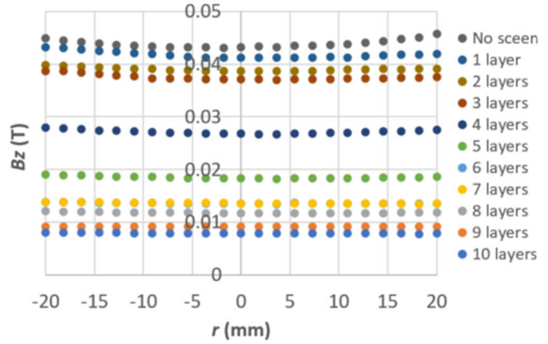

FIGURE 10. Magnetic field inside superconducting solenoidal screens as a function of the number of layers for a mmf of 1760 A-t.

On the other hand, the linearity of the response with the current is clear since the distribution of the curves for different currents show the same pattern.

To quantify and better understand the shielding capacity of the solenoidal screens, the *shielding factor*, *sf*, is introduced as:

$$sf = \frac{B_{coil} - B_{shield}}{B_{coil}} \tag{3}$$

where B_{coil} and B_{shield} are the flux densities inside the coil without and with screen, respectively. In order to characterize the shielding properties of the screens with a single parameter, and since the field profile within them is almost a constant, B_{coil} and B_{shield} have been estimated as the average of the axial flux density along the diameter. The results for 1100 A-*t* and 1760 A-*t* are shown in Fig. 11 and have no significant differences.

The conclusion is that above 9 layers, *sf* is greater than 80%, i.e., the magnetic field is less than 20% of the original magnetic field, which is sufficient for SFCL applications.

It is interesting to note the trends of the curves, which reasonably fit to a smooth step function (to illustrate this fact, a hyperbolic tangent function has been included as a dotted line on the graph), but this behavior is beyond the scope of the present work and its study will be performed as a further task.

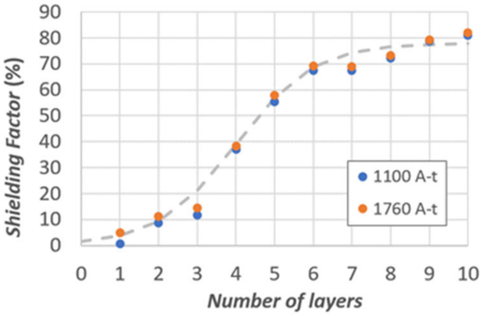

FIGURE 11. Dependence of shielding factor, sf, with the number of layers in the solenoidal screens under study.

IV. SHIELDING MECHANISM IN SUPERCONDUCTING SOLENOIDAL SCREENS

A. MEASUREMENT SETUP

As the non-insulated solenoidal layers are in electrical contact, one over the next, demagnetizing transport currents, as in a short-circuited transformer, are expected. So, we must study what part of the field reduction is due to theses currents and what part is due to the diamagnetic property of the superconductor inside the tape. To evaluate this question, the previous tests were repeated adding a Rogowski coil around the superconducting screen wall, from top to bottom. Fig. 12 shows a detail of the setup into the cryostat.

For the measurements, an additional DAQ channel is enabled to read the Rogowski electromotive force (*emf*) previously adapted by another IA. The computer calculates the total screen transport current by integrating the *emf*. This current is in fact the demagnetizing *mmf*.

Geometrical restrictions due to the thickness of the Rogowski coil prevented testing screens with more than 5 layers.

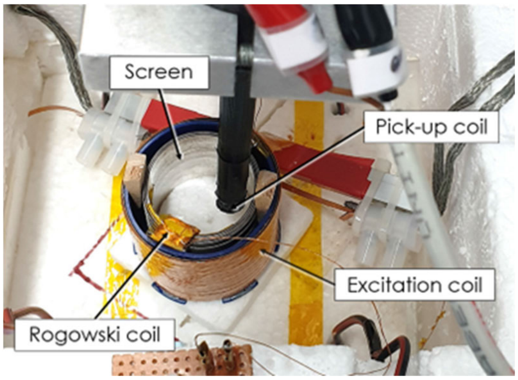

FIGURE 12. Detail of the setup for measurement of transport current in the screen.

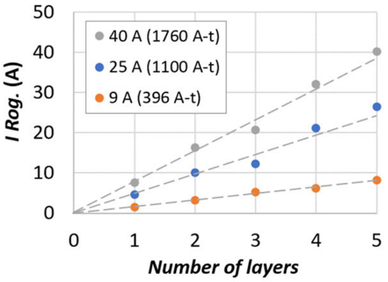

FIGURE 13. Demagnetizing mmf by transport current (Rogowski current) in screens with different number of layers, under different magnetization conditions.

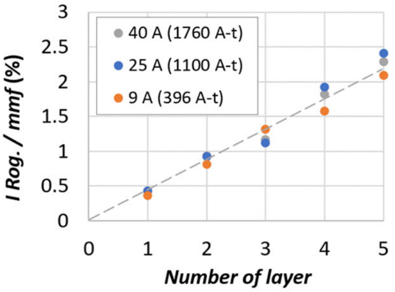

FIGURE 14. Ratio to the total demagnetizing mmf by transport current (Rogowski current) in screens with different number of layers, under different magnetization conditions.

B. RESULTS AND ANALYSIS

The results are summarized in Fig. 13 for excitation currents of 9, 25, and 40 A (rms), corresponding to magnetizing *mmf* of 396, 1100, and 1760 A-t. As can be seen, the effect is not very significant. In Fig. 14 the ratio of the transport current demagnetizing *mmf* to the magnetizing one is plotted, obtaining linear relations quite independent to the magnetization.

The low values of the induced transport current may be due to a) the reduction of the magnetic field by the diamagnetic property of the screen and b) the resistance of the contact between tapes through the silver layers (note that, with the configuration used, the tape superconducting layers are nor directly in contact, but through the substrate and external Ag layers).

Although these results do not allow for any significant improvement in the design of the screens for the I-R SFCL, as an example, for a conceptual understanding of the screening mechanism, we evaluated the behaviour of a 10 layers screen:

At 1760 A-*t*, we have a field reduction of about 80% (Fig. 10) so, the screen produces a reduction of 1408 A-*t* of which about 80 A-*t* (5.7% of the reduction) are due to induced transport current (extrapolating in Fig. 12), and the rest, 1328 (94.3% of the reduction).

V. CONCLUSION

To replace the bulks of the superconducting cylinders in the I-R SFCL, solenoidal screens based on superconducting tapes with different number of layers have been built and tested.

The shielding capacity increases with the number of layers in a nonlinear way. This is mainly due to the increment of superconducting (diamagnetic) material. The transport current *mmf* measured in the solenoidal screens have been found to be very small with respect to the external *mmf*, what indicate that the shielding mechanism is mainly the diamagnetism of the superconducting material in the screen, although, as it is known, the superconducting material on a tape is a very small part of its total thickness.

The solenoidal configuration for magnetic screens made of superconducting tape seems to be the best solution for I-R SFCL applications. The 10-layer solenoid screens reduce the magnetic field by more than 80%, which is sufficient in our prototypes, and have the advantages of cost and reliability (no damage has been observed in any case).

As a consequence of this study, a smooth step function type dependence between the shielding factor and the number of layers has been found. Understanding this behavior will be the objective of a further work.

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