

Complex research of the unclosed HTS shield for improving homogeneity of the magnetic field

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Abstract. Homogeneous magnetic fields are required in different applications. The resolution of MRI techniques depends on the quality of the magnetic field, as well as the efficiency of electron cooling systems used at particle accelerators. Unclosed magnetic shield made of superconducting tapes is able to nullify the radial component of a solenoidal magnetic field, forming the long region of the homogeneous magnetic field. The shield is a lengthwise winding made from YBCO tapes are wound along a carcass generatrix. Then it is positioned coaxially inside an electromagnet. The measurements were carried out under quasistationary conditions, magnetic fields up to 1 kG at 77K. This paper discusses the design of the superconducting shield and presents experimental and numerical studies into the homogeneity of the magnetic field in solenoids with the superconducting shield.

1. Introduction

The unique properties of HTS materials make it possible to use them for magnetic field shielding in multiple applications. As it is noted in ref. [1] magnetic shields made of superconducting tapes were applied to increase the operating magnetic field of superconductive integrated circuits and the efficiency of contactless power transfer. Using the shielding effect of the superconductors it is possible to create a magnetic cloak [2], to stop the interference between the particle beams [3]. Finally, the magnetic shielding effect is important for the stability of toroidal field coils of fusion reactor such as CFETR [4].

Forming of the highly homogeneous magnetic field is the main requirement to construct an electron cooling system for charged-particle beams, as a part of NICA accelerator complex [5, 6]. The magnetic field homogeneity must be at least 10^{-5} with the length of the cooling system solenoid of about 6 m and the magnetic field of up to 0.2 T. It is very expensive due to the complexity of the precision winding. Generation of a highly homogeneous magnetic field using unclosed superconducting shields is the most promising direction to solve this problem.



The modern 2G HTS materials are produced as a thin ($50\ \mu\text{m}$ - $100\ \mu\text{m}$) tapes of standard width (up to 12 mm). It is possible to use such narrow tapes by folding pieces of these tapes with an overlap or in another way making a layered web of the required width, from which the shield is made later [5]. The gaps between the superconducting tapes are insuperable for superconducting shielding currents. As a result, the presence of the magnetic field inhomogeneities is inevitable at the edges of pieces of superconducting tapes. The question of the magnitude of these inhomogeneities is crucial for the possibility of using narrow 2G HTS tapes to form highly homogeneous magnetic fields with uniformity at a level of 10^{-4} and higher.

So, the present work is aimed at solving this fundamental issue. Secondly, a new technique is proposed to determine the homogeneity region from the curves intersection point of the magnetic field radial components with and without the shield. It allows us to determine the effective length of the shielding region inside the long solenoid more accurately and to obtain a number of useful results, which will be described later.

2. Shield design and experimental procedure

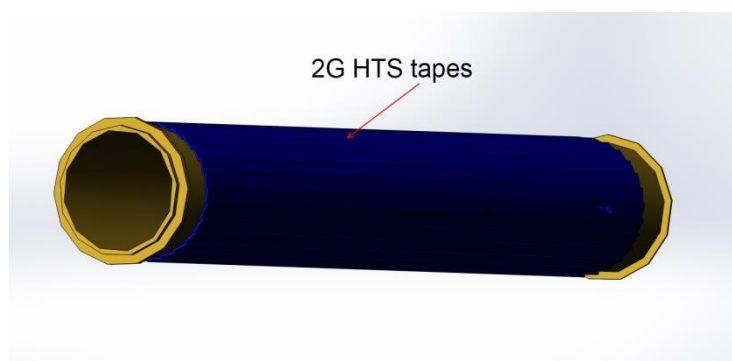


Figure 1. View of the HTS shield.

A 12-mm wide 2G YBCO tape produced by SuperOx was used as a base element of the construction. Its critical current – up to 300 A, the field of one tape full magnetization is about 250 G. Its thickness is $100\ \mu\text{m}$, with $1\ \mu\text{m}$ of YBCO as a superconducting layer. Since the HTS material has several drawbacks: permissible minimum bending radius as the superconductor is hyperfine ceramics and anisotropy of tape wide

physic-technical properties, which causes undesirable edge effect.

For this reason lengthwise shield winding technology was offered. The tapes are laid closely to each other on the non-magnetic steel tube along its generatrix. The following layers were put with a shift of pieces from layer to layer equal to a half of the tape width to form the “tile” (figure 1).

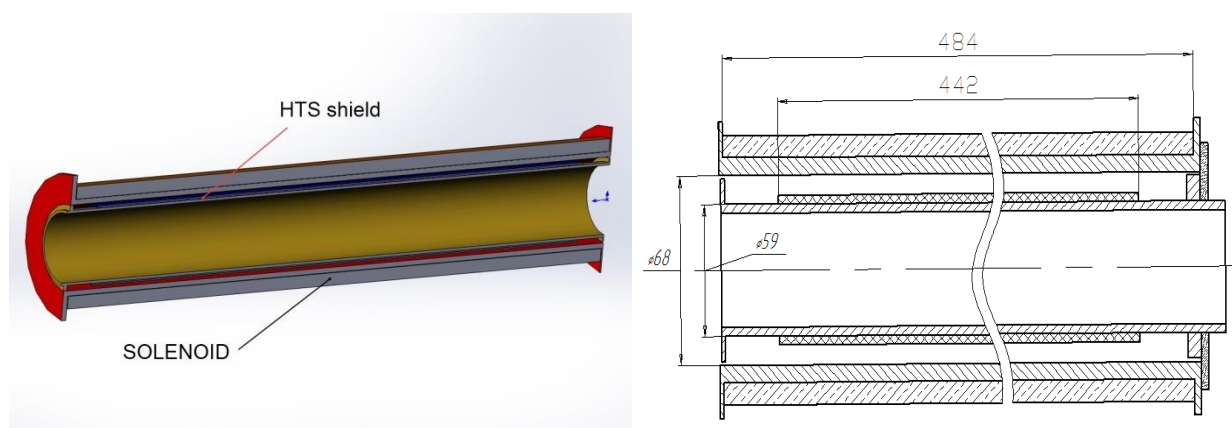


Figure 2. Shield and solenoid design.

The shield is placed coaxially inside a solenoid. The dimensions of the solenoid and the HTS shield are shown in figure 2. The electromagnet and the shield are placed in a cryostat and cooled down to the temperature of about 77 K with liquid nitrogen. Two layers of the tapes are applied. Measurements start with the cool-down of the system at zero-field conditions. After that the current in

the magnet is sequentially increased. When a selected value of current in solenoid is reached the probe holder is moved along the axis of the magnet using a step motor and field is measured. The radial component of magnetic field is measured in two positions: 3 mm and 9 mm to the inner shield surface respectively (figure 3); axial along the axis of the shield. So, the measurements of two components of the magnetic field are performed using three PHE-606817A Hall sensors. The holder is attached to a long rod and submerged in liquid nitrogen. The probes are supplied with the current of 100 mA by a current source.

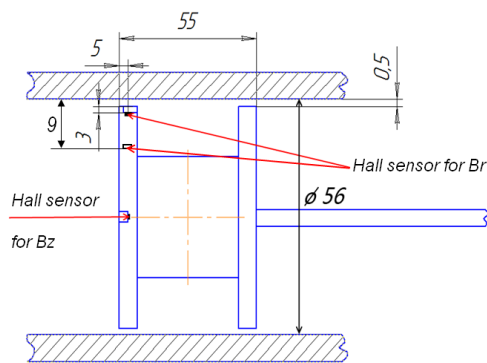


Figure 3. The probe holder with Hall sensors.

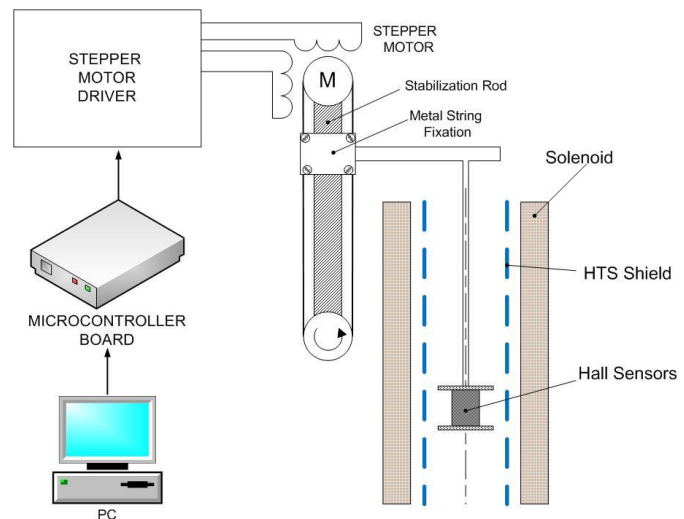


Figure 4. The experimental set-up (the cryostat is not drawn).

The stepper motor is used to position and move the probe inside the assembly of the electromagnet and the shield. For each step the motor's rotor turns by a constant angle. The probe position is calculated based on the number of steps and the dimensions of the wheel driving the movement of the probe. The control system was based on an Atmel ATmega microcontroller board connected to the PC. The motor is supplied by DC power supply and controlled by LeadShine M880A step motor driver by the control signals from the microcontroller board, as shown in figure 4. The steering of the motor and experiment data saving are done using the same computer.

3. Results and discussion

Comparison between the magnetic field distribution with and without the HTS shield is shown in figure 5. The significant improvement of the magnetic field homogeneity in the shielded region is visible. The disappearance of B_r , is hinting that the field direction is straightened. The magnetic field in the central part of the assembly is almost fully homogeneous. Radial component of the field disappears almost entirely in the shielded region, however close to the end of the shield it quickly increases.

Figure 6 gives dependence of the homogeneous area length of the HTS shield vs. applied magnetic field in the solenoid. It can be seen that an increase of the magnetic field reduces by 3 times the homogeneous area length of the HTS shield only slightly.

A new technique of the homogeneity region determining allows us to get response of the shield on the applied magnetic field (figure 7). Residual magnetic field is $B_r = B_1 - B_2$ (figure 7) where B_1 - the radial component of the magnetic field without shield; B_2 - the radial component of the magnetic field with shield.

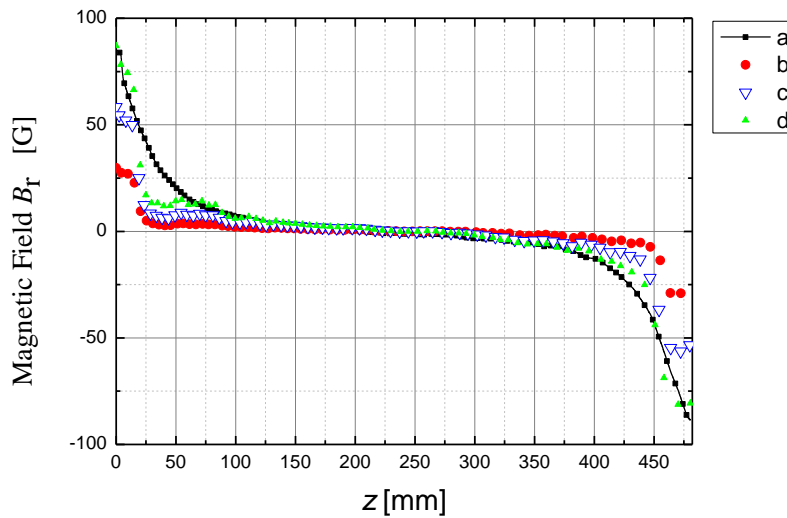


Figure 5. Penetration of the radial magnetic field into the shield under different magnetic fields (B_z component) in the solenoid: a- without shield, 780 G; with shield: b- 260 G; c- 520 G; d- 780 G.

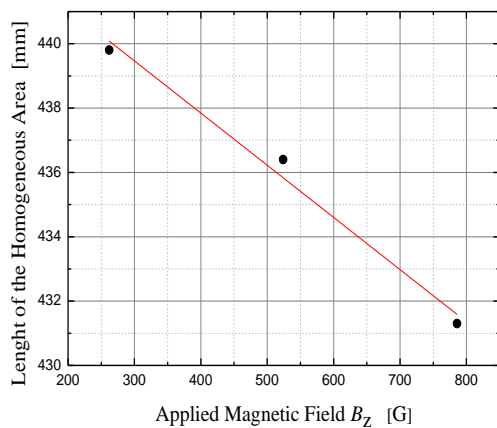


Figure 6. Homogeneous area length of the HTS shield under different magnetic fields in the solenoid.

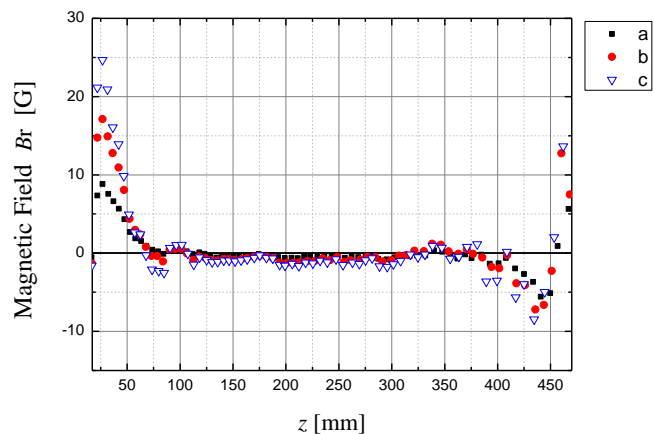
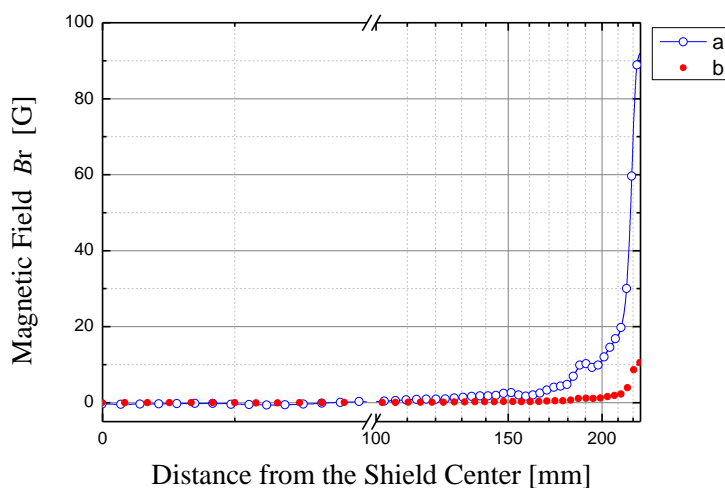


Figure 7. Calculated residual magnetic field under different magnetic fields (B_z component) in the solenoid : a- 260 G; b- 520 G; c- 780 G.



The gaps between the superconducting tapes are insurmountable for superconducting shielding currents. However, the inhomogeneity of the magnetic field sharply drops with increasing radial distance from the shield surface (figure 8).

Figure 8. The radial magnetic field component under different distance from inner shield surface and 780 G: a- $r=3$ mm b- $r=9$ mm.

4. Conclusions

The magnetic measurements carried out confirmed the performance of the unclosed HTS shield. The radial component of the magnetic field is decreased over almost entire length of the shielded region. A new technique is proposed to determine the homogeneous area into the shield which one clarified the results obtained earlier [7]. An increase the magnetic field by 3 times from 260 G till 780 G reduces the homogeneous region length of the long HTS shield only 10 mm. The residual magnetic field of the HTS shield is calculated. The inhomogeneity of the magnetic field sharply drops with increasing radial distance from the shield surface. The accuracy of the magnetic field measurements was about $\Delta B/B \sim 10^{-3}$, which was basically determined by the stability of its power supply. Actually, this is the maximum precision available for magnetic field measurements in this methodology. To reach 10^{-5} - 10^{-6} accuracy it is planned to use a magneto optical method [8]. Analysis of the results suggests the methods to further improve the efficiency of the unclosed HTS shields for electron cooling systems.

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