SUPERCONDUCTING UNCLOSED SHIELDS IN HIGH ENERGY PHYSICS

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Abstract

This paper presents the experimental and theoretical results of studying the unclosed shields made from LTS (low temperature superconductor) and HTS (high temperature superconductor) materials to obtain a homogeneous magnetic field in solenoids. There is a comparison of LTS and HTS shields, the construction peculiarities are described. HTS shield was proposed to obtain the required magnetic field homogeneity (about 10^{-5}) in the 6 meters length solenoid of the electron cooling section which will be installed in the heavy ion collider of the NICA project (JINR, Russia).

INTRODUCTION

The main requirement at the development of the electron cooling system for charged-particle beams of the NICA collider is to form a highly homogeneous magnetic field [1,2]. At the same time the electron cooling system solenoid will be multisectional with a magnetic field up to 0.2 T. Generation of a highly homogeneous magnetic field using unclosed superconducting shields is the most promising direction to solve this problem.

It is known that low-temperature superconductors can be used for these purposes [3,4,5]. Still, the need of cooling to the liquid helium temperature (4.2 K) forms a major disadvantage of the shield and raises exploitation costs.

For this reason the idea of an HTS shield, which works under 77K, is even more attractive. This paper presents the comparison between conventional LTS shields and HTS shields requiring a fundamentally different winding technology, their construction peculiarities are described as well. It also contains data on characteristic homogeneity of magnetic fields which appear in HTS shield in the gap between two magnetic dipoles.

LTS SHIELD

Investigations on unclosed shields were first carried out in the 1970s; the shields were made of low temperature NbTi alloy superconductor [3]. First papers lacked a clear physical model and had pure experimental nature. Thus there was no unified approach like the one described in our papers [4,5] to the problem of unclosed superconducting shields.

The LTS shield structure is formed by multilayer winding of superconducting foil on a cylindrical frame [4,5] (Fig.1).

A characteristic property of the technology is cross arrangement of superconducting foil pieces to the frame. Shield layers are isolated with condenser paper.

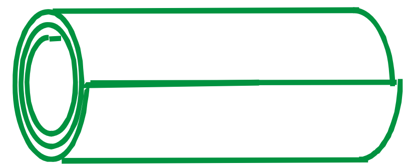

Figure 1: The scheme of spiral winding.

The carried out experiments and numeric researches proved high efficiency of conventional LTS shield usage to improve the magnetic field homogeneity in a straight solenoid [5]. Data analysis showed that the existence of an area with the homogenous magnetic field longitudinal component resulted from screening the external field's radial component by the superconducting unclosed shield.

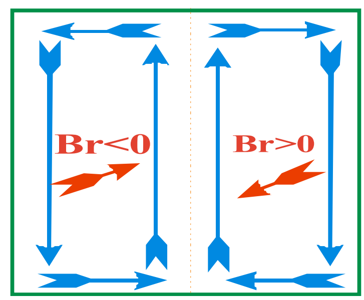

Figure 2: The unfolded shield with effective shielding currents on its surface.

In particular on the end of the shield the shielding currents flow in the same direction as the major solenoid currents, while in the center they have an opposite direction which explains the formation of typical homogenous field areas. (See in Fig.2.)

The derived results formed a basis for works upon the next technical solution – the unclosed HTS shield.

2-G HTS SHIELD

A 12-mm wide 2-G HTS (Re)BCO produced by Super Power and SuperOx was used as a base element of the construction. Its critical current – up to 300 A (i.e. $2.5x10^6$ A/sm^2), the field of one tape full magnetization is about 25 mT.

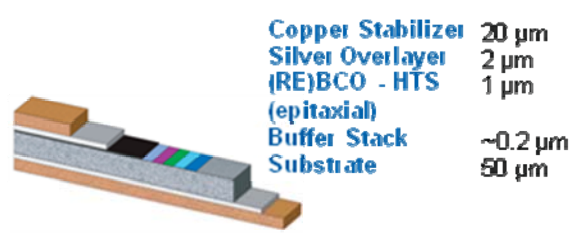

Figure 3: Structure of 2-G HTS tape (Re)BCO.

ISBN 978-3-95450-170-0

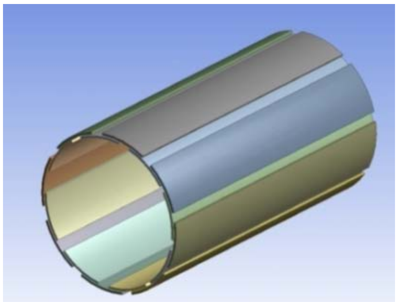

Figure 4: The unclosed HTS shield in the form of the lengthwise winding.

However the HTS material has several drawbacks: permissible minimum bending radius as the superconductor is hyperfine ceramics (Fig.3) and anisotropy of tape-wide physicotechnical properties, which causes undesirable edge effect. For this reason lengthwise shield winding technology was offered, when the HTS tape is laid along the frame (Fig.4.). At the same time control over the critical current distribution inhomogeneity on tape length is required. (See in Fig.5.)

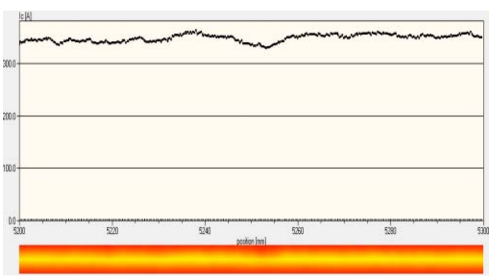

Figure 5: Critical current distribution along the tape length.

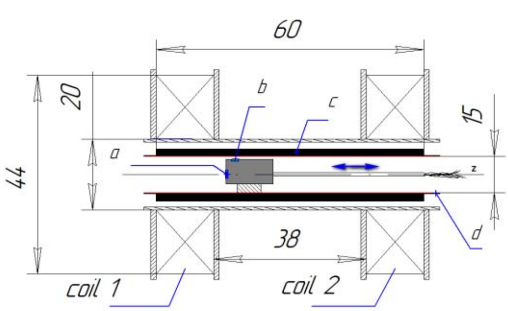

Figure 6: Experimental set-up with HTS shield. **a**- Hall sensor to measure the longitudinal field component , **b**– Hall sensor to measure the radial field component, **c** – HTS share shield, **d** - non-magnetic steel tube.

Paper [6] explored the effect of HTS shield on the coaxial coil system magnetic field. The experimental set-up is shown in Fig.6. A lengthwise shield eliminated the dip of the longitudinal component in the gap between magnetic dipoles; it was determined that its "tile" structure (see in Fig.4) performed as a uniform piece of the LTS foil. In that way the principal possibility to use the existing HTS tape for unclosed shields was shown.

Let's estimate the slope angle of lines of force to the longitudinal axis of the magnetic system according to the results of the mentioned paper. It is clearly shown that the slope ratio is delivered by the formula

$$tg(\varphi) = \frac{B_\rho}{B_Z} \tag{1}$$

Using $\varphi << 1$, we get

$$\varphi \approx \frac{B_\rho}{B_Z} \tag{2}$$

The absolute value of this angle is called characteristic magnetic field homogeneity.

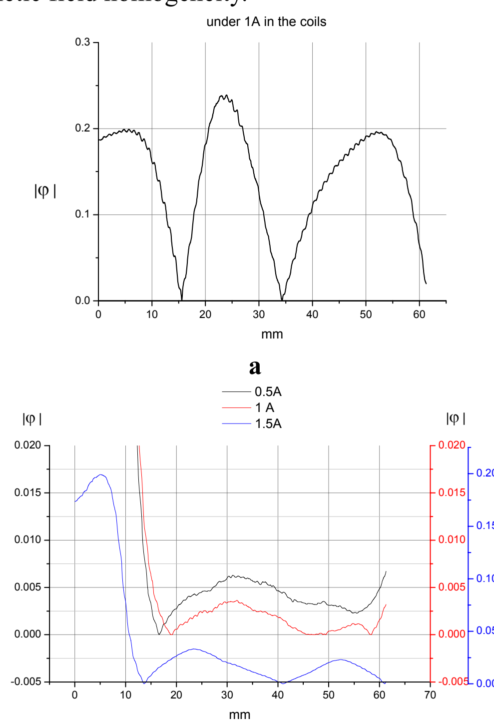

Figure 7: Characteristic homogeneity of the magnetic fields: **a**- without shield; **b**- with shield under different currents in the dipoles.

The graphs (Fig. 7a vs. Fig 7b) show that HTS shield reduces the maximum angle between the magnetic field lines and the longitudinal axis of dipoles up to 100 times. This is a significant value for the electronic cooling technique as dissipative friction force strongly depends on angles [2].

The magnetic field was measured with Hall probes in all presented papers. 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. This is the reason why a totally different approach is needed to measure fields with 10^{-5}-10^{-6} accuracy. For example, an optical-mechanical method with magnet-sensitive "compass" element offered by our Novosibirsk colleagues [7].

FUTURE PLANS

In October 2014 shield prototypes experiments start. These shields are planned to be used for charged-particle beam electron cooling within the NICA project. The authors of this paper have developed and produced a test bench for large-dimension HTS shields.

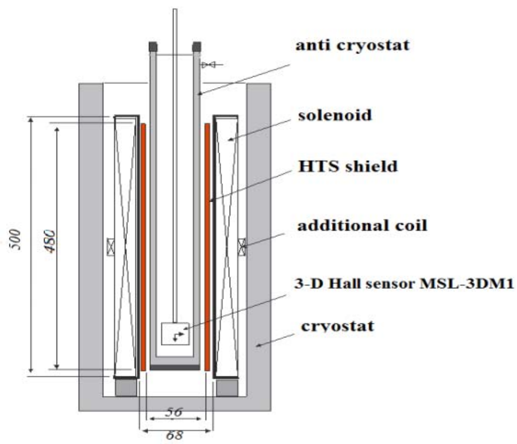

Figure 8: Test bench for large-scale HTS shields.

The bench consists of:

1. solenoid which is made of a copper wire with ø = 1.4 mm
2. additional coil which forms inhomogenious areas of the magnetic field to emulate intersection junctions or defects of winding. It has an individual power supply
3. MSL-3DM1 Hall probe for 3-D magnetic field measurements
4. anti cryostat which holds the operating temperature for the MSL-3DM1 by means of compressor and heaters (20 ±0.5 ^{0}C)
5. foam-plastic cryostat with liquid nitrogen. The magnetic system with HTS shield sinks into it.
6. HTS shield

The solenoid generates maximum magnetic field up to 0.2 T. The magnetic field homogeneity length with 10^{-3} level is about 150 mm. Instrumental resolution of the MSL-3DM1 is 0.1 mT; precision of the magnetic field measurement is 0.5% in the range of 0.1 – 0.35 T.

We hope that the existing HTS shield will improve the solenoid magnetic field homogeneity two orders up from 10^{-3}. At the moment an electron cooling system for booster is being constructed at BINP, consisting of a 2 m solenoid with a magnetic field of 0.2 T [8]. The unclosed superconducting shield is also planned to be installed for the investigation of its parameters.

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ISBN 978-3-95450-170-0