SUPERCONDUCTING SHIELD FOR SOLENOID OF ELECTRON COOLING SYSTEM

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Abstract

The homogeneity of the magnetic field in the straight solenoid of the electron cooling system is the very important task. The superconducting solenoids are planned for electron cooling systems of collider rings of NICA project [1]. To reach the necessary homogeneity in the straight section the superconducting shield was proposed. The design of the superconducting shield, experimental and numerical investigation of the field homogeneity in the solenoid with the superconducting shield are presented.

INTRODUCTION

Special properties of superconducting materials (Meissner Effect, high current) permits to use these materials for magnetic field screening in different facilities, for example: chambers with magnetic vacuum, current limiters, and tomography. For maximum current density 5×105 A/cm2 the magnetic field difference on the thin superconducting layer with the thickness about 20 µm can reach a value up to 1000 G. The using of the NbTi superconducting shield for the increasing of the field homogeneity was investigated in the different works [2, 3].

The aim of these investigations is the problem of the field homogeneity in the straight section of the electron cooling system. The price of the straight solenoid with field homogeneity up to value ΔB/B=10-5 [1] is very high. When the length of the high precision solenoid is 10 m and more than the solenoid is divided on a few sections. This situation leads to the field unhomogeneity between solenoid sections. The using of the superconducting shield can resolve this problem.

For the investigation of the high homogeneity magnetic field in large volumes the experiments with superconducting shields which are placed inside superconducting solenoid were done in Laboratory of High Energy Physics (JINR, Dubna, Russia). The design of the superconducting shield is a multilayer close-coiled winding from the superconducting foil. This article presents the comparison of experimental and numerical results which were done with standard simulation programs and original program code.

EXPERIMENTS WITH SHORT SOLENOID

Laboratory of High Energy Physics JINR has a large experience in the production of superconducting systems [4]. In first experiment the existing superconducting solenoid with length 150 mm, outer diameter 130 mm and inner diameter 100 mm was used. The superconducting shield was made from the NbTi foil with thickness 150 µm and width 138 mm. The shield was wind on the tube with diameter 78 mm and has 5 layers which have a close-coiled shape and are divided by the isolator paper.

The dependence of the magnetic field homogeneity on different solenoid currents is presented on Fig.1. Initially measurements were done without the superconducting shield then with the shield for the same values of solenoid currents. The field measurements were made with the Hole probe along the solenoid axis with step 5 mm. A sensitivity of the Hole probe was 73 mV/T.

The using of the superconducting solenoid leads to the increasing of the field range with high homogeneity even in the short solenoid (Fig.1). At the same time the value of magnetic field decreases in the solenoid center and increases on the edge. The size of the field range with high homogeneity has a dependence on the absolute value of the magnetic field: the higher field value the smaller range size. This behavior can be explained by the saturation of the superconducting shield. The efficiency of the shield is decreasing when the current in the foil reach the critical value.

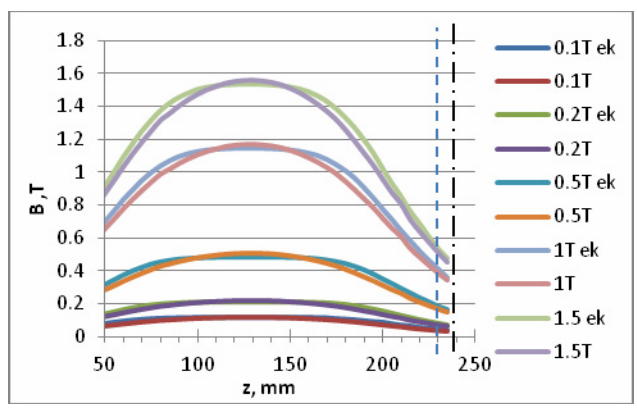

Figure 1: The dependence of magnetic field (arbitrary units) on the longitudinal coordinate for different values of the magnetic field B = 0.1, 0.2, 0.5, 1, 1.5 T) with the superconducting shield (ek) and without it. Vertical lines correspond to boundaries of the solenoid and shield.

EXPERIMENTS WITH HIGH HOMOGENEITY FIELD

For further investigation of the influence of the superconducting shield on the field homogeneity the solenoid with large ratio of the length and diameter was constructed. The solenoid has four layers of the NbTi/Cu superconducting ware with diameter 0.5 mm. The length is 480 mm and inner diameter 80 mm. The shield was made from NbTi/Cu foil with the thickness 20 µm and width 80 mm. Each section has 15 layers of the superconducting foil which are divided by the isolator paper. Sections overlap each over with the shift 40 mm. An additional superconducting coil was placed in the center on the shield. It was used for the imitation of the magnetic field unhomogeneity.

The longitudinal magnetic field was measured on the solenoid axis with the Hole probe. The solenoid current was about 30 A. The dependence of the magnetic field with the superconducting shield and without it was presented on Fig. 2. The accuracy of the field measurement was about ΔB/B~10-3 which was mainly defined by the stability of the solenoid power supply. The numerical simulation of the screening effect has only quality agreement with the experiment when the superconducting shield was simulated like the material with zero permeability (Fig. 2).

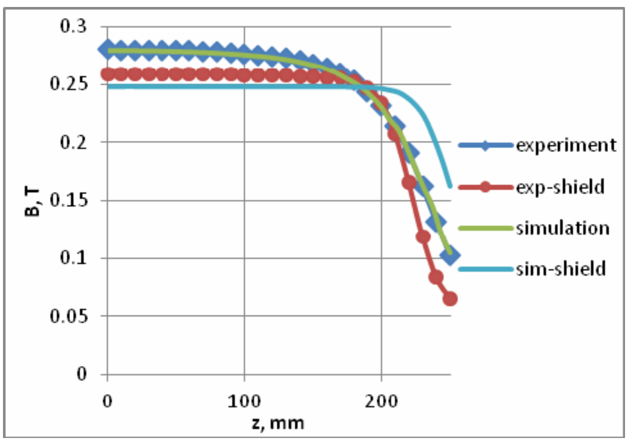

Figure 2: The dependence of the magnetic field on the longitudinal coordinate with the superconducting shield and without it. Zero coordinate corresponds to the solenoid center.

For the investigation of the screening effect the additional coil was used. It was placed in the solenoid center outside of the superconducting shield. The coil has 4 winding from the superconducting ware with diameter 0.5 mm. The coil current was about 10 A. The difference between magnetic fields normalized on the absolute value between measurements with the additional coil and without it are presented on Fig.3. The additional coil increases the absolute value of the magnetic field and does not change the field homogeneity in the solenoid center. It means that non regular winding of the solenoid ware does not destroy the field homogeneity when the superconducting shield is used.

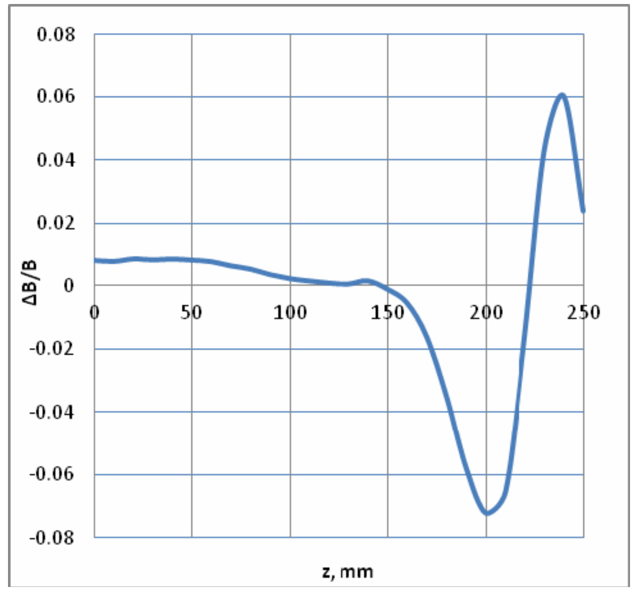

Figure 3: The difference between magnetic fields with the additional coil and without it.

SIMULATION OF SUPERCONDUCTING SHILED

Standard programs cannot correctly simulate the screening effect from the superconducting solenoid. In the case when the superconducting shield is replaced on the material with zero permeability the simulation result has only a quality agreement with experiments (Fig.2). Then a special program code was proposed for the simulation of the superconducting shield.

In the simple geometry when the superconducting shield is placed inside a solenoid and its axis is parallel the radial component of the magnetic field is perpendicular to the shield surface. It means that the close-coiled shield in the first approximation is equal to the superconducting plate with the perpendicular magnetic field which is correspondents to the radial component of the solenoid field. In the solenoid center the radial component is zero. As result the variable magnetic field leads to the appearance of two closed screening currents in the different part of the plate with opposite directions.

In the superconducting shield the independent currents are screened the radial component of the solenoid magnetic field which has zero value in the solenoid center. Screening currents completely compensate the radial component in the solenoid center and has opposite currents on the solenoid edge. In the accordance with the theory of the critical state of the superconducting materials the current density has to be critical in shield regions where the transverse component of the magnetic field goes through the superconducting shield. This behavior defines the distribution of the screening current and the shield efficiency. Thus the screening currents leads to the increasing the field homogeneity in the solenoid center and decreasing the field homogeneity (increasing of the radial component of the magnetic field) on the solenoid edge.

For the simulation of the screening effect from the superconducting shield the special program code was used. The influence of shield was simulated with additional coils which were placed in three layers along the solenoid axis. Currents in coils were chosen under conditions that the radial component of the magnetic field leads to zero on the shield surface and current summary is zero in each layers. Simulation results (Fig.4) have a good agreement with experimental results [2]. Thus coil currents have the same direction on the solenoid edge and the opposite direction in the solenoid center.

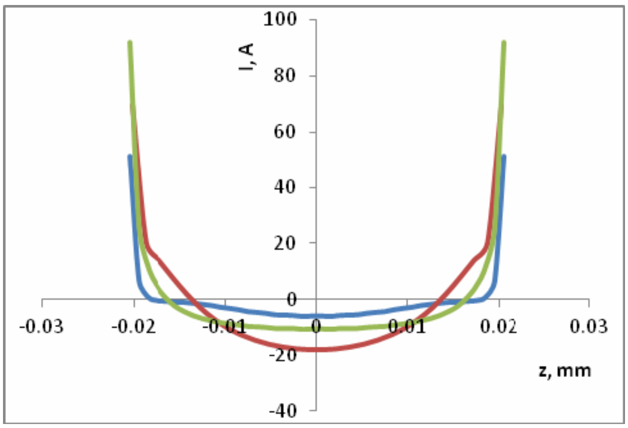

Figure 4: The distribution of currents in additional coils which reproduce the effect of the supeconducting shield. Possitive values correspond to the same direction of the solenoid current.

CONCLUSION

Present experimental and numerical investigations show enough high efficiency of the superconducting shield for the increasing of the magnetic field homogeneity in the straight solenoid. The first experiments with the high temperature superconducting materials shows that they can be used for the superconducting shield.

Further investigations will have the aim to the choosing of the optimal material for the superconducting shield (including high temperature superconducting materials) and the technology of the shield winding. For the investigation of the field homogeneity the stability of the power supply and the accuracy of the field measurement have to be improved. For the simulation of the superconducting shield the special algorithms have to implemented into program code for the optimization of shield parameters. Present experimental and numerical investigations show enough high efficiency of the superconducting shield for the increasing of the magnetic field homogeneity in the straight solenoid. The first experiments with the high temperature superconducting materials shows that they can be used for the superconducting shield.

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REFERENCES

[1] I. Meshkov, R. Pivin, A. Smirnov, G. Trubnikov, et al. Application of Cooling Methods to NICA Project // Proceeding of COOL'09 Workshop. Lanzhou, China, 2009.

[2] Лазарев Б.Г., Лазарева Л.С. , Полтавец В.А. О получении однородного постоянного магнитного поля в сверхпроводящих соленоидах при помощи экрана из сверхпроводника с высокими параметрами // ДАН СССР. 1972. Т.203, № 4. С. 810-812.

[3] Бычков Ю.Ф., Комаров А.О., Хлопков А.К. Изучение факторов, влияющих на эффективность сверхпроводящих экранов, применяемых для повышения однородности магнитного поля // Металлургия и металловедение чистых металлов. М.: Атомиздат,1980. Вып. 14. С. 53-63.

[4] Дробин В.М., Малиновски Х. и др. Сверхпроводящая магнитная система с криокулером для источника ионов DECRIS-SC // Письма в ЭЧАЯ. 2006. Т3, №1 (130). С. 45-62.