

## Split coil made of (RE)BCO pancake coils for $I_c(B)$ anisotropy measurements of superconductors

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**Abstract.** Measurement of the  $I_c(B)$  anisotropy is standard characterization of superconducting tapes, wires or cables. This contribution presents a split coil consisting of two superconducting pancake coils in order to generate the magnetic field necessary for this kind of measurement. Both coils were made using (RE)BCO - based second generation (2G) coated conductor tape with cross section 0.1 mm x 12 mm. The individual turns of the tape were insulated by a fiberglass tape without impregnation. These coils have identical inner and outer diameter and number of turns. Their inner and outer diameters are 50 mm and 80 mm, respectively, and they have 62 turns. The length of conductor in each coil is approximately 13 m. The distance between both pancake coils is 22 mm. Individual coils and the complete split coil were characterized in liquid nitrogen bath. Their parameters, like the critical currents,  $E(I)$  characteristics and magnetic field of complete split coil, were measured and interpreted. The split coil can be used up to magnetic fields of 210 mT. The length between the potential taps on the sample can be up to 20 mm, while the magnetic field decrease is lower than 1% on this length.

### 1. Introduction

Copper split coils commonly used for  $I_c(B)$  anisotropy measurements have oftentimes big dimensions and their cooling requires great volume of liquid nitrogen. These coils are starting to overheat and are electrically unstable at higher currents. For these reasons, we constructed a superconducting split coil. This coil was made using (RE)BCO – based second generation (2G) coated conductor tape. The tapes of this type are commercialized and some (RE)BCO coils have been developed [1-2]. This is in line with an effort to use high-temperature superconductors (HTS) in many applications. Their advantage is that these superconductors can operate at much higher temperatures than low-temperature superconductors (LTS). The split coil consisting of two pancake coils was made without impregnation, because epoxy impregnation can substantially degrade its performance [3-4]. Important parameters as dependences of electrical field on current ( $E(I)$  characteristics) and critical currents ( $I_c$ ) were measured and compared for each pancake coil separately and also together (in final configuration and in serial connection) in liquid nitrogen bath. For the complete split coil, we measured the axial component of the magnetic field along the radial and axial axes and compared with calculated values. The hysteresis of magnetic field in the centre of split coil was measured and discussed too.

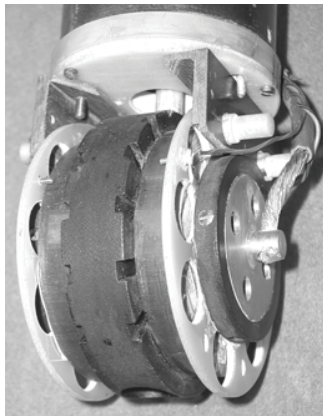
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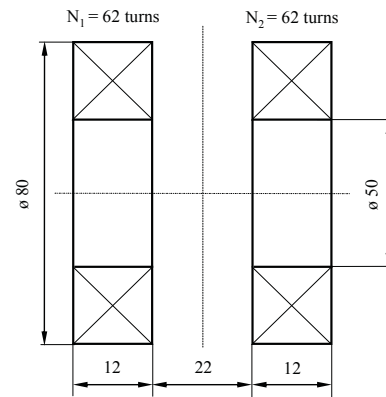


## 2. Description of the split coil

The split coil consists on two superconducting pancake coils. Both of these coils are connected in series and the distance between them is 22 mm. Each coil have inner diameter 50 mm, outer diameter 80 mm and 62 turns of superconducting tape. The length of conductor in each coil is approximately 13 m. They have been made from Super Power's (RE)BCO coated conductor SCS12050-AP which has a copper stabilizing layer. Cross section of the coated conductor is 0.1 mm x 12 mm and the self-field critical current ( $I_c$ ) is 480 A at the temperature of liquid nitrogen (77K). Photography of the complete split coil is shown in figure 1 and the dimensioned sketch is shown in figure 2.



**Figure 1.** Photography of the complete split coil.



**Figure 2.** Dimensional sketch of the split coil.

The individual turns in these coils were insulated with a fibreglass tape 0.12 mm thick and 12 mm wide and were wound simultaneously with the superconducting tape. The bobbin of this coil is made from fibreglass and in the centre there is a hole with diameter 20 mm for sample placement. Current leads were located on the inner part of individual coils and the coils were interconnected on their outer part. The complete split coil was made without impregnation and forms a compact unit.

## 3. Achieved parameters and discussion

### 3.1. Comparison of the important parameters of individual coils

First were measured  $E(I)$  characteristics for each pancake coil separately and then for each one pancake coil together in complete split coil (with common supply). The potential taps were soldered on both ends of superconducting tapes. The coil terminal voltage was measured to achieve corresponding electric field in range 1  $\mu$ V per 1 cm of tape. In order to prevent the damage of coils during measurement, for assessment of safe terminal voltage was taken the length of innermost (first) turn into account, because the innermost turn limits the maximum DC current the coil could carry [5-6]. Measured data were used for determination of critical currents according to power law dependence given by equation (1)

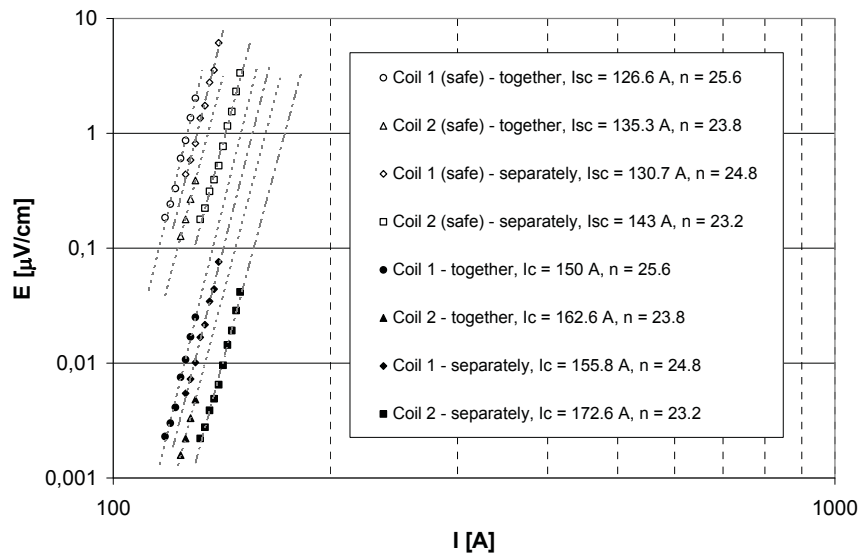
$$E(I) = E_0 \left( \frac{I}{I_c} \right)^n \quad (1)$$

where

$E$  = electric field [ $\mu$ V/cm],  $E_0 = 1$  [ $\mu$ V/cm],  $I$  = current [A],  $I_c$  = critical current [A],  $n$  = parameter.

Critical currents of both coils ( $I_c$ ) (assuming that the voltage is uniformly distributed on the whole coil) and safe critical currents ( $I_{sc}$ ) (assuming that the entire voltage is on the first turn) were established.

Using the safe critical currents, the coils are protected, because in reality the entire voltage is not only on the first turn.

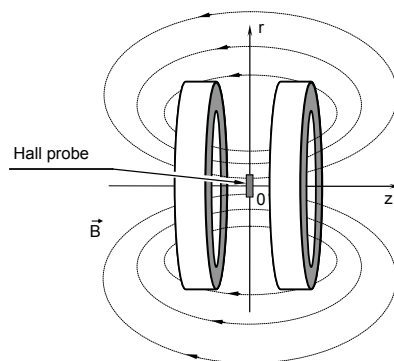


**Figure 3.** Graph of the  $E(I)$  characteristics of both coils measured both separately and together forming the complete split coil using safe critical current ( $I_{sc}$ ) and usual ( $I_c$ ) interpretation.

Measured  $E(I)$  characteristics with critical currents and  $n$  parameters are shown in figure 3. Comparison of the critical currents of the first and second coil in individual cases reveals a difference between values between 6 and 11%, although the coils have identical geometry and were made by identical technology. This is probably due to inhomogeneities or local  $I_c$  degradation of the tape [6]. Therefore the maximum supply current of complete split coil was established on 120 A, which is certainly safe current (considering the first coil).

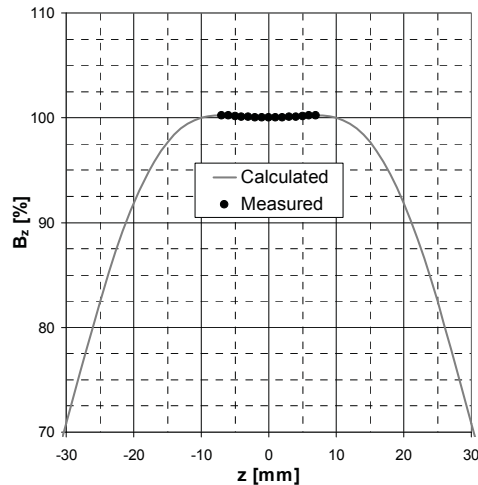
### 3.2. Important parameters of the split coil

The distribution of magnetic field inside the split coil is one important parameter significant for  $I_c(B)$  anisotropy measurements. The system axis and method of measurement are sketched in figure 4. As method of measurement, the Hall probe mapping method was used.

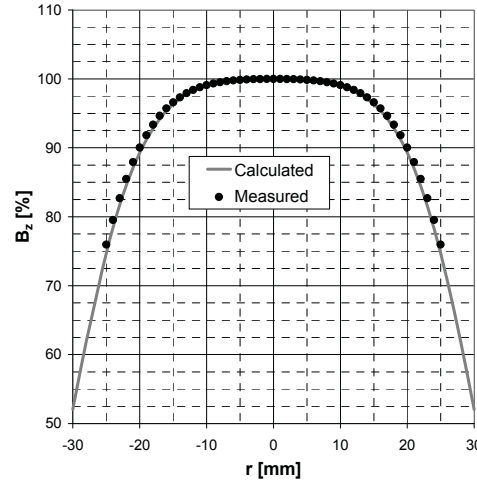


**Figure 4.** Methodological sketch for measurement of the split coil magnetic parameters. Zero point (0) is the centre of the split coil and the axis system together.

The axial part of magnetic field in axial ( $z$ ) and radial ( $r$ ) direction were measured and compared with calculated one assuming uniform current density in the coil. These distributions are shown in figure 5 and figure 6.



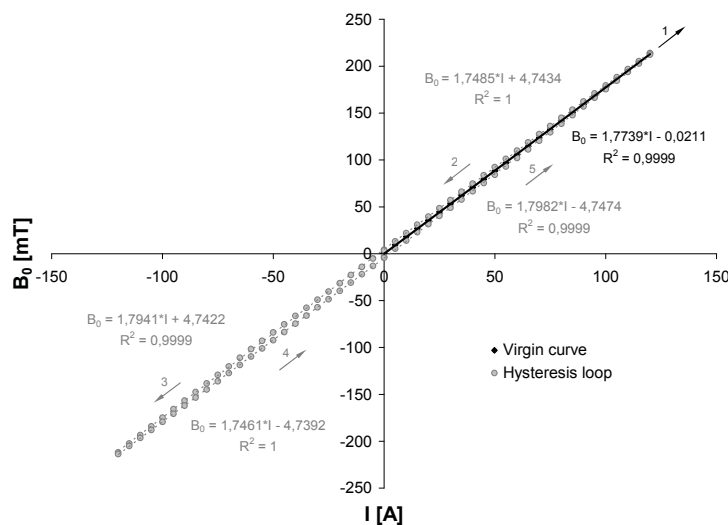
**Figure 5.** The distribution of magnetic field along the axial direction (on axis  $z$ ).



**Figure 6.** The distribution of magnetic field along the radial direction (on axis  $r$ ).

The calculations and measurements are in good agreement in both cases. On axis  $z$  is homogeneity of magnetic field up to distance  $\pm 10$  mm better than  $\pm 0.3\%$  and on axis  $r$  at the same distance is drop of magnetic field lower than 1% (in the centre of the split coil is value of magnetic field 100%). This is important information for  $I_c(B)$  anisotropy measurement. If the length between the potential taps on the sample will be 20 mm, decrease of magnetic field on this length will be lower than 1%. For higher precision the length between the potential taps must be reduced.

Another important parameter is hysteresis of magnetic field. This hysteresis of the split coil was measured in Zero point (in the centre of the split coil) and results of measurement are shown in figure 7.



**Figure 7.** The hysteresis of magnetic field measured in the centre of the split coil (in Zero point). The arrows indicate the sequence of measurements.

From figure 7 is noticeable that the split coil has hysteresis, which can cause inaccuracies at  $I_c(B)$  anisotropy measurements. The inaccuracies are the highest at the lowest magnetic fields. Either this fact is necessary to take into consideration during all measurements or all experiments have to start from zero-field cool and the current rising monotonically following the virgin curve (if afterwards a lower magnetic field is desired, the coil has to be previously warmed up). The constant of split coil determined from virgin curve is  $k = 1.774$  mT/A. Using supply current of 120A, will be magnetic field of 212.88 mT in the centre of the split coil and so 210 mT is certainly safely achievable magnetic field.

#### 4. Summary and conclusions

A split coil appointed for measurements of  $I_c(B)$  anisotropy of superconductors was made using two (RE)BCO pancake coils without impregnation. Based on the parameters of the coils, the safe supply current was established up to 120A. Guaranteed magnetic fields in the centre of the split coil are up to 210 mT and constant is 1.774 mT/A. The length between the potential taps on the sample can be up to 20 mm, while the magnetic field decrease is lower than 1% on this length. The coil has magnetic field hysteresis, therefore, for accurate measurements all experiments have to start from zero-field cool and the current rising monotonically following the virgin curve. The main advantages of this coil in comparison with a copper split coil are: no overheating at high supply currents, small size and low liquid nitrogen consumption at measurement. Proposed future work is to study relaxation effects.

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