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Magnetization of the stack of HTS tapes

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Abstract

New results of dependence of magnetic field, trapped by a stack of HTS tapes, on amount of tapes in a stack are reported. Commercial GdBCO tape 12 mm width and without Cu layer was used for the research. Tape was divided in square pieces 12 x 12 mm^2 from which stacks were formed. Filling factor of the tape was about 1.4%. Measurements were carried out for stacks with height from 5 to 250 pieces and at wide temperature range from liquid helium to liquid nitrogen. Both FC (field cooling) and ZFC (zero field cooling) cooling methods were used in the research. These two methods show matching results with good accuracy. As a result dependences of trapped magnetic flux on amount of tapes for different temperatures were received. Research shows, that with increasing height of the stack trapped magnetic field value reach saturation at about 60 tapes in a stack for low temperatures. From 60 to 100 tapes increase of magnet flux is only 5%. Thus increase amount of tapes in a stack is not profitable. Also investigation of trapped magnet field relaxation was carried out. Relaxation speed decreases with increasing amount of elements. It means that the higher the stack is, the longer trapped flux will be held in cause of the same temperature.

Keywords: Coated conductors, HTS stacks, trapped field magnets, relaxation of magnetic flux

1. INTRODUCTION

The idea of using stacks of tapes as trapped field magnets have been suggested earlier [1]. They have some significant advantages in comparison with HTS (high temperature superconductor) bulks. Maximum trapped flux for bulks is limited by the properties of material it is made from. Ceramics REBaCuO (where RE means rare earth) are rather fragile that's why interaction between trapped field and volume currents is able to break the sample. Calculations show that theoretical maximum trapped field for pure bulks ranges from 6.0 up to 9.4 T [2]. In order to reach greater values it is necessary to use external mechanical reinforcement.

Another problem is a low thermal conductivity of REBaCuO. During the magnetization process under 30 K, jumps of trapped flux are observed because of low thermo-stability, which can lead to degradation of the bulk sample [3, 4]. In order to increase thermal conductivity inserts like metal rods are used and the surface of the sample need to be covered with alloy with high thermal conductivity and close value of thermal expansion coefficient.

When attempting to increase the geometric dimensions of the grown samples volumetric uniformity of critical current density falls.

Maximum trapped field obtained on REBaCuO is 17.24 T at 4.2 K [2] between two bulks 2.65 cm in diameter. But the samples were greatly prepared in order to realize mechanical reinforcement and increase thermal conductivity.

HTS tapes do not have such disadvantages through its structure. Mechanical strength of the tape is provided by substrate properties. Stiffness of Hastelloy layer corresponds theoretical trapped magnetic field limit about 42.8 T [5]. Producing tape technologies allow to reach high uniformity critical current density inside the tape. Silver layers produce high thermal stability of the stack because of its good value of thermal conductivity and periodical arrangement. Critical currents of modern HTS 2G tapes are close to REBaCuO bulks. All this makes stacks perspective for trapping magnetic field. One more feature of the stack is little fill factor value. Superconducting material is about 3% of the total volume. This means that it is necessary far fewer rare earth metals for the production. Properties of the tape stacks make them the natural choice for making trapped field magnets.

Currently, the maximum value of the trapped magnetic field obtained by using stacks is 7.34 Tesla at 4.2 K [5]. The field is measured between two stacks of industrial superconducting tapes height of 120 elements. The result obtained for tape pieces 12 mm × 12 mm size and critical current value 240 A (at 77 K self-field). Magnetization was realized by FC method. Calculations show, that increasing size of pieces leads to significant improvement of trapped flux [6]. Using tapes with larger critical current value and increasing the number of elements in the stack will also lead to an improvement in the field value.

Levitation force, magnetic field values and configurations for HTS tape stacks have been already studied in [7-9]. Researches on creating levitation bearings and laboratory magnets for nuclear magnetic resonance were carried out [10-15]. But no dependence of trapped

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field on amount of elements in a stack was studied. That data may be the key for understanding the ways of trapping and holding magnetic flux by the stack and for determining the optimum amount of tapes.

2. INVESTIGATED SAMPLES

Commercial unstabilized GdBCO tape was used for the research. Properties of the tape are shown in Table 1.

In order to identify sites with inhomogeneous critical current density, tape was put into liquid nitrogen, magnetized and then scanned with Hall sensor and magneto-optics visualization by using methods described in [16-18]. Regions with homogeneous critical current density were divided in square pieces 12 mm × 12 mm. Stacks were formed from pieces. Substrate of higher square was placed on the surface of lower one. Stack elements were not glued together. Squeezing of pieces inside the stack is realized by construction elements of sample holder. Measurements were carried out for stacks of 5, 10, 15, 20, 25, 40 and 60 tapes by using superconductive Cryogenic Industries 8 T magnet. Experimental setup is able to change field inside the magnet coil with speed up to 0.5 T/min.

Zero field cooling method (ZFC) consist in preliminary sample cooling to temperature lower then critical one, which is followed by increasing coil field up to necessary value with defined ramping rate. Stack traps magnetic field. External field must be high enough to saturate the stack. Hall detector was placed strictly in geometrical center of the highest tape. External magnet field is defined by the current source calibration. Sample is cooled by cryocooler. Cold head is connected to copper bus. Helium gas provides heat exchange between sample and copper head. Temperature control is realized by heater, placed near the sample.

Field cooling method (FC) consists in applying external field while temperature of the sample is higher then it's critical. Then stack is cooled to required temperature. Trapped flux remains in a stack after external field is ramped to zero at constant temperature. Both cooling methods were realized in that research. Results are compared.

15 T Oxford Instruments superconducting magnet was used for investigating stack of 100, 150 and 250 tapes. Sample was put into sealed insert with helium gas inside. The inset is cooled directly by liquid helium from outside.

Temperature control is realized by heater placed near the sample. External magnet field is defined by calibration of the current source. Field near the surface of stack was measured by Hall sensor.

TABLE I
PROPERTIES OF HTS TAPE UNDER RESEARCH.

Tape property	Value
Width	12 mm
Critical current	250 A at 77.4 K, self-field
Tape thickness	65 microns
SC layer thickness	1-3 microns
Filling factor	1.3 %
Substrate material	Hastelloy C276, non-magnetic

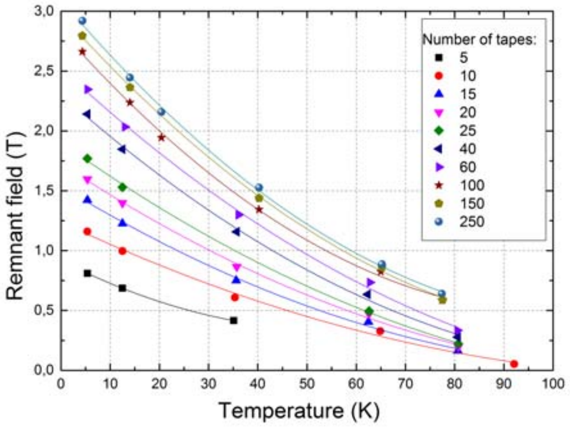

Fig. 1. Temperature field of remnant magnetization at different numbers of layers in the stack.

3. RESULTS

Dependencies of magnetic field above the stack surface on the external magnetic field were measured for various numbers of tapes in the stack. All measurements have been carried out in ZFC mode. For comparison, some measurements have been conducted in FC mode. Comparison have shown no significant difference between FC and ZFC measurements (discrepancy between FC and ZFC magnetization curves were within 3%). Measurements were conducted at temperature range 4-80K. Magnetic field ramping rate was 0.5 T per minute. Upper magnetic field was 6 T for stacks of 5, 10, 15, 20, 25, 40 and 60 tapes and 10 T for stacks of 100, 150 and 250 tapes. As a result, remnant magnetic field as function of temperature and number of tapes in the stack was found. (Fig. 1). Second order polynomial fitting was used for calculating dependencies of remnant field on number of tapes at important for cryogenics temperatures: 4.2K, 27K, 40K, 65K, 77K (Fig. 2).

Also, relaxation of trapped field after the magnetization process was measured. The measurements were carried out at a constant temperature for a period of time about 5-10 minutes. Fig. 3 shows an example of relaxation curves for 15 tapes in stack at various temperatures. The relaxation rate S was defined from the relaxation curves by using of the formulas:

$$S = -\frac{\partial \ln M}{\partial \ln t} \qquad (1)$$

where S - the relaxation rate, M - irreversible magnetization at H=0, t - time. From relaxation rate one can find pinning energy U:

$$U = \frac{k \cdot T}{S} \qquad (2)$$

where k - Boltzmann constant, T - temperature, U - pinning energy.

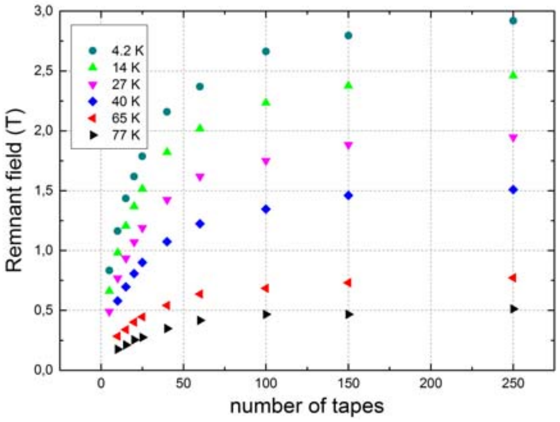

Fig. 2. The dependencies of remnant field on the number of layers in the stack at different temperatures.(4,2 K – helium boiling point, 14 K – hydrogen melting point, 27 K – neon boiling point, 40 K – typical for cryocooler systems, 65 K – liquid nitrogen vapor pumping , 77 K – nitrogen boiling point).

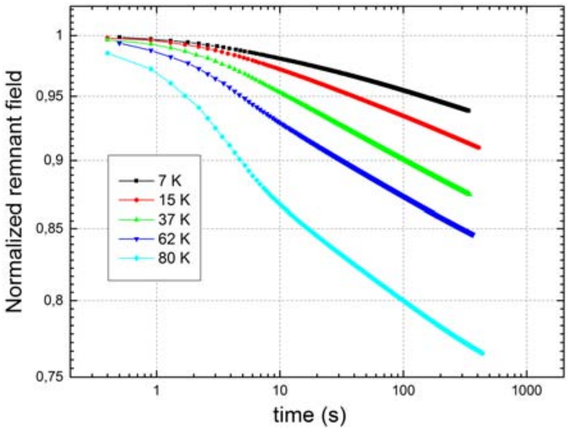

Fig. 3. Time dependence of the normalized remnant field of the stack of 15 tapes. Dependence is normalized to the value at zero. Double logarithmic scale.

4. DISCUSSIONS

Magnetization curves in ZFC mode are similar to well-known hysteresis loops of bulk HTS. The temperature increase leads to higher values of the critical current in the tape, which in turn leads to higher values of remnant fields. Some stacks were also studied in FC mode. Discrepancy between FC and ZFC measurement was within 3%.

Analysis of the data presented in the Fig. 2 shows that remnant magnetization is non-linear function of stack thickness: magnetization increases significantly for small number of tapes (5-25) and saturates in the region of 100-150 tapes. Magnetization of 150 tapes stack demonstrates an increase in 5% only in comparison with 100 tape stack, while tape consumption increased by the 50%. It means that a simple increase in the number of elements in the stack is ineffective to achieve a high value of trapped magnetic field. So, it is becoming commercially unprofitable to create large stacks of HTS tapes, because of the relatively high cost of HTS tape. The reason of saturation of B_{rem} (n) dependencies is, presumably, the shielding of the inner layers by the outer layers of the stack.

To use the stacks of tapes as the trapped field magnets it is necessary to know not only the maximum value of the trapped field, but also temporally stability of trapped field at various temperatures. So it is necessary to examine the ability of the stacks hold the magnetic flux in the absence of an external field. For this purpose, time dependence of trapped field was measured after the magnetization process. The measurements were carried out at a constant temperature for a period of time about 5-10 minutes. The relaxation processes of the magnetic field for all the samples can be divided into two stages: the fast relaxation and linear on a logarithmic scale relaxation (Fig. 3)

But it was already mentioned [5] that at temperatures below 15 K relaxation becoming faster than logarithmic. Temperature increase leads to increasing in pinning energy and relaxation rate (Fig.4, 5)

The relaxation rate decreases (Fig.6) and pining energy increase (Fig.7) as number of tape increases. This means that the higher stack will keep the magnetic flux for a longer time at the same temperature. This means that the higher the stack will keep the magnetic flux for a longer time at the same temperature.

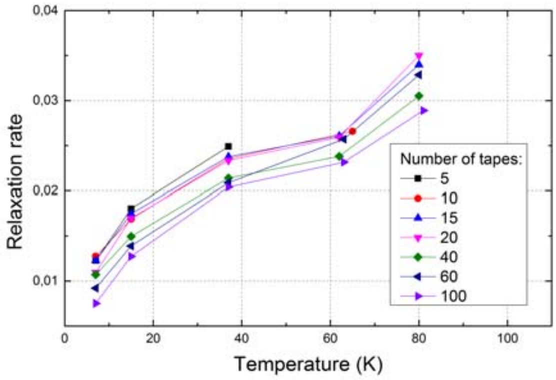

Fig. 4. Temperature dependence of the relaxation rate for various number of tapes in the stack.

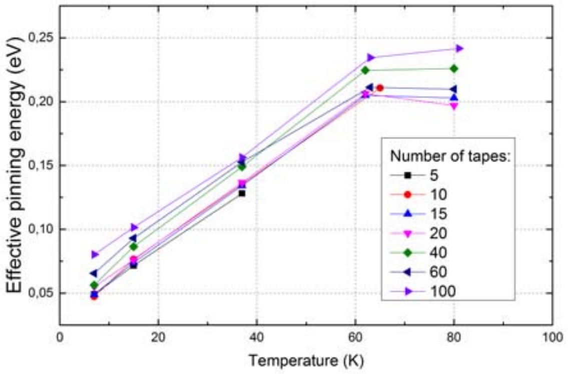

Fig. 5. Temperature dependence (arbitrary units) of the pinning energy for various number of tapes in the stack.

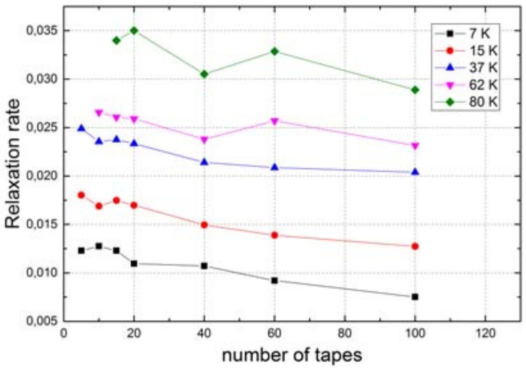

Fig. 6. The dependence of the relaxation rate on the number tapes in the stack at various temperatures.

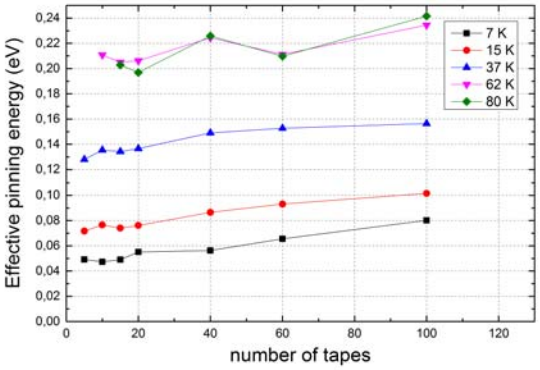

Fig. 7. The dependence of the pinning energy on the number tapes in the stack at various temperatures.

5. CONCLUSION

Trapped flux of stacks of tapes was measured in a wide range of temperatures and external magnet fields. Results show that the remnant flux reaches saturation with increasing amount of tapes in a stack. From the other side, the relaxation rate decreases and the time of flux keeping grows respectively. Thus it is not profitable to increase the stack height more than the certain value because trapped flux value changes insignificantly, but amount of the tapes should be enough to provide the required operating time of the magnet.

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