Levitation properties of pre-magnetized HTS tape stacks

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Abstract This study presents new results on investigation of the levitation force between a permanent magnet and pre-magnetized HTS tape stacks containing from 20 to 100 tapes of 12 mm × 12 mm. Stacks were magnetized in superconducting magnet capable of creating a field of up to 8 T and placed in a levitation force measurement system. Experimental data on levitation force value and the effect of lateral displacement on it for stacks of tapes with different values of the captured flux and thickness have been obtained. Levitation force decay during the lateral displacements above a permanent magnet was observed for different stacks.

1. Introduction
High-temperature superconductors (HTS) are very promising for magnetic-force-based applications. They can be used to create levitation systems and trapped flux magnets. They are already widely used for bearings, rotating separation systems, levitating transport, kinetic energy storage devices, engines and generators [1–3].

However, if earlier for these applications bulk superconductors grown by various methods were usually considered, then now second-generation HTS tapes are actively used.

Nowadays, researchers actively investigate the possibility of using HTS tapes in levitation applications. A detailed comparison of the advantages and disadvantages of stacks of tapes and bulk HTS for levitation applications is given in work [4]. In our previous papers we studied the possibility of capturing the magnetic field by stacks of tapes [5, 6] and the levitation force of the stack of HTS tapes above the permanent magnet with respect to the lateral displacement, vibrations and crossed magnetic fields [4, 7, 8].

For the development and optimizing a levitation system, it is important to have information about influence of various parameters on the strength of interaction of HTS tapes with a magnet. In addition to the characteristics of the tapes, external factors, such as temperature, alternating magnetic field, as well as the preliminary magnetization of HTS tapes, also affect the levitation force. This work is devoted to the influence of preliminary magnetization on the magnitude of the levitation force, as well as on its behavior when the magnets and the superconductor are displaced relative to each other.

2. Experimental Techniques
2.1. Samples
The objects of research were HTS tapes produced by SuperOx. Their characteristics were as follows: no copper coating, 12 mm wide, critical current 550 A at 77 K self-field. They were cut into square fragments of 12 mm × 12 mm and formed in stacks of different heights with n = 20, 40, 50, 60, 80, and
100 elements. A number of measurements were performed to study the effect of pre-magnetization of such tape stacks on their levitation characteristics. The samples were cooled with liquid nitrogen in a field of a superconducting magnet with a magnetic induction of 3 T, then they were placed in a cryostat of the levitation force measuring system. The field captured by the tapes was measured using a Hall sensor immediately after magnetization. The measured values are shown in the Table 1.

**Table 1.** Magnetic flux capture for stacks of different thicknesses.

| Number of tapes in stack | Captured field, mT |
|--------------------------|--------------------|
| 20                       | 168                |
| 40                       | 223                |
| 50                       | 235                |
| 60                       | 247                |
| 80                       | 233                |
| 100                      | 246                |

2.2. *Experimental setup*

Measurements of levitation force between the stack of HTS tapes and a permanent magnet were performed by use of homemade experimental setup. The cryostat (2 on Fig. 1(a)) with the sample holder (4 on Fig. 1(a)) was mounted on a motion system (1 on Fig. 1(a)) capable of vertical and lateral movements with a minimal step of 2 µm. A stack of four Nd–Fe–B permanent magnets (5 on Fig. 1(a)) was used in the experiment to supply the applied magnetic field. Each magnet was 30 mm in diameter, 10 mm high, made of N45 grade material providing a surface remnant flux density of 0.30–0.33 T. The whole stack of magnets had a surface flux density of 0.58 T. The stacked magnets were fixed on a load cell (6 on Fig. 1(a)) for levitation force measurements. More experiment details can be found in work [9].

![Diagram of experimental setup](image)

**Figure 1.** a) Experimental setup for levitation force measurements. 1—motion system, 2—cryostat, 3—liquid nitrogen, 4—brass holder, 5—stack of Nd–Fe–B permanent magnets, 6—load cell, 7—stack of tapes, 8—Hall sensor.

b) The dependence of repulsive force between the stack and the permanent magnet on the vertical coordinate during descending of the stack. Results for stacks with different numbers of tapes. The temperature was 77 K.
First, the sample was placed in cryostat with liquid nitrogen at a distance of 60 mm above the center of the stack of cylindrical magnets and descended from this position with a step of 1 mm with repulsive force measurements on each step. In final position the distance between the stack and the permanent magnets was 6 mm. Descending curves are shown in Fig. 1b. At the final distance the sample was moved laterally in order to evaluate the dependence of the repulsive force on lateral displacement. A cycle of 20 reciprocating motions along the Y axis in the range of ± 20 mm relative to the center of the magnets was carried out. As a result, the dependences of the levitation force on the distance were obtained for stacks of HTS tapes of various thicknesses.

3. Results and Discussion
The dependence of the maximum repulsive force on the number of tapes in the stack for magnetized and non-magnetized tapes is presented in Figure 2. The difference in the levitation forces of the magnetized and non-magnetized stack depends on the number of tapes in the stack. The greater the thickness of the stack, the greater the difference between the forces of a magnetized and non-magnetized stack. A fully magnetized stack of 40 tapes (remnant field at the surface of 223 mT) demonstrates a 27% higher maximum levitation force at a distance of 6 mm. However, for a stack of 100 tapes, the repulsive force increases by 48%. This can be explained by the remagnetization of smaller stacks by stray magnetic field of permanent magnet.

![Figure 2](image2.png)

*Figure 2.* Dependence of the maximum repulsive force on the number of tapes in a stack for fully magnetized and non-magnetized stacks.

![Figure 3](image3.png)

*Figure 3.* a) Vertical repulsive force measurements for a magnetized stack of 100 layers. 20 lateral movements were performed in a range of ±20 mm. The distance to the sample is 6 mm, temperature 77 K. Stack was magnetized in magnetic field of 3 T, remnant magnetic field above the stack surface was 246 mT.

b) Vertical repulsive force measurements for a non-magnetized stack of 100 layers. 20 lateral movements were performed in a range of ±20 mm. The distance to the sample is 6 mm, temperature 77 K.
Results of a study of the effect of lateral displacement on levitation force for non-magnetized and magnetized stack of 100 layers are shown in Figs. 3a and 3b respectively. It can be seen that the levitation force decreases faster in the case of a magnetized stack. To more clearly demonstrate the decay of the levitation force the relationship between the weakening of the force and the number of cycles for stacks with different numbers of tapes is shown in Figure 4a. It also shows the results for a non-magnetized stack of 100 layers. Obviously, the decay rate of the force grows with increasing trapped magnetic flux.

Moreover, the levitation force rapidly decreases in the initial few cycles and the decay slows down with an increase in the number of cycles. It is clearly seen from the dependence of the attenuation coefficient of the levitation force in Figure 4b. The ratios of force decay were obtained by normalizing the levitation force with respect to the initial force value for each group of data and taking the natural logarithm of the reciprocating number. The attenuation coefficient of the levitation force in the case of fully magnetized stacks is almost the same for stacks of more than 50 tapes.

![Figure 4. a) The decrease in levitation force as a function of the reciprocating numbers for stacks with different numbers of tapes and various magnetizations. b) Attenuation ratio of the levitation force. The ordinate is the levitation force normalized on the initial force value and the abscissa is the logarithmic disposition of number of cycles.](image)

4. Conclusions
We have carried out an investigation of the influence of pre-magnetization on levitation properties for stacks of 20–100 HTS tapes. Based on the obtained results, we can conclude that:

(i) Pre-magnetized stacks show greater repulsive forces than non-magnetic ones for all measured elements in the stack. The difference in the levitation force of the magnetized and non-magnetized stacks increases with the number of tapes in the stack

(ii) Capture of the magnetic flux not only provides a greater levitation force, but also leads to a greater attenuation of the levitation force at lateral displacements.

(iii) The attenuation ratio of the levitation force during lateral displacement increases with increasing magnetization. However, in the case of fully magnetized stacks, the attenuation coefficient of the levitation force in the case of fully magnetized stacks is almost the same for stacks of more than 50 tapes.

(iv) The decrease in levitation force during lateral movements slows down with each movement and tends to saturate. In the case of a non-magnetized stack, saturation occurs earlier.

Summing up the above, we can conclude that in systems with transverse vibrations, non-magnetic stacks have higher stability and to increase the levitation force in such systems it is rational to increase the thickness of the stack, rather than using pre-magnetization.
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