

Superconductivity Centennial Conference

## Critical currents and AC losses in YBCO coils

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### Abstract

Measurements of V-I characteristics and AC losses of YBCO single pancakes and multipancake coils have been performed. YBCO pancakes and coils were wet-wound using non-insulated YBCO tapes. Layer-to-layer insulation was achieved by using epoxy filled with alumina particles that ensures higher effective current density of the coil in comparison with coils of standard insulated tapes. This procedure also improves the coil's thermal conductivity in the direction perpendicular to the tape plane. Static and alternating magnetic fields have been applied to the AC current carrying coils during measurements. DC magnetic fields up to 50 mT affect the V-I curves only slightly. On the other hand, AC magnetic fields with amplitudes up to 50 mT and frequencies 4-100 Hz change the form of the V-I curves and strongly reduce the critical current. AC losses and their distribution along the coil were measured by electrical and calorimetric methods. It was found that AC losses peak at the central region of the coil and depend strongly on distance between adjacent pancakes. Surprisingly, adjacent pancakes, even if kept in an open circuit state, increase the losses of a current carrying pancake. It is suggested that introduction of gaps between pancakes/double pancakes can be used as means for decreasing AC losses in multi-pancakes YBCO coils.

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*Keywords:* YBCO coils, I-V curves, external magnetic field, AC losses, calorimetric method, electric method

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### 1. Introduction

High- $T_c$  superconducting (HTS) tapes and coils are used in power devices either as conductors/coils carrying AC transport current and subjected to AC magnetic field as in transformers or in resistive Fault Current Limiters (FCL), or as coils carrying DC transport current. In the latter, the DC coil may also carry a small AC current component causing AC self-fields, as in Superconducting Magnetic Energy Storage (SMES) devices, [1,2] or the DC coil might be subjected to external AC magnetic field as in "saturated cores" FCL devices [3,4]. Second generation (2G) HTS tapes are used in most of today's HTS device prototypes and the properties of these conductors carrying DC and AC current and the AC losses of HTS tapes are well studied [5-8]. The properties of HTS coils are usually calculated based on single tape data

[9-11]. However, while for DC coils this approach gives good results, for AC coils it may fail [8]. It is therefore necessary to measure the AC losses in HTS coils. In this work we describe an experimental study of HTS coils made from YBCO pancakes. V-I curves of the coils have been measured for DC and AC fields perpendicular to the coil axis. We also measured the AC losses in multi-pancake coils using electrical and calorimetric methods.

## 2. Experimental

The pancakes were wound with non-insulated wire. We used a wet winding technique developed by Bar-Ilan and Ricor [12]. Epoxy filled with fine alumina particles was applied to the tape surface in the process of winding. The grain size of the ceramic powder defines the minimal distance between adjacent turns and enables the required level of electrical insulation along with higher thermal conductivity and higher filling factor, in comparison to insulated wire coils. The increase in coil filling factor is achieved by omitting insulation layers that can be as thick as 100 μm. With typical 2G wire thickness of 100μm or less, the improvement in filling factor hence in the overall current density is substantial.

Table 1. Parameters of YBCO pancake.

Parameter	V
Inner diameter, mm	10
Outer diameter, mm	11
Number of turns	20
Length of wire, m	6.
Inductance, μH	76-81
Critical current (77 K), A	70

Multi-pancake coils were made from single pancake coils connected by soldering 8 mm long pieces of HTS tape joints. It was found that 4 such joints give rise to a small resistance that practically does not change with increasing number of connections.

I-V curves were measured by standard four-point method. All I-V curve measurements were performed in liquid nitrogen. The device for measuring I-V curves of single pancakes in external magnetic field is shown on Fig. 1. The pancake 2 was placed between two counter wound copper coils 1. The field in between the coils at the pancake position is directed perpendicular to coils axis. The maximal amplitude of the field was 160 G limited by heat removal rate from the copper coils.

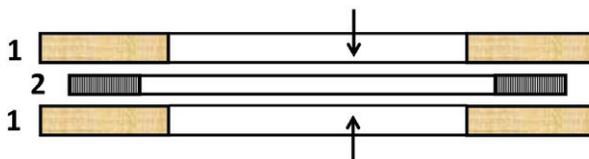


Fig.1. I-V measurement setup for measuring single pancakes in external magnetic field. 1 – copper coil, 2 – HTS pancake.

AC losses were measured by power meter LMG450 (ZES ZIMMER). To confirm the validity of the electric measurements and to estimate the temperature dependence of the AC losses, we used a cryocooled calorimetric measurement setup (Fig. 2a). Heat from the HTS pancakes, 2, flows to the cold head, 1, through thin copper plates, 4, (Fig. 2b), connected to a thick copper plate, 3, with copper blocks, 5. Heat flow was calibrated by NiCr-wire heaters, 6, of 100 Ohm resistance attached to the cylindrical surface of each pancake. An additional heater, (7 Ohm), attached to the cryocooler's cold head allowed to change and control the pancakes' base temperature. Measurements of AC losses in a cryocooled system at 75 K and in liquid nitrogen (77 K) gave the same results (Fig. 3a). Calorimetric and electric measurements were performed simultaneously and good coincidence of results has been obtained (fig. 3b). Since the coil temperature depends also on the heat release due to AC losses, it is necessary to stabilize its temperature by adjusting the power of both heaters. Results of AC losses measurements reported here have been obtained for  $T = 77$  K.

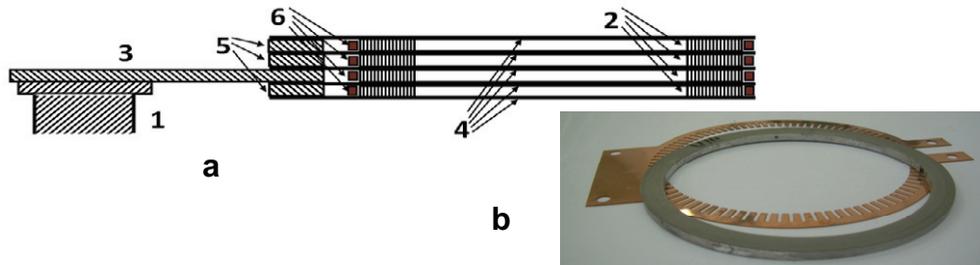


Fig. 2. (a) Schematics of the cryogen-free AC loss measurements setup: 1 - cold head; 2 - HTS pancakes; 3 - thick copper plate 4 - serrated copper ring; 5 - copper blocks; 6 - NiCr heaters 100 Ohm. (b) Serrated copper ring and pancake.

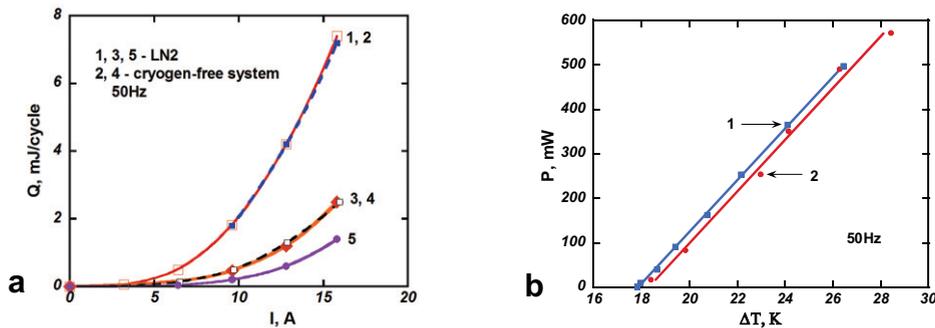


Fig. 3. (a) Comparison of AC losses measured by electric method in liquid nitrogen and in the cryogen-free system: 1, 2 – double pancake; 3,4 – single pancake with adjacent pancake; 5 – single pancake; (b) Results of AC losses measurements by electric, 1, and calorimetric, 2, methods.

### 3. I-V curves measurement in DC and AC magnetic fields

I-V curves of single pancakes were measured in DC and AC magnetic fields perpendicular to the coil axis. For DC fields up to 480 G, a relatively weak field-dependence of the critical current is obtained (Fig. 4a). The power-law index,  $n$ , is almost insensitive to the magnetic field in this range. The DC field shows a more pronounced affect when measuring the dependence of the coil's critical current on the number of pancakes in the coil (Fig. 4b). When a current of 65A flows in the coil, the maximal self-field radial component changes from 560G in a single pancake to 1150G in a 4-pancakes coil. This build-up of

the perpendicular field component with increasing pancakes number, explains the strong critical current dependence on pancakes number exhibited in Fig. 4b.

In contrast to the weak effect of DC field, the I-V curves are strongly affected by AC magnetic fields ranging from 80 to 240 G rms. A noticeable voltage appears much below the DC critical current and strongly depends on the frequency and amplitude. I-V curves of a single pancake in AC magnetic field of 240 G perpendicular to the coil axis are shown in fig. 5a. The frequency dependence of the critical current is not monotonic (fig. 5b): the critical current increases with increasing frequencies, reaches a maximum at frequencies of 10-20 Hz, and then decreases with a further frequency increase. Similar effect was observed in short tape samples [6]. In reference [12], I-V curves of BSCCO double pancakes were measured in AC magnetic field parallel to coil axis. The results presented mildly sloped curves similar to earlier findings for BSCCO short tape samples [7].

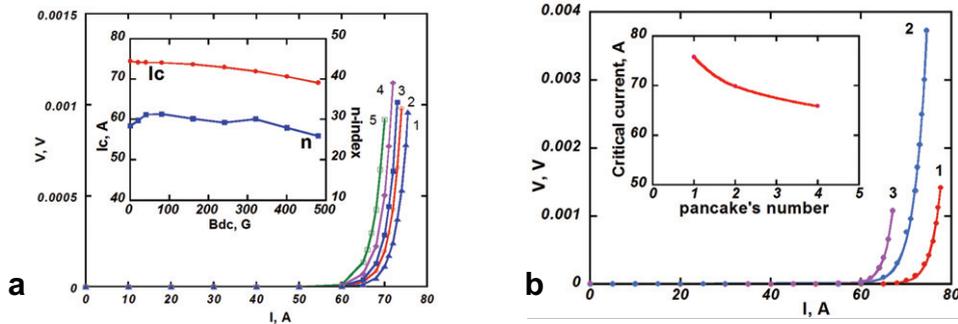


Fig. 4. (a) I-V curves of single pancake in perpendicular DC magnetic field; (b) I-V curves of single pancake, double pancake and 4-pancakes coil.

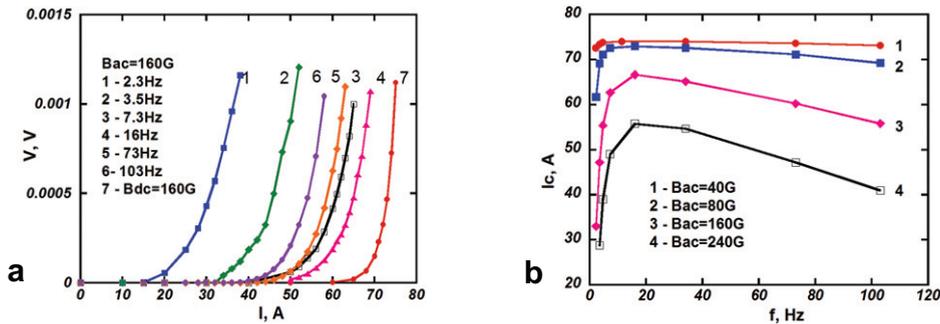


Fig. 5. (a) I-V curves of single pancake in AC magnetic field of 240 G perpendicular to coil axis; (b) The dependence of critical current on frequency of external AC magnetic field.

#### 4. AC losses in pancake coils

##### 4.1. Influence of an adjacent pancake on the AC losses in a single pancake

In [8] we described the results of AC losses in BSCCO coils. It was found that a pancake carrying no current placed in close vicinity to a current-carrying pancake causes a marked increase in the AC losses of the current-carrying pancake. The same effect is observed for YBCO pancakes. Fig. 6a exhibits the V-I curve of a current-carrying pancake for three levels of gaps to an adjacent, open-circuited pancake. The additional voltage increases with current amplitude. Increasing the frequency also causes a voltage

increase, but its influence gradually decays (Fig. 6b). Naturally, the influence of the adjacent pancake decreases with increasing gap value [8].

#### 4.2. AC losses in multi-pancake coils

Fig. 7a displays the distribution of losses between the single pancakes in a four pancakes coil. Clearly, the losses in the whole coil are equal to the sum of the losses in the four single pancakes and the sum of the losses in two double pancakes. A surprising result seen in the figure is that AC losses of single pancakes at the coil center (curves 4,5) are larger than the losses of outer placed pancakes (curves 6,7) although the perpendicular magnetic field on outer pancakes is higher.

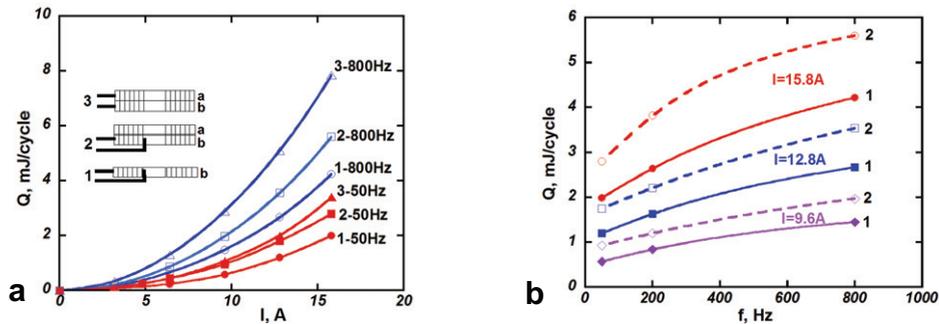


Fig. 6. (a) AC loss in single pancake coil with and without adjacent pancake as function of current at different frequencies as compared with AC loss in single pancake from the double pancake. (b) Dependence of the AC loss in single pancake with adjacent pancake (2) and without adjacent pancake (1) on frequency and transport AC current.

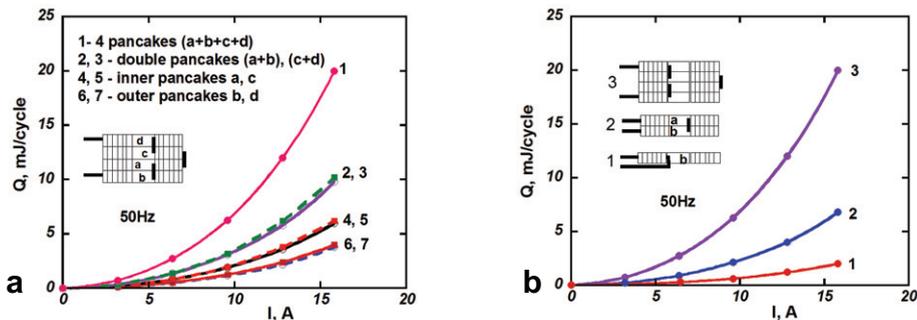


Fig. 7. (a) Distribution of losses between single pancakes in four pancakes coil; (b) Dependence of AC losses on current amplitude for single pancake, double pancake and 4-pancake coil.

Fig. 7b shows the dependence of AC losses on current amplitude for single pancake (1), double pancake (2) and 4-pancake coil (3). The increase in losses with increases number of pancakes is much higher than linear. An attempt to explain this finding by the increase in the magnetic field fails because the pancakes at the edge that experience the highest magnetic field are shown to generate the least loss. Further investigations are required to understand the distribution of losses within coils.

#### Summary

I-V curves of YBCO pancakes are strongly affected by perpendicular external AC magnetic field. The effect strongly depends on frequency and amplitude. These findings resemble qualitatively the observations in single tapes but the frequency dependence is not monotonic.

AC losses in YBCO pancakes coils were measured by calorimetric and electrical methods. It is revealed that:

- Distribution of losses between single pancakes in four-pancakes coil shows higher losses in inner pancakes and lower losses in outer pancakes. Similar results have been observed in BSCCO coils as well.
- Adjacent, open circuited pancake strongly influences the losses in single pancakes; the effect depends on the gap between the pancakes and on frequency.

### Acknowledgements

This work was supported by the Israeli Ministry of National Infrastructures.

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