

## AC losses in HTS multi-pancake coils made of BSCCO-tape

**Friedman Alex, Wolfus Yeoshua, Kopansky Faina, Yeshurun Yosef**

Institute of Superconductivity, Department of Physics, Bar-Ilan University, Ramat Gan 52900 Israel;

freidma@gmail.com

**Abstract.** We present measurements of AC losses in Bi-2223 multi-pancakes coils with different geometries. Measurements were performed at 77 K at frequencies ranging from 50 to 1600 Hz. The losses are found to depend strongly on coil configuration and linearly increase with increasing frequency. The centre pancakes in the coils exhibit larger AC losses than pancakes situated at the ends. Also, AC losses within pancakes depend on adjacent pancakes, even if kept in an open circuit state. The strong change of inductances of pancakes in multi-pancakes coils was observed in opposite to negligible change for single pancake. Introducing a gap between pancakes/ double pancakes can be used as a means of decreasing AC losses in multi-pancakes HTS coils.

### 1. Introduction

Power devices based on high temperature superconductors (HTS) are expected to be incorporated in future power applications. The issue of AC losses in coils made of HTS is, therefore, of current interest. Characteristics of HTS coils carrying DC current can be calculated on the basis of known wire properties by integrating voltage on each segment of the wire in the coil depending on the value and direction of local magnetic field [1]. Under AC mode of operation, the situation becomes more complicated as mechanisms for AC loss generation, such as flux creep, dynamic resistance and flux hysteresis, play important roles [2]. While some studies continue to use loss data obtained for short wire sample to calculate AC losses in coils [3,4] and to optimize the geometry of coils and minimize AC losses [5], other recent work has shown [6] that HTS wires behavior in stacks is different from that of free wires. There is only limited number of experimental research of AC losses in HTS coils confined by single [7-12] and double [13] pancakes. Results of these works show only that problem of losses in multi-turn HTS coils is complicated [7]. It is the goal of this paper to experimentally study the AC loss in HTS pancakes forming a coil. We present a detailed study of AC losses of single pancakes, double pancakes and multi-pancake coils with different geometry containing several double pancakes. The measurements were carried out at current much below critical current of the coils at frequencies from 20 Hz to 1600 Hz. We present new results of the distribution of the AC losses inside coils that surprisingly show that AC losses are significantly higher in central pancakes than in edge pancakes.

## 2. Experimental

Bi-2223, high current density, tapes by AMSC have been wound to form 8 pancakes. A photo of a such pancake and the basic characteristics of the pancakes are presented in fig. 1 and Table 1. 4-pancakes and 6-pancakes coils were assembled by soldering pancakes in series. For improved heat transfer between the coil and the cold head of the cryocooler, a split, toothed, electrically isolated copper ring was inserted in between pancakes (fig. 1). V-I curves of single pancakes and 4-pancakes coil are shown in fig. 2. Critical currents (1  $\mu\text{V}/\text{cm}$  criterion) are about 80 A for single pancakes, 74 A for double pancakes, and 61 A for the 4-pancakes coil. Outermost pancakes in the 4-pancakes coil exhibit critical current of about 57 A, slightly below the critical current of the whole coil. Inner pancakes exhibit an average critical current of 85 A.

Table 1. Parameters of HTS wire and pancake

<b>Bi-2223 tape</b>	
Cross section, $\text{mm}^2$	4.2x0.3
Critical current (minimum at 77 K, self-field), A	125
<b>Pancakes (Average data)</b>	
Inner diameter, mm	100
Outer diameter, mm	117
Length of wire, m	6.8
Inductance, $\mu\text{H}$	76-81
Critical current (77 K), A	80

AC losses were measured with precise power analyzer LMG95 of ZIMMER Electronic Systems. The measurements were performed on single pancakes, double pancakes (DP) and 4- and 6-pancakes coils. We checked influence of the toothed copper ring on the losses in double pancakes with and without the ring. A PACIFIC Power Source model 140AMX, with maximal current 20 A and frequency range 20-5000 Hz, was used for the AC current source. Voltage taps were soldered to each pancake for measurements of AC losses distribution in multi-pancakes coils.

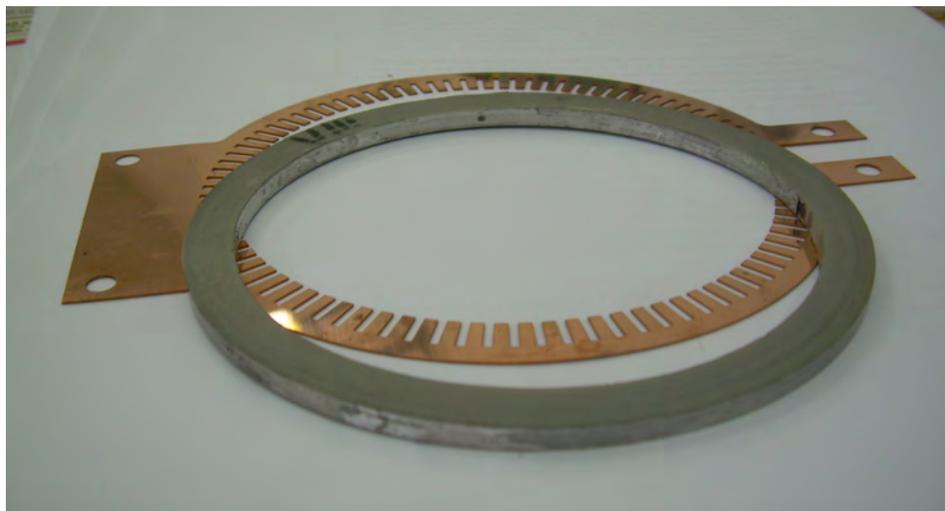


Fig. 1. Single pancake and toothed copper ring

### 3. Results and discussion

#### 3.1. AC losses in 4 and 6-pancakes coils

Fig. 3 shows dependences of AC losses in 4-pancakes coil and in its constituent single and double pancakes. The results are presented in linear scale for greater data details. As the radial component of the DC magnetic field peaks at the coil edges, it is natural to assume that AC losses also reach their maximum at the outer pancakes. However, as opposed to such expectations, one clearly sees in fig. 2 that the losses in the inner pancakes are higher than in losses in edge pancakes. The sum of all measurements made on constituent pancakes/ double pancakes (curves 2, 3, 4 in fig. 3) equals the losses measured on entire 4-pancakes coil (curve 1, fig. 3).

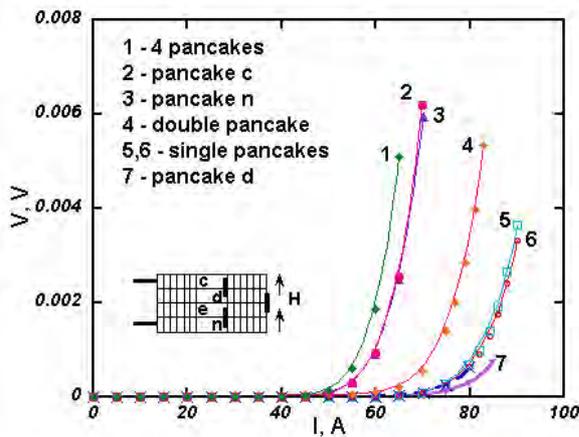


Fig. 2. V-I curves of 4-pancakes coil and constituent single and double pancakes

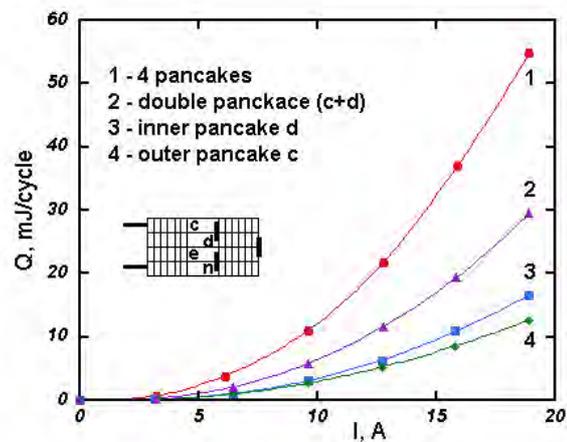


Fig. 3. AC losses of 4-pancakes coil and constituent single and double pancakes

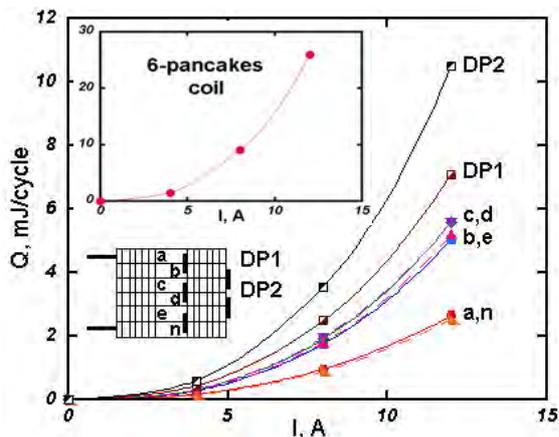


Fig. 4. AC losses of 6-pancakes coil and constituent single and double pancakes

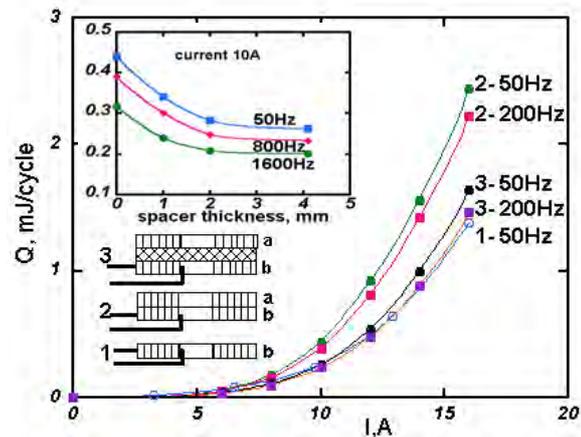


Fig. 5. AC losses in single pancake and in the same pancake with attached another single pancake

Similar results were obtained for a 6-pancakes coil (fig. 4). In this case, the difference between losses in outermost and in inner pancakes is even more pronounced. At the same time, the difference between losses in inner pancakes located in the center of the coil and in more remote pancakes is almost negligible. Detailed study of 6-pancakes coil is described later.

The results clearly imply that the distribution of DC magnetic field in the coil cannot be used as a basis for estimating AC losses in the coil. One possible explanation could be that the AC and DC field

distributions are different. A source for this difference could be the magnetic coupling between pancakes when in AC mode.

### 3.2. Influence of interaction between pancakes on AC losses

To further investigate the assumption that adjacent pancakes may mutually affect each other and change the magnetic field and loss distribution, we measured AC losses in single pancake and in the same pancake with another single pancake brought to close vicinity. This additional pancake is kept in an open circuit state so that AC current generated in the current source flows in the original pancake only. The results are shown on fig. 5. A strong increase in the losses of the single pancake is observed when another pancake is brought in contact. The influence of the second pancake decreases with its distance from the current carrying pancake (insert in fig. 5). We observe a slight decrease of AC losses in single pancake with increase of frequency (fig. 6).

Fig.7 shows losses in the case when the current flows in both pancakes, i.e. in a double pancake configuration with a gap between the pancakes. One can see that AC losses in double pancake strongly depend on the distance between pancakes (fig. 7, insert).

When the toothed copper ring of fig. 1 (0.45 mm thickness) is inserted between pancakes, a minor change only in losses of the double pancake is obtained.

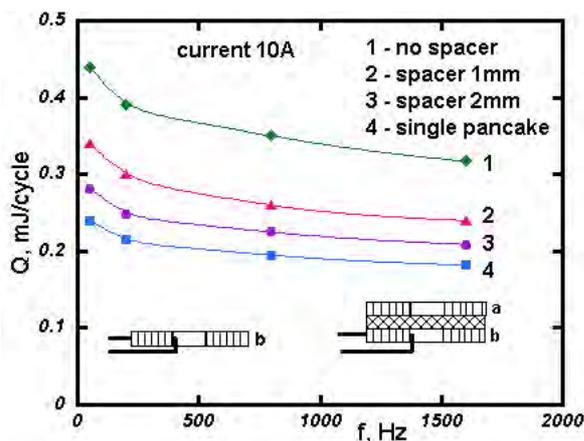


Fig. 6. Dependence of AC losses on frequency for single pancake with attached another single pancake

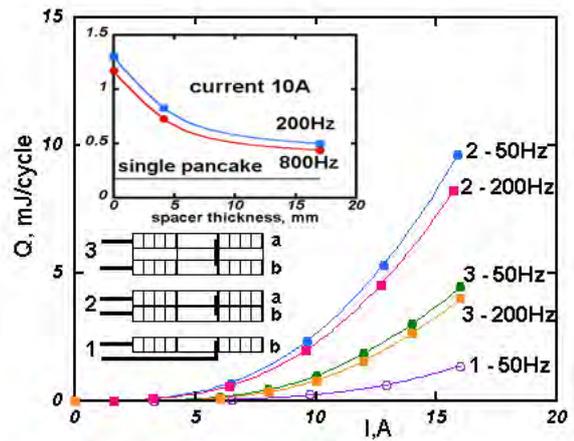


Fig.7. AC losses in double pancake with and without gap

### 3.3. AC losses distribution in a 6-pancakes coil with a gap

Fig. 8 shows the influence of inserting a gap of 10 mm in between double pancakes in a 6-pancakes coil on the losses. Double pancakes are marked DP1, 2 and 3 where DP2 is the centre DP. Loss data was collected for two cases: 1. when the coil is made of the 3 DP without gap and 2. when a 10 mm air gap is added between DP1 and 2. A decrease in losses is observed in all DP, on both sides of the gap. Even DP3, the most distanced DP from the gap shows a significant drop in losses. This result remains valid even if DP1 is switched open and disconnected from the rest of the coil.

Losses in each pancake of the 6-pancakes coils with and without gap are shown on fig. 9 and fig.10. Losses in upper pancake, **a**, do not change noticeably with introducing the gap. Strong decrease of losses in, **b**, and, **c**, close to the gap was observed (fig. 10). At the same time the losses in the inner pancakes **d** and **e** decrease appreciably although their relatively remote distance from the gap. The results imply that introducing a gap can be used as means for decreasing AC losses in multi-pancakes coils.

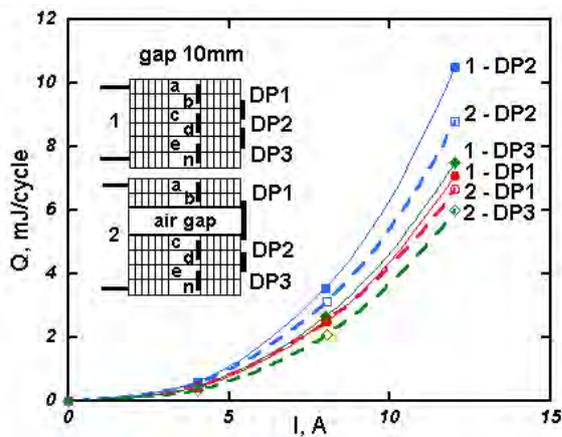


Fig. 8. AC losses in double pancakes of 6-pancake coils with and without gap

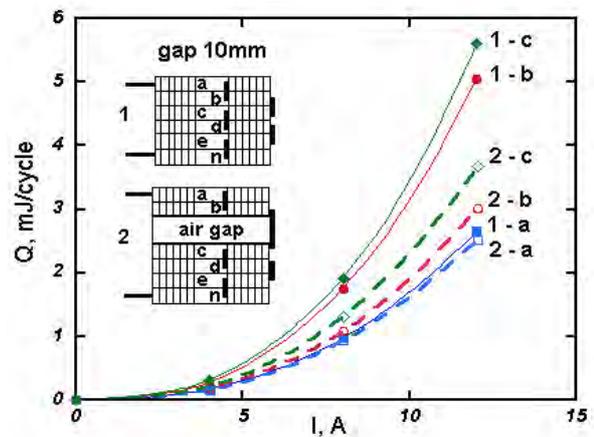


Fig. 9. AC losses in single pancakes close to 6-pancake coils with and without gap

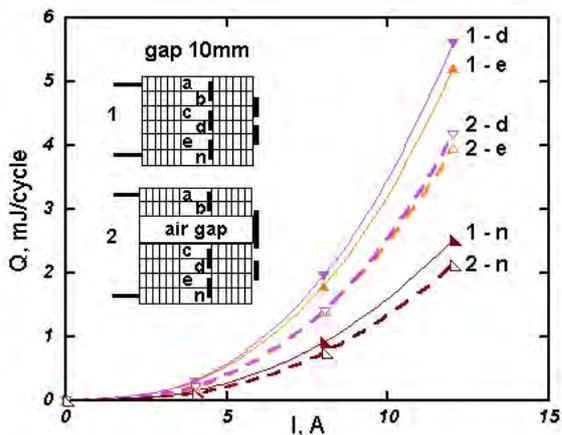


Fig. 10. AC losses in single pancakes remote from gap in 6-pancake coils with and without gap

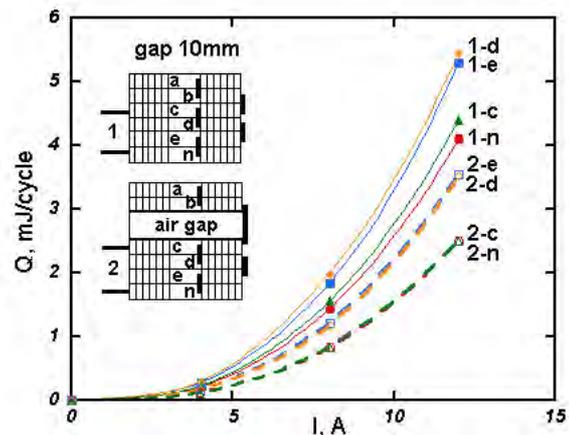


Fig. 11. AC losses in single pancakes in 4-pancake coils with two attached pancakes

Fig. 11 shows AC losses in single pancakes of a 4-pancake coil with two additional pancakes in open circuit state added with and without gap. The data clearly show a significant decrease of losses in all pancakes, even most remote, with the introduction of an air gap.

### Summary

New results of the distribution of AC losses in solenoidal multi-pancake HTS coils have been presented for AC currents below the DC critical current. The results show that:

- the distribution of losses in the coils is unexpected: minimal losses are observed at the edges of the coil where the radial component magnetic field, calculated for DC current, peaks; maximal losses are found in inner pancakes where the radial DC magnetic field component is minimal
- calculation of AC losses and its distribution in solenoidal multi-pancake coils cannot be based on static magnetic field distribution;
- losses in single pancake and in multi-pancake coils are strongly influenced by adjacent pancakes even if the latter are in open circuit state;

- losses in multi-pancake HTS coils are strongly depend on distance between pancakes;
- introduction of an air gap may be utilizes as a means for decreasing AC losses in multi-pancakes coils.

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