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Use of Second Generation HTS Wire in Filter Inductor Coils

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***Abstract*— AMSC's process for manufacturing Second Generation (2G) YBCO High Temperature Superconductor wire provides the flexibility to engineer practical 2G conductors with various architectures. For applications with high frequency ac components, a stainless steel stabilizer is used to minimize eddy current losses. An example of such an application is the so-called Buck Inductor, a filter inductor carrying a DC current onto which a 5 KHz ac current is superimposed. Previously we reported on the development and initial testing of the first 2G HTS toroid for this application. We demonstrated a strong reduction of the ac losses with a DC bias current. In this work, we present results on a toroid using a different double pancake design with better cooling. This design allows operation of the double pancake in liquid nitrogen at high frequencies without heating effects.**

***Index Terms*— High-temperature superconductors, ac loss, superconducting inductor coils.**

I. INTRODUCTION

For the production of Second Generation (2G) High Temperature Superconductors, based on YBCO Coated Conductor technology, American Superconductor (AMSC) uses a bi-axially textured NiW substrate onto which a thin epitaxial oxide buffer layer is deposited (RABiTS^{TM}) [1]. The superconducting $YBa_2Cu_3O_{7-x}$ (YBCO) layer, about 1 μm thick, is grown using a low-cost, solution-based Metal Organic Deposition (MOD) process [2-4]. The coating processes allow a wide (40 mm or wider) format. The process is also amenable to chemical modifications and doping to improve flux pinning and enhance in-field performance. After YBCO reaction and Ag coating the conductor is slit to multiple 4 mm wide "insert" wires which are laminated on both sides to either copper or stainless steel. In this geometry, sold as "344 superconductors", the lamination provides electrical and thermal stability and facilitates a winding process by providing additional mechanical strength.

Copper alloys are typically used for lamination stabilizers in dc applications such as MRI magnet systems and power frequency applications with low magnetic fields such as transmission cables. For the Buck Inductor in this work, a 5 kHz component would induce unacceptable eddy current losses in a Cu stabilizer, and for this reason a 316 stainless steel stabilizer was selected. The stainless steel foil (0.026x4.3 mm^2) is also half the thickness of the standard Cu stabilizer, which further reduces the eddy current loss component.

The other AC loss components are hysteretic loss in the superconducting HTS layer, and, in the case of a magnetic substrate, the ferromagnetic loss [5]. The NiW substrate which is used in the AMSC process is weakly ferro-magnetic (T_{Curie} ~50-60°C), and its influence on total loss in 344 superconductors is somewhat complex. Fig. 1 [6] shows the total transport loss behavior as a function of applied ac current in self-field and in a small DC background field. The magnetism of the NiW tends to enhance the self-field transport loss in the HTS layer at low current amplitudes. At higher amplitudes, the total loss approaches the hysteretic loss of the HTS layer only, and the losses are close to the values predicted by the Norris ellipse model. Application of a small DC background field reduces the total loss so that it approaches the Norris ellipse line. This reduction is believed to be due to a magnetic saturation of the NiW, resulting in a reduction in the relative permeability to μ_r=1 in the presence of this DC field.

A Low Pass Filter Inductor looked like an ac application which could benefit from this loss property. The regular version of this Buck Inductor is a heavy gauge copper toroid operating at 156 A dc with a superimposed 5 KHz ripple of 6 A or less. In a superconducting version, this particular DC+AC operating condition appeared to be able to saturate the NiW substrate and reduce AC loss. The desired inductance ranged from 2 to 20 mH. Inductors with an inductance at the lower end would need the smallest amount of superconductor.

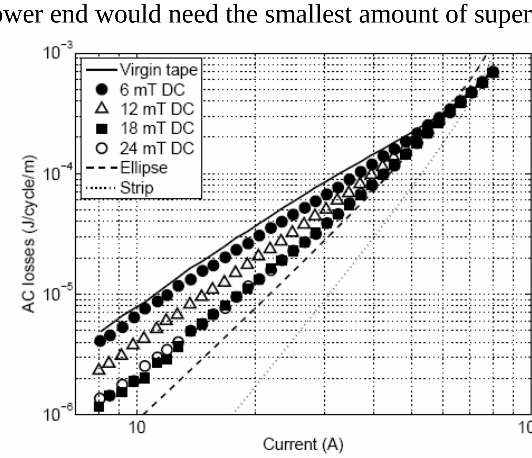

Fig. 1Transport losses of an insert wire (no laminate) as a function of peak current, various DC background fields [6]

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This inductor would see the largest ac amplitude and losses. An inductor with high inductance would need more superconductor but would have the benefit of lower ac amplitude. We selected an inductance in the 3-6 mH range based on the available amount of wire.

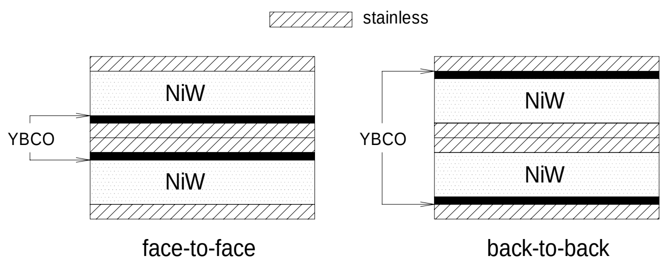

Fig. 2. A two-in-hand winding configuration. Left: face-to-face, YBCO layers (black) are separated by the stainless stabilizer layers. Right: back-to-back, YBCO layers are separated by stainless and NiW.

Two prototype inductor coils were fabricated using a toroid configuration with a 3-6 mH inductance. A two-in-hand winding was used, for which two options for the stacking orientation of the individual wires were available as depicted in, Fig. 2. Both the first and second prototype toroid coils used a face-to-face configuration for the two-in-hand winding. This method has the advantage of efficient current sharing and ease of positioning of current leads and voltage taps. The maximum DC current was scaled down to 70-90 A for operation at 77K, well below the estimated critical current of 120-140 A of two-in-hand set of wires at 77K, SF. The difference between the prototype toroids was in the manner of insulation. The first toroid used epoxy-impregnated double pancake (DP) coils, which were robust but had limited heat transfer to the L_{N2}. The second toroid used an open DP construction with easy access for L_{N2}. This type was less robust, and needed more care with cooling/warming cycles. Previously we reported on the building and testing of this first toroid which consisted of 16 double pancake (DP) coils, all epoxy-impregnated [7]. The toroid used 256 m of stainless-clad 344 superconductors, and had an inductance of 5.2 mH. At 400 Hz the inductor showed a strong reduction of the ac losses with a 20-40 A DC bias current, confirming the short length results from Fig. 1. A high quality factor Q=~400 (Q=Lω/R) was demonstrated.

The second prototype aimed at demonstrating the open DP design, in which the 344 superconductors were wound with an insulating woven material to separate the windings, but without the additional epoxy impregnation, for improved heat transfer to the nitrogen.

The back-to-back arrangement as shown in Fig. 2 is more difficult to make as single current leads and voltage taps are no longer feasible. They need to be replaced with a thin U-shape which splits the current injection and voltage measurement over the two wires at each location. The arrangement does potentially offer significant AC loss reduction in the absence of a DC current. Tsukamoto et al [8] demonstrated a loss reduction in a back-to-back arrangement of 2G HTS wire containing a magnetic substrate of unknown chemistry when the wires were connected in series. While the individual superconductors showed transport losses which agreed with Fig. 1 (no DC background), positioning them back-to-back reduced the loss to an ellipse-type Norris loss. Such an arrangement should not make the loss any different for the actual inductor when running with a DC+AC current (where the DC field reduces the permeability to 1). However, we were interested to see if the effect could be reproduced in AMSC's NiW-based 2G wire. For this, we fabricated and compared the losses in two DPs, one using a face-to-face configuration and the other a back-to-back configuration, both using the same open coil construction and parameters as the other DPs in the toroid. In addition, we developed a 4-ply superconductor in which two HTS insert wires are laminated back-to-back to two metal stabilizers (see Fig. 9) in a back-to-back configuration.

II. Toroid Manufacture and Characterization

A. *Manufacture of Double Pancake coils*

The 344 superconductors for this toroid were made using a standard 0.8 μm thick YBCO layer. The laminate material was 316 stainless, with a thickness of 26 μm. All 344 superconductors are tested at 77 K, in a reel-to-reel I_c system, in which the voltage taps are 1 m apart. Nominal I_c of each wire was 70 A. Each double pancake (DP) coil used 16 m in total, or 2x4 m in each pancake. For the DPs, polymer pre-forms were used, as shown in Fig. 3 after winding. The open structure allowed easy access for L_{N2}. The mid sections were milled away to allow space for pancake-to-pancake connections, and soldering of the current leads. Copper foils were used for all current leads and voltage taps. The co-winding included the two conductors, face-to-face, and one layer of open polymer mesh for insulation and L_{N2} access. DPs were tested after winding at 77 K.

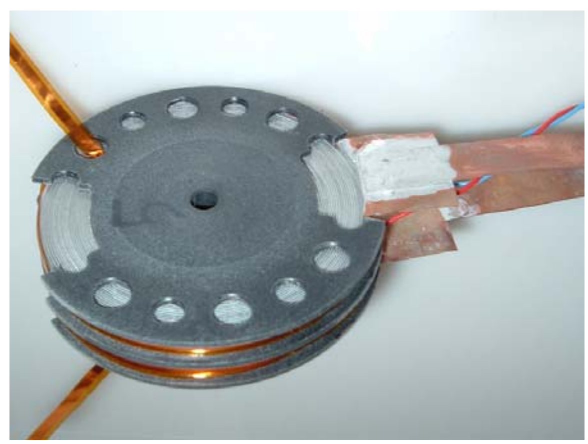

Fig. 3. Double pancake coil wound on polymer pre-form. Slots were machined for current lead access and pancake-to-pancake connection.

B. *Assembly of toroid*

The tested DPs were mounted into a toroid configuration, as shown in Fig. 4. A G10 ring forms the support structure, visible at the bottom. The center of the inductor shows the copper current leads, connected in series, and voltage taps for the pancake coils. These allowed checking of coil soundness, pancake-to-pancake resistance within a DP, and the resistance between DPs. Details of the toroid are shown in Table 1. The characteristics are similar to the first Inductor. The lower inductance (3.6 mH versus 5.2 mH) was a consequence of the somewhat larger DPs for this toroid due to the pre-forms, and use of thicker insulation, leading to fewer turns.

Fig. 4 Toroid with sixteen double pancake coils, connected in series.

The toroid inductor was tested in L_{N2} using DC currents up to 90A, well below the transition. The combined resistance of all copper connections was 350 μΩ.

TABLE 1 TOROID CONFIGURATION

Number of double DPs	16
Number of windings per DP	41
Total inductance	3.6 mH
ID/OD pancake coils	48/74 mm
Toroid radius to center line	64 mm
Length of superconductor per DP	16 m (2x4 m/pancake)
Critical current at 0.1 μV/cm	> 90 A
Insulation between windings	Woven polymer, no epoxy

C. AC loss characterization of the Toroid

Fig. 5 shows the equivalent resistance R_{AC} (ohms) versus frequency with no DC current applied to the toroid.

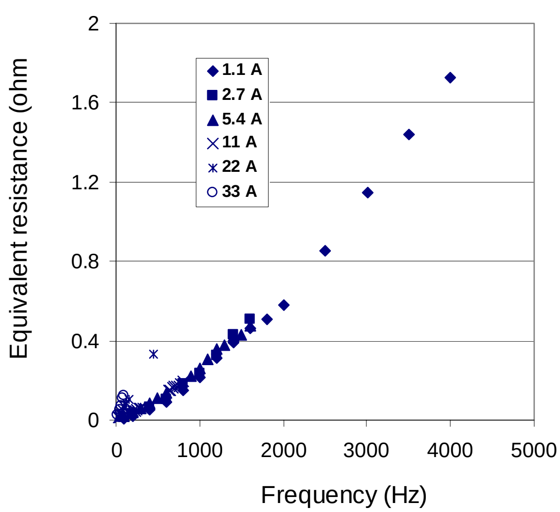

Fig.5. Equivalent ac resistance, R_{AC}, of toroid versus frequency, for various rms ac currents 1 to 30 A , with no DC current, 77 K.

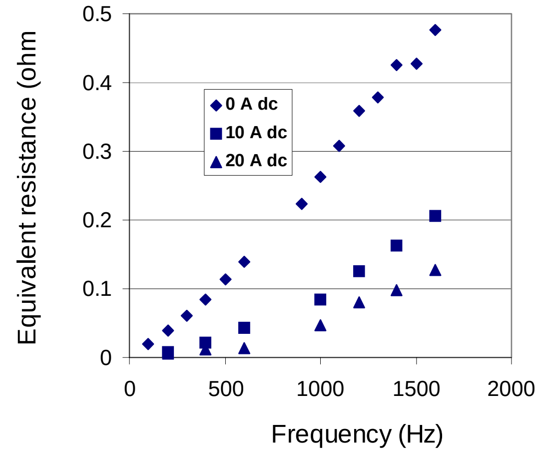

Fig.6. Equivalent ac resistance, R_{AC}, of toroid, versus frequency for 5.4 A_{RMS} and 0-20 A DC, 77 K.

Here $R_{AC}=P/I_{rms}^2$ where P is loss in coil, and I_{rms} the AC current. The AC current was varied from 1 to 30 A_{RMS}. The maximum frequency was decreased with increasing AC current due to power limitations. Curves are linear up to 500-1000 Hz, but at higher frequencies the slope increases. At low frequencies, the slopes are comparable for 1-10 A_{RMS} but increases with higher amplitudes.

Fig. 6 shows R_{AC} versus frequency for a 5 A_{RMS} AC current and 0-30 A DC, up to 1700 Hz. A reduction in loss is apparent with increasing DC current. At 30 A DC, R_{AC} was quite low, below the range of error of the instrumental set-up. A comparison with the earlier inductor, which used epoxy-impregnated DPs, is limited to the curve without DC current, and to frequencies up to 400 Hz. For this condition the earlier inductor showed R_{ac}=0.12 Ω, slightly higher than the 0.09 Ω in the present inductor, but very similar when considering the difference in inductance (5.2 versus 3.6 mH). The open coil appears to allow higher frequencies without danger of quenching, as has been observed in epoxied coils [7].

D. AC loss characterization, two DPs with different superconductor configurations

Two double pancake coils were measured, both at 77 K. The first had a face-to-face configuration, as used in the toroid. These losses are presented in Fig. 7. The second double pancake used the back-to-back configuration, with losses presented in Fig. 8. AC currents were 5.4 A_{RMS} in both cases. The difference between the two configurations is most pronounced at 0 A DC, where, at 5 kHz, the loss in the DP with back-to-back configuration is about 2.3x lower.

The effect of a DC current, while less than in the toroid, is still observable in the DP losses as shown in Fig. 8. This suggests that in coils the magnetic influence of the NiW can be reduced but not eliminated. This effect is probably influenced by the self field of these coils which has a relatively strong component at an angle with the YBCO plane.

E. AC loss characterization of a 4-ply conductor

The earlier discussed transport loss reduction in a back-to-back arrangement was tested using the '4-ply' geometry, see Fig. 9. The 4-ply used two 4 mm wide 2G insert wires.

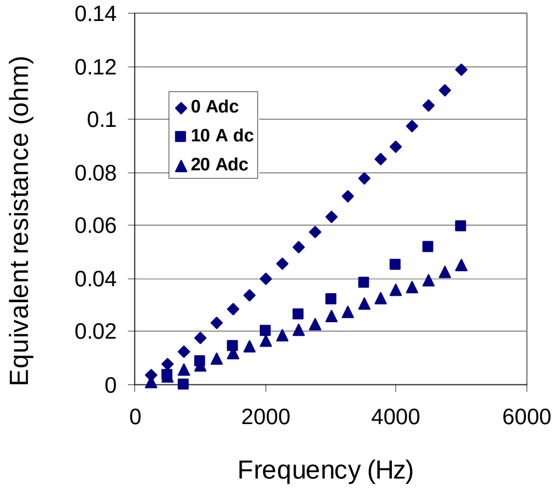

Fig.7. Equivalent resistance R_{AC} versus frequency, in one DP with a face-to-face orientation of the two superconductors, 5.4 A_{RMS}, at 77 K, SF.

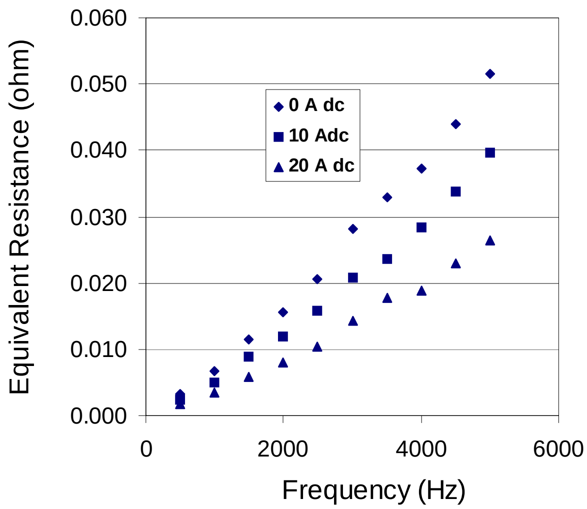

Fig.8. Equivalent resistance R_{AC} versus frequency, in one DP with a back-to-back orientation of the two superconductors, 5.4 A_{RMS}, at 77 K, SF.

These were laminated back-to-back to two copper stabilizers positioned on the outside. The HTS layers were produced with experimental double coat YBCO layers, 1.4 μm thick, with I_c ~125 A for a single insert wire, resulting in a critical current of around 250 A in the 4-ply conductor. Fig. 8 shows the transport loss Q versus current amplitude at 50, 100 and 170 Hz. Q is virtually independent of frequency. The loss Q is comparable to that predicted by the Norris strip model, and slightly below this at higher amplitudes indicating that the magnetic loss associated with the substrate is almost entirely suppressed in this conductor configuration.

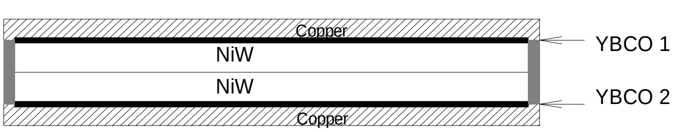

Fig. 9. Sketch of a 4-ply superconductor, with two 2G HTS inserts.

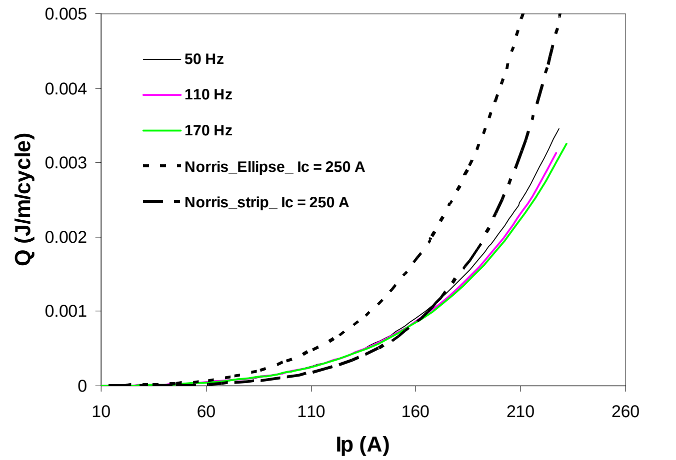

Fig. 10 Transport loss Q versus transport current of a 4-ply superconductor, I_c = 250 A, at 76 K, SF (D. Nguyen and S. Ashworth, LANL). Loss is comparable or below that predicted by the Norris strip model.

III. Conclusions

The toroid inductor built using an open double pancake coil design had, as expected, losses comparable to the design which used epoxy-impregnated double pancakes. The open design does allow better cooling, and consequently, the operating regime was extended to much higher frequencies.

The back-to-back configuration for the NiW substrates in a 4-ply conductor led to significant reduction in transport losses, to the same level as predicted by the Norris strip model. Small double pancakes which compared a back-to-back versus a face-to-face winding of the two conductors showed lower losses for the back-to-back configuration in the absence of DC currents. In the transport measurement the substrate is completely shielded from the fields generated by the current. This is not the case for a coil, and indeed we still see a reduction in loss with a DC current, suggesting that the influence of the NiW substrate cannot be fully eliminated.

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