# Magnetic AC Loss Characteristics of 2G Roebel Cable

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*Abstract*— **Roebel cable has been successfully manufactured using second generation (2G) YBCO wire. Roebel shaped strands of width 2 mm and a transposition length of 90 mm were cut from 40 mm wide tape supplied by American Superconductor Corporation. The tape has a weakly ferromagnetic Ni-5at%W alloy substrate. Eleven insulated strands were assembled to form the cable. This paper reports results for the magnetic AC loss as a function of field amplitude for an insulated 2G Roebel strand and insulated multi-strand Roebel cable in perpendicular and parallel field orientation. In parallel field, the loss at the highest field amplitude measured is reduced by a factor of approximately 30 below the losses in the perpendicular field. In perpendicular field, the losses at the low field amplitude of the Roebel cable sample is influenced by the magnetic substrate. At high field amplitudes (> 0.1 T), the cable and total strand loss converge as expected for an insulated cable, where coupling currents are absent.**

*Index Terms*— **AC loss, HTS coated conductors, Roebel cables.**

## I. INTRODUCTION

THE last decade has seen impressive advances in the development and processing of second generation (2G) high temperature superconducting (HTS) wire. 2G wire technology offers, beyond the promise of lower cost per kA.m, several important advantages such as high engineering current density, better in-field performance at higher temperatures, reduced AC loss in parallel field and significantly improved mechanical properties over its predecessor, *i.e.* the first generation BSCCO HTS wires. But the application of 2G wire technology to AC device applications such as transformers, motors, generators, and fault current limiters remains a challenging goal. The high aspect ratio of the YBCO layer means that magnetic AC loss in perpendicular field is high, so reducing AC losses further is a key step in the realization of 2G YBCO wire technology in large scale ac power applications.

One strategy for reducing AC loss is to divide the YBCO wire into filaments using techniques such as laser scribing [1]. Filamentization has been shown to reduce AC loss in short samples of coated conductor [2-4], but simply dividing the superconducting film in parallel strips may not be a practical solution. To achieve reduced AC loss, magnetic flux has to be able to enter between the filaments. Because the filaments are not transposed, flux can only penetrate between them at the ends of the conductor or at resistive gaps inserted at regular

intervals. The fabrication of coated conductor with transposed filaments has been recently demonstrated [5] in a two layered sample with Rutherford cable geometry. Reduced magnetic AC loss was measured, but the links between the segments are resistive. If the transposed filaments can be realized without resistive links, they have the potential to significantly reduce magnetic loss in perpendicular field, although a lower limit is imposed as filament width becomes comparable to the grain size in the HTS film. The filamentization approach does not help to achieve high currents however; for this we need a multi-strand transposed cable.

The first application of Roebel cable with HTS conductors was achieved by Siemens with a multi-strand BSCCO cable for an application in an HTS traction transformer [6,7]. The limited in-plane bending capability of BSCCO tape imposed a long transposition length of 3 meters [7]. Short transposition length Roebel cable based on 2G YBCO wire has been demonstrated to be a viable approach to reducing the ac loss and increasing the current carrying capability [8, 9]. Since the coated conductor tape has similar limitations for in-plane bending, the tape must be cut into Roebel strand shape before assembling into a cable. Short length laboratory scale samples of 10 and 11 strand cables with 2 mm strand width [9] and 11 and 12 strand cables with 4 mm and 5 mm strand width respectively [8] have been demonstrated.

In this paper, we report magnetic AC loss measurements at 59 Hz on samples of cable with insulated strands as a function of field amplitude in perpendicular and parallel field orientations. We show that the cable sample has a lowered loss compared to the total loss of isolated strands over the entire range of the applied field. In the high field limit, the losses of the cable sample converge to the total loss of the isolated strands comprising the cable. In parallel field, the loss at the highest field amplitudes measured was reduced by a factor of approximately 30 below the loss in perpendicular magnetic field. The AC loss in the parallel field orientation appears to be dominated by hysteretic magnetic loss in the weakly ferromagnetic Ni-5at%W substrate material throughout the measured range of field amplitude.

## II. PREPARATION OF 2G ROEBEL CABLE SAMPLE

We have developed the methodology and manufacturing process for the automated production of HTS Roebel cable [9]. The test cable sample was prepared using 2G YBCO tapes with a weakly ferromagnetic Ni-5at%W substrate, manufactured by American Superconductor Corporation (AMSC). The 40 mm wide and 0.2 mm thick tape was first stabilized by electroplating with 25 microns of copper on each side. Then the

wide strip was cut into narrow Roebel strands using a precision punch tool. The transposition length was 90 mm with step-over angle of 30°. For this sample, current sharing was eliminated by insulating each strand with an epoxy coating of approximately 25 μm thickness. Eleven such strands were then hand wound together to form a Roebel cable. A fully automated winding machine has been developed for assembling longer lengths of cable. Figure 1 displays a segment of the Roebel cable sample of the present study.
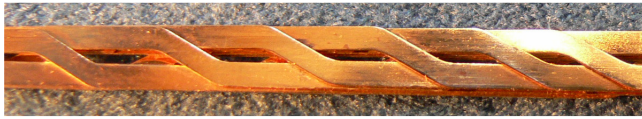


Fig. 1 A segment of the Roebel cable sample consisting of 11 strands of 2 mm width and a transposition length of 90 mm with a step over angle of 30°.

## III.  EXPERIMENTAL DETAILS

Magnetic AC loss experiments were carried out using a calibration-free measurement technique modeled on the system described by Šouc *et. al.* [10]. The basis of the calibration-free technique is to measure the power delivered by the AC power supply to the magnet coil. This is given by the product of the current and the in-phase voltage across the coil. This will be dominated by the resistive heating in the magnet if the voltage is measured directly on the magnet coil. However, by winding the magnet coil with a secondary pick-up winding which measures the identical induced voltage as the primary, current-carrying wire, one can eliminate the voltage corresponding to the ohmic dissipation in the primary winding. Thus, only the power absorbed by a sample placed in the magnet coil is measured. The racetrack magnet coil is solenoid wound using a coaxial copper cable consisting of 6 strands wound around an insulated central strand. The bore was 165 mm long and 9 mm wide. The outer strands carry the AC current to generate the applied magnetic field , while the central strand picks up the induced voltage. The component of the induced voltage that is out-of-phase with the current is typically about $10^3$ times larger than the in-phase component and makes it difficult to accurately measure the in-phase signal. The out-of-phase voltage is subtracted from the induced voltage on the sample coil using an identical cancellation coil. The current passes through the primary windings of the two coils in series, whereas the secondary windings of the coils are connected anti-serially to cancel the inductive voltage. The magnitude and phase of the current are derived from the voltage induced in an additional pick up coil placed in the bore of the cancellation coil. Both coils are immersed in liquid nitrogen.

Three samples, each of length 150 mm were cut from the original 1 meter long cable with a DC critical current of ~ 435 A. Measurements were made on the multi-strand cable samples and on the individual strands with their wide face oriented perpendicular and parallel to direction of the externally applied magnetic field. The measurement frequency was 59 Hz and the field amplitude ($B_{amp}$) was varied in the range 0 to 170 mT. Special care was taken not to apply excessive mechanical strain while disassembling and reassembling the cable strands.

## IV.  RESULTS AND DISCUSSION

The measured magnetic AC loss ($Q$) is expressed in Joules per meter of the sample length per magnetic field cycle (J/m.cycle). Measurements on the three different samples of the cable show that the loss characteristics with the amplitude of the externally applied perpendicular field agree within one percent with each other. This confirms the uniformity of the cable along its length. Next, we took apart the individual strands comprising the cable and recorded the magnetic ac loss of each isolated strand in the perpendicular magnetic field. The cable was subsequently re-assembled and the AC loss measured again. There was no significant change from the original measurement, confirming that careful winding and rewinding of the cable causes no damage, at least with respect to magnetic AC loss.
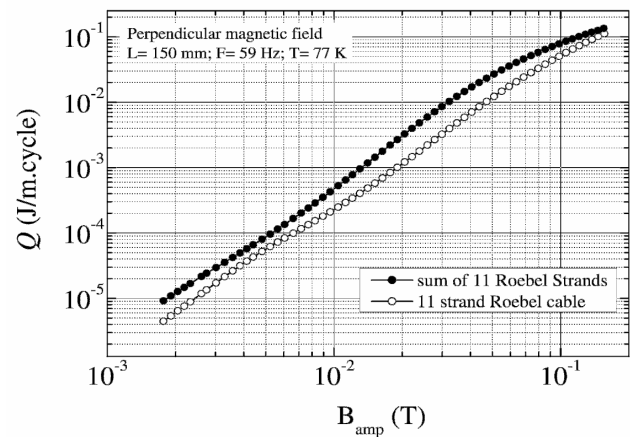


Fig. 2 Magnetic AC loss as a function of field amplitude in perpendicular magnetic field for an insulated 11 strand Roebel cable sample of length 150 mm and the sum of the losses of the insulated 11 strands comprising the cable measured individually. Measurements were made at 77 K at a field frequency of 59 Hz.

Figure 2 shows the loss of the Roebel cable sample and the sum of the loss of the isolated strands comprising the cable as a function of field amplitude. The cable sample has a lower loss than the total loss of isolated strands over the entire range of the applied field. For example, at the lowest field amplitude, the magnetization loss of the cable is reduced by about 50 % compared to the total loss of the respective strands. Further, in the high field limit, the loss of the cable sample tends to converge with the total loss of the isolated strands comprising the cable.

In order to bring out the influence of the weakly ferromagnetic substrate of the coated conductor on the magnetic ac loss characteristics, we have normalized $Q$ with respect to the square of the field amplitude $\left(B_{amp}^2\right)$. The resulting function $\Gamma$ , is expressed in J/(m.cycle.T$^2$). The $\Gamma$ curve improves the visualization of loss data spanning several orders of magnitude. Figure 3 shows the AC loss data for the Roebel cable sample and strands comprising the cable. Note that both the curves are qualitatively similar over the entire range of field amplitude.
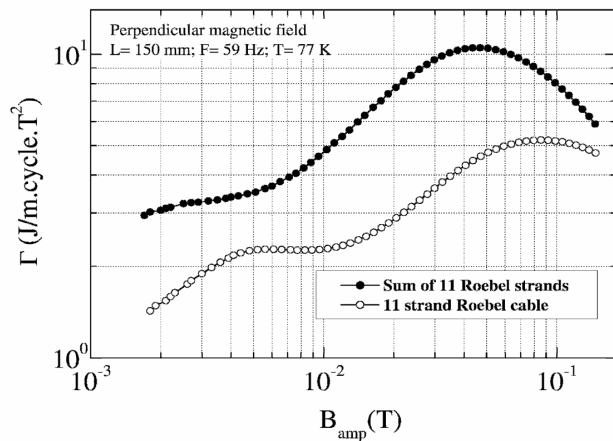
Fig.3: Measured value of $\Gamma = Q / B^2_{amp}$ as a function of the field amplitude for the data displayed in Fig.2.

The AC loss data for the strand and cable can be understood qualitatively as arising from the interaction of the superconducting layer and the ferromagnetic substrate, combined in the cable with the mutual screening of the stacks of strands.

The effect of the weakly ferromagnetic Ni-W alloy substrate on the magnetic AC loss has been elucidated in measurements on stacks of substrate material and HTS tape with a non-magnetic substrate [11]. HTS tapes on non-magnetic substrates are well described by the Brandt model for a thin strip of type II superconductor [12] with just two parameters; the width and critical current density which determine the magnitude and the field amplitude of the maximum of $\Gamma$ respectively.

When the superconducting film is deposited on a ferromagnetic substrate, the local flux distribution is modified by both layers. The magnetic loss is significantly modified and deviates from the Brandt model especially for lower and intermediate field amplitudes. There are three characteristic field amplitude regimes for the perpendicular field orientation. At low field amplitude (below about 5 to 10 mT), the loss is dominated by hysteretic loss in the ferromagnetic substrate because the superconducting layer steers the magnetic flux so that it is concentrated within the plane of the substrate. At intermediate field amplitudes, as the hysteretic loss in the substrate is saturating, the effect of the substrate is to retard the penetration of the flux front into the superconducting layer. As a result, the hysteretic loss in the superconductor is much reduced compared with a 2G superconductor on a non-magnetic substrate. In the high field limit, the Roebel strand is fully penetrated and the magnetic flux is then orientated perpendicular to both the superconductor and the magnetic substrate. The magnetic loss of the substrate is then negligible and the loss is dominated by the superconducting layer. The peak position in the plot is no longer simply determined by $j_c$.

Additional interactions between layers operate in stacks of tapes. At lower field amplitudes, the outermost tapes shield the inner tapes and thereby retard flux penetration within the stack of tapes. In the high field limit, the influence of the magnetic substrate becomes insignificant and the total loss of the stack converges to the total loss of the individual tapes. Figure 1 and Figure 2 support the fact that similar effects operate in the multi-strand Roebel cable as well, but with one significant difference from the situation in a stack. Roebel cable is a transposed conductor, not a side by side pair of stacks of tapes. Each strand of the cable is equivalent and, in the present case, is insulated from neighboring strands. As a result, the circulating magnetization currents and thus the general extent of flux penetration in all the strands of a Roebel cable with insulated strands is the same. So the magnetically induced circulating currents are confined within each strand. Unlike the case of tape stacks, no single strand remains as the outermost layer. Each strand is exposed to the cable surface only for 1/N of each transposition length at the top and bottom cross-over. Note that in cable made from 2G wire with a ferromagnetic substrate, the top and bottom cross-overs are not equivalent; one has the HTS layer on the outside, the other has the ferromagnetic substrate outermost. The current distribution in the strands of a Roebel cable is schematically depicted in Figure 4 in comparison with a non-transposed stack of strands.



(a) a side by side stack of non- transposed strands
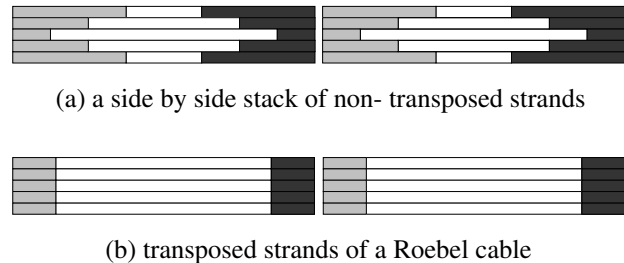


(b) transposed strands of a Roebel cable

Fig.4 A schematic diagram depicting the extent of flux penetration of (a) a side by side stack of non transposed strands and (b) insulated transposed strands of a Roebel cable, at the peak amplitude of the alternating magnetic field corresponding to about $0.5B_p$, where $B_p$ is the field amplitude corresponding to the maximum in $\Gamma$. The extent of flux penetration is denoted by grey and black regions at either side of the stacks. Grey and black regions denote that screening currents are flowing out and flowing in respectively. White denotes the un-penetrated region of the stacks.

In a non-insulated Roebel cable, coupling currents will flow predominantly between neighbouring strands at the point that each strand emerges from the stack as the strand above it deviates into the cross-over. Lesser coupling currents will flow between neighbouring strands towards the middle of the stack until the cable is completely penetrated by flux in the high field amplitude limit. The distribution of magnetization currents in the cross-section of a coupled Roebel cable is in this respect similar to that in non-transposed stacks.

In order that all the strands of a cable sample should be equivalent, as they are for an idealized long cable sample, one should make measurements on samples that are an integral number of the transposition lengths. The present sample with 5/3 transposition length, is not ideal, but comparison with 90 mm samples suggests that there is no significant difference in the loss characteristics.

Figure 5 compares the AC magnetic loss of the cable sample in parallel and perpendicular field orientations. In parallel magnetic field the loss ($Q_∥$), at the lowest field amplitude is
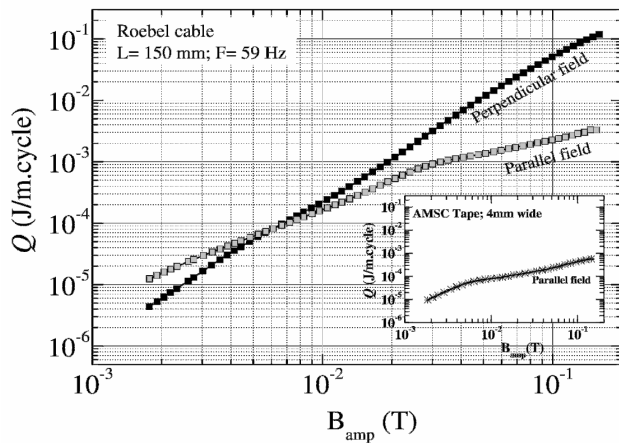
Fig.5 Magnetic AC loss as a function of field amplitude in perpendicular and parallel magnetic field for an insulated 11 strand Roebel cable sample recorded at 77 K and at a field frequency of 59 Hz. Inset shows the magnetic AC loss as a function of field amplitude in parallel magnetic field for a 4 mm wide and 150 mm long 2G YBCO production tape [✳] supplied by AMSC.

approximately three times larger than that in the perpendicular field ($Q_\perp$). Both $Q_\parallel$ and $Q_\perp$ increase with increasing field amplitude, but at different rates, and at about 6 mT, $Q_\perp$ crosses over the $Q_\parallel$. Over the entire field range $Q_\perp$ increases approximately as $B_{amp}^{2.4}$. Compared to single strand 2G tape with non-magnetic substrate where the loss at low field amplitude varies typically between $B_{amp}^3$ and $B_{amp}^4$, this reflects the effect of mutual screening; the progress of flux penetration is extended to higher field amplitude. In contrast, $Q_\parallel$ increases approximately as $B_{amp}^{1.5}$ up to about 30 mT, and then increases sub-linearly at higher field amplitude, roughly as $B_{amp}^{0.7}$. At the highest field amplitude of the measurement (~ 0.16 T), $Q_\parallel$ is about a factor of 30 less than $Q_\perp$. These results are qualitatively consistent with those we have measured for 4 mm wide production YBCO wire with a Ni 5 at%-W substrate (inset of fig.5) and also for stacks of such tapes. On the other hand, $Q_\parallel$ for a 2G wire (and also stacks of up to 8 tapes) on a non-magnetic substrate is too low to measure with our system, at least three orders of magnitude less than $Q_\perp$. When the external field is parallel to the plane of the cable, the magnetic flux is expected to be concentrated in the substrate, producing a large magnetic loss in the substrate compared with that in the HTS layer. In the HTS layer one expects $Q_\parallel$ in the high field limit should be drastically reduced compared to $Q_\perp$, by the ratio of the conductor thickness to its width. Measurements of $Q_\parallel$ on a Ni-W substrate without HTS film are also consistent with $Q_\parallel$ for a tape. It thus appears that in Roebel cable manufactured from HTS tape with a Ni-5%W substrate the hysteretic loss in the substrate dominates the magnetic AC loss in the parallel field direction, as it does in the tape.

## V. Conclusion

We have measured the magnetic AC loss of a Roebel cable with 11 insulated strands of 2 mm width fabricated from the 2G YBCO wire with a weakly ferromagnetic Ni-5 at.% W

substrate supplied by American Superpower Corporation. In the perpendicular field direction, the cable loss is dominated by the hysteresis loss of the substrate at low field amplitude, and at intermediate field amplitude, the loss in the HTS conductor is reduced by flux steering in the substrate. At the high field limit, the loss of the cable and of its component strands converges confirming that the strands in the cable are decoupled. In the parallel field, hysteretic loss in the substrate dominates the loss in the superconductor.

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