AC Losses in MgB_2 Wires and Tapes in Frequencies up to 18 kHz

Yasha Nikulshin, Shuki Wolfus, Vladimir Ginodman, Alex Friedman, Matteo Tropeano, Gianni Grasso, and Yosef Yeshurun

***Abstract*—We present a study of the ac losses in MgB_2 superconductors under operation mode typical of applications such as SMES and HVDC, utilizing large dc current superimposed with small, switching frequency ac current. The ac losses in two MgB_2 superconductors—a wire with 36 filaments in Monel sheath and a tape with titanium sheath—are compared in a wide range of ac amplitudes and frequencies up to 18 kHz, at different temperatures and dc current levels. Strong influence of the sheath material on the ac losses was found. The wire with Monel sheath shows a strong nonlinear contribution of the magnetic material to the losses. The losses reduce as the Monel approaches saturation at high dc current. In contrast, losses in the tape with Titanium sheath are practically independent of the dc level, and are smaller than losses in the Monel wire for the whole range of measured parameters. The results demonstrate the importance of further development of nonmagnetic low-loss MgB_2 wires and tapes for applications that involve exposure to ac ripple current in switching frequencies.**

***Index Terms*—AC loss, MgB_2, SMES superconducting magnet energy storage.**

I. Introduction

Since its discovery [1], MgB_2 attracts interest as a low-cost, high-performance material in superconductors applications such as Superconducting Magnetic Energy Storage (SMES) and High-Voltage Direct Current (HVDC). In these applications, the superconductor operating in DC current carrying mode is also exposed to a small AC current component superimposed on the main large DC current. This AC current component may be a result of residual grid frequency or switching frequency of the surrounding power electronics. In the latter, switching frequencies of Pulse Width Modulation (PWM) controllers would be the origin for the AC current component in the superconductor, typically in the range of 3–10 kHz. In SMES, the frequency of the AC current component due to charge/discharge cycle is also in the kHz range. Although small compared to the DC current, the amplitude of this AC component can vary by orders of magnitude depending on the actual grid energy need. While most recent works have studied the AC loss performances in frequencies from grid frequency up to several hundred Hertz [2]–[4], little is known about loss performances of MgB_2 under the above described operating conditions, namely large DC current superimposed with small AC current in the kHz regime.

Studies of AC loss in MgB_2 addressed the superconductor coupling and hysteresis as sources for generation of loss, see, e.g., Refs. [5]–[7]. Young *et al.* [8] pointed to a contribution from the ferromagnetic sheath in the wire but concluded that the coupling current is the dominant factor for the losses in applied field. Gomory *et al.* [9] suggested that adding a magnetic layer to BSCCO or MgB_2 may reduce the AC losses with the alteration of the magnetic field path in the wire. Several research groups have shown that magnetic materials in superconducting wires have an impact on AC losses, see, e.g., Refs. [10] and [2], [4]. In a recent work [11], we have demonstrated that MgB_2 multifilament wires embedded in Monel magnetic matrix, present significant losses in the magnetic matrix when in mode of superimposed DC and AC current at typical switching frequency. It was suggested that the high frequency ripple in the superconducting filaments induces large flux changes which results in eddy current losses within the Monel matrix which dominate the AC losses of the entire wire.

In the present work, we further study the losses under such operating mode where the MgB_2 superconductor is carrying DC current with superimposed AC ripple current at frequencies extending up to 18 kHz. Measurements are performed on MgB_2 with magnetic (Monel) and non-magnetic (Titanium) sheath materials. AC losses for both wires are compared at various measurement parameters.

II. Experimental

Loss measurements have been conducted on two MgB_2 wire specimens, both manufactured by Columbus Superconductors. The first is a 36 filamentary, 1.3 mm diameter, MgB_2 wire with Monel outer sheath and Nickel matrix. The critical current at 20 K and 1T is 500 A [12]. The wire cross-section is shown on Fig. 1(a). The second is flat tape (2.85×0.45 mm^2) consists of 19 filaments surrounded by both titanium sheath and matrix with 550 A critical current at 16 K, 1 T [13]. An image of the cross section of each sample is shown in Fig. 1(b). A thin layer of copper was chemically deposited on both ends of the 18 cm long Ti-MgB_2 tape and then soldered with indium to current leads to minimize contact resistance. The Monel wire did not require any special techniques since Monel is easily soldered. The area of the

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Y. Nikulshin, S. Wolfus, V. Ginodman, A. Friedman, and Y. Yeshurun are with the Department of Physics, Institute of Superconductivity, Bar-Ilan University, Ramat Gan 5290002, Israel (e-mail: yasha.nick@gmail.com).

M. Tropeano and G. Grasso are with Columbus Superconductors SpA, Genova 16133, Italy.

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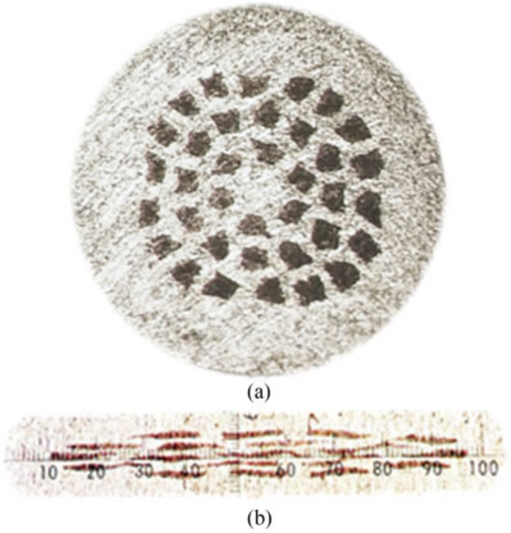

Fig. 1. Specimen cross section: (a) Monel wire with 36 filaments. The diameter of the wire is 1.3 mm (b) Titanium tape (2.85 × 0.45 mm^2) with 19 filaments.

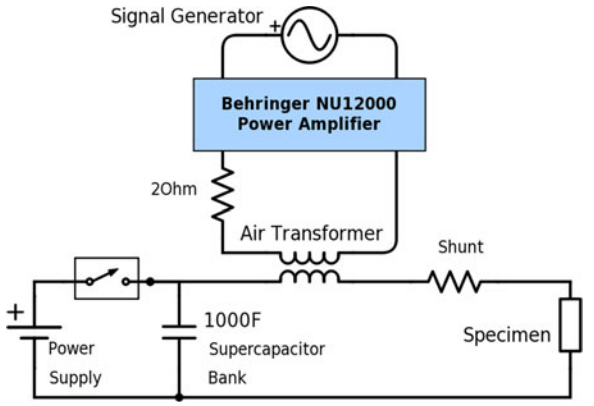

Fig. 2. Electrical scheme of measurement system.

tape between the voltage taps remained untreated. Voltage taps were mechanically attached to the tape, 60 mm apart. Electrical resistivity values at 10 K as 3.65 × 10^{-7} and 14 × 10^{-7} Ohm•m for Monel and for pure Titanium, respectively [14].

AC loss measurements are based on the electrical method [15], namely measuring the time integral of the product I·V waveforms per cycle. Electrical scheme of the measurement setup is presented in Fig. 2. DC current is supplied by Xantrex (20–300) power supply connected in parallel to a 1000 F supercapacitor bank. The capacitor bank serves as a high-pass filter to eliminate AC currents passing through the DC power supply and filter high frequency noise from the switching DC power supply. AC current is driven by Behringer NU12000 6 kW/ch high-power audio amplifier and coupled to the measurement circuit through an air transformer connected in series to the main loop. The system thus allows superimposing DC and AC currents through the measured sample. The current through the wire and the voltage across the taps are measured by Newtons4th PPA5510 high precision power analyzer.

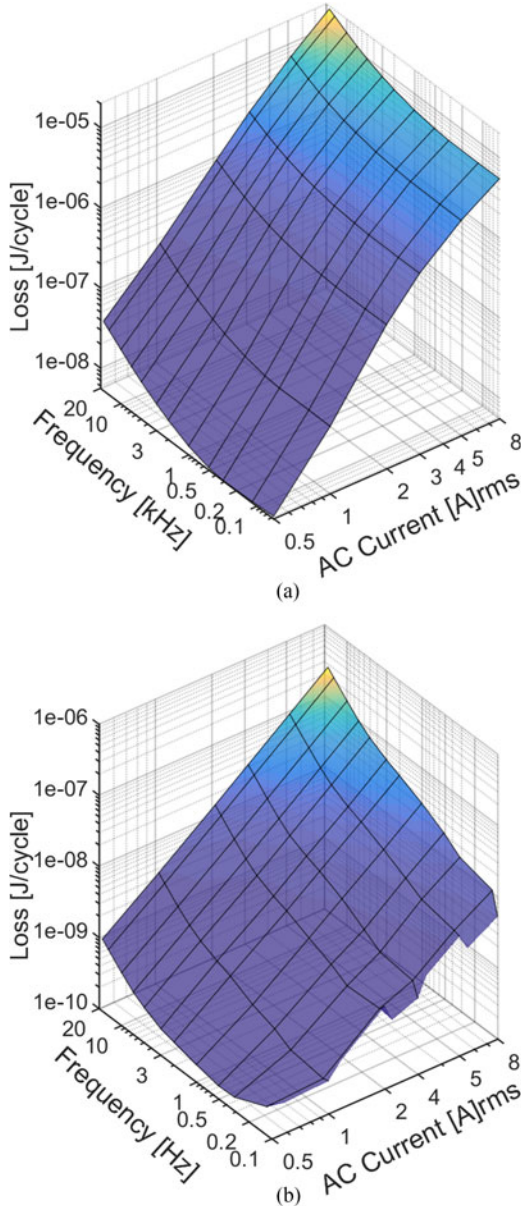

Fig. 3. Loss vs frequency vs AC current at 10 K, zero DC current in (a) the Monel wire, and (b) the titanium tape.

The instrumentation is connected and controlled by MATLAB environment with feedback loop to stabilize the currents. In measuring each of the samples, four parameters were changed independently. Temperature was varied from 5 to 40 K, DC current from 0 to 40 A, AC current from 0.5 to 8 A rms and frequency from 57 Hz to 18 kHz.

III. RESULTS

The energy loss per cycle per length at 10 K and zero DC current is shown in Fig. 3(a) and (b) for the Monel sheath wire and the Titanium sheath tape, respectively. The figure shows clearly that the Titanium tape has lower loss.

As demonstrated in a previous work [11], the inclusion of magnetic materials in MgB_2 wires increases dramatically the

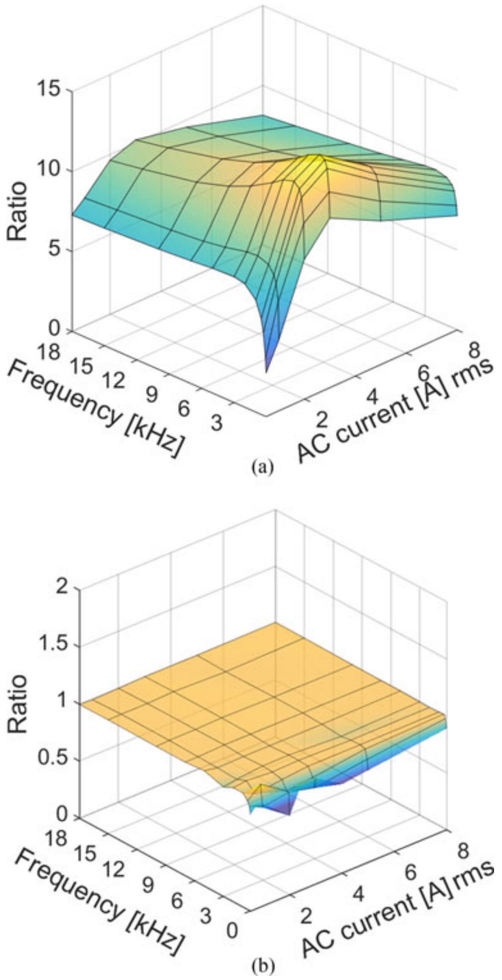

Fig. 4. Loss reduction ratio at 40 A DC vs frequency vs AC current at 10 K relative to zero DC current in Monel wire (a), in titanium tape (b).

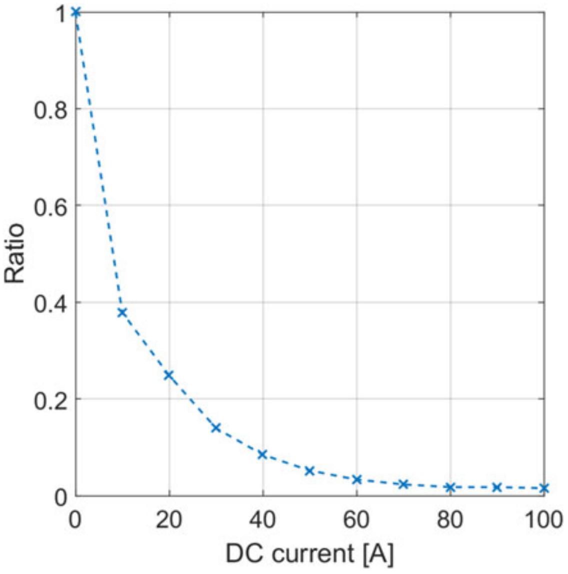

Fig. 5. Ratio of losses in Monel wire vs DC current relative to zero DC current.

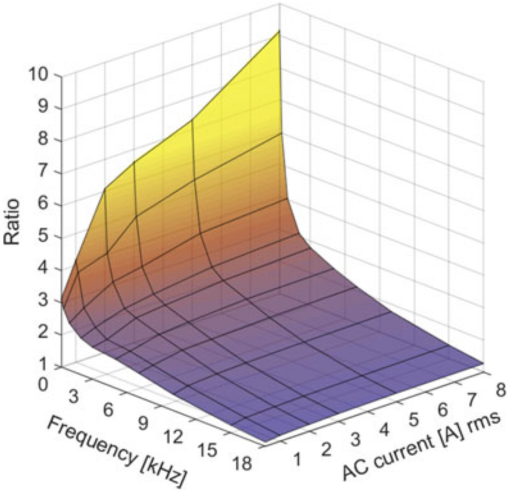

Fig. 6. Ratio of losses between the Monel wire and the Titanium tape under 100 A DC current at 10 K.

AC losses. However, such materials saturate in high enough magnetic field, hence the magnetic loss contribution to the total losses is expected to strongly depend on the magnetic state of the matrix. Superimposed DC current to AC current produces a DC magnetic field which saturates the Monel matrix surrounding the filaments and reduces the effective permeability. This causes a significant reduction in AC losses with increasing DC current. Fig. 4 demonstrates the effect of such saturation by showing the ratio between losses obtained with the application of finite DC current to losses with zero DC current for the Monel wire [see Fig. 4(a)] the titanium tape [see Fig. 4(b)]. Fig. 4(a) shows clearly a significant reduction in the loss in the wire due to the application of 40 A DC. This loss reduction is evident for all measured AC frequencies and amplitudes and reaches a maximum of 14.3 at frequency of about 1 kHz and amplitude of about 3 A. At the same time, the Titanium tape [see Fig. 4(b)] is not affected by the DC current and for the whole frequency and amplitude ranges the reduction ratio is practically one.

A further increase in the DC current still reduces the losses in the Monel wire. This is shown in Fig. 5 for DC current up to 100 A. The data in this figure were obtained for 5 A, 3017 Hz AC current. This frequency is of special interest because it is a common operating frequency of PWM power electronics and represents the operation of the superconducting wire under switching ripple mode. The figure demonstrates that deeper magnetic saturation further reduces the AC losses.

Since practical usage scenario of superconductors involves high DC currents the comparison of saturated Monel wire to Titanium is even more interesting. In Fig. 6 the loss ratio between Monel wire and Titanium tape under 100 A DC current is presented. Again, the ratio is frequency and amplitude dependent. The lowest ratio is 1.2 at 18 kHz.

As described in [8] the main source of loss at high frequencies are eddy currents in the metal components of the superconducting wire. In deep saturation, the loss is mainly proportional to the electrical conductivity of metal which for Monel is 3.8 times higher than titanium. However different topology and higher filament number could in principle suppress this ratio to lower values. In any case, the results shown in Fig. 6 show that even for the best operating conditions for MgB$_2$ Monel wires, losses are still higher than in an equivalent MgB$_2$ Ti tape.

IV. DISCUSSION

The introduction of DC current does not influence the AC losses in Titanium tape. On the other hand, DC component in Monel sheathed wire saturates the Monel and dramatically reduces the losses. The reduction is DC and AC amplitude and frequency dependent. Despite the loss reduction, our results imply that a tape with Titanium sheath is superior to a wire with Monel sheath for applications involving high frequency switching. With high enough DC current, losses are reduced to the same order of magnitude as in Titanium sheath tape. However, losses in the Ti tape are smaller than in the Monel even for the best operating conditions. The minimal loss ratio of Monel wire to the Ti tape is 1.2. The difference in minimal losses, where the magnetic matrix is deeply saturated, might be the attributed to the different filament number and topology and to the different electrical properties of Monel and titanium. This work shows that the electromagnetic characteristics of the matrix sheath in MgB_2 superconductors is crucial for the loss performances of the wires. In particular, Monel sheathed wire is less suitable than Titanium sheathed tape for use in SMES coils because inside the coil there are always windings exposed to low magnetic fields leaving the Monel unsaturated with high AC losses when discharging the coil.

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