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# TRANSPORT AC LOSSES IN STRIATED YBCO COATED CONDUCTORS (POSTPRINT)

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DC current-voltage characteristics and transport ac losses of striated and non-striated $Y_1Ba_2Cu_3O_{7-\delta}$ (YBCO) coated conductors have been measured. Transport ac loss measurements have been performed in frequencies from 40 Hz up to 2 kHz at 77.4 K. Degradation in the critical current of about 40% due to the laser striation process has been found. The striated sample was much more thermally stable than the non-striated one. Transport ac losses were weakly frequency dependent up to 2 kHz, and mainly determined by the losses in the substrate and Ni layer up to currents of about 50% of the critical current. Striation had no effect on normalized transport ac losses, which are basically hysteretic. Comparison of transport ac losses with in-field losses showed that the dominant loss contribution is the in-field loss.

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# Transport AC losses in striated YBCO coated conductors

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**Abstract.** DC current-voltage characteristics and transport ac losses of striated and non-striated $Y_1Ba_2Cu_3O_{7-\delta}$ (YBCO) coated conductors have been measured. Transport ac loss measurements have been performed in frequencies from 40 Hz up to 2 kHz at 77.4 K. Degradation in the critical current of about 40% due to the laser striation process has been found. The striated sample was much more thermally stable than the non-striated one. Transport ac losses were weakly frequency dependent up to 2 kHz, and mainly determined by the losses in the substrate and Ni layer up to currents of about 50% of the critical current. Striation had no effect on normalized transport ac losses, which are basically hysteretic. Comparison of transport ac losses with in-field losses showed that the dominant loss contribution is the in-field loss.

## 1. Introduction

The recent development of $Y_1Ba_2Cu_3O_{7-\delta}$ (YBCO) coated conductors has made superconducting machines (such as generators and motors) for high density power applications much closer to reality, especially with the associated progress toward practical conductors in long lengths. One concern in ac applications is the attendant ac loss in these materials [1]. The US Air Force Research Laboratory (AFRL) has developed the concept of YBCO conductors with narrow filaments to minimize the in-field loss contribution [1-7]. In this paper, we present measurements of dc current-voltage characteristics, critical currents and transport ac losses in RABiTS (Rolling Assisted Biaxially Textured Substrates) for both non-striated as well as striated coated conductors.

## 2. Experimental

The samples obtained were YBCO coated conductors prepared by RABiTS method [6,7]. The width of the samples was 1 cm and the length 6 cm. The tapes consisted of a ~75 μm thick Ni-5at%W based substrate, insulating buffer layers, YBCO and a silver protective layer. The striated samples had 20 strips (each 458 μm wide) separated by narrow resistive barriers (each 39.5 μm wide). DC current-voltage characteristics have been measured using the 4-point method in self-magnetic field. The critical currents were determined at an electric field of 1 μV/cm. Transport ac losses were measured by a lock-in amplifier technique [8] in self-magnetic field in the frequency range 40 Hz – 2 kHz. All the measurements were made in a liquid nitrogen bath at 77.4 K.

## 3. Results and discussion

*3.1. DC current-voltage characteristics.* The results are shown in Fig. 1. The monolayer sample showed a significant degree of thermal instability at $I<I_c$ as indicated by noisy regions below 200 A in Fig. 1a; the striated sample was more stable (Fig. 1b). The critical current of the monolayer sample was 220 A and for the striated one it was 120 A. Taking into account the filling factor of the striated sample (91.68% of the monolayer sample), the striated sample should have a critical current of 201 A. The measured value of 120 A represents about 40% degradation which, although the samples are independent, is probably caused by the laser striation process and handling. It is not clear at this point if this result is representative of the process or merely one case. Further investigation is necessary.

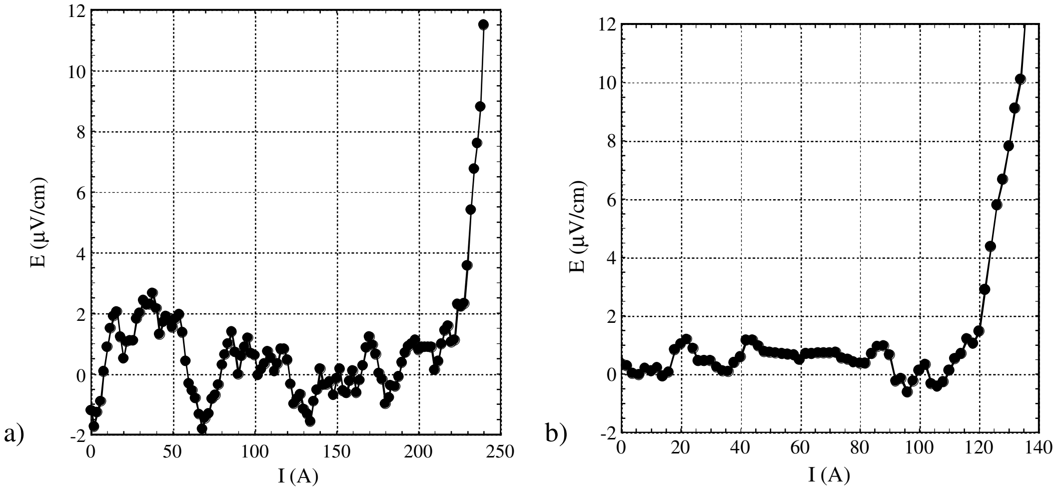

**Figure 1.** DC current-voltage characteristic of the monolayer sample (a) and the striated sample (b).

*3.2. Transport AC losses.* The results for the monolayer sample are shown in Fig. 2a. The energy loss per cycle is nearly independent of frequency and the losses are basically hysteretic. However, their dependence does not follow $I^3$ as expected from the critical state model [9], but follows an $I^2$ dependence that is more characteristic of losses in a ferromagnetic material. Only at currents close to the critical current do the measured losses follow the expected theoretical dependence for a superconducting cylinder of an elliptical cross-section [9], shown by the continuous blue line in Fig. 2a. We believe that this behaviour is caused by magnetic losses in the substrate due to the self magnetic field generated by the transport current. A similar increase of ac losses has also been observed in samples containing magnetic materials [10]. Moreover, some instabilities started to be visible at frequencies of 960 Hz and 1920 Hz (Fig. 2a, open diamonds and solid triangles, respectively). These results are important when considering the application of these tapes in power generators at high frequencies. AC losses at 100 A, i.e. at about 50% of $I_c$, are about a factor of 2 higher than expected for a pure superconducting sample with no substrate [9].

AC losses of the striated sample are shown in Fig. 2b. As for the monolayer sample the energy loss per cycle is nearly independent of frequency. The losses are due to the magnetization losses in the substrate structure caused by the self magnetic field generated by the transport current. Also in this sample, some instabilities appeared at frequencies of 960 Hz and 1920 Hz (Fig. 2b solid triangles and solid diamonds, respectively). AC losses of both samples are shown in a single graph in Fig. 3. Fig. 3a shows the losses of the samples plotted against the transport current, while Fig. 3b shows the normalized loss plotted against the normalized current. The ac loss was normalised by dividing the loss in Joule/m/cycle by $\mu_o I_c^2/\pi$. Both figures show that the losses of the monolayer sample are slightly lower than those of the striated one. Although a somewhat higher self magnetic field component perpendicular to the substrate surface may be present in the striated sample, some of the increase is due to coupling losses from filamentary connection via the substrate caused during ablation.

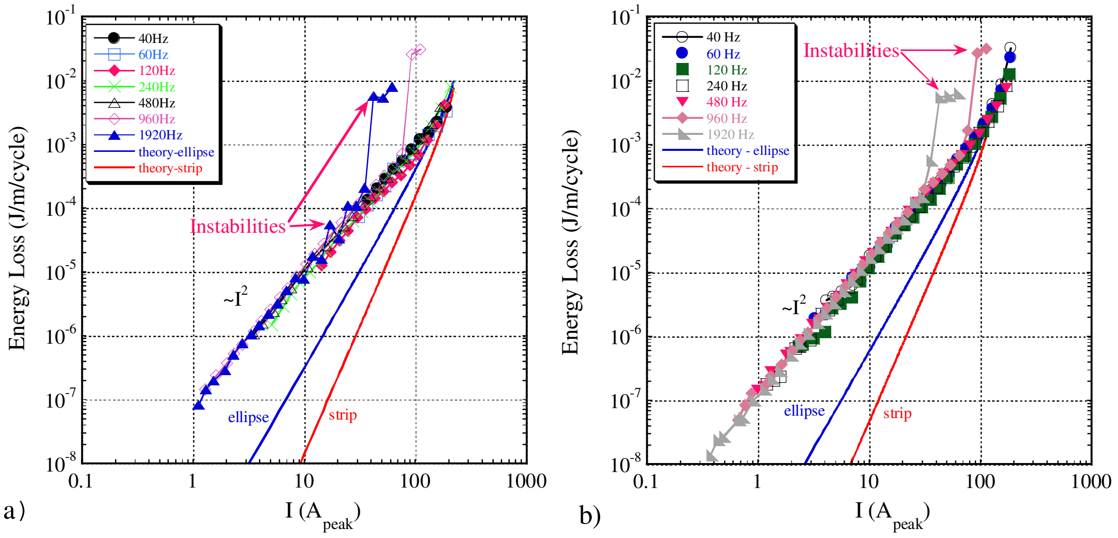

**Figure 2.** Transport ac losses of the monolayer sample (a) and the striated sample (b) measured in the frequency range 40 Hz – 2 kHz. Continuous lines represent the theoretical dependencies for a conductor of an elliptical cross-section and for a strip, obtained from the critical state model [9].

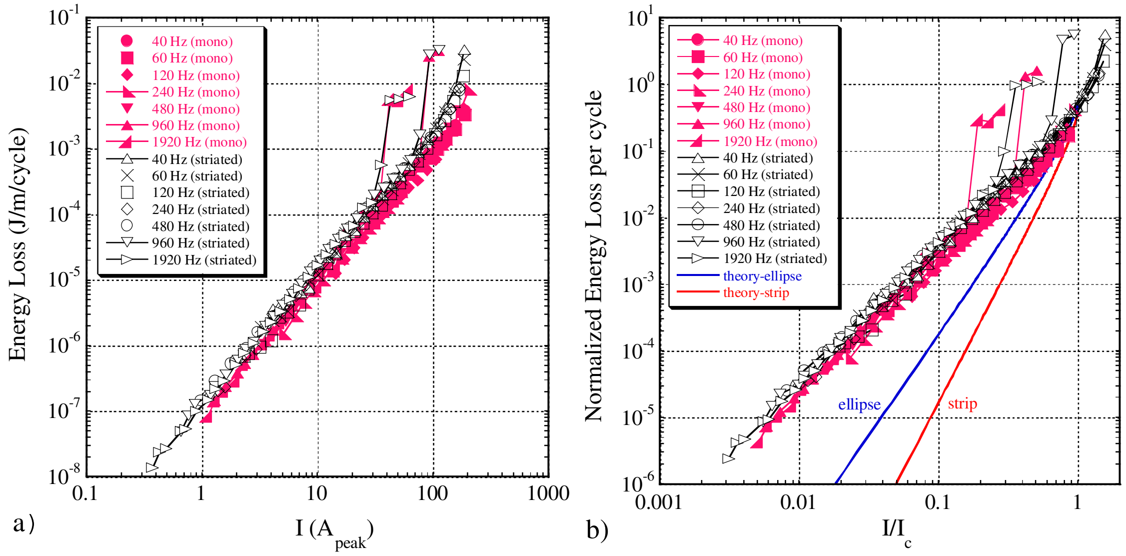

**Figure 3.** Comparison of the transport ac losses (a) and the normalized losses (b) of the monolayer and the striated sample. Continuous lines represent the theoretical dependencies for a conductor of an elliptical cross-section and for a strip, obtained from the critical state model [9].

*3.3. Comparison of transport ac losses with the losses in applied ac magnetic field.* AC losses in a monolayer sample due to an applied magnetic field of 1 T (peak) extrapolated from the data in [7] are substantially higher (by about 2 orders of magnitude) than transport ac losses at the critical current. Subdivision of the monolayer sample into filaments (strips) with superconducting bridges [7], to increase the stability, suppresses magnetization losses by a factor of about 2. Such a sample would have a critical current $I_c$ of about 100 A. The magnetization loss of such a "practical" sample at 1T (peak) would be about 0.3 J/m/cycle, which is still much higher than the transport ac loss at $I=I_c$ (0.01 J/m/cycle, Fig. 3a). However, this loss is the so-called "cold loss", which does not include the power needed to cool the sample. To calculate the real loss, i.e. the so-called "room temperature loss", one needs to employ the second law of thermodynamics (the Carnot cycle). The power P required to cool the sample heated by the power loss $P_{loss}$ is then $P=P_{loss}\{1+\eta^{-1}(T_{amb}-T_o)/T_o\}$,where $P_{loss}$ (in watts) is the power loss of the sample at operating temperature $T_o$, $T_{amb}$ is the ambient temperature and $\eta$ is the efficiency of the cooling cycle with respect to the Carnot cycle. For $T_o$=77 K, $T_{amb}$=300 K and a frequency of 400 Hz (typical for an aircraft generator) we obtain $P_{loss}$=120 W/m. If we cool the sample by a cryocooler, most cryocoolers achieve $\eta \cong 0.4$ at 77 K [11]. Then we obtain P=988.8 W/m. A comparison of this value with the loss of 3676.4 W/m in an equivalent Cu round wire at 300 K (without any heating) (diameter 4.6 mm, current density J=6A/mm$^2$, resistivity $\rho=1.69 \times 10^{-8}$ Ωm, 400 Hz, 1 T (peak)) shows that the losses of the copper wire are about 3.7 times higher than the losses of the coated conductor. An another advantage of using the coated conductor is its much smaller size, because the ratio of the volumes of YBCO and Cu is $V_{YBCO}/V_{Cu}=6\text{x}10^{-4}$ – i.e. the volume of Cu wire is more than 3 orders of magnitude higher than the volume of the coated conductor.

## 4. Conclusions

We found the transport ac losses much smaller than the in-field losses at 1 T (peak) for the given samples. The in-field losses, when converted to the "room temperature loss", are about 3.7 times lower than the losses in an equivalent copper wire. There is a huge reduction in weight and volume of a superconducting machine compared with a conventional one. The relative importance of HTS machine efficiency vs the reduction in weight and volume of a superconducting machine is application dependant.

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