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MILESTONE REPORT

HTS NUCLOTRON CABLE PRODUCED

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ABSTRACT

Two samples of the Nuclotron CORT cable were manufactured and tested for their magnetization loss. The cables were designed to have a critical current of 1350 A at 77.3 K and around 10 kA at 4.2 K. The cable was made using commercial REBCO coated conductor from a non-European manufacturer, which had excellent mechanical properties. The experiments were conducted at IEE Bratislava and at University of Twente in Enschede at 77.3 K and 4.2 K, respectively. The results confirm the expectation that there are negligible electrical contacts between the copper-stabilized tape strands and that it is possible to estimate hysteresis loss analytically for accelerator-magnet-relevant operating conditions.

For more information on IFAST, its partners and contributors please see https://ifast-project.eu/

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TABLE OF CONTENTS

1 INTRODUCTION..5

2 DESIGN AND MANUFACTURING OF SAMPLES..5

3 AC LOSS MEASUREMENT..6

4 CONCLUSIONS AND FUTURE PLANS..9

Executive summary

The Conductor-On-Round-Tube (CORT) concept uses a metallic tube with layers of CC (coated conductor) tapes to make a cable. This design is similar to the Nuclotron conductor, which uses LTS instead of HTS. The SIS100 accelerator at GSI Darmstadt uses the Nuclotron conductor.

Two short samples of the Nuclotron CORT cable were made, and their magnetization loss was tested. The cables were made of 10 REBCO CC tapes each, arranged in two layers. The design current is 1350 A at 77.3 K and up to 10 kA at 4.2 K in self-field. A commercial REBCO CC from a non-European supplier was used for this purpose.

The magnetization experiments were conducted at IEE Bratislava at a temperature of 77.3 K, using AC magnetic fields with amplitudes up to 150 mT and frequencies in the range of 36 Hz to 144 Hz. Similar experiments were performed at the University of Twente in Enschede at 4.2 K, with AC magnetic fields of frequencies between 10 mHz and 80 mHz and amplitudes up to 1 T.

Both experiments show that the electrical contacts between copper-stabilized tapes are negligible. It was also demonstrated that using a simple analytical method, it is possible to estimate the hysteresis loss for a REBCO CC cable in accelerator magnet conditions.

In the next period, a similar study will be conducted using REBCO tape provided by a European supplier.

1 Introduction

Superconducting cables with circular cross-section are being considered for use in several particle accelerators that are currently under development. These cables are made using Coated Conductor (CC) tapes that are wrapped helically around a circular former to achieve the desired shape. One arrangement of this kind is the Conductor-On-Round-Tube (CORT) cable, which uses a central metallic tube to support several layers of CC tapes. This design is similar to the Nuclotron NbTi-based cable used in the SIS100 accelerator at GSI Darmstadt, where the central tube is used to force the flow of coolant.

This report describes the manufacturing and testing of the first short samples of the Nuclotron CORT cable, which is designed to transport up to 10 kA at 4.2 K. Two samples were made using 3 mm wide tape, with each sample consisting of two layers of 5 tapes. In one sample the two layers have opposite helicity, while in the other layout the layers have coinciding helicity. We conducted experiments to investigate the loss in applied external AC magnetic fields, addressing two questions:

Does the layout with coinciding layer helicity result in additional loss compared to the traditional layout with opposing sense of helicity in two adjacent layers?

Can the AC loss at large AC field amplitudes reliably be predicted with an analytical model that assumes a complete saturation of all the tapes with superconducting currents?

We used theoretical methods, including numerical and analytical approaches, to predict the loss and complemented this with experiments performed at 77.3 K (IEE) and at 4.2 K (UT).

2 Design and manufacturing of samples

The samples used in the experiment were made at IEE from a commercially available Coated Conductor (CC) tape SCS3050-AP produced by Furukawa/SuperPower. For the cable core, a carbon composite tube with very low electrical conductivity was selected.

Previous studies have demonstrated that wrapping the 3 mm wide tape by hand around the 7 mm outer diameter carbon composite tubes did not cause any reduction in critical current for this particular REBCO CC.

A lay angle of 45 degrees was used, and four twist lengths were completed in each sample, which were eventually 88 mm long. There was no electrical insulation placed between the two layers. The outer layer was secured by Kapton tape and an additional heat-shrink tube provides outer mechanical protection.

A photograph of the samples is shown in Fig. 1.

Fig. 1 Cable samples (centre) with two senses of helicity were prepared by cutting exactly 4 twist lengths from a longer hand-made cables.

3 AC loss measurement

The magnetization loss in an external AC field was measured at IEE in the samples at 77.3 K using magnetic fields of 36 Hz, 72 Hz, and 144 Hz and amplitudes up to 150 mT. The results are presented in Fig. 2.

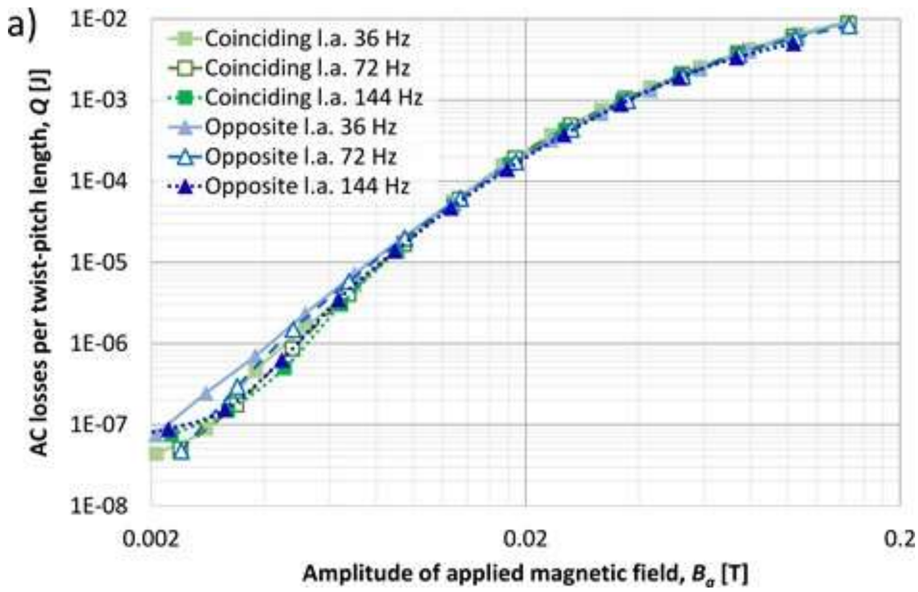

Fig. 2 Measured AC losses at T = 77 K *for two samples in the frequency range 36-144 Hz.*

The AC loss was found to be almost the same in both samples, regardless of the cable architecture, and there was no significant difference observed between different frequencies. This indicates that the coupling currents connecting the superconducting layers of various tapes through metallic stabilization are negligible.

To further analyze the AC loss behavior, the loss function, Γ=Q⁄(B_a^2), was evaluated, as shown in Fig. 3.

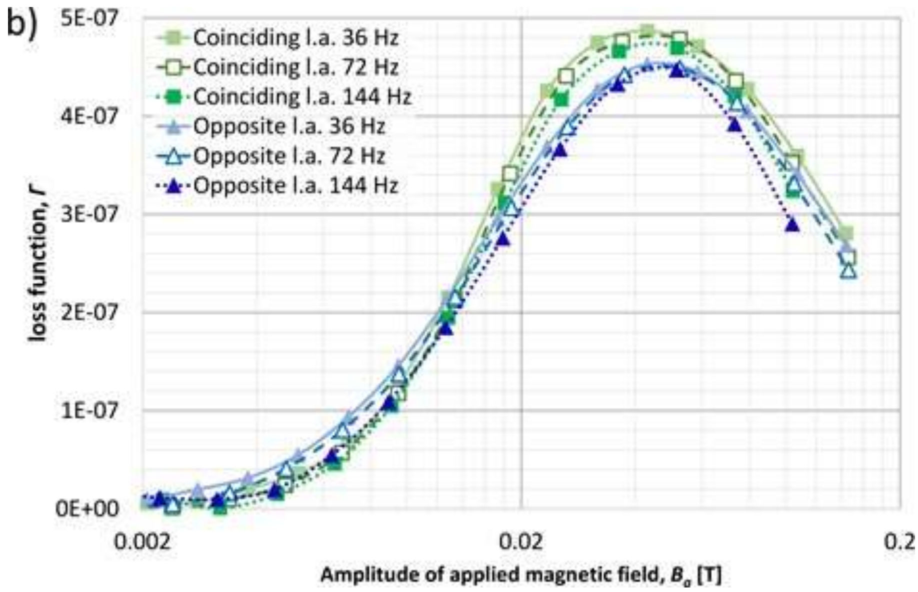

Fig. 3 Measured AC losses at 77 K *from Fig. 2 presented in form of the loss function, Γ.*

It was observed that the continuous layer of superconducting tapes in the sample with coinciding lay angles leads to slightly higher magnetization and loss compared to the case when there are places uncovered by superconductor at crossings of the tapes from opposite wound layers. However, this difference becomes negligible at high amplitudes, where the results for both samples converge.

This confirms the hypothesis that, at magnetic fields well above the penetration field, the magnetization loss of a round cable containing CC tapes that follow helical paths is independent of the details of the cable architecture.

The magnetization experiments were then performed on the same samples at 4.2 K at UT, using magnetic fields up to 1 T, and frequencies ranging from 10 to 80 mHz. The AC loss was determined from the area of the recorded magnetization loop, additionally the dissipation was evaluated calorimetrically from the amount of helium evaporated during the magnetization cycle. The results of these experiments are shown in Fig. 4.

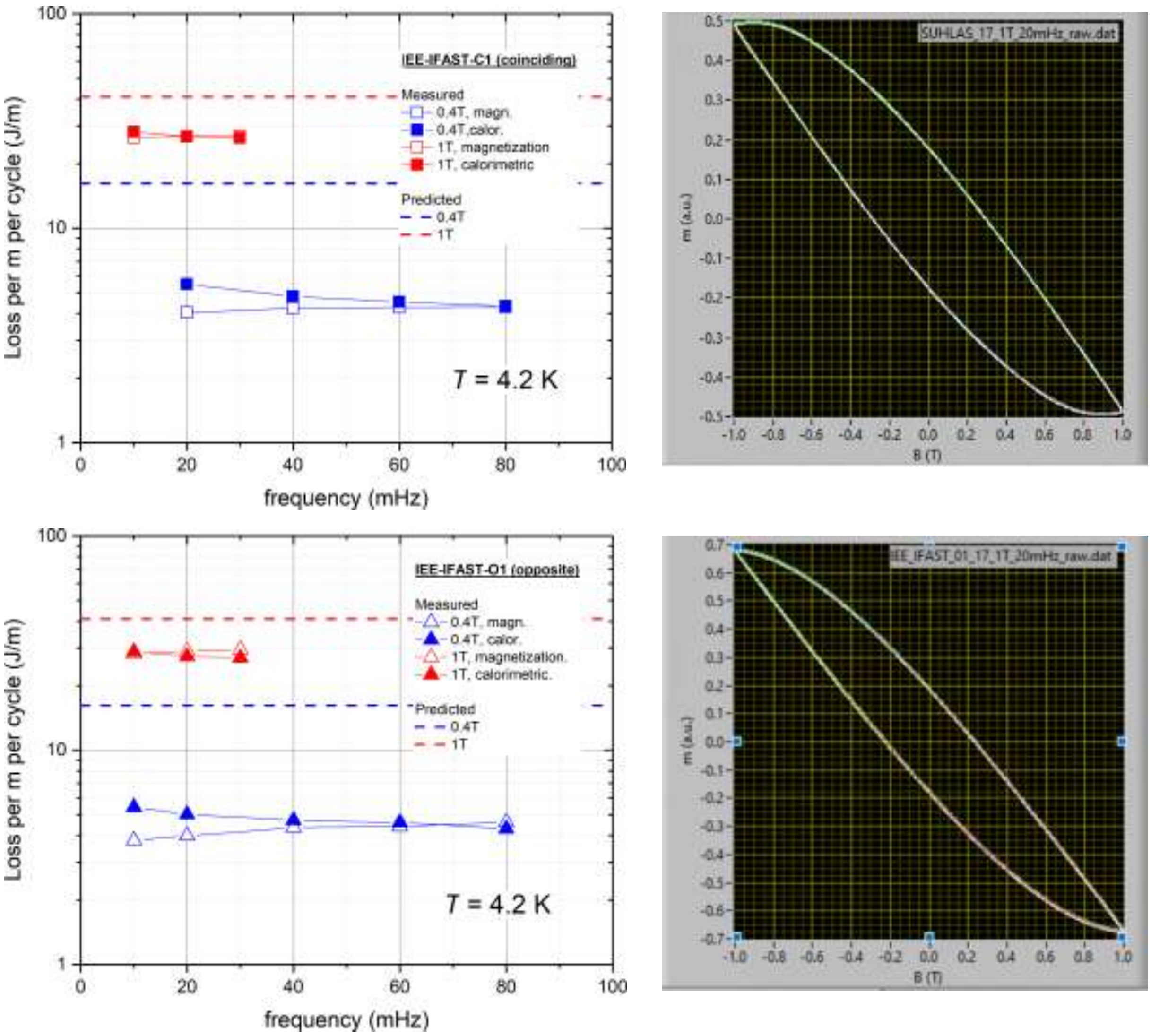

Fig. 4 AC losses at 4.2 K in the two IEE cable samples measured by two methods: calorimetric and inductively. Examples of magnetization loops are shown in the right-hand panels.

At 4.2 K, the measured losses are somewhat lower than the analytical prediction (the dashed lines in Fig. 4), but this is readily understood taking into account that at these amplitudes the samples are not fully penetrated throughout the cycle (magnetization loops right). Even so, both the essential features observed in experiments at 77.3 K, i.e. the frequency-independence of the AC loss and the negligible impact of cable architecture, are confirmed in conditions when the estimated critical current of the cable is 10 kA at 1 T.

4 Conclusions and future plans

The initial testing of the first Nuclotron CORT cable model yielded several important findings.

Firstly, the commercially available tapes provided by Furukawa/SuperPower, a non-European manufacturer, possess adequate mechanical properties for the manufacture of Nuclotron CORT cables.

Secondly, the negligible electrical connections between Cu-stabilised tapes is favorable for suppressing coupling loss, but may be a disadvantage if a local non-uniformity of critical current requires good sharing of current among the tapes at short distances.

Lastly, the hysteresis loss incurred when using CORT cables in an accelerator magnet and exceeding the penetration field of a single tape is not affected by the arrangement of the tapes, provided that some form of CC tape transposition is present.

In future research, we plan to conduct a similar study using CC tapes from a European producer. Due to the differences in manufacturing technology and the lower flexibility of the tape with a thick REBCO layer deposited on a on commercial available substrate with a thickness of 50 µm or less, the search for a suitable helix geometry will require careful testing of mechanical properties prior to manufacturing any CORT samples.