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BENDING RADIUS LIMITS OF DIFFERENT COATED REBCO CONDUCTOR TAPES - AN EXPERIMENTAL INVESTIGATION WITH REGARD TO HTS UNDULATORS*

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Abstract

Compact FELs require short-period, high-field undulators in combination with compact accelerator structures to produce coherent light up to X-rays. Likewise, for the production of low emittance positron beams for future lepton colliders, like CLIC or FCC-ee, high-field damping wigglers are required. Applying high-temperature superconductors (HTS) in form of coated REBCO tape conductors allows reaching higher magnetic fields and larger operating margins as compared to low-temperature superconductors (LTS) like Nb-Ti or Nb_3Sn.

However, short undulator periods like 13 mm may require bending radii of the conductor smaller than 5 mm which induce significant bending strain on the superconducting layer and may harm its conducting properties. In this contribution, we present our designed bending rig and experimental results for coated REBCO tape conductors from various manufacturers and with different properties. Investigated bending radii reach from 20 mm down to 1 mm and optionally include half of a helical twist. To represent magnet winding procedures, the samples were bent at room temperature and then cooled down to $T = 77$ K in the bent state to test for potential degradation of the superconducting properties.

INTRODUCTION

For the production of low emittance electron and positron beams for future linear and circular lepton colliders, like CLIC (Com-pact Linear Collider) or FCC-ee (Future Circular Collider), high-field damping wigglers are required [1, 2]. Here, period lengths are in the order of 50 mm.

Shorter undulator periods and accelerator structures are needed for compact free electron lasers to produce coherent light up to X-rays. Different options to achieve this goal are being investigated, e.g. in the European Union funded CompactLight (XLS) project [3]. Here, the current design for hard X-rays (photon energy > 8 keV) aims for a configuration of 13 mm period length and a magnetic peak field greater than 1 T.

High-temperature superconductors (HTS) like REBCO have the characteristics of not only staying superconductive in a broader temperature range (up to 90 K) but as well under high external fields up to several times 10 T before quenching (e.g. $B_{c2,\perp}$(YBCO, 4.2 K) ≈ 100 T) [4, 5]. When applying HTS to superconducting undulators, the temperature range may facilitate the operation compared to the state-of-the-art LTS technology like Niobium-titanium (Nb-Ti) or Niobium-Tin (Nb_3Sn). The higher magnetic field tolerance at low temperatures may enable higher magnetic field peaks on the beam axis. These advantages may make HTS a superior material for building future high-field superconducting undulators and wigglers.

When designing undulators with short periods like 13 mm for geometries, such as horizontal racetracks or helical (see Fig. 1), it may require bending radii of the conductor smaller than 5 mm. This bending will induce significant bending strain on the superconducting layer and can harm its conducting properties.

In this work we focus on investigating coated REBCO tape conductors and their minimum bending radius.

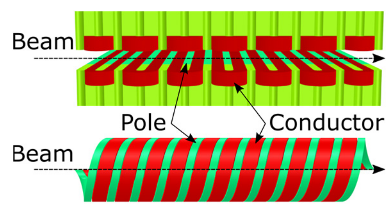

Figure 1: Investigated undulator geometries which may need a conductor bending radius smaller than 5 mm for a period length of 13 mm. Top: horizontal racetrack. Bottom: helical undulator around a beam pipe.

EXPERIMENTAL METHODS AND SETUP

From previous work it is known that compressing the REBCO layer leads to less degradation of the critical current I_c as compared to pull strain [6]. For this reason, all presented measurements were done under REBCO compression, keeping the superconducting layer on the inside, facing the bending body. Like in coil winding procedures, all samples were bent at room temperature and then cooled down to $T = 77$ K for the measurement. I_c of a sample was determined from V-I measurements using an electric field criterion of 100 µV/m. While the current was ramping up the voltage was measured with a nanovoltmeter over a defined length of 6 cm until the criterion was reached.

We used two different experimental setups for investigating the I_c behaviour under various bending radii. For each setup, the same sample was bent to smaller radii until the critical current I_c showed more than 70% degradation. The minimum bending radius R_{min} was defined as the smallest radius for which the measured I_c degrades less than 5% for bending without twist angle.

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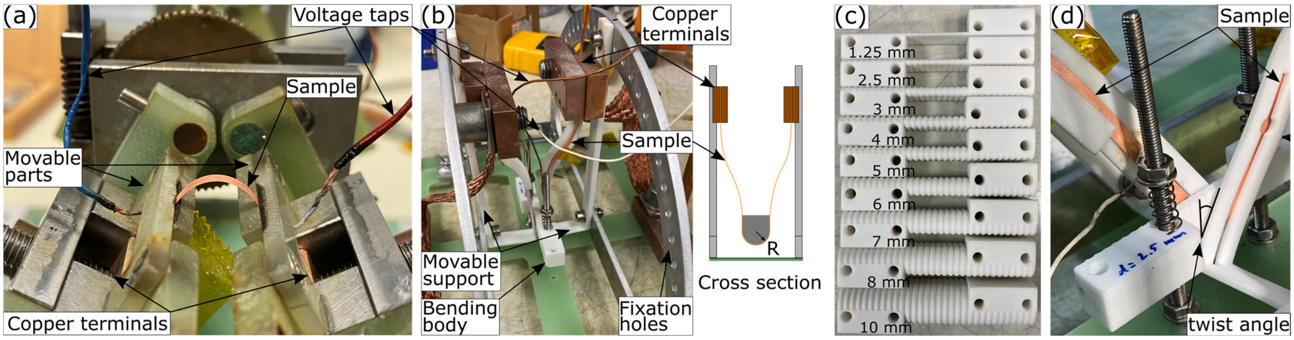

Figure 2: The used bending rigs. (a) close-up view of the Goldacker bending rig with a sample conductor and a bending radius of 8 mm. (b) detailed view plus sketch of the U-Bend rig with a sample conductor and a bending radius of 3 mm. Fixation holes can be used to turn the movable support for twist bending as shown on the right. (c) displays all used bending bodies with indicated radii, respectively. (d) shows a close-up view of a twist bend setup for 2.5 mm diameter, 30° configuration as well as the two nuts we used to apply pressure via springs to ensure a tight fit of the conductor tapes.

The Goldacker Bending Rig

This bending rig has been developed by the group of Goldacker and can bend samples continuously down to a radius of 5 mm by turning a rod [6, 7]. In Fig. 2(a) the rig can be seen in use with a sample clamped and bent. The bent curve is close to a circle, however due to material properties of the conductor there is an uncertainty of the exact shape (~2%) [8]. We used this rig for investigating reversible I_c degradation ($R = \infty$ after the measured radius, respectively) as well as to confirm measurements from the new U-Bend setup described below. All data points for the relative critical current were in agreement.

"U-Bend" Rig with Replaceable Bending Bodies

For investigating bending radii smaller than 5 mm we designed the U-Bend rig, displayed in Fig. 2(b) to (d). Everything was designed to be maximum lightweight to ensure a fast cool-down and warm-up procedure.

The exchangeable u-shaped bending bodies were 3D-printed for the bending radii $R = \{10, 8, 7, 6, 5, 4, 3, 2.5, 1.25\}$ mm. To ensure a total liquid nitrogen coverage in the bend region, a waved surface was added where the conductor tape touches the body. To make sure the tape conductors fit tightly, pressure was applied by two nuts via springs. The conductor tape was supported from the backside from the copper terminals down to the bending region. On top, we included two sleeves covering half the sample width to reduce the strain on the s-shaped transition after the copper clamps down to the bending body.

Besides normal bending, the U-Bend rig and its bending bodies are additionally capable of performing half helical twist bending for different angles. Fixation holes are placed with 5° steps along the D-shaped frames and can be used to turn the movable support for twist bending as shown in Fig. 2(d). The sample aligns then diagonal to the bending body.

RESULTS AND DISCUSSION

An overview of the tested samples and their parameters is given in Table 1. The I_c degradation of the samples can be seen in Figs. 3-6 respectively. The relative critical current is plotted as a function of the bending radius R.

Bending

Besides the ShanghaiSCT (SSCT) ST1911-78, all samples showed reversible or no degradation down to $R = 5$ mm. Bruker's tape is the only one degrading constantly from bending radii smaller than 10 mm (see Fig. 3). However it is the only one having a stainless steel substrate, whereas all others are based on Hastelloy. This could explain the worse I_c degradation trend. All other samples behave similarly with a steep I_c drop after their R_{min} is reached.

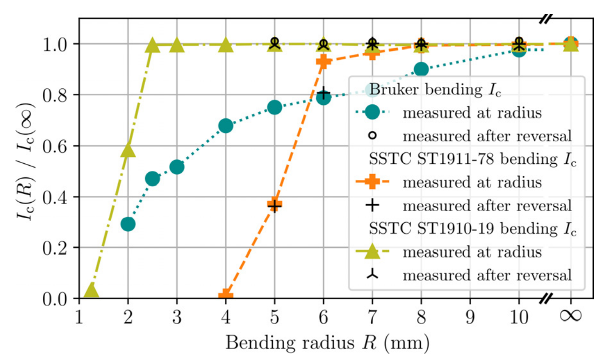

Figure 3: Relative critical current over bending radius for Bruker, SSTC ST1911-78 and ST1910-19 (all with 50 µm substrate).

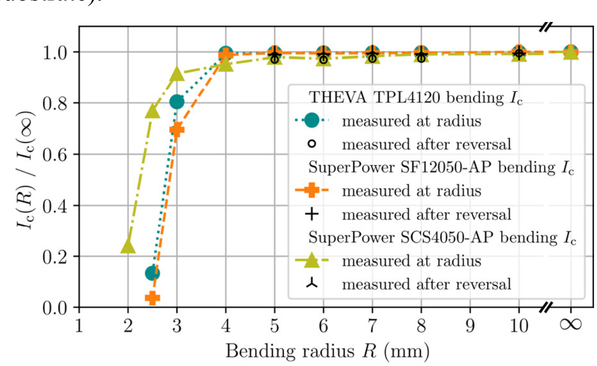

Figure 4: Relative critical current over bending radius for THEVA TPL4120, SuperPower SF12050-AP and SCS4050-AP (all with 50 µm substrate).

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Table 1: Tested samples, their parameters, measured critical current I_c and measured minimum bending radius R_{min}. The minimum bending radius is defined as the smallest radius for which the critical current degrades less than 5%.

Manufacturer	Reference	Tape Width	Tape Thickness	Stabilizer Thickness	Substrate Thickness	Measured I_c	R_{min}
Bruker	–	4 mm	105 µm	50 µm	50 µm	91 A	10 mm
THEVA	TPL4120	4 mm	80 µm	20 µm	50 µm	167 A	4 mm
ShanghaiSCT	ST19911-78	10 mm	95 µm	40 µm	50 µm	360 A	7 mm
ShanghaiSCT	ST1910-19	4 mm	95 µm	30 µm	50 µm	159 A	2.5 mm
SuperOx	942-R	4 mm	76 µm	10 µm	60 µm	127 A	5 mm
SuperPower	SF12050-AP	12 mm	55 µm	Ag only	50 µm	428 A	4 mm
SuperPower	SCS4050-AP	4 mm	100 µm	40 µm	50 µm	135 A	4 mm
SuperPower	SCS4030-AP	4 mm	42 µm	10 µm	30 µm	130 A	2 mm
SuperPower	SCS4025-AP	2 mm	36 µm	10 µm	25 µm	65 A	2 mm

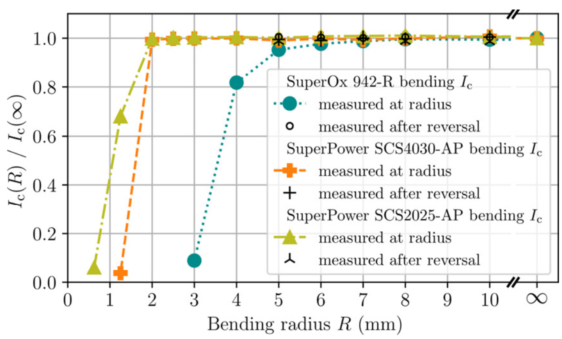

Figure 5: Relative critical current over bending radius for SuperOx 942-R, Superpower SCS4030-AP and SCS2025-AP (60 µm, 30 µm and 25 µm substrate, respectively).

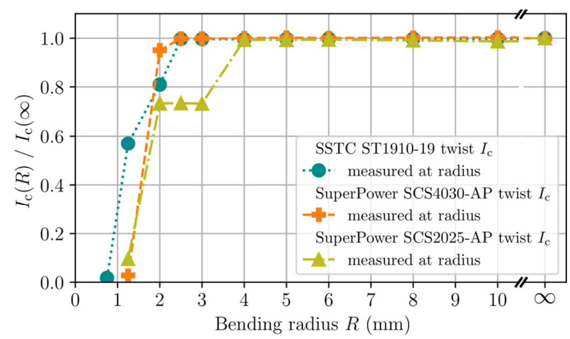

Figure 6: Rel. critical current over bending radius for SSTC ST-1910-19, Superpower SCS4030-AP and SCS2025-AP for half helical twist bending under an angle of 30º.

The two investigated SSCT tapes behaved significantly different for the same material parameters except their widths: ST1910-19 is 4 mm wide and showed an R_{min} of 2.5 mm whereas the 10 mm wide ST1911-78 degraded after 7 mm. THEVA TPL4120, SuperPower SF12050-AP and SCS4050-AP tapes have the same substrate thickness of 50 µm and behaved similarly with an R_{min} of 4 mm (see Fig. 4). The tapes with the thinnest substrates (30 µm and 25 µm) reached the smallest R_{min} of 2 mm (Fig. 5).

Half Twist Bending

Three samples were measured and the results are displayed in Fig. 6. The U-Bend rig does not allow to measure reversal degradation as facile and save as the Goldacker rig, so this was skipped. Similar performance as normal bending can be seen for SSTC ST-1910-19 and Superpower SCS4030-AP. As an exception, SCS2025-AP degraded after $R = 4$ mm (2 mm for normal bending), stayed constant down to 2 mm and then degraded completely.

The absence of an equally thick copper coating as stabilizer did not influence R_{min}, as seen for SuperPower SF12050-AP, nor did the half helical twist. An exception to this general result is the faster degradation of SuperPower SCS2025-AP. Because I_c stayed constant for two decrements of R after the first degradation, it appears likely that this degradation was caused by an external damage, thus needs further investigation. The different behaviour of same SSCT tape for different widths is not understood.

SUMMARY AND OUTLOOK

We tested nine different coated REBCO tapes from five manufacturers. THEVA, SuperOx and SuperPower tapes behaved similarly according to their substrate thickness. Bruker tape had a different degradation behaviour and samples from SSCT varied for different widths.

Overall, thinner substrate decreases the minimum bending radius. However, we noticed a manufacturer and substrate material dependency. The presented results show the feasibility of geometries with small period lengths, thus benefit the development of HTS undulators.

We envisage a subsequent experiment investigating full helical bends (three periods) as well as a larger variation of substrate thicknesses and more samples from the same manufacturer. This will allow to improve the link of applied strain on the superconducting layer to the bending radius for each individual tape conductor.

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