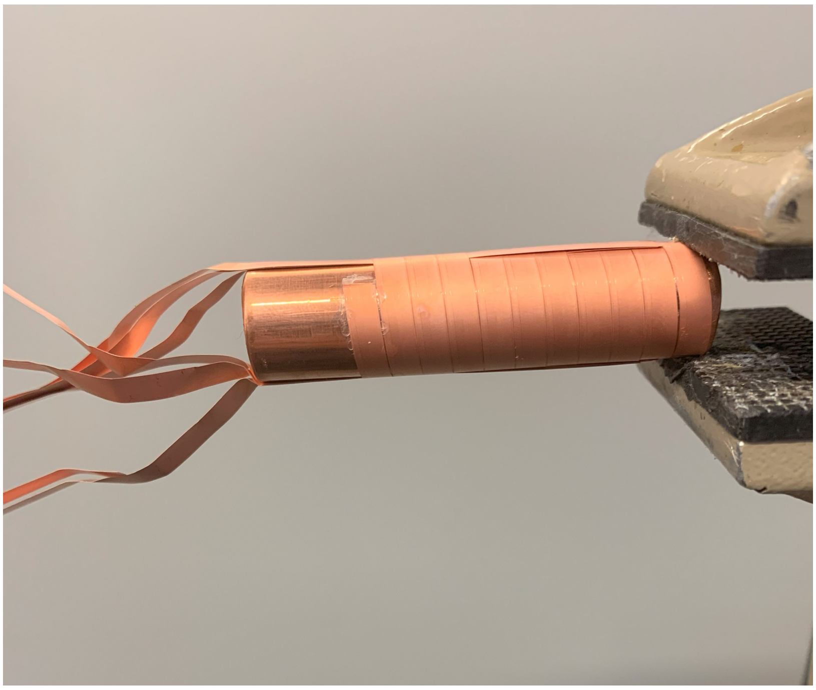
Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Information Technology and Electrical Engineering
Department of Electric Power Engineering

Erling Andreas Aabrekk

Production and development of HTS terminations for future HTS coil manufacturing

Master's thesis in Energy and Environmental Engineering
Supervisor: Jonas Kristiansen Nøland
Co-supervisor: Runar Mellerud, Christian Hartmann
June 2023



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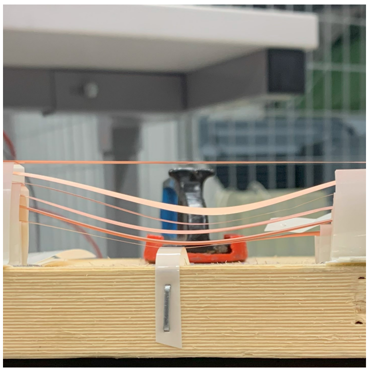

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Production and development of HTS terminations for future HTS coil manufacturing

Erling Andreas Aabrekk
Department of Electric Energy,
NTNU
Trondheim, Norway

***Abstract*—Termination methods for single and parallel coupled REBCO HTS tapes have been examined in laboratory experiments to gain handling knowledge for further experiments and production of HTS coils at the EME research group at NTNU in Trondheim. The literature review gathers and compounds factors that reduce the critical current of HTS tapes. Results obtained in the experiments could therefore be compared with more context. The effect of twisting was investigated, but it is suspected that the critical current reduction observed was not caused only by twisting, but also due to too high temperature during soldering. Non-twisted parallel coupled HTS tapes were also investigated, where the current measured before quench suggests that 5 of 6 HTS tapes functioned properly. The termination method for parallel coupling was found to have a better resistance area than the method that inspired it under similar conditions. The work performed in this thesis lays the groundwork for future lab experiments and the production of HTS coils, and many potential improvements for future lab experiments have been identified.**

***Index Terms*—HTS, superconductor, REBCO, parallel, twisting, termination, soldering, handling**

I. INTRODUCTION

Much research has already been done on HTS (High-Temperature Superconductor) coil production, resulting in multiple potential cabling methods such as Roebel-cables, TSTCs, CroCo and CORC, [1]–[4]. Designs have been proposed for hydrogen-powered aviation engines and [5] claims that superconducting machines (SCM) could be an option for future electric aviation. However, in order to achieve this, HTS coils must be appropriated for the machines. Many termination methods have previously been developed for REBCO (Rare Earth Barium Copper Oxide) HTS tapes, such as ”comb-teeth” joints [6], lamination joints [7], folding fan joints [8], amongst others.

The goal of the thesis is to find termination methods for REBCO HTS coils, for future use in a hydrogen-powered electric-aviation propulsion motor. In order to achieve this, handling knowledge about how to parallel couple and terminate the HTS tapes is vital. Specifically how to build the terminations, what the effect of different twist-pitches and bends is, along with knowledge about how to design the end windings. Knowledge about how sharp the twists and bends can be is of interest since this determines the size of the end windings. This ultimately affects the size of the SCM propulsion motor, and in aviation size and weight are of utmost importance.

REBCO HTS are shaped like tapes, where the tapes used in this thesis are produced by Shanghai Superconductor Technology, and is $4\,\mathrm{mm}$ wide. Commonly electric cables are shaped like wires, and therefore handling and termination of the tapes are fundamentally different. The objective is to investigate a simple termination method that also makes the power supply system simple. As a bonus, it should also be easy to replace should it break.

II. LITERATURE REVIEW

This literature review has been conducted to get a solid understanding of the current state of REBCO-coils, with a focus on the factors that can negatively impact the current carrying capabilities of the HTS tapes. The goal is to get a comprehensive overview of the results from previous research. Many of the effects discussed below occur simultaneously, and therefore it is at times difficult to differentiate the effects they have on the HTS from each other, the author has nonetheless attempted.

The search terms used to find the initial articles were ”HTS Coil and Twist”, ”REBCO Coil and Twist” and ”YBCO Coil and Twist”, where all the initial articles were found on IEEE. Articles referenced in the initial articles that were connected to the topic were explored further, with no regard to publisher, a concept called snowballing [9]. Finally, Makoto Takayasu, a prominent researcher in the field of HTS coil production that has authored several of the articles that have been cited in this thesis has been contacted for recommendations for further articles.

Articles that fit the initial search terms but were not used have not given much information regarding twisting of HTS tapes or had no relevant results that could be extrapolated. The articles chosen to be cited had information that could be of interest when producing an HTS coil from REBCO tapes. The information gathered in this literature review should make further HTS-tape coil production easier by compiling the knowledge available today.

The reported constraints found in the literature will be utilized during laboratory work to avoid degradations to the HTS tapes. Furthermore, the review will enable comparisons between the results obtained in this thesis's experiments and the reported performance in the literature, facilitating easier coil production in the future. Additionally, it will contribute to building the knowledge base at the EME research group at NTNU concerning HTS coil production for future production and testing of superconducting electrical aviation motors.

A. Definitions

Critical current, I_c in superconductors are regularly defined to be the current required to achieve a potential drop over the superconductor of $1\,\mu\mathrm{V/cm}$ [1].

Strain, or longitudinal strain as is discussed briefly in this thesis is here defined as the increase in length from its original state. A $10\,\%$ strain thus means a $10\,\%$ increase in length due to mechanical loads in the longitudinal direction of the REBCO tapes.

Twist pitch is defined as degrees of twisting per length, where a $360°$ twist returns the tape to its original direction, see Figure 1. Here the top tape has a $360°$ twist over its length. In some literature, twist pitch is only defined as a length, whereby the length provided commonly is the length for a $360°$ twist.

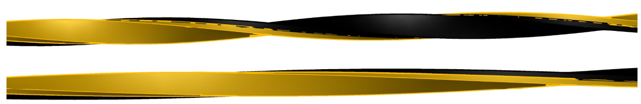


Fig. 1: Two twist pitches, where the top has double the twist pitch of the tape on the bottom.

B. Types of cabling methods

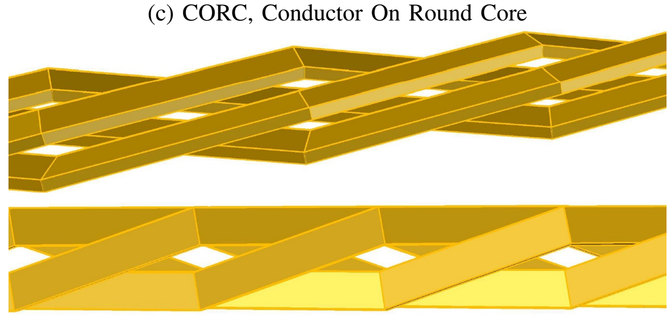
Twisted Stacked-Tape Cable (TSTC), see Figure 2a is a cabling method that stacks tape-shaped HTS, such as REBCO, often in square stacks. It is one of the simpler cable designs. TSTCs can also be soldered to improve their mechanical and electrical performance [10]. In [11] it was found that for a twisted stack, it was beneficial to not glue or solder the tapes in the stack together since they needed to be able to slide with respect to each other when making the windings. The engineering critical-current density of a TSTC was found to be $375\,\mathrm{A/mm^2}$ at $17\,\mathrm{T}$ at $4.2\,\mathrm{K}$ in [3] if only the cross-section of the conductor is considered. Here, the tapes were $4\,\mathrm{mm}$ wide and $0.14\,\mathrm{mm}$ high, and had artificial pinning centres (APC).

Cross Conductors (CroCo), see Figure 2b, is an alternative cabling method that builds upon the design of TSTCs. As presented in [4], the conductor makes use of more of the circular cross-section around a TSTC, which can be a cylinder-shaped outer layer consisting of solder, copper and insulation. Since the cross-section often becomes a circle, and the cross-section of a square stack tape conductor is square, there is room for more tapes that can increase the current density of the cable,

(a) TSTC, Twisted Stacked-Tape Cable

(b) CroCo, Cross Conductor

(c) CORC, Conductor On Round Core



(d) Top: Roebel from the side
Bottom: Roebel from the top

Fig. 2: Known cabling methods for tape-shaped superconductors. Yellow/Orange is HTS tapes, brown is insulation/plastic.

while at the same time retaining the same total cross-section area of a round TSTC. In [4] it was expected to increase the critical current density by $20\,\%$ compared to a similarly built TSTC. Comparing the engineering critical current density, J_{ce}, of a TSTC from [3], which at a magnetic field of $12\,\mathrm{T}$ at $4.2\,\mathrm{K}$ had a current density of $\sim 306\,\mathrm{A/mm^2}$, the CroCo in [4] was found to have a higher J_{ce} at $482\,\mathrm{A/mm^2}$. It should be noted that the height of the REBCO tapes was $95\,\mu\mathrm{m}$, and they were 2 and $3\,\mathrm{mm}$ wide. Also, the twist pitch for the TSTC was much smaller, at $100\,\mathrm{mm}$ compared to the $25\,\mathrm{cm}$ used for the CroCo. As will be discussed later, the twist pitch can have an effect on the critical current of HTS tapes. Investigation of whether the higher critical current density of the CroCo compared to the TSTC is worth the lesser twist pitch should be further studied, since this may be used to increase the critical current in the end windings of a machine. The authors of [4] expects current densities to exceed $1000\,\mathrm{A/mm^2}$ at $4.2\,\mathrm{K}$ at $12\,\mathrm{T}$ with newer REBCO technology.

Conductor On Round Core (CORC), see Figure 2c is a cabling method where HTS tapes are placed on and bent along the length of a cylinder. It is shown in [12] that the CORC cable has lower magnetization losses in an alternating magnetic field with various magnetic field strengths ranging from 0.015 to $0.15\,\mathrm{T}$ than a straight tape of equal width. Though it is not shown Figure 2c, there is commonly no space between the tapes on the cylinder, so all the space available is covered in tapes. Additionally, many layers can be placed on top of each other, increasing the diameter of the cable. An engineering current density of $322\,\mathrm{A/mm^2}$ was achieved for a 50 tape wire, while it was $412\,\mathrm{A/mm^2}$ for a 29 tape wire at $10\,\mathrm{T}$, $4.2\,\mathrm{K}$ in [2]. Here they used $2\,\mathrm{mm}$ wide REBCO tapes. The authors of [2] expect the current density to reach 700 to $900\,\mathrm{A/mm^2}$ at $10\,\mathrm{T}$, $4.2\,\mathrm{K}$ due to reduction in the substrate thickness of REBCO tapes in the future, reducing their height and allowing for sharper bends and therefore a smaller inner diameter of the cable.

A Roebel cable can be seen in Figure 2d. Because a stack of REBCO tapes has an inhomogeneous current distribution in the tapes, a transposition such as those found in a Roebel cable could be the solution to make the distribution more uniform [11]. There are however weaknesses to Roebel cables in the form of a more complicated production process and weak mechanical zones. A ROEBEL cable was punched from $12\,\mathrm{mm}$ wide, $71\,\mu\mathrm{m}$ high SCS12050 tape in 15 layers in [1]. It was found to have a critical current of $\sim$1505 A. By using values of the dimensions of the tape, a critical current has been calculated to be $128.47\,\mathrm{A/mm^2}$ at $77\,\mathrm{K}$ self field.

C. Lorentz forces

The force on a wire carrying current in a magnetic field is known to be $\mathbf{F} = \mathbf{J} \times \mathbf{B}$. Tests on TSTCs with Lorentz loads up to $102\,\mathrm{kN/m}$ have seen no clear evidence for electromagnetic degradation [8]. However, it was noted that it is important to give the conductor sufficient mechanical support.

D. Magnetization losses

Perpendicular magnetization losses have been investigated in [12], where samples of YBCO (a REBCO tape where the rare-earth metal is yttrium) Coated Conductor (CC) tapes from SuNAM were investigated. Here, they compared the magnetization losses in an applied magnetic field between pairs of end-connected tapes and not-end-connected (open) tapes. The results showed that the two cables that were connected in the end displayed magnetization losses of around one order of magnitude larger than the pair that was open-connected in small magnetic fields up to approximately $0.1\,\mathrm{T}$. The end connection resulted however in a lower magnetization loss when the tapes were arranged in a CORC cable. The CORC cables also displayed lower magnetization losses compared with their straight tape counterparts.

E. Safe handling

Handling of the superconductors is paramount. Handling errors can be unintended mechanical stress, exposure to too high temperatures, or fat damaging the delicate materials of the HTS before or during manufacturing. This can result in degradation of the tape, resulting in lowered performance. Therefore it is recommended to perform many tests with different coils produced in the same way so that inconsistencies can be observed and commented, and so that one can avoid basing the research on poor samples. One case where this occurred was in [13], where tapes were observed to have worse I_c at the same conditions after shipping to a new location. Another case is the "folding fan joint" in [8] that is discussed later in II-K.

A damaged HTS can not only result in lower critical currents, but it can also result in higher AC losses when the reduction is caused by mechanical loads, as was observed in [14]. Here they found that for a single $12\,\mathrm{cm}$ long BI-2223 when the critical current had been reduced by $14.1\,\%$ the AC losses increased threefold. Their other test resulted in double the AC losses, but not until the critical current had been reduced by $55.4\,\%$. A larger sample size would have given more useful data, but nonetheless, the trend is that higher I_c degradation leads to higher AC loss.

F. Impact of mechanical load

Experiments performed in [14] on a $4.2\,\mathrm{mm}$ wide BI-2223, found that the critical current degradation in a single tape was approximately $5\,\%$ when applying a force of $120\,\mathrm{N}$, and the force was applied gradually. Increasing the force further resulted in a degradation of approximately $55\,\%$ at $140\,\mathrm{N}$. However, if the force was increased immediately up to around $150\,\mathrm{N}$, only a degradation of $15\,\%$ was observed. These results could imply that a gradual increase in mechanical load is bad for the conductor, but it may also be an anomaly from a low sample size.

Strain-tests on HTS tapes at $77\,\mathrm{K}$ and no external magnetic field were also performed in [1]. They found that a $12\,\mathrm{mm}$ SuperPower wire experienced irreversible critical current degradation at strains of $0.63\,\%$. This strain corresponded to a tensile force of $840\,\mathrm{N}$, and from the graphs it appears to correspond to a $9.1\,\%$ I_c reduction. It was measured to be $0.53\,\%$ for a $5\,\mathrm{mm}$ Roebel wire, at a force of $73\,\mathrm{N}$. Here the graphs indicate a I_c reduction of $0.86\,\%$. It was also found that a stack of 15 such Roebel wires only could handle a strain of $0.36\,\%$, occurring at $850\,\mathrm{N}$ before irreversible critical current reduction occurred. At this point, the I_c reduction

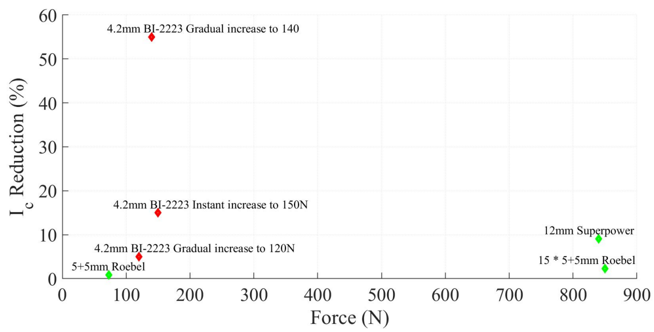


Fig. 3: Impact of mechanical load. Red colour denotes [14]. Green colour denotes [1].

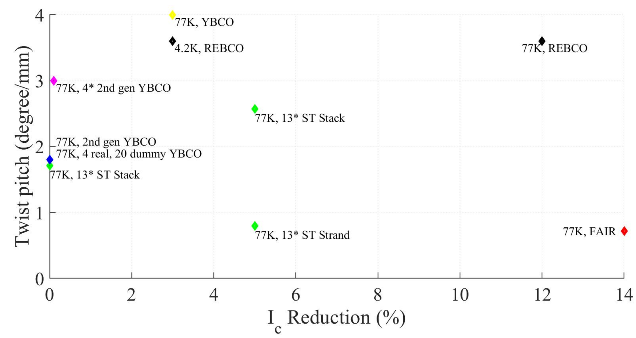


Fig. 4: I_c reduction due to twist pitch. [16] in yellow and blue. [17] in blue. [18] in pink. [3] in black. [19] in red. [20] in green.

appears to be $2.33\,\%$. At the point of mechanical failure, the force applied to the stack was $1950\,\mathrm{N}$ and an I_c reduction of $26.18\,\%$. The reduction in tensile strength was attributed to the fact that the strands restricted neighbouring strands from out-of-plane movements, and therefore resulted in higher stress concentration in the transposition elbow of the Roebel-cable, reducing the critical current. It appears that the Roebel-wire can handle a smaller tensile force than the straight-tape counterpart and that the irreversible I_c strain occurs closer to the non-strained I_c for Roebel-wires. From this research, it appears that Roebel-wires require more reinforcement if they should be subjected to the same loads as a straight-tape counterpart.

From tests in [15] it appears that an applied strain of $0.4\,\%$ in a magnetic field of $0.2\,\mathrm{T}$ at $77\,\mathrm{K}$ results in a I_c reduction of around $5\,\%$ for a $4\,\mathrm{mm}$ wide REBCO without APC. They also applied stress to REBCO-tapes with APC in fields of $0.5\,\mathrm{T}$, and the results are similar, although when the external field either was 0 or $90°$ to the tape, and the strain was between 0.1 to $0.4\,\%$, an **increase** in critical current above $10\,\%$ was observed. Since the force applied to the tapes has not been mentioned, the results were not added to Figure 3.

One way to reduce longitudinal strain in cables from the terminations is to solder flexibly movable tape ends onto the terminations allowing the tapes to slide, as done in [13]. Alternatively, it could also in some cases be possible to have the terminations themselves fastened in a way that allows them to move slightly in the longitudinal directions.

Results from [14] and [1] have been placed in Figure 3 where they can be easily compared. The results from [15] have not, since the force used to obtain the strains is not mentioned.

G. *Impact of twist*

The authors of [16] found that the minimum twist pitch was $1.8\,°/\mathrm{mm}$ without I_c degradation for a 2nd generation, $4\,\mathrm{mm}$ wide YBCO tape (no external field). The same tape was twisted to $4\,°/\mathrm{mm}$ in the same article, and only a $3\,\%$ I_c reduction was observed. This twist pitch of $1.8\,°/\mathrm{mm}$ has been confirmed by the same author to have only a minuscule effect on performance in [17] for tapes configured in TSTCs where 4 real and 20 'dummy' YBCO tapes where used. However, when [17] tested a cable consisting of 32 YBCO tapes in a TSTC with $1.8\,°/\mathrm{mm}$ twist pitch at $77\,\mathrm{K}$ self field, a I_c degradation of $44\,\%$ was observed compared to the combined I_c of 32 separate YBCO tapes not affected by one another. [17] claims this I_c reduction is caused by the self field effect.

TSTC consisting of four $4\,\mathrm{mm}$ wide 2nd generation YBCO tapes with a twist pitch of $3\,°/\mathrm{mm}$ was found to be able be twisted with a miniscule $<1\,\%$ I_c degradation in [18].

In [3], $4\,\mathrm{mm}$ wide single tapes where tested at $4.2\,\mathrm{K}$, and the difference in critical current between a twisted ($3.6\,°/\mathrm{mm}$) and non-twisted were tape no more than $3\,\%$ when the applied field around the tapes was changed from 2.5 to $20\,\mathrm{T}$. Comparatively, they had seen a difference of $12\,\%$ in the critical current in twisted and non-twisted tapes at $77\,\mathrm{K}$.

FAIR conductors, named from its production "friction stir welding (FSW), aluminum alloy jacket, indirect cooling, and REBCO tapes" [19, p. 1] were produced with $4\,\mathrm{mm}$ wide REBCO tapes in [19]. Their best design could withstand $0.72\,°/\mathrm{mm}$ with a I_c degradation around $14\,\%$. One reason why the results are so much worse than the results obtained in [11] could be due to the fact that the twist was applied after the FAIR conductor was manufactured. It is mentioned in [11] that it is beneficial to allow the tapes to slide with respect to one another, and that does not seem to be possible for the FAIR conductor manufactured in [19].

A similar result was observed in [20], where the HTS stacks were soldered inside copper encasings to counteract Lorentz forces. They performed tests where they soldered first and then twisted (ST, solder twist). They also differentiate between a strand and a stack, where the stack only consists of HTS and solder, but the strand also has a copper encasing. Measurements were done at $77\,\mathrm{K}$, and from their tests they found that their cable consisting of 13 $4\,\mathrm{mm}$ wide HTS tapes of $4\,\mathrm{mm}$ width already experienced a $5\,\%$ I_c deterioration at

$0.8\,°/\mathrm{mm}$ for the ST with a copper encasing. The ST stack could be twisted to $1.71\,°/\mathrm{mm}$ before degradation occurred. A $5\,\%$ deterioration was observed for the ST stack at a twist pitch of $2.57\,°/\mathrm{mm}$, in contrast to their calculated $4.5\,°/\mathrm{mm}$ needed for the same result.

Results from articles [3], [16]–[20] have been placed in Figure 4 for easy comparison. One $44\,\%$ I_c reduction was left out for readability.

H. Impact of bend

There are two ways one can bend a tape, defined as the *easyway* (EW) and the *hardway* (HW) in [11], see Figure 5. The minimal bending radius in these directions (not illustrated in the figure) was found in [11] to be $6\,\mathrm{mm}$ and $2\,\mathrm{m}$ respectively with no I_c degradation when the stack was $4\,\mathrm{mm}$ wide and high. In [21] the minimal EW bending radius in a lap joint was found to be $30\,\mathrm{mm}$ resulting in a $5\,\%$ I_c degradation, implying that joints are mechanically less resistant to bends compared to unaltered tapes.

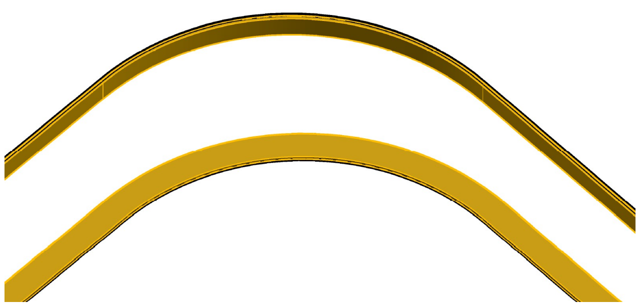


Fig. 5: Bend directions. Hardway for the bottom tape, and easyway for the top.

Additionally, there is a difference between bending a straight tape and a twisted tape. In [17], a bending diameter for a TSTC of $0.5\,\mathrm{m}$ was found to have no impact on the I_c. Bending tests were also performed in [10] on a TSTC consisting of 32 $4\,\mathrm{mm}$ YBCO tapes configured in a square stack and bent. At a bending diameter of $0.14\,\mathrm{m}$, a critical current degradation of $5.4\,\%$ was observed compared to when the tape was straight, and after straightening the tape the critical current was $3.6\,\%$ lower.

I. Impact of fields

The effect of the angle of the magnetic field on different REBCO-conductors under strain with and without APC was inspected in [15]. For the tape without APC, it was found that at $0.2\,\mathrm{T}$, the critical current was highest when the applied magnetic field was parallel (defined as $90°$) to the flat side of the tape, and approximately $20-30\,\%$ lower when the angle of the field changed more than $30°$ from the parallel position.

Curiously in [15], for the tape with APC in at $0.5\,\mathrm{T}$, the worst critical current was seen when the field angle was $90°$. The critical current nearly doubled when the field was allowed to stand perpendicular 0 or $180°$ to the flat side of the tape.

In [18], Takayasu *et al.* investigated the effect of self-fields for untwisted YBCO tape stacks. They found that for a $4.05\,\mathrm{mm}$ wide 4-tape stack without spacers between the tapes, the critical current was reduced by $\sim24\,\%$ compared to the total I_c of the individual tapes. They conclude that this is likely caused by the perpendicular self-field created by the stacked tapes. Afterwards a test with 4 tapes stacked in between $4\,\mathrm{mm}$ high spacers was conducted, and it was found that the critical current only was reduced by $\sim3.32\,\%$ compared to the total I_c of the individual tapes. This means that it appears to be possible to drastically reduce the effect the self field has on the critical current, although with great loss of current density of the stack, since the space one of the $4\,\mathrm{mm}$ spacers needs could instead be filled with 30 HTS tapes.

In [3] it was found that a stack of 40 tapes configured in a TSTC had a $16\,\%$ I_c reduction per tape between 10 and $17\,\mathrm{T}$ compared to a single tape.

Takayasu *et al.* has observed that "the hysteresis loss of a twisted tape over one twist pitch in high fields is about $2/\pi$ times ($64\,\%$) the hysteresis loss of a single tape in a perpendicular field" [17, p. 274]. Specifically in fields above $1\,\mathrm{T}$ with $4\,\mathrm{mm}$ wide YBCO tapes.

J. Impact of time/Cycles

A reduction of $3\,\%$ of I_c have been observed in copper-cored Rutherford cables after performing 1000 cycles where the current through the cable went from $0\,\mathrm{A}$ to its operating current of $50\,\mathrm{kA}$ at $12\,\mathrm{T}$ [22].

The impact of quickly increasing the current through a TSTC at $4.2\,\mathrm{K}$ has been tested in [10]. Here, the current was initially increased with $20\,\mathrm{A/s}$ to the peak current of $10\,\mathrm{kA}$ was reached, which was lower than the critical current of the cable. The final test increased the current with $10\,\mathrm{kA/s}$. Resistive voltage signals were not recorded in any of the tests. This could imply that there should be no issues increasing the current quickly in the subsequent laboratory work. Although since the current was not ramped up to the critical current of the cable, it is still not certain that it could be detrimental to immediately increase the current to the critical current. Therefore, caution should still be taken when increasing the current through a superconductor.

K. Joints and terminations

One way to join two ends of asymmetrical HTS tape is to spot weld the two ends together, then place another HTS tape face to face with the two tapes and sandwich all the tapes between copper strips, before passing it through a liquid solder bath. This has been done in [7] on $4\,\mathrm{mm}$ wide REBCO tapes, where they called it a lamination joint. They compared

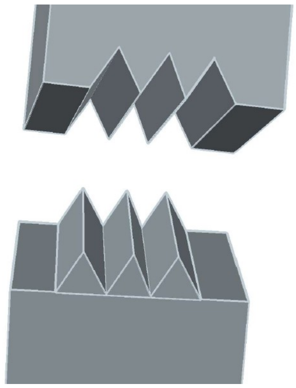


Fig. 6: Comb teeth joint blocks.

it with a normal solder joint where the two ends of the HTS tape were connected through a soldered face-to-face HTS tape without spot welding, solder baths and additional copper strips. They compared the two types of joints under axial tension. From their tests, the lamination joint could handle axial tension between 680 to $700\,\mathrm{N}$, similar to what a single non-jointed tape could handle, while the normal soldering joints could handle between 300 to $350\,\mathrm{N}$. V-I curves for the joints were also made, and it was found that the voltage at any current was highest over the single tape where no joint was present, lowest in the sections where the lamination tape and the end tapes were parallel, and slightly higher over the section that was spot welded. In [21], the minimum bending radius of the lamination joint was found to be $3\,\mathrm{cm}$ for a $5\,\%$ I_c degradation.

Another joint method for HTS tapes is the "comb teeth" joint developed in [6]. Here a metal block is divided into two parts, with 'zig-zag' indentations cut out between them, see Figure 6. HTS tapes is then placed face out on the sides of the teeth in both blocks so that it becomes a face-face connection when the joint block is put together. This joint was found to have $30\,\mu\Omega\,\mathrm{mm}^2$ average joint resistance area, although the exact pressure used to achieve this resistance was not mentioned.

A BSCCO-TSTC joint developed in [23] had an average joint resistance area of $276\,\mu\Omega\,\mathrm{mm}^2$, much higher than the comb teeth joint at $77\,\mathrm{K}$. Various pressures were tested for the joint, and it was found that the highest pressure tested, at $67\,\mathrm{MPa}$ gave the lowest resistances. Takayasu *et al.* claims to have used this method over 30 times over the course of a year and states that "This termination method would be very useful for various applications and laboratory uses [23, p. 4]".

The authors of [8] conclude that performance degradation of a stacked cable can be caused by nonuniform joint resistance for the tapes. If one tape has lower joint resistance, more current will pass through it, and it will reach and eventually exceed its I_c earlier than the other cables, potentially breaking down.

Some joint methods for stacked-tape conductors can be used as termination methods as well, since it in some cases should be easy to instead of joining the stack, to another stack to fasten it to a copper termination block. One joint method that seems promising for this purpose is the lap-joint method illustrated in [24], although it does not discuss its resistance to strain. This lap-joint method consisted of applying a pressure of $40\,\mathrm{MPa}$ onto a lap-joint, and applying indium between the terminations. It was found that a resistance of approximately $400\,\mathrm{n}\Omega$ could be expected in the joint between two tapes, and that the tapes' critical properties were unaffected by repeated assembly and disassembly. The required length of the joint was not mentioned, although it appears from the figures in [24] that the joint area is very low, resulting in a lower joint resistance area than the one found in the 'comb teeth'.

One way to terminate a stack of tapes is to solder or clamp them between other tapes that themselves have been soldered onto copper termination blocks. This has been done in [16], [25], where the REBCO tapes were clamped between BSCCO tapes at $50{-}55\,\mathrm{MPa}$, and the BSCCO tapes were soldered onto the copper terminals. It was observed in [16] that higher pressures resulted in lower termination resistances. One advantage of this method is that the section of the stacked tape cable that is tested with twists or bends is separate from the terminations, and therefore it is unlikely that the terminations' I_c degrades during testing, as the stacked tape often does. Since the critical temperature T_c of BSCCO is higher than YBCO, in a section that typically would introduce some resistance in the joints, the BSCCO tapes can handle the heat. Additionally, the termination method is easily demountable. The average resistance in a $70\,\mathrm{mm}$ long termination between a BSCCO and a YBCO tape in at $68\,\mathrm{MPa}$ was observed to be approximately $0.8\,\mu\Omega$, resulting in a resistance area of $224\,\mu\Omega\,\mathrm{mm}^2$.

A "folding fan joint" has been proposed by Takayasu *et al.* where one BSCCO tape was placed between two REBCO tapes and soldered inside a termination block made of copper where inside the block the tapes were bent slightly in the hardway-direction (HW) so that the tapes did not lie perfectly on top of each other [8]. Their first attempt resulted in significantly degraded I_c, but their second attempt performed without BSCCO resulted in a cable termination resistance of $6.0\,\mathrm{n}\Omega$, and a joint resistance area of $66.64\,\mu\Omega\,\mathrm{mm}^2$. This suggests that although the resistance area is low, it could be prone to degradation, and thus should be avoided if other simpler methods with comparable resistance areas are available.

An YBCO-YBCO joint has also been developed and tested in [23], and it was found that it can reach lower termination-resistances than the BSCCO-YBCO termination. It is made by placing two YBCO tapes, one on the top and one on the bottom along the length of a copper cylinder, face away from the cylinder. Then a third YBCO tape is wound around the cylinder face down so it gets a face-to-face connection with the two already placed YBCO tapes. Then another two tapes are placed on top of the previous two tapes, and the process is repeated. When all tapes have been connected to the copper tube, the cylinder is soldered inside another larger copper tube. The termination resistance between the copper rod and the YBCO-cable tape was found to be $0.43\,\mu\Omega$, with a resistance area of $60\,\mu\Omega\,\mathrm{mm}^2$. It is also mentioned that Mylar insulation sheets were stacked together with the contact joints, presumably between them.

A termination for a VIPER cable ("vacuum pressure impregnated, insulated, partially transposed, extruded, and roll-formed" [26, p. 1]), consisting of 4 square stacks of HTS tapes, achieved joint resistances between 1.3 and $5.5\,\mathrm{n}\Omega$ at $77\,\mathrm{K}$, between "zero magnetic field and average magnetic field [26, p. 4]". This was achieved with a simple copper saddle, silver plating and some indium wire, showing that a well-designed cable can achieve low joint resistances. The design of the VIPER cable also allowed the joints to be disassembled and reused.

III. Lab 1, twist lab

The first twist lab was performed with the intention to observe the effect of twisting on a superconducting tape, and to test the results stated in the literature review. The results from the twisted superconducting tapes will be compared with results obtained in [27] in 2022 for untwisted tapes, where the same measuring equipment and method were used.

In [27], the voltage over the test rig was ramped up until the critical current was observed through the superconductors before it was set to zero. Afterwards, the polarity of the voltage over the rig was switched and ramped up again. This was done to test if the measurement equipment had a bias. The critical current was measured to be $142\,\mathrm{A}$ in one direction and $140\,\mathrm{A}$ when the polarity of the voltage over the test rig was switched. This gives an average I_c of $141\,\mathrm{A}$ with a $\pm\,0.709\,\%$ error.

A. Preparation for lab 1

Much work was done in [27] in order to learn how to solder the HTS properly to the termination blocks, and two termination-block designs were tested. S. Austad designed the termination block used in the first lab for [27], and can be seen in Figure 7. These "sandwich-type" termination blocks make use of bolts that can be tightened in order to apply pressure on the solder and HTS tape in order to reduce the joint resistance between the HTS and the termination block. Additionally, one bigger M8-bolt is present to allow the $70\,\mathrm{mm}^2$ infeed copper cable from the DC source to be fastened to the termination block.

The slot in the termination block where the HTS is placed is $70\,\mathrm{mm}$ long, and $5\,\mathrm{mm}$ wide. The width is wider than the $4\,\mathrm{mm}$ of the HTS so that it would fit without any trouble. The dimensions of the slot therefore provide a $280\,\mathrm{mm}^2$ contact area.

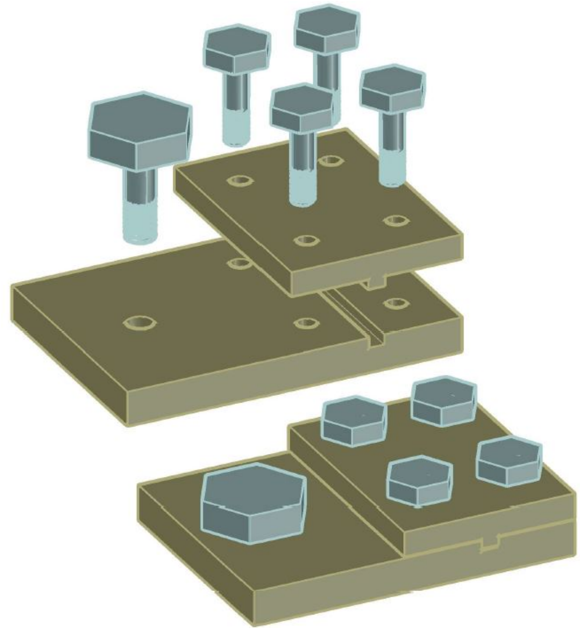


Fig. 7: Sandwich-termination blocks designed in AutoCAD by S. Austad, reproduced with permission from [27].

The termination blocks were fastened inside wooden blocks, one such seen in Figure 8, that originally was designed to allow the termination blocks to twist 0, 90, 180, 270 and $360°$.

Fig. 8: Wooden block to hold the termination-blocks in place, originally designed for [27].

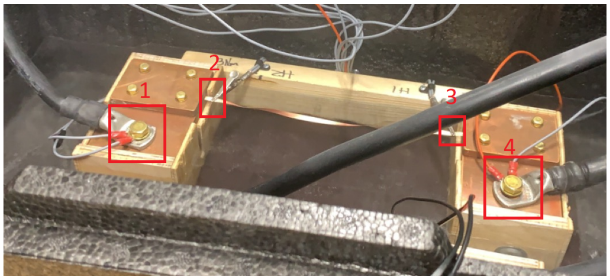


Fig. 9: The points where the measurement probes were fastened.

A full test rig consists of two wooden blocks fastened on a wooden plank with $20\,\mathrm{cm}$ between the outer walls of the wooden blocks, as seen in Figure 9.

The HTS tape was soldered onto the termination blocks using the following method, while always using clean plastic gloves when handling the HTS to avoid moisture, fat and oil damaging the HTS. The method is similar to the one used in [27], but with higher heat and with less solder.

1) Sand the termination slot with a P240 grit sandpaper.
2) Polish the sanded area with metal polish.
3) Wipe the area clean with rubbing alcohol.
4) Heat both sections of the termination-block to $225\,^{\circ}\mathrm{C}$.
5) Apply $7\,\mathrm{cm}$ of solder inside the slot of the bottom (biggest) part of the termination block.
6) Precisely place the HTS so that it fits the entire length of the slot, face down (so that the lowest resistance side faces the bottom block).
7) Fasten the top-termination section to the bottom by tightening the bolts with $3\,\mathrm{N\,m}$ torque.
8) Leave the termination blocks to cool.

The solder that was used was $Sn_{42}Bi_{57}Ag_{1}$, and it was chosen since it was easy to work with. This was because it contained soldering flux, and therefore it was not necessary to apply it separately.

The reasoning behind each step is listed below

1) Sanding was done to make the surfaces of the slots more even.
2) Polishing was done to remove the imperfections left after the sanding.
3) Cleaning alcohol was used to remove traces of polish.
4) Previous testing had shown that when hot liquid solder came into contact with the copper termination, it would solidify instantly because of the excellent thermal conductivity of copper. Therefore the copper must be heated beforehand to avoid this issue.
5) Applying a known and equal amount of solder for each test reduces the chances of getting results that are affected by the amount of solder since this is not the purpose of the testing.

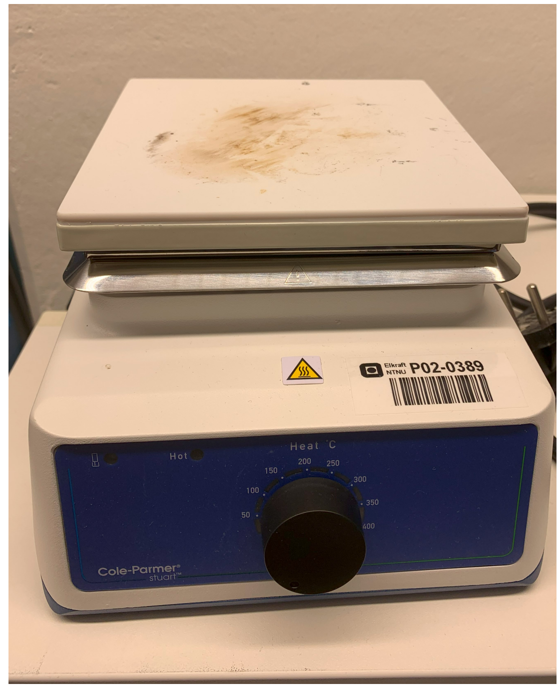


Fig. 10: Heat plate used instead of conventional soldering tools.

6) Inaccurate placement of the HTS in each termination could lead to unequal surface area for the joints, which would affect termination resistance significantly.
7) Using bolts to fasten the terminations allows for high pressure to be applied to the joints. Previous testing has shown that higher pressure yields lower joint resistance, as seen in [27] and as discussed in II-K.

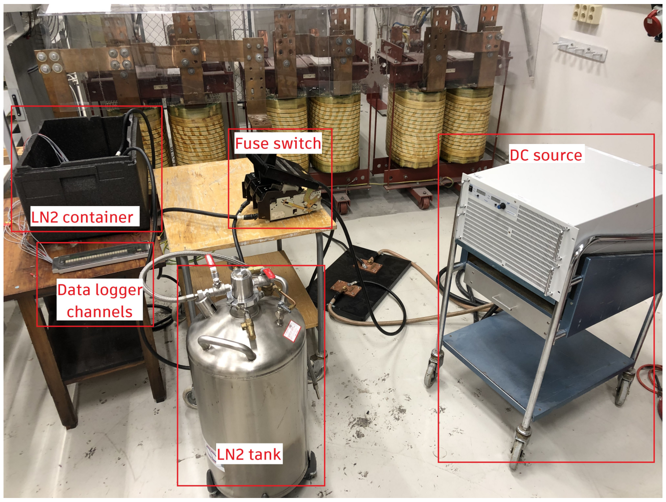
Step 4 was performed with the use of a heat plate, as seen in Figure 10. This plate heated the termination blocks to $225\,^{\circ}\mathrm{C}$ before the solder was applied in step 5, and the termination blocks were moved off the plate before step 6 so that the solder later could solidify in step 8.

The specific equipment used for testing is listed in Table I, and is the same as was used in [27]

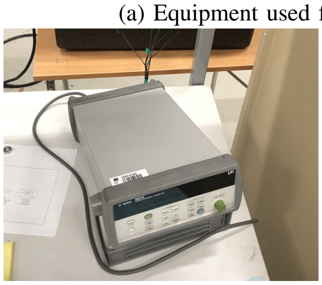
TABLE I: Equipment list reproduced with permission from [27].

Equipment	**Producer**	**Type/model**
DC source	ET System	LAB/HP/E 2020 (SN: 18.51.759)
Data logger	Agilent	LXI 34972
20 Channel Multiplexer	Keysight	34901A
Current clamp	Fluke	175 TRUE RMS
Fuse Switch	Siemens	3NP52 0CA00
LN2 Tank	Cryo Diffusion	XRP 30-S
Rubbing alcohol	Fisherbrand	70% isopropyl, 30% deionized water

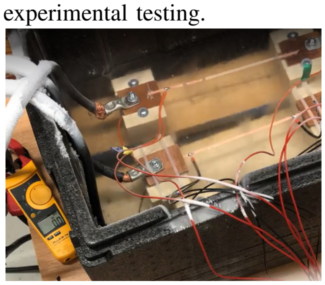
In order to measure the voltages over the system components, voltage taps were utilized. The taps were connected to a 20-channel multiplexer as seen in Figure 11d. The card was



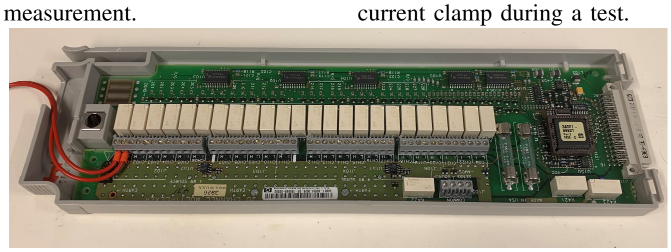
(a) Equipment used for experimental testing.



(b) Data logger used for voltage measurement.



(c) Current measurement with current clamp during a test.



(d) 20 Channel multiplexer used to measure the voltages from the measurement probes with the data logger.

Fig. 11: Laboratory setup for experimental testing, reproduced with permission from [27].

slotted inside a data logger as seen in Figure 11b. A current clamp was used to measure the current running through the system, as seen in Figure 11c, although the termination blocks seen in the figure is not the one used in the first lab. The entire lab setup without the data logger is shown in Figure 11a.

The circuit diagram for the rig and the measurements are shown in Figure 12. The measurement probes at the termination blocks were fastened onto the same points as the infeed cables from the DC source, namely the M8 bolt on the termination blocks, as seen in boxes 1 and 4 in Figure 9. The measurement probes on the HTS were clamps, where three cables were fitted into one clamp. The clamps were fastened with a distance of approximately 19 cm between each other on the HTS, as seen in boxes 2 and 3 in Figure 9. This meant that the critical current would occur when the voltage measured

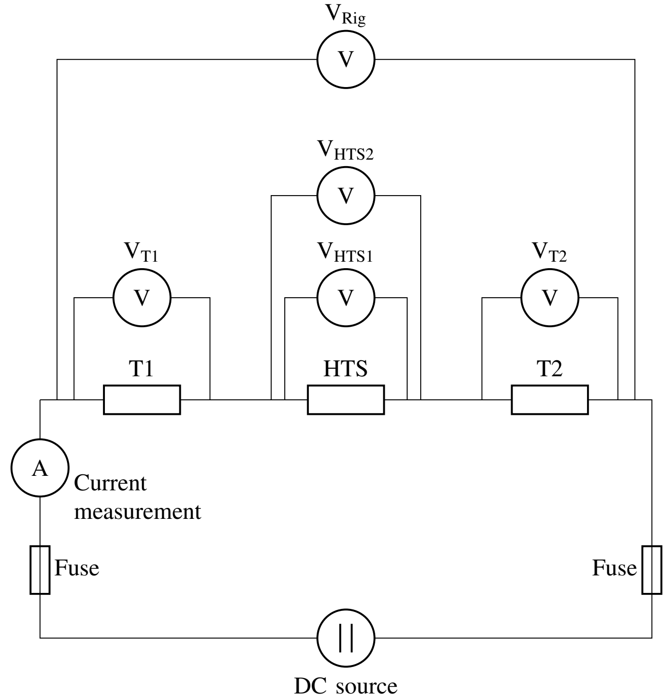


Fig. 12: Circuit diagram for the tests of the slotted sandwich termination, reproduced with permission from [27].

over V_{HTS1} or V_{HTS2} reached $19\,\mu\mathrm{V}$.

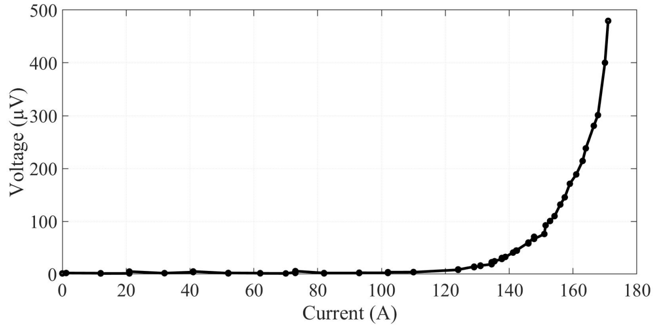
Two test rigs were constructed for the first lab, where one had strain reliefs, while the other did not since the LN2 container used did not have enough room.

B. Results and discussion, lab 1

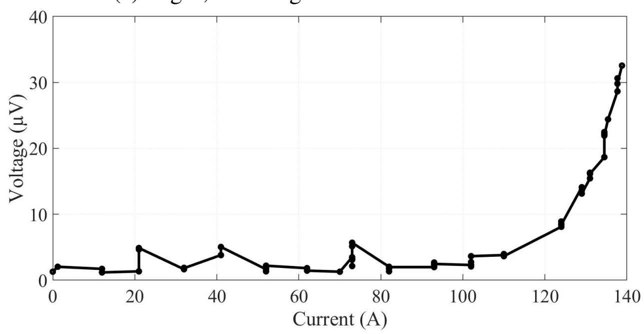
One issue that arose for the test samples in this experiment was that the twist pitch was not even over the length of the test. Meaning that one section of the superconductor had a twist pitch of $2.77\,°/\mathrm{mm}$ over $6.5\,\mathrm{cm}$, instead of having $1.714\,°/\mathrm{mm}$ over the entire $21\,\mathrm{cm}$ length of the test rig. During testing it was the area with the higher twist pitch that quenched. It shows the importance of keeping the twist pitch even, and it is a source of error.

For the second rig, the one without the strain relief, the highest twist pitch was $2\,°/\mathrm{mm}$, but the quench was not observed over this area. Rather, it was observed immediately after the superconductor exited from one of the termination blocks. The quench in this area was probably caused by degradation on the superconductor due to too high temperatures during soldering. The damaged section can be seen in Figure 15.

From Figure 13 it can be observed that the critical current over the first rig was $134.5\,\mathrm{A}$, while Figure 14 shows that the critical current over the second rig was $109\,\mathrm{A}$. It would be ideal to have more tests, both twisted and non-twisted to draw

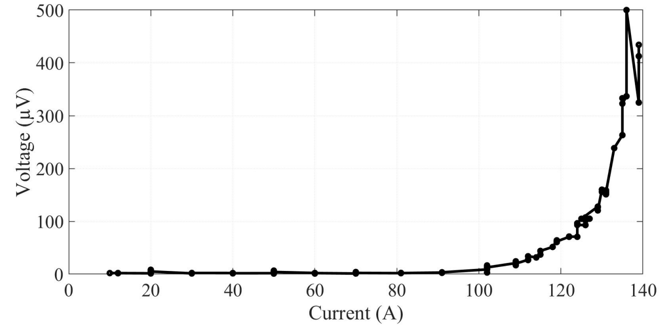


(a) Rig 1, Showing the entire test results.

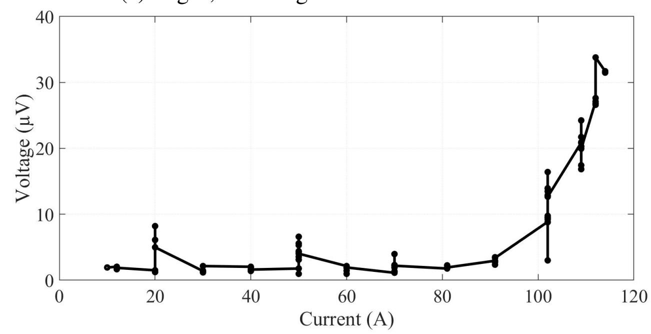


(b) Rig 1, Zoomed in.

Fig. 13: The results from the first rig during the twist-lab. Critical current occurs at $19\,\mu\mathrm{V}$.



(a) Rig 2, Showing the entire test results.



(b) Rig 2, Zoomed in.

Fig. 14: The results from the second rig during the twist-lab. Critical current occurs at $19\,\mu\mathrm{V}$.

conclusions from. However, due to time constraints, no more time could be allocated to this section of the thesis.

The first rig had a reduction of critical current compared to the baseline of $141\,\mathrm{A}$ of $4.91\,\%$, well over the $\pm\ 0.709\,\%$ bias error that was observed in the straight baseline test in [27]. Comparing this I_c reduction with the expected reduction claimed in the literature, it is evident that the reduction in critical current is higher than expected. Most of the discussed effects of twisting in the literature review were observed on multiple parallel superconductors, often in magnetic fields. This first lab however had no such external fields and only a single superconducting tape. The arguably best twist results mentioned in the literature review is stated in [18], where a twist pitch of $3\,°/\mathrm{mm}$ was achieved with $<0.01\,\%$ I_c degradation. In future work, more than two rigs should be made to check if a lower I_c loss can be achieved, in order to reduce the impact handling errors can have on the results.

The second rig had a much more substantial I_c reduction, although the highest twist pitch observed on the rig was much lower than the first rig, and much closer to the ideal and evenly distributed twist pitch. The I_c reduction of $22.70\,\%$ is most likely attributed to the heat damage that was observed on the HTS before testing. This is especially likely since this was the area that quenched when the voltage over the rig was increased further after the critical current had been measured. Considering that the heat damage was so severe on the second rig, it could also have contributed to worse than expected performance of the first rig.

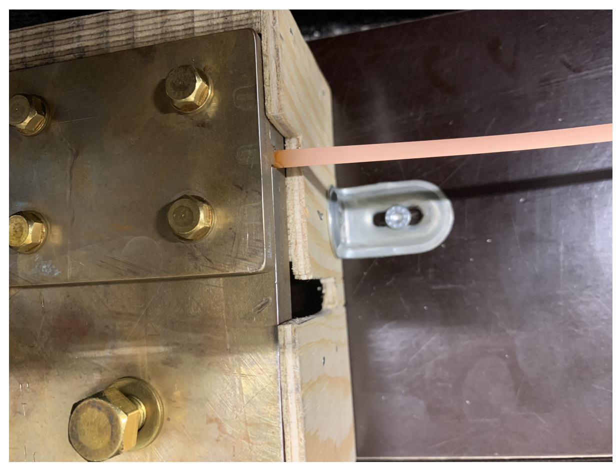
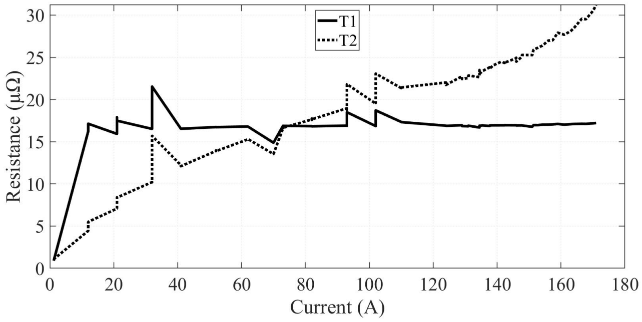
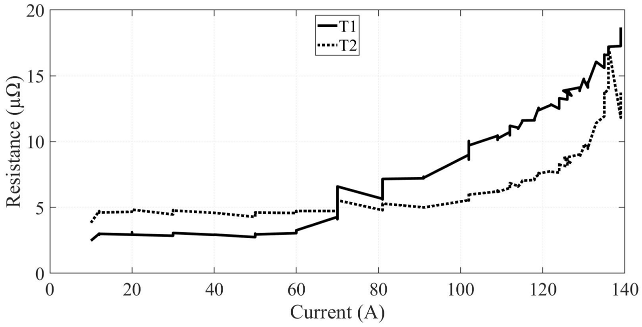


Fig. 15: Heat-damaged section observed before twisting and testing, at the entrance to the termination block.

With the data displayed in Figure 16, the termination resistance area can be calculated. Using the resistances calculated at the critical currents shows an average termination resistance area of $5.6\,\mathrm{m\Omega\,mm^2}$ for the terminations in rig 1, and $2.3\,\mathrm{m\Omega\,mm^2}$ for the terminations in rig 2. These are much higher than the ones observed in II-K, where the best termination had approximately 100 times higher resistance area than the "comb teeth" joint, and 10 times higher than



(a) Rig 1, calculated termination resistances.



(b) Rig 2, calculated termination resistances.

Fig. 16: Calculated termination resistances for both rigs.

the BSCCO-TSTC joint that was fastened at $67\,\mathrm{MPa}$. One should keep in mind that those joints only connect two HTS tapes together, while the one tested here also is affected by the resistance in the copper of the termination block.

IV. Lab 2, First parallel lab

The second lab made use of new cylindrical termination blocks, inspired by the design used by Takayasu *et al.* in [23], described as the YBCO-YBCO joint in II-K. Although it had a higher joint resistance area than the comb teeth joint, it appeared to be easy to scale. A difference between the design made in [23], and the design used in this lab is that this lab does not utilize an external copper tube around the cylinder. Additionally, this design connects the copper termination block directly to the infeed cables, where the design from [23] inserts the copper tube and cylinder inside a bigger copper block that was connected to the infeed cables. Finally, there was no insulation between the HTS tapes in the joints, and no soldering was used for this new design.

A. Preparation for lab 2

There are some positives and negatives to this copper cylinder design. It has been found that this design can give very low termination resistances between the termination blocks and the individual HTS tapes, where [23] claims to have achieved a termination resistance between an HTS tape and the termination-block of $0.13\,\mu\Omega$. However, because of its shape, it is much harder to handle than the termination blocks used in the previous experiment.

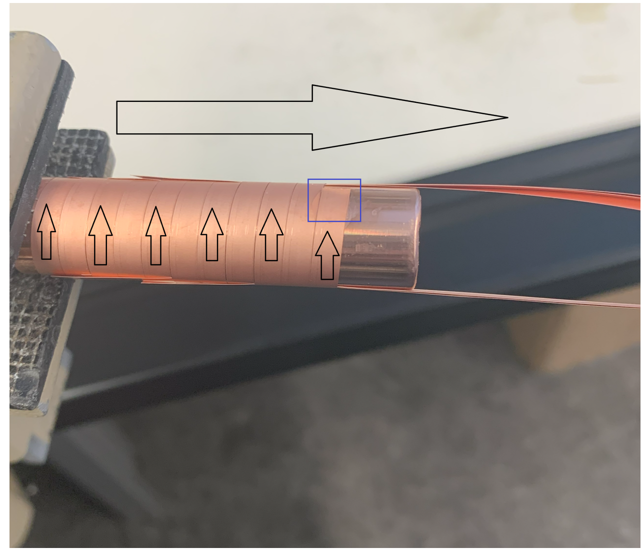


Fig. 17: A termination section.
Upwards arrows: Fastening HTS tape.
Right-pointing arrow: Connecting HTS tapes.
Blue box: One of the two areas where the fastening tape was glued to the cylinder.

A termination section is seen in Figure 17, where the HTS that goes around the cylinder, connecting the other HTS tapes to the termination block will be called the fastening tape. This tape is oriented with its face, the lowest resistance side, towards the copper cylinder. The connecting HTS tapes are oriented with its faces away from the copper cylinder. This results in a face-face connection between the connecting and the fastening HTS tapes and should yield a low resistance when pressure is applied at later stages.

Initially, it was intended to solder the fastening tape onto the cylinder at its endpoints so that it would be easier to wind it around the connecting HTS tapes leaving the termination block. This was however much harder to achieve than anticipated since it was difficult to heat the termination block enough to melt the solder while still allowing someone to handle it because of the heat and shape. Additionally, the termination section must be kept still so that the fastening tape does not slide off during cooling.

It was therefore decided to use metal glue at the end-points for the fastening tape instead. This would most likely lead to a higher resistance between the fastening tape and the copper cylinder termination block at these points, but at the same time, it would make it easier to get a more even termination resistance for all the termination sections.

The method used for making the new termination sections is shown below

1) Sand the termination cylinder with a P240 grit sandpa-

per.
2) Polish the sanded area with metal polish.
3) Wipe the area clean with rubbing alcohol.
4) Cut the fastening-tape at $70\,\mathrm{cm}$ length, and the desired number of connection HTS tapes at $12\,\mathrm{cm}$ length.
5) Glue the start point of the fastening tape face-down onto the end of the copper cylinder, at the side close to the termination bolt.
6) Place the first two connection-HTS tapes face away from the copper cylinder, at its top and bottom, and wind the fastening tape around the cylinder so it becomes face-face with the connection-HTS tape 3 times before adding another pair of connection-HTS tapes.
7) Repeat until the desired number of parallel connected HTS tapes is reached, then glue the endpoint as well.
8) Fasten the copper cylinder between two plates that apply a clamping pressure of $50\,\mathrm{MPa}$ from both sides.

This process was repeated four times to make four termination sections which would allow two tests to be performed during one lab. One unclamped termination section can be seen in Figure 22c.

The pressure applied is calculated by first finding the force applied by the bolts, using Equation 1. Here, F is the force applied from one bolt, k is a constant dependant on the materials used, T is the torque the bolt is tightened with, d is the diameter of the bolt, and l is a lubrication factor that for the calculations was set to 0. With these parameters, the force from the bolts utilized can be calculated with respect to the torque they are fastened with.

$$F = \frac{1}{kTd(1 - \frac{l}{100})} \tag{1}$$

Considering that the length of the copper cylinder is $6\,\mathrm{cm}$ and the width of the HTS tape is $4\,\mathrm{mm}$, the pressure applied by 4 bolts can be calculated. The lubrication factor has been set to zero due to no lubrication, and with this in mind, the bolts should be tightened with a torque of $7.2\,\mathrm{N\,m}$ to reach $50\,\mathrm{MPa}$. However, the actual pressure achieved has not been measured, since no equipment that could do such measurements was at hand. Therefore the pressure can be estimated, but not exactly defined. Some likely sources for error are the k constant for the material and the size of the steel bolt which was set to 0.2. Additionally, the torque wrench could be improperly calibrated, and therefore not apply the correct torque. The assumption for the lubrication being zero could also be slightly off although no lubrication was used. Finally, since the termination block is cylindrical, it is likely that a greater pressure was experienced for the sections of HTS tape at the exact top and bottom, and therefore it is unlikely that the pressure was evenly spread out over the entire width of the tapes. Due to these factors, one can imagine that the pressure achieved was close to, but not exactly $50\,\mathrm{MPa}$. The finished termination section clamped can be seen in Figure 18.

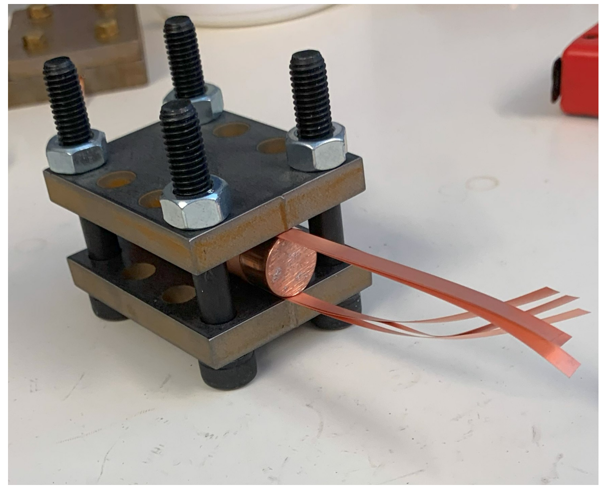


Fig. 18: The termination section clamped between two steel plates.

Additionally, two smaller steel plates similar to those used for the termination sections, but of $4\,\mathrm{cm}$ length was made to apply pressure on the joints between the termination-sections 'connection HTS tapes' and the HTS tapes that should be placed between the two termination sections. These can be seen to the right of the termination-section block seen in Figure 22b. Since the area over these joints was smaller than the area of the termination sections, a smaller torque was needed to achieve the same pressure. Therefore, the bolts for the smaller steel plates were fastened with $4.8\,\mathrm{N\,m}$ instead in order to achieve approximately $50\,\mathrm{MPa}$ pressure.

Before the joint between the termination section and the HTS section could be fastened, the connection HTS tapes and the HTS tapes spanning the gap between the termination sections had to be braided. The bottom 3 HTS tapes spanning the gap were face up, and the top 3 were face down. Therefore, in order to get face-face connections the order was as follows:

HTS
Termination
HTS
Termination
HTS
Termination

Termination
HTS
Termination
HTS
Termination
HTS

A coloured version showing the face-direction for the 6 bottom HTS tapes can be seen in Figure 19.

The HTS tapes are shipped and stored on rolls, and therefore they tend to bend slightly. This made the braiding complicated,

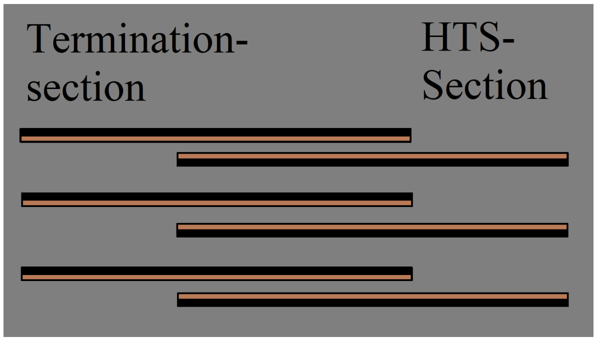


Fig. 19: Order in which the 6 bottom HTS tapes were braided between the steel plates. The brown color indicates the face-side of the HTS tape.

Fig. 20: Two clips were used to keep the already braided HTS tapes in place during the braiding process.

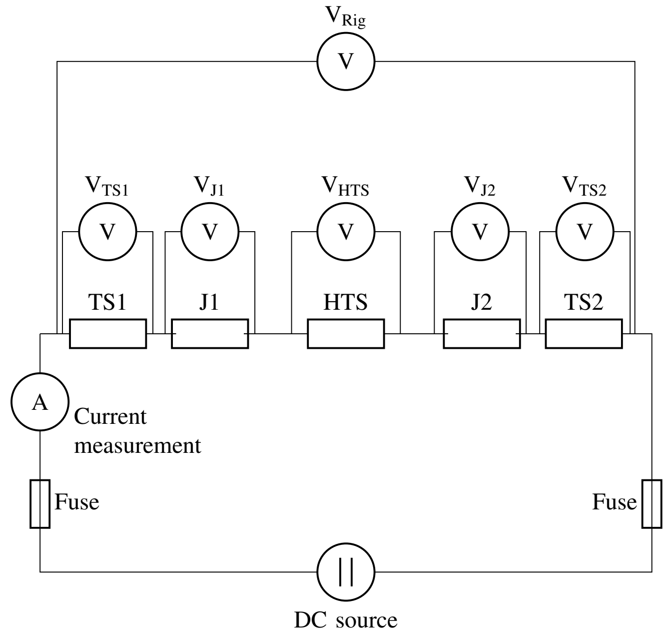


Fig. 21: Circuit diagram for the tests of the new rig capable of parallel-coupled HTS tapes. The lines between TS1 and TS2 is in reality 6 parallel lines, and the voltage measurements are individual voltage measurements for each parallel HTS tape.

and two people were required to perform the braiding to reduce the risk of damaging the tapes. Clips were used to keep the already-braided HTS tapes in place, while the next tape was placed on top. An example of this can be seen in Figure 20. When all 12 HTS tapes were braided in the correct order, the metal plates were then introduced and clamped the HTS tapes together.

The measurement equipment from the previous lab test could not be reused in its entirety, partly because the new more complex termination sections are utilized instead of the simpler termination blocks used previously. Also, all the parallel-coupled HTS tapes should have their voltages measured. Because the new test rig had more sections and HTS tapes than the old test rig, a new and more complex measurement system was built, as shown in Figure 22a. The circuit diagram for the rig and measurement system can be seen in Figure 21.

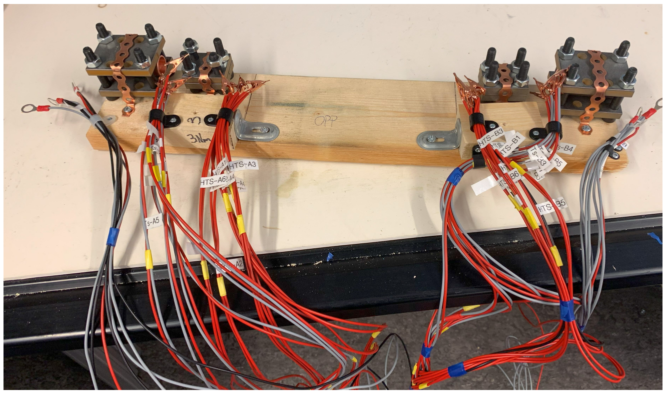
Compared to the previous measurement setup, the new setup required more than 6 times the cabling. Therefore proper cable management was required to keep track of where the cables should go, so as to not mistake them with each other and end up misplacing them, which would give incorrect measurements.

It was suspected that unintended interaction between neighbouring copper clamps used for voltage measurements could lead to cross-contamination. This could occur when direct or indirect contact between the clamps creates conductive paths. Consequently, a high voltage measured by one pair of clamps can be transmitted through these conductive paths to another clamp that measures a lower voltage. Consequently, the total voltage measured may include contributions from multiple tapes instead of just the intended one.

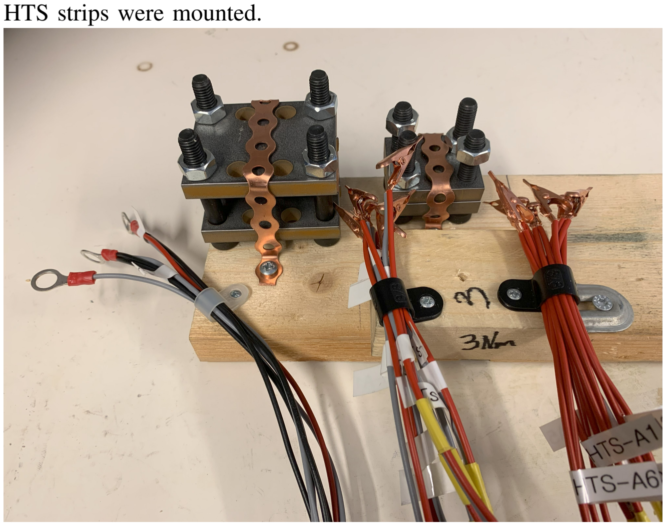
Therefore, for one of the test rigs, Mylar plastic was placed between each clamp to insulate and isolate them from each other. The insulation between the clamps was similar to the one seen in Figure 31 during lab 3, although here no insulation was placed between the HTS tapes, contrasting what is visible in the figure.

The test rig had fasteners for the 4 metal blocks that applied pressure on the termination sections and the joints, to hold those in place during transportation and testing. Additionally, the cables had strain reliefs so that the clamps would not be ripped away from their positions during testing.

The rest of the lab setup was similar to the setup seen in Figure 11.

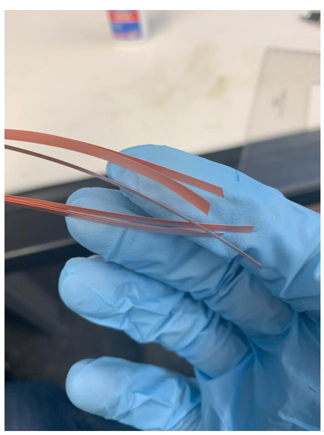


(a) The entire test rig before the termination section and the parallel HTS strips were mounted.



(b) Close up of one termination-section block in the top left-hand side, the joint section in the top right-hand side, and measurement clamps below.

(c) The termination section before it was clamped.



(d) The HTS-ends sticking out from the termination-section that was clamped in the joints called J1 and J2 in Figure 21.

Fig. 22: Preparation for the first parallel lab

B. Results and discussion, lab 2

Before analyzing the results from lab 2, it is worth mentioning some results from the 3rd lab that has retroactively affected the analysis of the 2nd lab. During lab 3, a quench occurred around $830\,\mathrm{A}$.

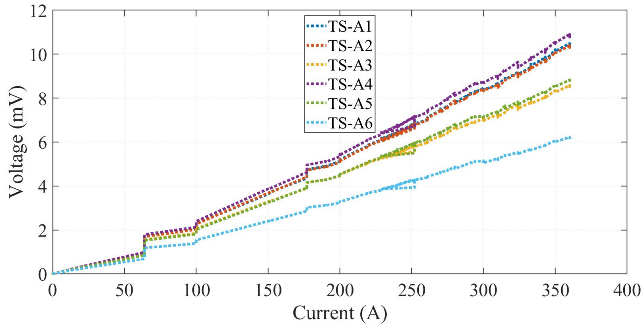
Considering the observations made in the twist lab and previous labs done on superconductors in [27], where quenching occurred around $170\,\mathrm{A}$, it seems improbable that only one superconductor functioned properly as the voltage measurements indicate. Considering the resistance HTS tapes would have when they are not superconducting, one would assume that most of the current sent through the rig would go through the functioning HTS tapes. Therefore, it is much more likely that 4 or even 5 out of the 6 HTS tapes were superconducting, and the voltage measurements were erroneous, possibly due to unsatisfactory insulation.

Labs 2 and 3 were performed in short succession. Therefore it was not noticed before the results were analyzed that current measurements should have been taken for each separate HTS tape, in addition to the measurement through the entire rig. This leads to issues since one can only make assumptions about the magnitude of current running through the HTS tapes without being able to tell for certain. Attempts of analysis have nevertheless been made.

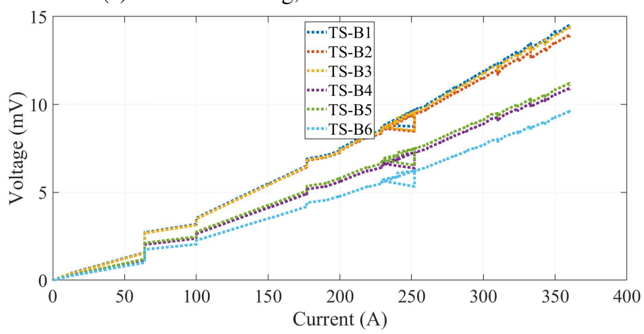
The voltage measurements taken during the tests have been divided into three sections and graphs. One section is the measurements taken over the two termination sections A and B, one section is the measurements over the two joints, and lastly, the section of HTS tapes spanning the gap between the two joint sections. See Figure 22a, where the positions of the clamps should clarify where the sections start and end. The numbers of the lines in the graphs indicate the position of the HTS tapes. For instance is HTS 1 the topmost, and HTS 6 the one closest to the wooden plank that is the base of the rig. Finally, the insulated rig is the one with Mylar insulation between the clamps, and the non-insulated rig has no insulation.

1) Insulated rig L2: As can be seen in Figure 23, the measured voltage appears to increase linearly for all the tapes, although at different rates. Assuming that the current is distributed evenly to the different connecting HTS tapes through the termination section, the average termination resistance area of the insulated rig is approximately $7.1\,\mathrm{m\Omega\,mm^2}$ for termination A, and $9.7\,\mathrm{m\Omega\,mm^2}$ for termination B at $50\,\mathrm{A}$. This is over an area of 3 face-face connections between the fastening and connecting HTS in the termination section, totalling an area of $48\,\mathrm{mm^2}$. Comparatively, one YBCO-YBCO joint made in [23] with $63\,\mathrm{MPa}$ with 320 grit sanding of the YBCO tapes achieved a resistance area of approximately $16\,\mathrm{m\Omega\,mm^2}$.

The measured voltages over the joints can be seen in Figure 24. The clamped joint area is $160\,\mathrm{mm^2}$, thus the average resistance area is $5\,\mathrm{m\Omega\,mm^2}$ for joint A and $4.4\,\mathrm{m\Omega\,mm^2}$ for

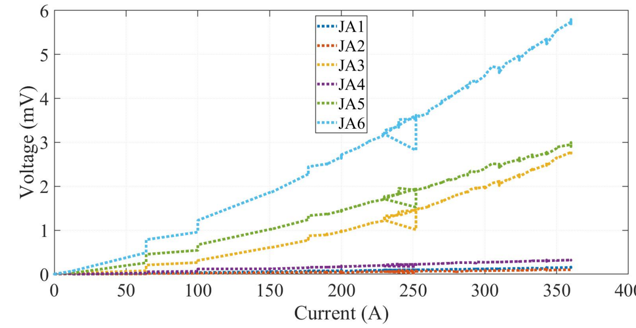


(a) L2 Insulated rig, Termination-section A.

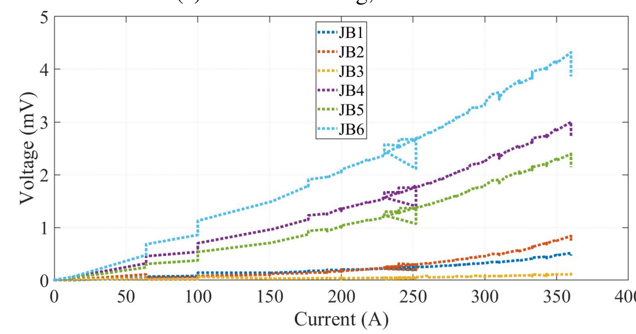


(b) L2 Insulated rig, Termination-section B.

Fig. 23: L2 Insulated rig, measured voltages over the termination sections to the individual HTS tapes.



(a) L2 Insulated rig, Joint A.



(b) L2 Insulated rig, Joint B.

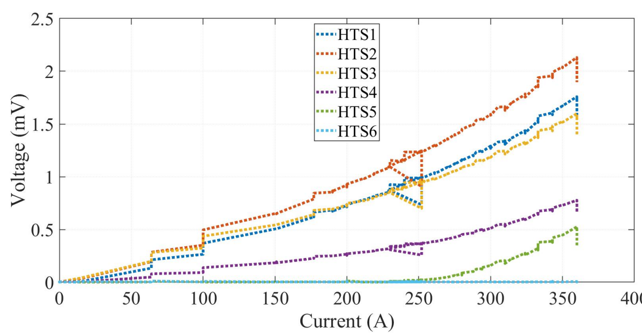
Fig. 24: L2 Insulated rig, measured voltages over the joints for each HTS pair.

joint B at $50\,\mathrm{A}$. It is worth noting that the order of magnitude of the resistance area over the joints and terminations is the same, and also the same as through the terminations in lab 1.

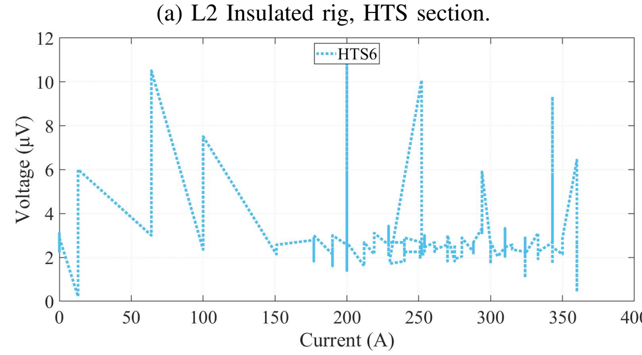
As mentioned earlier, the voltages measured over the HTS section seem much too high, and if the voltages seen in Figure 25 is to be believed, only HTS6, the lowest HTS tape physically in the joints would be the only one superconducting after approximately $250\,\mathrm{A}$ was reached. If this was the case, it should have quenched much earlier. This is because the distance between the voltage measurement clamps was approximately $19\,\mathrm{cm}$, meaning that the critical current should occur at a measured $19\,\mu\mathrm{V}$. The voltages observed in Figure 25 are much too high.

2) Non-insulated L2: As can be seen in Figure 26, the voltage appears to increase linearly, suggesting a relatively unchanging resistance. However, it appears that the voltages over the termination section to its connecting HTS tapes are much more similar in magnitudes than the voltages measured for the insulated rig. This could be caused by a more even termination resistance or because of the problem of the earlier discussed voltage cross-contamination being more prominent without insulation.

Again assuming evenly distributed current to the different connecting HTS tapes through the termination section, the average termination resistance area of the non-insulated rig is approximately $5.5\,\mathrm{m}\Omega\,\mathrm{mm}^2$ for termination A, and

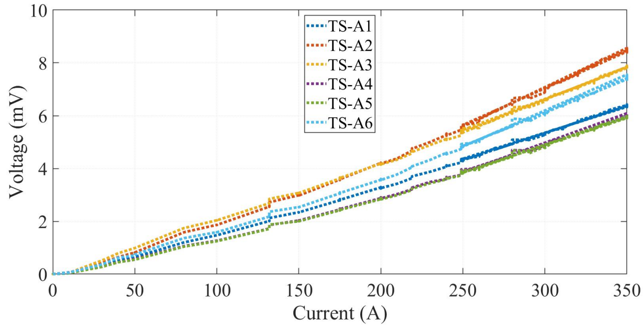


(a) L2 Insulated rig, HTS section.

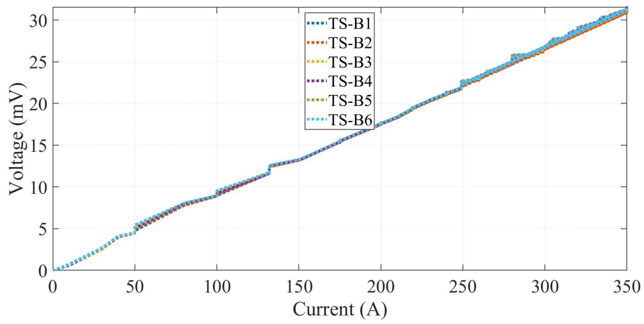


(b) L2 Insulated rig, scaled graph for HTS 6. Note the y-axis.

Fig. 25: L2 Insulated rig, Measured voltages over the tapes in the HTS section.

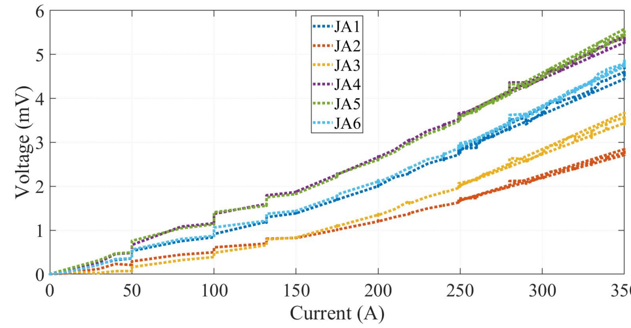


(a) L2 Non-insulated rig, Termination-section A.

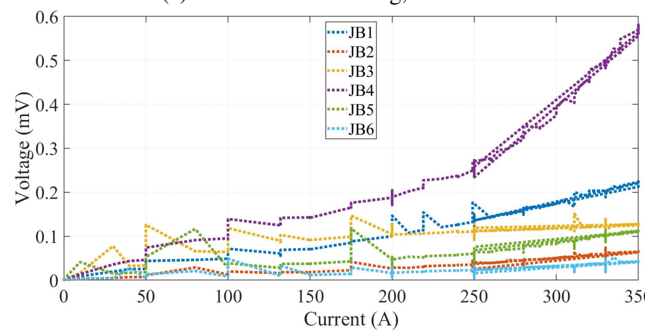


(b) L2 Non-insulated rig, Termination-section B.

Fig. 26: L2 Non-insulated rig, measured voltages over the termination sections to the individual HTS tapes.



(a) L2 Non-insulated rig, Joint A.



(b) L2 Non-insulated rig, Joint B.

Fig. 27: L2 Non-insulated rig, measured voltages over the joints for each HTS pair.

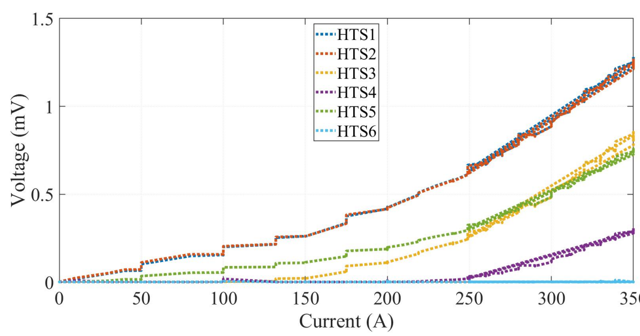
$25.6\,\mathrm{m\Omega\,mm^2}$ for termination B at $50\,\mathrm{A}$.

Again it appears in Figure 27 that the non-insulated joints have a more similar resistance than the one observed over the insulated joints. For the joint sections on the non-insulated rig, the average resistance area is $11.4\,\mathrm{m\Omega\,mm^2}$ for joint A and $0.5\,\mathrm{m\Omega\,mm^2}$ for joint B at $50\,\mathrm{A}$. This difference is very big, and it is likely that a high voltage over one of the joints in Joint A got transmitted, disturbing the other voltage measurements.

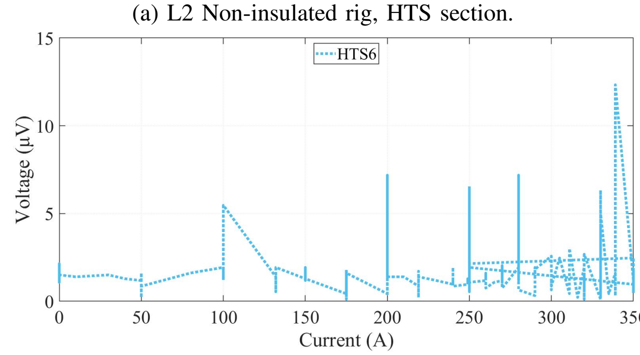
As mentioned earlier, it appears that the voltages measured are too high, since it in Figure 28 shows only HTS 6 is experiencing a low enough voltage to be below the critical current limit, after which, the HTS tapes should quickly stop superconducting.

3) Summary of lab 2: It is a trend observed for both rigs that it is HTS 6 that appears to experience the lowest voltage. The reason for this could be that it is more isolated from the other tapes since it does not have another tape below it. Thus it could more easily avoid direct contact and therefore voltage cross-contamination.

One can also observe that tapes 4, 5 and 6 have the lowest voltage over the HTS section during both rigs, although it is more unclear for tape 5 in the non-insulated rig. One possible reason for this could be a change in elevation from building to mounting the termination section and joint blocks to the wooden rigs. This could potentially have favoured the lower



(a) L2 Non-insulated rig, HTS section.



(b) L2 Non-insulated rig, scaled graph for HTS 6. Note the y-axis.

Fig. 28: L2 Non-insulated rig, Measured voltages over the tapes in the HTS section.

HTS tapes since they are closer to the wooden plank that is the basis of the rigs.

V. Lab 3, second parallel lab

A third and final lab was planned and conducted. In this lab, the same measurement equipment and rig setups were used, with some slight changes. During this lab, it was expected that the current flowing through the rigs would be much higher since it was planned to test if the rigs could reach the max-limit of the DC source of $1\,\mathrm{kA}$. Therefore the fuses were removed, and larger dimension in- and outlet copper cables were used, which in retrospect potentially have made the comparison between lab 2 and 3 less accurate.

A. Preparation for lab 3

Since the goal was to reach a total current of $1\,\mathrm{kA}$ through the rig, the fuses that contributed to safety during the first two rigs either had to be changed or removed. The fuses used during the first two labs could handle $200\,\mathrm{A}$ and would melt before the targeted current could be reached. Since no bigger fuses could be acquired at the time when all planned participants of the lab were available, it was decided to remove the fuses and be more careful when starting and shutting down the labs. The circuit diagram for this lab is the same as the one seen in Figure 21, but without the fuses.

During the first two labs, the copper in- and outlet cables were $70\,\mathrm{mm}^2$. These cables were swapped for bigger $180\,\mathrm{mm}^2$ copper cables that should be better suited to handle the high currents expected for this lab.

Cables of bigger dimensions are usually more rigid, and therefore it was more difficult to connect the cable shoes to the non-HTS side of the termination sections. Therefore, a new copper block was introduced as a link between the copper cables and the termination block of the termination sections, see Figure 29.

Due to human errors, the placement of the voltage measurement probes that were connected to the non-HTS side of the termination section was placed on the wrong side of the additional copper, as seen in Figure 30. This meant that the voltage over the additional copper length also was counted as a part of the voltage over the termination sections, which it should not have.

Fig. 29: Additional copper that was added to make it easier to connect the bigger dimension copper cables.

Fig. 30: The placement of the voltage measurement probes meant that an additional resistance through the added copper also was measured for the termination section.

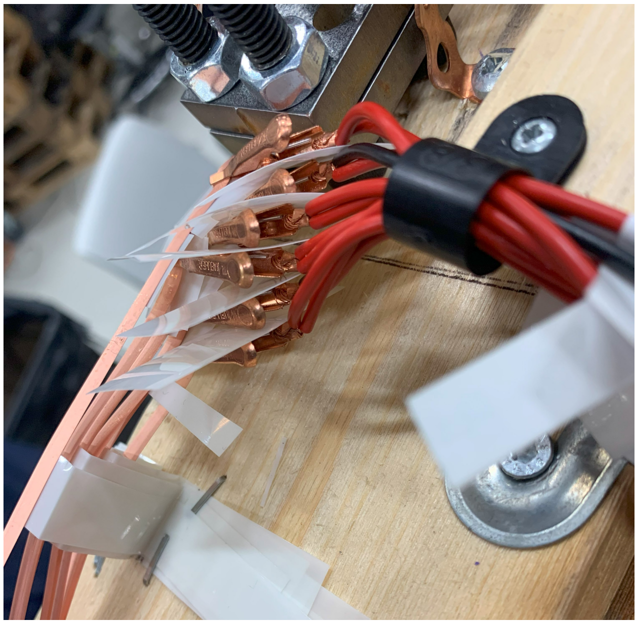


Fig. 31: Insulation between the clamps.

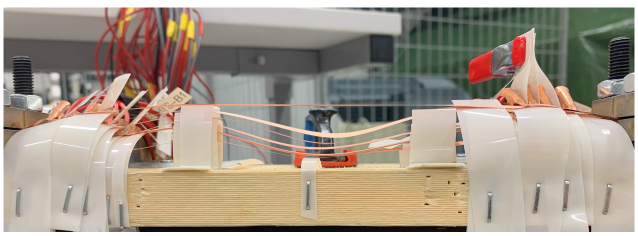


Fig. 32: The final iteration of the insulation before the rig was lowered into the empty LN2 container from Figure 11a.

Finally, more insulation was added to the one rig that already had been slightly insulated, in an attempt to make the voltage measurements more intelligible compared to lab 2. The clamps were also insulated between each other, see Figure 31, as done on the same rig during the previous lab.

Additionally, attempts were made to insulate and isolate the individual HTS tapes from each other, between the two joint blocks at either side of the rig. This was done in several iterations, where bridges were built out of Mylar plastic shoving the HTS tapes away from each other, see Figure 32.

After lowering the rig into the box, it was correctly assumed that tension in the measurement cables could move the clamps slightly, thereby also moving the HTS tapes themselves. This was observed with a small mirror as seen in Figure 33. Additional Mylar plastic bridges were added afterwards until no HTS tapes were visibly in contact.

B. Results and discussion, lab 3

The insulated rig was run to $400\,\mathrm{A}$ and then turned off. This was because the additional insulation did not appear to give the intended results, since the voltage measurements over 5 out of 6 HTS tapes still seemed nonsensical, as explained in section IV. Although it could be of interest for this thesis to run both rigs to quench in order to enable comparisons between them, it was also wished to investigate the reasons behind the observed voltage measurements further. Sparing one rig allows the supervisors of this thesis to quickly perform more tests in the future without having to build new rigs, furthering the investigations already performed.

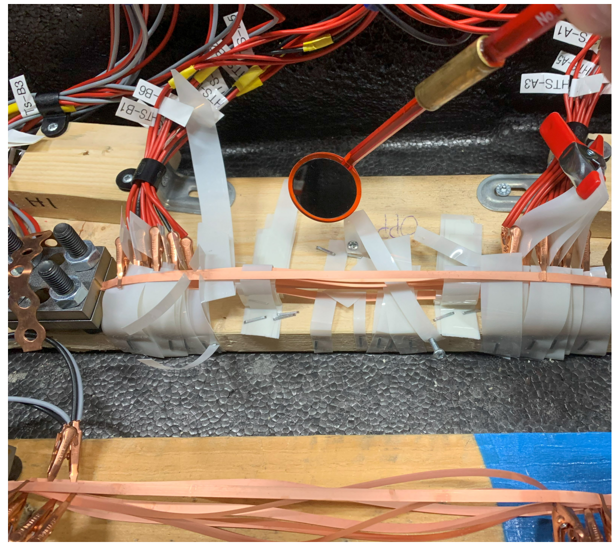
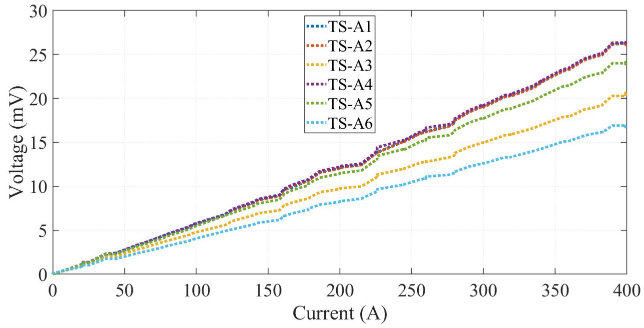


Fig. 33: Mirror used to inspect and verify that no HTS tapes touched each other.

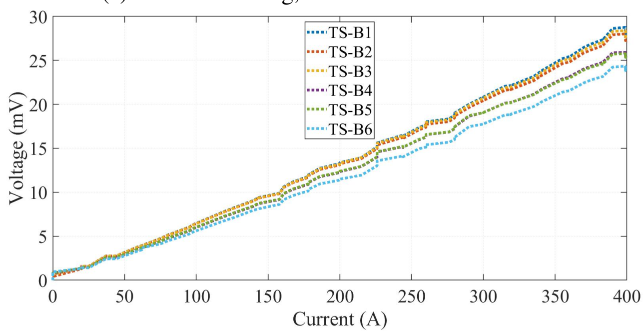
1) Insulated L3: The voltages over the termination section for the insulated rig can be seen in Figure 34. The current is assumed, as also done for lab 2, to be distributed evenly to the different connecting HTS tapes through the termination-section to so that the voltages can be analyzed. The average calculated termination resistance area of the insulated rig is approximately $16.5\,\mathrm{m\Omega\,mm^2}$ for termination A, and $18.8\,\mathrm{m\Omega\,mm^2}$ for termination B over the $48\,\mathrm{mm^2}$ area at $50\,\mathrm{A}$. These results are much higher than during lab 2, but now the total resistance is also higher due to the additional copper block that got included in the measurement, as mentioned earlier, see Figure 30.

For the $160\,\mathrm{mm^2}$ joint sections on the insulated rig the average resistance area was $8\,\mathrm{m\Omega\,mm^2}$ for joint A, and $5.1\,\mathrm{m\Omega\,mm^2}$ for joint B at $50\,\mathrm{A}$. It should be noted that it is a big difference between the highest and lowest calculated resistances for these joints that the average does not communicate. The resistances were calculated based on the voltages seen in Figure 35.

Again, as observed for both rigs during lab 2, the voltages over the HTS section appear to be too high, see Figure 36. According to this figure, only HTS 6 should be in a superconducting state after approximately $200\,\mathrm{A}$, and it should not be able to handle $400\,\mathrm{A}$ alone, considering the quenches observed

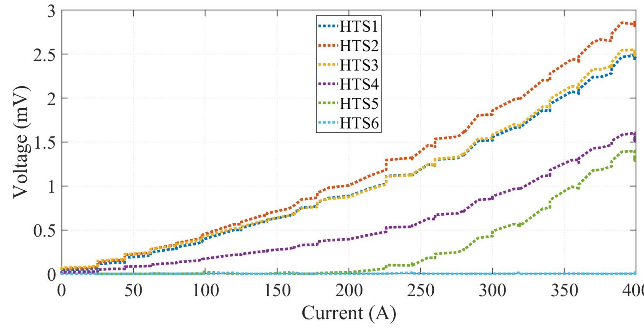


(a) L3 Insulated rig, Termination-section A.

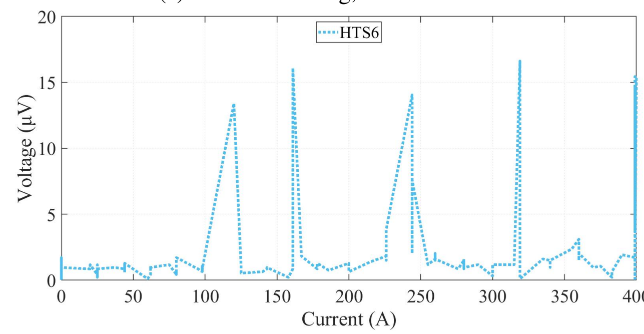


(b) L3 Insulated rig, Termination-section B.

Fig. 34: L3 Insulated rig, measured voltages over the termination sections to the individual HTS tapes.

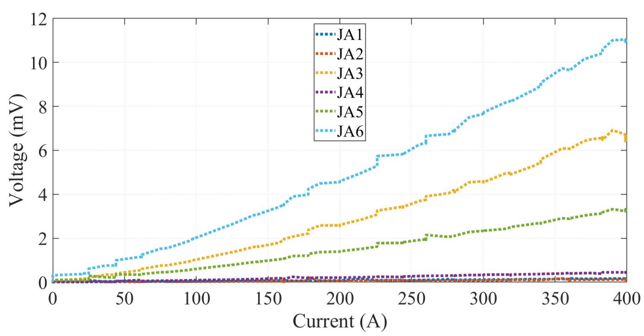


(a) L3 Insulated rig, HTS section.

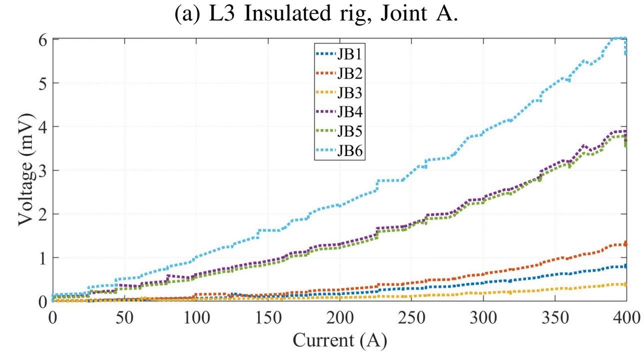


(b) L3 Insulated rig, scaled graph for HTS 6.

Fig. 36: L3 Insulated rig, measured voltages over the tapes in the HTS section.



(a) L3 Insulated rig, Joint A.



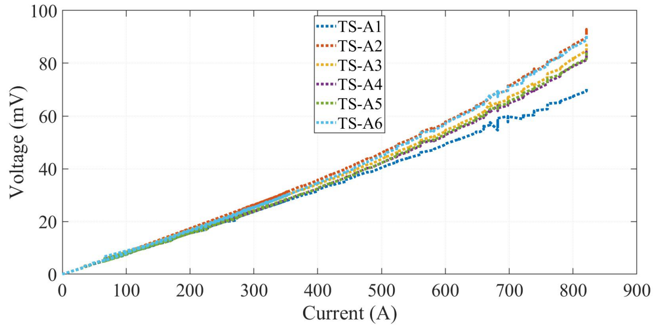
(b) L3 Insulated rig, Joint B.

Fig. 35: L3 Insulated rig, measured voltage over the joints for each HTS pair.

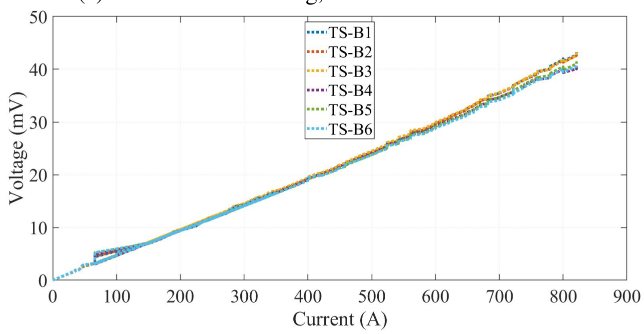
in lab 1.

2) Non-insulated L3: Voltages over the termination section for the non-insulated rig can be observed in Figure 37. Assuming evenly distributed current as previously, the average termination resistance area of the non-insulated rig is approximately $23.8\,\mathrm{m\Omega\,mm^2}$ for termination A, and $13.7\,\mathrm{m\Omega\,mm^2}$ for termination B over the $48\,\mathrm{mm}^2$ area at $50\,\mathrm{A}$. These results are much higher than during lab 2, probably affected by the additional copper block.

See Figure 38. For the joint sections on the non-insulated rig, the average resistance area was $10.8\,\mathrm{m\Omega\,mm^2}$ for joint A, and $0.4\,\mathrm{m\Omega\,mm^2}$ for joint B at $50\,\mathrm{A}$. However, as is visible in Figure 38b, the voltage over the joint is not increasing linearly, and therefore the resistance over the joint is not constant either. For the HTS tapes in joint B, it appears all are linear except JB4 until approximately $700\,\mathrm{A}$ is reached. Here, it appears that JB4 breaks down, and the voltages over the other HTS tapes in the joint start to increase exponentially. This could indicate that the JB4 quenches, then the current that previously went through that conductor must go through the other tapes, which also possibly experience higher temperatures due to their proximity to JB4, which is one of the middle HTS tapes. However, it should be noted that no visual quench was observed at around $700\,\mathrm{A}$ in the video that recorded the lab. A visual quench was observed when attempting to increase the current from 820 to$840\,\mathrm{A}$, as seen in Figure 41.

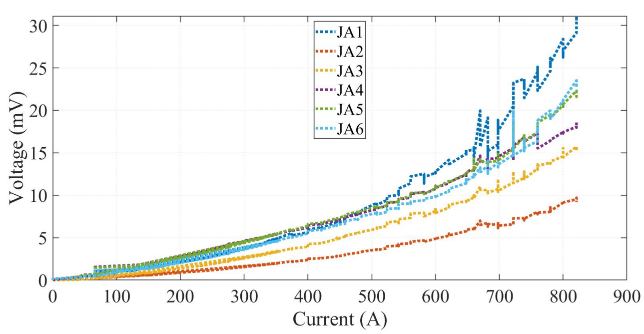


(a) L3 Non-insulated rig, Termination-section A.

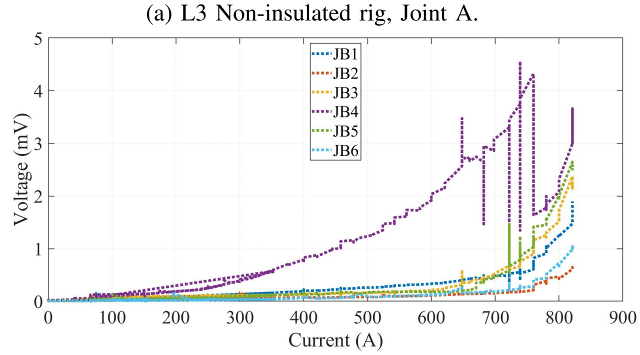


(b) L3 Non-insulated rig, Termination-section B.

Fig. 37: L3 Non-insulated rig, measured voltages over the termination sections to the individual HTS tapes.

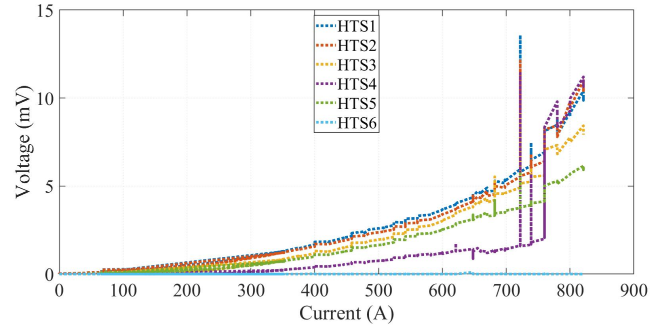


(a) L3 Non-insulated rig, Joint A.

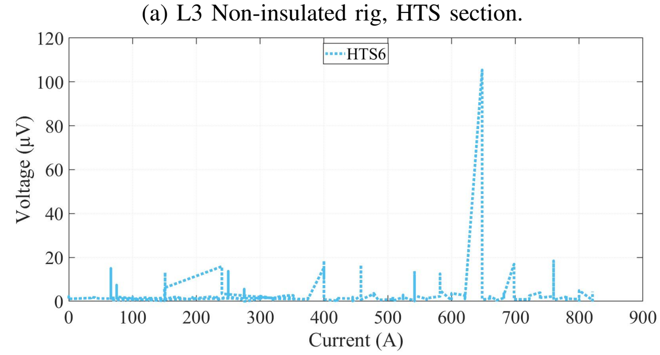


(b) L3 Non-insulated rig, Joint B.

Fig. 38: L3 Non-insulated rig, measured voltage over the joints for each HTS pair.



(a) L3 Non-insulated rig, HTS section.



(b) L3 Non-insulated rig, scaled graph for HTS 6.

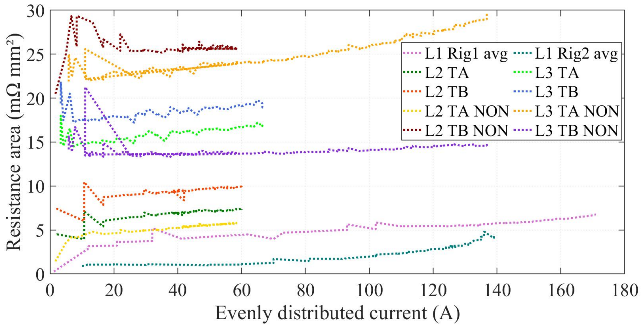
Fig. 39: L3 Non-insulated rig, measured voltages over the tapes in the HTS section.

In Figure 39b it appears that the quench in joint B first causes a spike in the voltages before a jump in voltage occurs at 760 A. Curiously, HTS6 appears to not be affected by the quench at all although you would expect the voltage over it to rise as well.

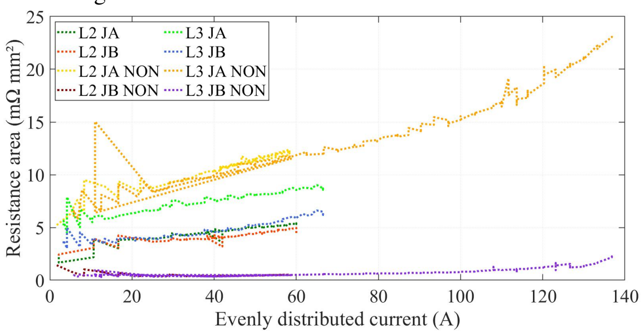
The non-insulated rig was dismantled after the lab was finished, and visually inspected. It was found no signs of damage on sections of HTS tape that had been subjected to high pressure in the joints and termination section due to clamping. This could suggest that greater pressure could be applied in order to achieve even lower joint resistances.

3) Summary L3 and comparisons: Two plots have been made that compare the average resistance areas of the joints and terminations, see Figure 40. These graphs show the average calculated resistance areas of the joints and terminations for all three labs, with the assumption of evenly distributed current through the individual HTS tapes.

In Figure 40a, the graphs for lab 2 and 3 show that there is some discrepancies between the same rigs. For the insulated rig, the resistance in the termination sections is lower during lab 2 than in lab 3. This is as mentioned earlier possibly due to the additional copper that got included accidentally in the measurements. It is somewhat less clear for the non-insulated rig, where the resistance area is curiously reduced for termination B. The resistance area is lowest in the terminations for lab 1, but this lab also made use of solder, which labs 2



(a) Termination resistance area comparison, over an area of $280\,\mathrm{mm}^2$ for L1, and $48\,\mathrm{mm}^2$ for L2 and L3. NON indicates NON-insulated rig.



(b) Joint resistance area comparison, over an area of $160\,\mathrm{mm}^2$. NON indicates NON-insulated rig.

Fig. 40: Average resistance area based on the assumption of evenly distributed current.

and 3 did not.

For the resistance areas for the joints, seen in Figure 40b, it is a much clearer correlation between the same rigs in the different labs. This further strengthens the assumption that the additional copper block provided not-insignificant resistance to the measured termination voltages. Curiously, the non-insulated joint B in lab 3, as also can be seen in Figure 38b had the lowest average resistance area, but still was the one that quenched.

It appears that there is a reasonable possibility that poor handling has affected the performance of the rigs. One way to make handling easier, and thereby reducing the chances of I_c reduction due to handling could simply be a bigger lab box with space for longer rigs and more rigs. Longer rigs would allow for more space between the termination section and the joints, where it is suspected that a sharp bend could have been the reason why the HTS voltages were consistently lower for the HTS tapes placed lower, on the underside, of the termination cylinder. Elongating this section would also make it easier to fasten the measurement clamps without having to insulate them. A bigger LN2-container as seen in Figure 11a that could allow more rigs to be tested during one lab would also result in more data that could be analyzed. If proper care is taken when building the rigs, it is unlikely that the same handling error would happen for all rigs, and therefore a higher chance for a no-error rig to be produced. It should however also be noted that a larger box would require more LN2, which could take time to get hold of.

Fig. 41: Three frames from a video of the quench.

It was probably too optimistic to attempt to parallel couple 6 HTS tapes, and it would have been much easier to make a measurement setup and do troubleshooting on a rig with only 2 parallel coupled tapes, and afterwards scale up if the results were comprehensible. The reason why 6 HTS tapes were chosen initially was because it seemed like a manageable number since the termination section had space for up to 18 parallel coupled tapes.

There are some ways one could attempt to reduce joint and termination resistance. As seen in [23], using solder and increasing the pressure can significantly reduce joint resistance. However, when soldering, it must be noted that it is much more difficult to re-use the joints should any part break and need replacing. The bolts and steel plates used to clamp over the HTS tapes during labs 2 and 3 are capable of applying much higher pressures, and there is also space for more bolts should an even higher pressure be desired. This means that further experiments using the same joints and termination sections can be performed. Another potential way to reduce the resistance in the termination section is to alternate the fastening HTS tape to have face-connection to the copper termination block instead every other turn. This is so that the pressure applied by the clamps also gives a lower termination resistance between the termination block and the fastening tape. In the current configuration, no significant pressure is applied to the fastening HTS tape when it is connected face directly to the termination block.

Probably the greatest flaw of labs 2 and 3 was the lack of individual current measurements for the HTS tapes. This resulted in many assumptions as to where the current was flowing and reduced the accuracy of the analysis for the labs. This issue could have been omitted with the use of a hall current sensor device, such as the one used in [16]. Additionally, some insulation material such as Mylar should be placed between the non-face sides of HTS tapes in joints to reduce the chance of voltage cross-contamination for the measurement equipment. Also, clamps that are only conductive inside their ”mouths” should further reduce the insulation problem experienced in this lab.

VI. Conclusion

From the 3 labs conducted in this thesis, it is evident that the handling of HTS tapes is of utmost importance. Handling can result in too high or uneven twist pitch, damages to the HTS due to too high temperature during soldering, or unintended bends which all reduce the I_c of the tapes.

The results gained by the measurement equipment could have been more exact and useful if more insulation and more space had been allotted to it. Additionally, the analysis suffers from the lack of individual current measurements.

Acceptably low termination and joint resistances have been observed based on the voltage measurements and assumption of evenly distributed current, even outperforming a joint with higher clamping pressure but rougher sanding produced in [23], the article that inspired the termination-section used in lab 2 and 3. Lower resistances is expected to be easy to achieve with higher pressure and solder, especially in the joints. It was mentioned earlier that the pressures achieved over the termination block and the joints were assumptions based on calculations, that were prone to different potential sources of error.

If the current was distributed evenly between the remaining 5 HTS tapes after the first quenched in Figure 39a, each individual HTS tape carried 166 A. This "quench-current" was approximately the same as the one achieved in lab 1 and during the preliminary project [27].

A. Further work

Considering the final goal of making HTS coils for electric aviation, multiple continuations furthering the work done in this thesis are of interest.

The limits of the termination and joint sections should be investigated, to find the maximum pressures the HTS tapes can handle with the equipment in question. Due to the potential sources of error when calculating the pressure, it should instead be measured with pressure measurement equipment to make certain whether the pressure calculated is correct or not. Additionally, the shape of the copper termination cylinder should be modified so that it becomes flatter, or even completely flat on the top and bottom, resembling an elliptic cylinder. Then the pressure should distribute evenly over the HTS tape.

The number of parallel conductors should be scaled down, starting with 2 HTS tapes. It is recommended to scale up only after the measured voltages give results that should indicate the actual performance of the tapes. The termination and joint blocks have space for at least 18 parallel coupled HTS tapes, but for the existing measurement equipment considering the multiplexer and data logger used, a maximum of 11 parallel HTS tapes can be tested.

Because of the shape of the termination section and the joints, it is quite simple to facilitate twist-tests for the parallel coupled tapes, although one would be restricted to multiples of 90° twists, and then adjust the total length of the HTS section to achieve different twist pitches without adding more complexity to the latest rig. After finding the critical current of a parallel-coupled rig and letting the liquid nitrogen boil off, one could easily investigate the effect of twists on the rig by simply tilting the joint and termination sections. With this in mind, one could find the highest twist pitch achievable with the present equipment, with regard to a chosen acceptable maximum I_c reduction.

Bending-tests is also a topic of interest that should be investigated. The reason is that an end winding for an electric motor needs to bend 180°. A combination of two 90° twists and one 180° bend should allow the tapes to lie flat along the tangent of the circle that the centre of the motor would have, and make the 180° bend without bending the tape in the hardway-direction discussed in II-H. The results of the twist and bending tests would dictate the minimum required area for end-windings in the final electrical motor for aviation.

Acknowledgements

I'm extremely grateful to co-supervisor Runar Mellerud for his continuous guidance throughout the thesis, and a special thanks to co-supervisor Christian Hartmann for his assistance during the 2nd and 3rd labs which undoubtedly heightened their quality. I am also grateful to my supervisor Jonas Kristiansen Nøland for giving me such an interesting master's topic. I'd also like to recognize Svein Erling Norum for his guidance regarding the measurement-equipment, and Morten Flå for building the termination blocks and pressure plates to my specifications. Additionally Makoto Takayasu for answering my enquiries with no obligations to do so, and Sverre Vegard Pettersen for supplying liquid nitrogen for the labs. Lastly, I'd like to thank Hildegunn Nedregård for her encouragement.

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