JANUS: A Robust ReBCO Tape Design for Increased Performance in Magnetic Fields

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***Abstract*—We propose the JANUS (Joint ANgled Unconventional Superconductor) compound tape design with two oppositely tilted c-axes. This design takes advantage of the 30° inclination of the c-axis to the substrate normal to broaden the angle dependence of the critical current. The minimal critical current along the coil is raised and the amount of ReBCO tape required for a given field strength is reduced. For 8 T and 20 K, the averaged minimum I_c of the two tapes is raised by 14%. By restricting the angle to $\pm$ 60 ° between field and the tape binormal direction, the local I_c minimum is even 20% higher. Furthermore, JANUS shows an increased robustness to manufacturing errors. The maximum I_c drop for a 5° deviation in the angle between ReBCO tape and magnetic field is reduced from 18% to 13%. The use of JANUS in an exemplary stellarator coil also shows an increase of 10% in I_c and encourages numerical optimization of the tape orientation for a further performance increase.**

***Index Terms*—HTS coils, Fusion magnets, 2G HTS Conductors**

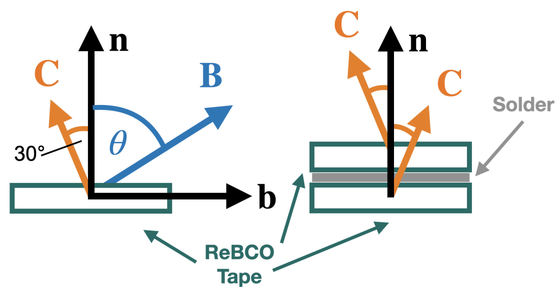

Fig. 1. Schematic of a ReBCO tape cross section with a tilted c-axis in a magnetic field (left). The **JANUS** tape configuration (right) consists of a stack of two tapes with oppositely tilted c-axes. The complementary c-axes enable a broader angle dependence and robustness to manufacturing errors. $\mathbf{n}$ and $\mathbf{b}$ indicate the normal and binormal direction of the tape.

I. Introduction

High temperature superconductors such as Rare-earth Barium Copper Oxide (ReBCO) have the potential to significantely accelerate the advent of fusion energy. Several efforts aim to build high-field magnetic confinement devices which can be built smaller and faster than lower-field devices [1], [2]. However, HTS magnets have their own challenges. Due to its anisotropic crystal structure, the critical current (I_c) of a ReBCO tape is strongly dependent on the angle between the c-axis of the crystal and the applied magnetic field. The critical current is highest if the magnetic field is perpendicular to the c-axis [3]–[5]. Tapes from most suppliers have the c-axis of the ReBCO crystals aligned with the substrate normal. In contrast, for tapes from THEVA, the c-axis is inclined by 30° from the normal of the tape [6]. Doping the superconductor with artificial pinning (AP) centers reduces the anisotropy of the critical current considerably. For example, in THEVA AP tape the I_c ratio between the best and worst angle is reduced from approximately 4 to 2.3 (at 8 T and 20 K) [7], [8]. However, this effect is still large enough to significantly impact the manufacture of shaped electromagnetic coils.

Several projects are using this anisotropy to optimize the critical current, especially as peaking of the angular dependence increases for stronger fields [9], [10]. However, this narrow peak is prone to manufacturing errors. A small deviation of the alignment changes the critical current significantly. Especially for stellarator magnets, this only worsens the issue of tight manufacturing tolerances [11], [12].

This work proposes a compound tape design with a broader critical current angle dependence. It increases the minimal I_c and is more robust to manufacturing errors. The **JANUS** (**J**oined **AN**gled **U**nconventional **S**uperconductor) design consists of two THEVA tapes with oppositely tilted c-axis, using the 30° inclination to the substrate normal. They are assumed to have good current sharing i.e by soldering them face-to-face [13]. A schematic of this tape configuration is depicted in figure 1. A possible application of **JANUS** conductors is in stellarator coils. The angle between the magnetic field and the c-axis varies greatly over the length of these complex coil shapes. Not only would a more robust angle dependence be advantageous, but the orientation of the winding pack may be subject to numerical optimization to further increase the tape performance.

This work is part of the EPOS stellarator project, which aims to confine an electron-positron pair plasma in a tabletop stellarator with non-planar ReBCO coils [14]. While the confinement of a large enough number of positrons to achieve collective effects is the primary target, it can also serve as a testbed for advances in stellarator (coil) optimization and magnet design.

This paper is structured as follows: In section II, we construct an interpolation of the angle and field dependence of the critical current from measurements on THEVA AP tape. In section III, we discuss the efficiency of current sharing between two soldered ReBCO tapes. In section IV, we show the increased minimum critical current due to the **JANUS** design as well as its improved robustness to manufacturing errors. Furthermore, we apply the **JANUS** design to an example stellarator coil. Section V gives an outlook onto a possible use of this work in future optimization of stellarator coils.

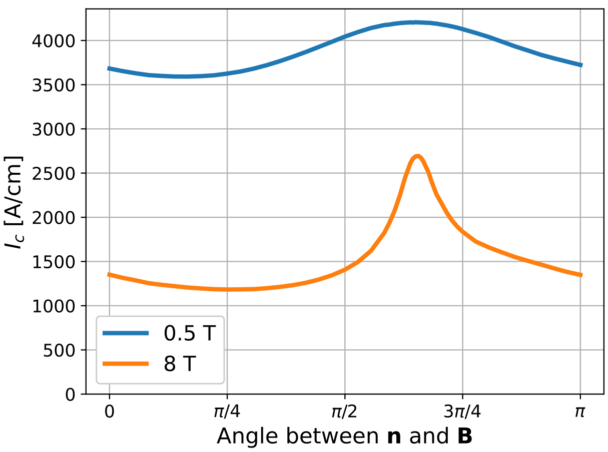

Fig. 2. Anglular dependence of the critical current for THEVA AP tape at 20 K temperature, 0.5 T and 8 T. The maximal critical current is at 30° from the tape normal. The peak becomes higher and more narrow for stronger fields. Measurement data provided by THEVA.

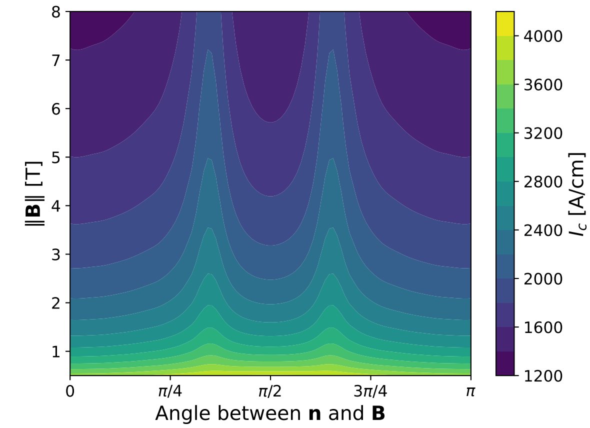

Fig. 3. The interpolation of the critical current in the **JANUS** configuration at 20 K and between 0.5 T and 8 T magnetic field. Based on the measurement data from Figure 2.

II. Cricital current interpolation

In order to assess the performance of the **JANUS** design in a stellarator coil, the critical current must be interpolated over the entire relevant space of angles and field strengths. Here, we use measurements of the angle dependence at 0.5 T and 8 T from THEVA AP tape. These are displayed in Figure 2. We restrict this study to a constant operating temperature of 20 K. We fit the angle direction with a univariate spline interpolation. The dependence of the critical current on the field strength B at constant angle θ is modeled by a power law $I_c(B, \theta = \text{const.}) \sim B^{-\alpha}$, fitted seperately to the two points for the 0.5 T and 8 T data at each respective angle. This gives a critical current interpolation in the field range of 0.5 T and 8 T and for all angles between 0 and π. To construct the interpolation for the **JANUS** case we mirror the critical current across the normal of the tape.

$$I_{c,JANUS}(\theta, B) = \left(I_c(\theta, B) + I_c(\pi - \theta, B)\right)/2 \quad (1)$$

The sum of the critical currents is divided by two so that a comparison with a single tape can be made. A contour plot of the interpolated critical current is displayed in figure 3. Due to the weak peaking of the angle dependence at 0.5 T the **JANUS** function has only one peak at lower fields which develops into two peaks for higher field strengths. To use the above interpolation in an optimization framework, a fast calculation of the magnetic field on the coil is requisite. For simplicity, we assume that the magnet is wound as a tape stack and the orientation between the c-axis and the magnetic field does not change inside the stack. The goal is to use this work in a stellarator optimization framework like `SIMSOPT` [15], so it only considers quantites that are fast to evaluate. To compute the field, we use a recently developed technique [16] which adds a regularization to the Biot-Savart law to avoid the singularity in the magnetic field on a 1-dimensional curve.

$$\mathbf{B}(\phi) = \frac{\mu_0 I}{4\pi} \int d\phi' \frac{\mathbf{\Gamma}'(\phi) \times (\mathbf{\Gamma}(\phi) - \mathbf{\Gamma}(\phi'))}{(\|\mathbf{\Gamma}(\phi) - \mathbf{\Gamma}(\phi')\|^2 + \delta ab)^{3/2}} \quad (2)$$

$$\delta = \exp\left(\frac{25}{6} + k\right)$$

$$k = \frac{4b}{3a}\arctan\frac{a}{b} + \frac{4a}{3b}\arctan\frac{b}{a} + \frac{b^2}{6a^2}\ln\frac{b}{a} + \frac{a^2}{6b^2}\ln\frac{a}{b} - \frac{a^4 - 6a^2b^2 + b^4}{6a^2b^2}\ln\left(\frac{a}{b} - \frac{b}{a}\right).$$

Here, $\mathbf{\Gamma}$ refers to the quadrature points of the coil filament, $\mathbf{\Gamma}'$ is its derivative with respect to the curve parameter ϕ and I is the current through the coil. The winding pack is assumed to be rectangular with dimensions a and b. For simplicity, we neglect the variation of the magnetic field across the cross section of the coil. Equation 2 is then used together with a regular filament Biot-Savart calculation for the other coils to calculate the magnetic field along the target stellarator coil.

A rotated Frenet frame is added to the filamentary curve representing a coil in `SIMSOPT`. It consists of three unit vectors $(\mathbf{t}, \mathbf{n}, \mathbf{b})$ in the tangent, normal and binormal direction. This frame can at every quadrature point be rotated in the normal-binormal plane by an angle α. This angle will be optimized to find a tape orientation with higher minimal critical current. Finally, we can evaluate the angle between the c-axis $\mathbf{c}$ and the projection of the magnetic field into the normal-binormal plane

$$\mathbf{B}_{proj} = \mathbf{B} - (\mathbf{B}\cdot\mathbf{t})\,\mathbf{t} \quad (3)$$

$$\theta = \arccos\left(\frac{\mathbf{B}_{proj}}{\|\mathbf{B}_{proj}\|} \cdot \mathbf{c}\right)$$

Using the interpolation we can calculate the critical current along the coil for different field strengths and angles between field and c-axis $I_c\left(\theta, \|\mathbf{B}_{proj}\|\right)$.

III. Current sharing

The viability of the **JANUS** Design demands efficient current sharing between the two soldered superconducting

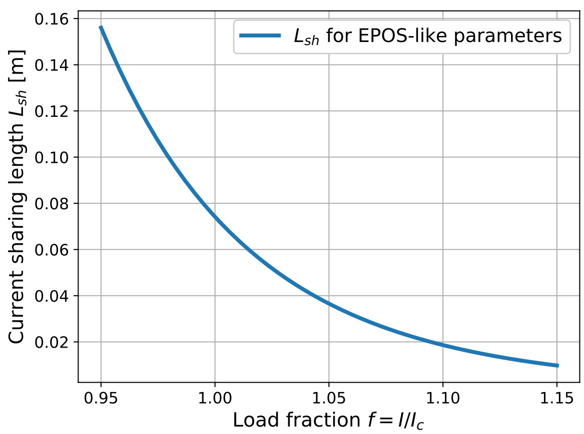

Fig. 4. Characteristic current sharing length L_{sh} as a function of the load fraction $f = I/I_c$. The resistance of the superconducting layer along a tape of length L_{sh} conincides with the resistance between the two tapes.

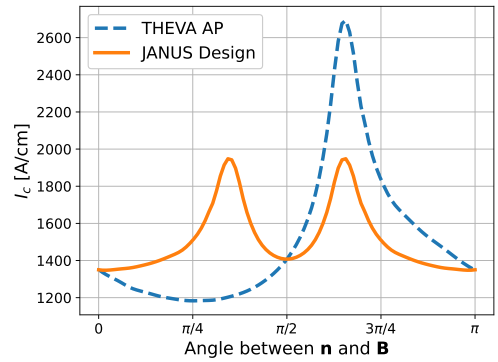

Fig. 5. Interpolated angle dependence of THEVA AP tape at 8T field and 20 K temperature. The plot compares a regular tape and the **JANUS** design with the I_c calculated according to equation 1. **JANUS** has a 14% higher global minimum and a 20% local minimum that can be utilized by restricting the tape orientation to ±60° around the tape normal. .

tapes. Current sharing between layers becomes relevant if the resistance of the superconducting layer R_{sc} becomes comparable to the resistance between the two tapes R_{tt}. We model R_{sc} with the well-known power law [17]

$$R_{sc} = \frac{E_0 L_{sh} f^{n-1}}{I_c}. \tag{4}$$

The resistance between two tapes is given by

$$R_{tt} = \frac{\rho_{tt} d_{tt}}{w L_{sh}}. \tag{5}$$

The length of tape L_{sh} at which these resistances in formulas 4 and 5 coincide ($R_{sc} = R_{tt}$) reads

$$L_{sh} = \left(\frac{\rho_{tt} d_{tt} I_c}{w E_0 f^{n-1}}\right)^{\frac{1}{2}} \tag{6}$$

In the above equations 4 - 6, E_0 is the electric field over the superconductor at the critical current, $f = I/I_c$ is the load fraction, ρ_{tt} is the resistivity between the tapes, d_{tt} refers to the distance between the two superconducting layers and w is the width of the tape. Figure 4 shows the current sharing length as a function of the load fraction f for parameters that apply to the conductor used in the EPOS project: $I_c = 550\,\mathrm{A}, w = 3\,\mathrm{mm}, n = 30$. We take the resistivity from literature $\rho_{tt} d_{tt} = 3{\cdot}10^{-12}\,\Omega\,\mathrm{m}^2$ [13]. $E_0 = 1\,\mu$V/cm is the critical field criterion.

For a load fraction above unity, the current sharing length becomes small compared to the length over which the magnetic field is expected to vary along a coil (tens of cm). This allows the current to locally redistribute from one tape into the other if the resistivity along the tape increases due to the magnetic field.

IV. JANUS Performance

The **JANUS** design shows a 14 % increased minimum critical current (at 8 T) of 1349 A/cm averaged over both tapes compared to 1182 A/cm for the case of a single THEVA AP tape. In the interpolation of the critical current in figure 5, the **JANUS** design shows an angle response with two peaks at ±30° from the tape normal, with a local minimum at 0°. This is due to the peak of of one tape compensating for the minimum of the other tape. This local minimum is even higher than the **JANUS** global minimum and improves the critical current by 20 % (1419 A/cm) compared to THEVA AP case. This higher local minimum is relevant if the angle between magnetic field and coil can vary in the comparatively wide range between ±60° from the tape normal.

Another benefit of **JANUS** is its robustness against manufacturing errors. While a higher critical current may be possible if the angle between tape and magnetic field aligns perfectly to the I_c-peak in figure 5, reality still provides for manufacturing and operational errors. Small angle deviations may result in large I_c drops due to the strongly localized peak. Figure 6 shows the change in critical current $\Delta I_c/I_c$ at a 5° deviation of the tape orientation for both the **JANUS** and non-**JANUS** case at 8 T. The deviation in current is reduced from 18% to 13% for the **JANUS** design, confirming its increased robustness against manufacuring errors.

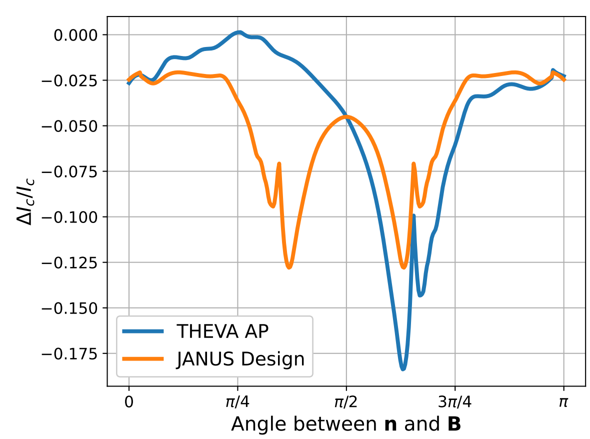

Fig. 6. I_c drop for a 5° deviation in angle alignment for THEVA AP tape and **JANUS** design. The latter shows a much more robust angle profile with only 13% maximal I_c drop compared to 22% for non-**JANUS**.

This work is motivated by stellarator coil optimization. As an example, one preliminary coil from the EPOS stellarator is

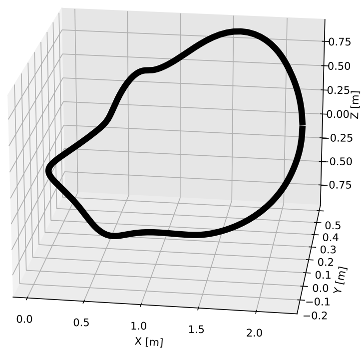

Fig. 7. The central filament of the stellarator coil considered for figure 8. This is a coil optimized for a candidate magnetic field of the EPOS stellarator experiment.

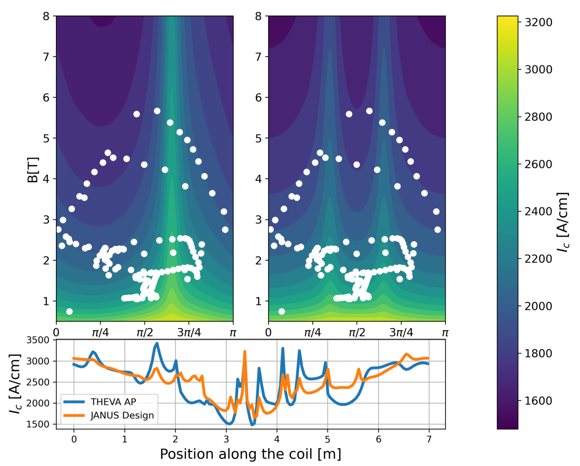

Fig. 8. Critical current for a stellarator coil in angle-field space for a **JANUS** (right) and non-**JANUS** (left) tape design. The bottom plot shows the critical current along the coil. The minimal I_c is raised by 10% in the **JANUS** case. The orientation of the coil leaves room for optimization to further increase the I_c.

used to evaluate the performance of **JANUS** in a stellarator coil. In figure 8 the coil is plotted in field-angle space with the interpolation for non-**JANUS** and **JANUS** in the background. The minimum I_c is raised by 10% by the use of **JANUS**. While this is only a minor improvement in I_c, optimizing the coil orientation may hold potential for further performance increases.

V. Conclusion and Future Work

The critical current in ReBCO superconductors has a strong dependence on the applied magnetic field strength and the angle between the field and the c-axis of the crystal structure. Tape from THEVA shows a 30° angle between the crystal axis and the normal of the tape. To utilize this property, we propose a conductor design in which two tapes with oppositely tilted c-axis are stacked. This **JANUS** (Joint Angled Unconventional Superconductor) design has a much flatter angle dependence of the critical current, which increases the global minimum critical current by 14% at 8 T and 20 K. Therefore, less tape is needed to achieve a given field strength. A local minimum at the tape binormal is 20% higher than the minimum I_c of the regular tape. This can be used if it is possible to keep the angle between field and tape normal between $\pm$ 60°. **JANUS** is also more robust to manufacturing errors, with the maximum I_c drop at 5° angular misalignment being only 13% compared to 18% for a single THEVA AP tape. Evaluating **JANUS** for an exemplary stellarator coil shows an increase in minimal I_c along the coil of 10%. However, the orientation of the winding pack shows potential for numerical optimization. Optimizing the tape orientation to further increase the minimal critical current along the coil is part of ongoing and future work within the `SIMSOPT` framework.

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VI. References Section

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VII. Biography Section

Paul Huslage recieved his B.Sc. in Physics from University of Würzburg, Germany in 2019 and his M.Sc. in Applied and Engineering Physics from Technical University Munich, Germany in 2022. From 2020 - 2022 during his Master's degree, he worked in the R&D department of THEVA, where he initiated a project to construct and test a mock-up stellarator ReBCO coil. Since 2022, he is a PhD student at IPP in Garching, Germany working on the EPOS stellarator to confine a electron positron plasma with non-planar ReBCO coils. His research interests are the optimization, design and manufacturing of non-planar ReBCO stellarator coils.