Mechanical limitation of stack type Coated Conductor cables for magnet applications

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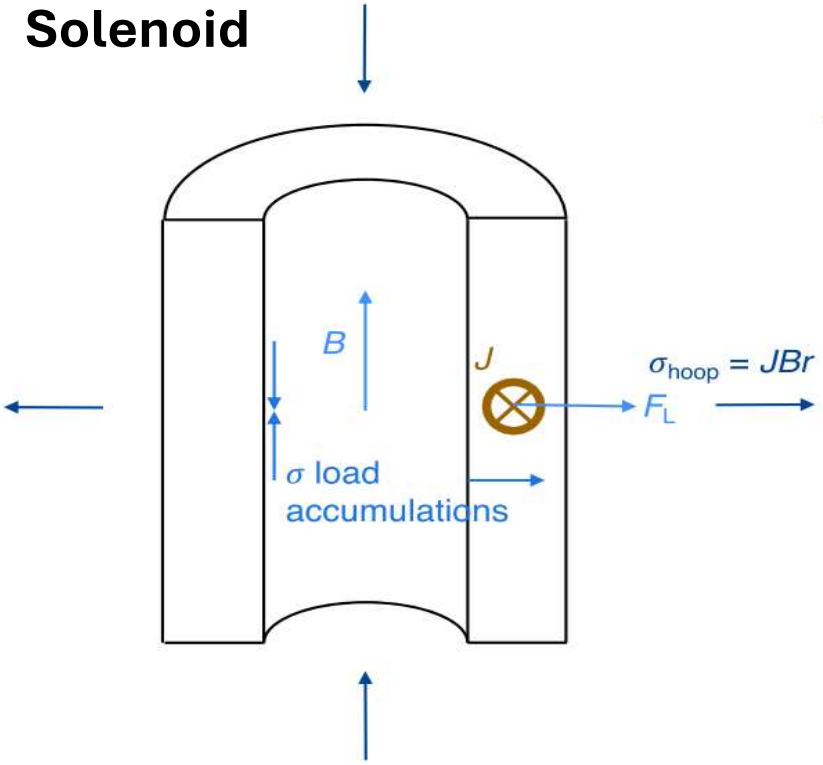
Selection of properties and issues of a few stack cable designs and constructions

IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 59, May 2025. Presentation given at CCA 2025, March 11-13, 2025, Geneva, Switzerland.

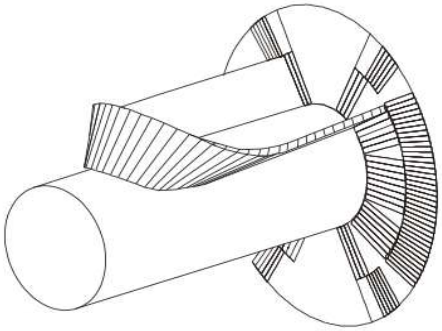
Mechanical loads in magnets

Solenoid

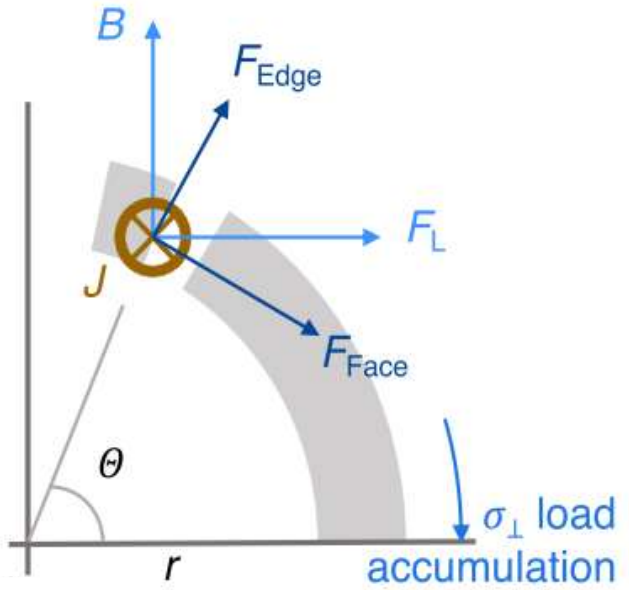


- Axial contraction and radial expansion
- Hoop stress accumulating radially
- Axial load accumulation in mid-plane.

Accelerator type



Cosine theta



A. Godeke, 2023, SuST 36, 113001.

- The main mechanical stress accumulates on the mid-plane, or magnet pole

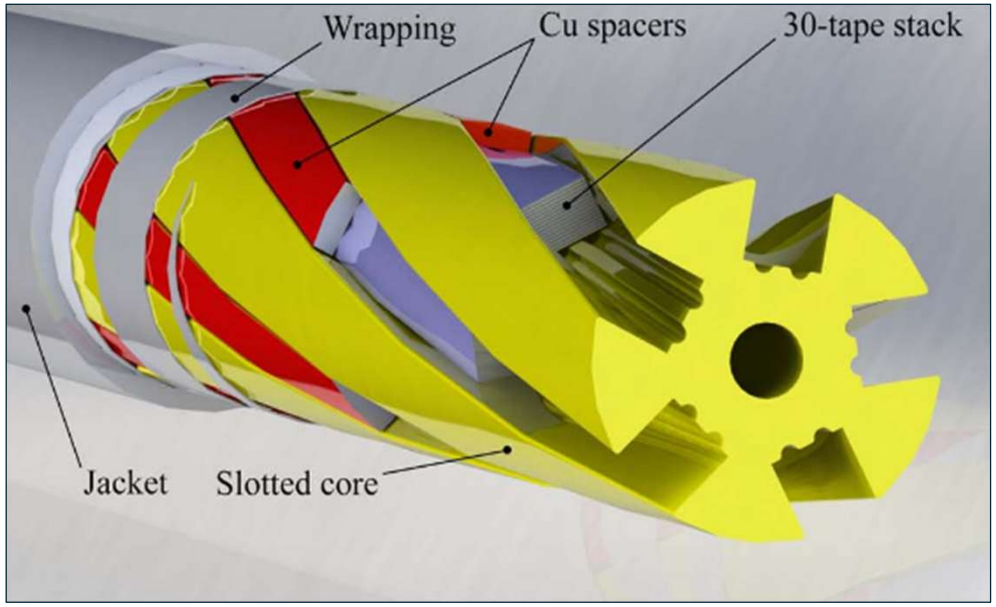
IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 59, May 2025. Presentation given at CCA 2025, March 11-13, 2025, Geneva, Switzerland.

Stacked *Re*BCO tape (sub)cable, dry and soldered concepts

Twisted Stacked- *Re*BCO Tape Cable (TSTC)

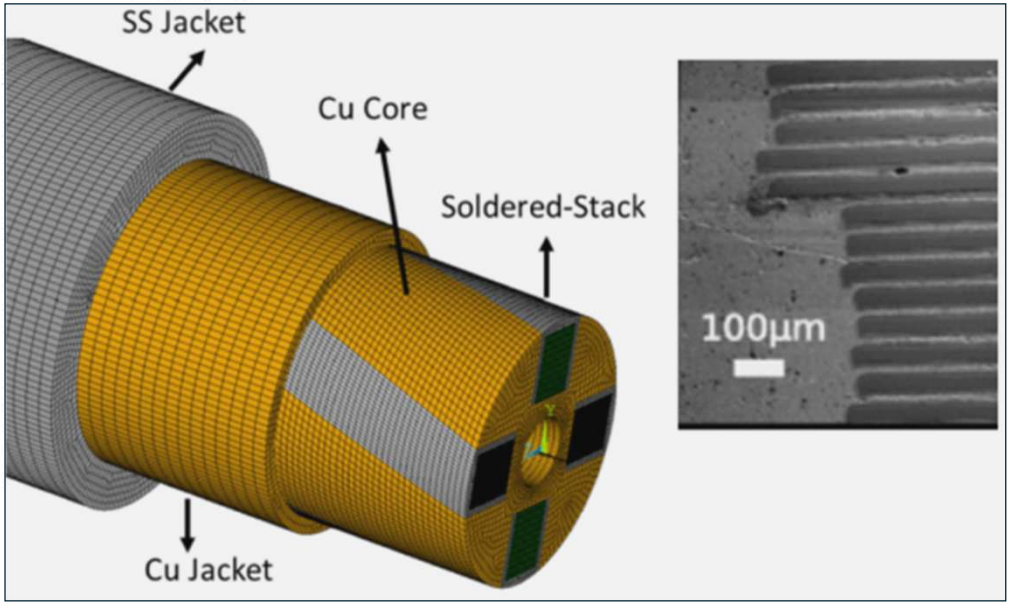
Takayasu M, et al SuST 25, 014011.

*Re*BCO-CICC, Cable-in-Conduit Conductor, developed by ENEA



G. Celentano, et al., IEEE TAS, Vol. 24, No. 3, 6 2014.

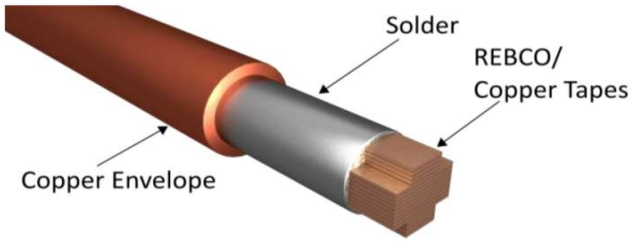
VIPER Cable-in-Conduit Conductor (CICC) developed by MIT/Commonwealth Fusion Systems



Z. Zhao et al., IEEE TAS, Vol. 32, No. 6, 9 2022.

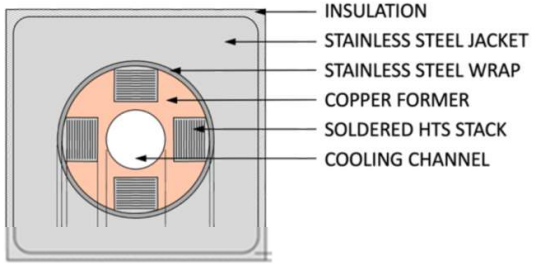
.... and many more variants

*Re*BCO-HTS Cross-Conductor (HTS CroCo)



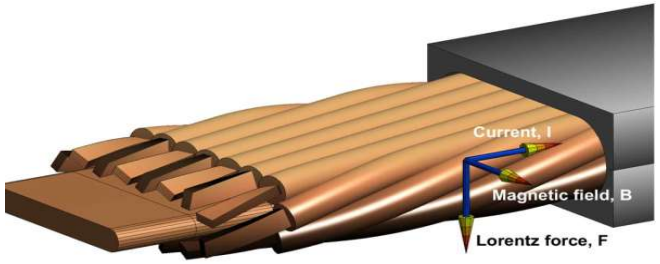
D.S. Nickel et al., IEEE TAS, Vol. 31, No. 5, 7 2021.

Modified VIPER for Muon Collider



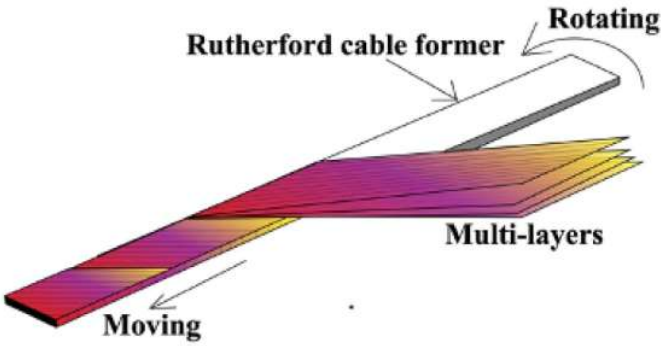
L. Bottura, et al., Cryogenics 144 103972, 2024.

Cored Rutherford cable by Center for Research in Plasma Physics (EPFL-CRPP)



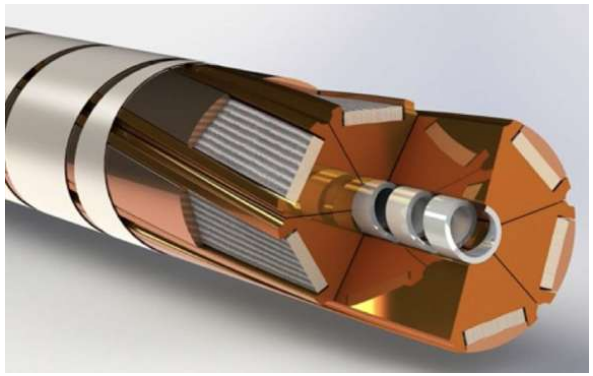
N. Bykovsky et al., IEEE TAS, Vol. 26, No. 2, 3 2016.

Flat Round-edge former Tape Cable (FReTC)



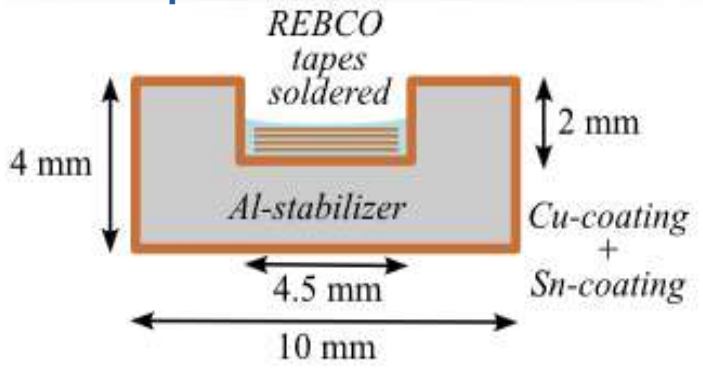
M. Takayasu, SuST, 34 125020, 2021.

SECtor ASsembled Cable (SECAS)



L. Muzzi et al., IEEE TAS, Vol. 33, No. 5, 8 2023.

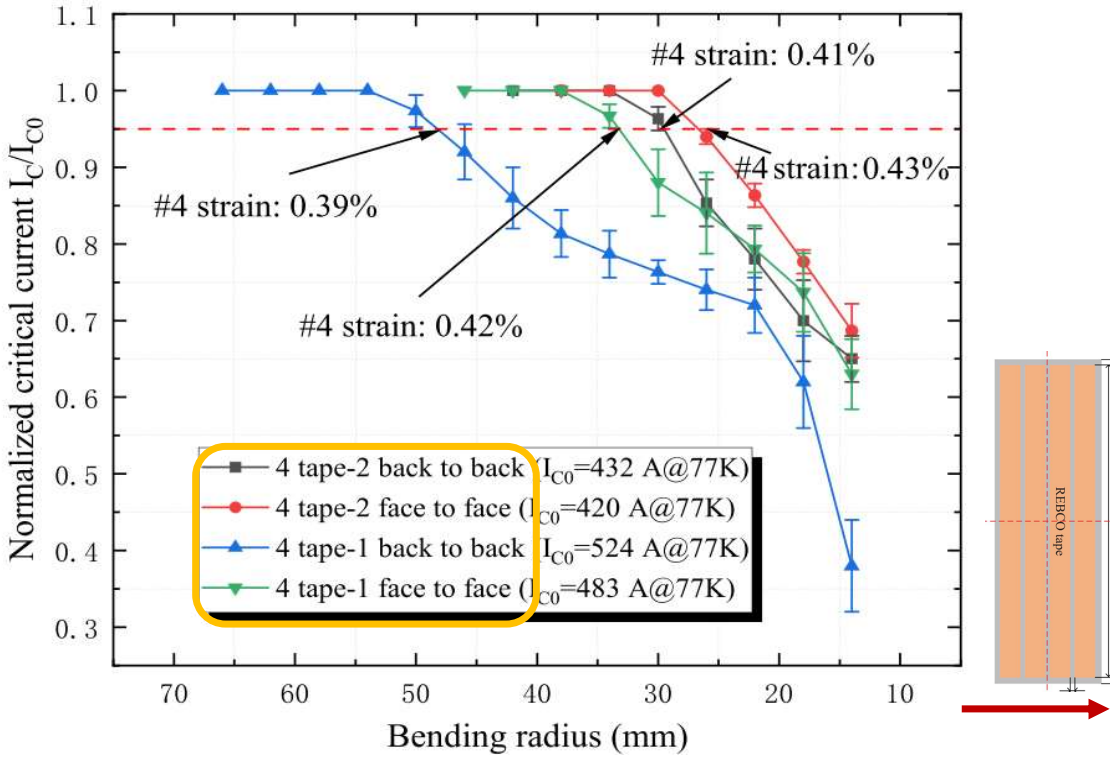
Aluminum stabilized *Re*BCO stack cable for particle detectors



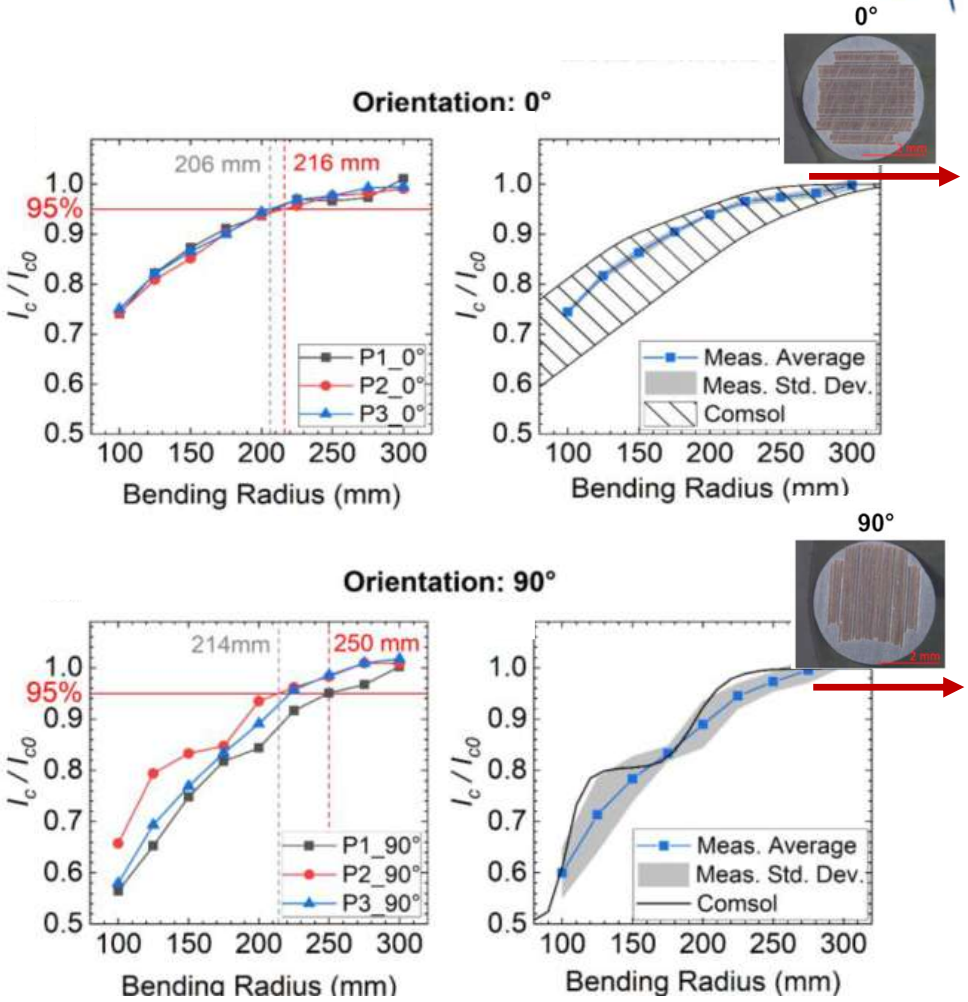
A. Vaskuri et al., IEEE TAS, Vol. 33, No. 5, 8,2023.

IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 59, May 2025. Presentation given at CCA 2025, March 11-13, 2025, Geneva, Switzerland.

Bending properties of a stack cable



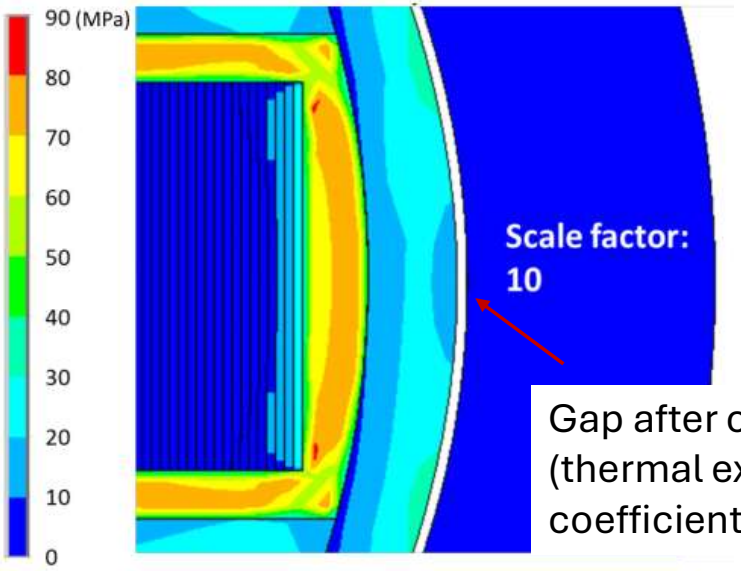
S. Yuan et al Supercond. Sci. Technol. 36 095007, 2023.



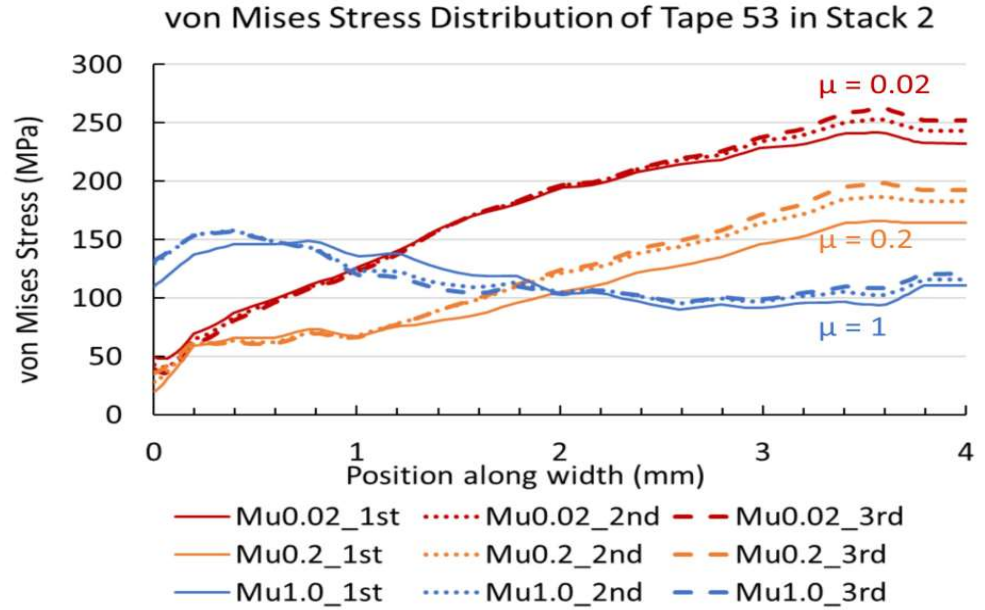
Daniel S. Nickel et al., IEEE TAS, Vol. 31, No. 5, 8 2021.

- The *Re*BCO layer strain is corresponding to the I_c degradation of the cable.
- It is consistent with the test results of a single tape.

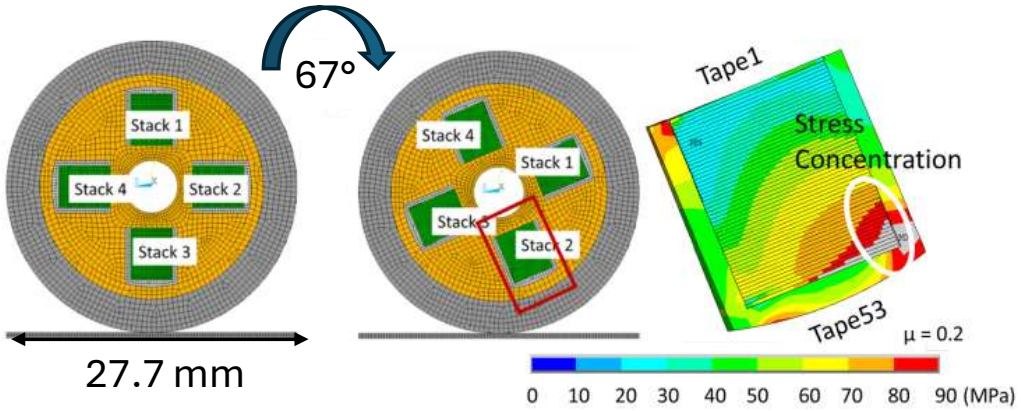
Structural modeling of a stack cable



Gap after cool down (thermal expansion coefficient mismatch)



Z. Zhao et al., IEEE TAS, Vol. 32, No. 6, 9 2022.



- A low friction is desired during bending.
- During operation, a solder that is hard to deform (high friction) is preferred.
- Wind the magnet first, then impregnate the channel with solder.

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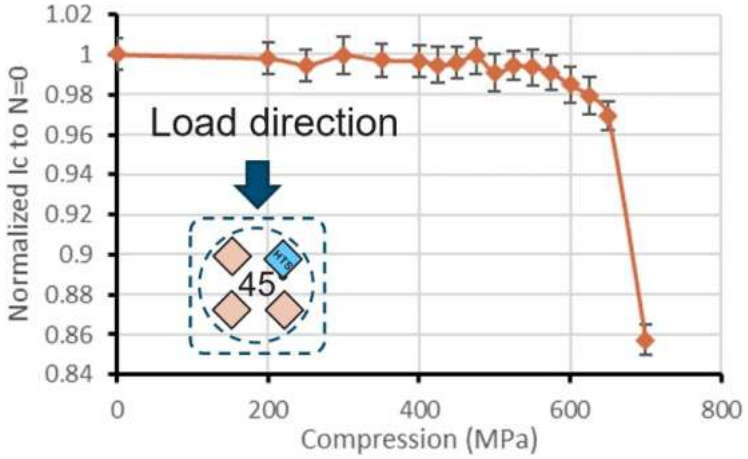
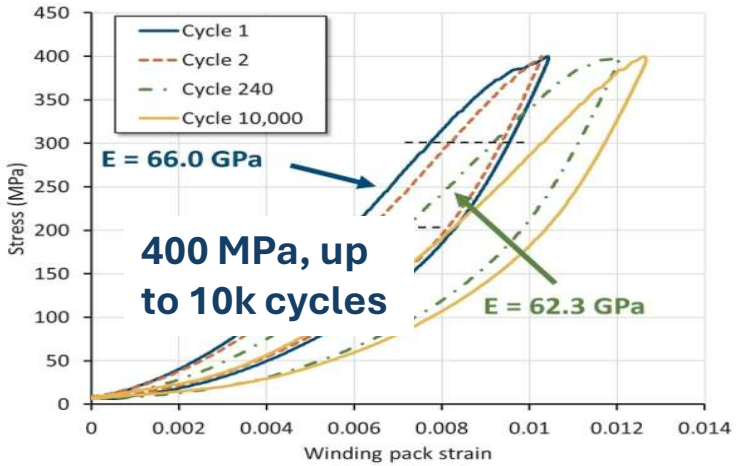
Transverse cycling load response of PIT VIPER cable



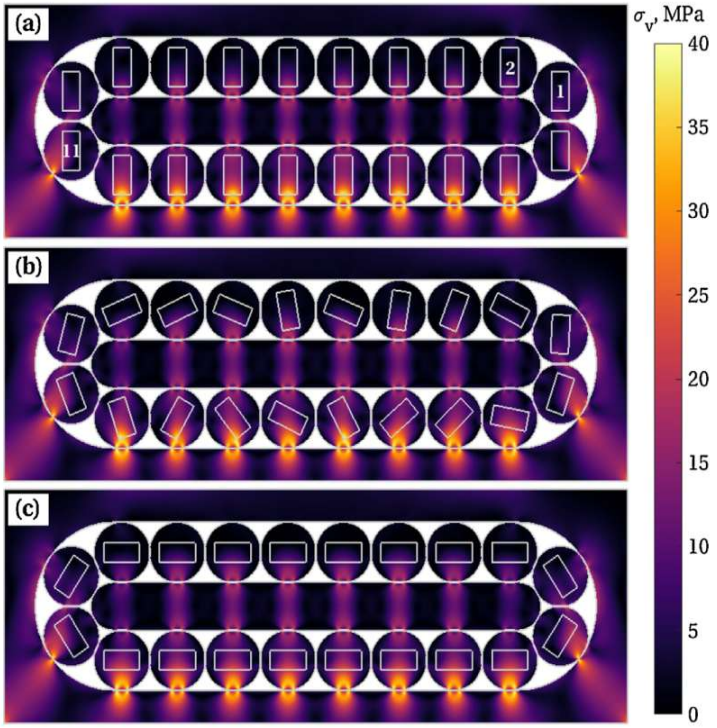


- The cable can sustain up to 600 MPa of transverse compression when applied to a single cable without degradation of current transport properties (in LN_2).

C. Sanabria et al., SuST 37 115010, 2024.

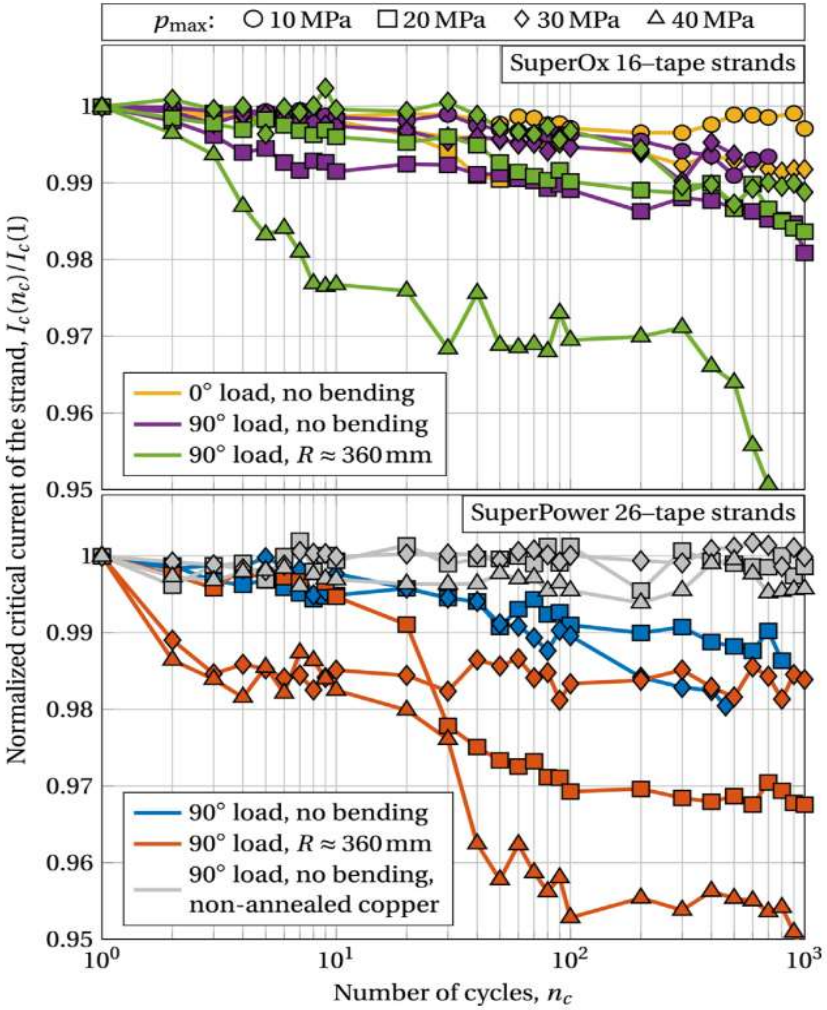
IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 59, May 2025. Presentation given at CCA 2025, March 11-13, 2025, Geneva, Switzerland.

Cycling loading of Cored Rutherford cable
(EPFL-CRPP)



Distribution of von Mises stress in the cable operating at 60 kA in 12 T background magnetic field for the different stack's orientations.

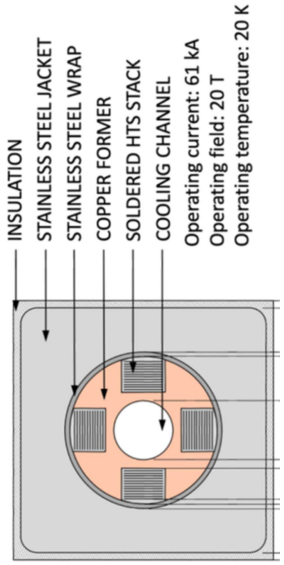
N. Bykovsky et al., Fusion Engin. and Design 124 (2017) 6–9.



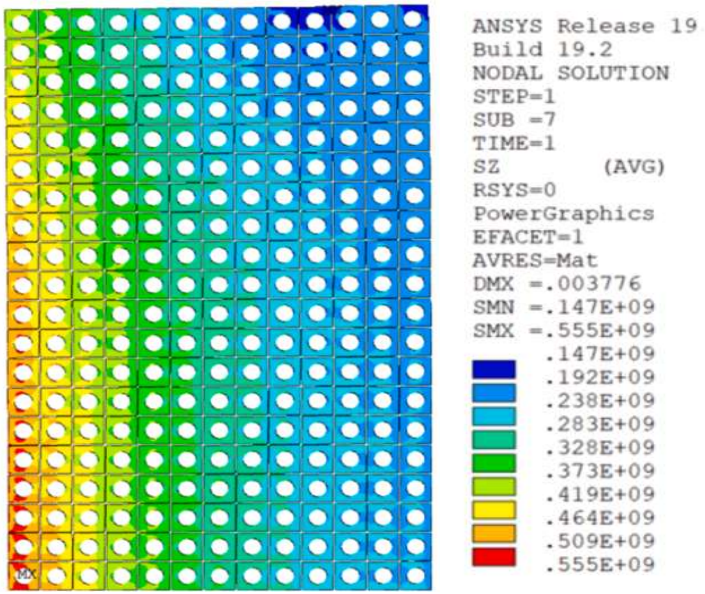
- Calculated and Measured *Re*BCO CICC performance.
- Force orientation on the stack and bending can largely affect the CICC performance leading to significant critical current degradation with cycling.

Stress components in modified VIPER cable

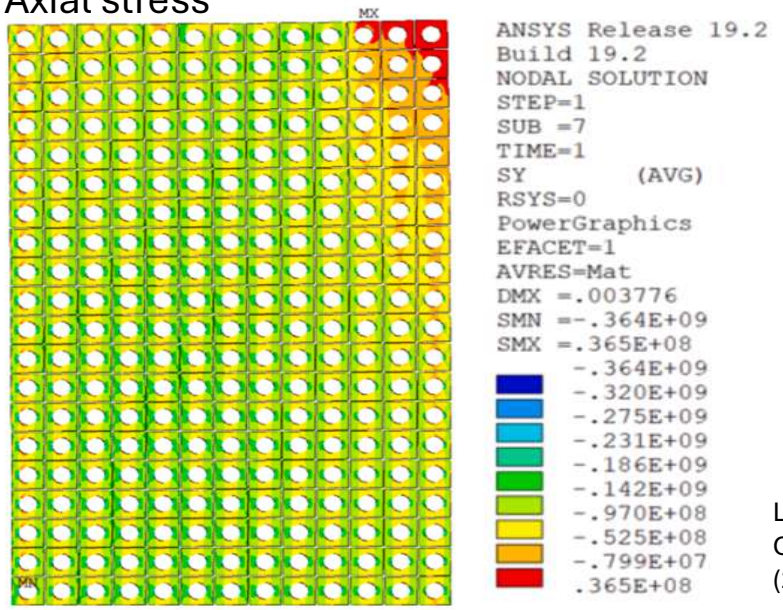
(square jacket, proposed CICC for 20 T target solenoid in Muon Collider)



Hoop stress



Axial stress



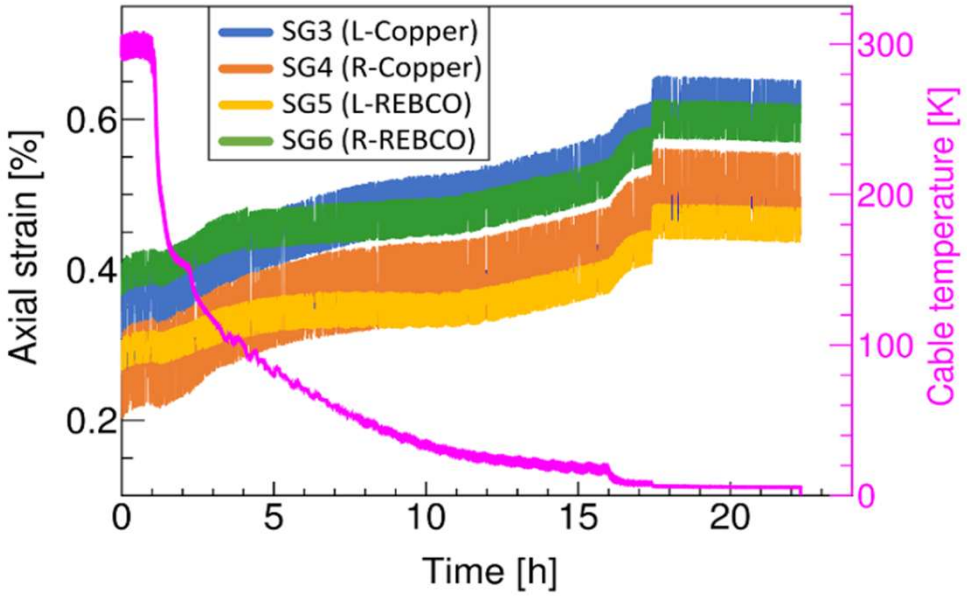
L. Bottura, et al., Cryogenics 144 (2024) 103972.

- Compressive stress must remain below 600 MPa, and tensile strain must be prevented.
- Tensile stress is below 10 MPa with peak values in some corners that can reach up to 60 MPa for the bonded case.
- Shear stress 40 MPa for the stacks bonded to the copper profile and in the range of 30 MPa if the stack is not bonded.

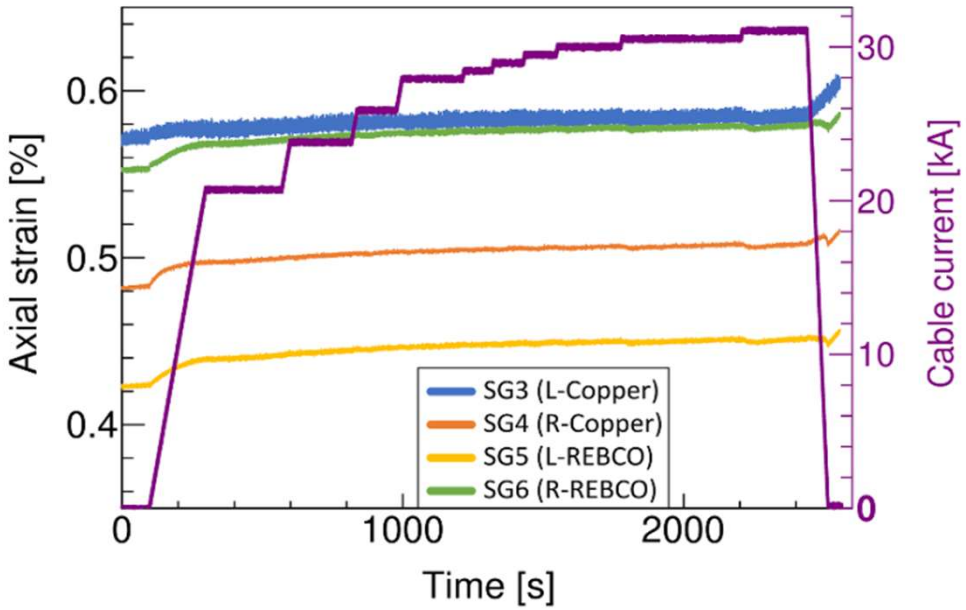
IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 59, May 2025. Presentation given at CCA 2025, March 11-13, 2025, Geneva, Switzerland.

Transverse loading & Axial strain in VIPER cable
(Sultan test results)

V. Fry et al., 2022 SuST 35 075007.



Measured increase in axial strain on the left cable (SG3, SG5) and right cable (SG4, SG6) during assembly cooldown in the SULTAN facility.



Measured axial strain on the left cable (SG3, SG5) and right cable (SG4, SG6) during one of the final current ramps after 500 IxB mechanical cycles.

- Thermal shrinkage on cool down of selected materials can lead to significant stress increase.
- Strain state with time when (500x)cycling shows stable performance, predictable…

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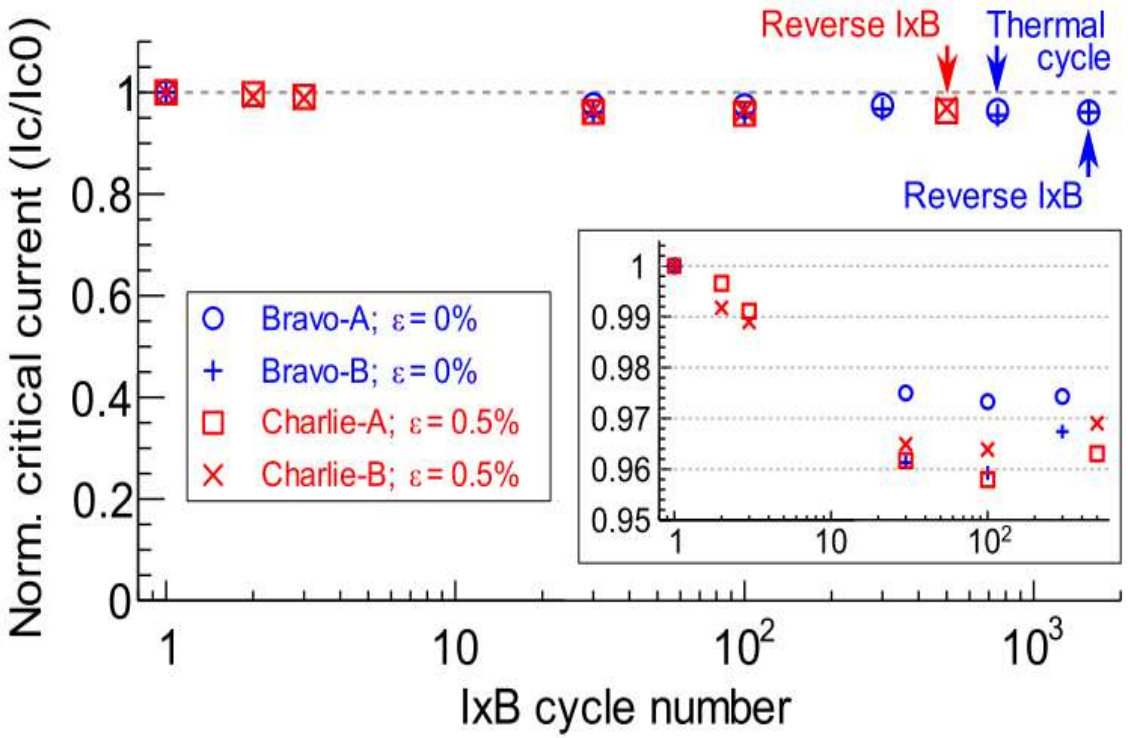
Cyclic loading of VIPER cable



Results of I×B mechanical cycling for the Bravo and Charlie VIPER cable pairs at T = 5 K, and I×B = 382 kN/m.

Charlie cables had an additional 0.5% axial strain applied.

Z. S. Hartwig et al., 2020, SuST 33 11LT01.

- Satisfactory behavior. The initial degradation of 3 % to 4 % consistently stabilizes after some 30 cycles.
- Thermal cycling and current reversal events show a negligible impact on the critical current.

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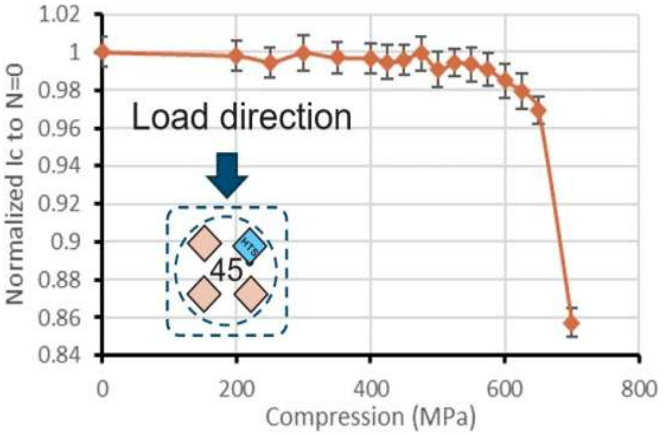
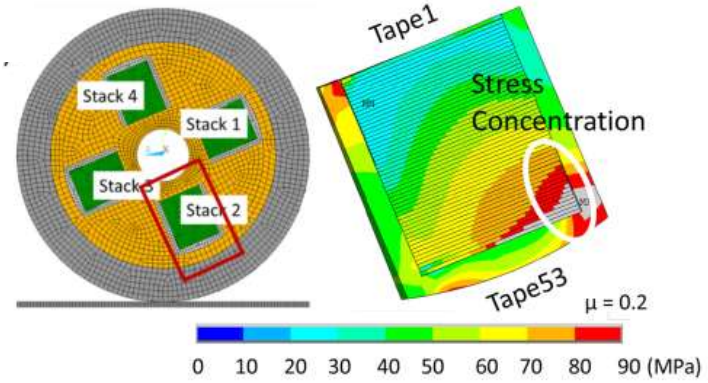
Mechanical limitation of stack type Coated Conductor cables

- Few different concepts and variations of stack cable exist.
- **Bending** properties in easy direction are compatible with single tape results.
- Stack cable can sustain up to **600 MPa** of **transverse** compression when applied to a single cable (VIPER slot).
- Solder-connected tapes and increase in **shear strength** from 30 to 40 MPa (modelling); still a critical issue in *Re*BCO tape stack cables.





Z. Zhao et al, IEEE TAS, Vol. 32, No. 6, 09 2022.

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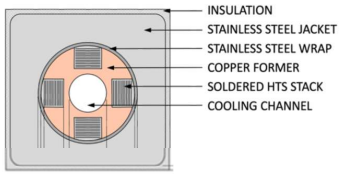
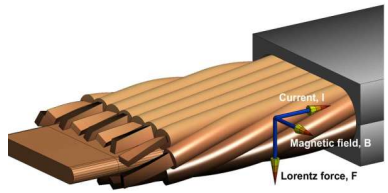
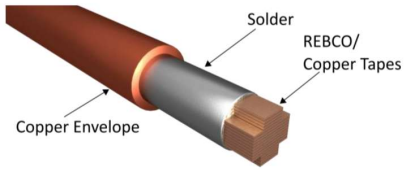
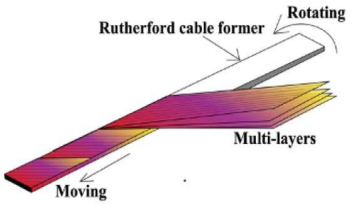
Mechanical limitation of stack type Coated Conductor cables

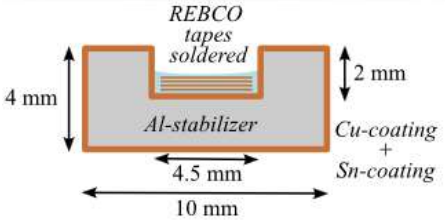
- Load cycling in same cables show good results, but requires verification in variants.
- Cables require **three-dimensional** mechanical characterization.
- Mechanical test measurements and simulations are to be performed on **tape / coated conductor and on cable** level.
- Much more mechanical characterization of variants and repeated tests are needed for **comparison, optimization and qualification**.

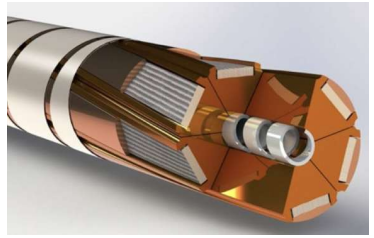












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