Self-regulated current sharing in HTS cables and magnets: an option beyond insulation or no-insulation

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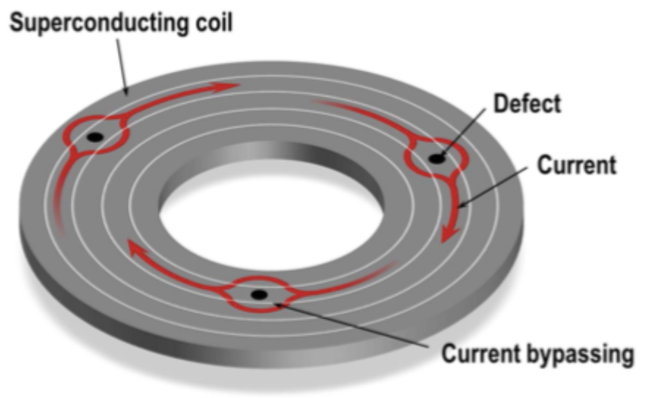
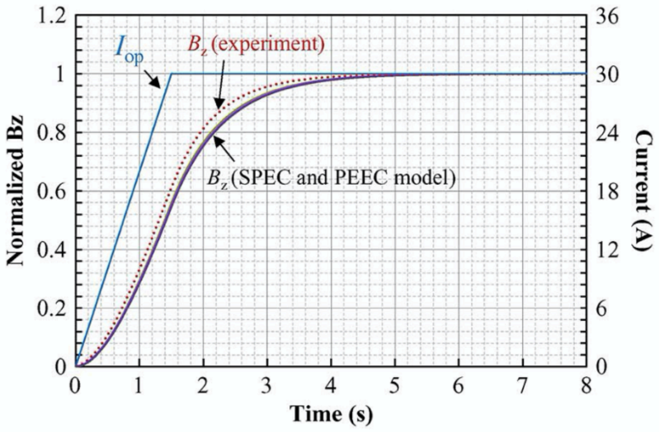
The magnet community is facing a dilemma: Insulation or non-insulation for future high-field magnets?

Non-insulation pros -> current sharing
- Self-quench protection
- Higher engineering current density
- Operation regardless of defects

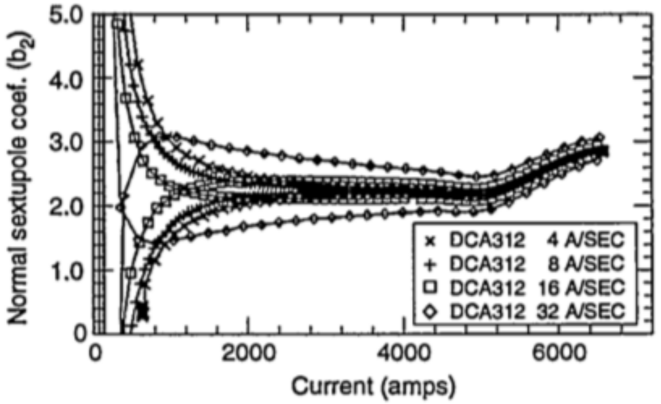
Non-insulation cons -> excessive eddy currents
- Charging/discharging field delays
- Ramp losses
- Field distortions and ramp-rate dependence



S. Hahn *et al.*, 2019 *IEEE TAS* 29 105017



X. Wang et al., 2015 *IEEE TAS 25* 4601805



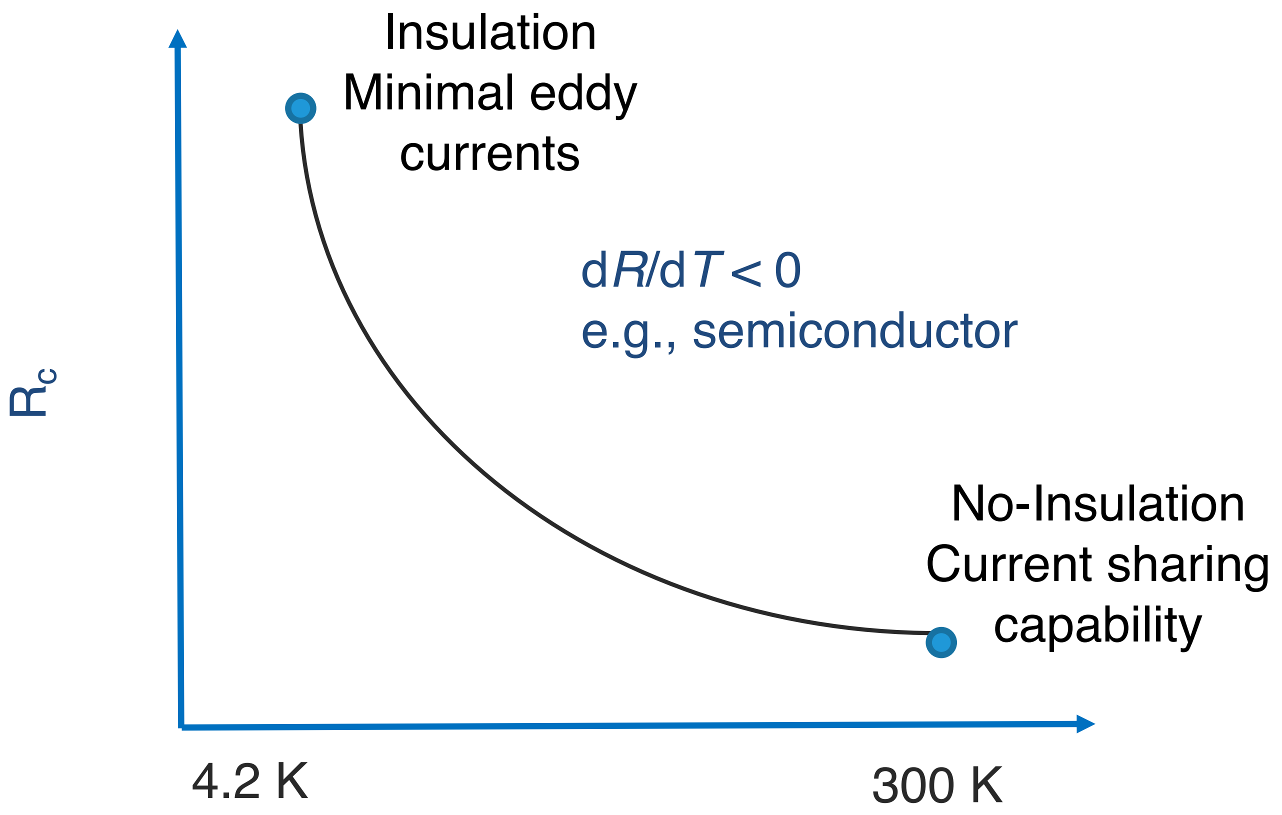
Ogitsu *et al.*, *SSCL* report 1994

A potential solution is to control the contact resistance (R_c) between REBCO tapes

- **Co-wind REBCO tapes with metal strips** (J. Kim *et al.*, 2016 *IEEE TAS* 26 4601906)
  - Cu; stainless steel
- **Coating REBCO tapes with various resistive films** (J. Lu *et al.*, 2018 *SST* 31 085006)
  - Electro-plating Ni, Cr, Ni-P
- **Oxidation of REBCO surface using an Ebonol® C solution** (J. Lu *et al.*, 2018 *SST* 31 085006)

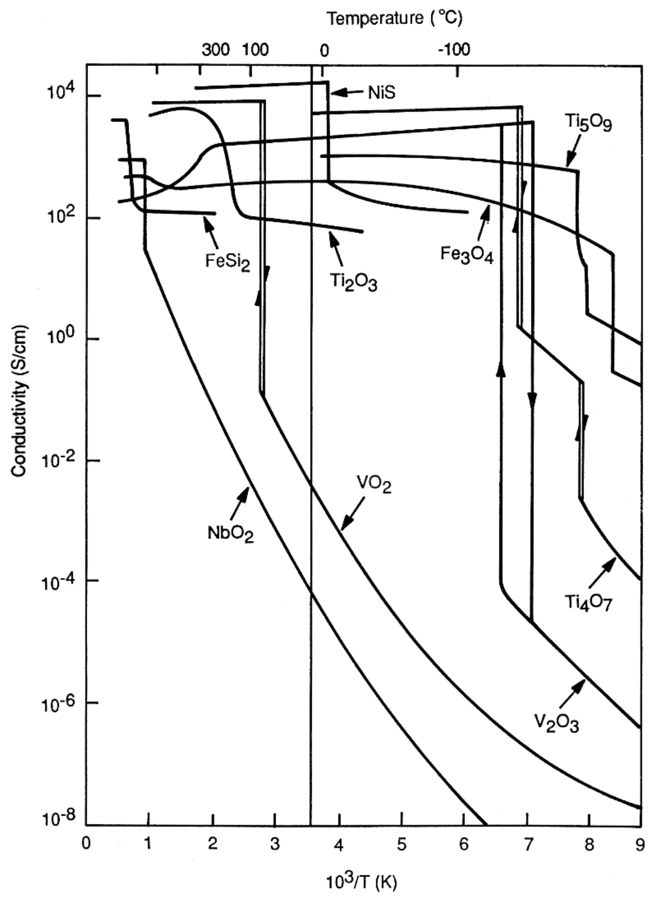
Drawbacks –> Limited current sharing capability

Would an R_c with a negative temperature dependence work?



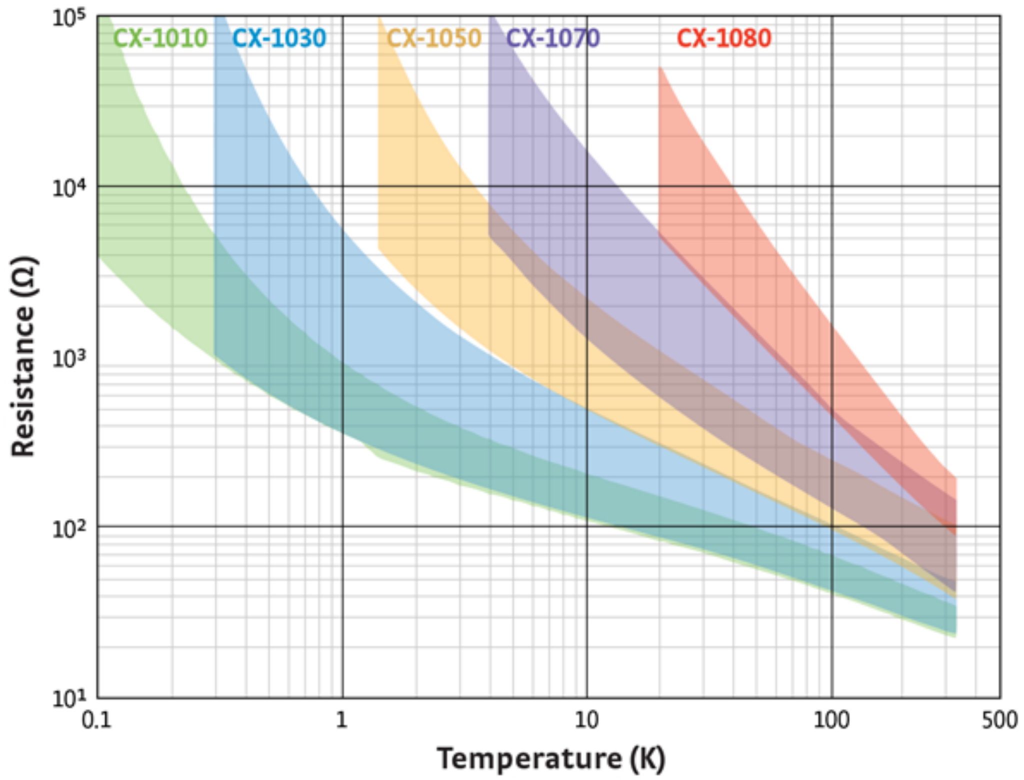
Semiconducting materials can have the desired negative temperature dependent R_c

Metal-insulator transition (MIT) materials



G. V. Jorgenson and J. C. Lee, 1986 *SEM* 14 205

CERNOX®



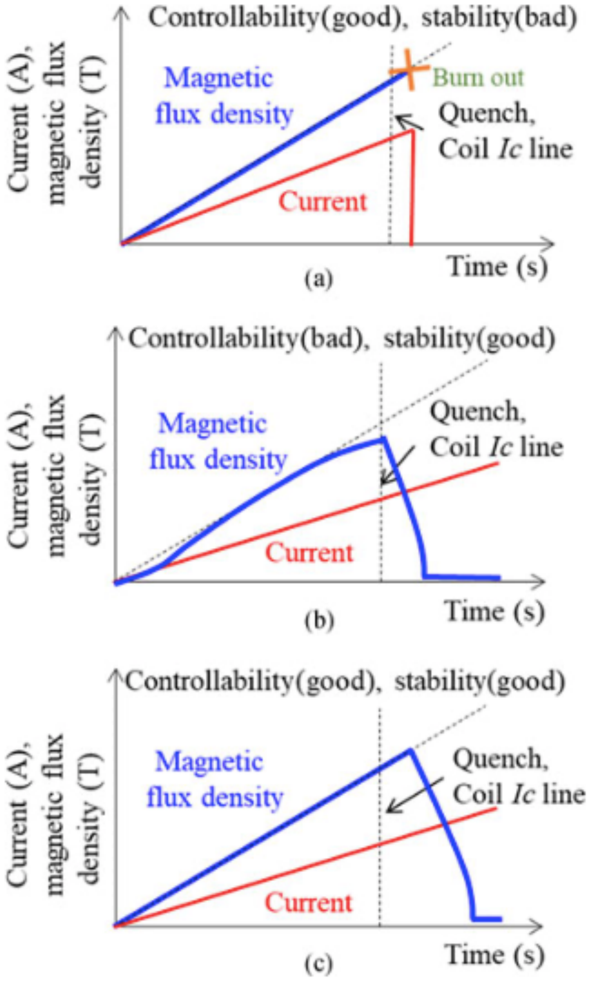
https://www.lakeshore.com/products/categories/overview/temperature-products/cryogenic-temperature-sensors/cernox

V_2O_3 applied on REBCO tape demonstrated the self-switching resistance behavior. However, a better deposition method is required for large scale applications

Insulated coil

Non-insulated coil

V_2O_3 added to coil



H. Kim *et al.*, 2018 *IEEE TAS* 28 4600205

HTS coil with V_2O_3 paste

H. Kim *et al.*, 2018 *IEEE TAS* 28 4600205

We studied the impact of vanadium oxide (VO_X) coated on REBCO tapes as a temperature-regulated passive medium

Advantages of cathodic arc method

- Low-temperature deposition ~ 100°C
- Potential adjustment for industrial applications
  - Control of film thickness
  - Roll-to-roll deposition process

Journal of Applied Physics

Vanadium oxide coatings to self-regulate current sharing in high-temperature superconducting cables and magnets

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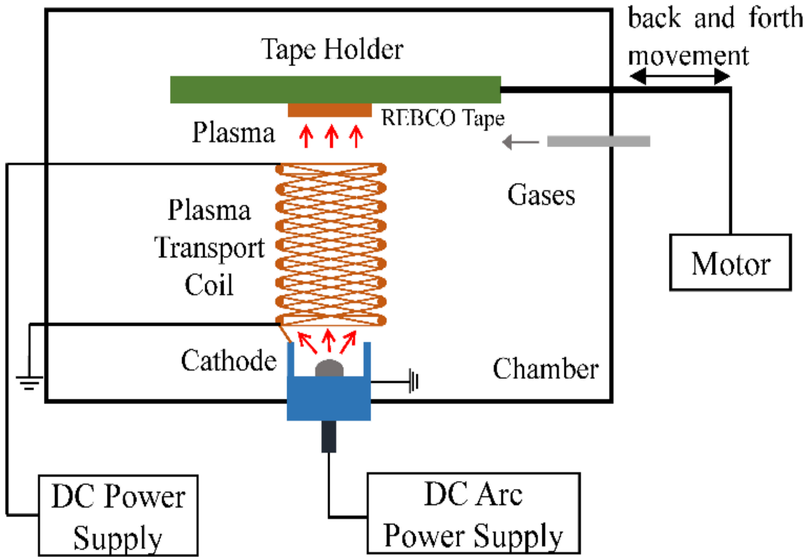
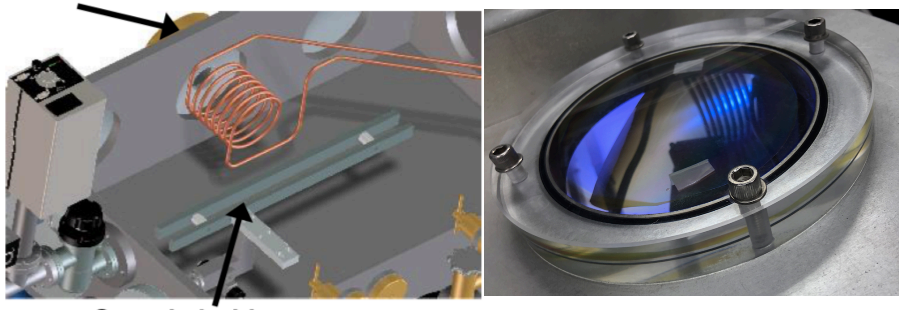
COLLECTIONS

Paper published as part of the special topic on Phase-Change Materials: Syntheses, Fundamentals, and Applications
Note: This paper is part of the Special Topic on Phase-Change Materials: Syntheses, Fundamentals, and Applications.

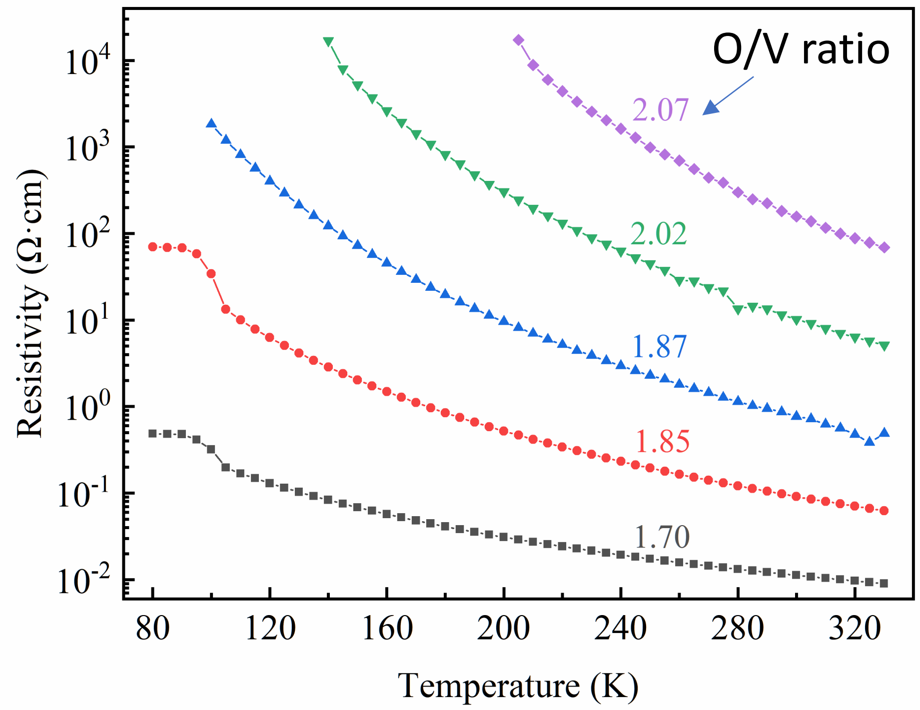
Cathodic arc deposition system





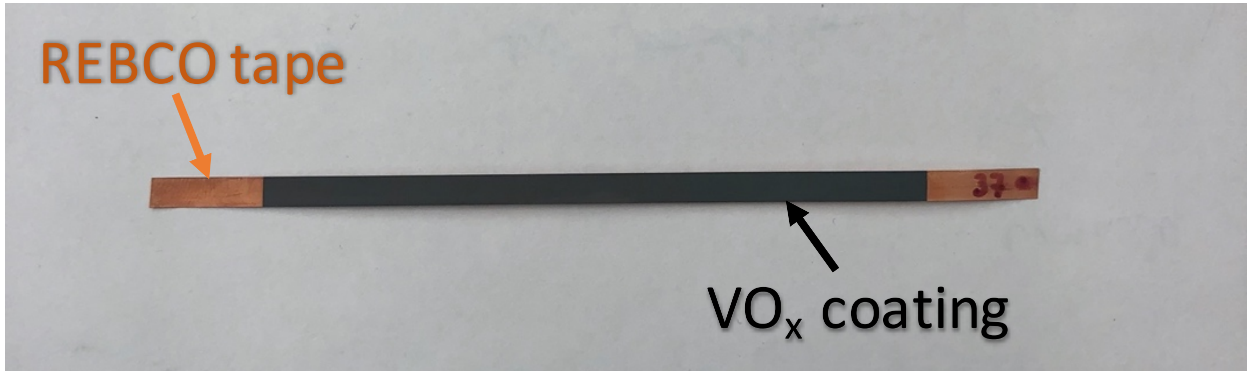
Electrical resistivity of VO_X can be controlled by the oxygen flow rate during deposition

VO_X resistivity vs. Temperature



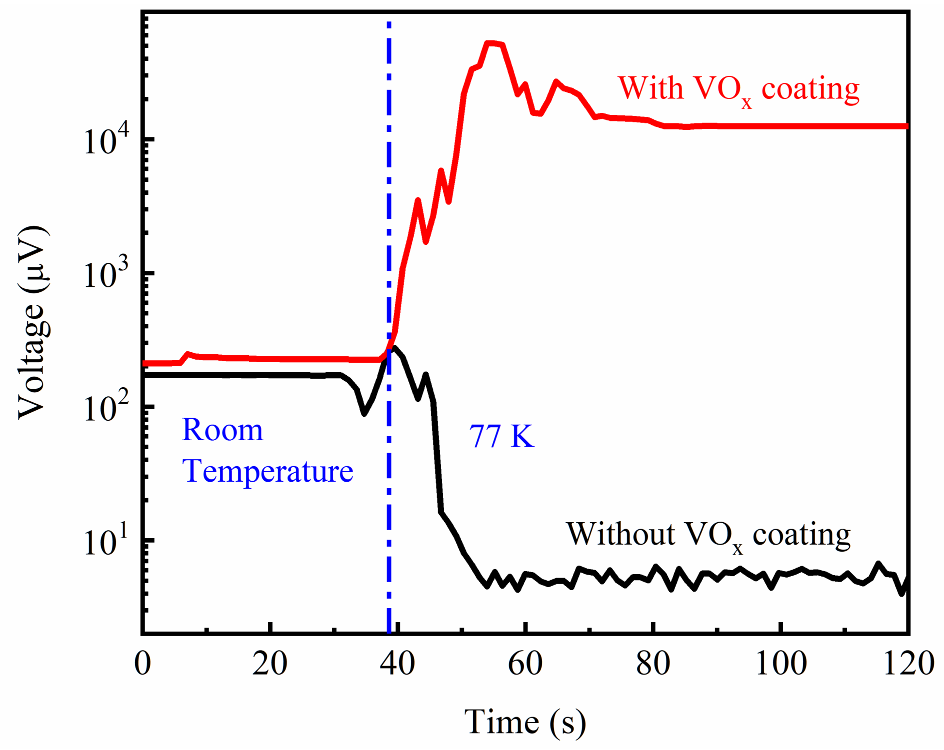
*Measured on glass substrate with Ecopia HMS-5000 Hall measurement system with a 0.55 T background magnetic field.

VO_X coating deposited on REBCO tape

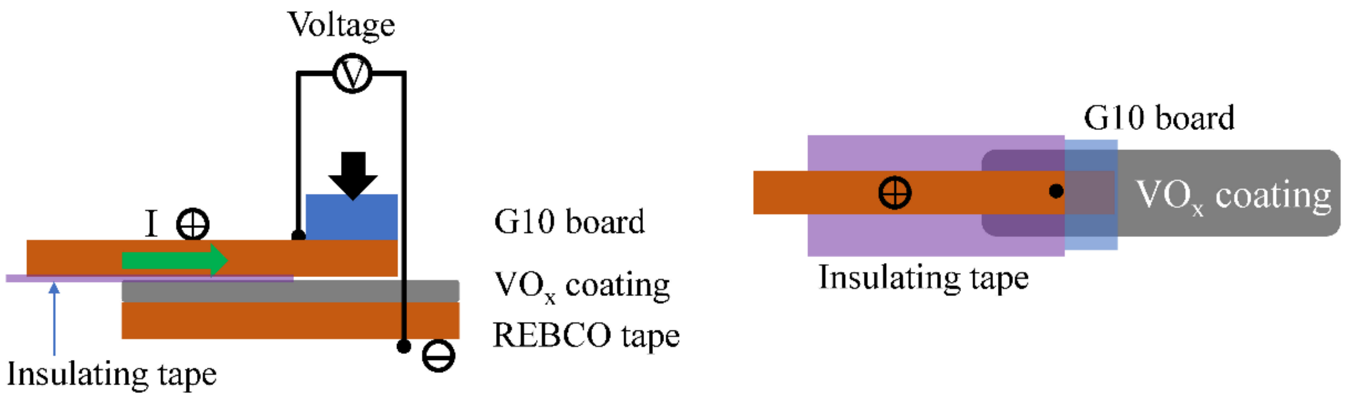


Electrical resistivity of VO_X measured directly on REBCO tape also showed negative temperature dependance

Measured voltage on lap-joint configuration



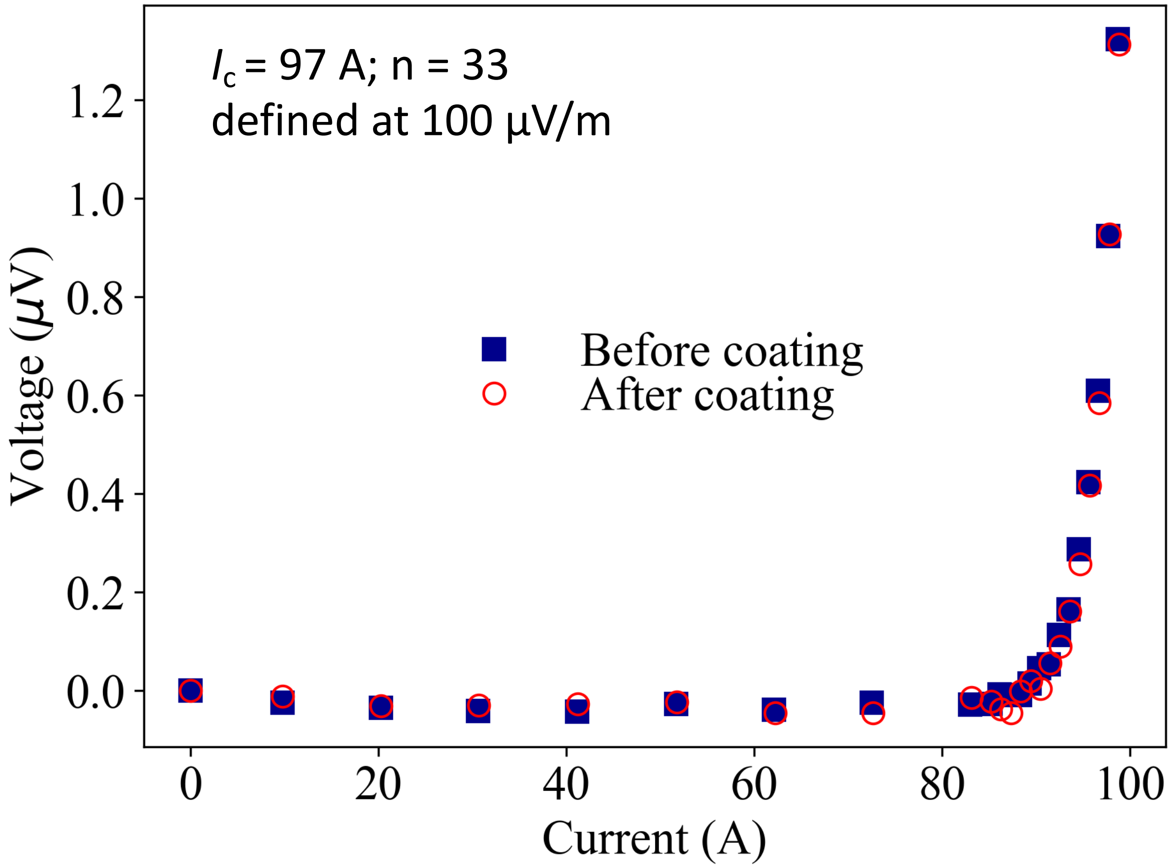
Lap-joint setup



The coating process preserved the current-carrying capability of the REBCO tape

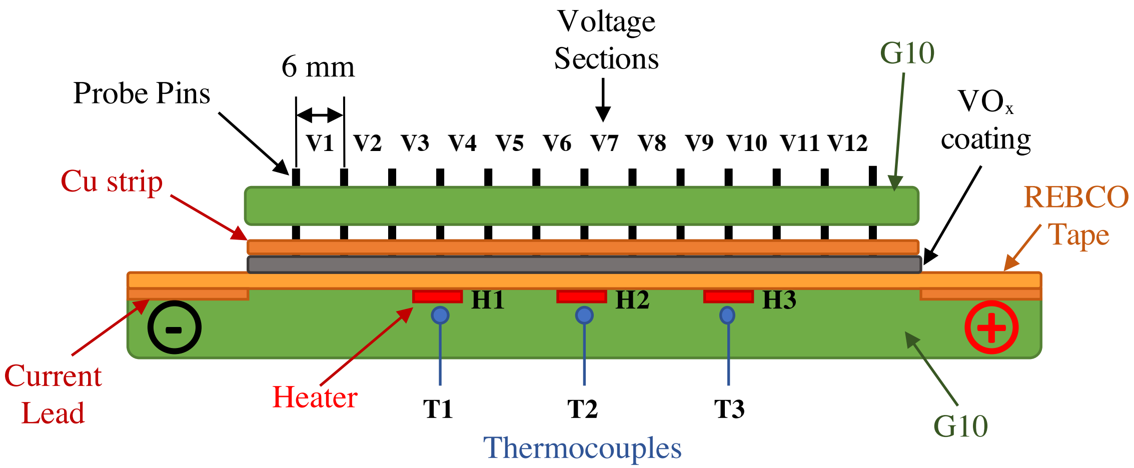
- No I_c degradation after coating
- Tape peak temperature during deposition < 100°C

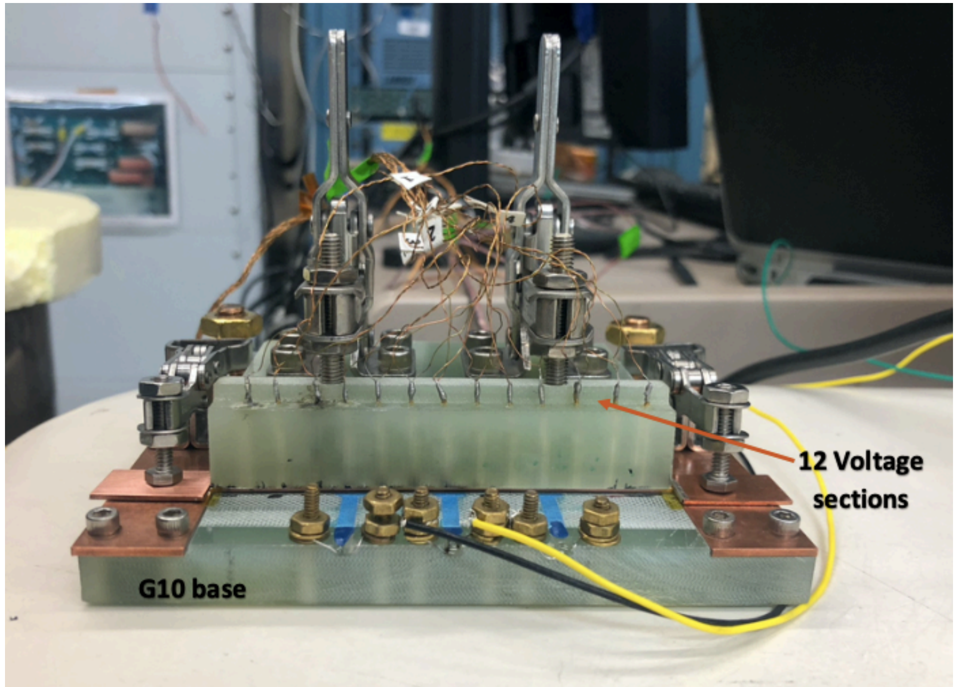
I_c measurement on uncoated side of REBCO tape



We developed an experimental setup to study the impact of the VO_x coating on current sharing in REBCO tapes

Experimental setup





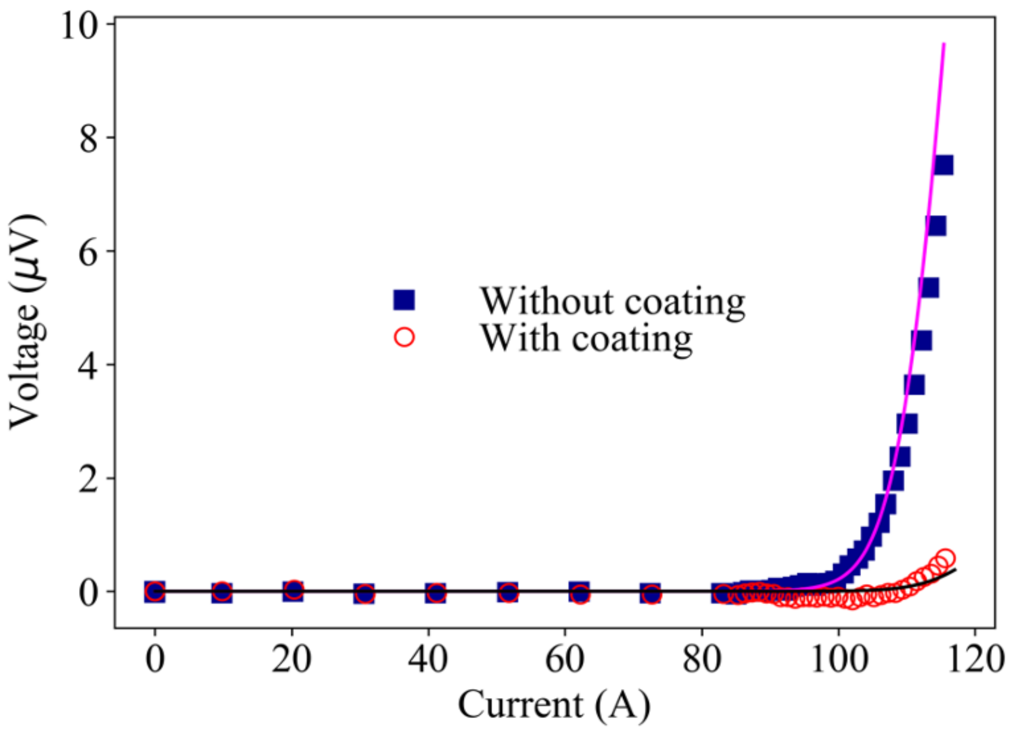
Two sets of experiments were performed to study current sharing in coated and uncoated REBCO tapes

- Experiment 1
  - Constant temperature 77 K
  - Ramping current

- Experiment 2
  - Constant current ~ 82% I_c
  - Introduced local hot spot at the center of the tape

High electrical resistance of the VO_x coating at 77 K effectively reduced the current sharing from the REBCO tape to the Cu strip

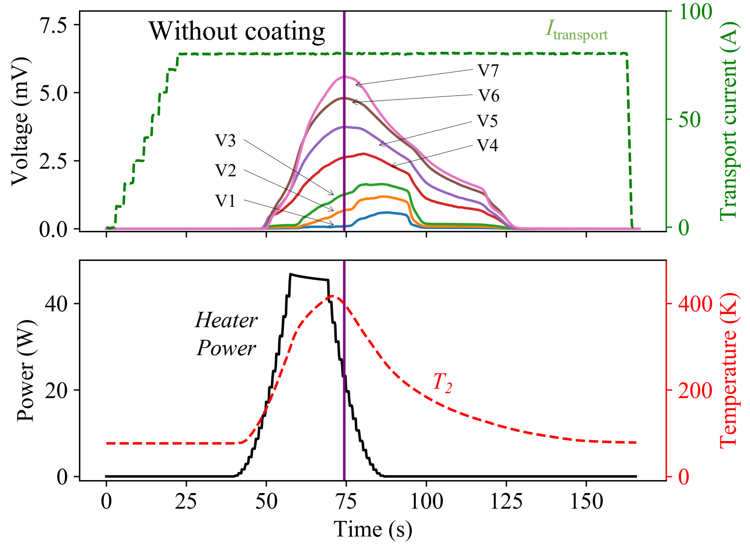
Experiment 1



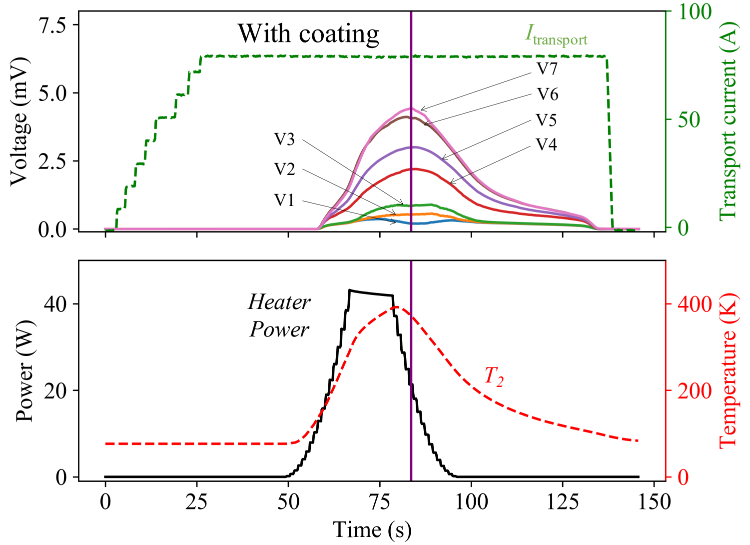
Voltage rise showed the coating allowed current sharing when a local hotspot was introduced in section V7

Experiment 2

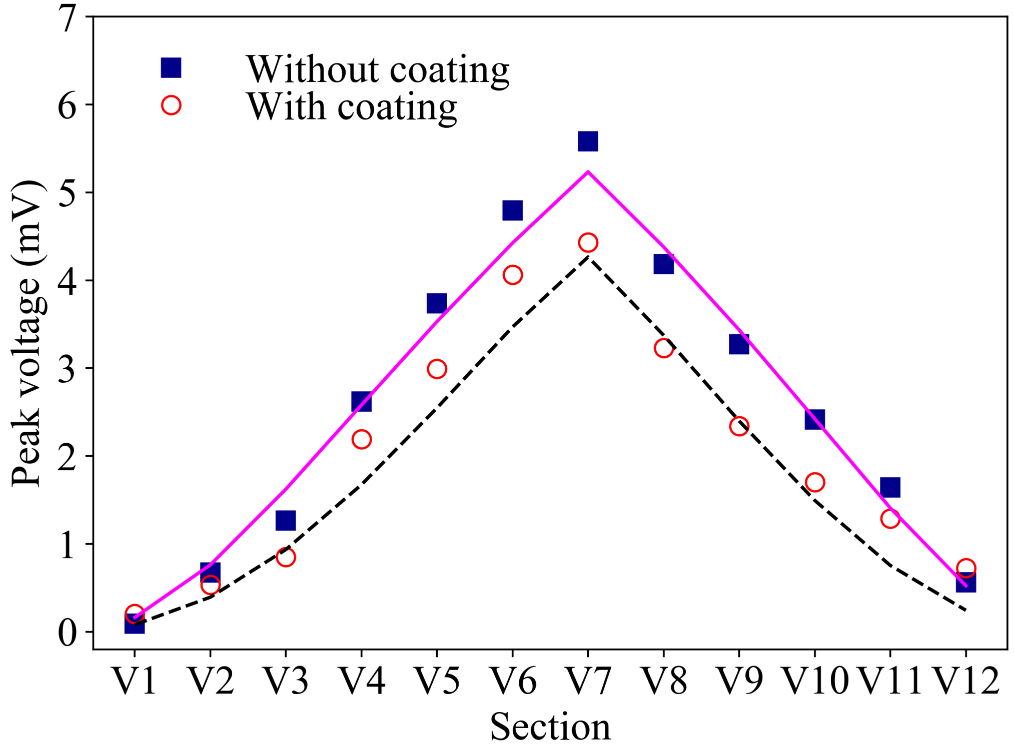
Without coating



With coating



Spatial voltage profiles along REBCO tape



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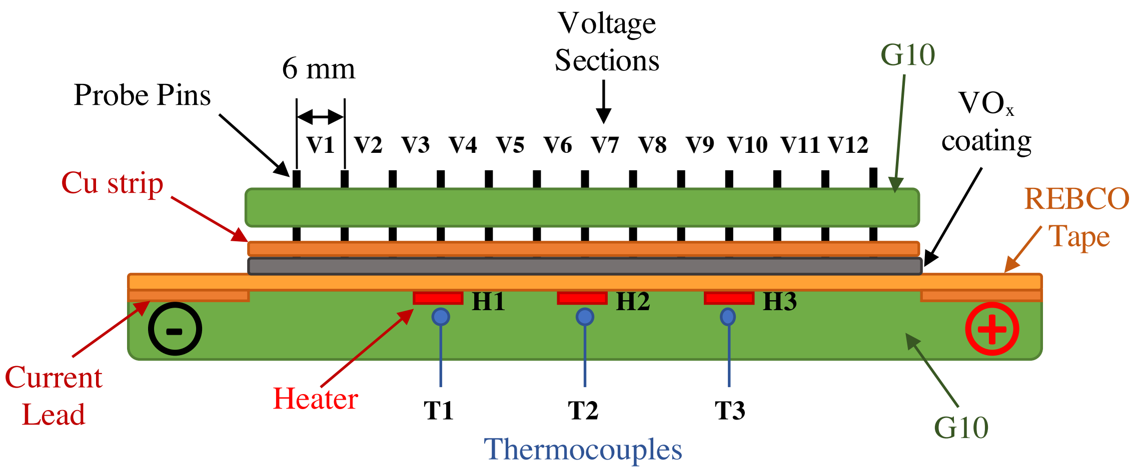
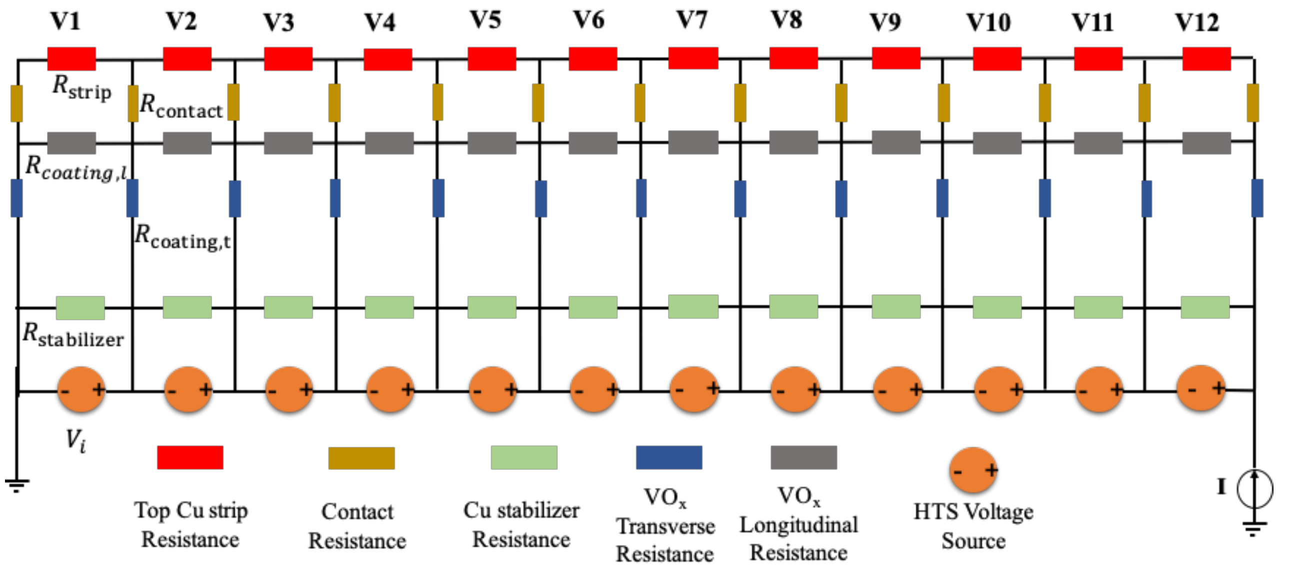
We used an electric-circuit model to analyze the impact of the VO_x coating on current sharing

Experimental setup

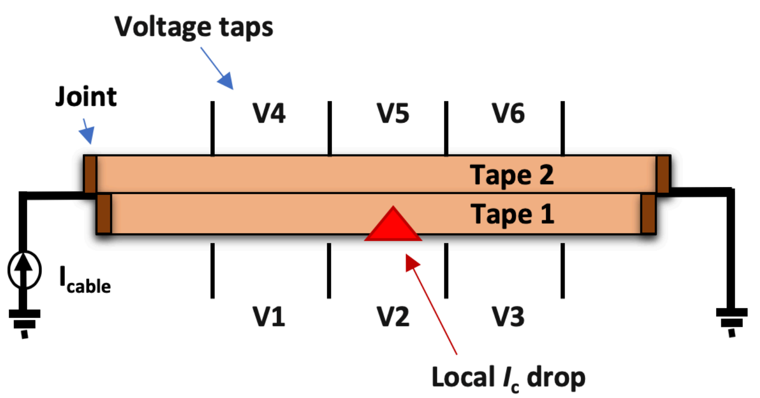


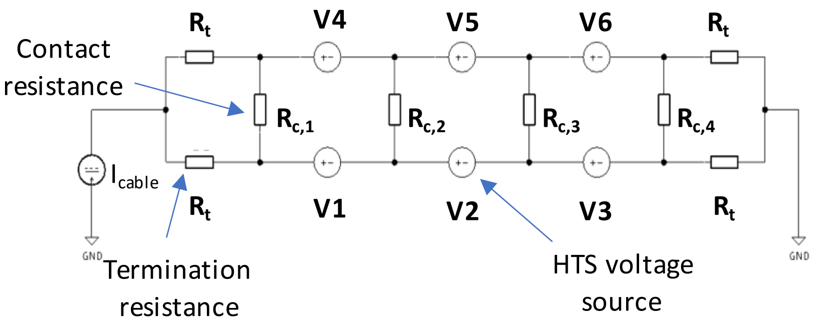
Electric-circuit model



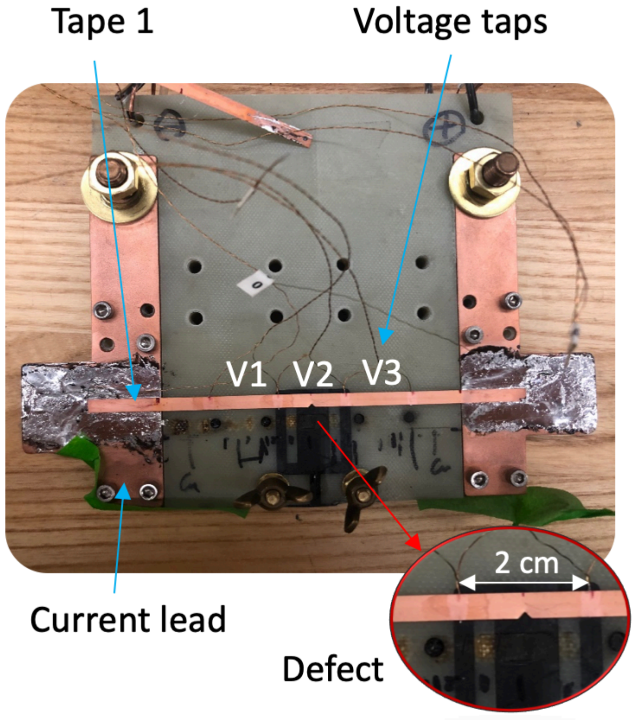
$$V = V_c\left(\frac{I}{I_c}\right)^n$$

The REBCO model was validated with experiments on a 2-stacked-tape cable

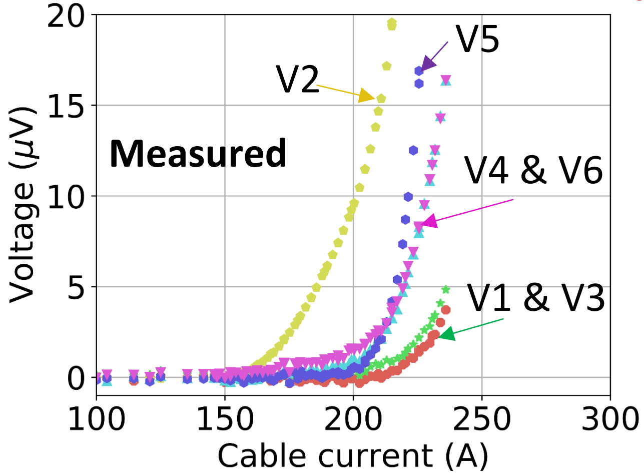


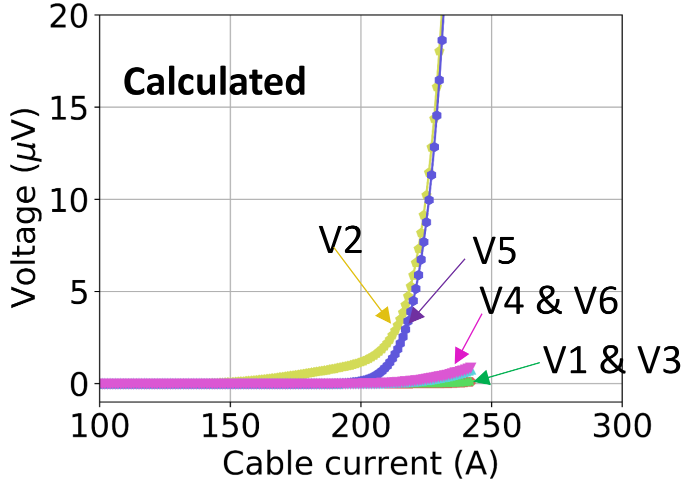


$$V_i = LE_c\left(\frac{I}{I_c}\right)^n$$



TAPES SOLDERED → LOW R_c

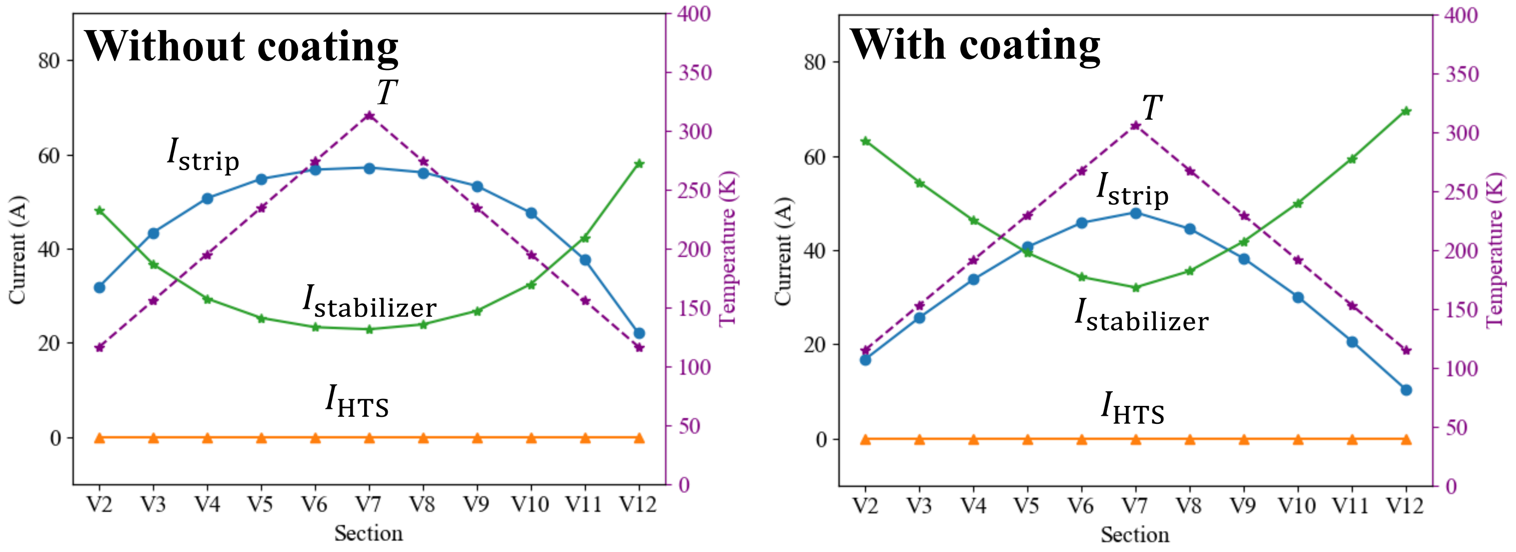




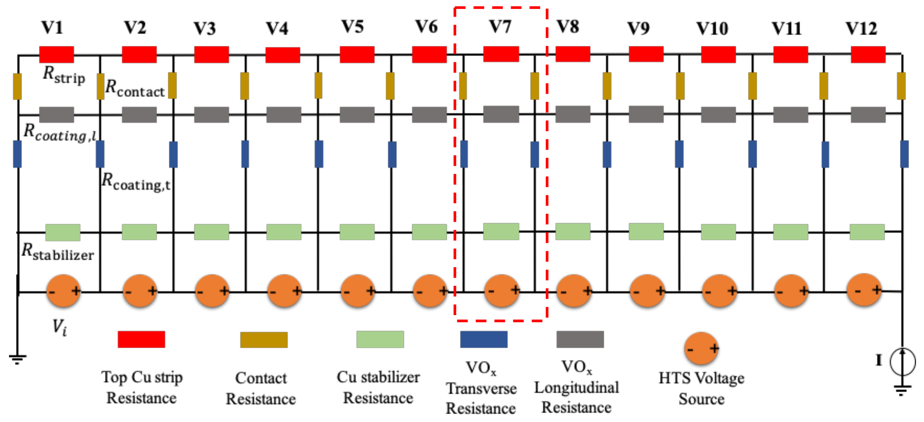
A.C. Araujo Martínez et al., 2020 *IEEE TAS* 30 6600605

Compared to the case without coating, the VO_x coating suppressed current sharing at the cold ends and allowed it near the hot zone

Calculated current distribution in the the 12 sections of the circuit model



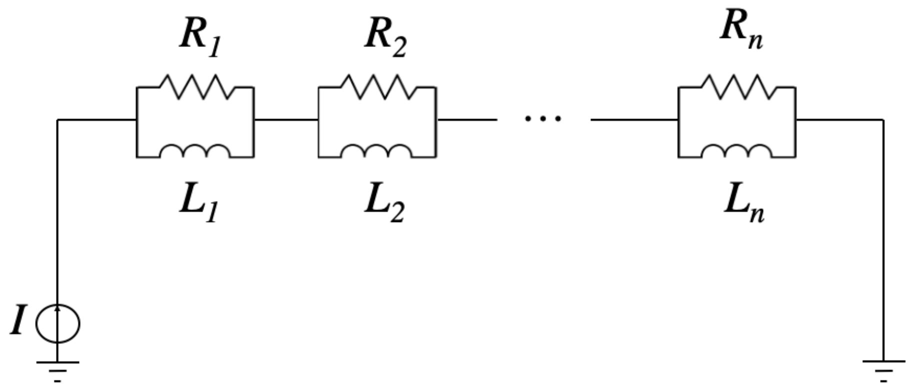
Heated section



Can the VO_x coating suppress eddy currents that cause delays in the magnetic field?

- We studied the impact of the inter-tape electrical resistance on a 7-turn REBCO pancake coil at 77 K

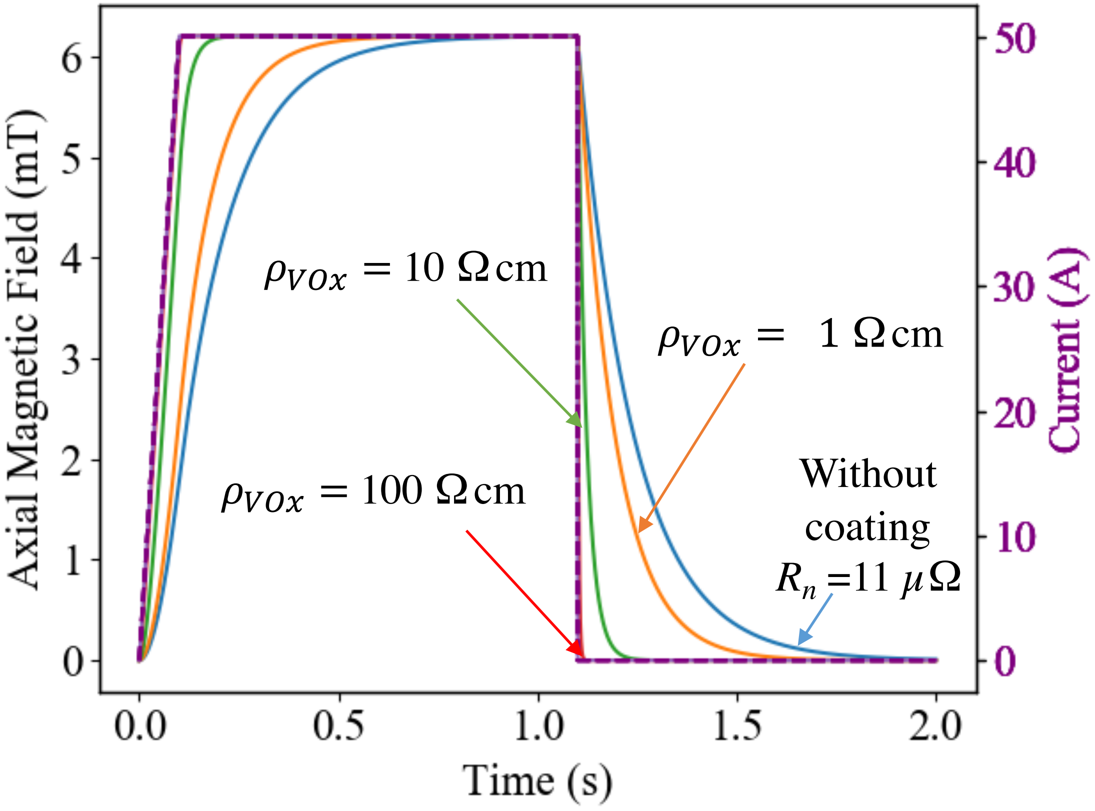
Electric-circuit model for pancake coil

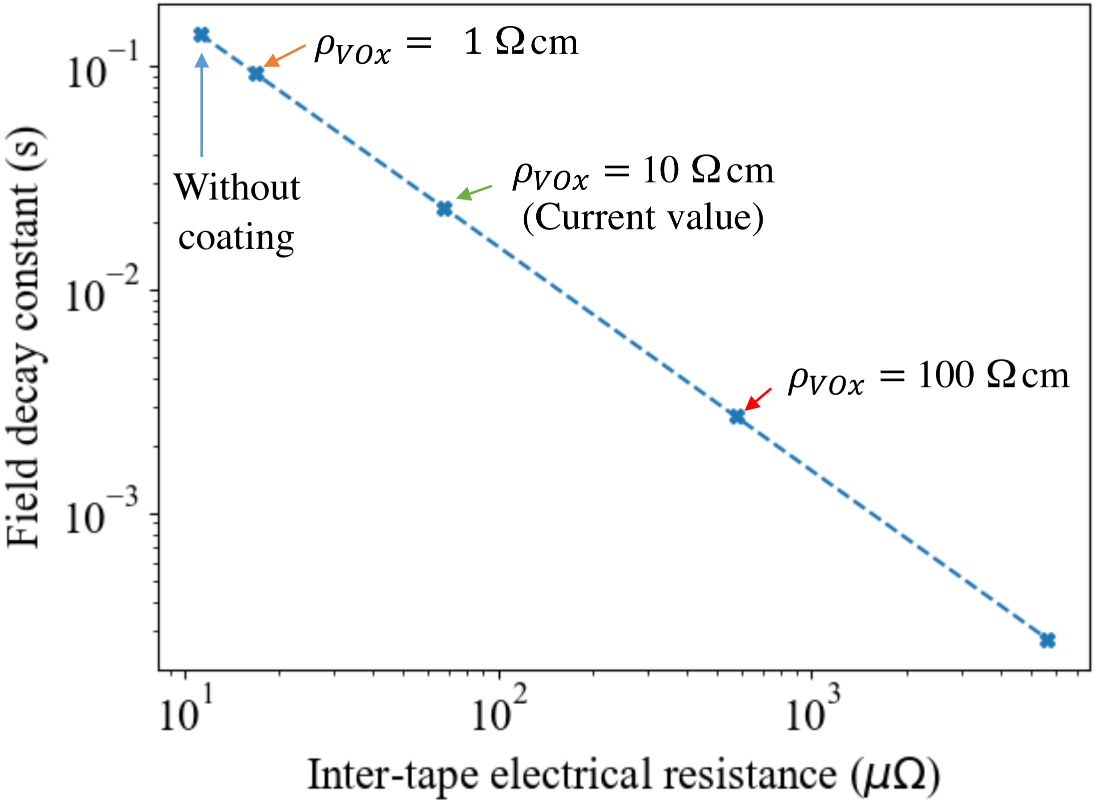


$$R_n = R_{contact} + R_{coating}$$

The VO_x coating resistivity at 77 K can achieve the necessary inter-tape resistance to minimize field delays

Calculated magnetic field of the 7-turns REBCO pancake coil with coating





VO_x coating has the potential to self-regulate current sharing and to suppress eddy currents. But there is more work to do!

Next steps

- Implement a roll to roll coating system for longer coated tapes
- Build a test pancake coil with REBCO coated tapes

Summary

- **VO_x coatings are a potential solution to move beyond insulation or non-insulation, the negative temperature dependence of its resistivity allows them to self-regulate current sharing**
  - High temperature -> Conductor to allow current sharing during a quench
  - Low temperature -> Insulator to suppress eddy currents
- **The VO_X resistivity range can be tuned depending on the application**
  - Electrical resistivity of VO_X can be controlled by the oxygen flow rate during deposition
- **The coating process is compatible with REBCO tapes**
  - The current-carrying capability of the REBCO tape is preserved after coating

Additional slides

Resistance values of the electric-circuit model for the experiment with a local hot spot in section V7