Contact resistivity measurement and simulation of current sharing around dropouts in CORC cables

Summary of FES SBIR Phase 1 with ACT

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U.S. DEPARTMENT OF ENERGY | Office of Science

BCMT
BERKELEY CENTER FOR MAGNET TECHNOLOGY

Background and Outline

Advanced Conductor Technologies LLC
www.advancedconductor.com

- Phase 1 SBIR via DOE FES to develop long-length CORC cables (ACT -> LBNL)
  - Large coils will need cables longer than tape lengths
    - R&D is relevant to developing lower-cost HTS cables using lower-quality tapes
      - ***See Lance Cooley / Jeremy Weiss et al previous VIC cable program for motivation***
  - Ongoing FES phase2B on Hall-based Quench Detection producing results, but not discussed today

- Outline for today
  - Difficulties scaling CORC network model
  - Contact resistivity extraction in Tapes (see Virginia Phifer + Lance Cooley's paper)
  - Potential as future modeling tool for CORC cables with low / variable performance tapes

No MDP resources being used for these, but making progress

AIIId-M13	***Develop quality control capabilities to identify defects and performance limiting regions in REBCO cables and accelerator magnets***	*In progress*	*Nov-23*	*R. Teyber*
AIIId-M14	***Advance numerical and experimental abilities to monitor and predict current distributions in ReBCO cables for accelerator magnets***	*In progress*	*Mar-24*	*R. Teyber*

Challenges with Network modeling

- LBNL Goal: use published CORC network model to inform cable design
  - First focus on contact resistivity extraction
  - Scale model to fit ACT measurements on cable with / without dropouts
    - Scaling model to more tapes + longer lengths proved problematic!
      - Needs future development towards high performance computing

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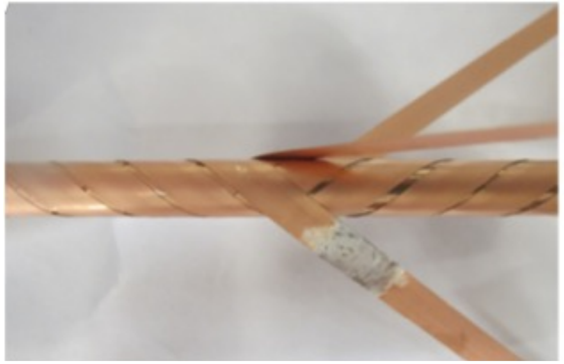
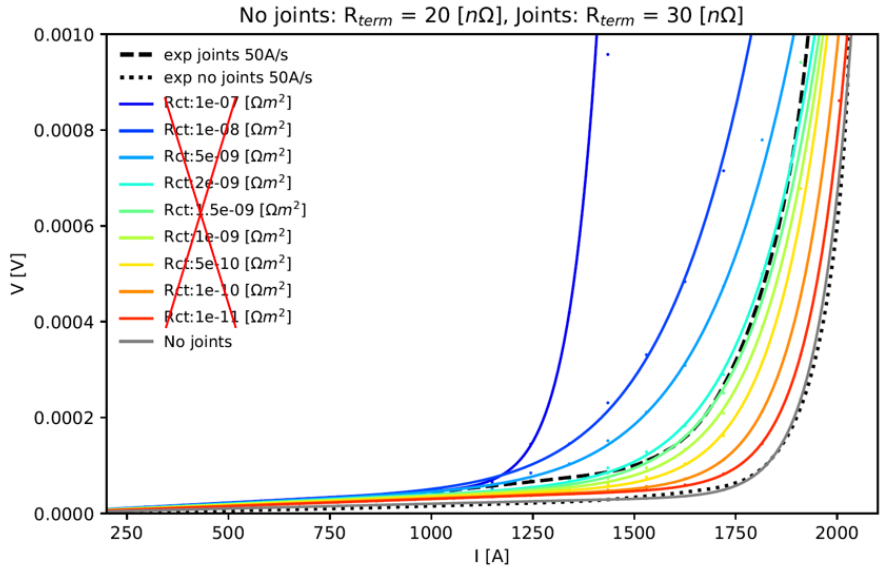
Supercond. Sci. Technol. **35** (2022) 094008 (13pp) — https://doi.org/10.1088/1361-6668/ac86fd

Numerical investigation of current distributions around defects in high temperature superconducting CORC® cables

Reed Teyber[1,*], Maxim Marchevsky[1], Aurora Cecilia Araujo Martinez[1], Soren Prestemon[1], Jeremy Weiss[2,3] and Danko van der Laan[2,3]

ACT - Tape-to-tape joint / “dropout”





TITO – Tape In Tape Out

- Moved to more "direct method" of extracting contact resistivity
  - Recreating work by Virginia Phifer and Lance Cooley
    - See similar measurements by Twente
  - Measure voltage between individual tapes - $R_{CT}[\Omega m^2] \sim \frac{\Delta V A_{overlap}}{I}$

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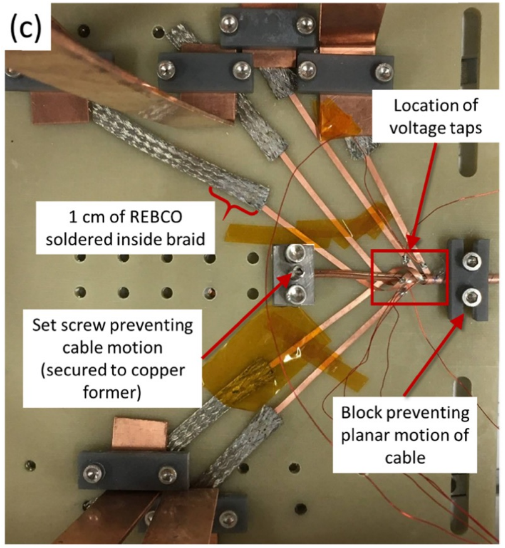
Superconductor Science and Technology
Supercond. Sci. Technol. **35** (2022) 065003 (11pp)
https://doi.org/10.1088/1361-6668/ac662f

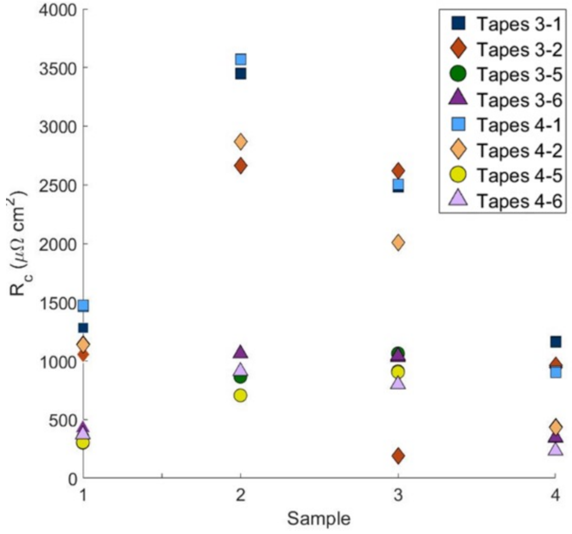
Investigations in the tape-to-tape contact resistance and contact composition in superconducting CORC® wires

Virginia Phifer[1,2,*], Michael Small[1,2], Griffin Bradford[1,2], Jeremy Weiss[3,4], Danko van der Laan[3,4] and Lance Cooley[1,2]

Table 4. Contact resistance results ($\mu\Omega$ cm^2).

CORC® wire	Straight	After bending to 10 cm diameter
CO	1300 ± 1000	403 ± 63
NL	160 ± 80	35 ± 13
HC	41 ± 25	13 ± 5
PbSn Before HT	2 ± 0.4	0.8 ± 0.1
PbSn After HT	0.7 ± 0.4	0.6 ± 0.1





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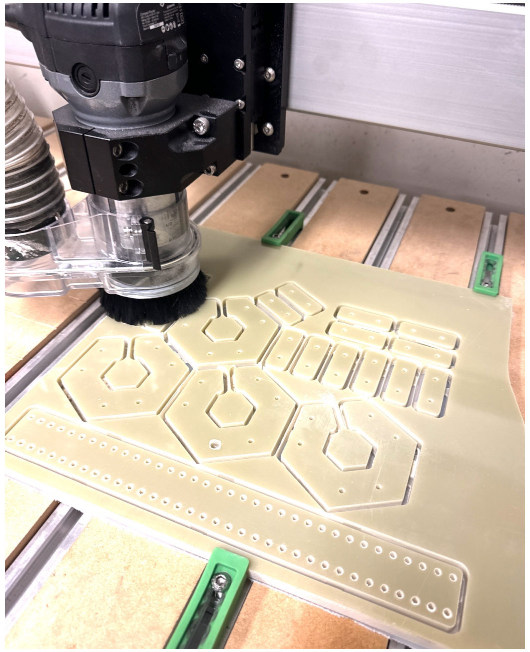
Supercond. Sci. Technol. **33** (2020) 085009 (14pp)
https://doi.org/10.1088/1361-6668/ab97ff

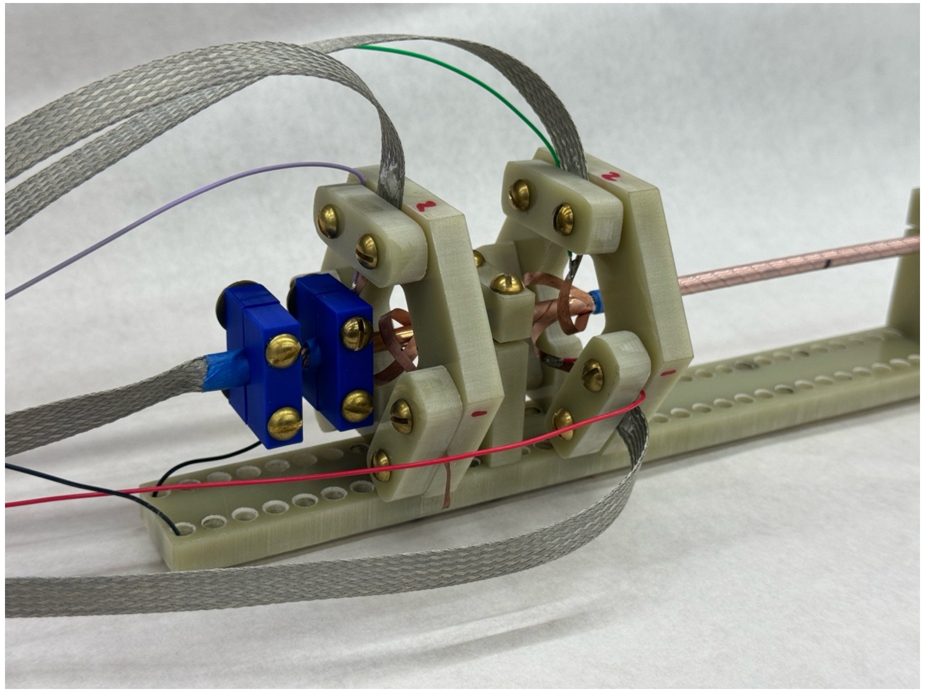
AC loss and contact resistance in REBCO CORC®, Roebel, and stacked tape cables

K Yagotintsev[1], V A Anvar[1,2,6], P Gao[1], M J Dhalle[1], T J Haugan[3], D C Van Der Laan[4], J D Weiss[4], M S A Hossain[2,5] and A Nijhuis[1]

Terminations for Individual Powering

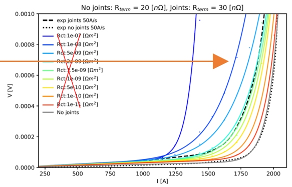
- Designed and fabricated a fixture for individual tape powering
  - Practiced full procedure on 6-tape CPRD CORC cable
    - Thanks CPRD + Ian + Lance!

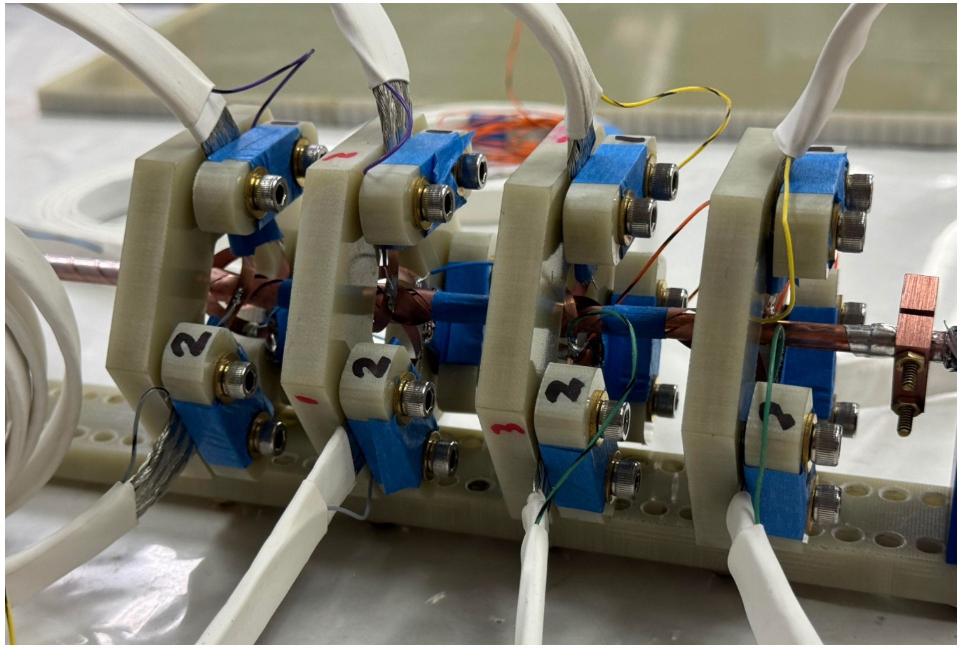


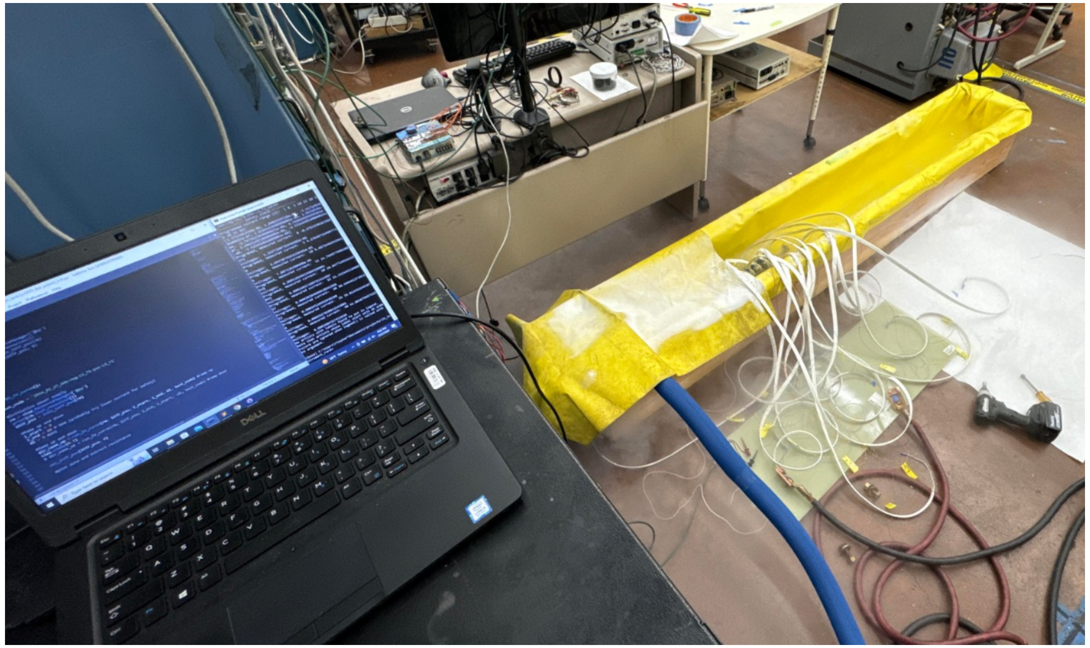


TITO experiments

- Used ACT no-defect control cable for TITO measurements
  - ~1 m, 12 tape, current injection / extraction on same side
  - Manually swapped leads and taps, powered 0->40 A: Need to automate!

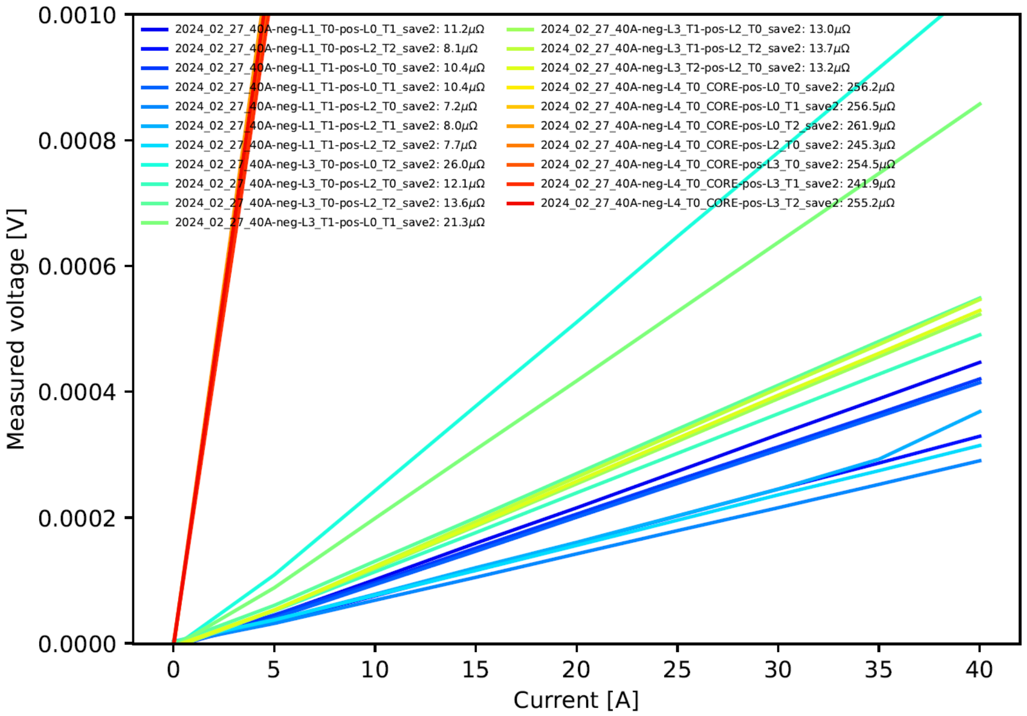


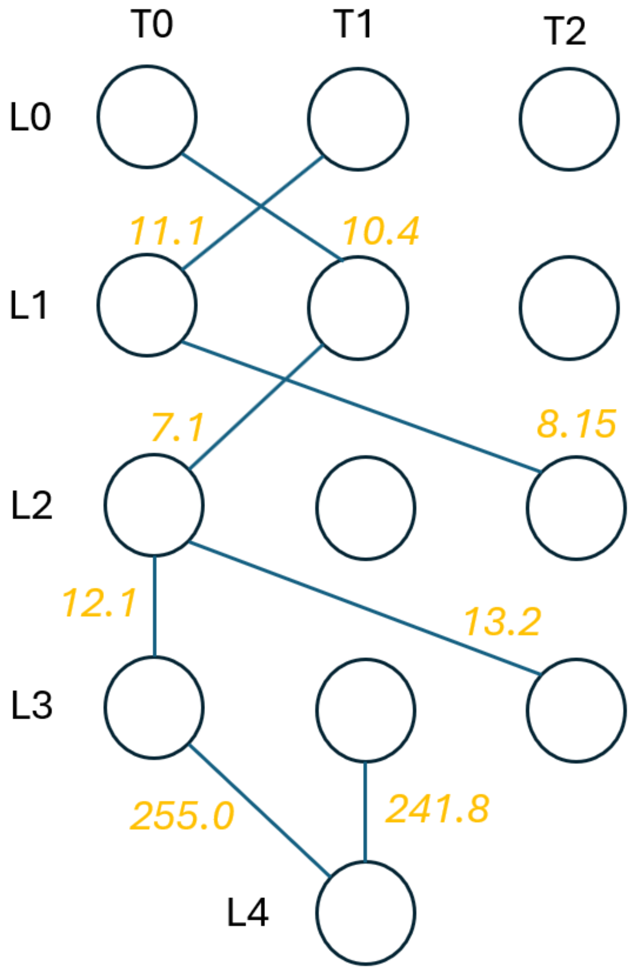




TITO Measurements

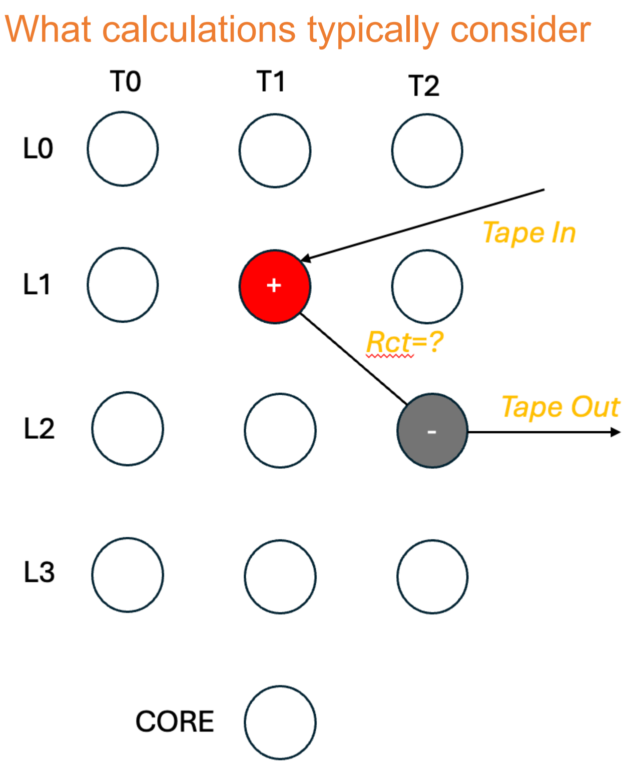
- Yellow text is measurement $R = \frac{V_{in} - V_{out}}{I_{psu}}$ $[\mu\Omega]$
  - Lower Resistance on layers with more neighbors

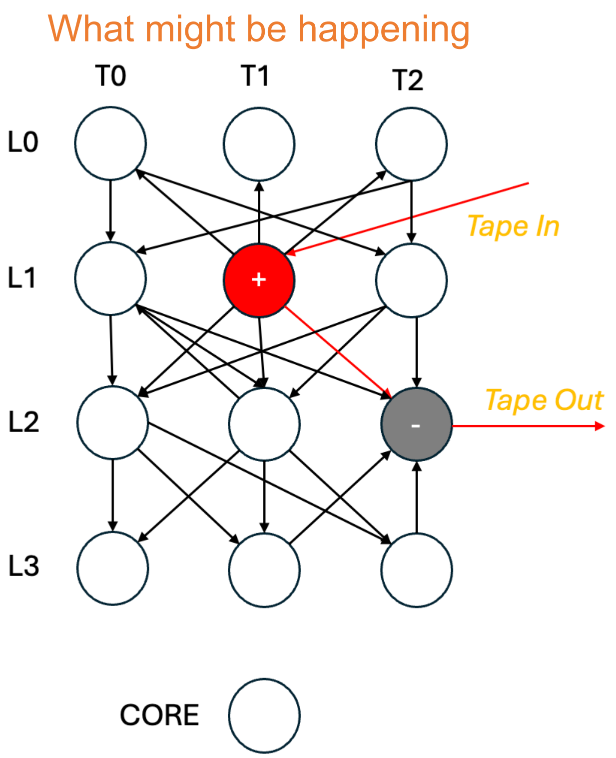




Percolation of Current

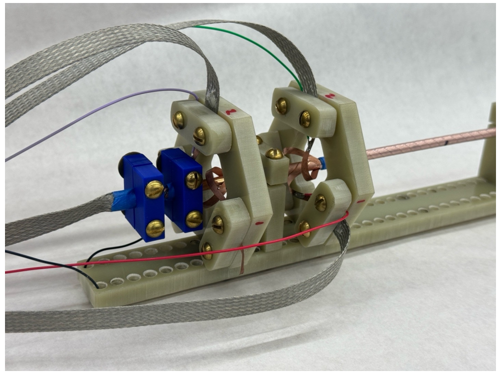
- Previous figure suggests current percolation effects need to be considered in these experiments

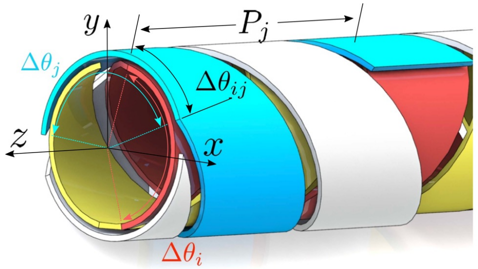


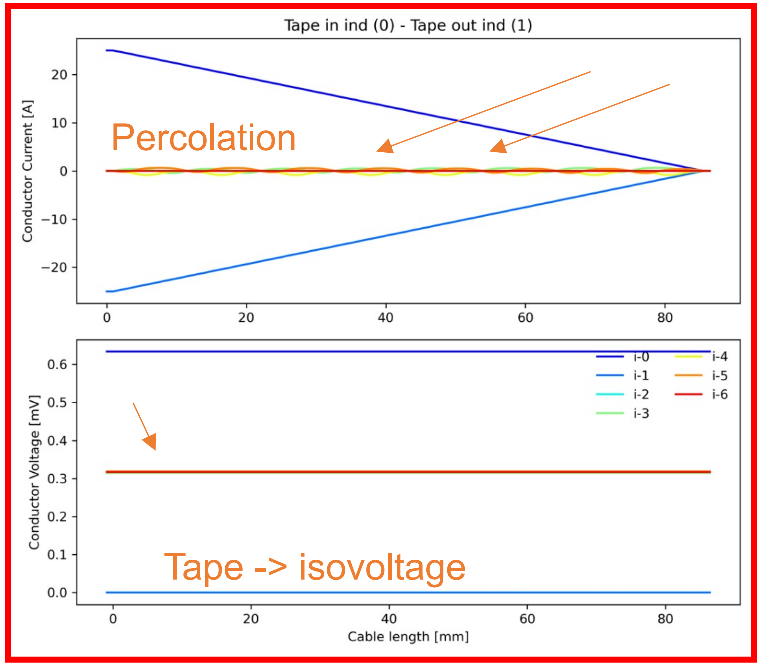


Modeling TITO Expeirments

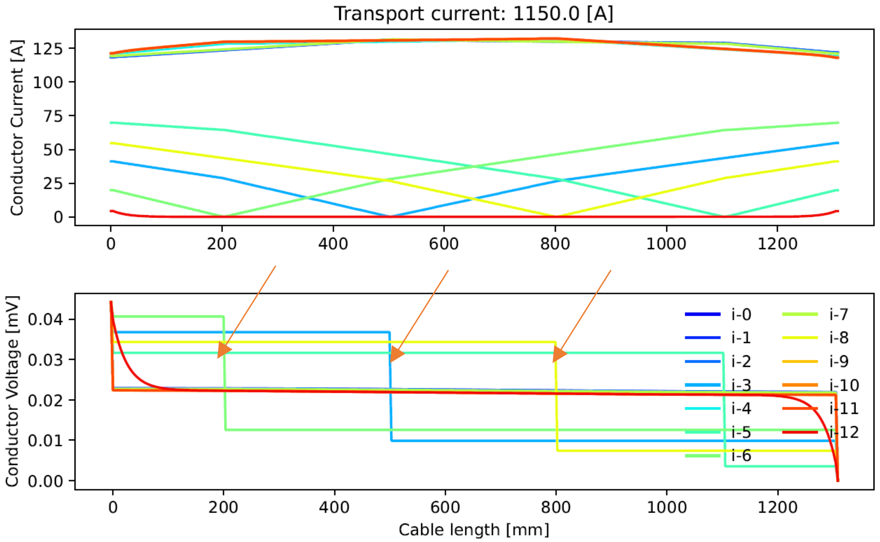
- Network model setup for short CPRD TITO experiment
- Both TITO experiments and CORC cables with (intentional!) dropouts seem almost entirely governed by linear resistive current sharing and terminations
  - Can we neglect superconductivity in modeling these (niche) superconducting cables?







Prior network model simulation w/ 4 dropouts
~ constant tape voltage between defects / joints!

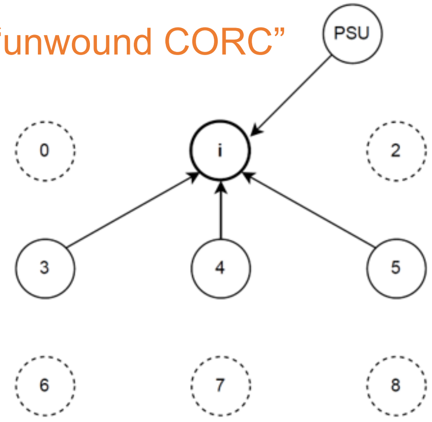


Percolation Model

- Prior model of 100mm cable motivated additional modeling
- What is the single tape voltage that balances current?
  - Write expression for current sharing to 3 tapes above, 3 tapes below
  - Repeat to build 12x12 matrix system $[1/R][V] = [I_{psu}]$
- Finite-difference Newton-Rhapson of this solution to find $R_{ct}[\Omega m^2]$
  - x is contact resistivity, $f(x) = V_{sim} - V_{exp}$

Percolation model Ax=b

“unwound CORC”



$$0 = \sum_{j=0}^{8} \frac{V_j - V_i}{R_{i-j}} + I_{i,psu}$$

Contact resistivity & total area between tapes

$$-I_{i,psu} = -V_i\left(\frac{1}{R_{0i}} + \frac{1}{R_{1i}} + \frac{1}{R_{2i}}\right) + \frac{V_0}{R_{0i}} + \frac{V_1}{R_{1i}} + \frac{V_2}{R_{2i}}$$

Voltage of tape i as function of voltage of neighboring tape voltages

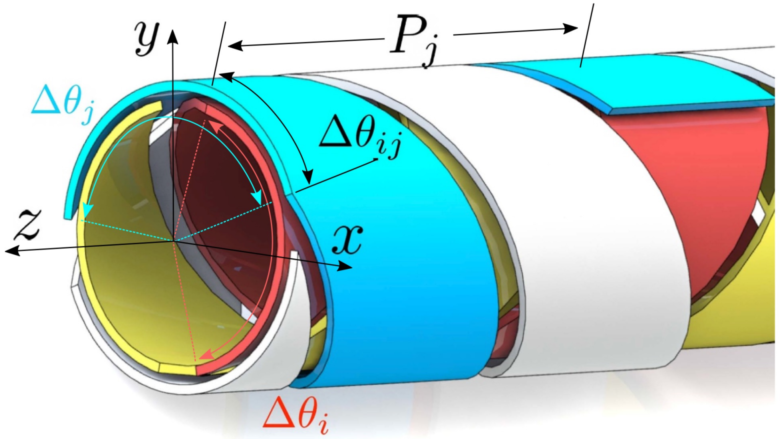
Iterative solver of Ax=b to extract Rct

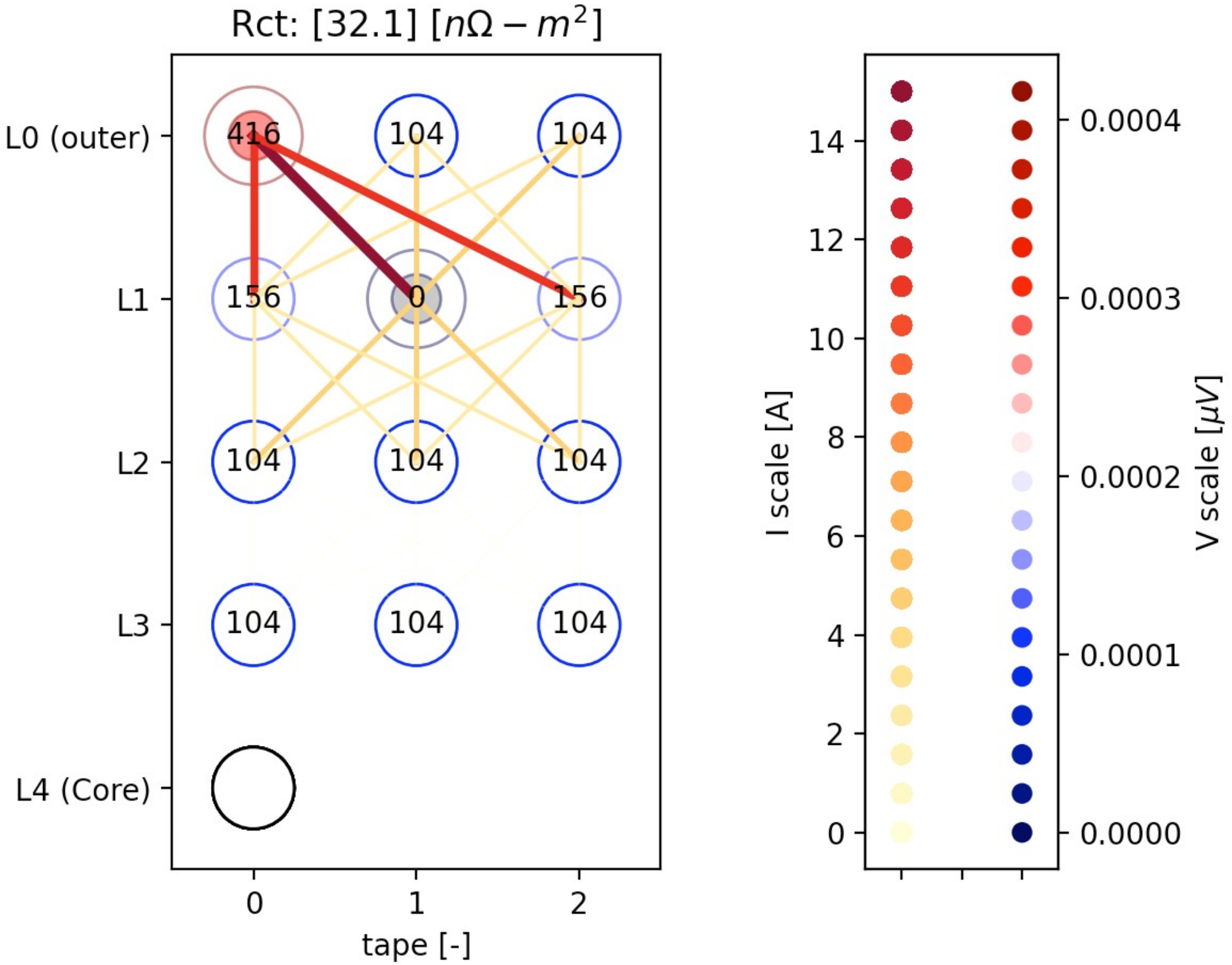
$$x_1 = x_0 - \frac{f(x_0)}{f'(x_0)}$$

$$x_1 = x_0 - \frac{\Delta x * f(x_0)}{f(x_0 + \Delta x) - f(x_0)}$$

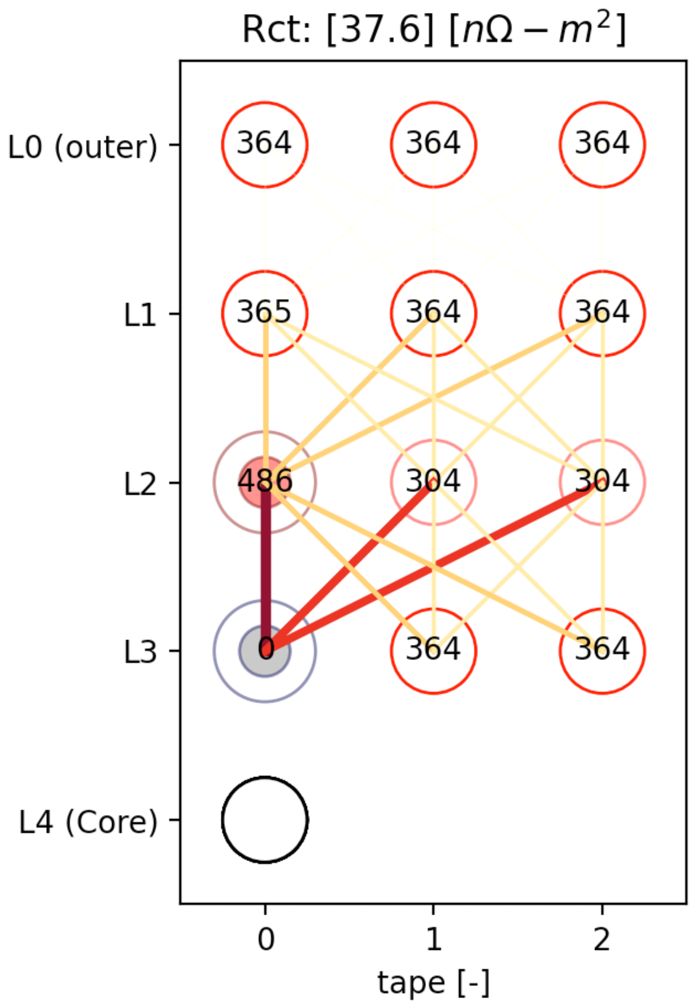
TITO Results

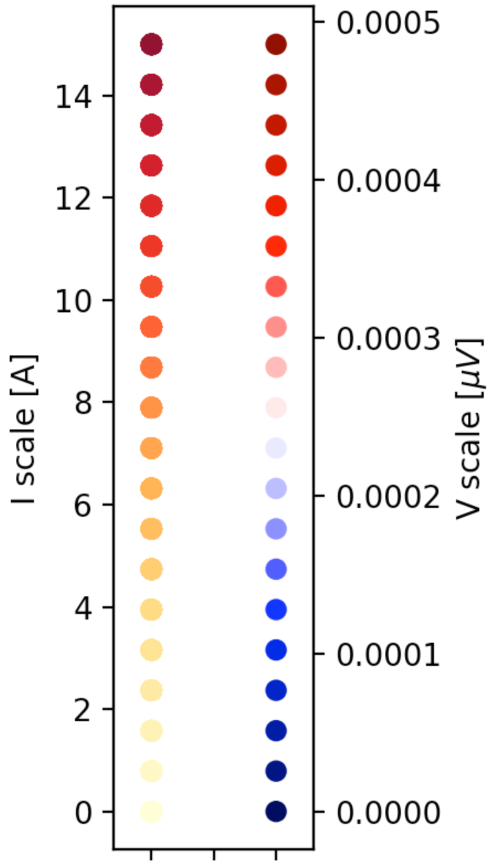
- Circles are individual tapes
- Line width, line color shows current between given tapes
- Circle color shows tape voltage (microvolts)
- Solid red, gray are in, out tapes



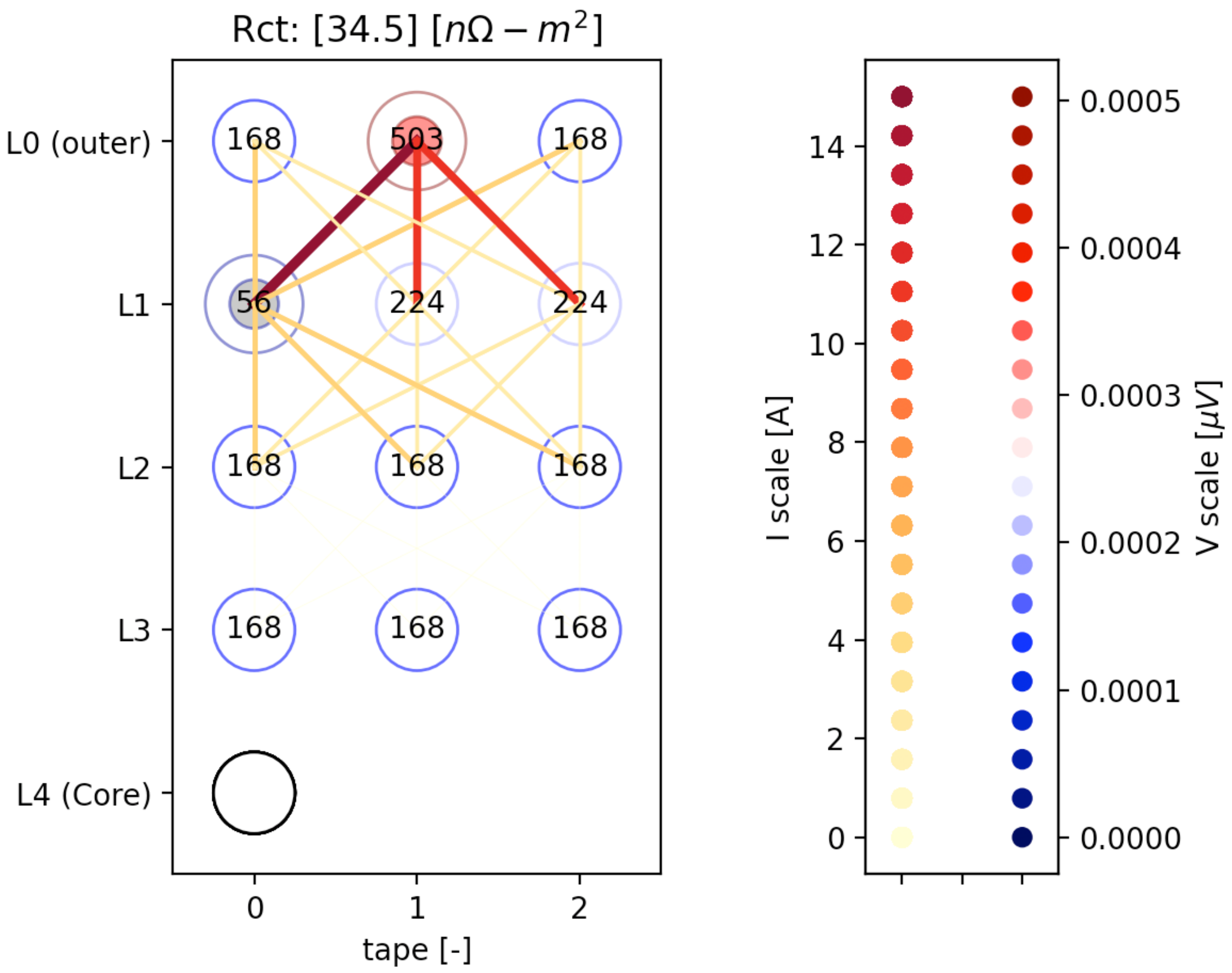


TITO Results





TITO Results



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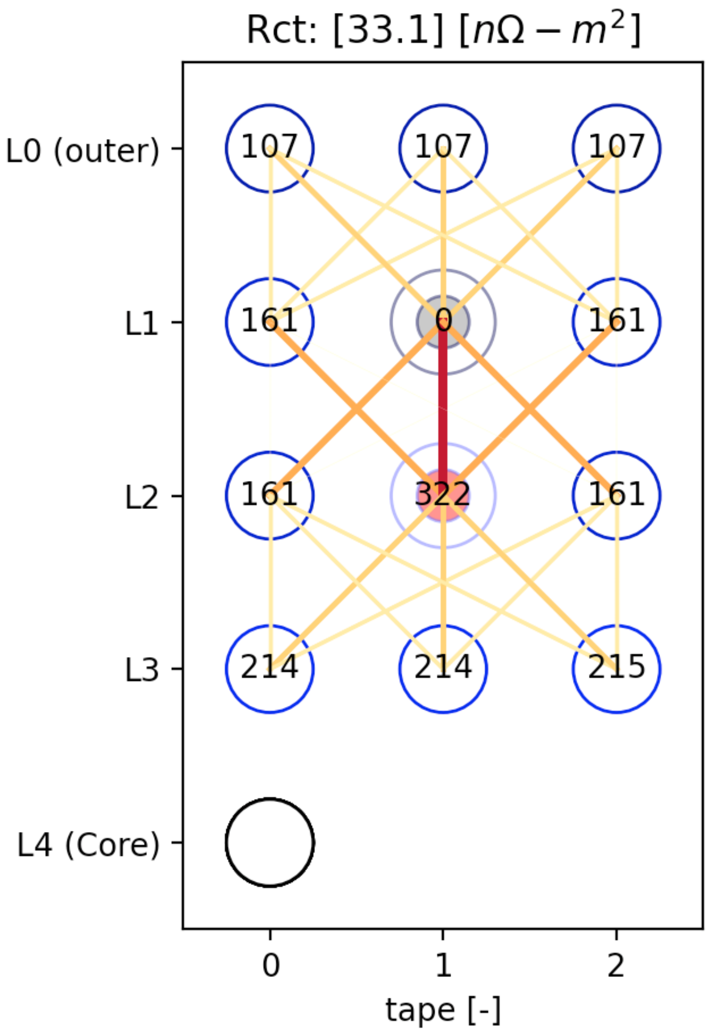

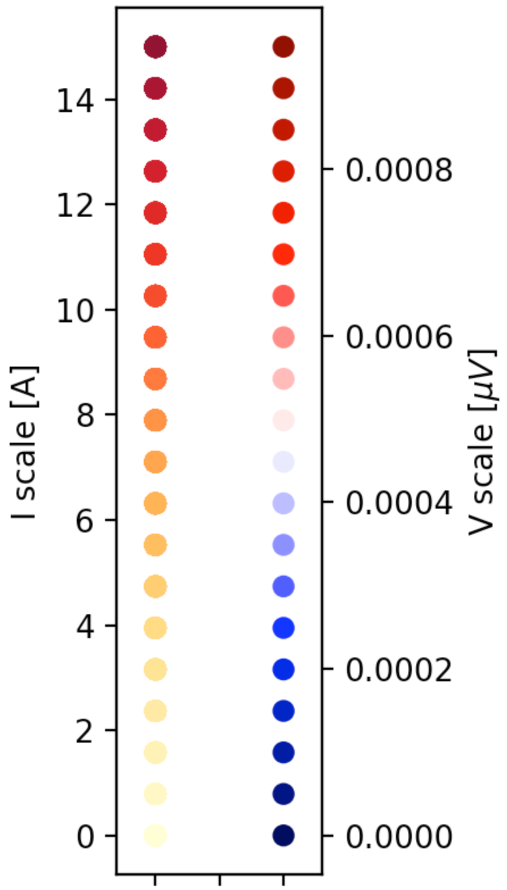

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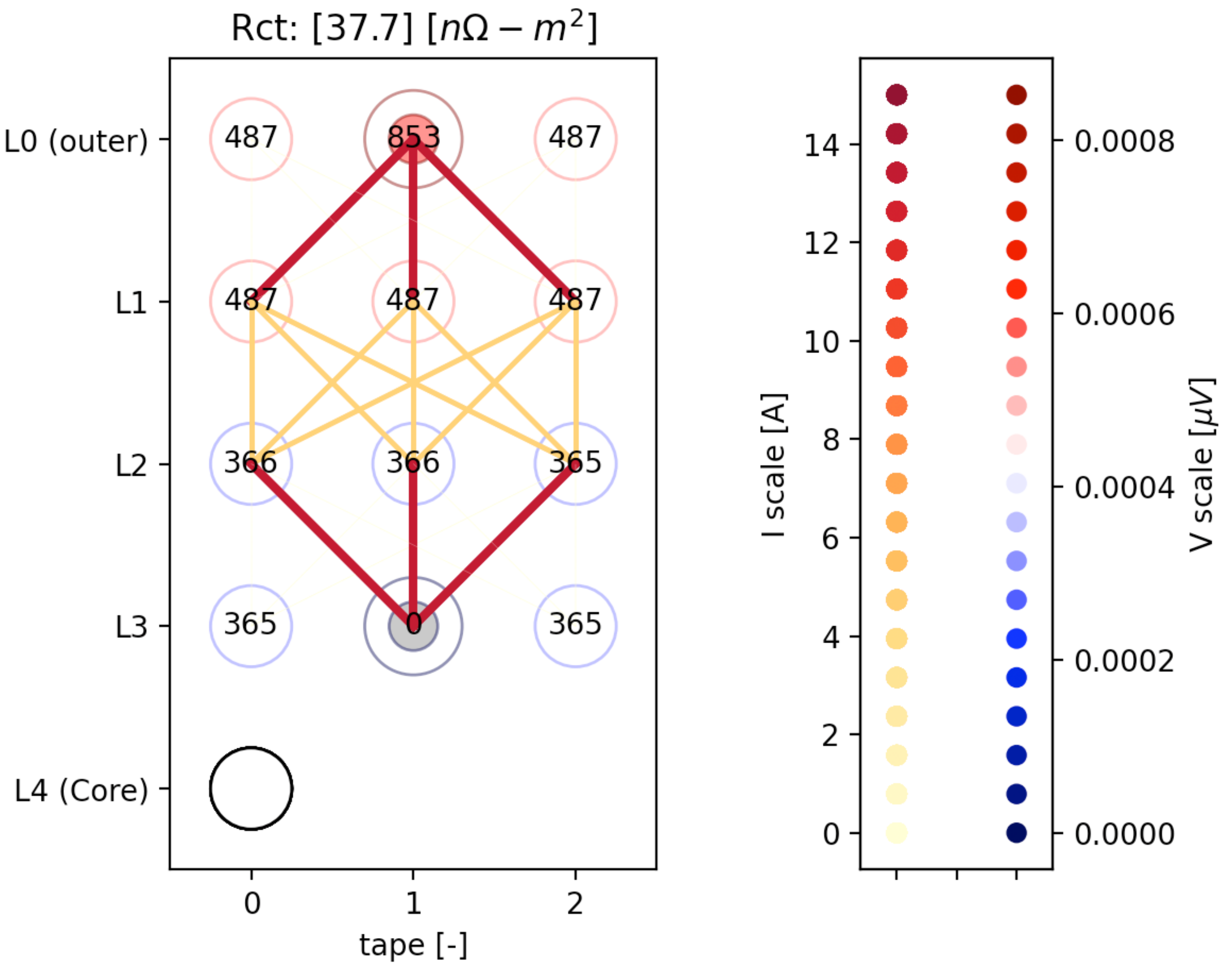
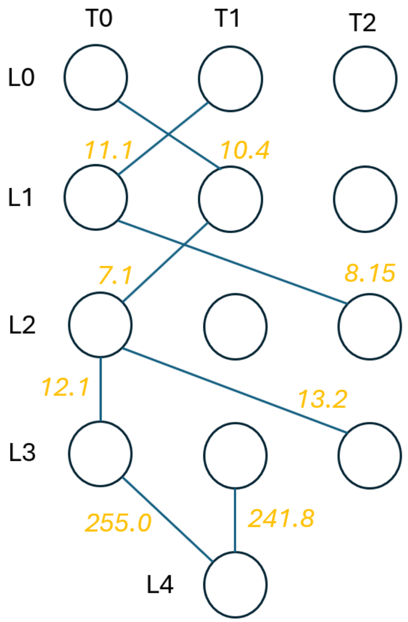
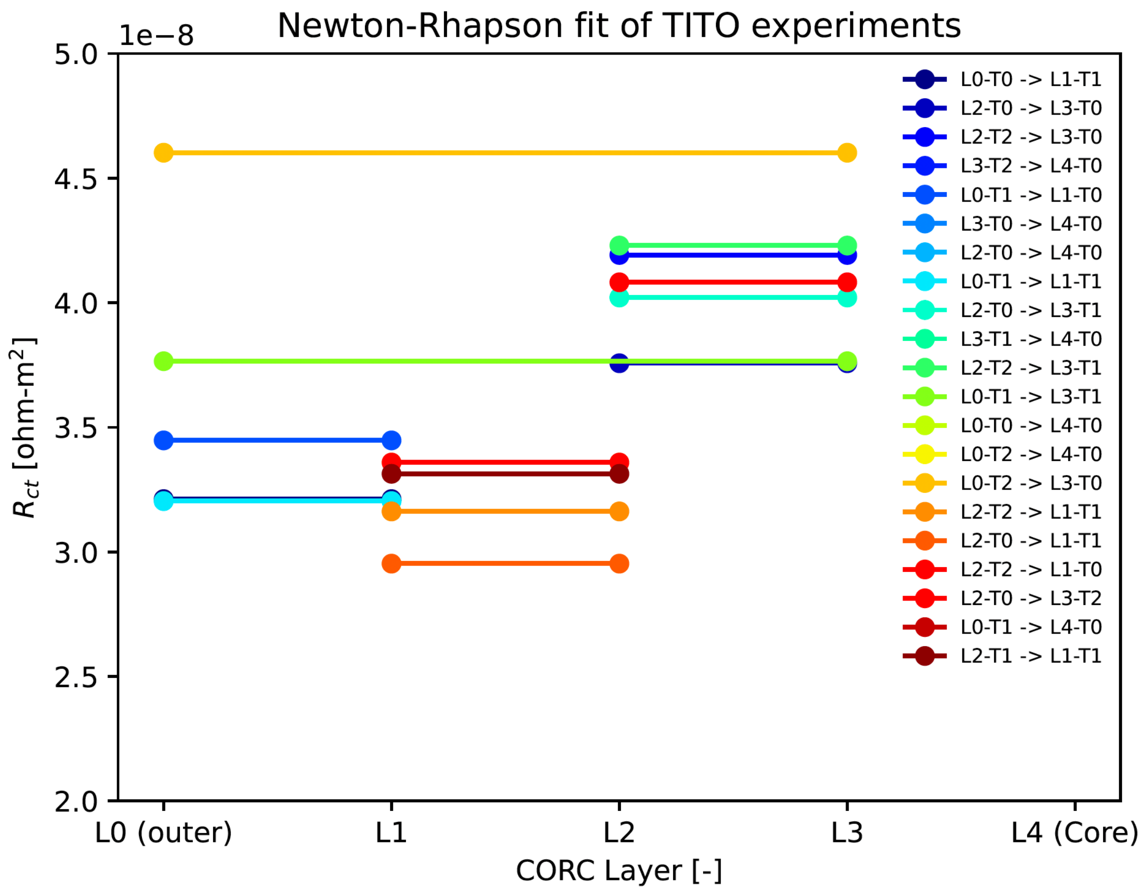


Layer Dependent Resistivity

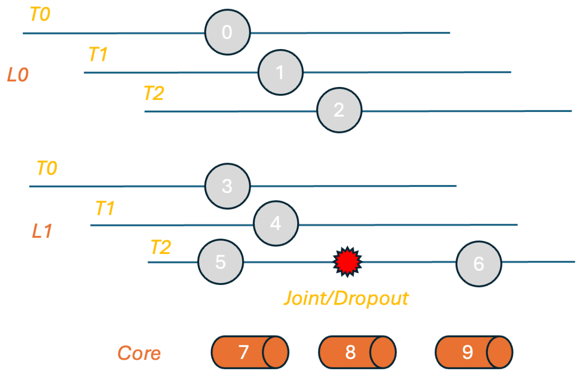
- Appears that layer-dependent contact resistivity can now be resolved in-situ
  - Results from single cable suggest higher contact resistivity in inner layers

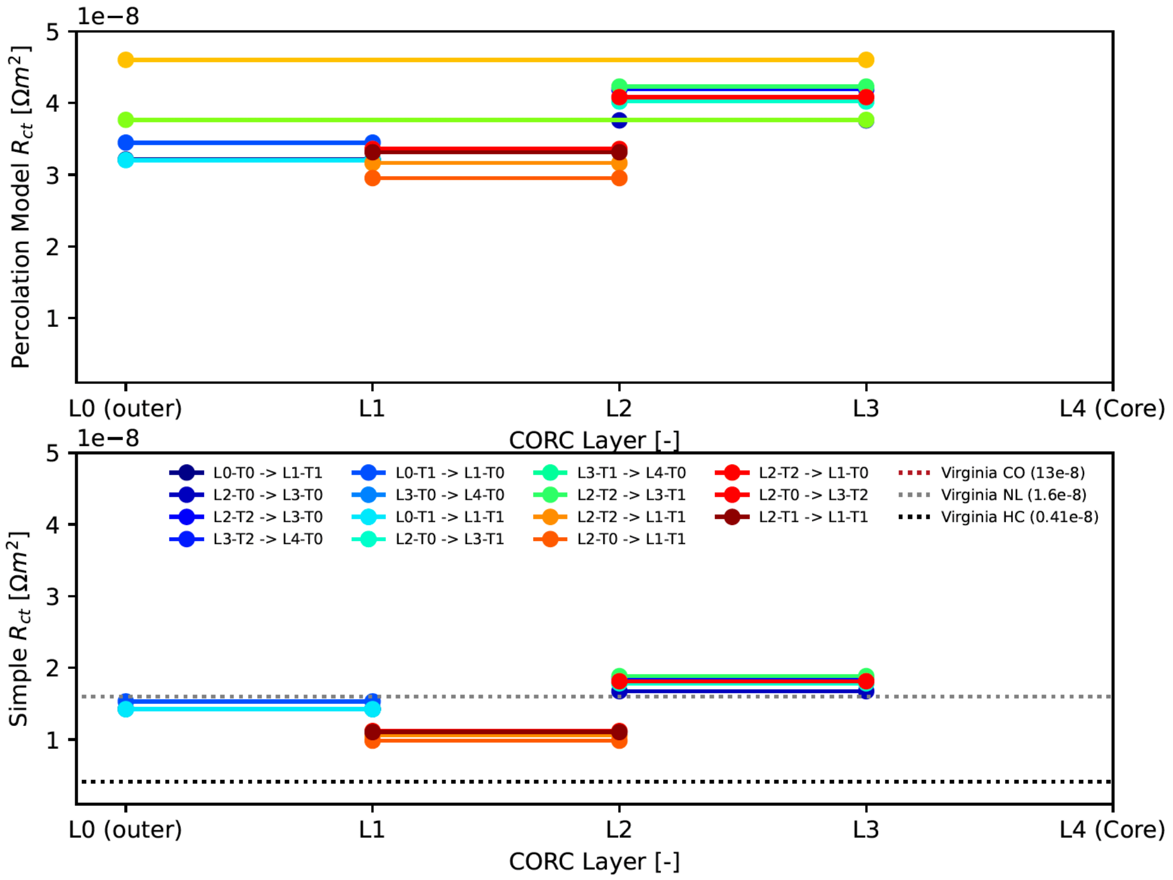




The impact of percolation

- Results suggest importance of considering percolation effects for in-situ contact resistivity measurements in HTS cables
  - Factor of 3 difference here, drives heating in cables with defects
- This concept serves as the basis for a possible new, fast way to model CORC cables with defects (hopefully get phase 2)





Disclaimer

- Very thankful for all the prior work done to date in this area (Virginia + Lance, Twente,…)
  - This effort was initiated out of respect for their work, after I did not succeed in extracting resistivity from network model fit to two cable I-V curves
  - Non-percolation approach great for relative comparison of different cable winding approaches, which is most useful
    - *E.g. impact of different lubricants, solder-coated, bending effects – et cetera*
  - I should be careful here as well as I need to spend more time developing percolation model and testing more cables!

Summary

- Work by ACT in Phase 1 shows encouraging results for being able to build and operate CORC cables consisting of full, intentional defects (not discussed today)
- Tape-in-tape-out experiments reveal a lot of interesting information about the cable under test, many possibilities as cable quality control / magnet post mortem
- Numerical method developed to account for current percolation in TITO experiments, extracting contact resistivity in-situ for any layer under test (think – diagnostic for real time measurement as cable is bent)
- Contact resistivity consistent with previous cables, however current percolation considerations suggest significantly higher values (i.e. internal heating) than previously shown
- The approach for considering percolation in TITO experiments is promising as the kernel for a new, fast modeling approach for CORC cables driven by defects / dropouts / joints which will be explored (hope to get phase 2)
- Thanks to ACT for including me in their research – they did the "heavy lifting" here

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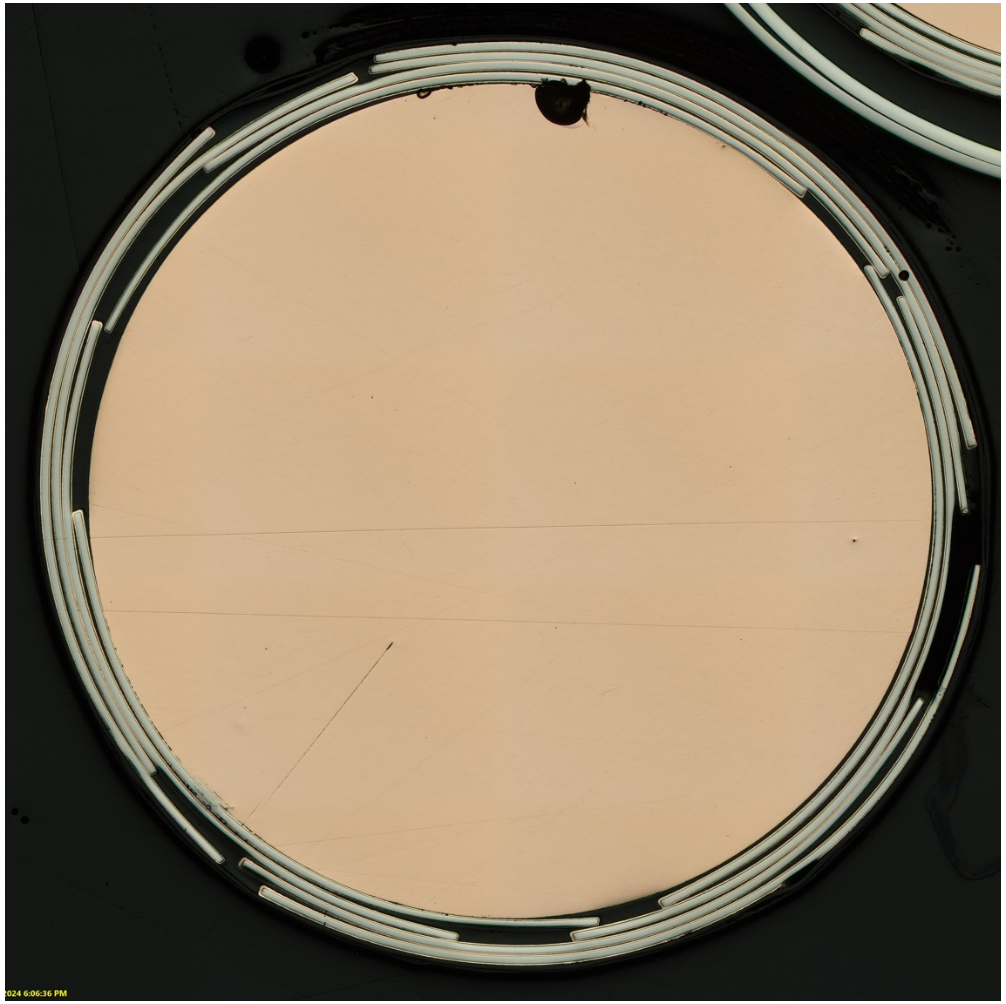
Thanks



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