Contact resistance and current sharing in superconducting cables

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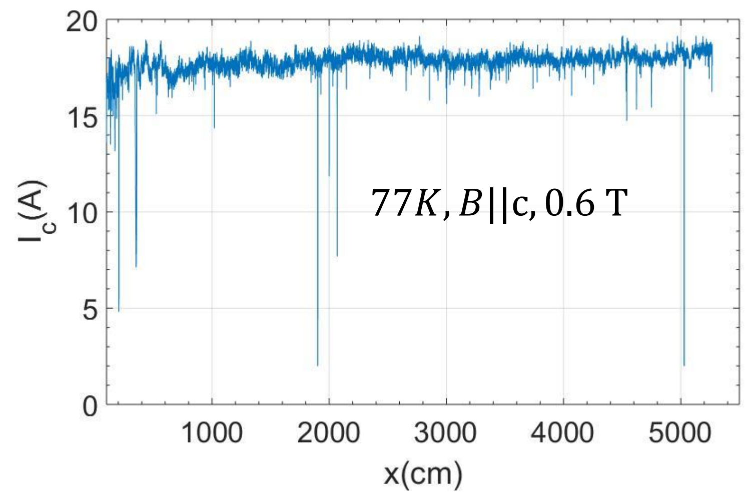
Problem: I_c dropouts along conductor length

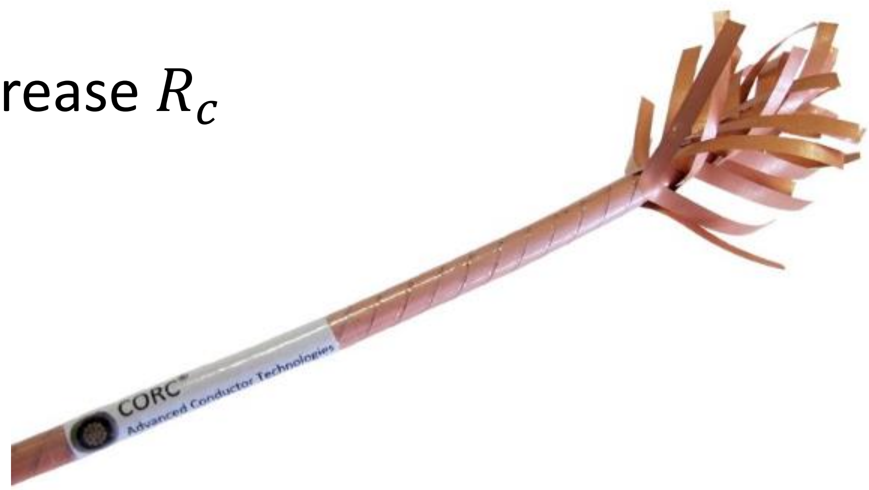
- Inevitable defects in REBCO manufacturing
  - Drops in I_c along length
- Magnet design
  - Minimize hot spot formation
  - Use best pieces of conductor
  - Frequency of I_c drops > Frequency of long defect free tapes
- Promote current sharing
  - Current bypass local I_c drops
  - Use variable I_c (VIC) tapes in winding
  - Increased yield of viable tapes



What frequency of I_c drops can we tolerate?

Conductor on Round Core (CORC®) Cables

- Manufactured by Advanced Conductor Technologies (ACT)
- Flexible cables
- Multiple layers of REBCO tapes
  - Wound around Cu core
- Current sharing depends on tape-to-tape contact resistance R_c
- Promoting flexibility could increase R_c
  - Lubricated tapes
  - Not soldered



R_c and Current Sharing in CORC® Cables

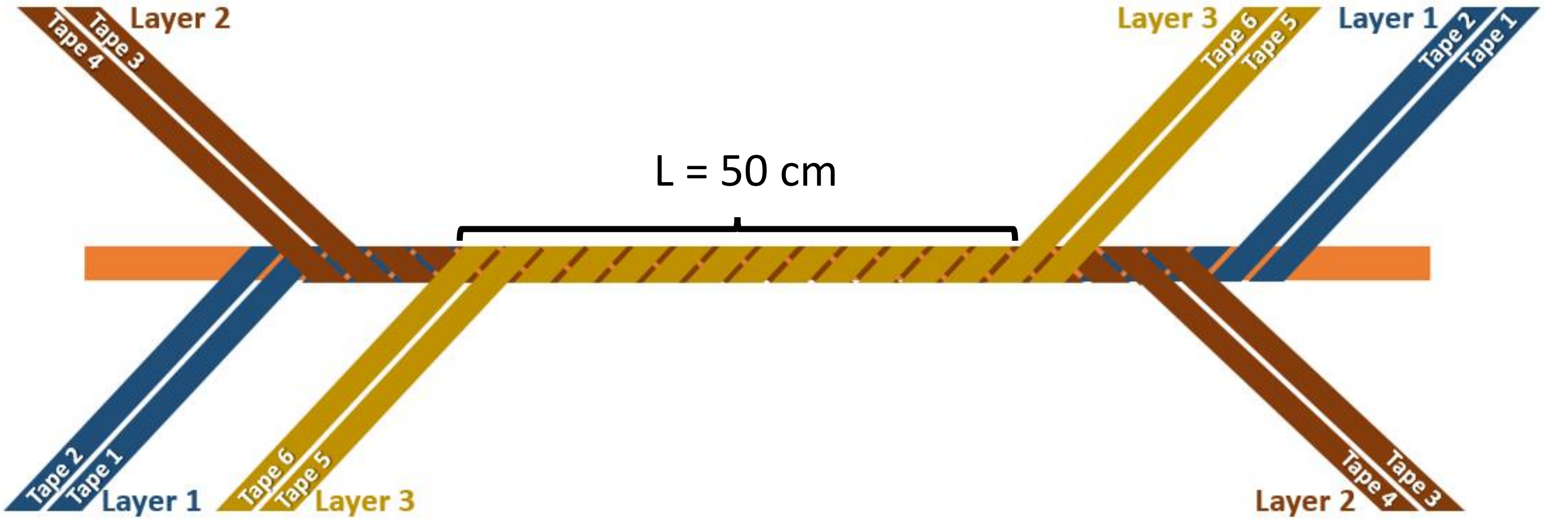
- How do winding parameters affect R_c?
- Is R_c low enough to promote current sharing?
  - Over what length?
  - 1 m long samples → comparable to 1 coil turn

4 CORC® Cables Constructed by ACT

Cable	Winding Tension (N)	Winding Lubricant
Control Cable (CO)	Normal	Normal
High Tension Cable (HT)	50% higher	Normal
No Lubricant Cable (NL)	Normal	None
High Conductivity Lubricant (HC)	Normal	High Conductivity

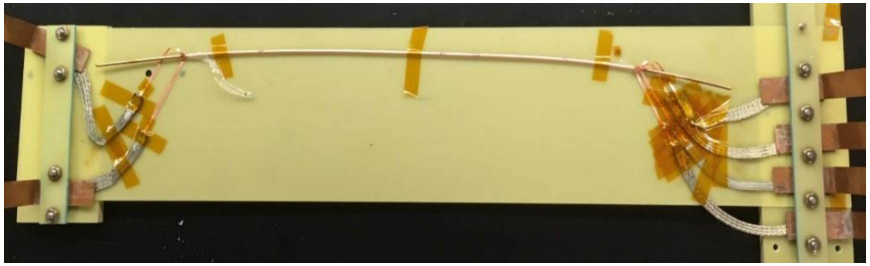
Cable Geometry

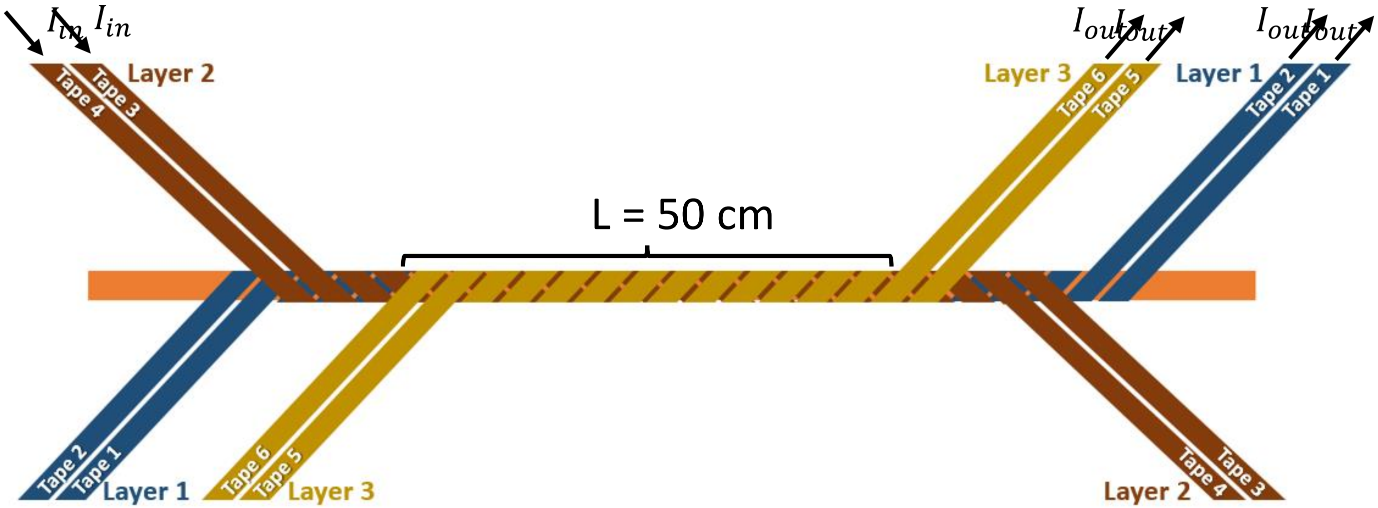
- 2 mm wide Superpower tapes
- 2.78 mm diameter Cu former
- 3 Layers
- 2 tapes per layer



R_c Measurement (SF,77 K)

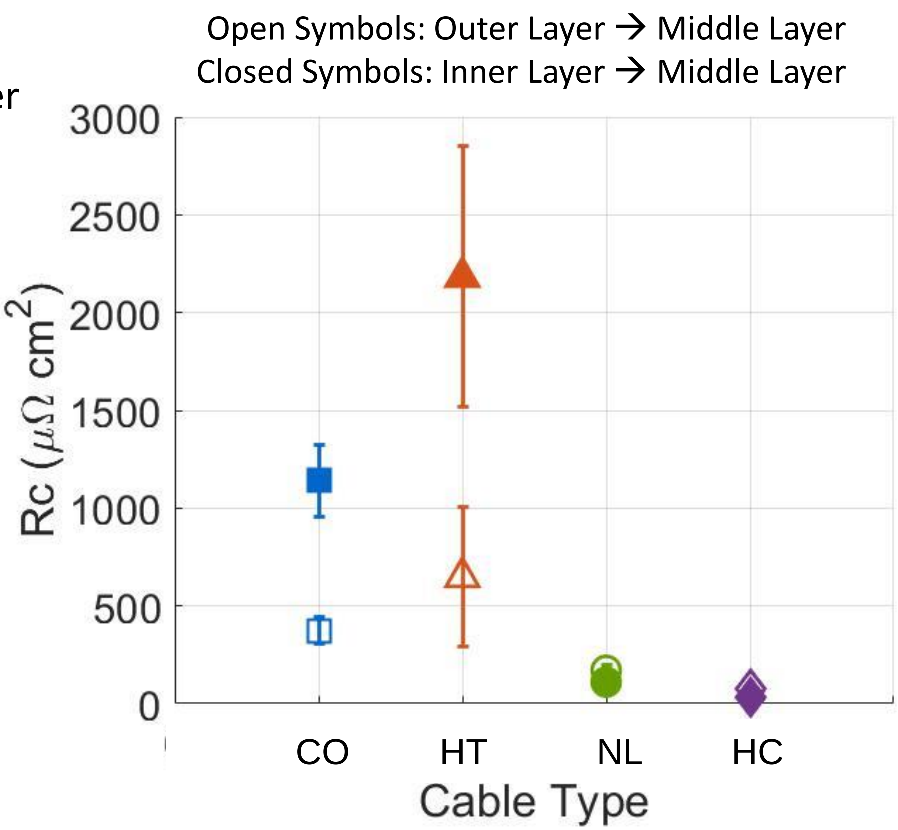
- Forced current to transfer between tapes
  - I_{in} Layer 2
  - I_{out} from Layer 1 and Layer 3
- Ramp current to 10 A
- Determine R_c from V(I) curves





R_c Results

Cable	Average R_c $(\mu\Omega \cdot cm^2)$ Inner Layer	Outer Layer
Control	1140	373
High Winding Tension	2182	648
No Lubricant	110	176
High Conductivity Lubricant	36	73



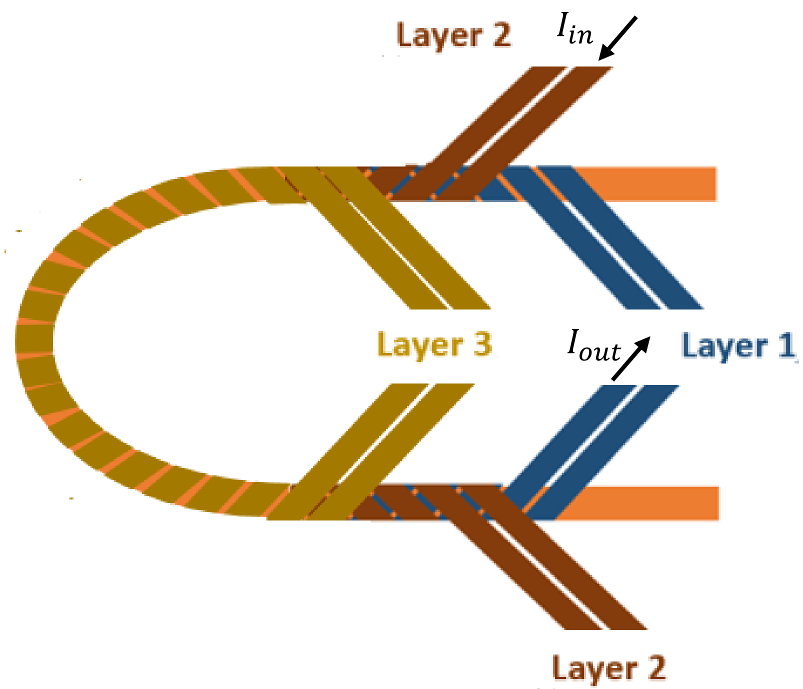
- Best REBCO-REBCO lap joints[1]
  - $R_c \sim 0.1\ \mu\Omega \cdot cm^2$
- ReBCO-Substrate under pressure 2.4-144 MPa[2]
  - $R_c = 20 - 100\mu\Omega \cdot cm^2$

1. H. W. Weijers, W. D. Markiewicz, A. V. Gavrilin, A. J. Voran, Y. L. Viouchkov, S. R. Gundlach, P. D. Noyes, D. V. Abraimov, H. Bai, S. T. Hannahs et al., "Progress in the development and construction of a 32-t superconducting magnet," IEEE Transactions on Applied Superconductivity, vol. 26, no. 4, pp. 1–7, 2016.
2. J. Lu, R. Goddard, K. Han, and S. Hahn, "Contact resistance between two rebco tapes under load and load cycles," Superconductor Science and Technology, vol. 30, no. 4, p. 045005, 2017.

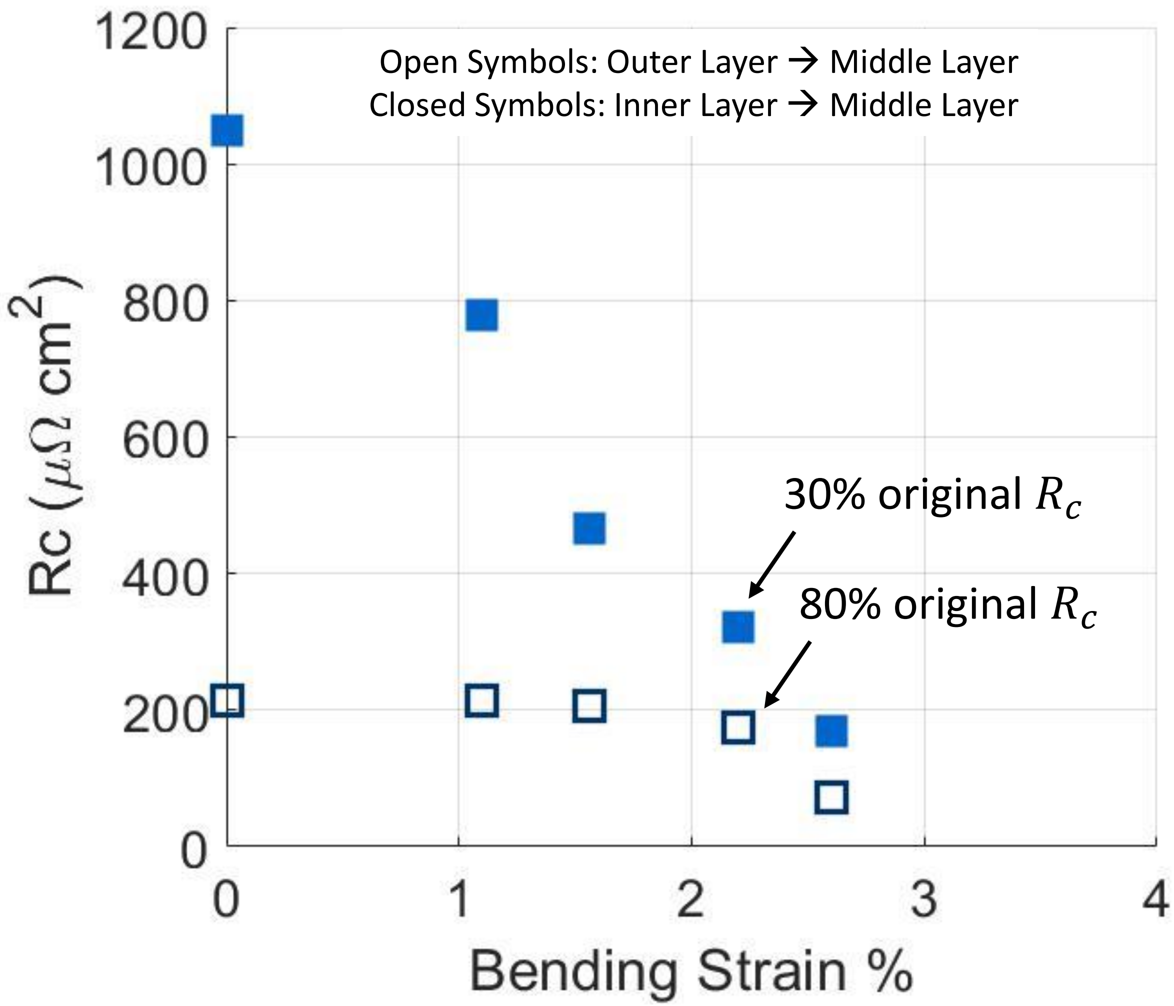
Effects of Cable Bending on R_c

- Performed the same R_c measurements
- 77 K, Self-field
- Ramp current to 10 A
  - I_{in} Layer 2
  - I_{out} from Layer 1 and Layer 3

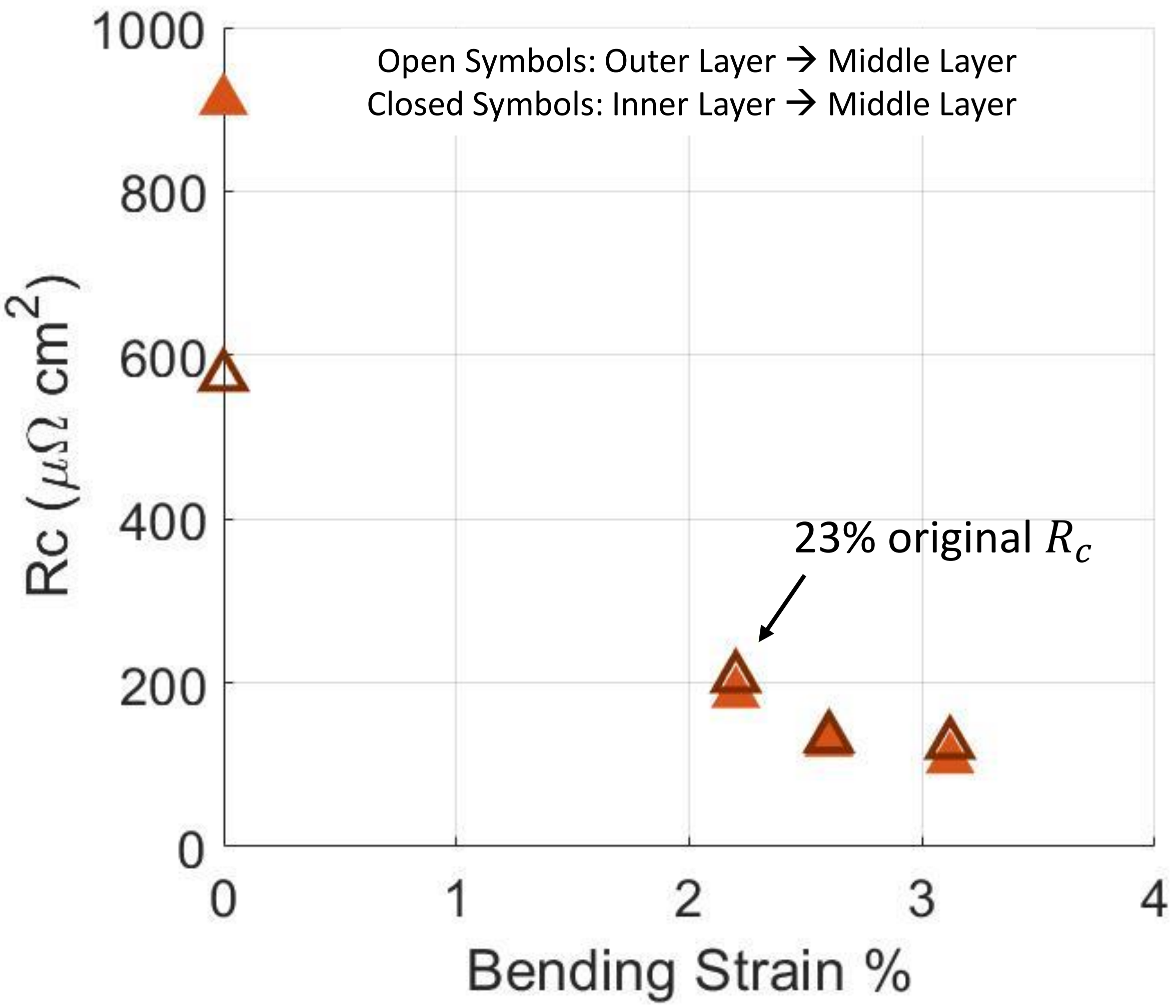
Bending Diameter (cm)
26
20
14
12
10



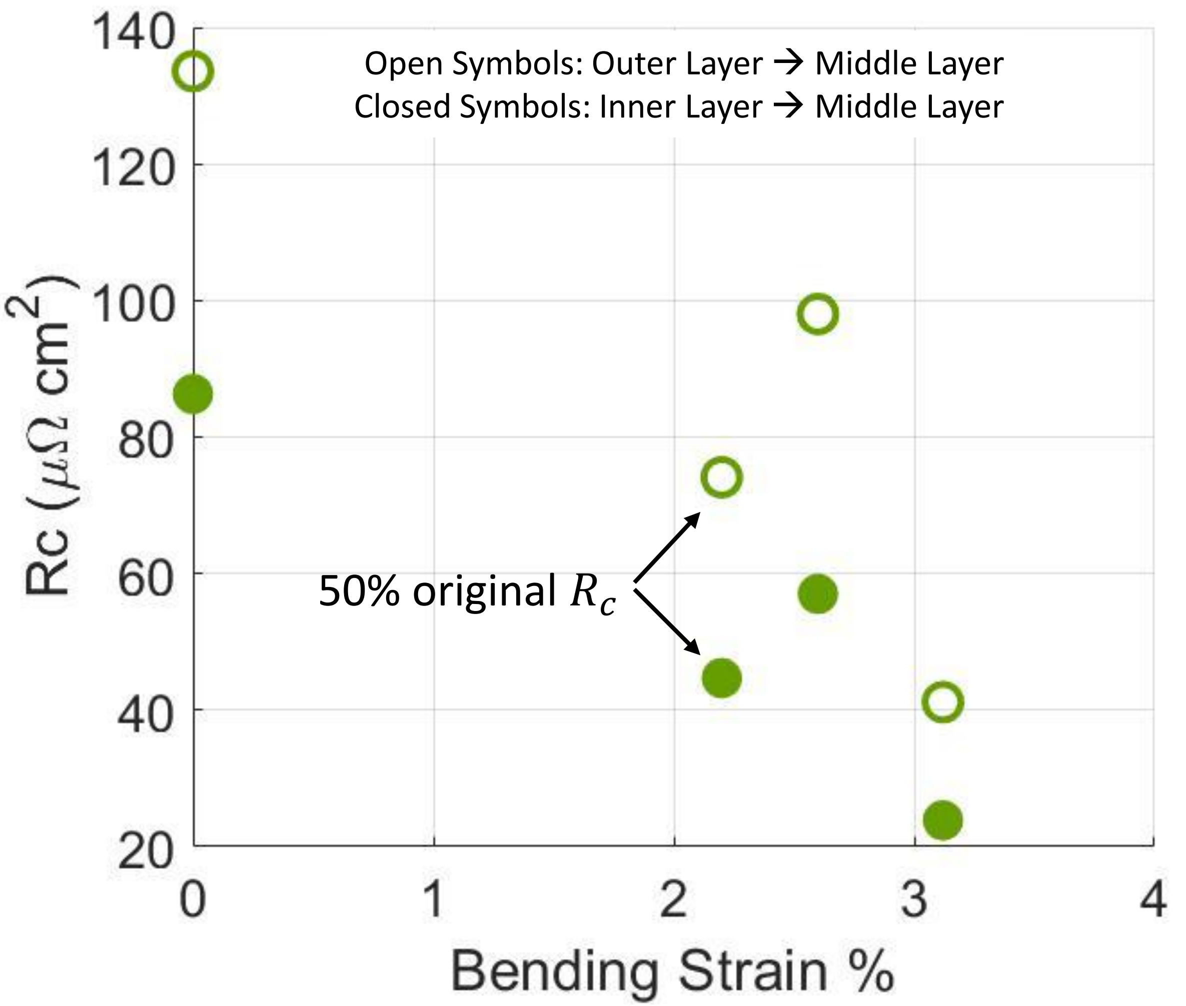
R_c in Control Cable



High Tension Cable



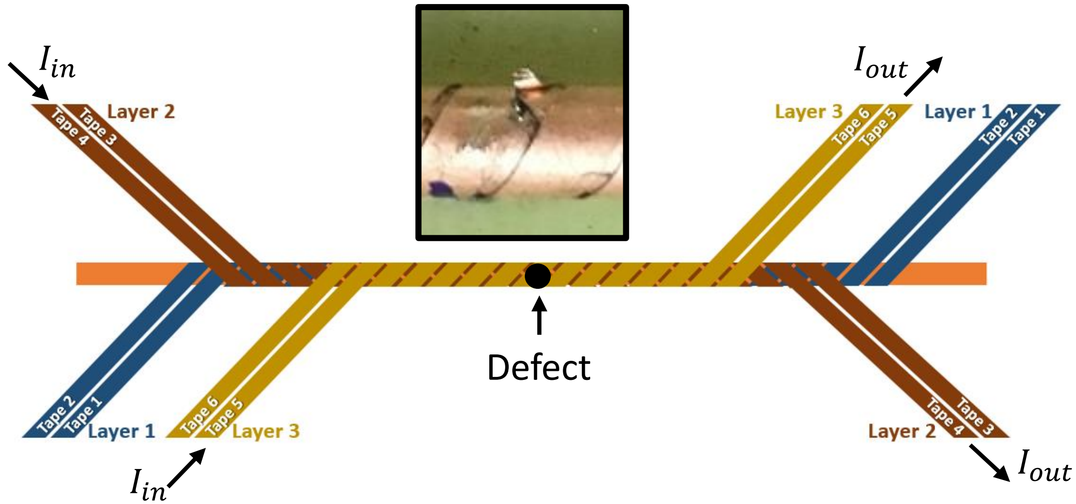
No Lubricant Cable



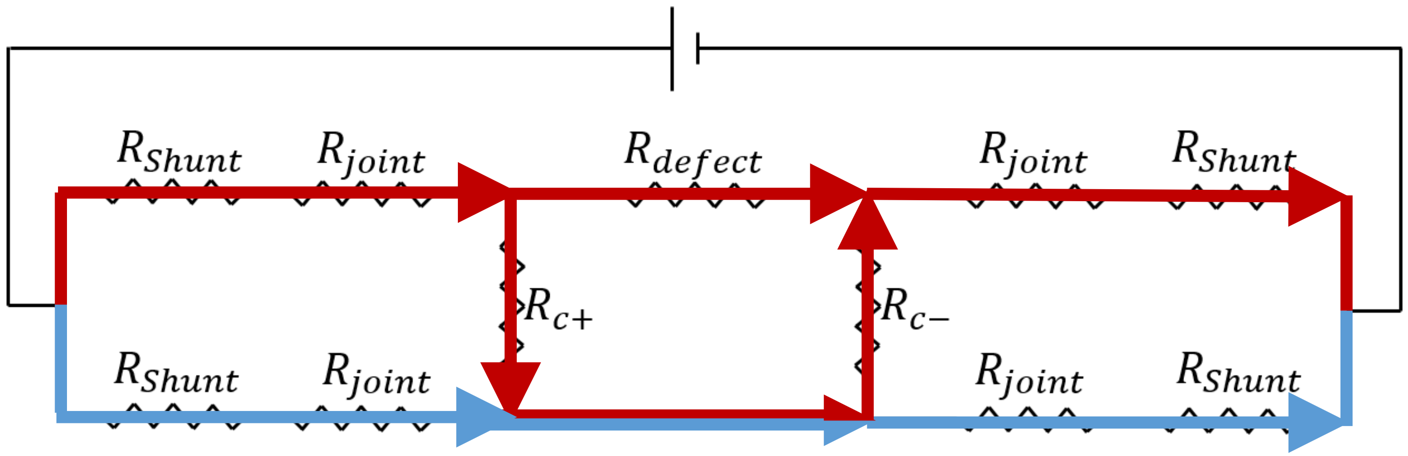
So What happens if there is a defect?

- Created defect in Tape 5 of HC cable
  - Decreased tape width by $\approx 50\%$
  - Decrease Local I_c by $\approx 50\%$
- Energize "Good" and "Defect" tapes in parallel

How will the current transfer between tapes?

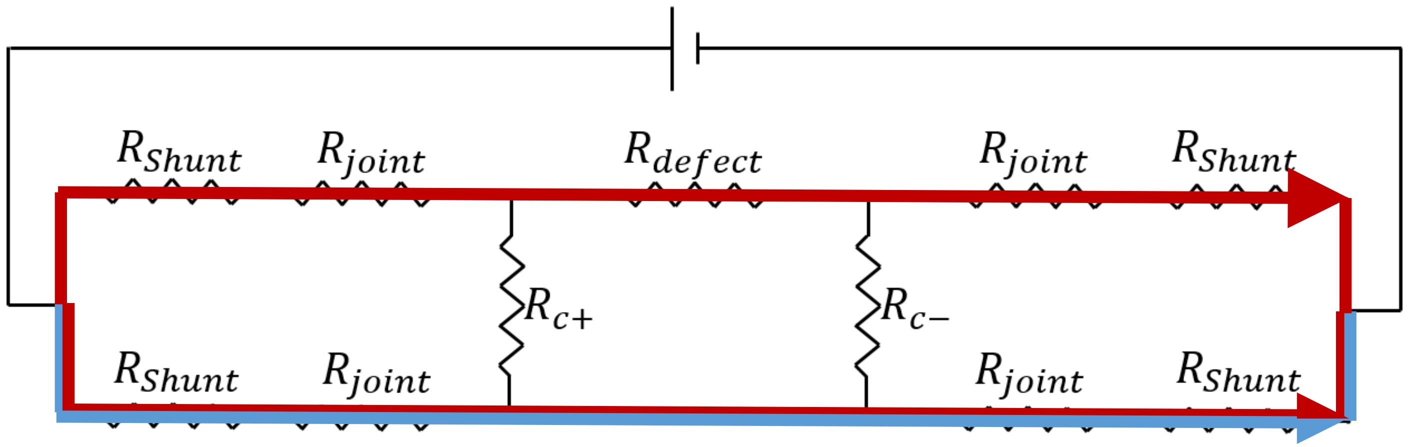


Current Bypass Defect?



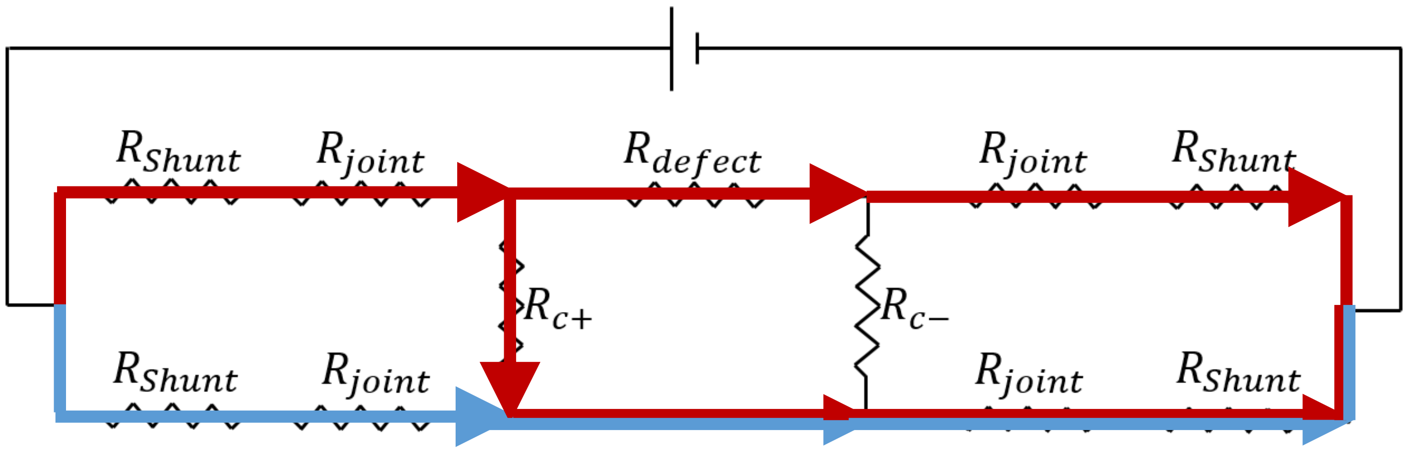
- Current split evenly between tapes
- Current > defect Ic transfer to good tape
- After defect current transfer back

Current Transfer at Leads?



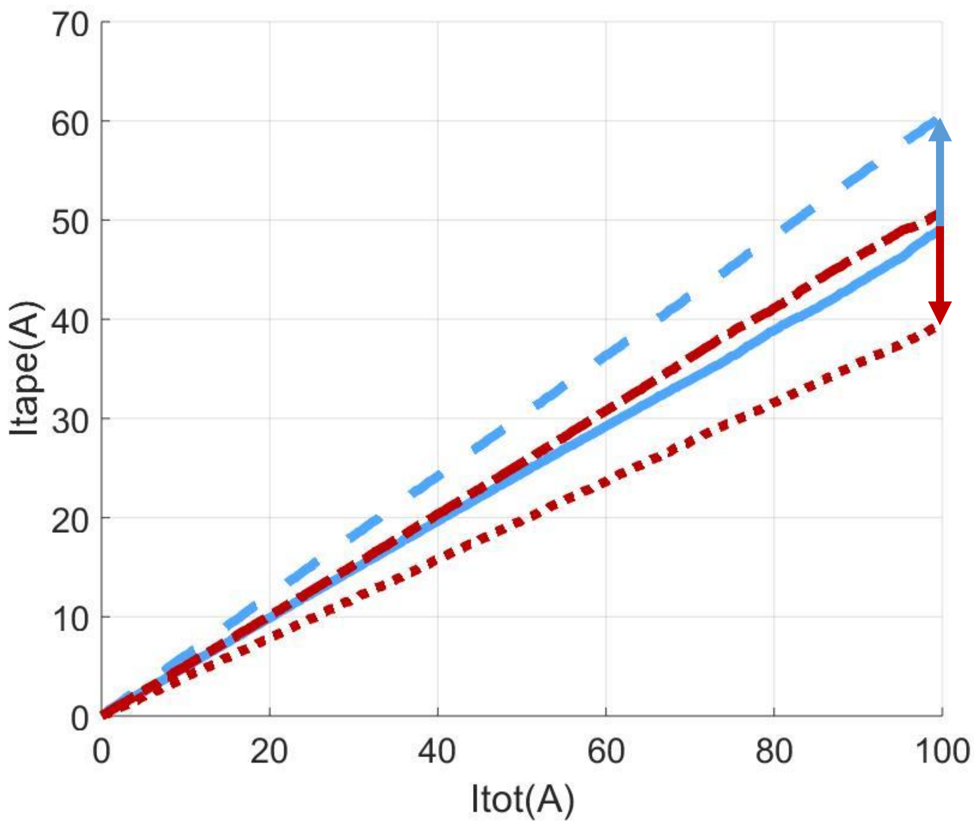
- Current split unevenly between tapes
- Defective tape carries I_c of defect

Current Transfer and Remain in Good Tape?



- Current split evenly between tapes
- Current > defect Ic transfer to good tape
- After defect current does not transfer back

Current Transfers in Cable



$I_{out}(Good) \approx 0.6\ I_{tot}$

$I_{in}(Defect) \approx 0.5\ I_{tot}$

$I_{in}(Good) \approx 0.5\ I_{tot}$

$I_{out}(Defect) \approx 0.4\ I_{tot}$

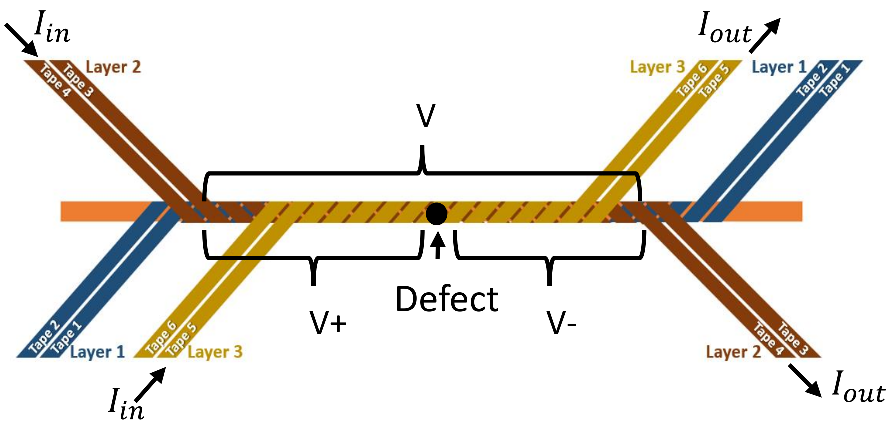
$I_{out} \neq I_{in}$

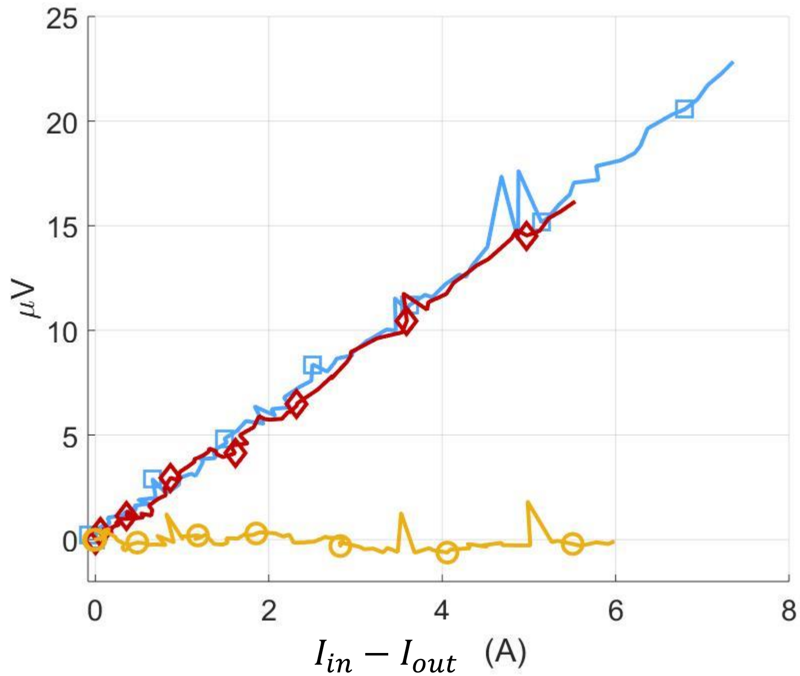
→ Current sharing within cable

Current Remains in Good Tape

Voltage Before Defect = Total Voltage

Voltage After Defect = 0





Length required for current sharing?

$$E_c = 1\,\mu V/cm$$

Voltage Produced →

$$E_c * L = I_{tr} R$$

Current Transferred

$$R = \frac{R_c}{nA_x}$$

Crossover Area

$A_x \approx 5\,mm^2$

Number of Crossovers

$$n = \frac{2N_{tapes}L}{p}$$

$n \approx$ 250 per meter in our experiment

Length Required for Current Transfer

$$L = \sqrt{\frac{I_{tr}R_c p}{2A_x N_{tapes} E_c}}$$

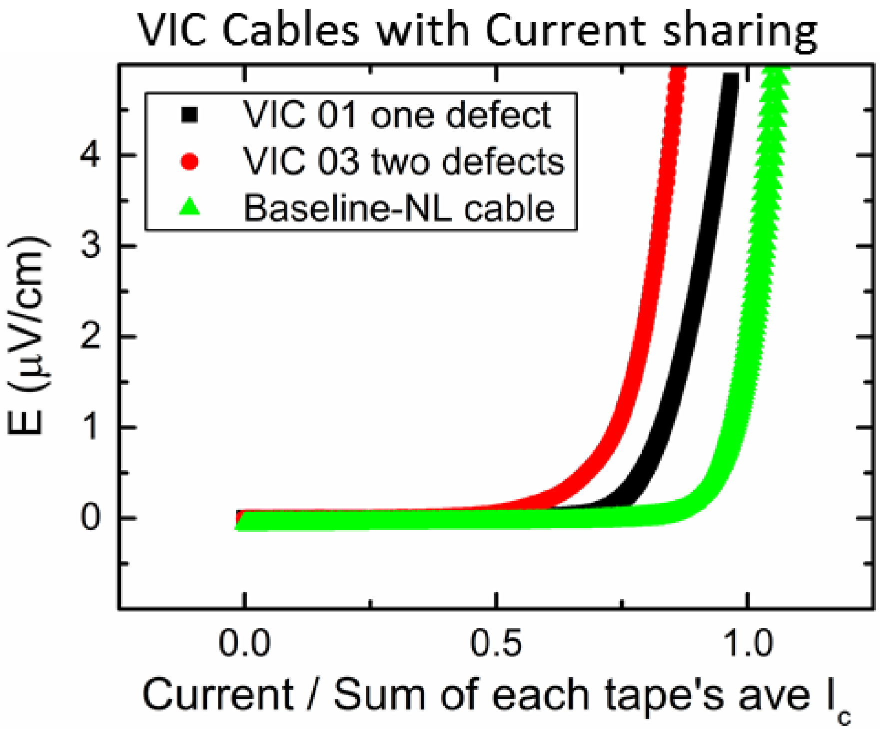
L ranged from 20 cm to a few meters

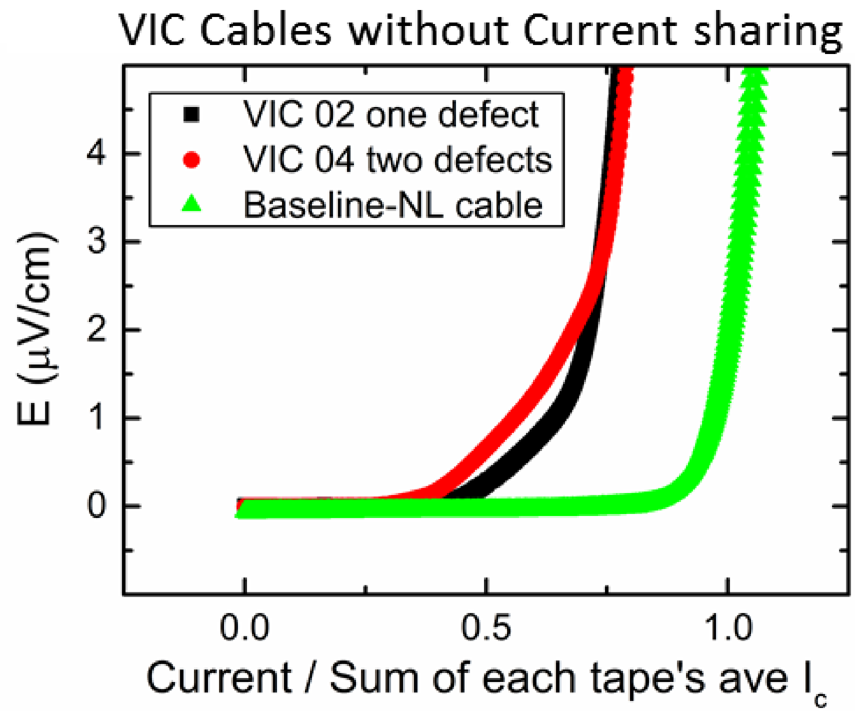
Further work by Jeremy Weiss and Danko Van der Laan

- ACT constructed cables containing tapes with a significant drop in I_c
- 3 layers, 6 tapes (2 tapes per layer)

Cable	# Defect Tapes	Layer with Defect	Insulation Between Layers
VIC-01	1	Middle	No
VIC-02	1	Middle	Yes
VIC-03	2	1-Middle 1-Outer	No
VIC-04	2	1-Middle 1-Outer	Yes

Comparison of VIC cables





With Current Sharing Enabled

- 1 defect
  - Retains 83% of I_c
- 2 defects
  - Retains 74% of I_c

With Current Sharing Disabled

- 1 defect
  - Retains 64% of I_c
- 2 defects
  - Retains 55% of I_c

Conclusions

- R_c in CORC® is relatively large for current transfers on 1 m length
  - Changes in lubricant reduce R_c by an order of magnitude
  - Bending cable reduces R_c
- Evidence of current sharing was obtained → It's more like a railway switch
  - About 20% of current in 1 tape was observed to transfer for $R_c \approx 50\ \mu\Omega \cdot cm^2$
- Working on R_c measurements in magnetic field as well as investigating current sharing in VIC cables