Electromechanical Performance of CORC® Cables and Wires under Axial Tension and Transverse Compression

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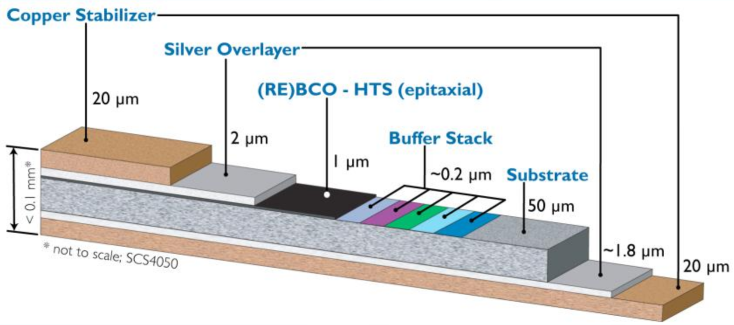
CORC® magnet cables and wires



RE-$Ba_2Cu_3O_{7-\delta}$ coated conductor made by SuperPower Inc.

Single tape wound into a CORC® cable

CORC® wires (2.5-4.5 mm diameter)

- Wound from 2-3 mm wide tapes with 30 μm substrate
- Typically no more than 30 tapes
- Highly flexible with bending down to < 50 mm diameter

CORC® cable (5-8 mm diameter)

- Wound from 3-4 mm wide tapes with 30-50 μm substrate
- Typically no more than 50 tapes
- Flexible with bending down to > 100 mm diameter

Electromechanical Characterization

CORC® feasibility as a practical magnet conductor

- High magnetic fields and high current density require mechanically robust conductors
- Will require extensive electromechanical characterization

Characterization critical for magnet design:

- I_c retention with applied transverse compressive stress
- I_c retention in axial tension

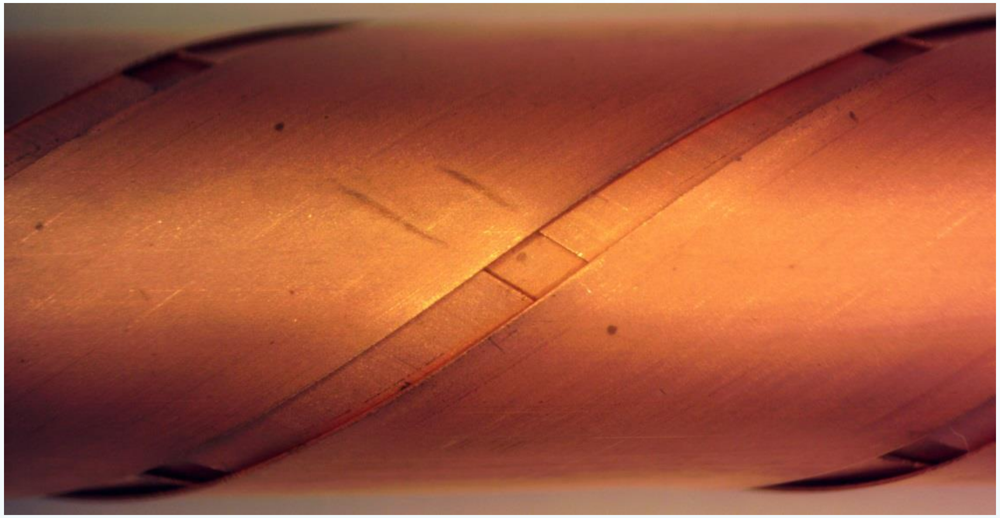
Testing and development of wires and cables:

- Understanding mechanisms of I_c degradation due to mechanical stresses will accelerate optimization of conductor architecture for specific applications

Sample Characteristics That May Influence Behavior

Gap spacing between tapes

- Tapes are wound at opposite direction between layers
- Tapes thus cross gaps of underlying layer
- CORC® cables and wires have gaps ranging from 0.2 to over 0.5 mm



Copper thickness

- Thicker copper is known to decrease critical transverse stress

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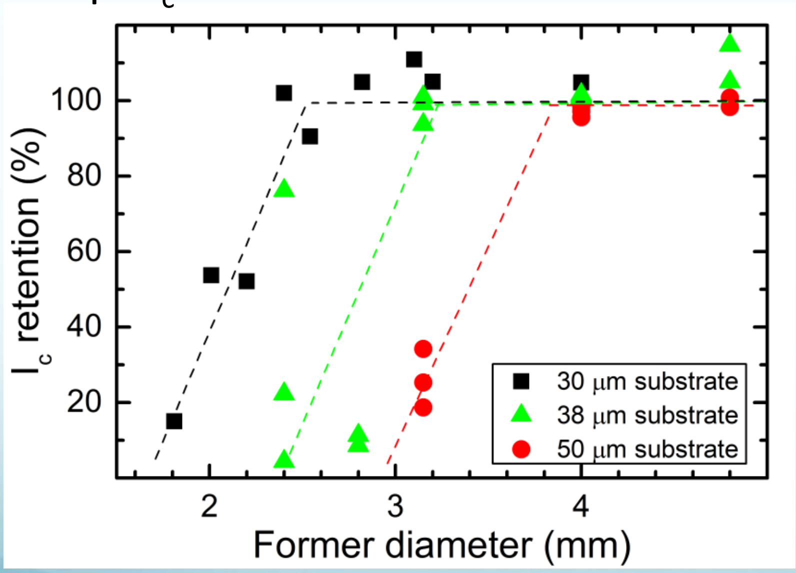
Sample Characteristics That May Influence Behavior

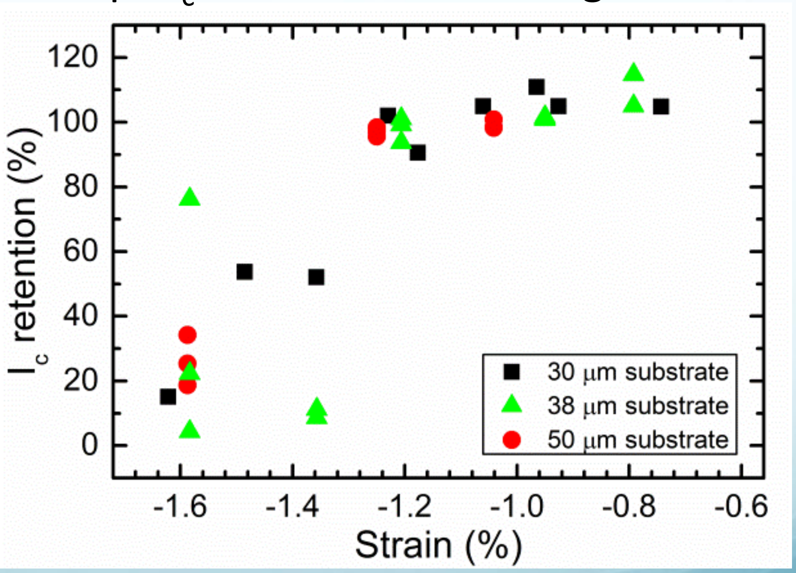
REBCO layer winding strain

- Bending strain added to REBCO layer during winding
  - Tapes are wound onto former with REBCO layer on inside (compression)
- Depends on former diameter and substrate thickness
- **Critical bending strain is about -1.25 %**

Tape I_c retention vs former diameter



Tape I_c retention vs winding strain



Sample Description

CORC® wire 1

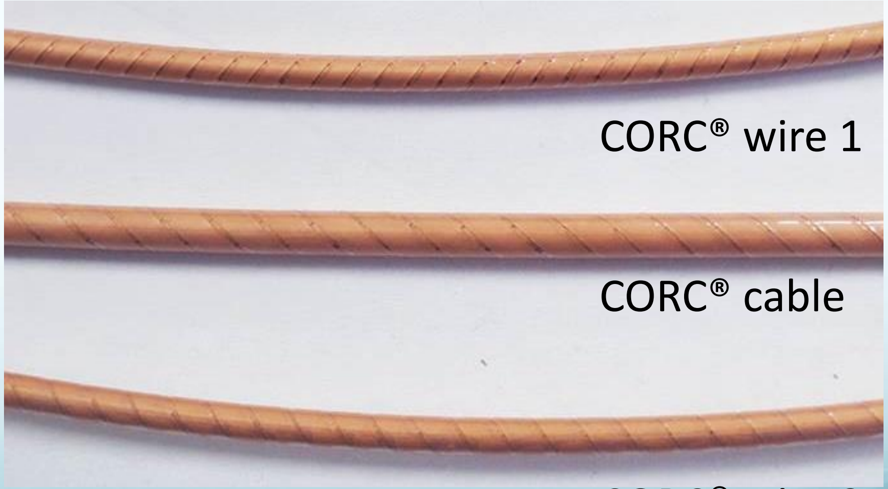
- 11 layers, 27 tapes total
- 2 mm wide tapes
- **Gap spacing 0.3 - 0.4 mm**
- 30 μm thick substrate
- 2.55 mm thick former
- **REBCO winding strain: -1.16 %**

CORC® wire 2

- 6 layers, 12 tapes total
- 3 mm wide tapes
- **Gap spacing 0.4 mm**
- 30 μm thick substrate
- 3.20 mm thick former
- **REBCO winding strain: -0.93 %**

CORC® cables

- 3 layers, 9 tapes total
- 4 mm wide tapes
- **Gap spacing 0.1 mm or 0.5 mm**
- 50 μm thick substrate
- 4.92 mm thick former
- **REBCO winding strain: -1.00 %**



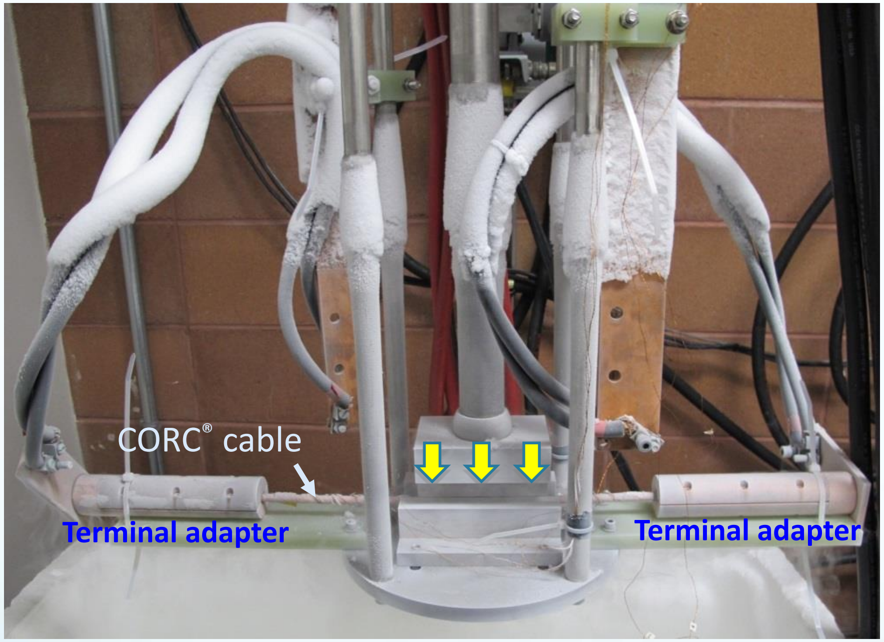
CORC® wire 1

CORC® cable

CORC® wire 2

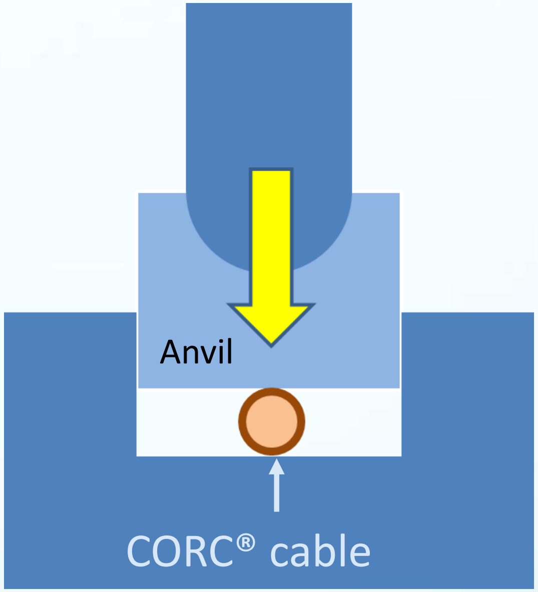
Transverse Compressive Test Equipment

MTS test setup, load capacity 10,000 lbs (44 kN)



Side view

Load applied results in a line-contact against the conductor



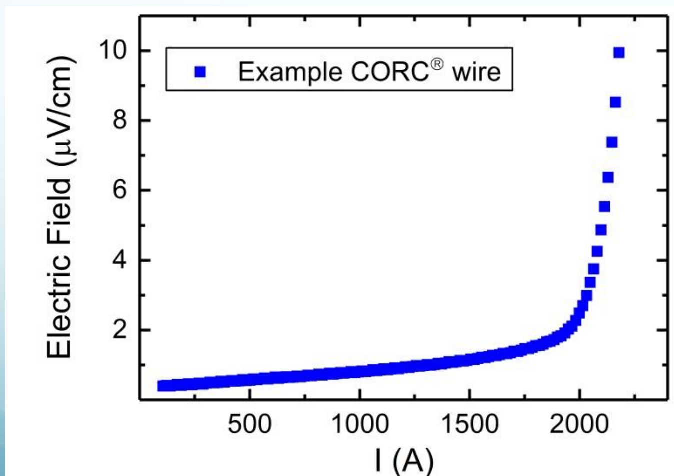
- Test Temp = 76 K
- Anvil Length = 50 mm
  - 2-6 twist pitches engaged

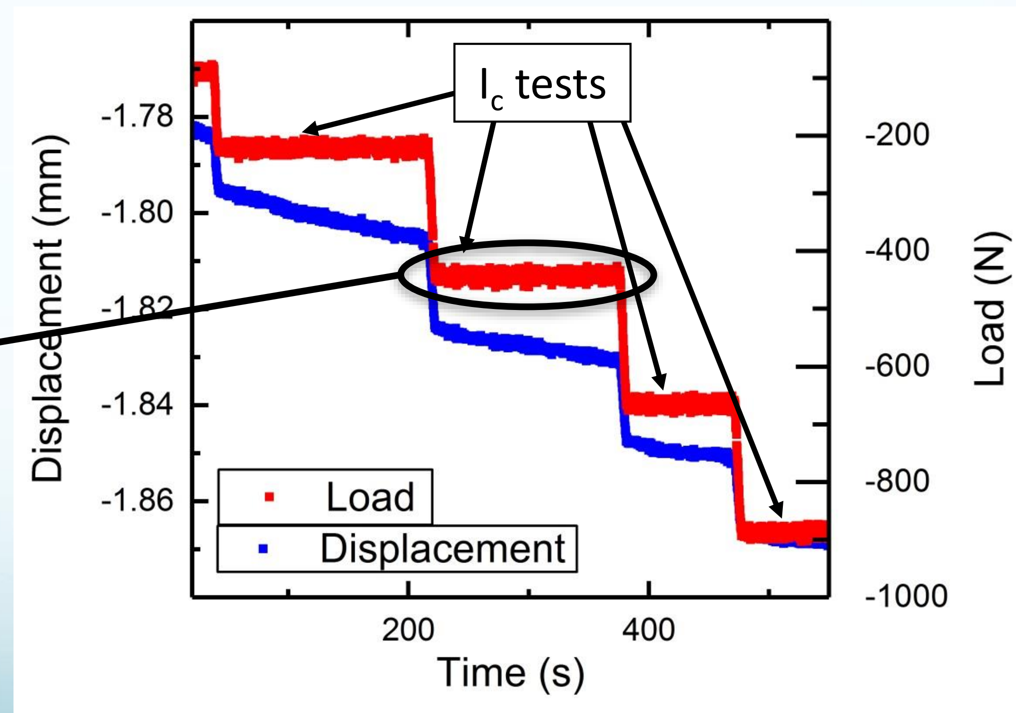
Monotonic Test Procedure

Monotonic loading procedure

- Performed incrementally in load control
  - Accounts for continuously-changing state of thermal contraction in load fixture

1. Hold load constant
2. Run I_c test
3. Load to next load increment
4. Repeat





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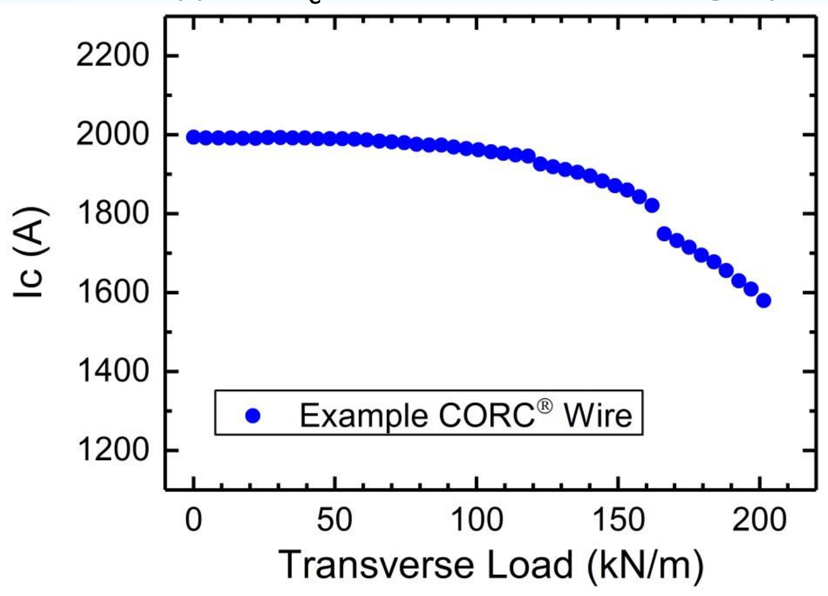
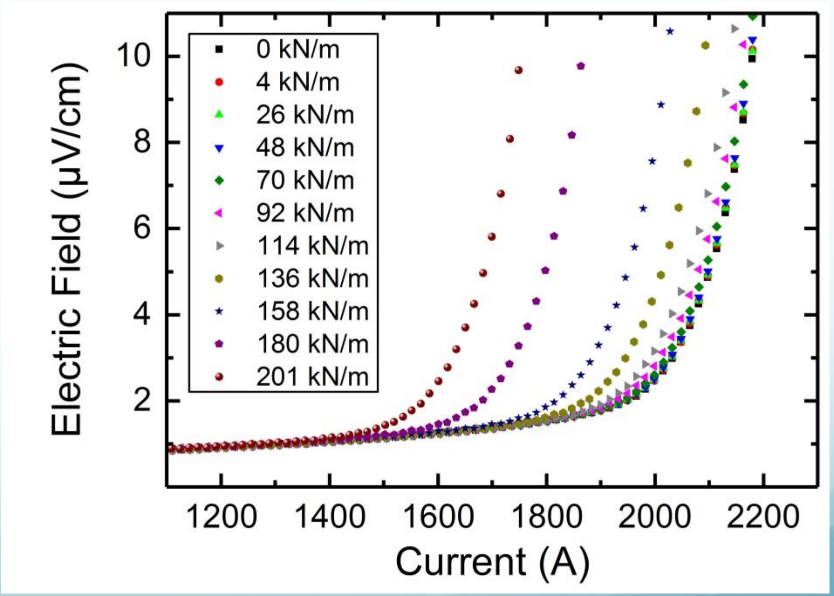
Typical I_c vs Transverse Load graph



V-I curves at several loads

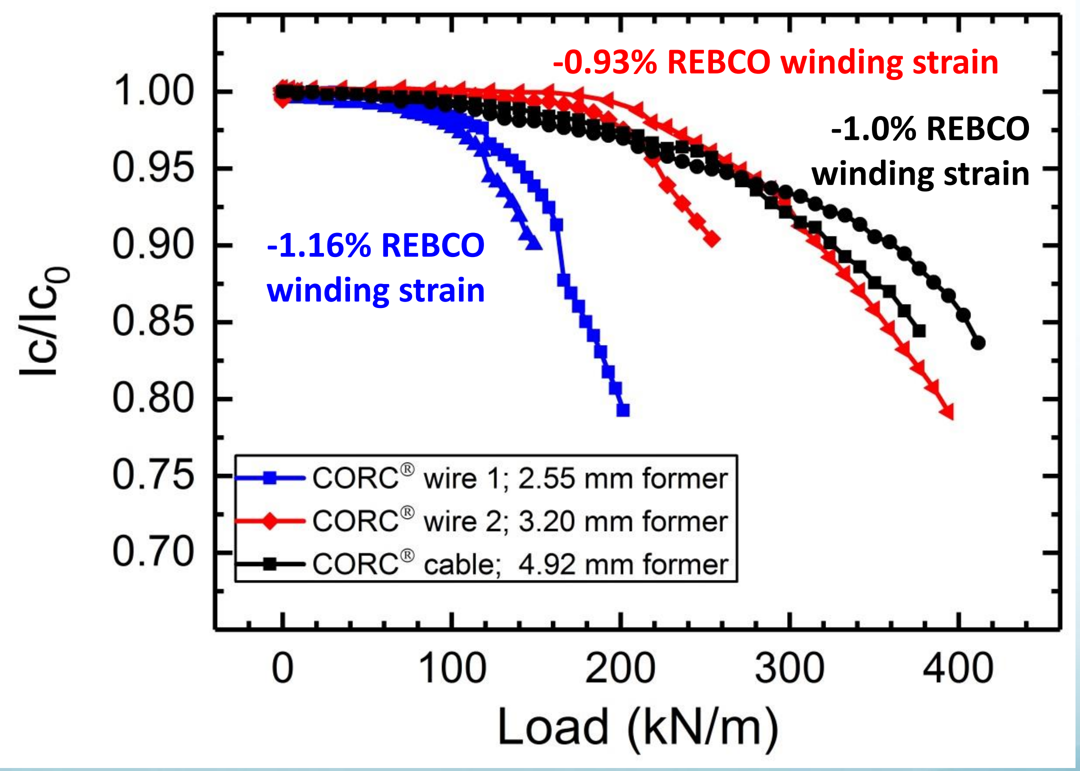


Monotonic Transverse Compression Data

General trends to note

- CORC® wires with smallest former, and REBCO layer close to -1.25 % critical strain are most sensitive to transverse compression
- CORC® wires and cables with comparable REBCO strain show similar load dependence

I_c/I_{c0} vs Transverse Load

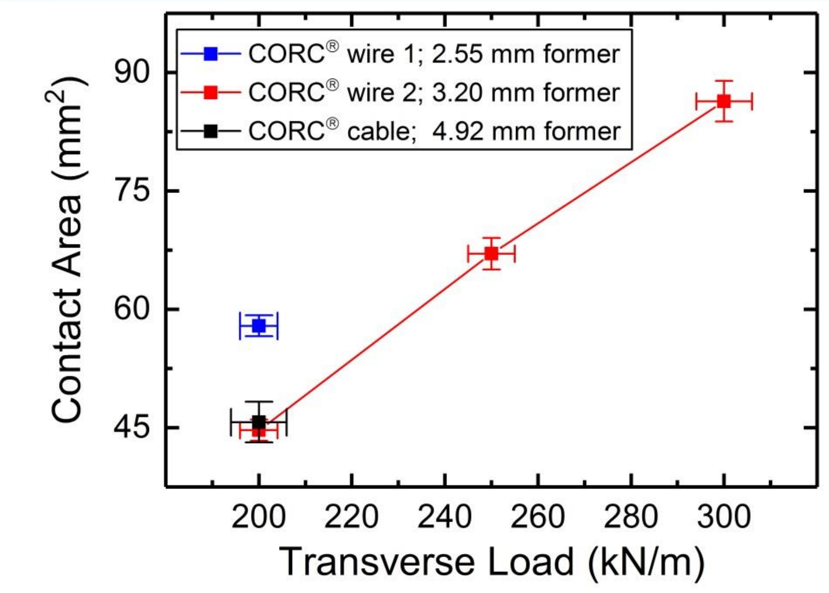


Contact Area Measurements

Contact Area Measurements

- Contact area begins as line contact and increases as load is increased
- Pressure film used in LN_2 to estimate contact area at selected loads:
  - ○CORC® wire 1: 200 kN/m
  - ○CORC® wire 2: 200, 250, 300 kN/m
  - ○CORC® cable: 200 kN/m
- Contact area calculated as (average width) x (anvil length)

Contact Area vs Transverse Load



CORC® wire 1 – 200 kN/m

CORC® wire 2 – 200 kN/m

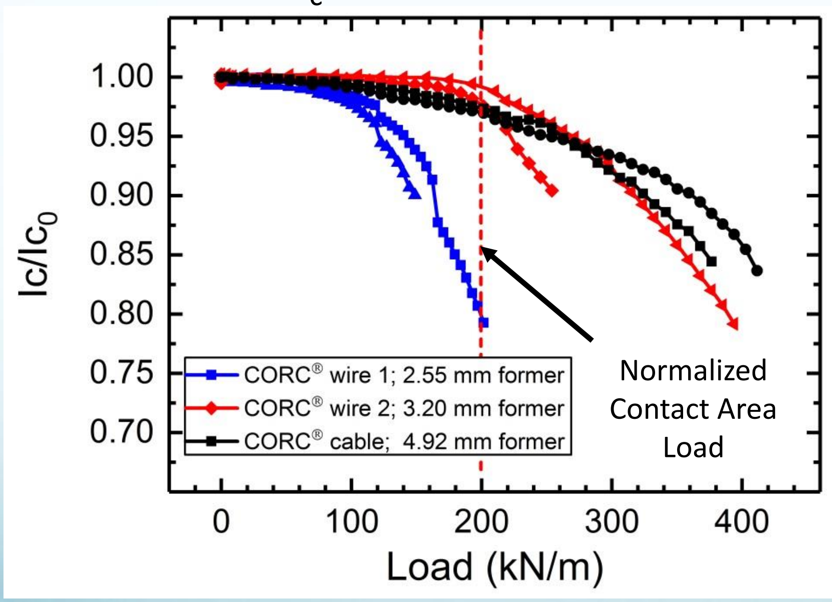
CORC® cable – 200 kN/m

Contact Area Stress

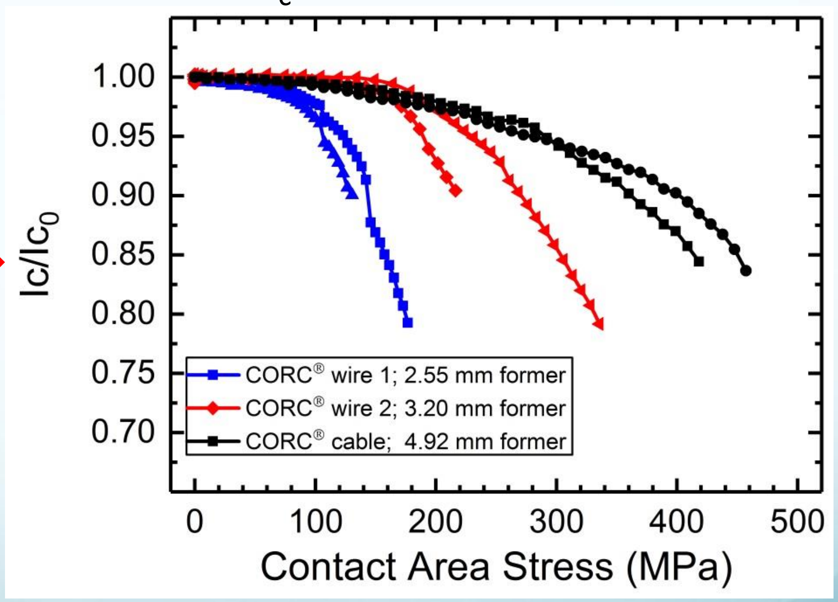
Contact Stress

- Contact stress normalized by pressure film measured area at 200 kN/m
- Rate of contact area increase with increasing load is likely different for each conductor, but this gives a first order estimate

I_c vs Transverse Load



I_c vs Contact Area Stress



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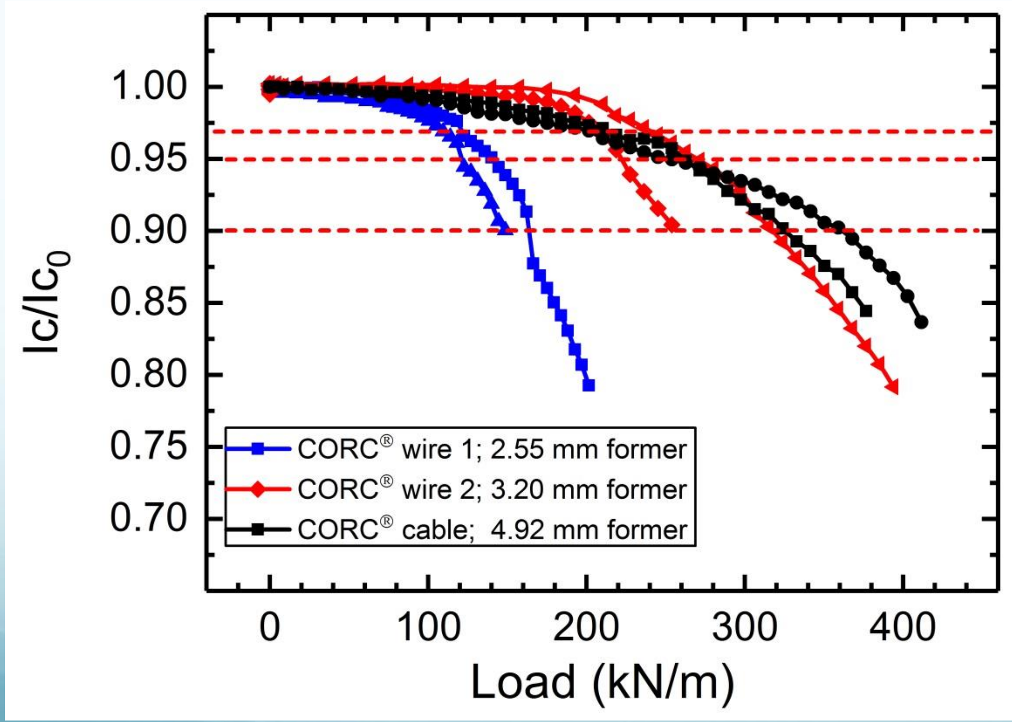
Assigning Critical Load Criterion

Setting a standard for I_c critical load

- Similar to 0.2% offset yield strength and 1 µV/cm offset I_c criteria, critical load can be standardized with a common I_c retention criterion
- This would allow easier electromechanical comparison between different conductor layouts, as well as different conductors altogether



Conductor		CORC® Wire 1	CORC® Wire 2	CORC® Cable
$Ic/Ic_0 = 0.97$	P_{crit} (kN/m)	115.4	217.0	218.8
	Error (± kN/m)	11.9	25.1	26.7
$Ic/Ic_0 = 0.95$	P_{crit} (kN/m)	133.4	243.1	259.9
	Error (± kN/m)	10.8	27.5	12.3
$Ic/Ic_0 = 0.90$	P_{crit} (kN/m)	162.6	283.8	329.3
	Error (± kN/m)	15.0	35.3	21.5
	# curves analyzed	3	4	4

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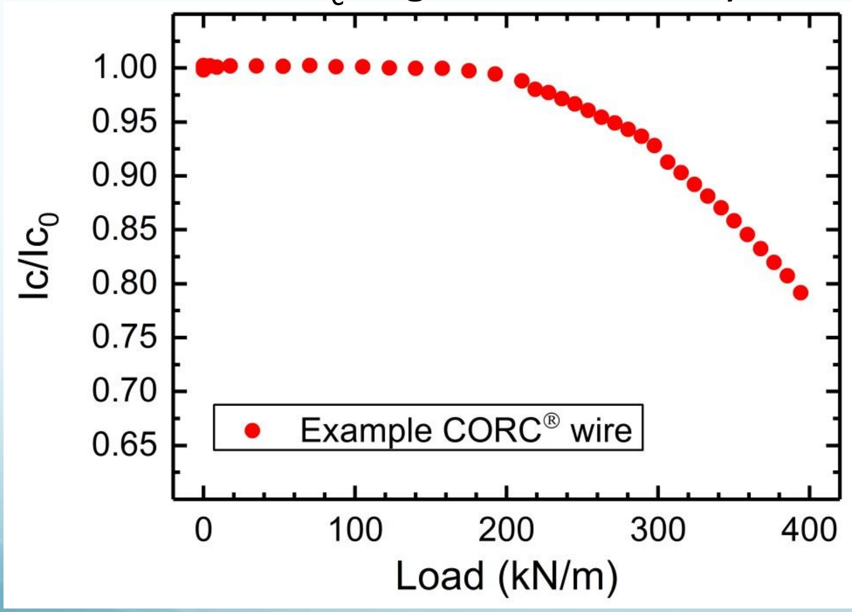
Fatigue Test Procedure

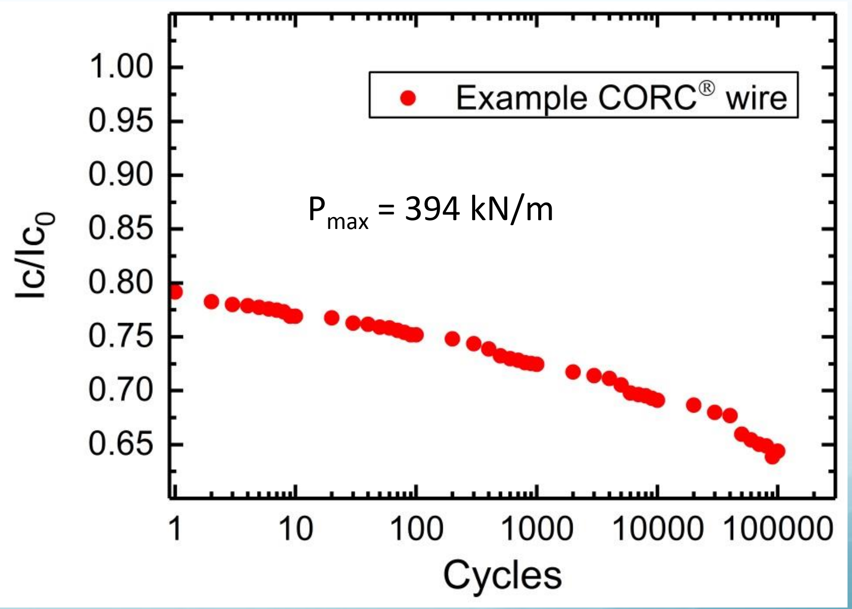
Fatigue test procedure

- Monotonic loading of virgin sample to pre-selected I_c degradation load (example shown: I_c/I_{c0} = 0.80 corresponding to P_{max} = 394 kN/m)
- Fatigue cycling at stress amplitude ratio P_{min}/P_{max} = 0.1
- I_c measured at peak load up to 100,000 cycles

Initial I_c degradation, first cycle



I_c/I_{c0} at P_{max} vs cycles



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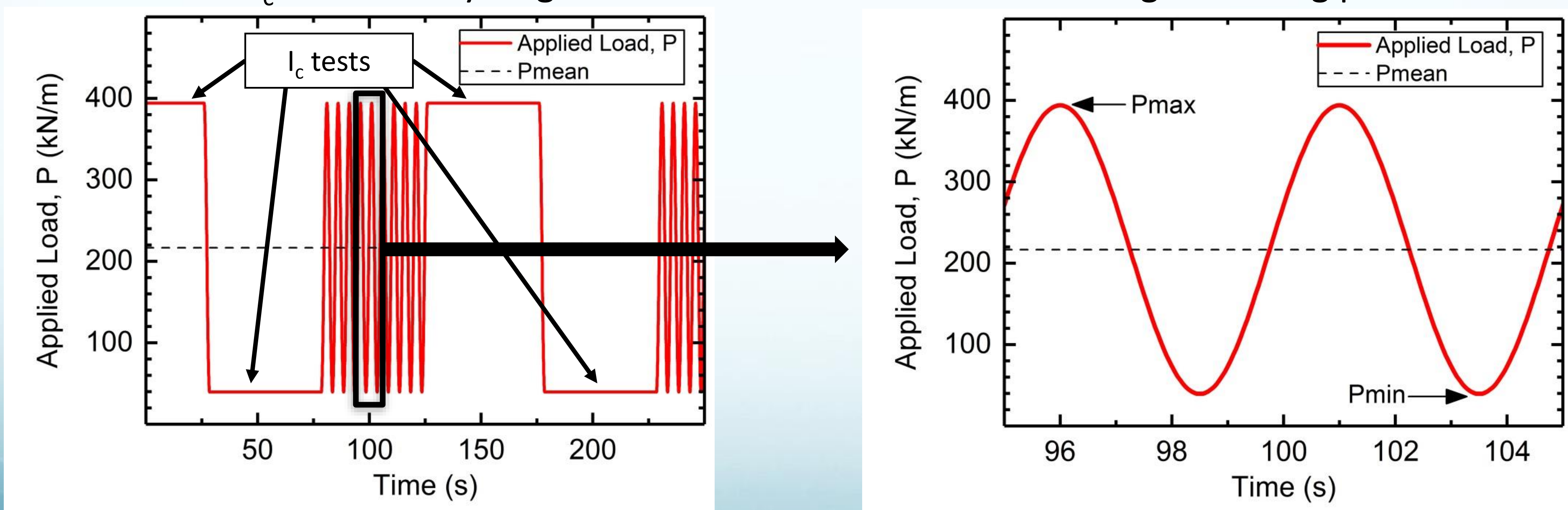
I_c tests mid-cycling — Fatigue loading profile



Fatigue Data under Transverse Compression

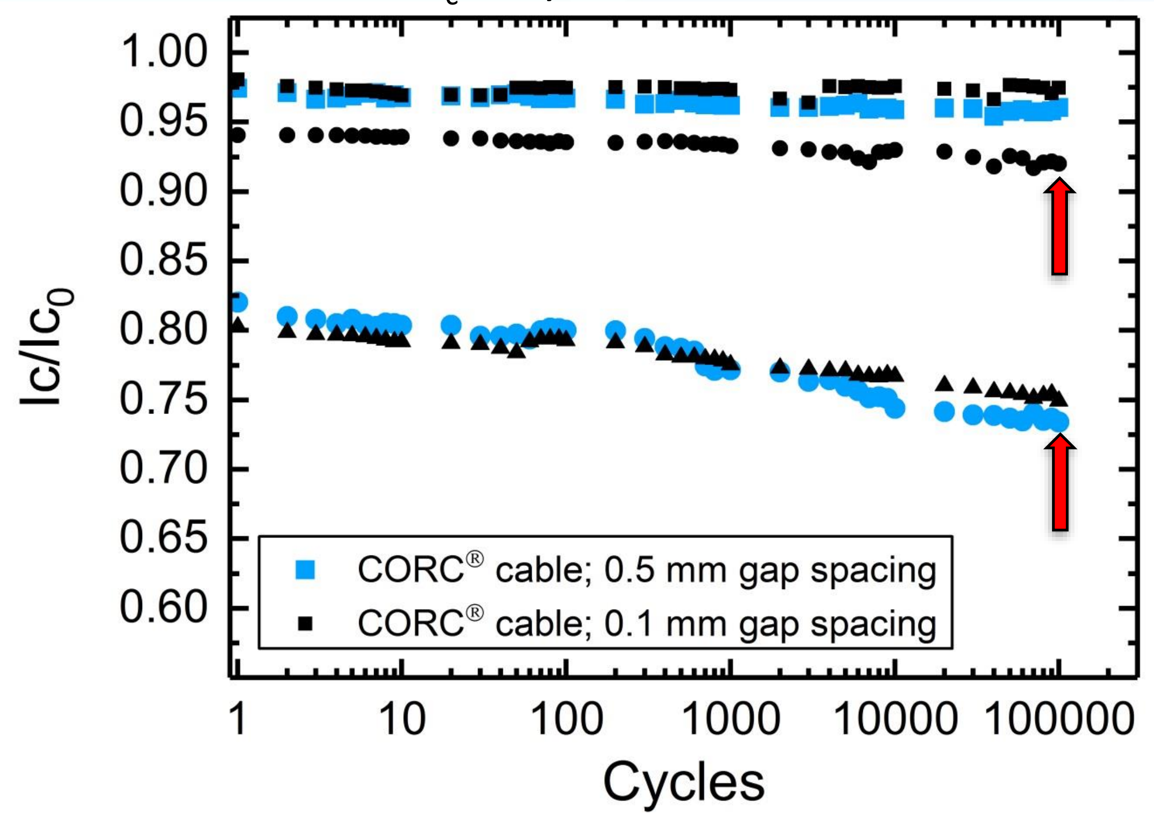
Overall promising for safe operation in magnet applications

- I_c does not drop off a cliff with cycle count at a constant load amplitude
- Degrades gradually and predictably, usually only after significant initial degradation

Some trends can be seen

- Gap spacing has small effect on fatigue degradation

I_c vs cycles, CORC® cables



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Fatigue Data under Transverse Compression

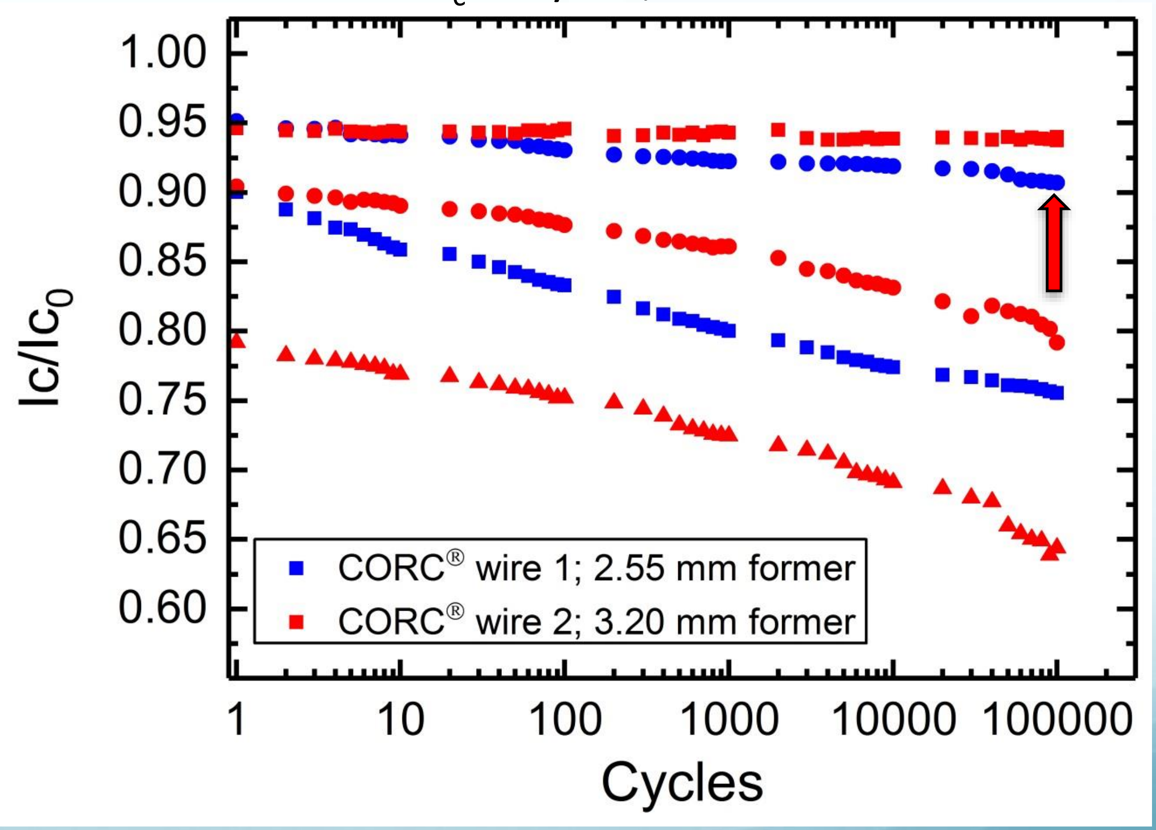
Overall promising for safe operation in magnet applications

- I_c does not drop off a cliff with cycle count at a constant load amplitude
- Degrades gradually and predictably, usually only after significant initial degradation

Some trends can be seen

- Gap spacing has small effect on fatigue degradation
- Former size and corresponding REBCO winding strain has significant impact on fatigue degradation

I_c vs cycles, CORC® wires



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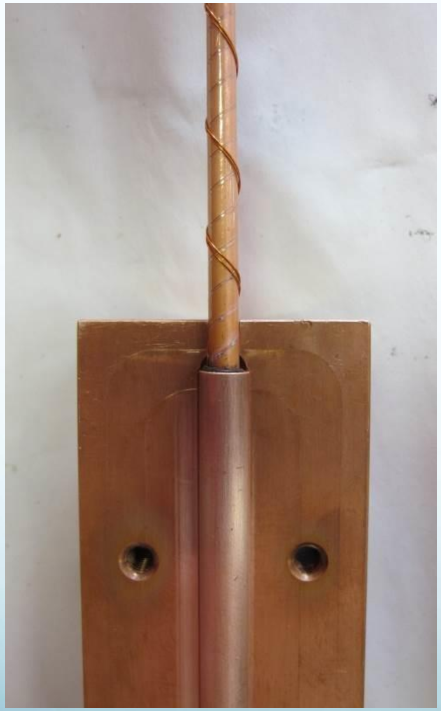
Preliminary Axial Tension Measurements

Test Setup

- Test machine capacity = 13 kN
- Load applied through current injection terminals
- Monotonic tests performed in load control increments

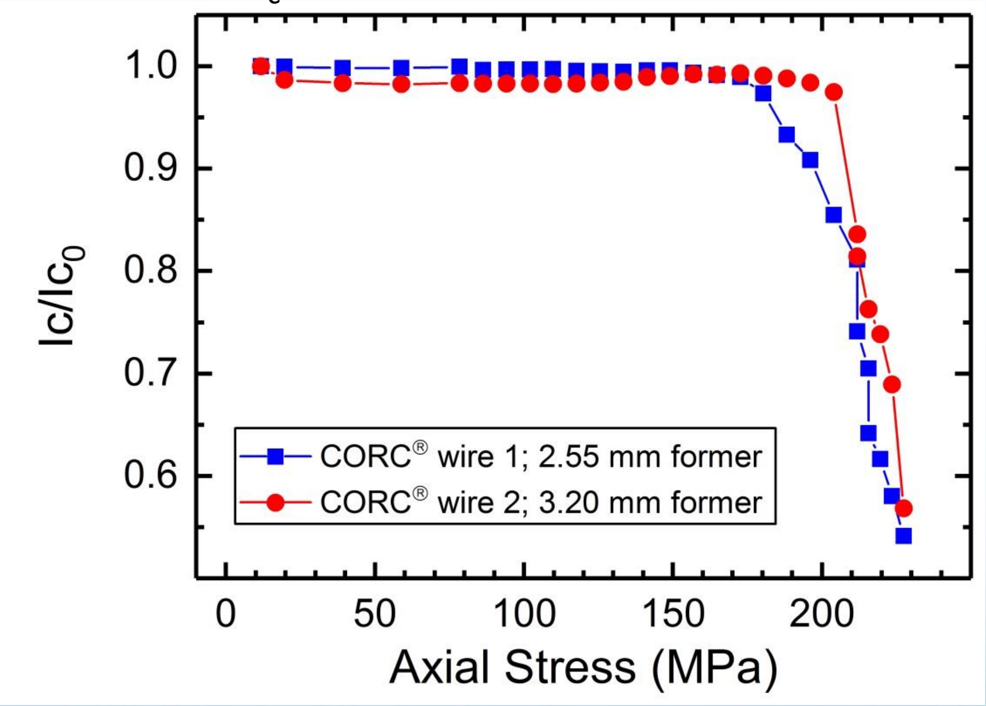


Preliminary Axial Tension Measurements

Preliminary data

- One monotonic specimen each of CORC® wires 1 and 2 tested to-date
- Cross-section calculated by wire outer diameter (including heatshrink)
- I_c degrades sharply after onset of degradation, similar to individual tapes

I_c vs axial tension, CORC® wires



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Preliminary Conclusions

Although tests are ongoing and different sample configurations are being tested as we speak

- The resilience of CORC® cables and wires in transverse compression up to 100,000 cycles is very promising
- The I_c retention after 100,000 cycles is especially high when the peak load did not degrade I_c by more than 5 – 10 % before cycling
- Magnets will likely be designed at transverse loads resulting in no more than 3 – 5 % I_c degradation, which means that load cycling likely won't have a significant impact on the magnet performance

Next investigations:

- Post-mortem extracted tape measurements on axial tension specimens, to investigate primary failure mechanisms in monotonic tension
- In-situ strain measurements in axial tension (I_c-ε)
- Fatigue behavior in axial tension
- Effect of winding angle on transverse compression performance