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

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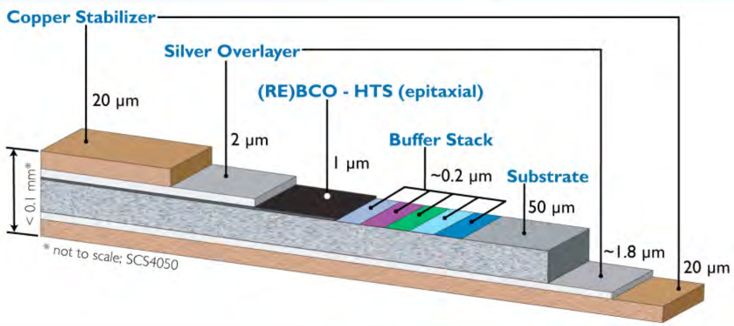
# CORC® magnet cables and wires




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

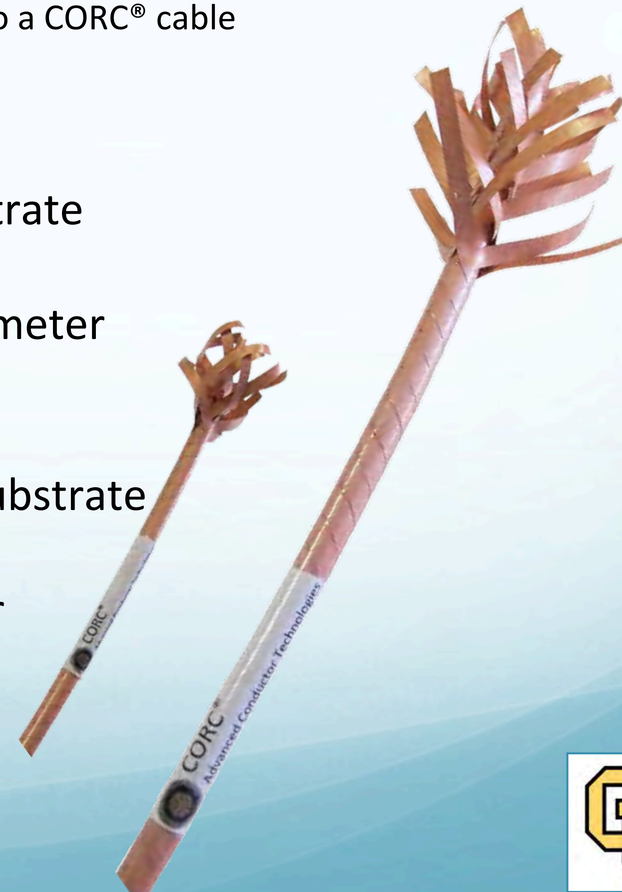
Single tape wound into a CORC® cable

## 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)

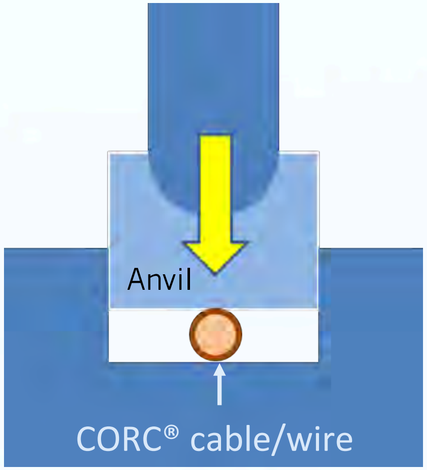
- Wound from 3-4 mm wide tapes with 30-50 μm substrate
- Typically no more than 50 tapes
- Flexible with bending down to > 100 mm diameter



# Application of transverse compressive load

**Measurement under transverse compressive load**

- Load applied by two flat stainless steel anvils
- Load applied at 76 K in liquid nitrogen




**Effects to be studied**

**Model CORC® samples**

- Effect of gap spacing between tapes
- Effect of copper plating thickness

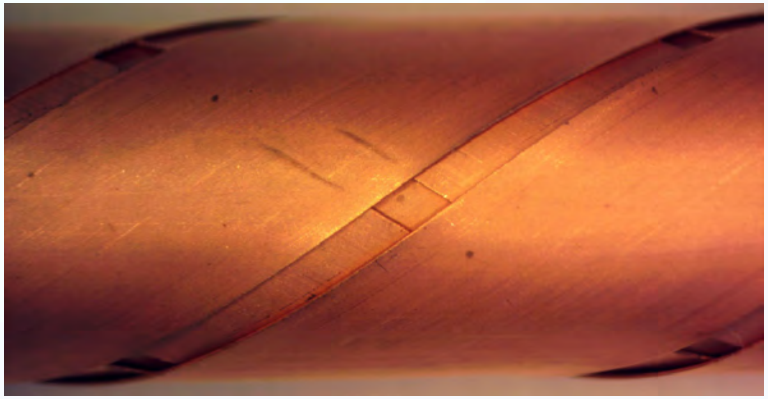
**Practical CORC® cables and wires**

- Effect of former size and substrate thickness
- Overall behavior of practical CORC® magnet cables and wires

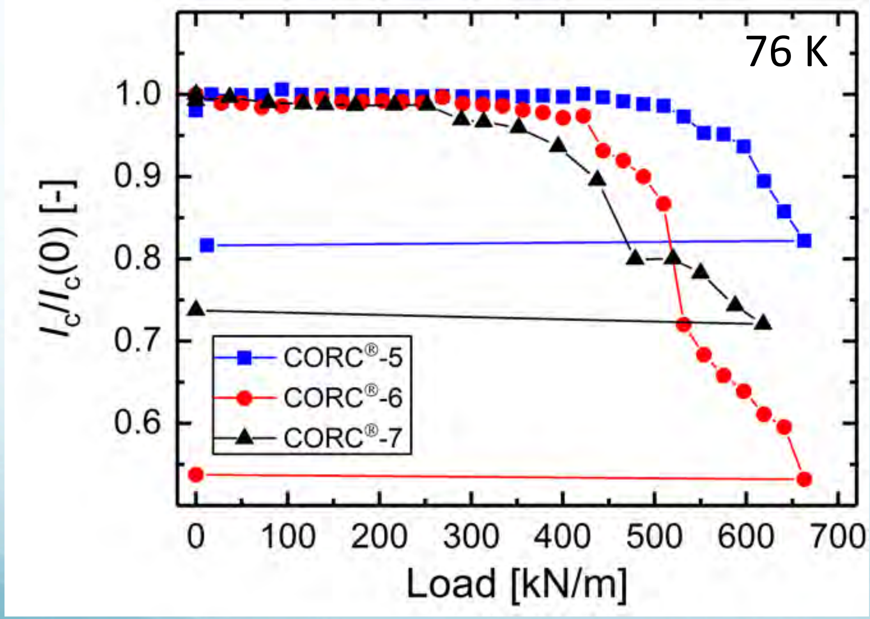
# Model CORC® samples: Effect of gap spacing

**Model CORC® sample**

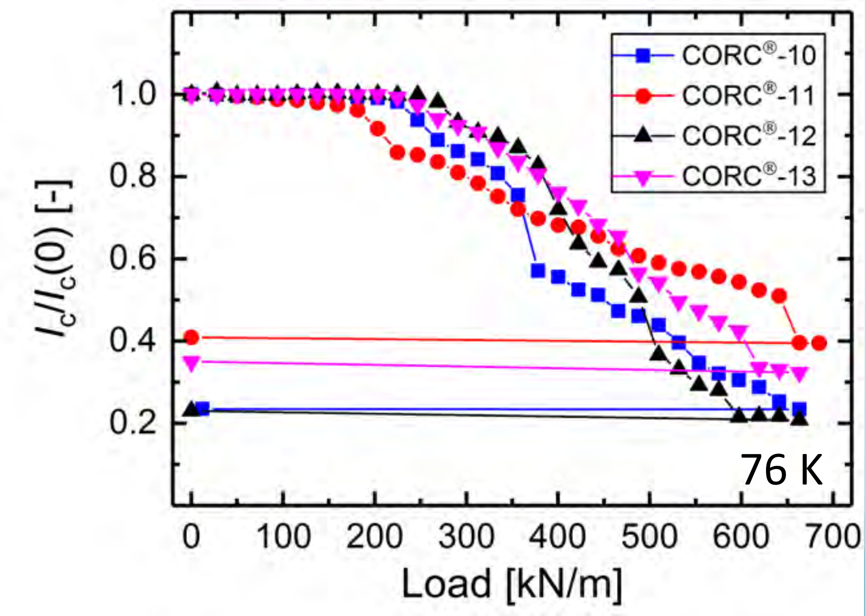
- Hand-wound
- **Solid stainless steel former**
- 3 layers, 6 or 9 tapes
- **No epoxy impregnation!**
- Gap spacing 0 or 1 mm
- Copper plating 5 μm thick



**0 mm gap spacing**

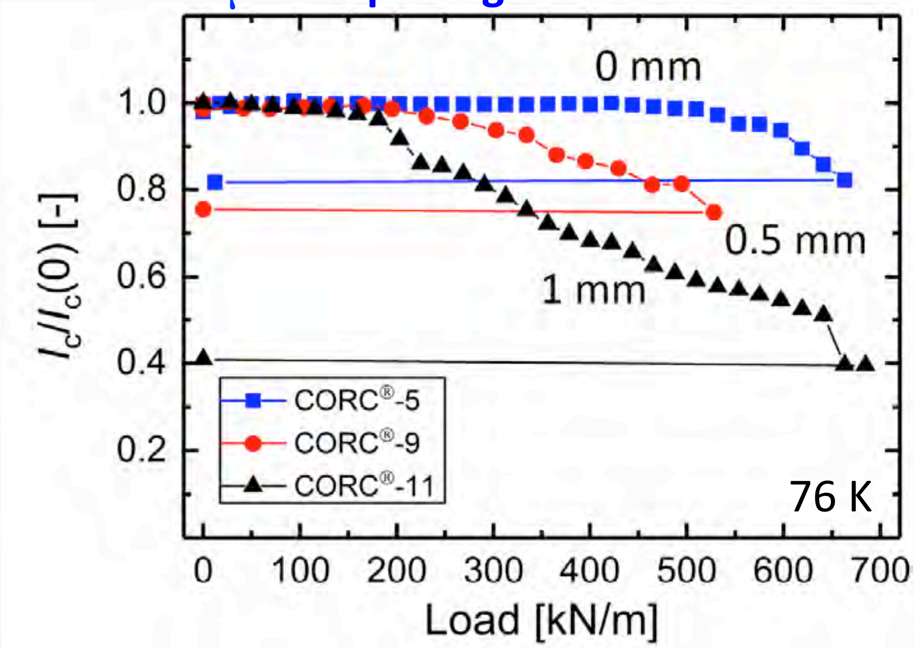



**1 mm gap spacing**

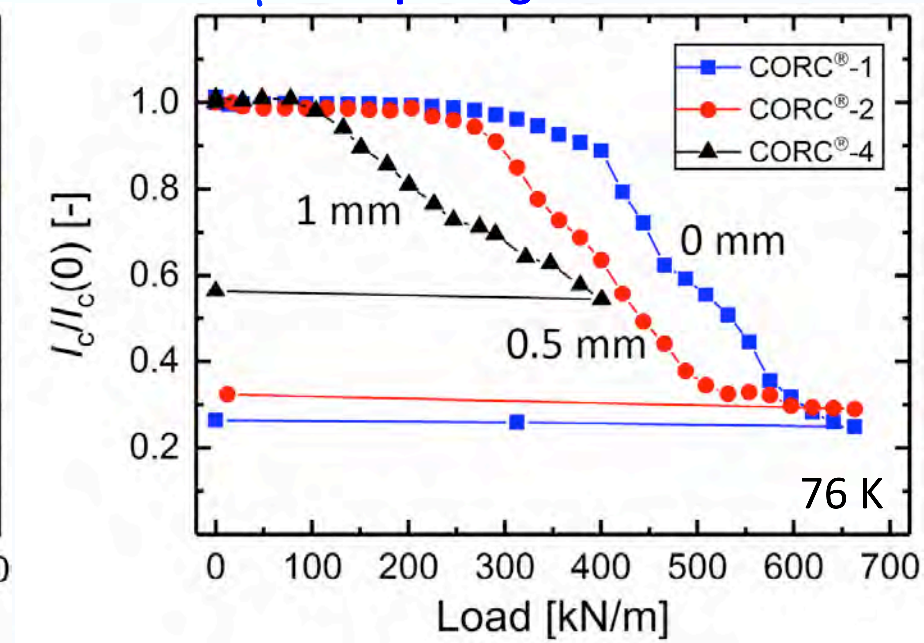


# Model CORC® samples: Effect of copper thickness

**5 μm Cu plating**




**20 μm Cu plating**




**Critical load decreases with copper plating thickness**

**Critical load decreases with gap spacing**

Critical load [kN/m]

| | 20 μm copper plating Gap spacing: | | | 5 μm copper plating Gap spacing: | | |
|---|---|---|---|---|---|---|
| **$I_c$ decrease** | **0 mm** | **0.5 mm** | **1.0 mm** | **0 mm** | **0.5 mm** | **1.0 mm** |
| **1%** | 250 | 200 | 150 | 360 | 210 | 200 |
| **3%** | 260 | 200 | 160 | 420 | 250 | 230 |
| **5%** | 270 | 220 | 180 | 450 | 290 | 240 |

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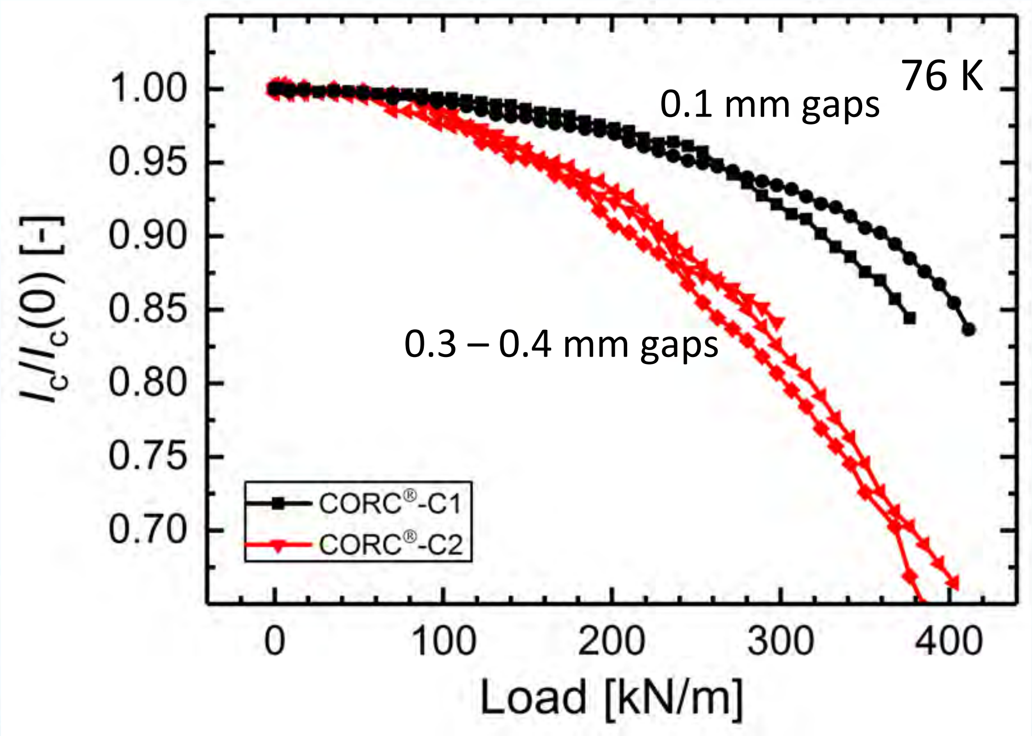
# Transverse Compression on CORC® cables

**CORC® cable layout**

- Machine-wound
- 4.9 mm thick copper former
- 9 tapes wound in 3 layers
- Tapes with 50 μm substrate
- 0.1 or 0.3 – 0.4 mm gap spacing




**Critical load decreases with gap spacing**
**Decrease in $I_c$ is more gradual**

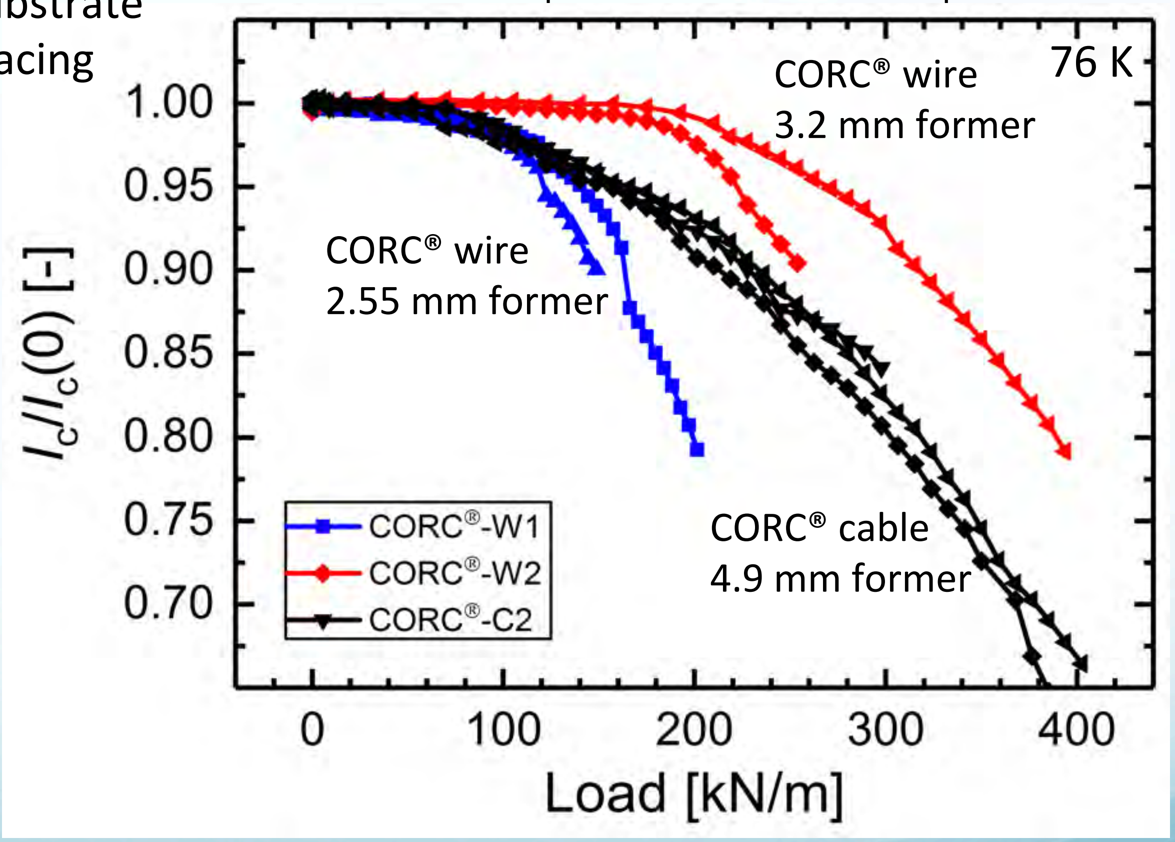
# Transverse Compression on CORC® wires

**CORC® wire layout**

- Machine-wound
- 2.55 mm or 3.2 thick copper former
- 12 or 27 tapes
- Tapes with 30 μm substrate
- 0.3 – 0.4 mm gap spacing

Critical load [kN/m]

| $I_c$ decrease | CORC®-C1 | CORC®-C2 | CORC®-W1 | CORC®-W2 |
|---|---|---|---|---|
| **3%** | 207 | 124 | 115 | 217 |
| **5%** | 255 | 160 | 133 | 243 |
| **10%** | 340 | 226 | 163 | 284 |

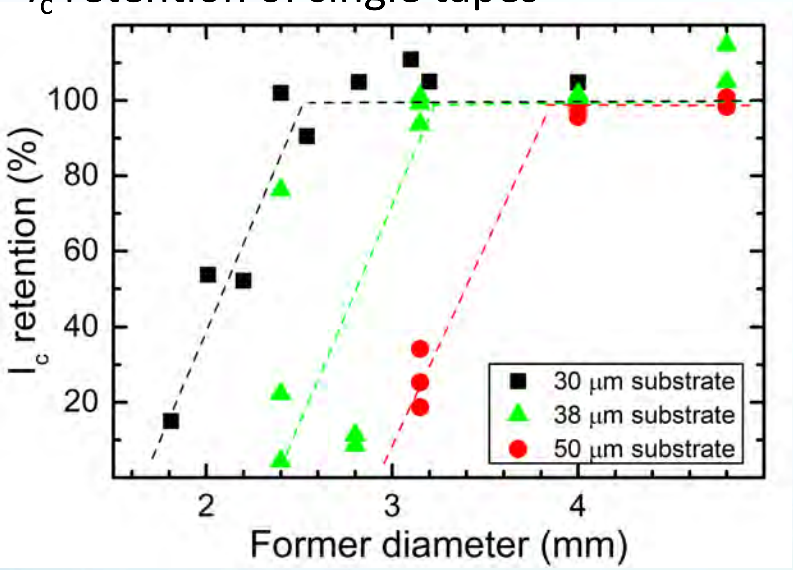


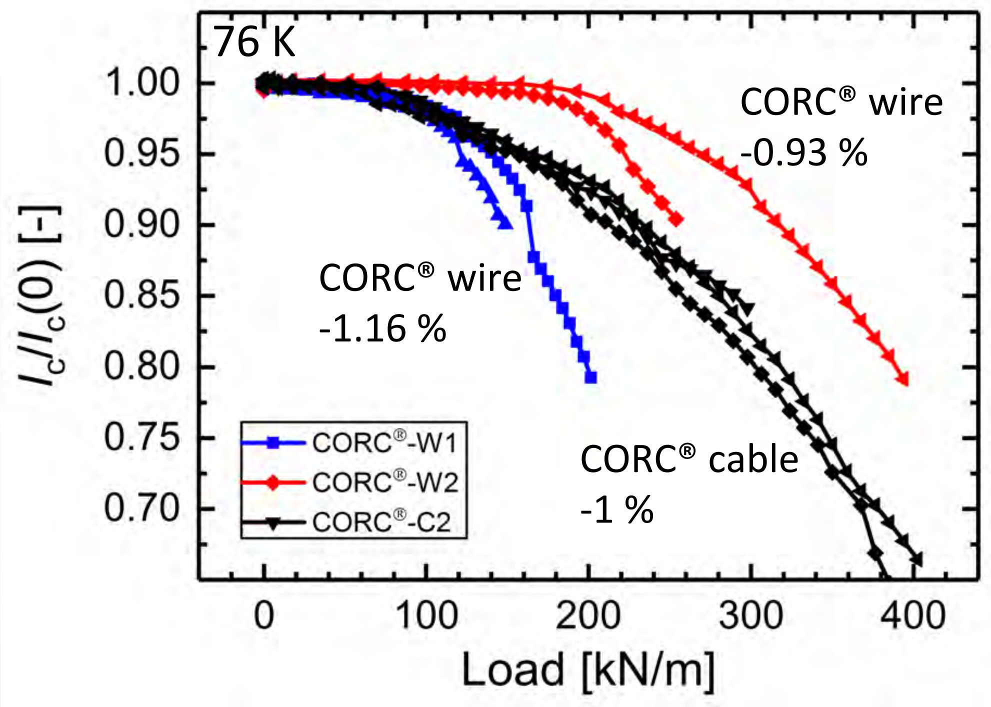
# Effect of winding strain on CORC® performance

**Winding strain in CORC® cables and wires**

- CORC® wire with 2.55 mm former and 30 μm substrate: -1.16 %
- CORC® wire with 3.2 mm former and 30 μm substrate: -0.93 %
- CORC® cable with 4.9 mm former and 50 μm substrate: -1.0 %

$I_c$ retention of single tapes



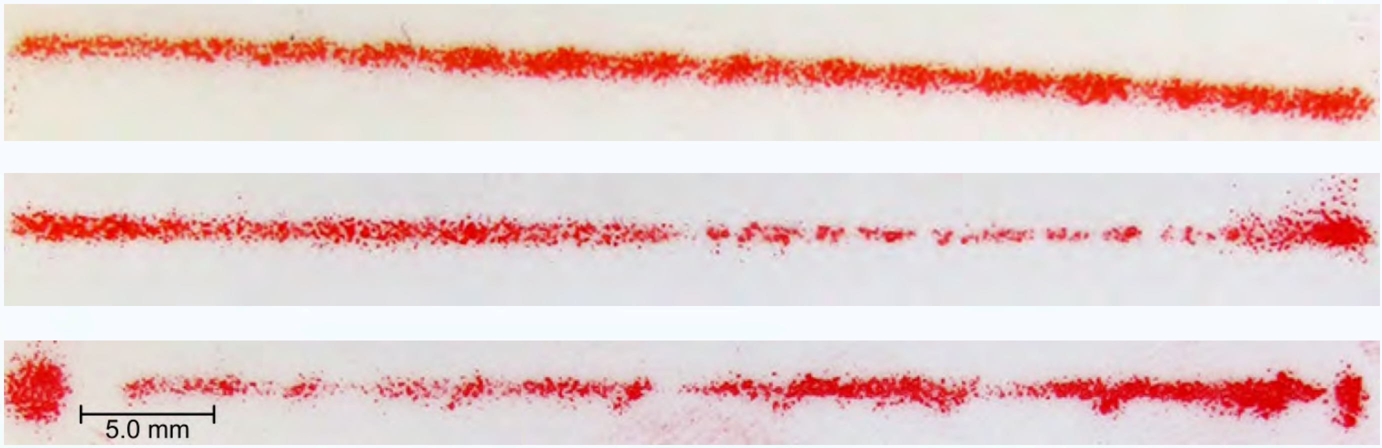

**Critical winding strain -1.25 %**

**Critical transverse compressive load depends on initial strain state of REBCO layer**
**Compressive load increase strain state toward irreversible limit**

# First estimate of critical transverse stress

**Width of contact area determined by pressure sensitive paper**

- Fixed applied load of 200 kN/m
- Average width of contact area between 0.9 and 1.16 mm




CORC® wire (2.55 mm former)

CORC® wire (3.2 mm former)

CORC® cable (4.9 mm former)

Critical load [MPa]

| $I_c$ decrease | CORC®-C1 | CORC®-C2 | CORC®-W1 | CORC®-W2 |
|---|---|---|---|---|
| **3%** | 230 | 138 | 99 | 241 |
| **5%** | 283 | 178 | 115 | 270 |
| **10%** | 378 | 251 | 141 | 316 |

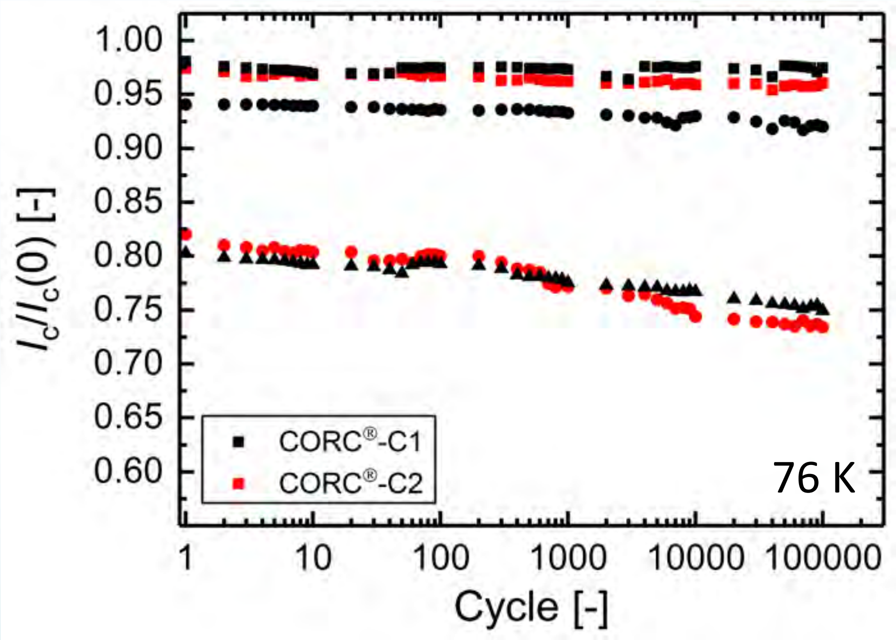
**Critical transverse compressive stress > 230 MPa in optimized CORC® cables and wires**

# Effect of transverse compressive load cycling

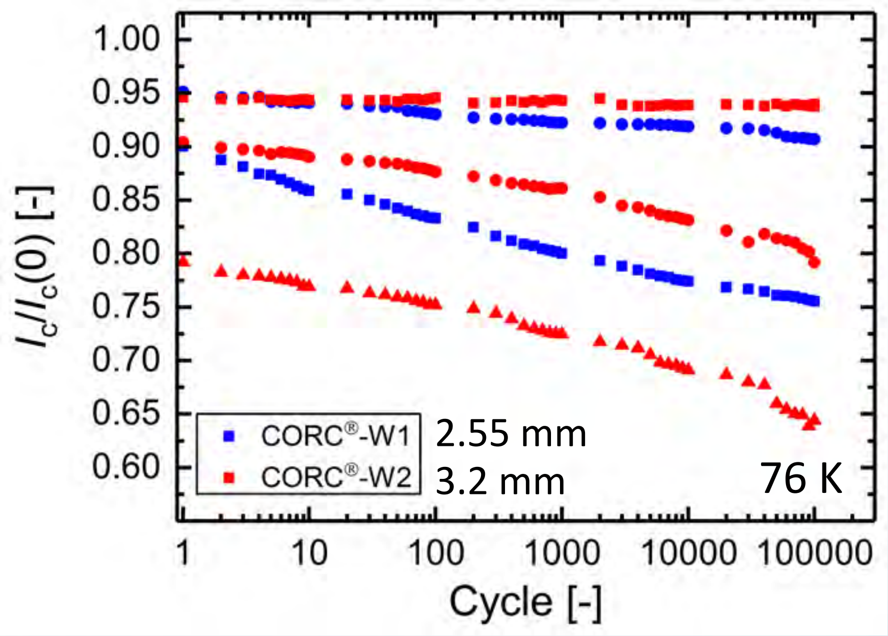
**Test procedure for cycling in liquid nitrogen**

- Each sample is loaded to peak load responding to predetermined $I_c$ retention: 95 – 97 %, 90 %, and 80 %
- Load cycled between 10 % and 100 % of peak load

**CORC® cables**




**CORC® wires**




**Peak load with $I_c$ retention > 95 %: No significant additional $I_c$ degradation after 100k cycles**
**Peak load with $I_c$ retention < 90 %: Additional $I_c$ degradation after 100k cycles < 5 – 10 %**

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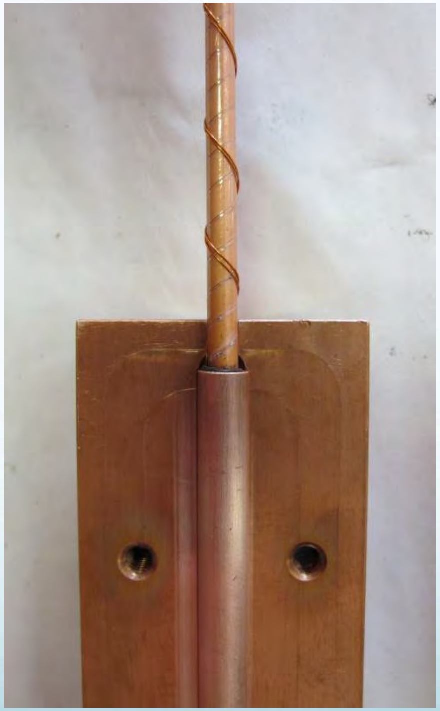
# Axial tensile stress setup

**Testing CORC® wires with copper former**

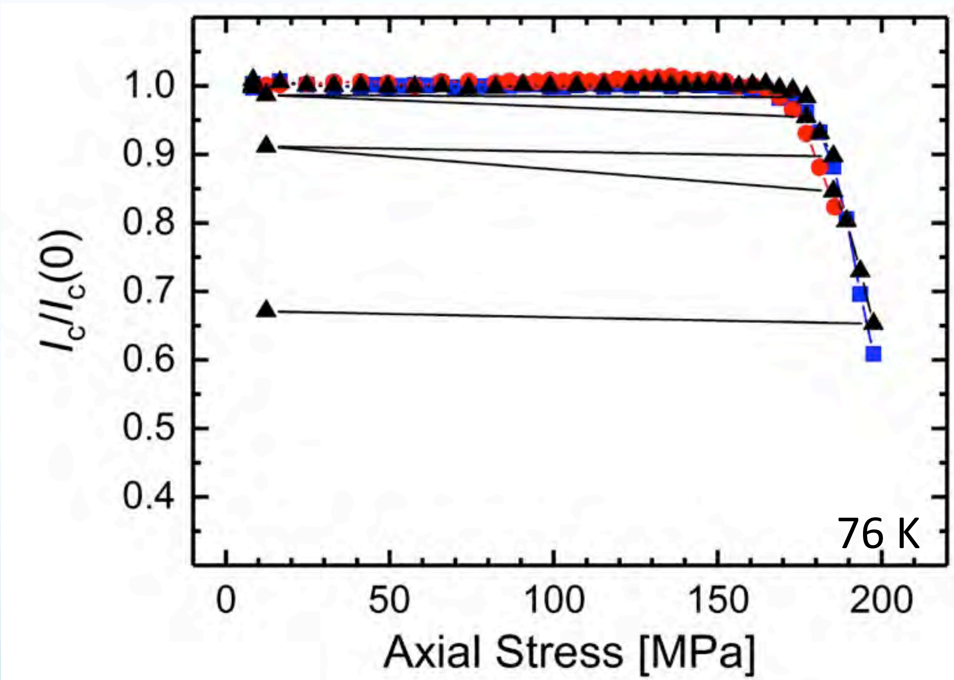
- Test machine capacity = 13 kN
- Load applied through current injection terminals
- Monotonic and cyclic stress applied in liquid nitrogen

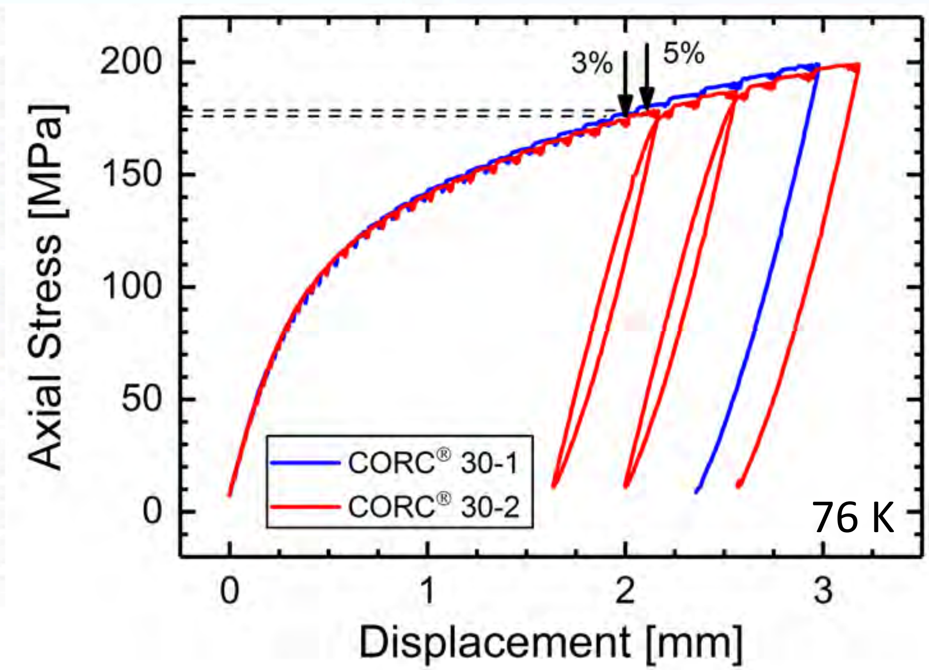


# Monotonic axial tensile stress test results

**Sample details**

- CORC® wire with 30 tapes
- Solid annealed copper former of 2.55 mm diameter

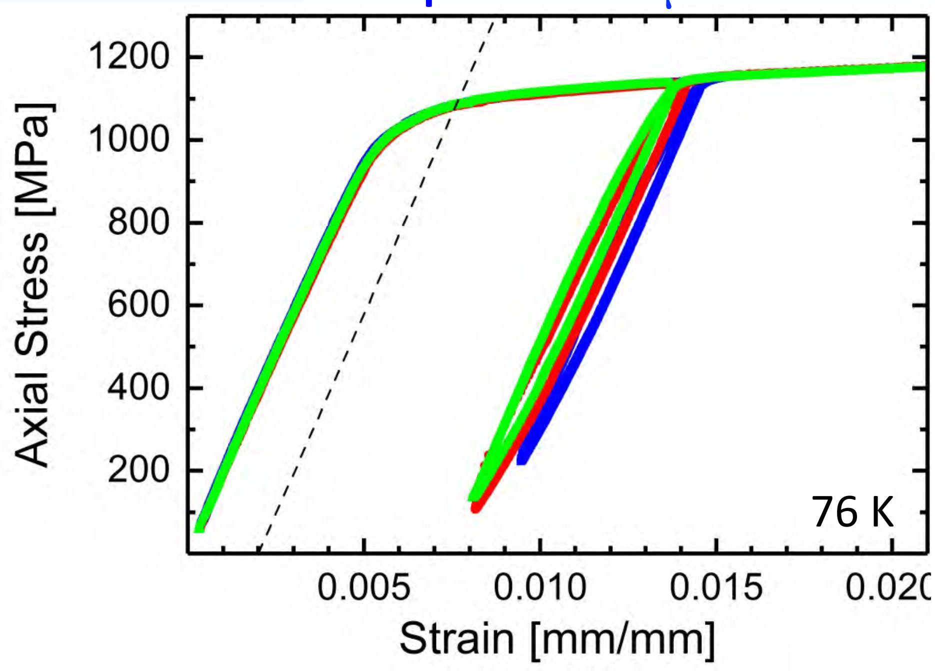


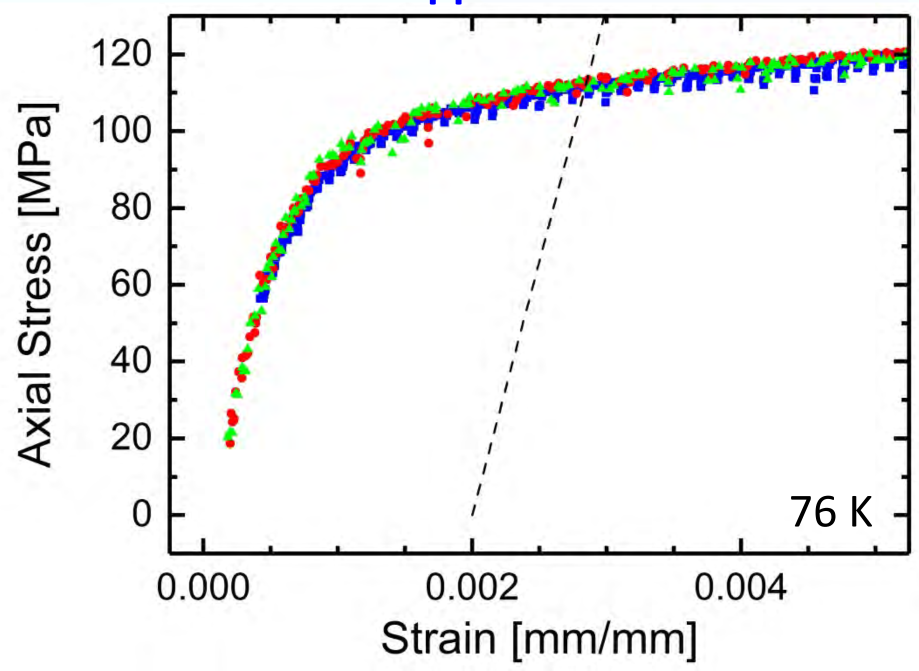

**No reversible $I_c$ reduction before irreversible stress limit of 177 MPa**
**CORC® wire has yielded significantly before $I_c$ degradation occurred**

# Stress-strain of CORC® wire former and tapes

**2 mm wide tapes with 30 μm substrate**




**2.55 mm copper former**




**Yield stress (76 K, 0.2 % strain)**

- **Tapes: 1,092.7 MPa**
- **Former: 109.7 MPa**

# Comparing stress-strain curves of CORC® wires

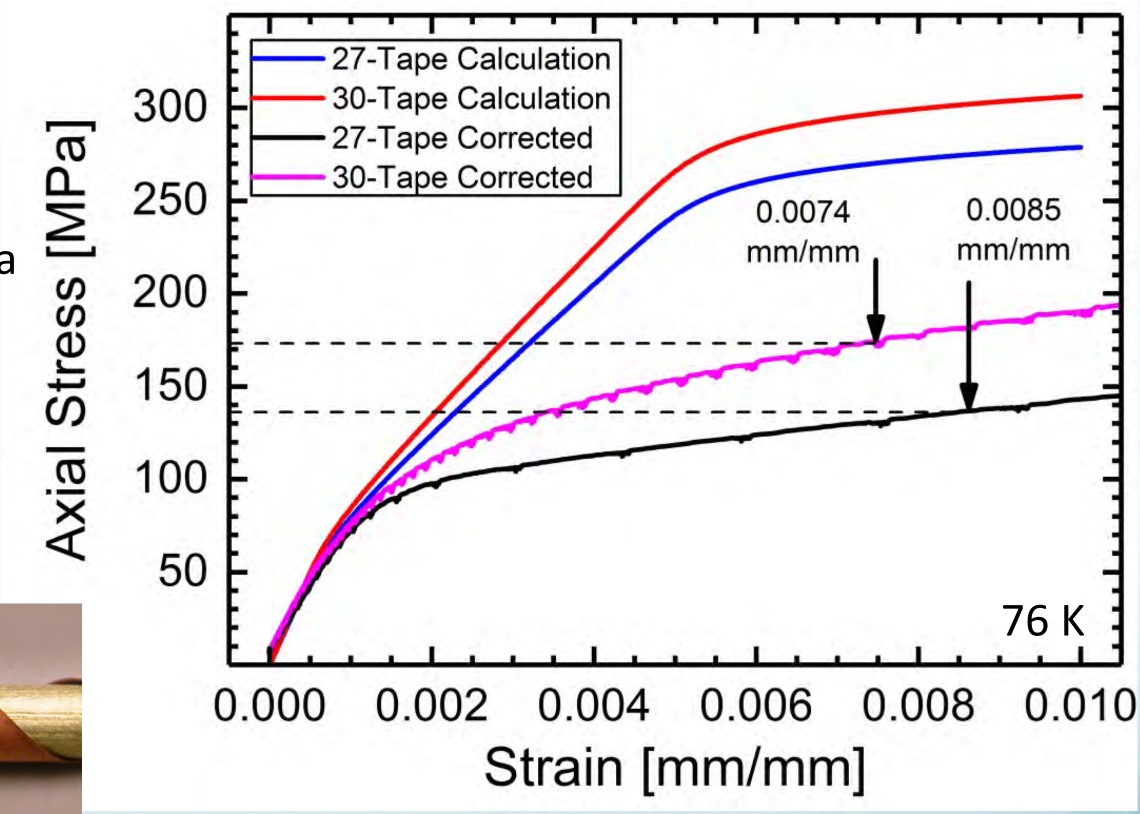
**Stress-strain dependence calculated with rule of mixtures (ROM)**

- 27 or 30 tapes with Yield stress 1,092.7 MPa
- 2.55 mm thick former with Yield stress of 109.7 MPa

**Large difference in CORC® wire Yield stress (0.2 %)**

- ROM: 250 – 270 MPa
- Actual samples: 100 – 120 MPa

**Difference explained by ROM assumes straight parallel tapes, while tapes in CORC® wire are springs**

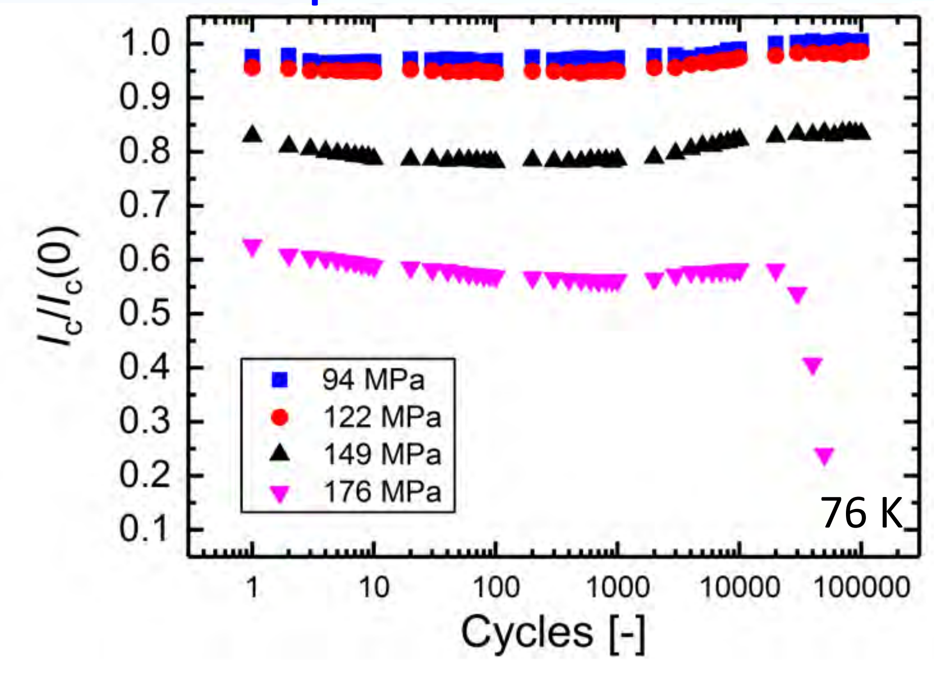



# Axial tensile stress fatigue of CORC® wires

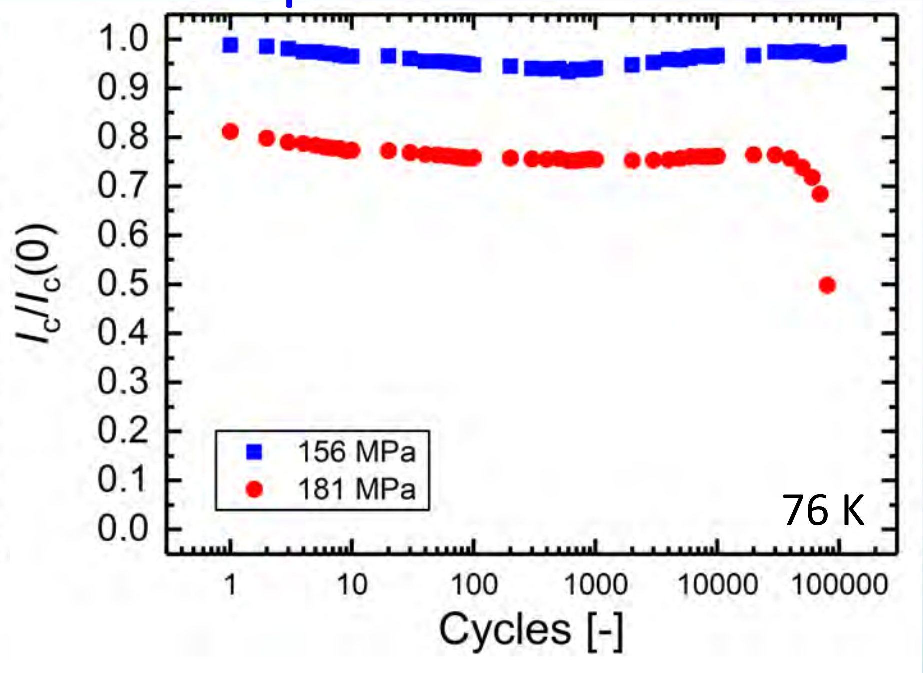
**Test procedure for cycling in liquid nitrogen**

- Each sample is loaded to peak load responding to predetermined $I_c$ retention: 95 – 97 %, 80 %, and 60 %
- Load cycled between 10 % and 100 % of peak load

**27-tape CORC® wire**




**30-tape CORC® wire**




**Source of the change in $I_c$ (decrease followed by recovery) during cycling unknown**
**Once real degradation occurs at stress exceeding the irreversible stress limit, $I_c$ falls off a cliff**

# Conclusions

**Effect of transverse compressive load on CORC® cables and wires**

- Effect of transverse compressive load on CORC® cable and wire $I_c$ was determined at 76 K
- Larger gaps spacing between tapes and thicker copper plating on tapes decrease irreversible load limit
- Irreversible transverse compressive load limit of practical CORC® cables and wires depends on strain state of their tapes after winding
- **Cyclic loading to 100,000 cycles doesn't cause significant additional degradation at peak stress where retention of $I_c$ is > 90 %**
- **First estimate of critical transverse compressive stress: > 230 MPa**

**Effect of axial tensile stress on CORC® wires**

- Effect of axial tensile stress on CORC® wire $I_c$ has been determined at 76 K
- **Critical stress of 30-tape CORC® wire with annealed copper former > 177 Mpa**
- Critical stress can be increased by using harder temper copper in former
- $I_c$ degradation occurs when CORC® wire has yielded significantly
- **Stress cyclic to 100,000 cycles only affects $I_c$ when peak stress much higher than irreversible stress limit**
- **Significant difference in failure mode between transverse compression and axial tension**