Current status of CORC® cables and wires

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CORC® magnet cables and wires overview

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: bending down to 50 mm diameter
- CORC® wires with 25 μm substrate coming soon

CORC® cable (5-8 mm diameter)

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

CORC®-Cable In Conduit Conductor (CICC)

- Performance as high as 100,000 A (4.2 K, 20 T)
- Combination of multiple CORC® cables or wires
- Bending diameter down to 1 meter

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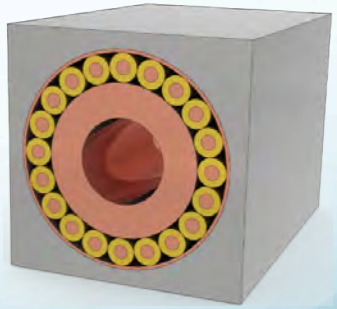


Exploring the mechanical limits of CORC® cables and wires

CORC® cables and wires now being used in actual magnets

- CCT accelerator magnets (Xiaorong Wang – Berkeley National Laboratory)
- Series-connected Common Coil hybrid (Ramesh Gupta – Brookhaven National Lab.)
- CORC® insert solenoid (Applied Superconductivity Center – NHMFL)

=> See talk Jeremy Weiss Wednesday 9:35 AM

Conductor requirements for safe use in magnets

- Electrical performance: I_{opp} > 5 – 20 kA and J_e > 300 – 600 A/mm^2
- Sufficient copper fraction of around 50 %
- Sufficient conductor transposition
- **Mechanical strength to ensure no performance degradation**

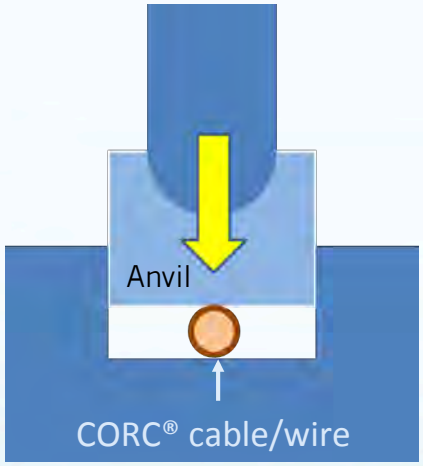
Major campaign underway to determine, understand and improve the mechanical performance of CORC® cables, wires and CICC

- Transverse compressive stress
- Axial tensile stress
- Conductor reinforcement where required

Application of transverse compressive load

Load applied by two flat stainless steel anvils

- Results in two line contacts
- Contac width likely changes with load
- Conversion of kN/m to MPa requires contact width to be known
- Top anvil 50 mm, bottom anvil 115 mm in length



D. C. van der Laan, D. M. McRae, and J. D. Weiss, *Supercond. Sci. Technol.*, **32**, 015002 (2019).

Load applied at 76 K in liquid nitrogen

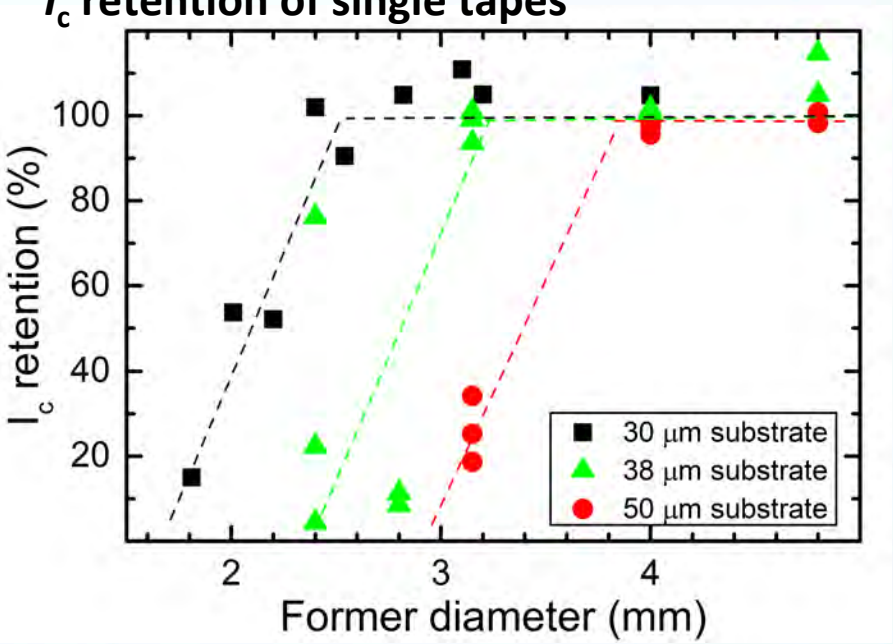
Effect of former size and substrate thickness

Minimum former size in CORC®

- Depends on substrate thickness
- About 4 mm for tape with 50 μm substrate
- About 2.3 mm for tape with 30 μm substrate

Critical winding strain -1.25 %

I_c retention of single tapes

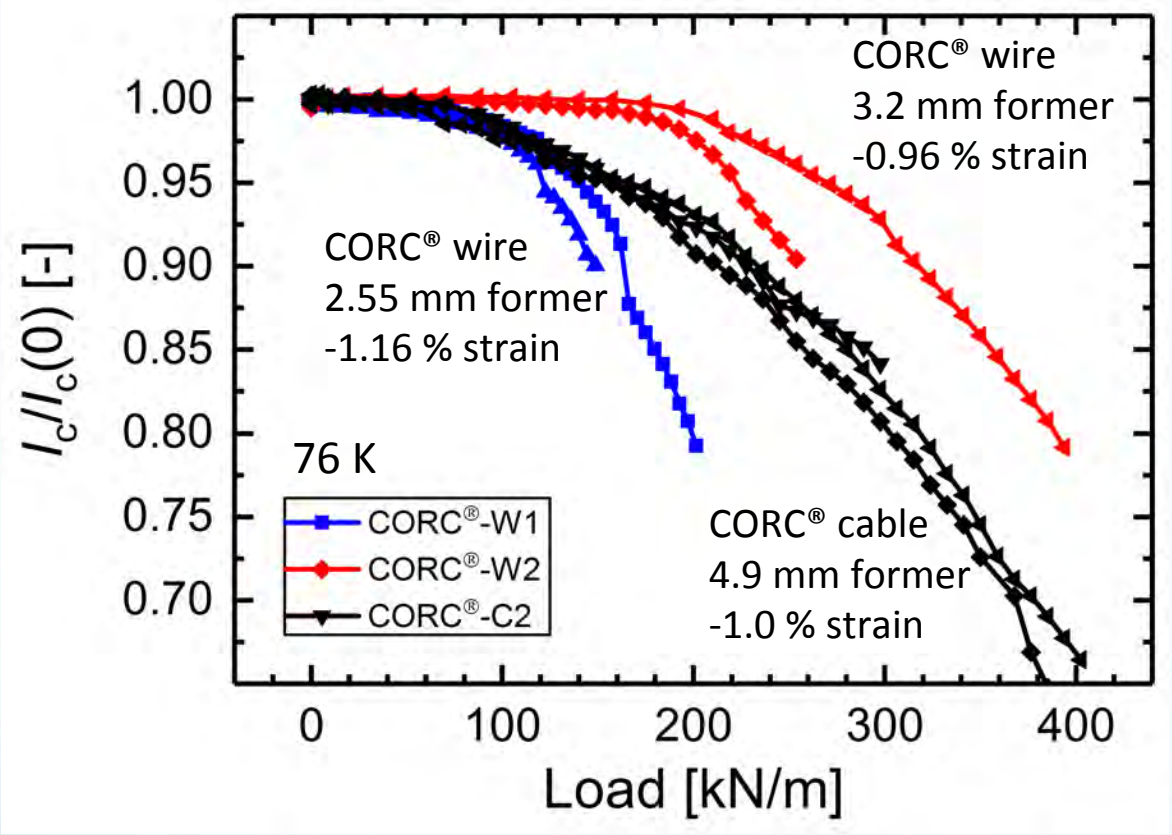


Transverse compression may reduce minimum tape bending diameter!

CORC® cables and wires to be studied

- 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 %

Transverse Compression on CORC® cables and wires



- **Initial REBCO strain state affects resilience to transverse compression**
- **Initial CORC® wire optimization already doubled the critical load**

Is the critical load high?

=> 200 kN/m corresponds to 10 kA operating current at 20 T.

Yes the critical load is already high, but could likely be extended!

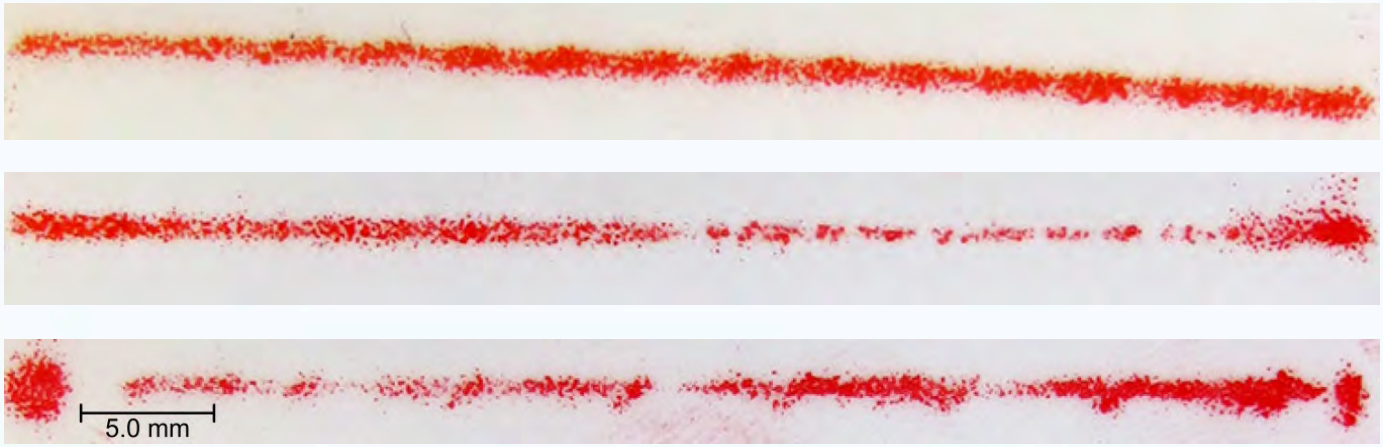
Critical load [kN/m]

I_c/I_{c0}	CORC®-C1	CORC®-W1	CORC®-W2
0.97	124	115	217
0.95	160	133	243
0.9	226	163	284

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 stress [MPa]

I_c/I_{c0}	CORC®-C1	CORC®-W1	CORC®-W2
0.97	138	99	241
0.95	178	115	270
0.9	251	141	316

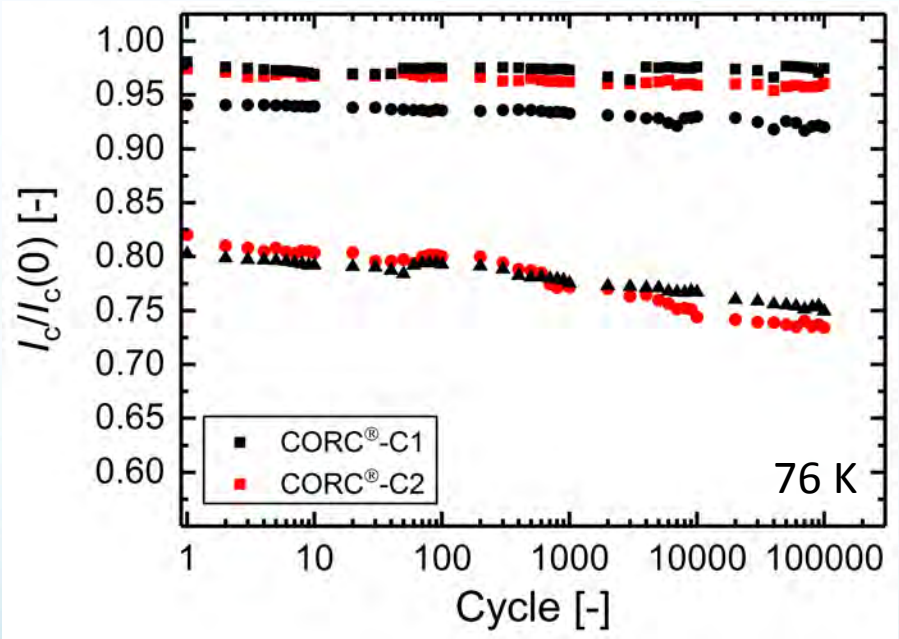
Critical transverse compressive stress > 240 MPa in optimized CORC® cables and wires

Effect of transverse compressive load cycling

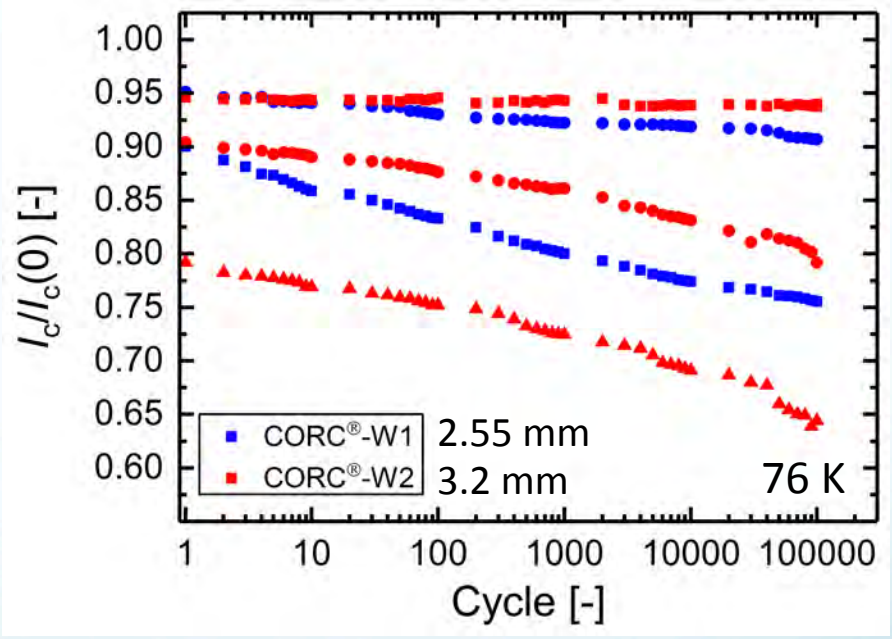
Test procedure for load cycling in liquid nitrogen

- 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 – 15 %

Axial tensile stress setup

Testing CORC® wires with copper former

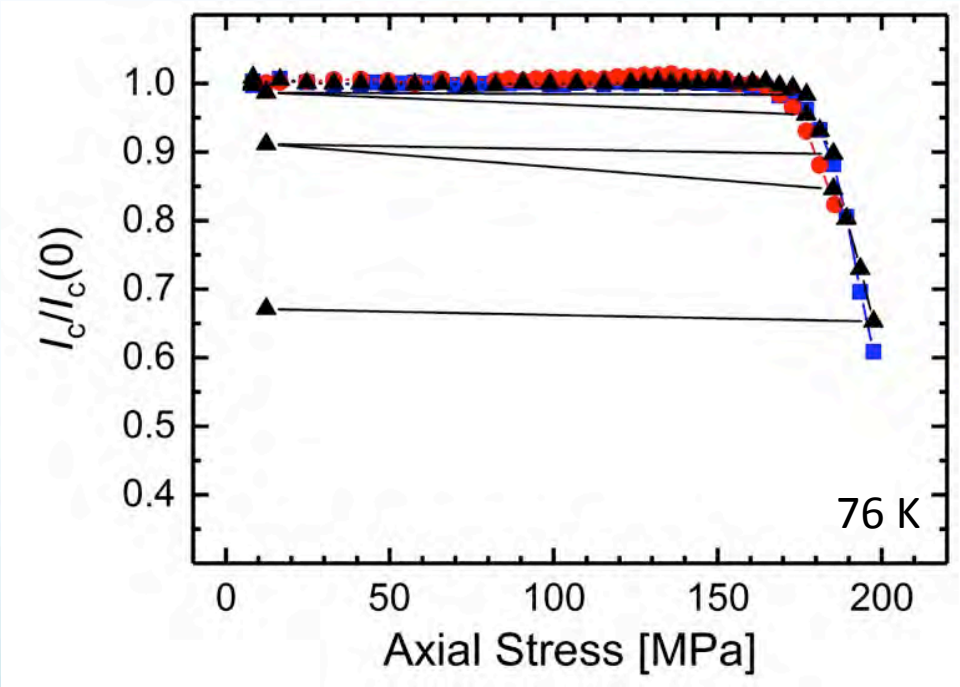
- Test machine capacity = 13 kN
- Load applied through current injection terminals
- Monotonic and cyclic stress applied in liquid nitrogen

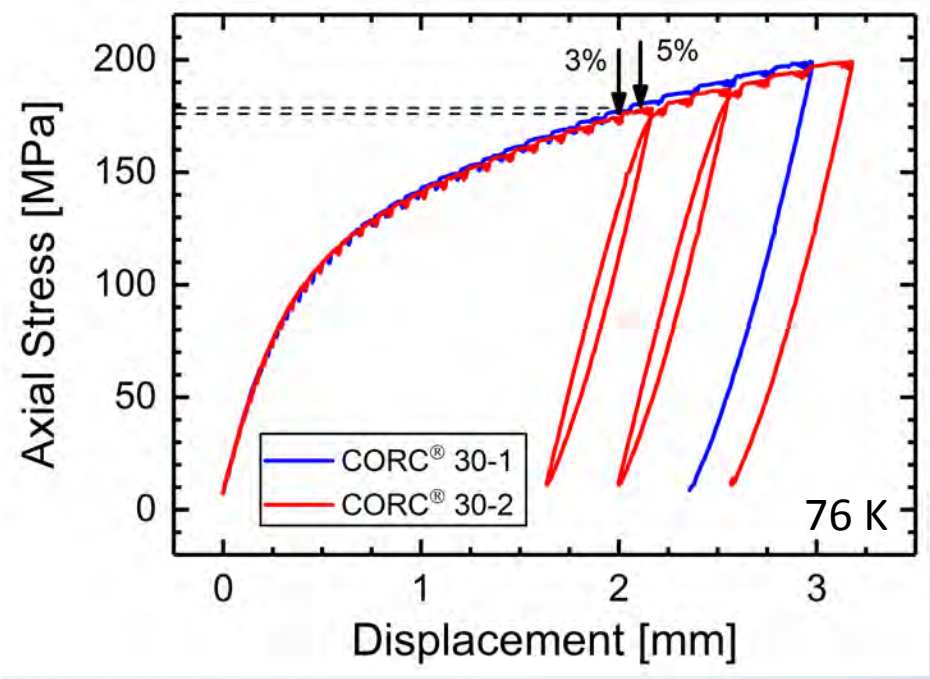
D. C. van der Laan, D. M. McRae, and J. D. Weiss, *accepted for publication Supercond. Sci. Technol.*, (2019)

Monotonic axial tensile stress test results

Sample details

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

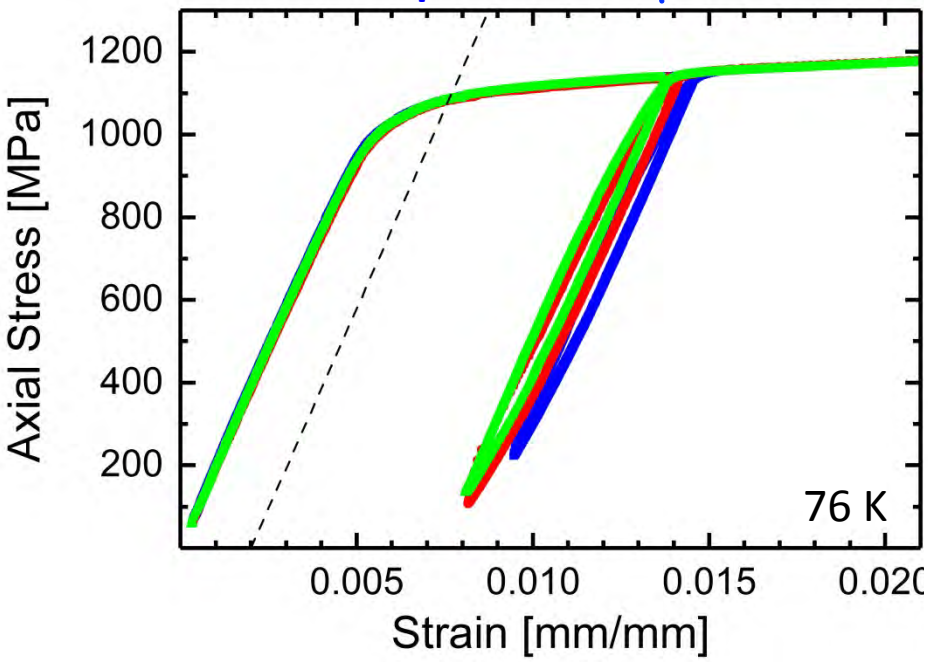




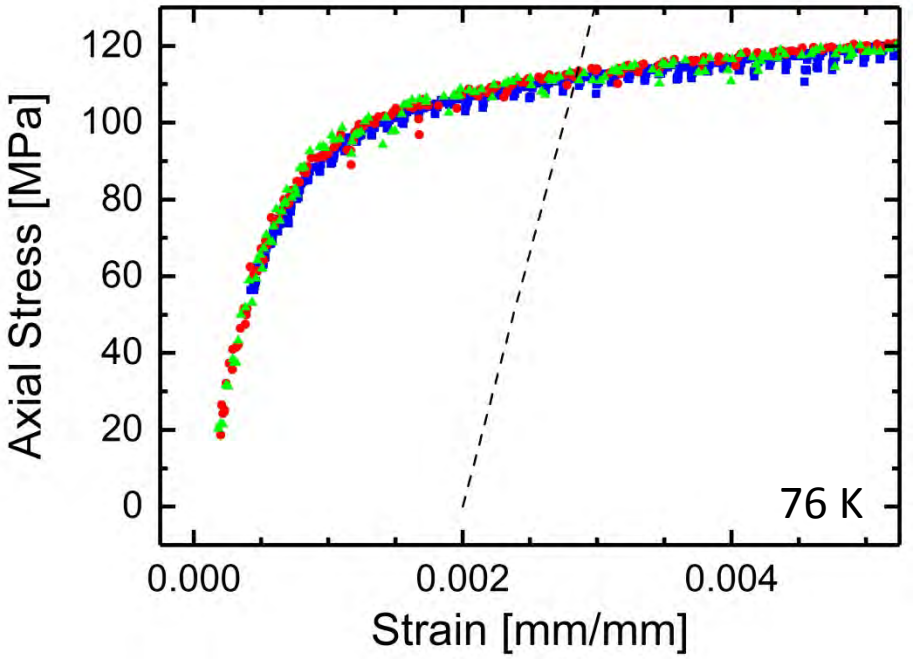
- **No reversible I_c reduction before irreversible stress limit of 177 MPa**
- **CORC® wire has yielded significantly before I_c degradation occurred**

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

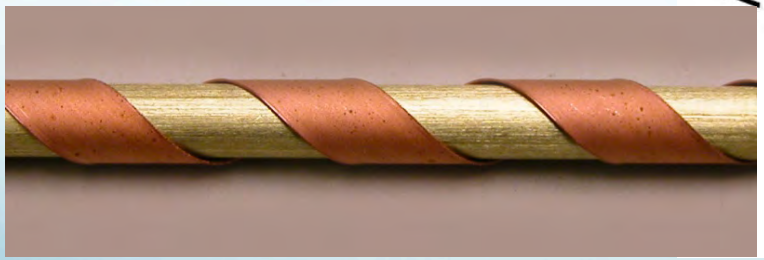
Stress-strain dependence calculated with rule of mixtures (ROM)

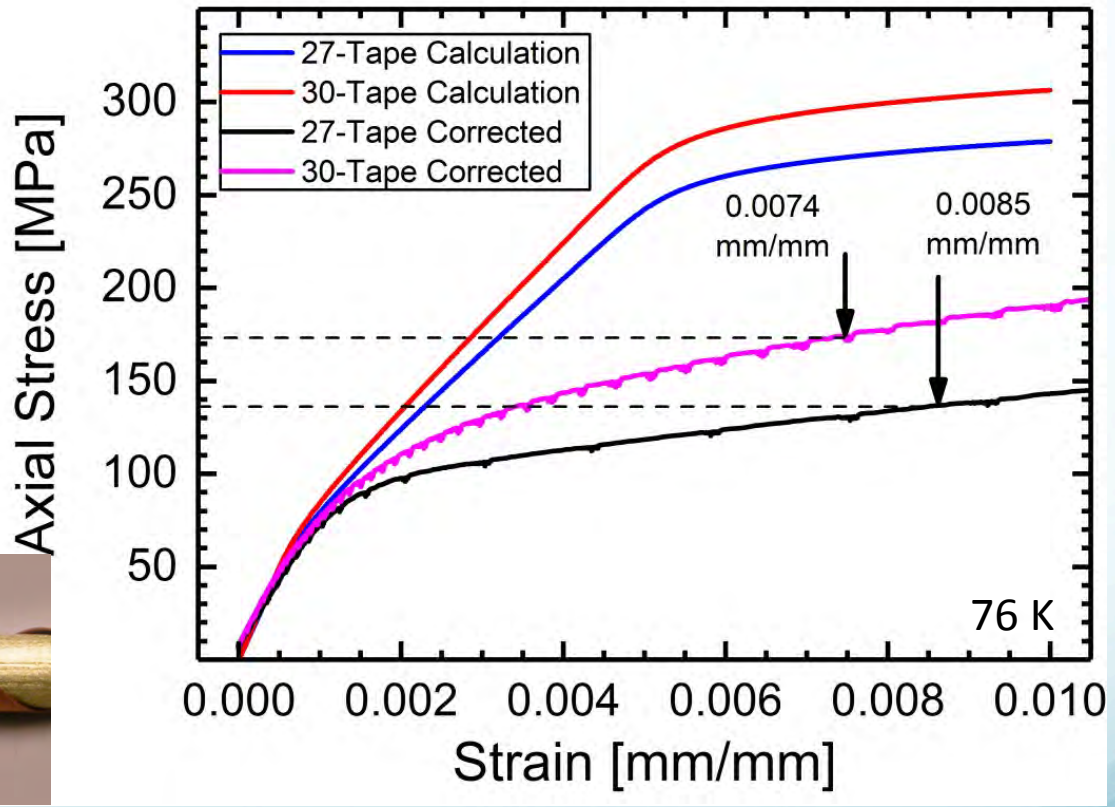
- 27 or 30 tapes with Yield stress 1,092.7 MPa
- 2.55 mm thick former with Yield stress of 109.7 MPa

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





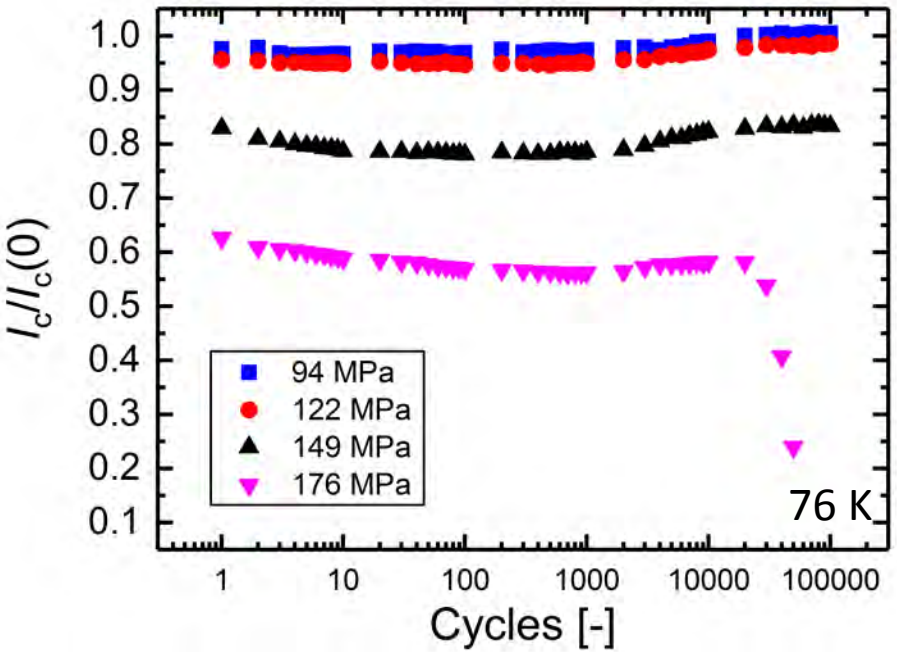
Critical stress could be increased significantly by using harder Cu formers

Axial tensile stress fatigue of CORC® wires

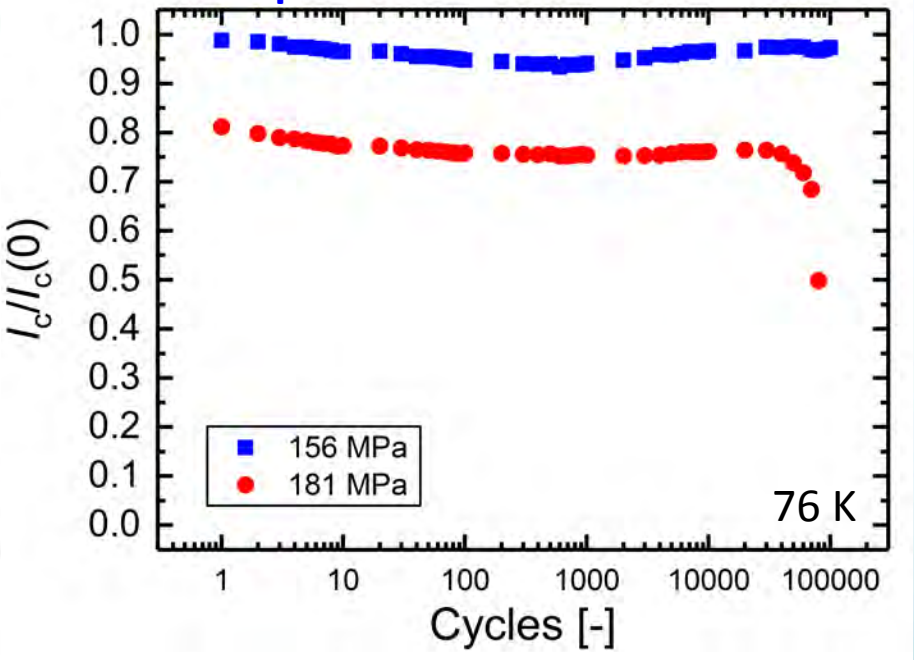
Test procedure for cycling in liquid nitrogen

- 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

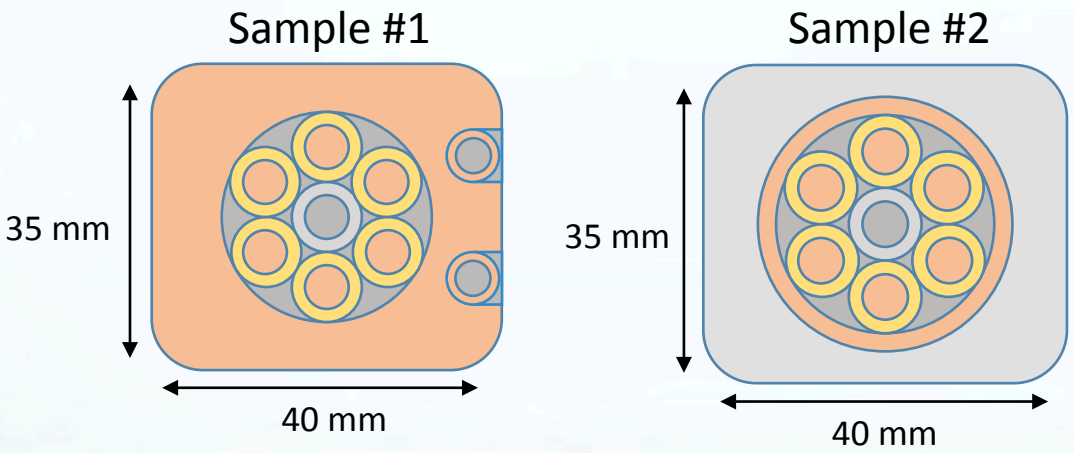


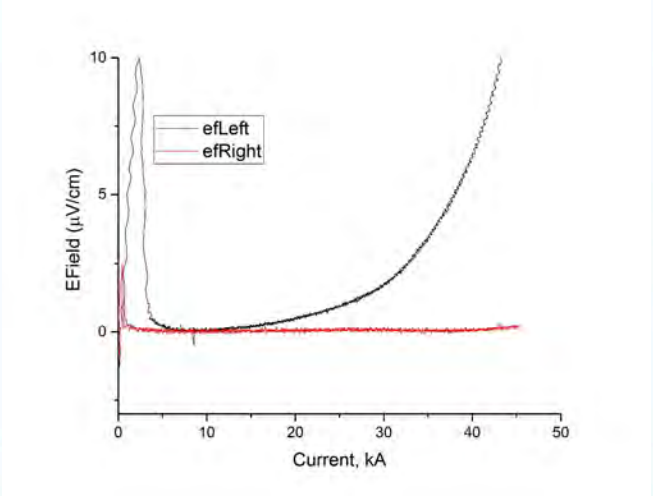
- **Source of the change in I_c (decrease followed by recovery) during cycling unknown**
- **Once degradation occurs at stress exceeding the irreversible stress limit, I_c falls off a cliff**

CORC®-CICC development for testing in SULTAN

CORC®-CICC #1 and #2 for testing in SULTAN

- Collaboration with Herman ten Kate and Tim Mulder (CERN)
- Both samples are 6-around-1 CICC based on CORC® cables
- Goal is 80 kA at 10.8 T background field

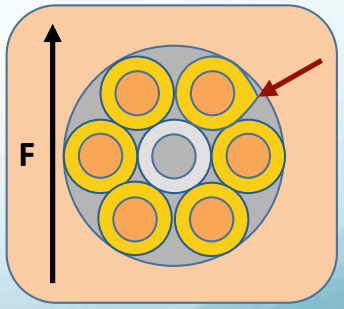




Initial SULTAN test results

- Sample #1 degraded due to strand deformation
- Sample #2 was limited to current of less than 50 % of I_c due to damaged Sample #1

Sample #1 has been replaced and next test is planned within 3 months

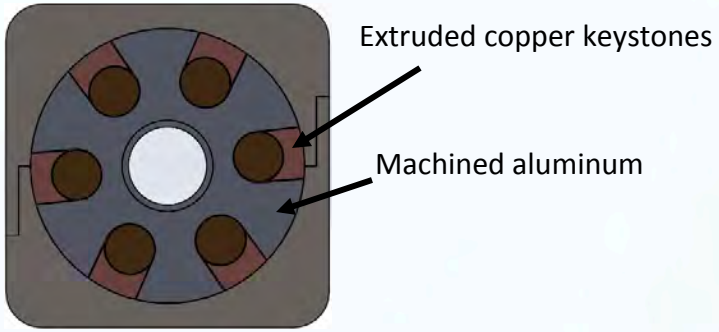


CORC®-CICC development for testing in SULTAN (Cont.)

CORC®-CICC #3 for testing in SULTAN

- Collaboration with Herman ten Kate and Tim Mulder (CERN)
- 6-around-1 CICC based on CORC® cables
- Goal is 80 kA at 10.8 T background field
- Using internal support to decouple CORC® strands
- Improved CORC®-CICC terminals
- SULTAN test in 5 − 6 months

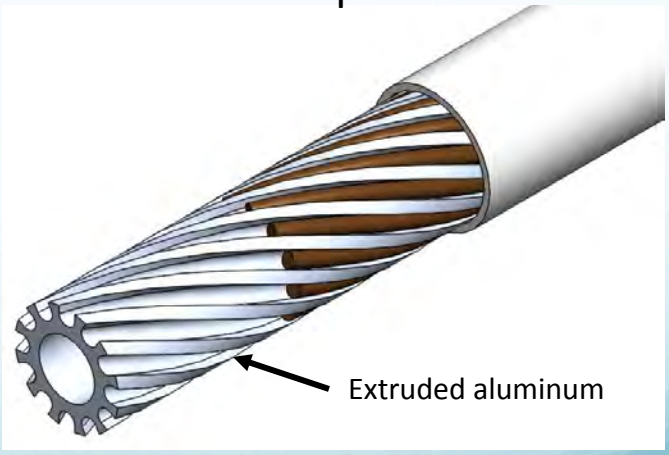
Sample #3



CORC®-CICC #4 for testing in SULTAN

- Collaboration with Herman ten Kate, Tim Mulder (CERN) and Xiaorong Wang (LBNL),
- Based on CORC® 12 − 14 wires for higher degree of transposition and better flexibility
- Goal is 80 kA at 10.8 T background field
- Using internal support to decouple CORC® strands
- SULTAN test in 9 − 12 months

Sample #4



Conclusions

Effect of transverse compressive load on CORC® cables and wires

- 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 %
- Increase of irreversible stress limit possible using thicker and/or harder formers

Effect of axial tensile stress on CORC® wires

- Critical stress of 30-tape CORC® wire with annealed copper former > 177 Mpa
- Critical stress could likely be increased by using harder temper copper in former
- Stress cyclic to 100,000 cycles only affects I_c when peak stress much higher than irreversible stress limit

Development of CORC®-CICC for SULTAN test

- Three samples planned for testing in 2019
- Internal support to decouple CORC® strands to prevent cumulative stresses
- Improved CORC®-CICC terminations with lower resistance and improved current distribution