This work was in part supported by the US Department of Energy under agreement numbers DE-SC0009545, DE-SC0013723, DE-SC0014009, DE-SC0015775, DE-SC0018125, DE-SC0018127 and DE-SC0018710.

# Recent Progress on CORC® Cables and Wires for High-Field Magnet Applications

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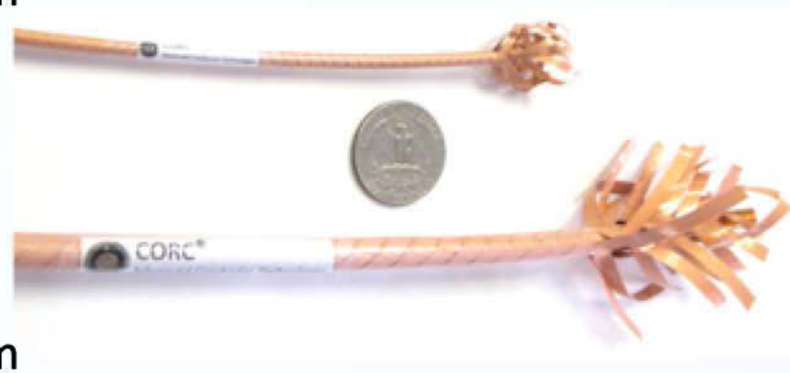
LTSW, February 28th, 2020, San Francisco, CA

# CORC® magnet cables and wires

**CORC® wires (2.5-4.5 mm diameter)**

- Wound from 2-3 mm wide tapes with 25-30 μm thick substrate
- Typically no more than 30 tapes
- Isotopically flexible with bending down to < 50 mm diameter

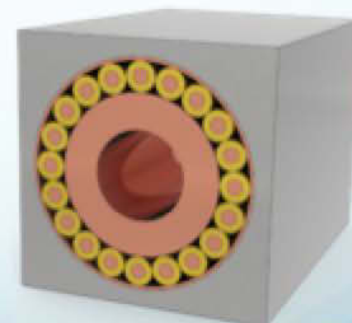


**CORC® cables (5-8 mm diameter)**

- 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

**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 about 1 meter



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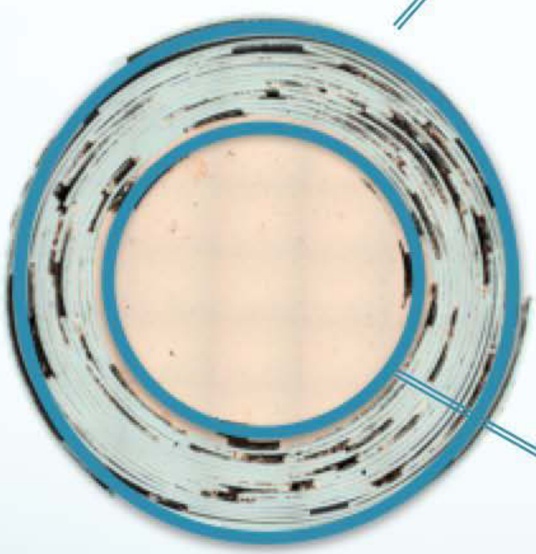
# Present anatomy of a high $J_e$ CORC® wire

2 mm wide REBCO Tapes
(60-40% area)

- Hastelloy (51%)
- Copper (17%)
- Void/lubricant (17%)
- CORC® insulation (8%)
- Silver (4%)
- ReBCO (2-3%)

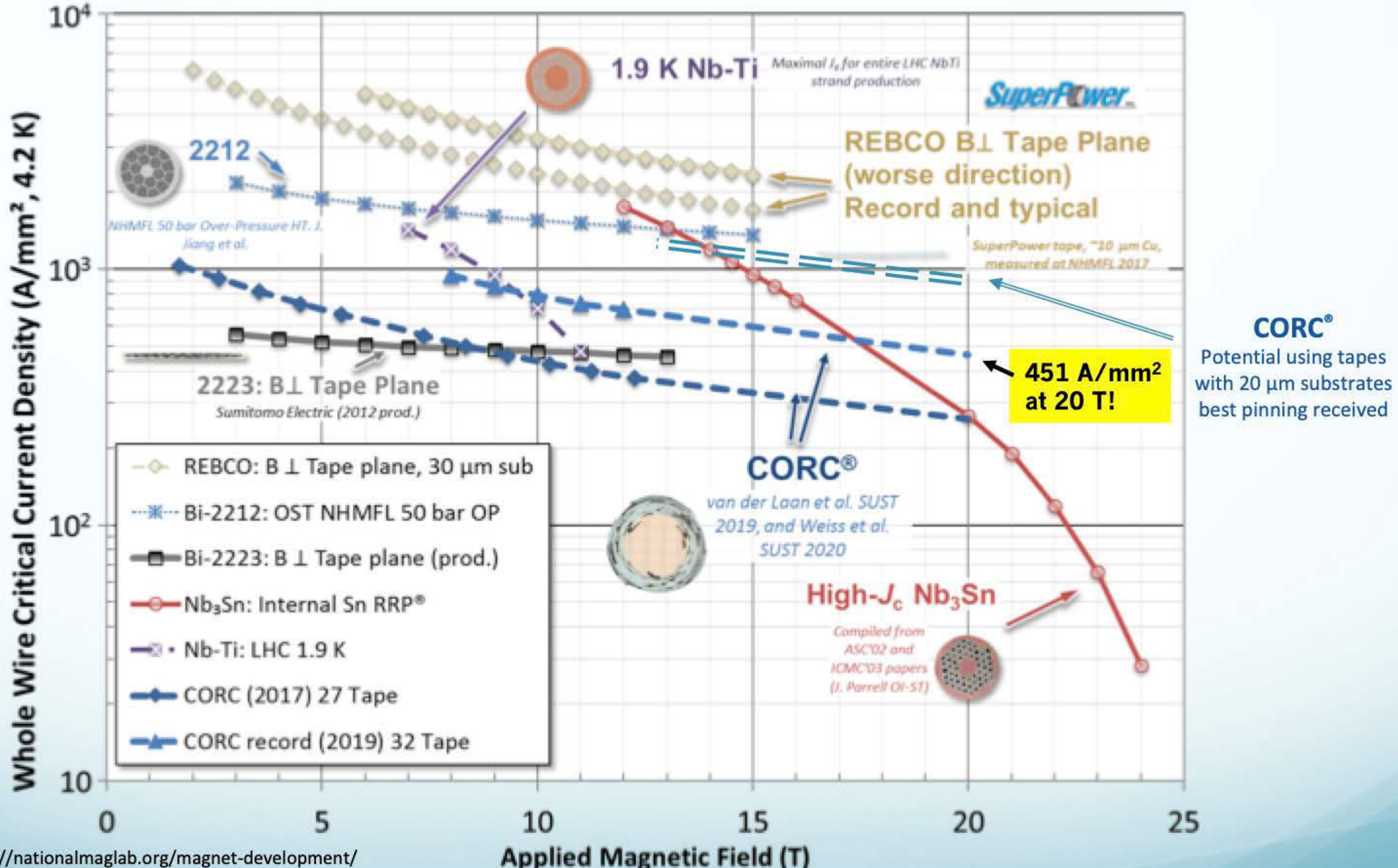


**Transverse cross section**

Core / former
(40-60% area)

- Typically OFHC copper
- Could be stronger
- Could be functional

# CORC® $J_e$ comparison to high-field magnet wires




Data from https://nationalmaglab.org/magnet-development/applied-superconductivity-center/plots

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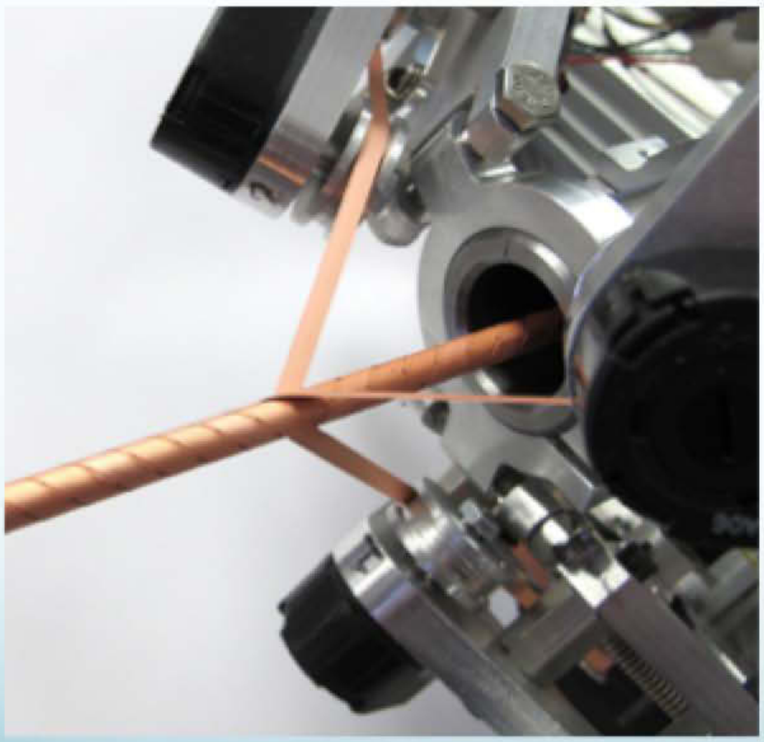
# CORC® production

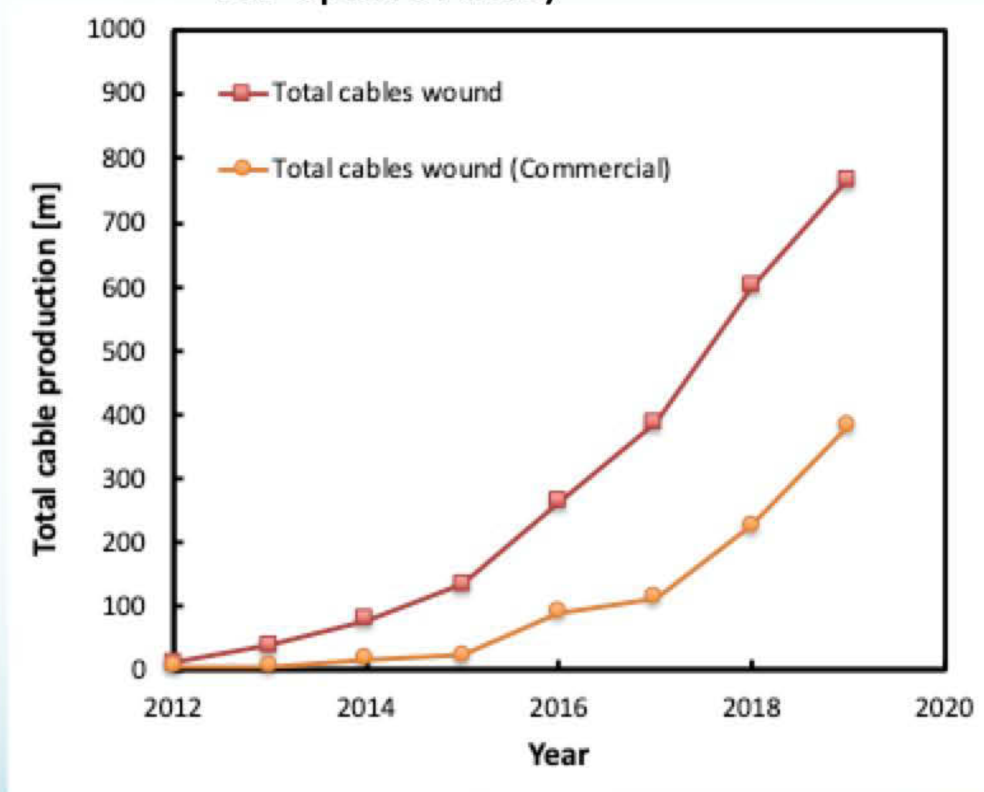
**Winding of long CORC® cables and wires with custom machine**

- Accurate control of cable layout
- Long cable lengths possible (> 100 meters)
- $I_c$ retention after winding 95-100 %

**Cumulative CORC® production**

- about 800 meters since 2012
- includes 400 meters for commercial orders (including about 130 meters for open orders)





# Newest CORC® wires demonstrated

Pushing the limits

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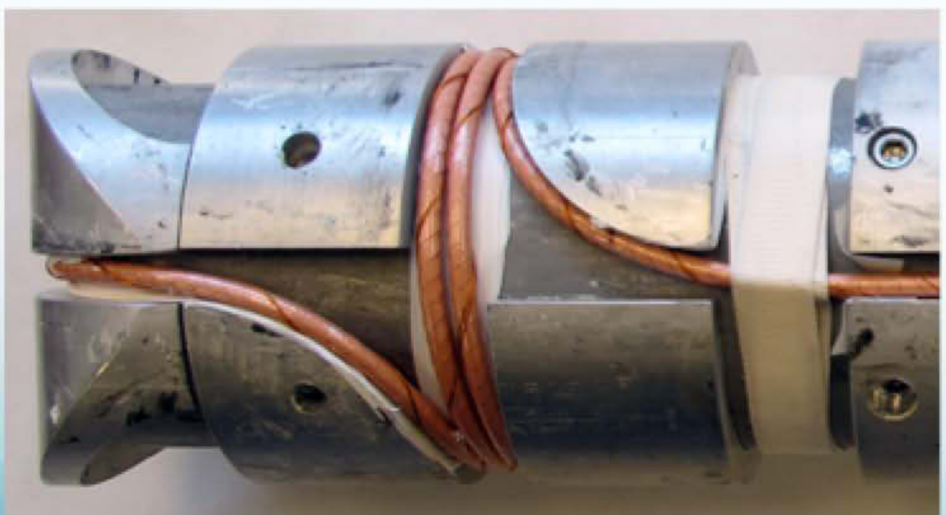
# Increasing $J_e$(20 T) in CORC® wires

**CORC® wires introduced 2016**

- Typically smaller than 4 mm thickness
- Wound from 2 and 3 mm wide tapes
- Wound from tapes with 30 μm substrates
- Bending down to 50 mm diameter allows testing in typical superconducting R&D magnets
- Testing now in 12 T solenoid magnet

Testing in 12 T magnet

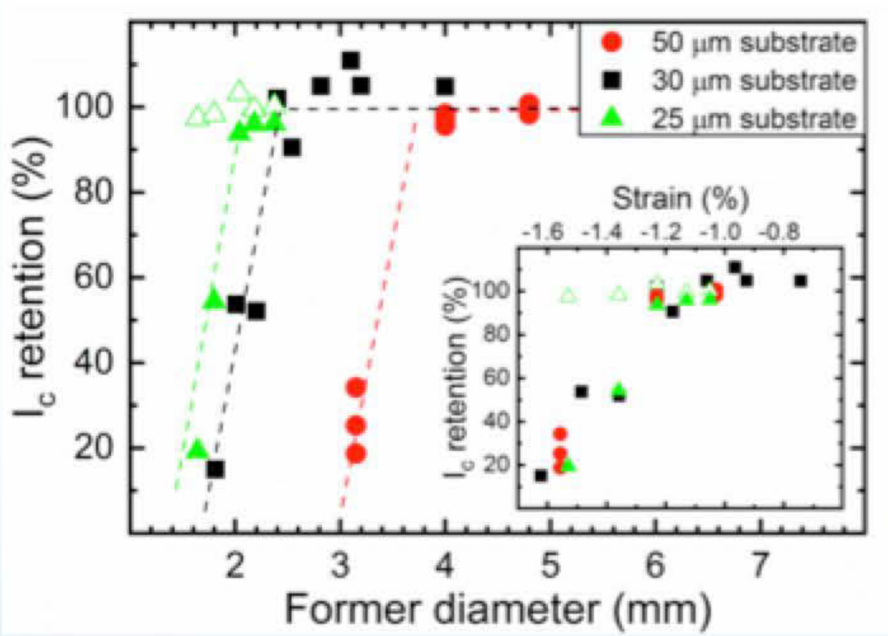
CORC® wire mounted on 63 mm diameter probe



# Increase $J_e$(20 T) by reducing the former size

**Thinner substrates allow smaller formers in CORC® cables**

- Winding a tape at 45 degrees with the REBCO layer **under compression**
- Measure $I_c$ at different former diameters



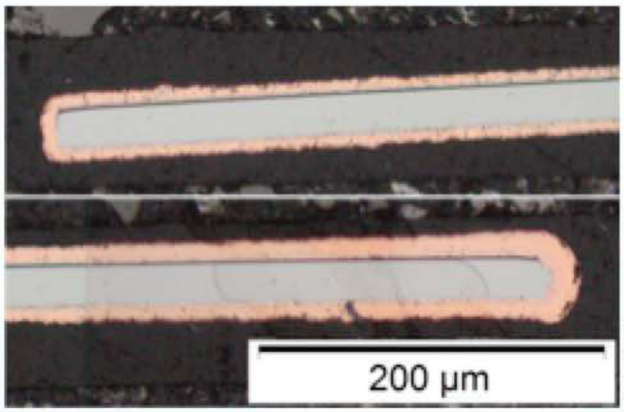

**Minimum former diameter**

- 4 mm for 50 μm substrate
- 3.2 mm for 38 μm substrate
- 2.4 mm for 30 μm substrate
- 2.0 mm for 25 μm substrate

# Introduction of REBCO tapes with 25 μm substrates

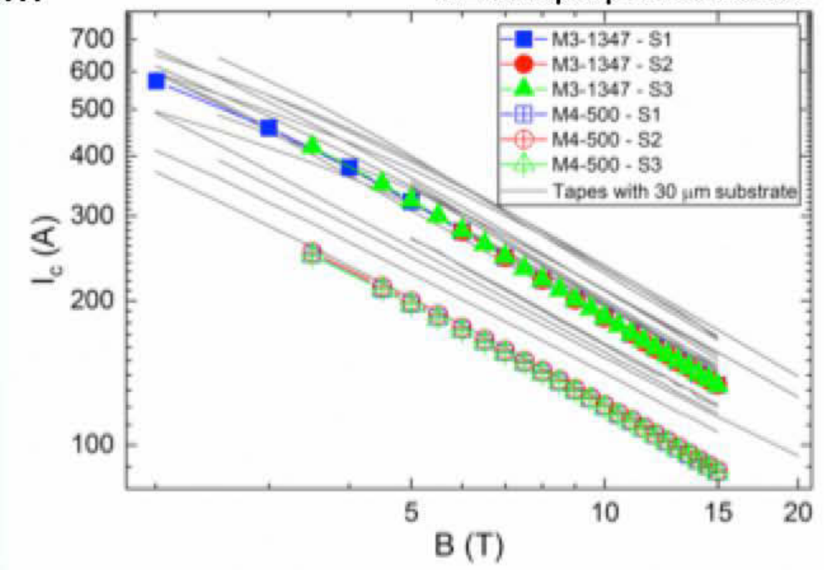
**SuperPower produced first batches of tape with 25 μm substrate**

- 400 meters of high-quality tape of 2 mm width delivered
- $I_c$(77 K) = 65 A and 4.2 K pinning similar to 30 μm
- Piece lengths in the order of 30 meters
- Actual substrate 22 – 23 μm thick
- Enables CORC® wires with 2 mm former




Picture courtesy of M. Small (ASC-NHMFL)

4.2 K tape performance




Data Courtesy of A. Francis and D. Abraimov (ASC-NHMFL)

TapeStar $I_c$(77 K) data

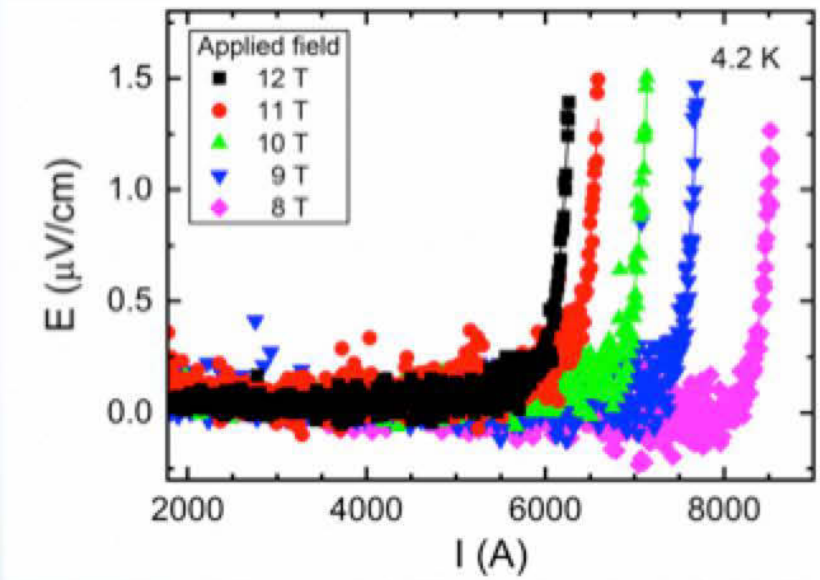
# Performance of next generation CORC® wires

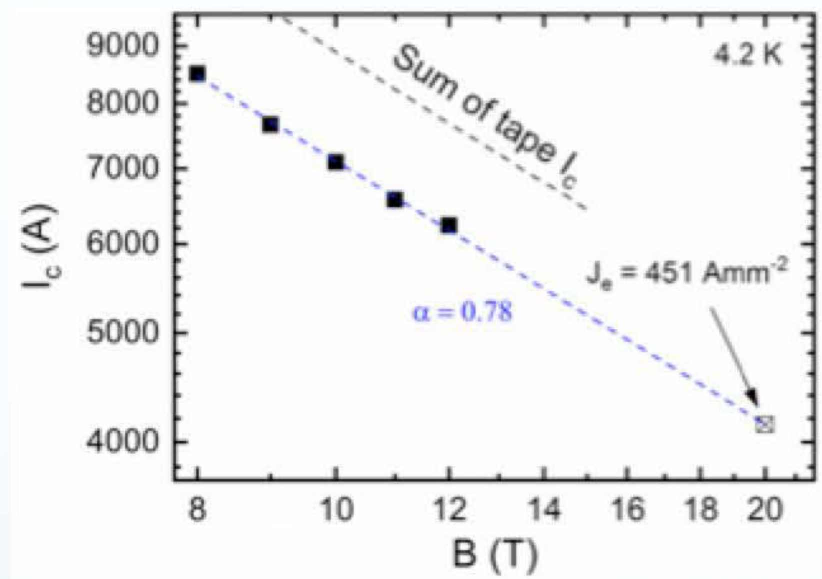
**CORC® wire to increase $J_e$(20 T)**

- 32 tapes
- 2 mm (25 μm) and 3 mm (30 μm) width
- Outer diameter 3.42 mm

Record CORC® wire (25 μm)

Record CORC® wire (30 μm)




**New record $J_e$ (12 T) 678 A/mm$^2$**
**Extrapolated $J_e$ (20 T) 451 A/mm$^2$**
**$I_c$(B) closely follows that of the tapes**

Weiss et al **SUST** 2020
https://doi.org/10.1088/1361-6668/ab72c6

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A Furukawa Company

# Integrated diagnostics

Smart conductors for complicated times

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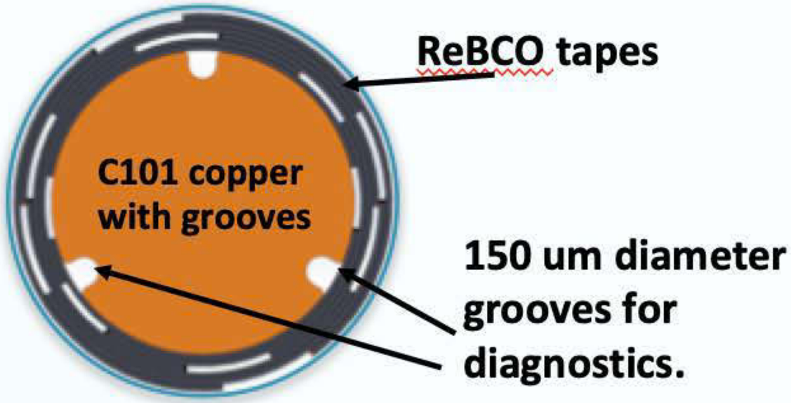
# CORC® Wires with integrated diagnostics

**Wire cross section**

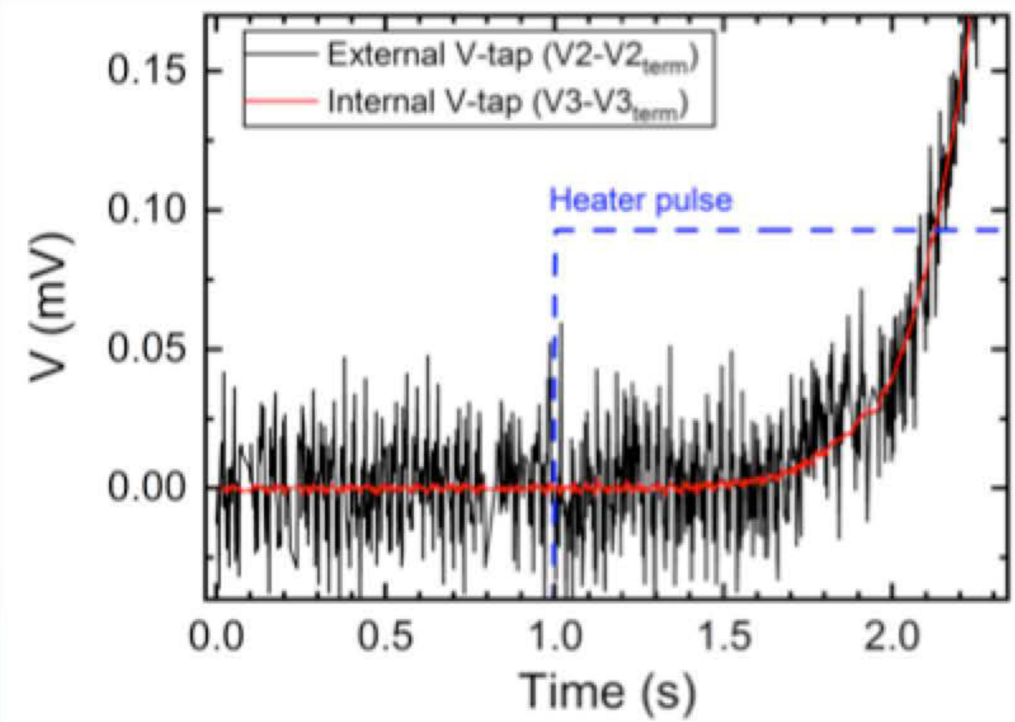



Grooved former allows integrated voltage taps, optical fibers, quench heaters, etc.

**Voltage tap exits the CORC wire termination**

# Voltage measured using heater induced hotspot

**Voltage measured over the sample terminations**




I ~ 350 A (85% of $I_c$)
76 K

**Internal V-Tap wire is tightly confined within CORC® wire following the current-path with almost no separation**

**Noise is much lower for internal V-Tap compared to external V-tap**

**5 m Long sample compared to 0.5 m Long sample show similar noise floor**

**Very little inductive pick-up, even at very high current ramping**

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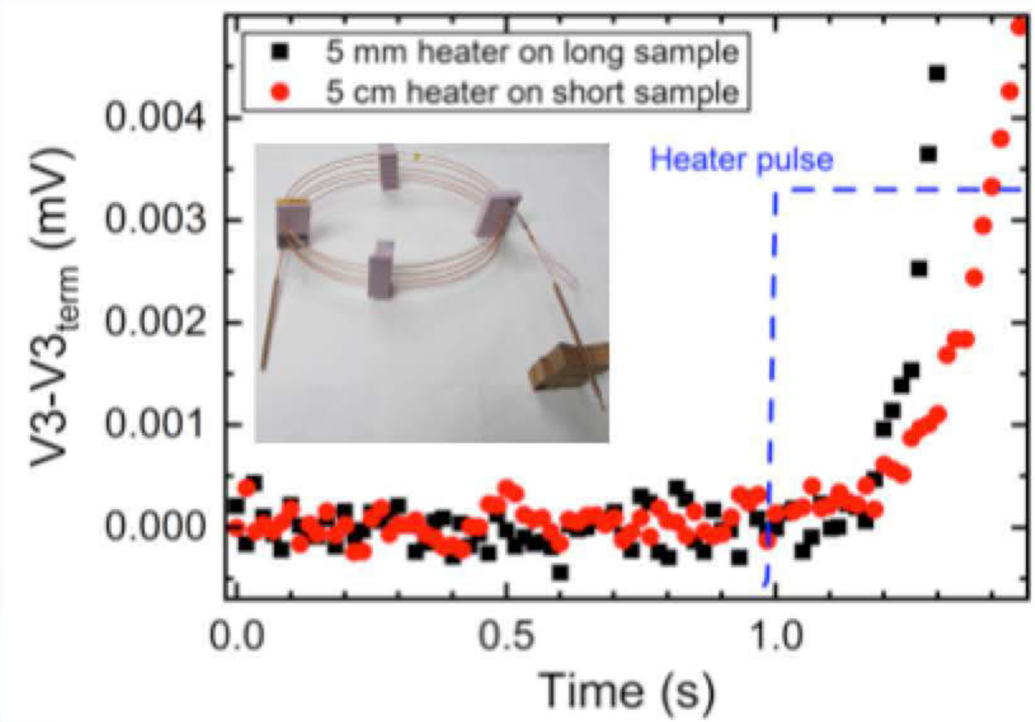


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# Mechanical properties of CORC®

Where are the limits and how do we push them?

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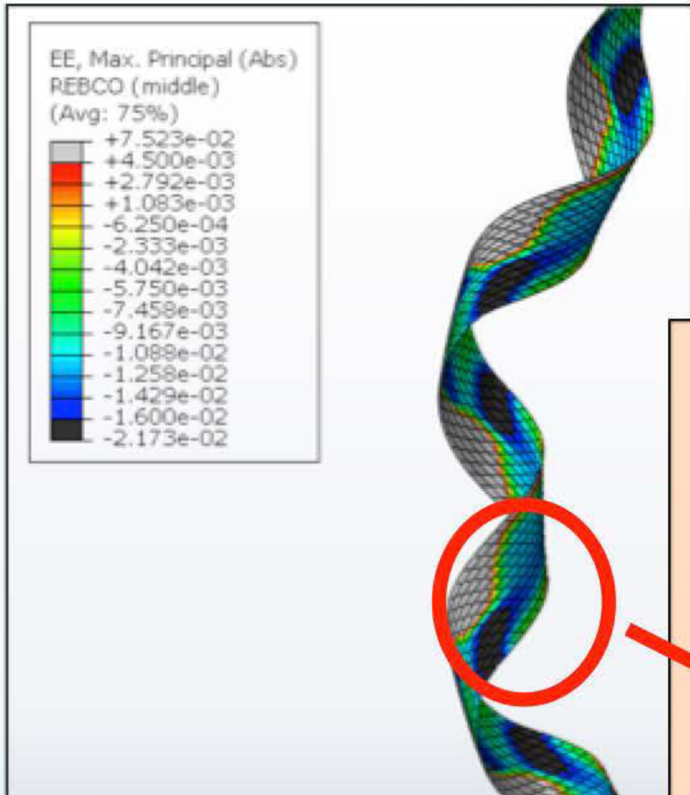
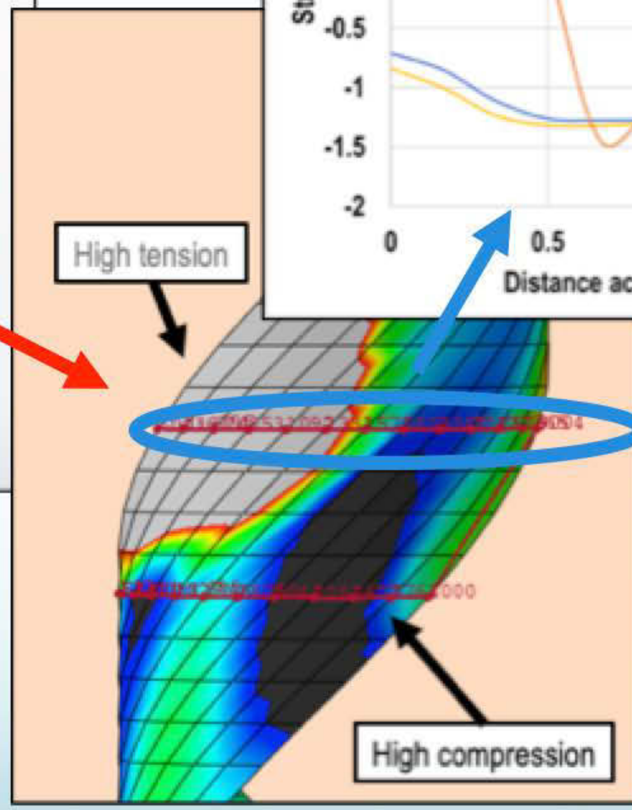
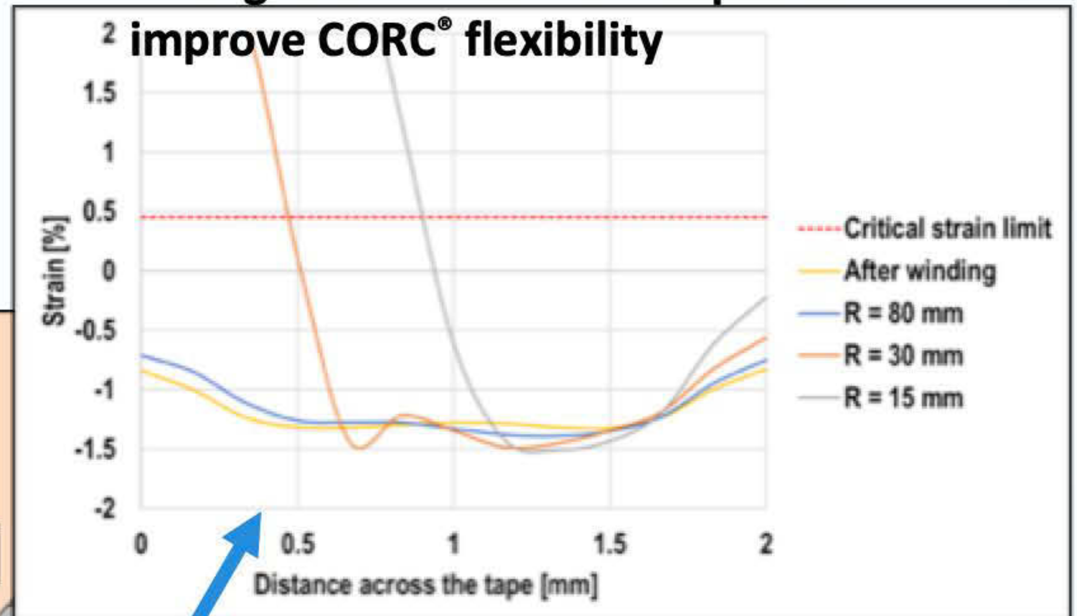
# Bent tape helix puts tape edge under tension




**Strong case for narrower tapes to improve CORC® flexibility**




**Cabling of tape into CORC® puts ReBCO layer under compressive pre-stress. This is a really good thing.**

A. Nijhuis, V.A. Anvar et al.

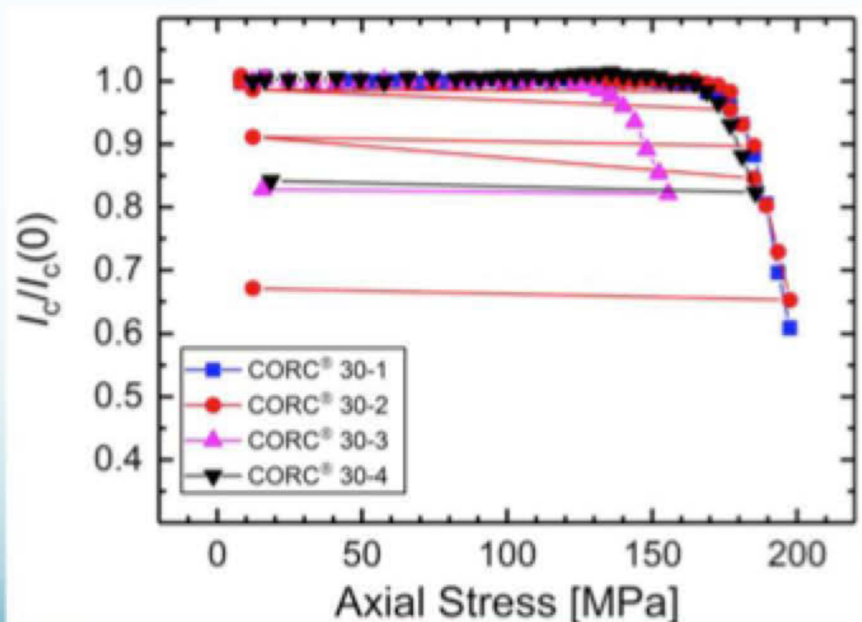
# Axial tension measurements

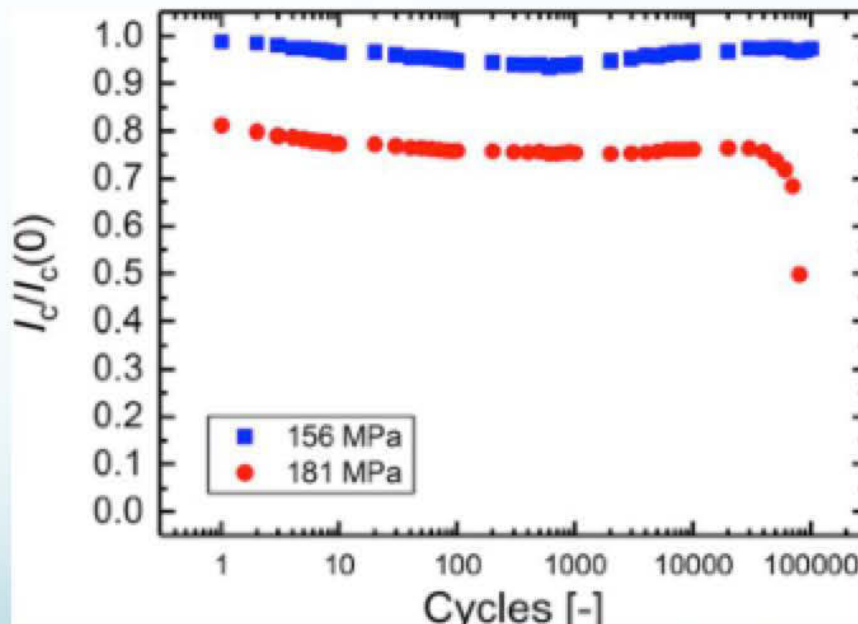
**Test Setup**

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

# Axial tension measurements

- 30 Tape CORC® wire with annealed copper core (YS of copper ~110 MPa at 77K)
  - We see core yields well before tapes
  - Due to the helix configuration of tapes, the conductor appears to be more strain tolerant than straight tapes. ie: $\varepsilon^{irr\,(3\%)}$ is close to 0.74 %!
  - So lets study CORC® with strong core
    - $\sigma^{irr\,(3\%)}$ from 170 MPa to 300 MPa to >500 MPa!
    - Strong desire to look at high-strength high-conductivity metal composites being developed for pulsed magnets



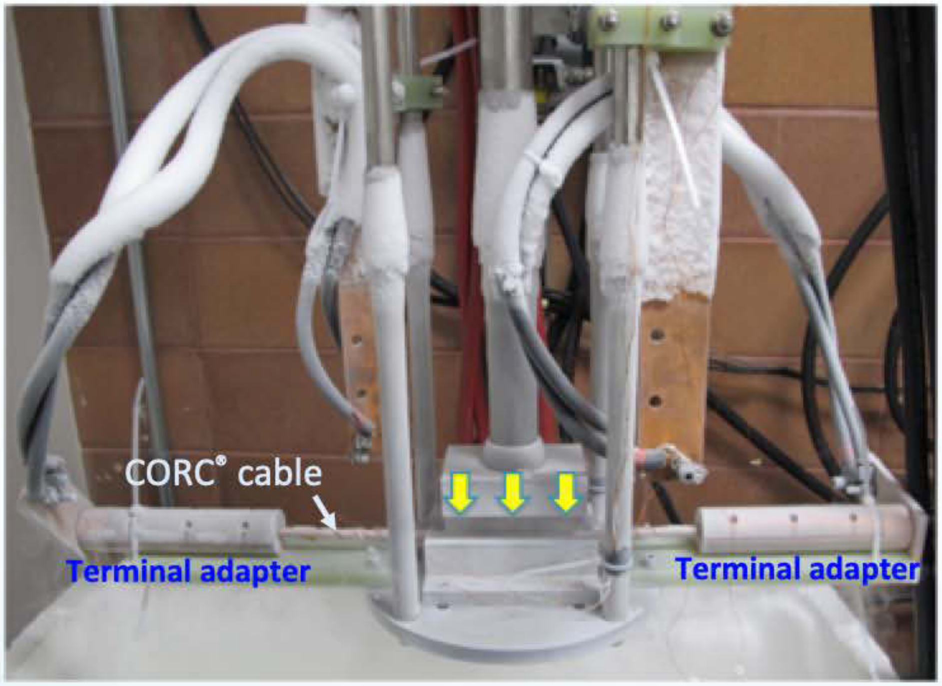



van der Laan et al **SUST** 2019

https://doi.org/10.1088/1361-6668/ab06a3

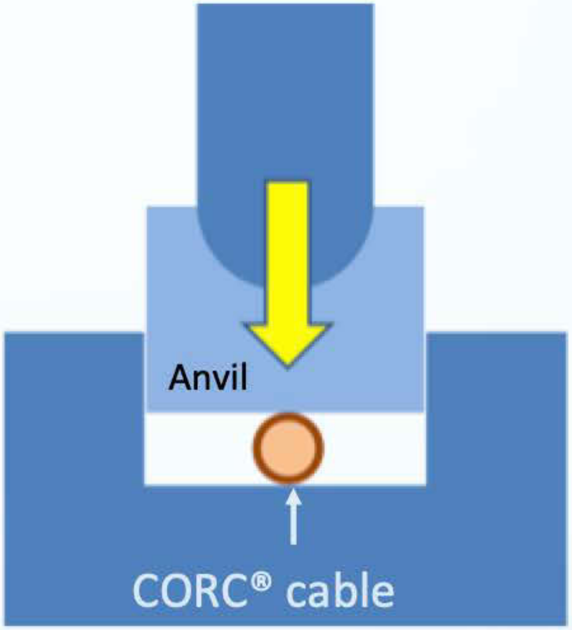
# Transverse compression measurements

**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

Van der Laan et al. SUST 2018 https://doi.org/10.1088/1361-6668/aae8bf

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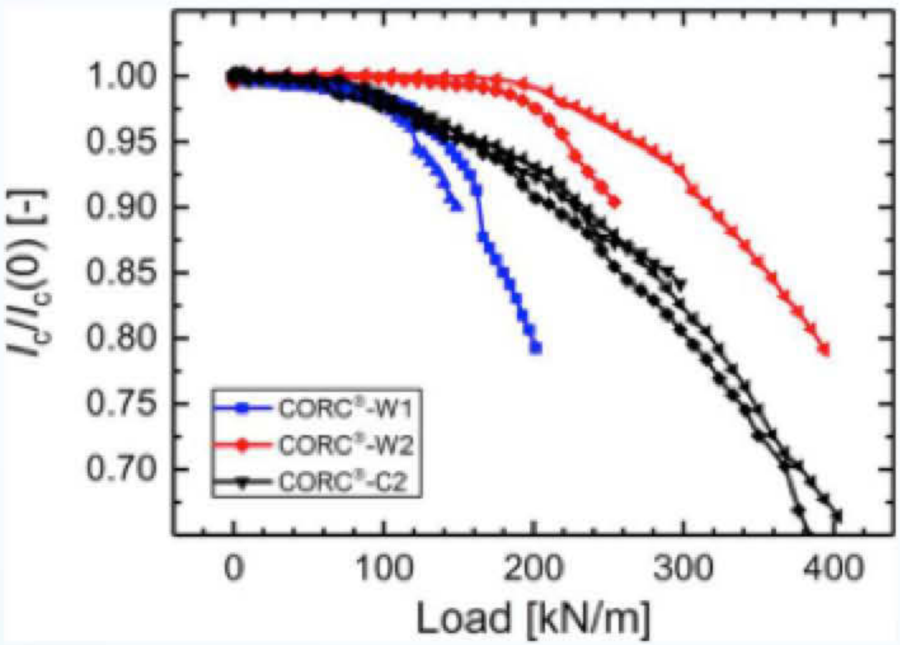
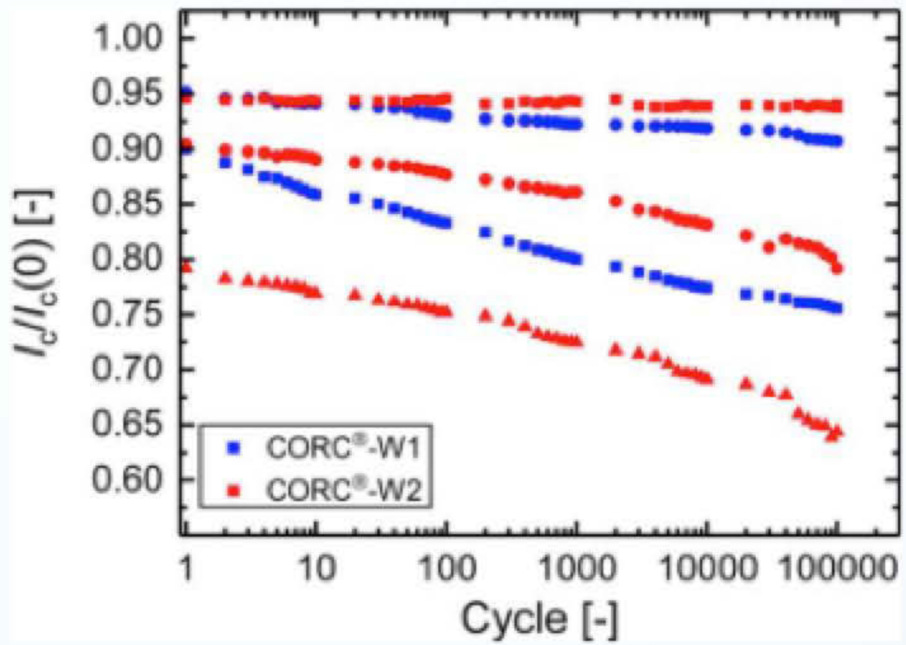
# Transverse compression measurements

3 CORC® layouts tested, optimized 30 tape wire W2 has best performance




Fujifilm imprint suggest contact width of W2 at 200 kN/m is about 1 mm

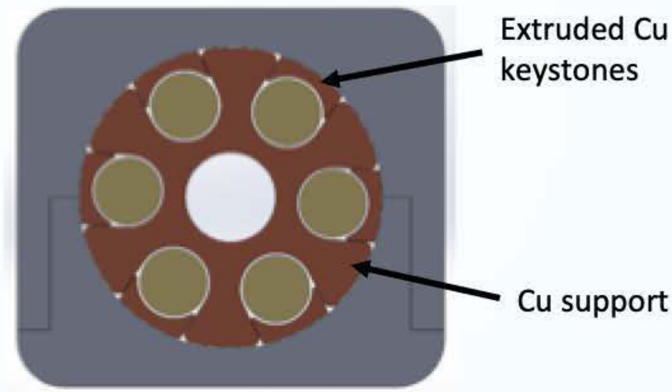
Van der Laan et al. SUST 2018 https://doi.org/10.1088/1361-6668/aae8bf

# CORC®-CICC development with internal bundle support

**CORC®-CICC #4 for testing in SULTAN**

- 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

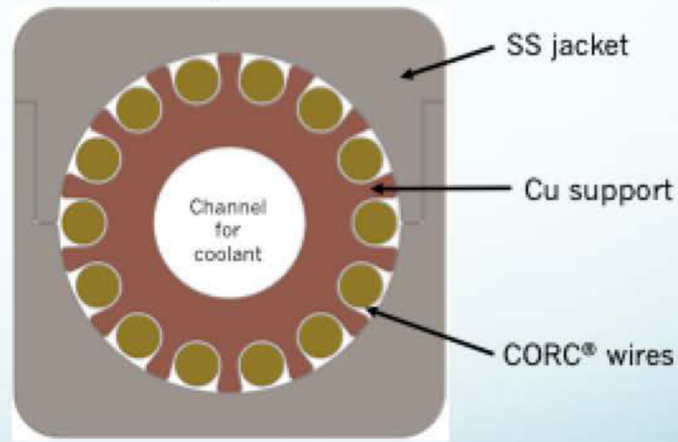
Sample #4




**CORC®-CICC #5 for testing in SULTAN**

- Based on CORC® 12 – 14 wires for higher degree of transposition and higher flexibility
- Goal is 80 kA at 10.8 T background field
- Using internal support to decouple CORC® strands

Sample #5



# Collaborative needs for CORC® development

**Tape development**

- To increase the flexibility of CORC®, we need narrower widths (1 mm, 1.5 mm)
  - Seems trivial but it's not
  - Good for decreasing magnetization effects too
- 20-25 μm thick substrates hit the sweet spot in terms of size and $J_e$
  - Demonstrated, value but R&D effort of tape from commercial venders is stalled
    - Many challenges remain with tape handling of long lengths
    - Large tape demand coming from fusion
- Will fusion really drive tape production in the direction we want?
  - FES CORC® has different needs than HEP CORC®
    - Fusion will not likely pull the production of thinner substrates and narrower widths needed for compact accelerator magnets!

**Magnet development**

- We need to develop the technology as soon as possible
  - More testing to understand how the conductor ticks
  - Paper designs
  - Demonstrators

# Recent CORC® Publications

## Topical review on 10 years of CORC® progress (2009-2019)

- Covers everything from conductor development to joints and magnets
- https://doi.org/10.1088/2F1361-6668/2Faafc82

## Recent publications (2019-2020)

- CORC® solenoid magnet tested in 14 T LTS outsert, van der Laan et al **SUST** (Under review)
- Studies on current sharing in CORC®, Phifer et al **Adv Cryo Eng** (Under review)
- AC loss and contact resistance studies, Yagotintsev et al **SUST** (Under review)
- CORC® wires with integrated Fibers and V-taps, van der Laan et al **SUST** (Under review)
- CORC® wires made with 25um Sub tapes, Weiss et al **SUST** https://doi.org/10.1088/1361-6668/ab72c6
- Progress on CORC® CICC development, Mulder et al **IEEE** https://doi.org/10.1109/TASC.2020.2968251
- Development of CORC® for FCL applications, Weiss et al **SUST** https://doi.org/10.1088/1361-6668/aafaa7
- 1.2 T CCT magnet demonstrator, Wang et al **SUST** https://doi.org/10.1088/1361-6668/ab0eba
- Axial tension and fatigue testing, van der Laan et al **SUST** https://doi.org/10.1088/1361-6668/ab06a3

## Papers and presentations from conferences and workshops available online

- https://www.advancedconductor.com/technicalinformation/

Not possible without the support of DOE, the US Navy, and various collaborators. Thank you!

# Summary

**CORC® wires and cables have matured into magnet conductors**

- High-quality, long-length CORC® conductors routinely produced for commercial orders
- High currents have been demonstrated: > 8,500 A (4.2 K, 12 T)
- High current densities have been reached: > 450 A/mm$^2$ (4.2 K, 20 T)
- Integrated V-Taps for quench detection show a lot of promise
- Conductor has high stress/strain tolerance
  - Axial tension
  - Transverse compression
  - Fatigue up to 100,000 cycles
- Commercial tape needs for further CORC® development
  - Thinner substrates (20-25 um) to improve $J_e$
  - Narrower widths (1 and 1.5 mm) to improve flexibility
  - Higher $J_e$ (thicker films, better pinning) to decrease magnet volume