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Development of high-strength CORC® conductors with record-breaking irreversible axial tensile strain limit exceeding 7 %

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CORC® magnet cables and wires

CORC® wires (2.5 – 4.5 mm diameter)

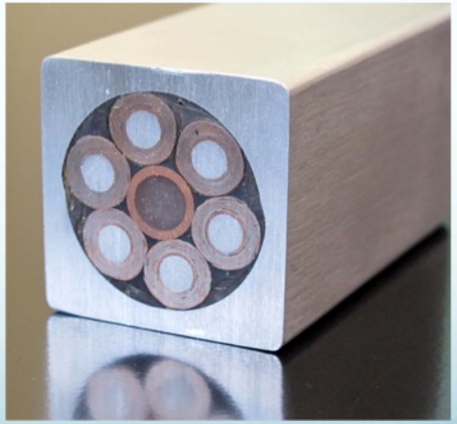
- Wound from 2 – 3 mm wide tapes with 25 and 30 μm substrate
- Typically, no more than about 30 tapes
- Flexible with bending down to < 60 mm diameter

CORC® cable (5 – 8 mm diameter)

- Wound from 3 – 4 mm wide tapes with 30 – 50 μm substrate
- Typically, no more than about 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



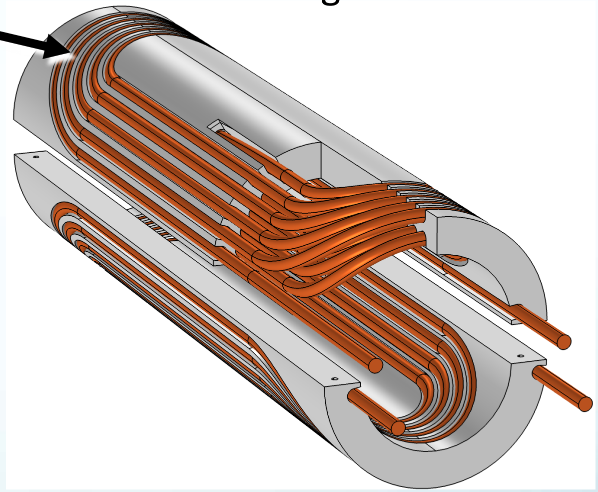
Mechanical aspects of CORC® cables and wires

CORC® wire bending limit

- Important for high-field solenoid and accelerator magnets
- Often requires high operating currents of 5 – 10 kA at small bending diameter
- Bending diameters of 30 – 60 mm are often required

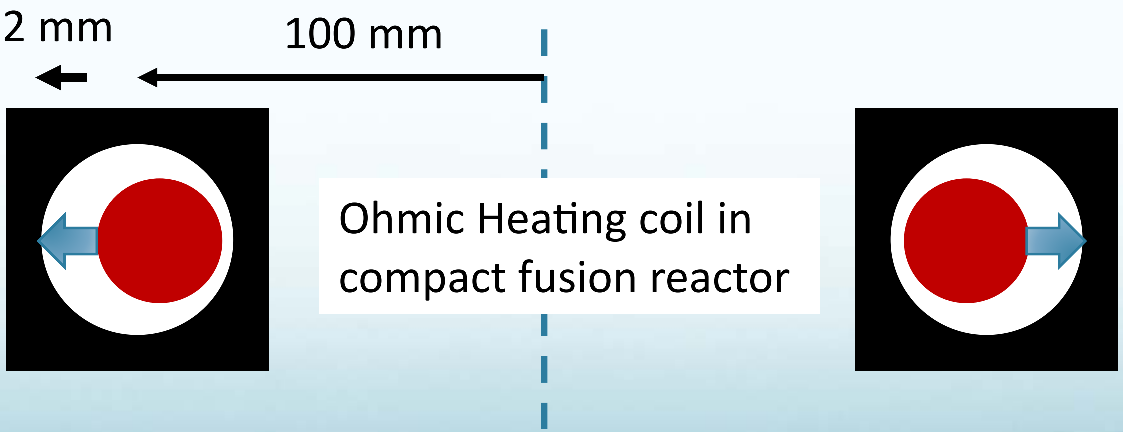
Canted-cosine-theta accelerator magnet – Berkeley Lab.

COMB accelerator magnet – Fermilab



CORC® conductors under axial tension

- Important for many magnets, such as solenoids, where hoop stress may dominate
- Axial tensile strain of the CORC® cable can exceed 1 – 2 % in jacketed fusion cables

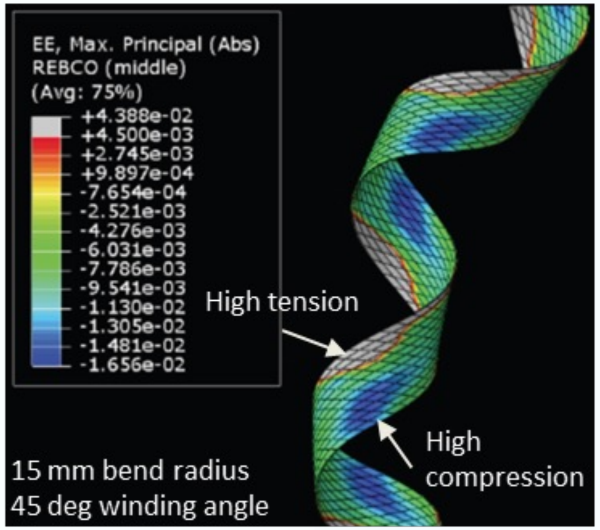


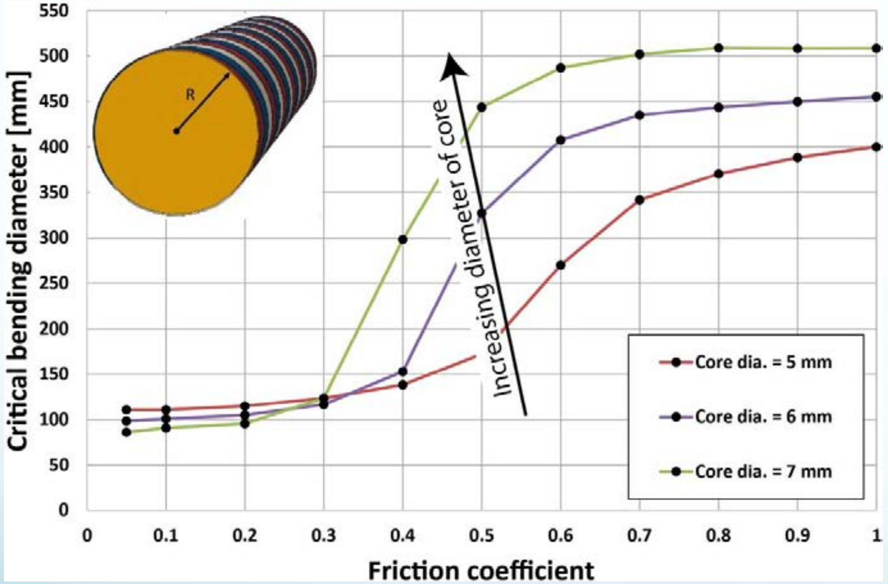
Bending of CORC® wires

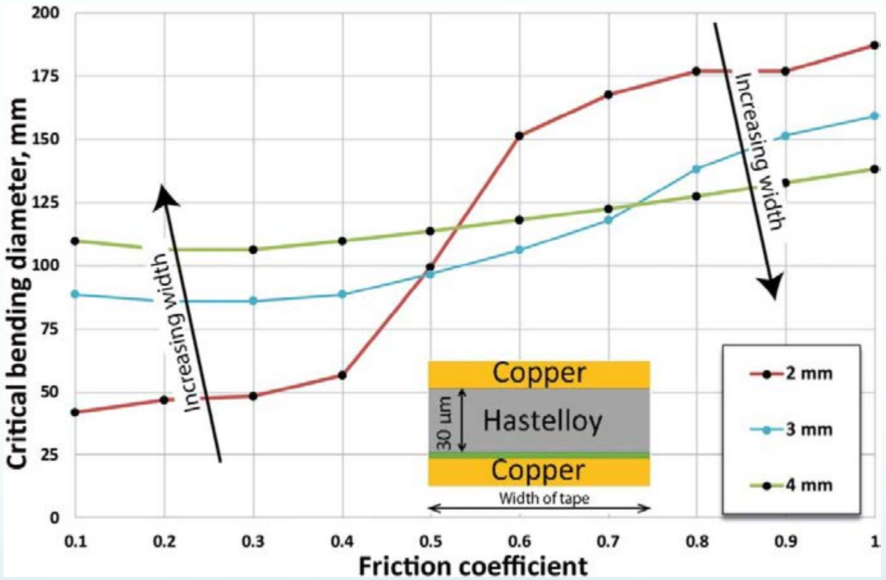
Bendability of CORC® wires due to helical tape wind, but affected by

- Tape width and thickness (both of substrate and Cu plating)
- Gap spacing between tapes and number of tape layers
- Core thickness and tape winding angle
- Friction coefficient: the tapes need to slide!!

FEM model showing single tape

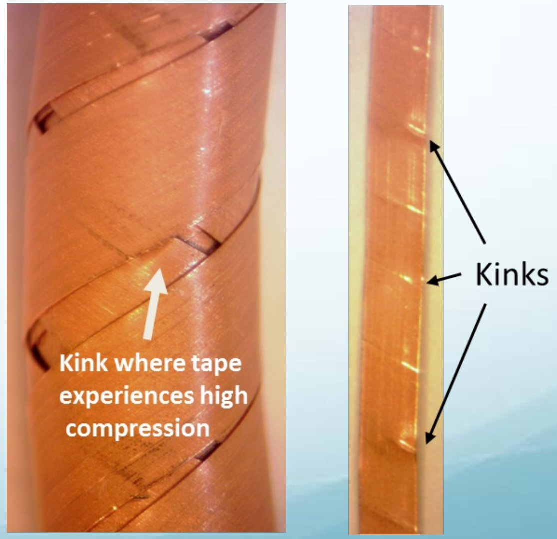






Bent CORC wire

Extracted tape



V.A. Anvar, et al., *"Bending of CORC® cables and wires: finite element parametric study and experimental validation", Supercond. Sci. Technology* **31**, 115006 (2018)

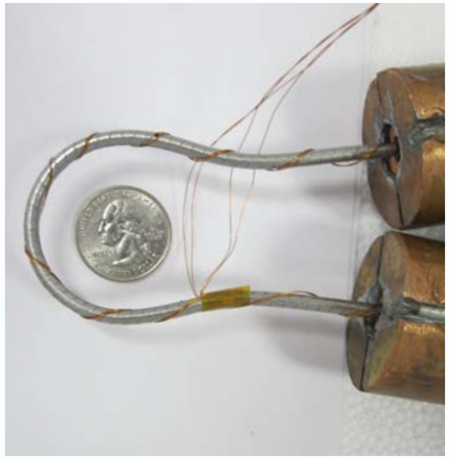
Bendability of previous generation of CORC® wires

Determining the bending limits of CORC® wires

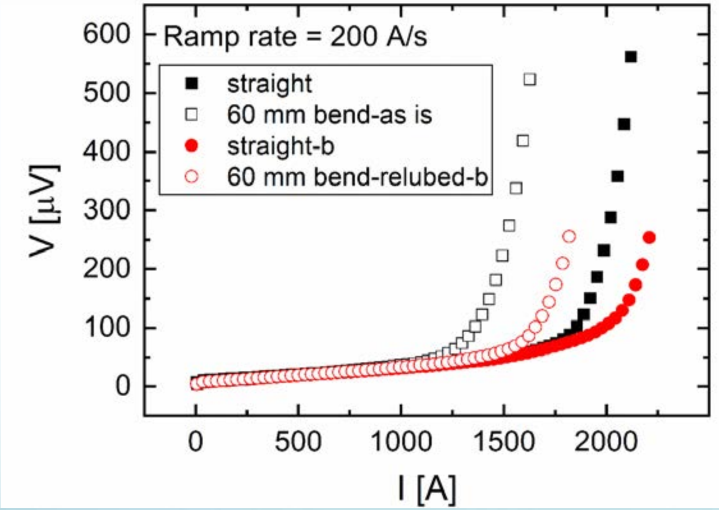
- Bend the CORC® wire and measure I_c, repeated until degraded
- Bend CORC® wire sections to fixed diameter, extract tapes and measure tape I_c

Previous generation of 30-tape CORC® wires

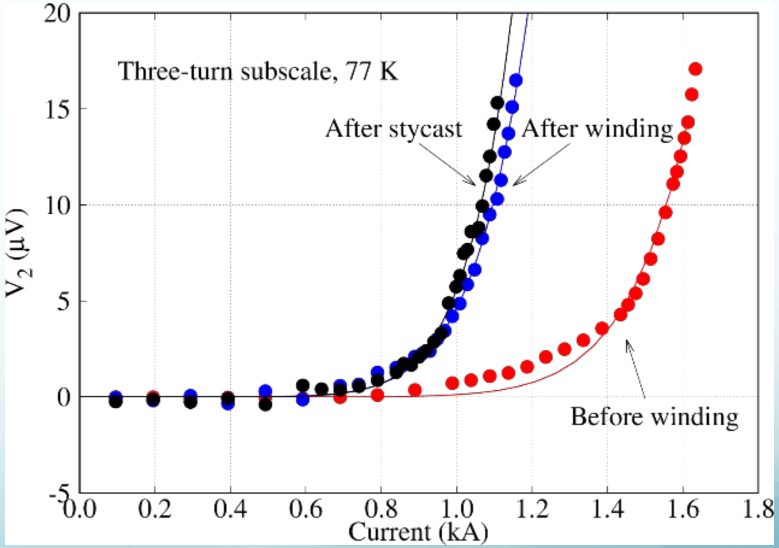
- Using “Old winding and lubrication process” (P1)
- Wound into CCT magnet structure with 60 mm bend at poles
- **About 70 – 80 % I_c retention => ok, not great**



Hairpin test



3-Turn CCT mandrel



Bendability of latest generation of CORC® wires

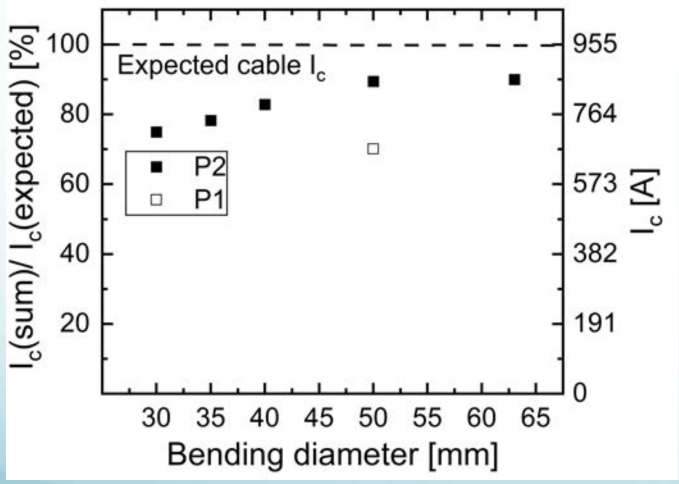
Why development of next generation CORC® wire?

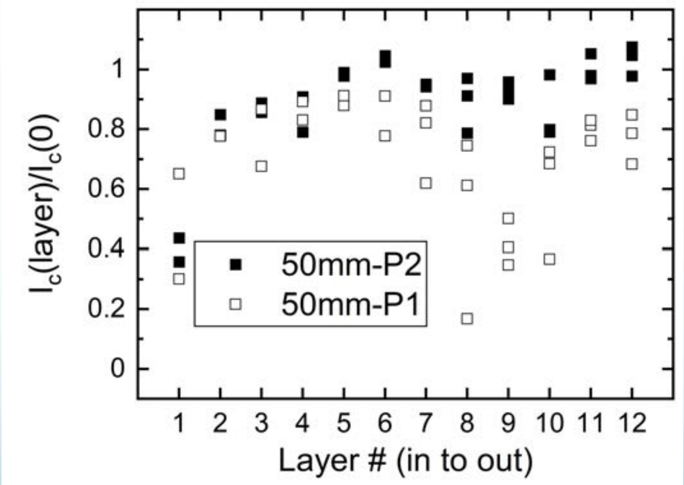
- Better flexibility is always better
- REBCO tape surface much rougher over the years, resulting in 60 – 65 % I_c retention at 63 mm bend with 2022 tapes

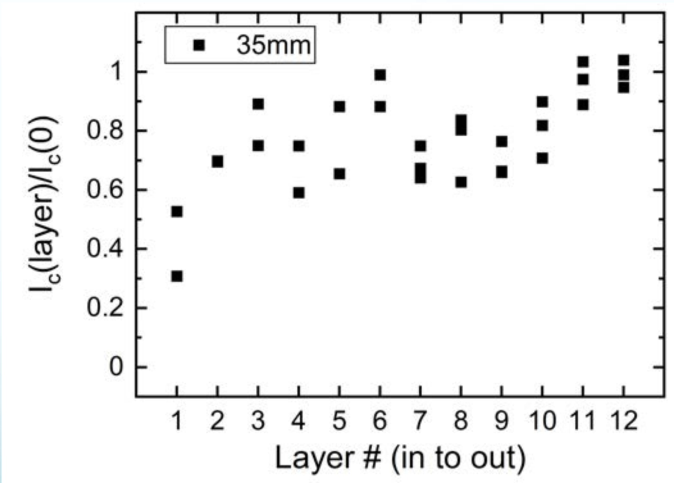
Next generation 30-tape CORC® wire

- Using new winding and lubrication process (P2)
- Compatible with much rougher tapes
- I_c retention **90 % at 50 mm diameter bend** and around **80 % at 35 mm diameter bend**

Next generation CORC® wires bending performance of extracted tapes







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Why is Nb-Ti the workhorse of superconducting magnets?

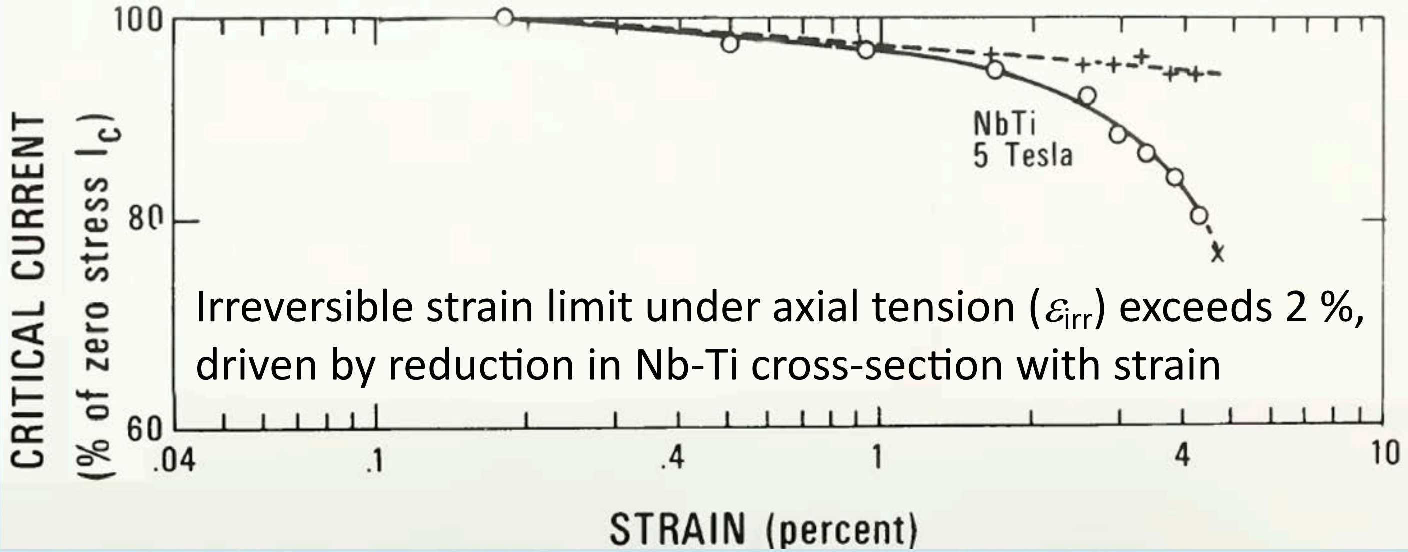
Nb-Ti is a superconducting magnet workhorse because

- It's a round
- It's fully isotropic (mechanically and electro-magnetically)
- Doesn't require reaction after magnet winding
- It's a transposed, multifilament wire
- It's highly flexible, allowing very tight bends

How about CORC® wires?

✓
✓
✓
✓ (At least partly)
✓ (Yes, much better now!)

We know this, so what's new? To find out, let's consider this 45 year old plot:



ε_{irr} defined at $I_c(\varepsilon)/I_c(0) < 97\text{-}98$ %

J.W. Ekin, IEEE Transactions on Magnetics, Vol. MAG-13, No. 1, January 1977

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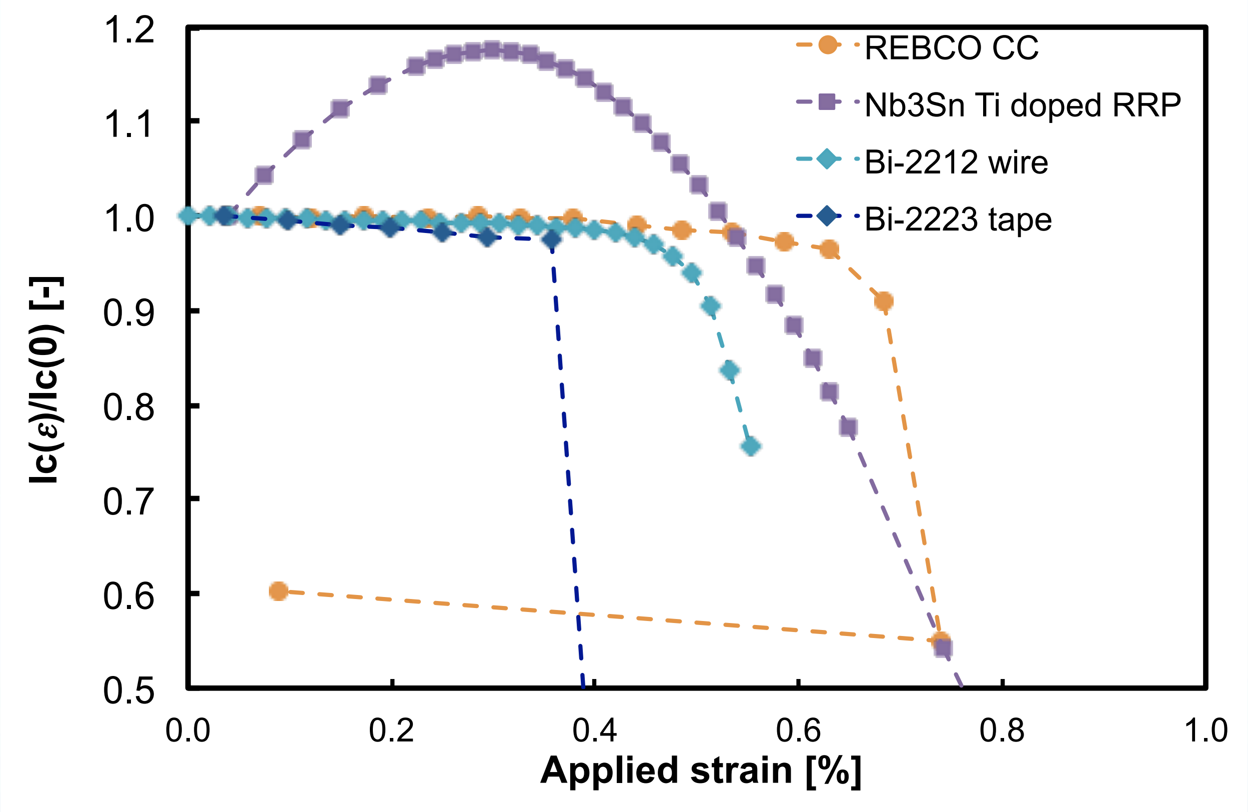
Irreversible strain limit of practical superconductors

Irreversible strain limit (applied strain)

- **Nb_3Sn:** 0.65 % [1]
- **Bi-2212 wires:** 0.3 % [2]
- **Bi-2223 tapes:** 0.4 % [3]
- **REBCO CC:** 0.6 % [4]

How about CORC® wires?



[1] Najib Cheggour, Theodore C. Stauffer, William Starch, Peter J. Lee, Jolene D. Splett, Loren F. Goodrich & Arup K. Ghosh, *Scientific Reports* **8**, 13048 (2018)
[2] N Cheggour, X F Lu, T G Holesinger, T C Stauffer, J Jiang and L F Goodrich, *Superconduct. Sci. Technol.* **25**, 015001 (2012)
[3] D.C. van der Laan, J.F. Douglas, C.C. Clickner, T.C. Stauffer, L.F. Goodrich, and H.J.N. van Eck, Supercond. Sci. Technol. **24**, 032001 (2011)
[4] van der Laan D C and Ekin J W, *Appl. Phys. Lett*. **90**, 052506 (2007)

The effect of axial tensile strain on I_c of CORC® wires

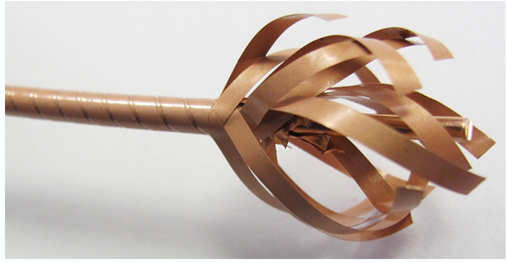
Simplified description of CORC® wire structure
- REBCO tapes wound in a helical fashion on solid core
- Tapes behave as springs; extending axially and contracting radially under tensile load
- The core acts a central support, but also confines the radial contraction of the springs

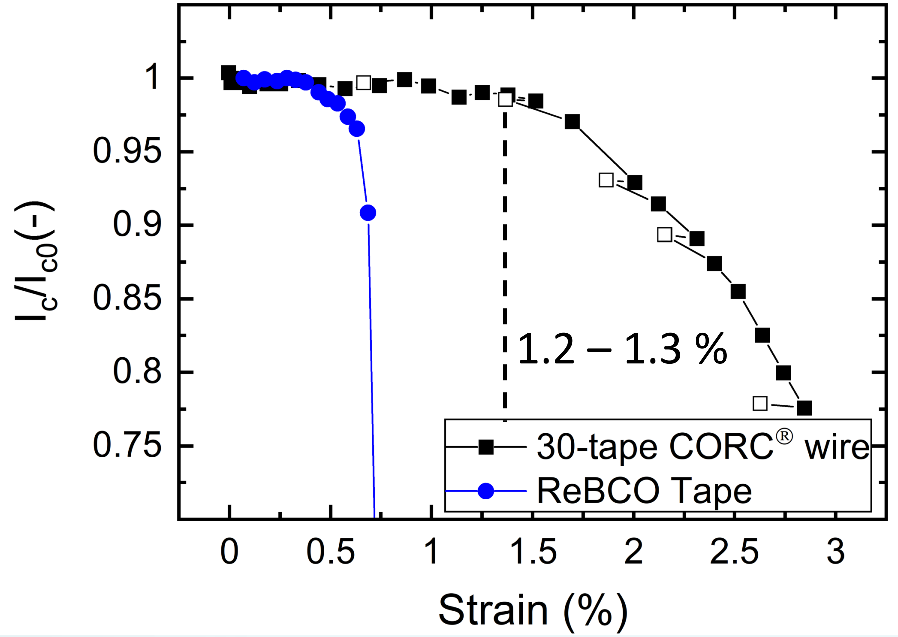
Testing CORC® wires under axial tension
- Test performed in LN_2 at 77 K
- Maximum load of 13 kN applied to terminations
- Sample strain measured with pair of clamp-on extensometers

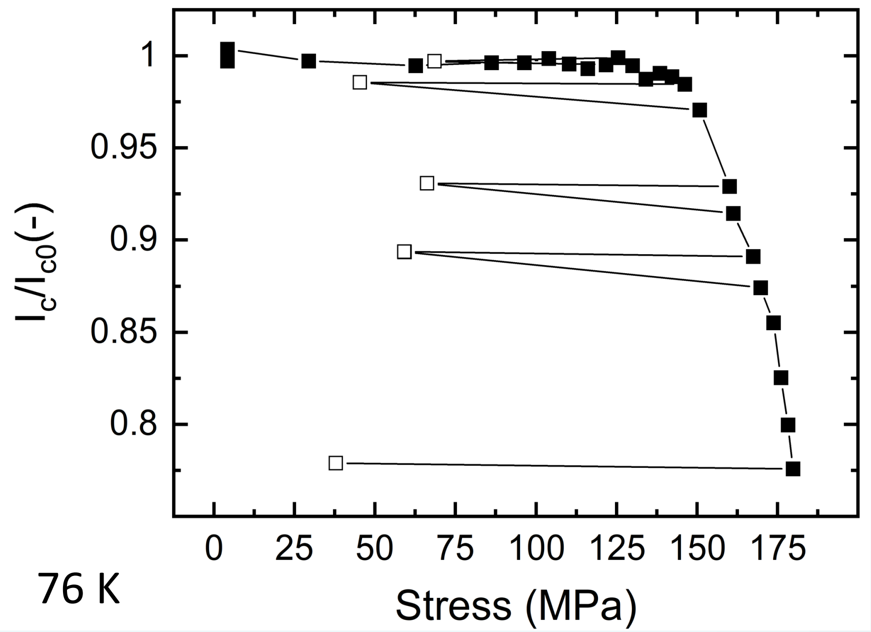
Performance of a standard 30-tape CORC® wire

Standard CORC® wire

- 30 REBCO tapes of 2 mm width
- Annealed copper former (2.55 mm diameter)
- Wire diameter 3.6 mm



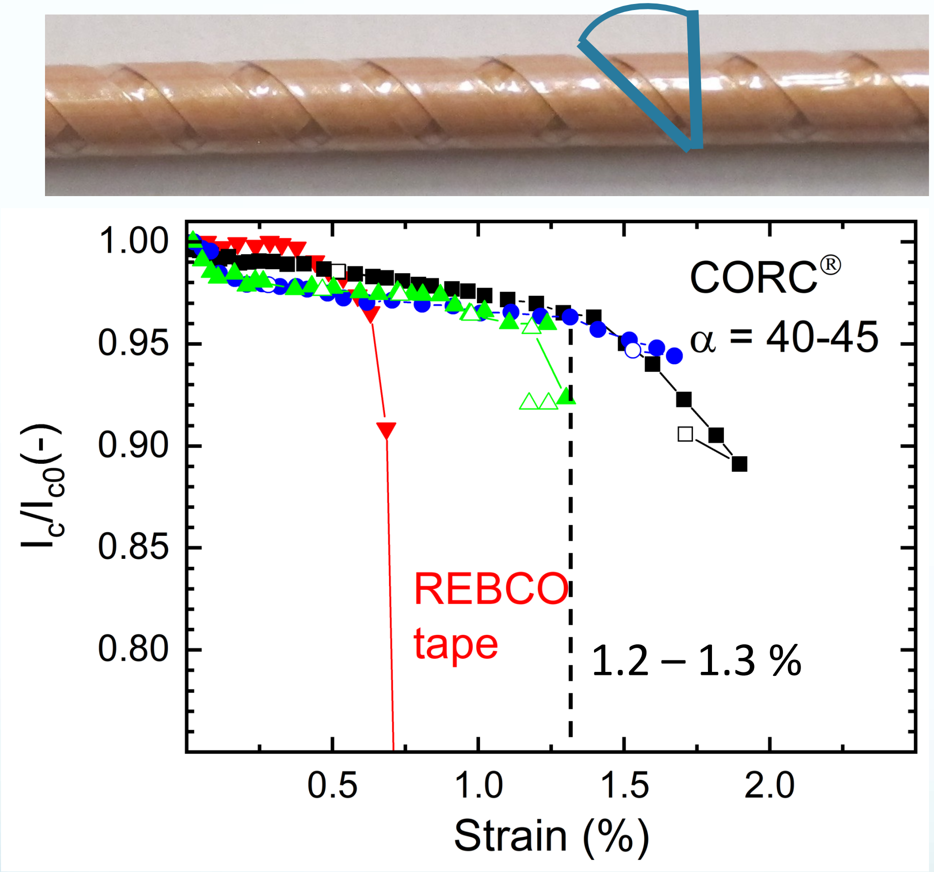




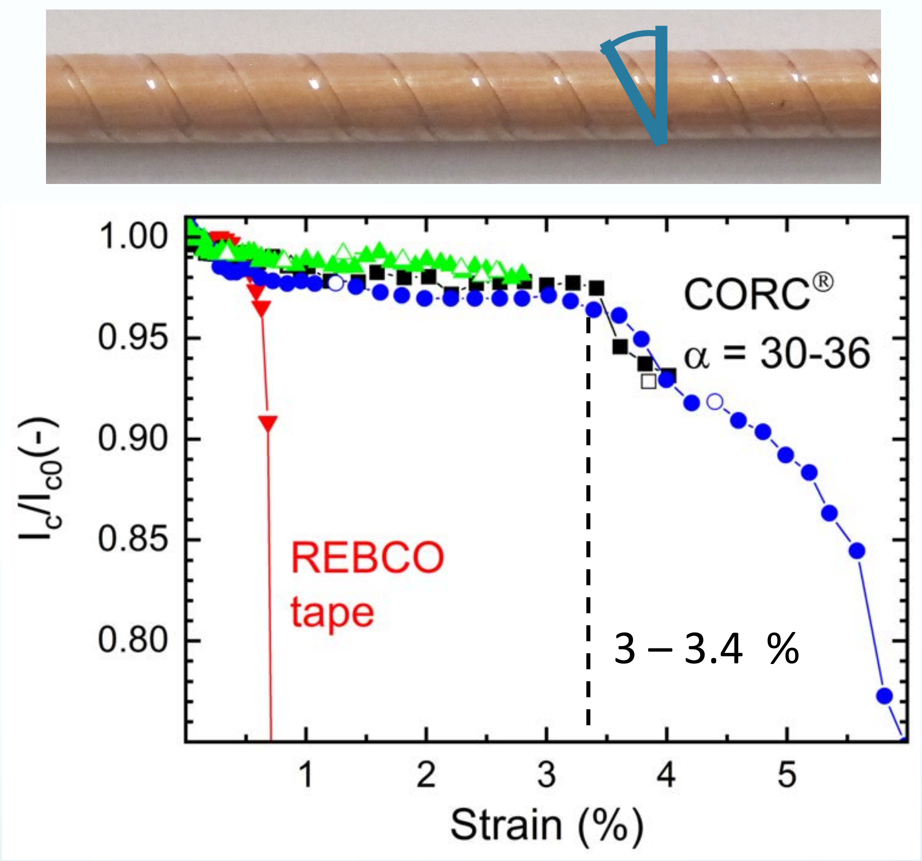
- **Critical strain is already twice that of a straight REBCO tape**
- **Critical stress of 150 MPa is competitive with magnet conductors such as Nb_3Sn**

Effect of tape winding angle on ε_{irr}

High angle: α = 40-45°



Low angle: α = 30-36°



Tape winding angle drives the irreversible strain limit in CORC® wires

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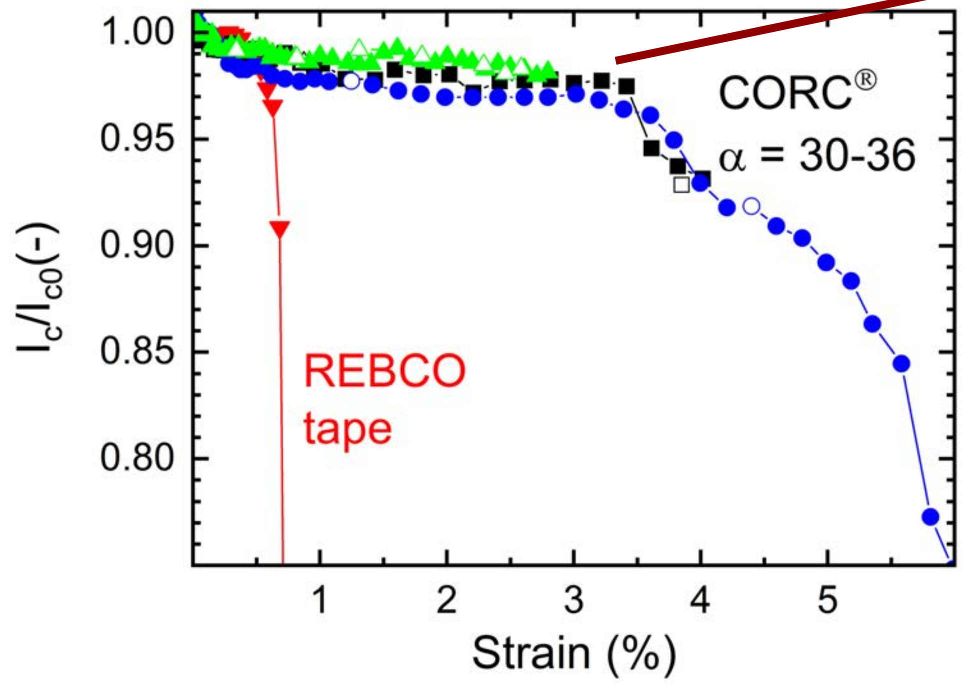
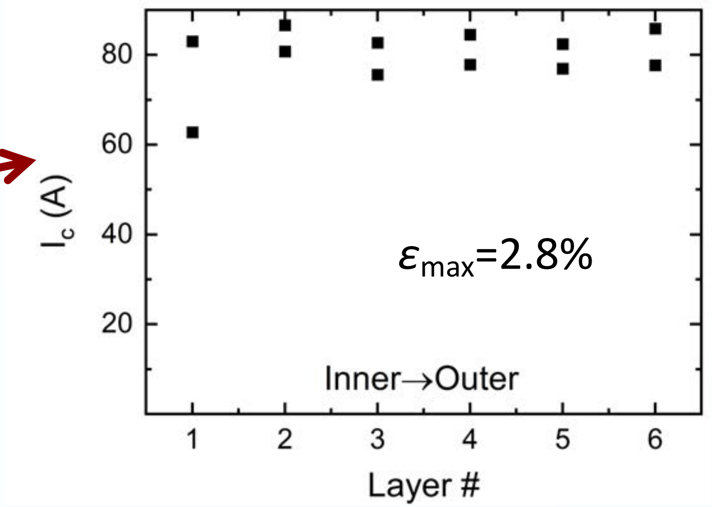
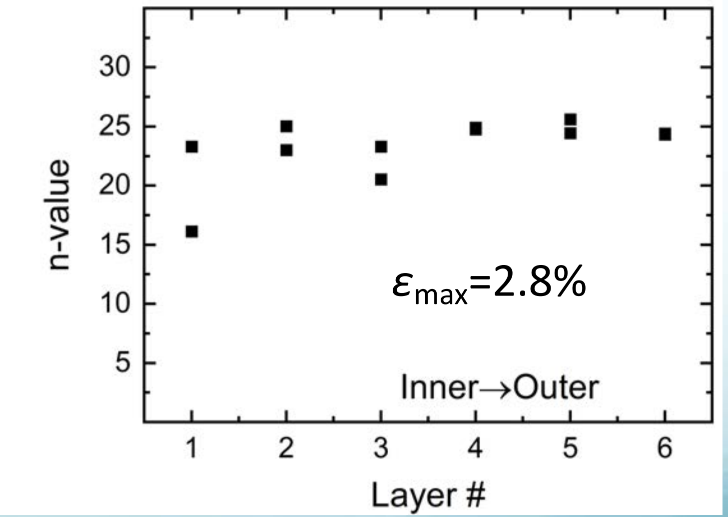
Verification of tape I_c retention after strain

Procedure

- Strain CORC® wire to 0.85 x ε_{irr}
- Extract tapes from CORC® wire
- Measure I_c from extracted tapes







Results

- CORC® wire retention 98 %
- Extracted tape I_c retention 98 %

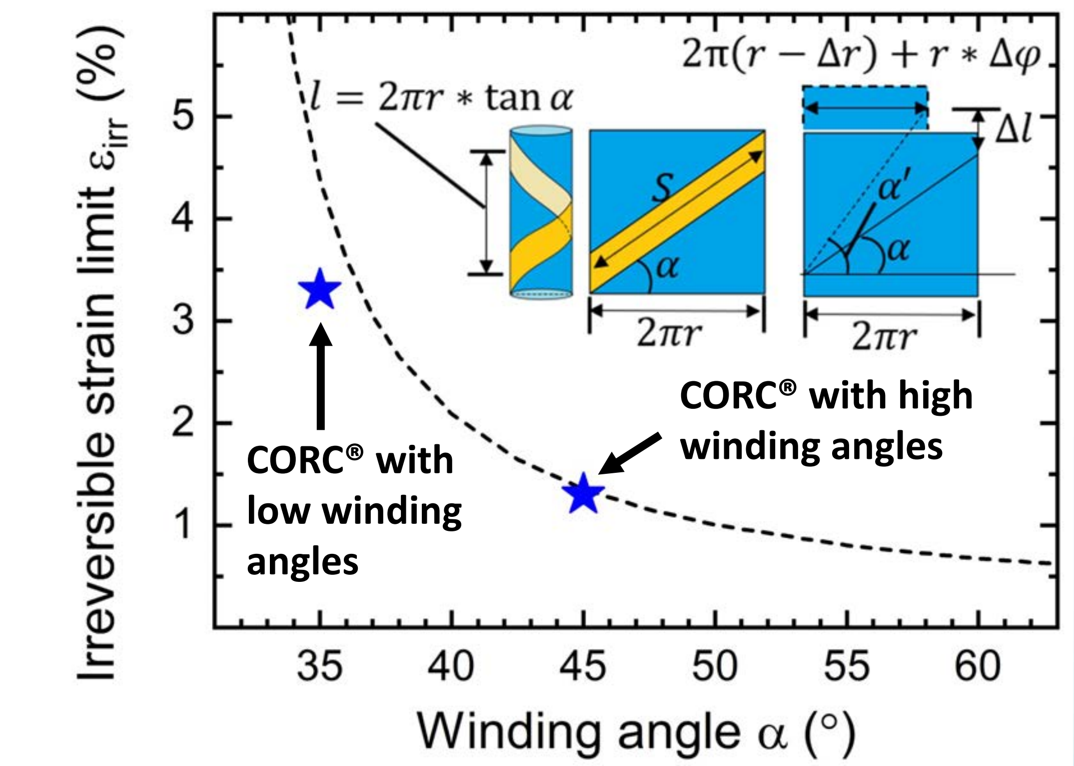
High ε_{irr} of 3.3 % is real!

Analytical verification of strain results

Analytical approach

- Calculate the tape axial strain from change in geometry
- Ignore the torsion component

$$\varepsilon_{tape} = \frac{\Delta S}{S} = \frac{\frac{l+\Delta l}{\sin\alpha'} - \frac{l}{\sin\alpha}}{\frac{l}{\sin\alpha}} \approx \frac{\Delta l}{l}(sin^2\alpha - \nu cos^2\alpha)$$

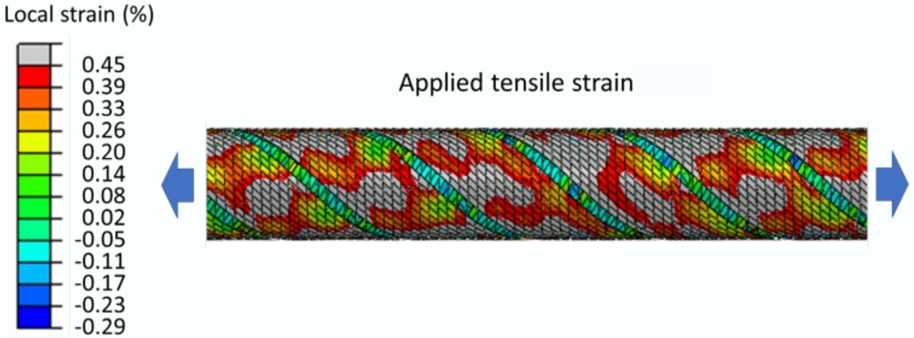


Enhanced critical axial tensile strain limit of CORC® wires: FEM and analytical modeling, V.A. Anvar, K. Wang, J.D. Weiss, K. Radcliff, D.C. van der Laan, M.S.A. Hossain, A. Nijhuis, *Supercond. Sci. Technol.* **35**, 055002 (2022)

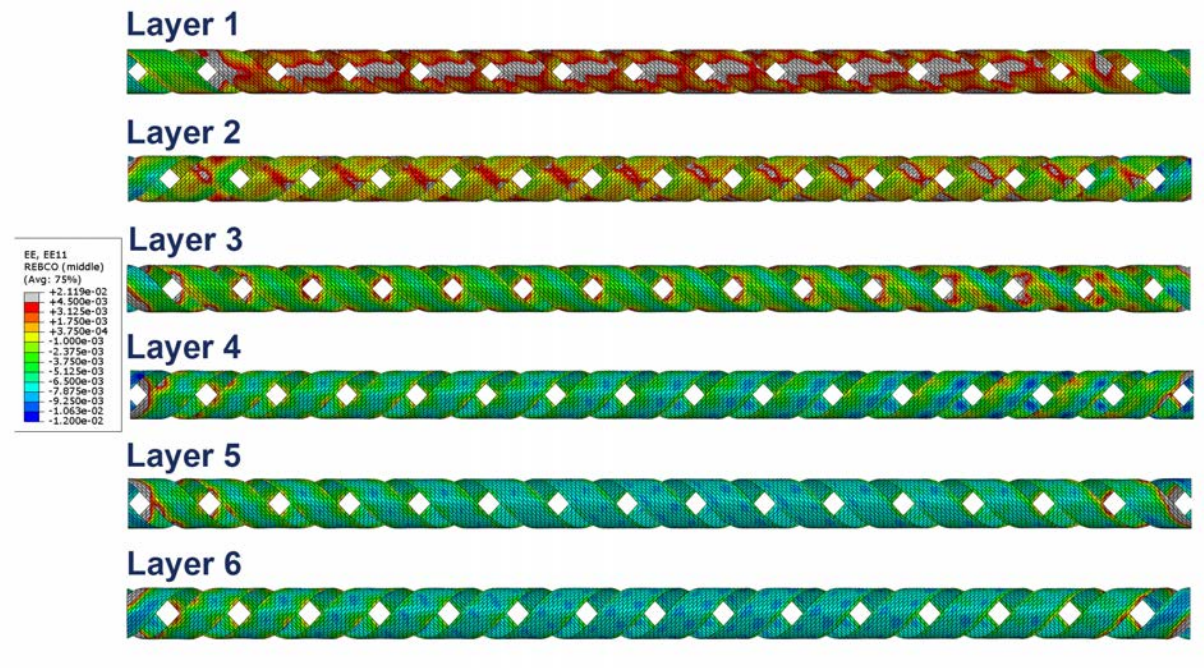
FEM verification of strain dependence

FEM approach

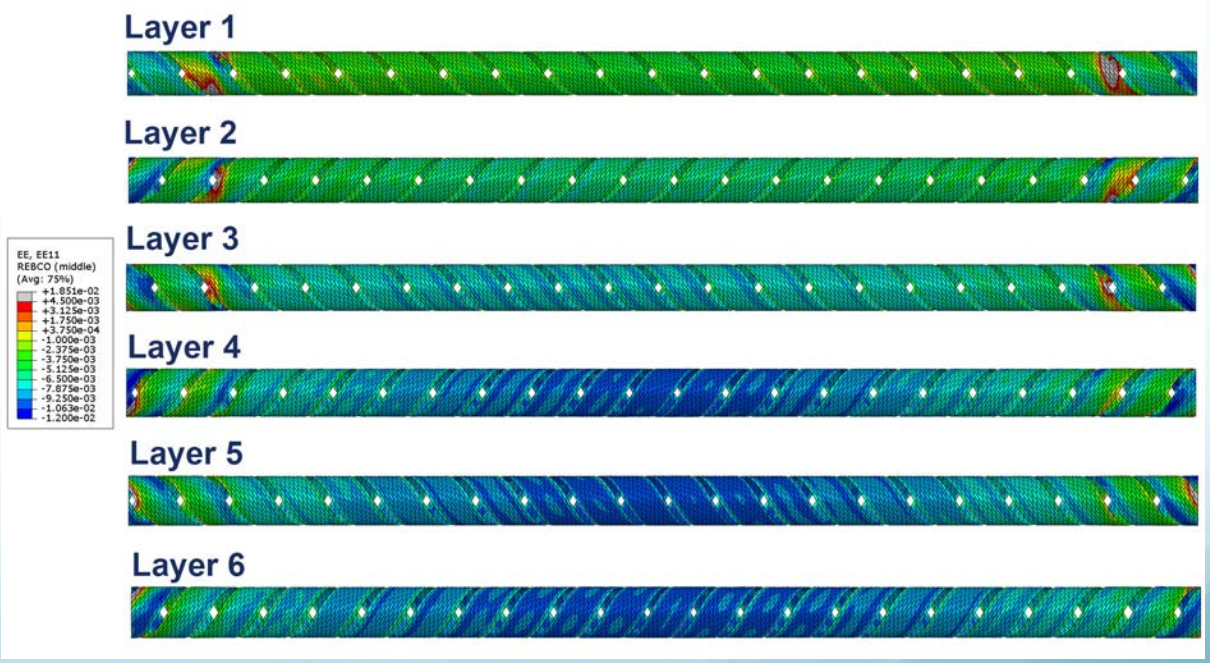
- Calculate REBCO value exceeding ε_{irr}
- Assumes I_c correlates to remaining superconducting volume



CORC® wire with high winding angles (ε = 3.7 %)



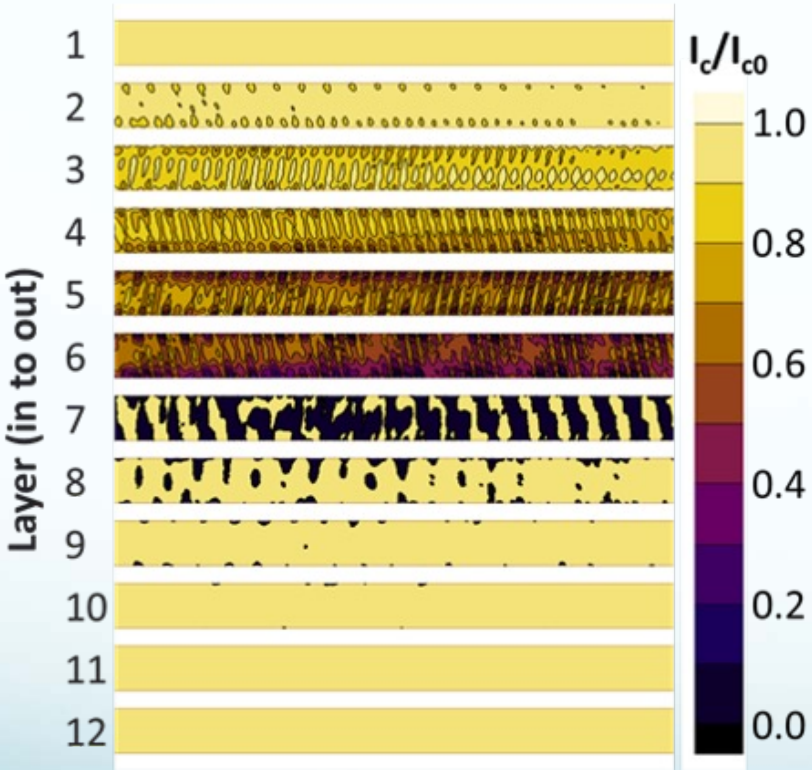
CORC® wire with low winding angles (ε = 4.8 %)

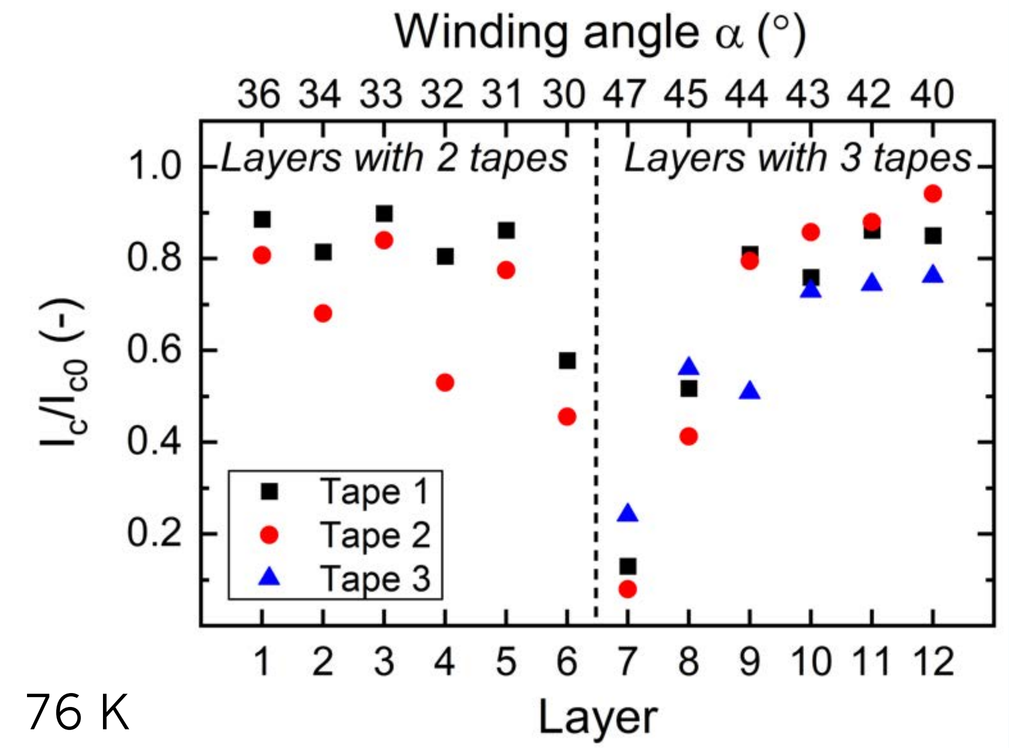


Predicting tape degradation of CORC® wires under strain with FEM

Example

- Non-optimized 30-tape CORC® wire (12 layers)
- Superconducting volume calculated at high ε

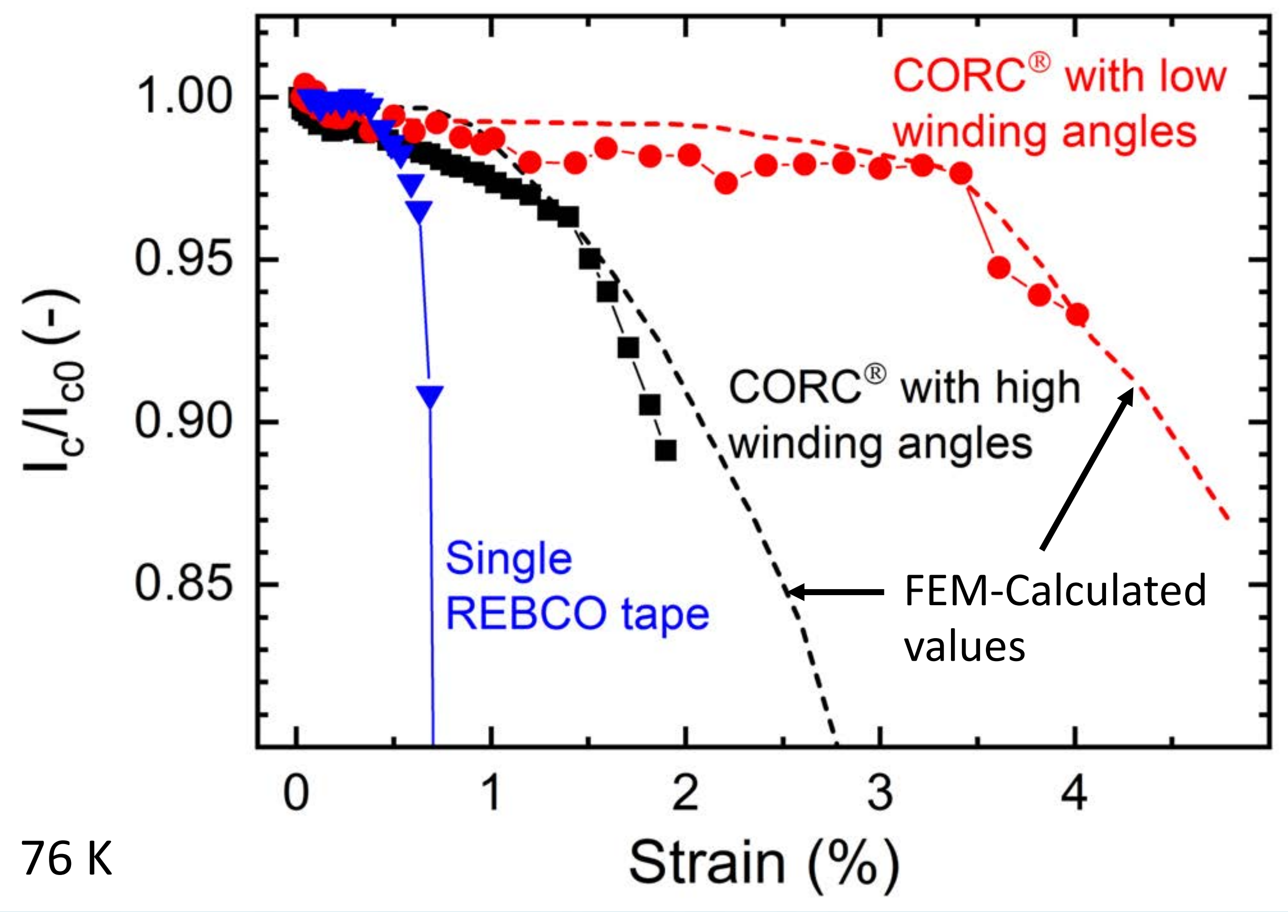




- De gradation in tape I_c is highest at higher winding angle
- Transition from 2 to 3 tapes per layer even affects the low-winding angle tape I_c

Predicting the strain dependence of I_c with FEM

FEM calculated results match the experiment well

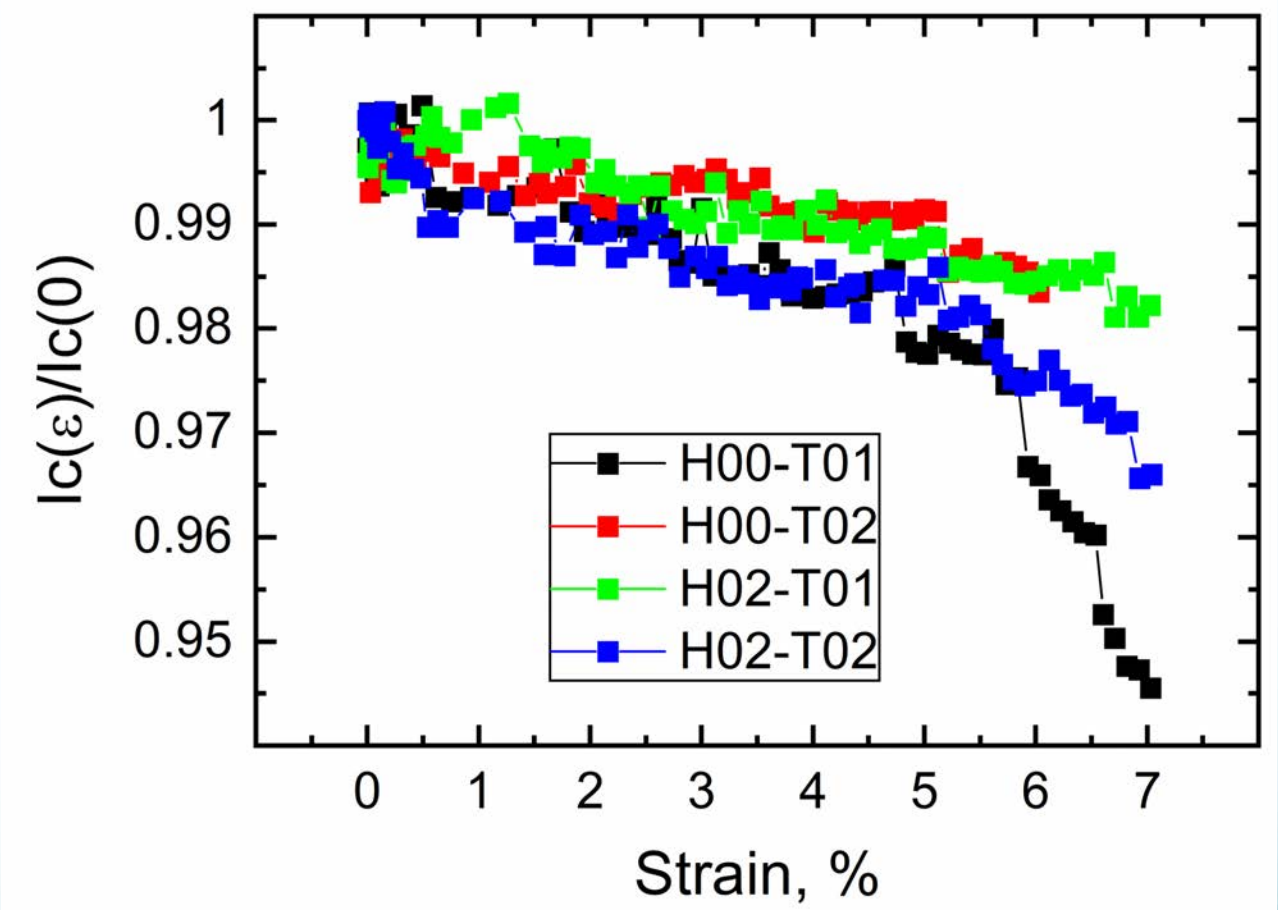


Extending ε_{irr} of high tape count CORC® wires

Optimized 28-tape CORC® wire layout

- 28 tapes of 2 mm width (30 μm substrate)
- 14 layers wound on 2.55 mm copper former
- tape winding angle 25 – 35°, depending on layer

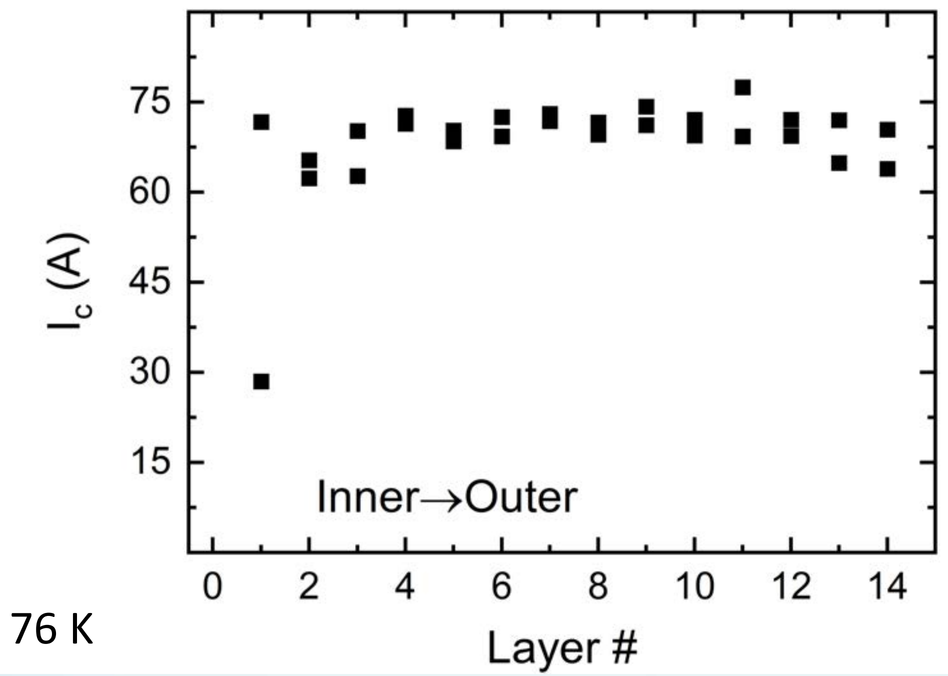
Optimized 28-tape CORC® wire : ε_{irr} = 6 – 7 % !!

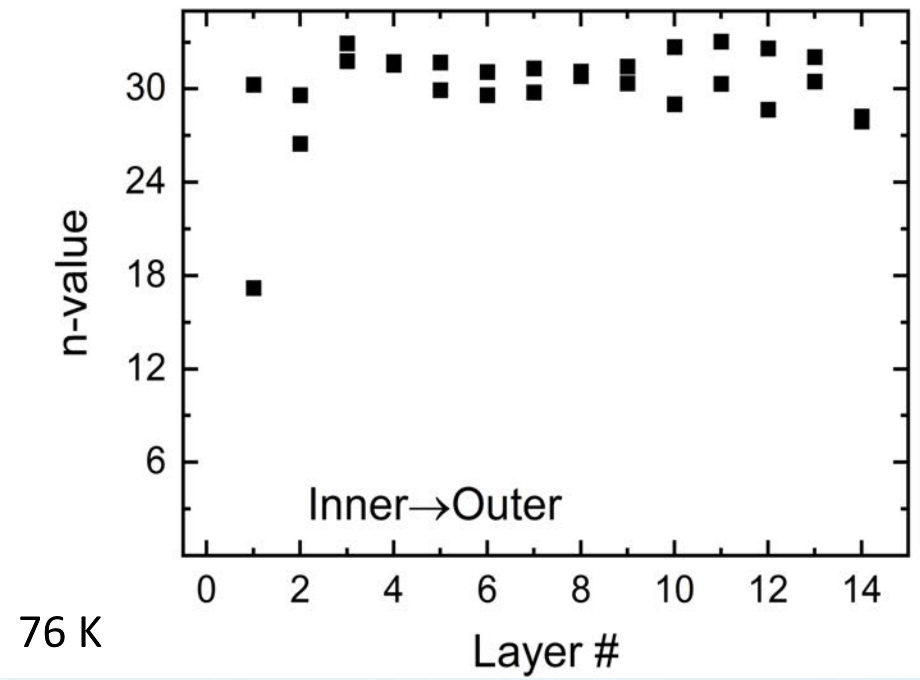


Verification of tape I_c retention after high strain

Optimized 28-tape CORC® wire

- CORC® wire I_c retention 98 % at 7 % strain
- Extracted tape I_c retention 99 %
- Only tapes in the inner layer are damaged





Irreversible strain limit in CORC® wires can be increased significantly by minimizing the tape winding angle

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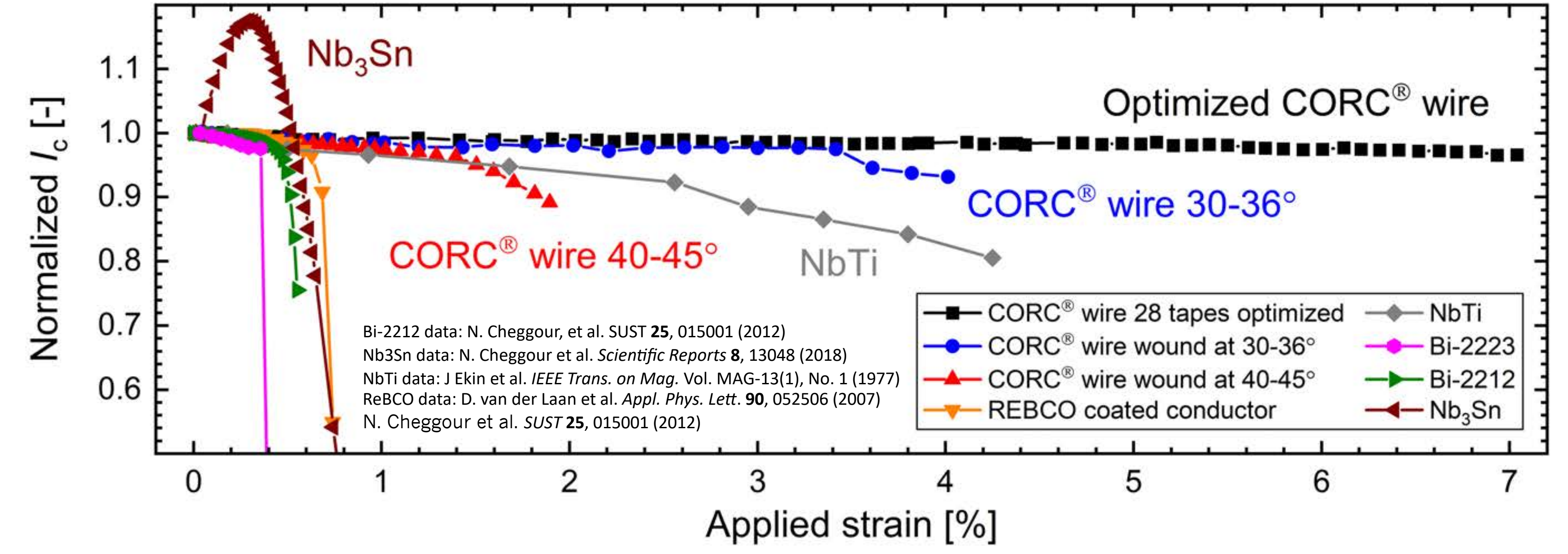
Axial strain practical superconductors Master Plot



CORC® wires can now be engineered to have ε_{irr}:

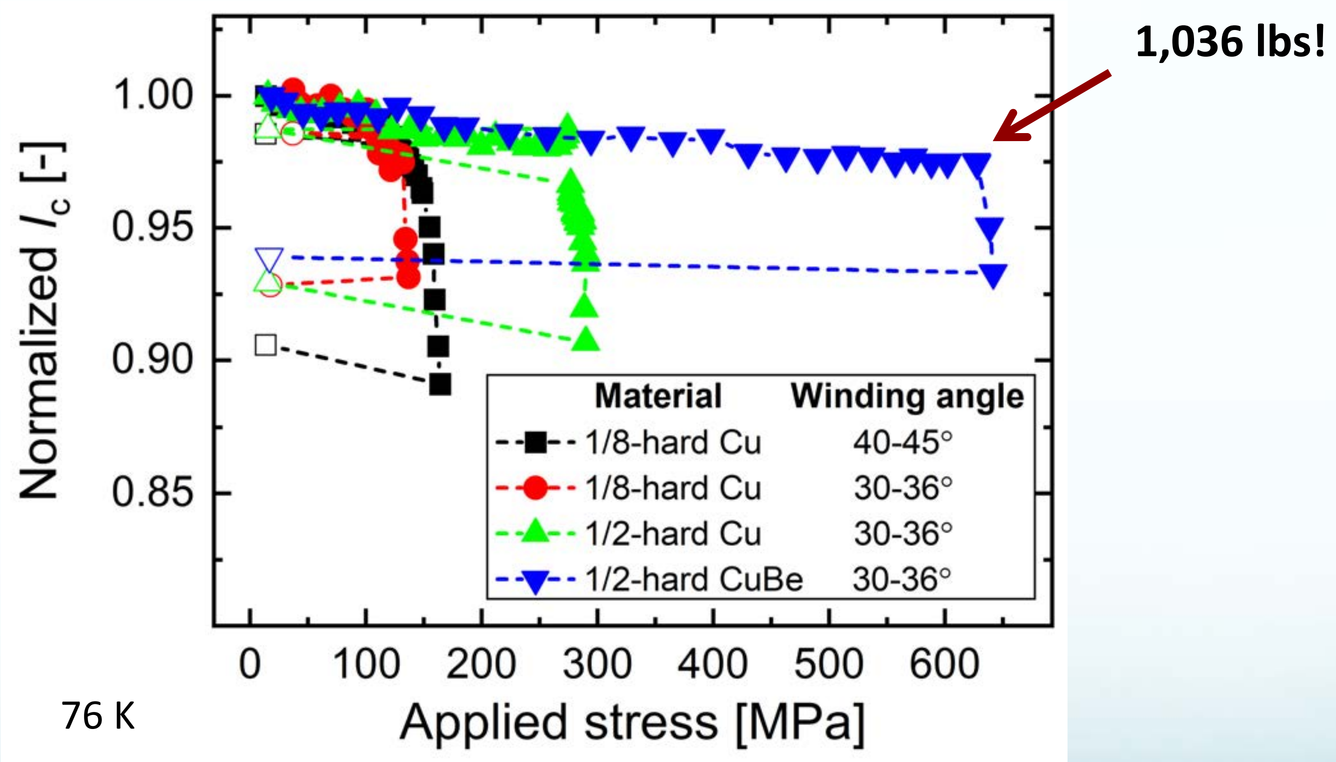
- **twice as high as Nb-Ti**
- **10 times as high as REBCO coated conductors**
- **20 times as high as Nb_3Sn, Bi-2212 and Bi-2223**

van der Laan *et al.* "High -temperature superconducting CORC® wires with record-breaking axial tensile strain tolerance present a breakthrough for high-field magnets", *Supercond. Sci. Technol.* **34**, 10LT01, (2021)

CORC® wires with improved mechanical tensile strength

Critical stress limit under tension (12-tape CORC® wire)

- Critical stress limit with **soft annealed copper** former: **134 MPa**
- Critical stress limit with **half hard copper** former: **280 MPa**
- Critical stress limit with **CuBe** former: **613 MPa**



Irreversible tensile stress limit of CORC® wires can be engineered to exceed 600 MPa at 77 K

Summary

Next generator of CORC® wires allow for much smaller bending diameters

- New winding and lubrication process is compatible with high-surface-roughness REBCO tapes
- Bending to below 50 mm diameter at 90 % I_c retention
- Bending to below 35 mm diameter at almost 80 % I_c retention

The helical winding of REBCO tapes is CORC® wires allows

- To mechanically decouple the ceramic REBCO film from the CORC® wires
- Reduce the strain transfer from the CORC® wire to the REBCO film
- Allow the irreversible strain limit under axial tension in CORC® wires to far exceed that of the REBCO tape
- This allows extremely high irreversible strain limits in CORC® wires of 7 %

Optimized CORC® wires have an irreversible strain limit under tension

- More than 10x that of REBCO tapes
- More than 20x that of other HTS and Nb_3Sn
- Double that of NbTi

Mechanically decoupling of the REBCO layer allows

- The CORC® wire strength under axial tension to be determined almost entirely on that of the former
- CORC® wires with very high critical stress exceeding 600 MPa at 77 K have been demonstrated