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Development of High-strength and High Strain Tolerant CORC® Conductors for High-Field Magnets

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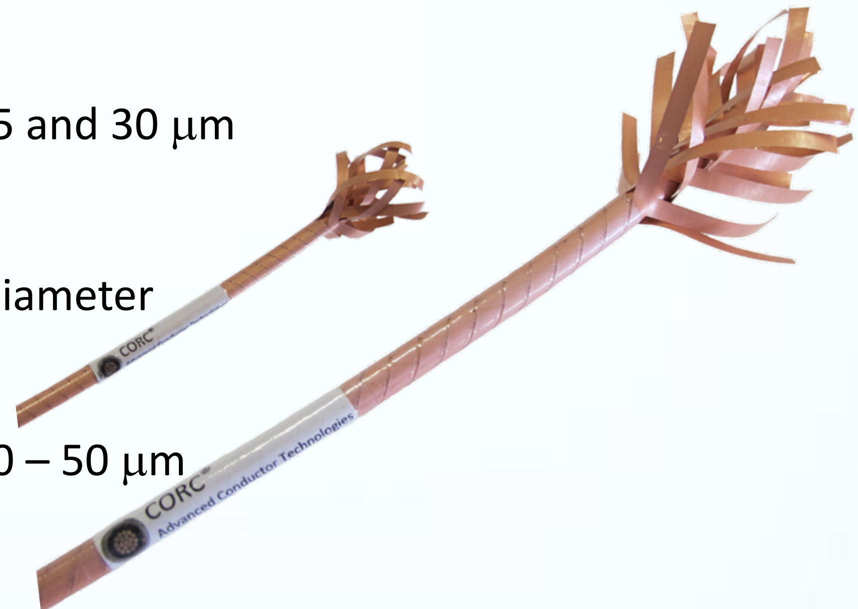
CORC® magnet cables and wires



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 < 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 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

High-field insert solenoid wound from CORC® cables

Addresses main challenges of low-inductance HTS magnets

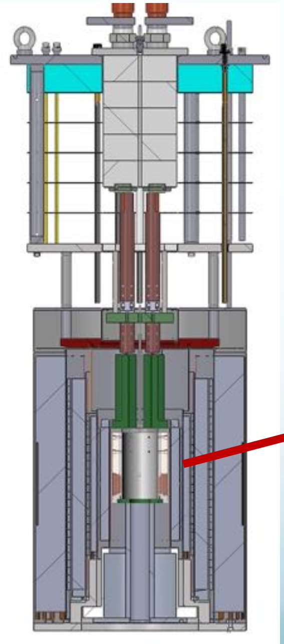
- Operate CORC® insert solenoid in **14 T background field**
- CORC® insert should have meaningful bore: 100 mm diameter
- High operating current: **4,000 – 5,000 A**
- **J_e > 200 A/mm^2**
- Operate at **JBr source stress >250 MPa**

CORC® cable layout

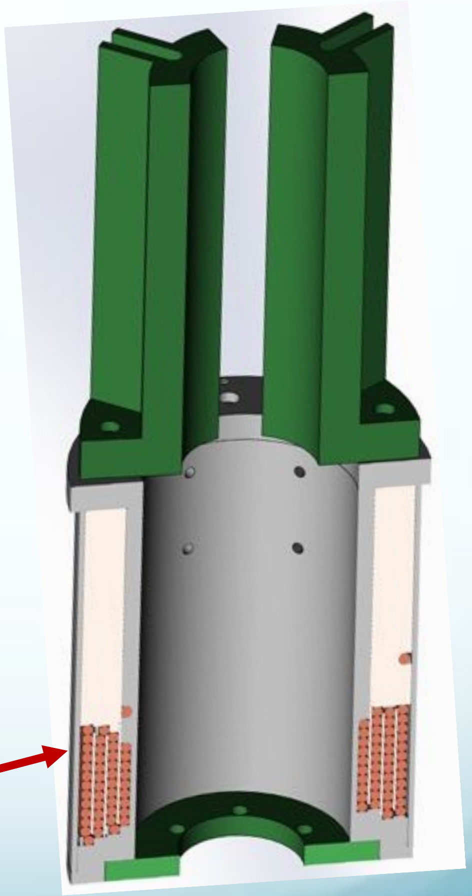
- 28 REBCO tapes of 3 mm width containing 30 μm substrates
- 4.56 mm CORC® cable outer diameter

CORC® insert layout

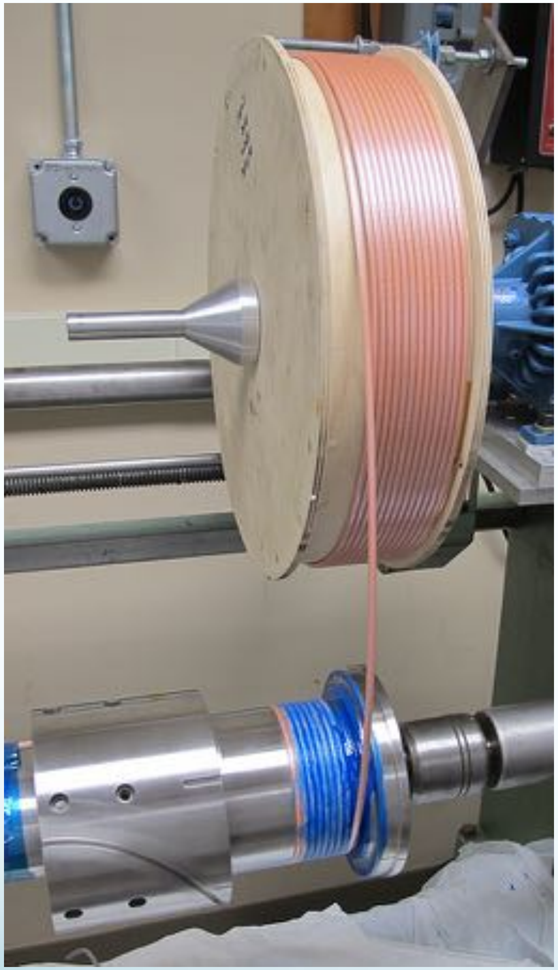
- 100 mm inner diameter, 143 mm OD
- 4 layers, 45 turns
- 18.5 m of CORC® cable
- Wet-wound with Stycast 2850
- Stainless steel overbanding between layers

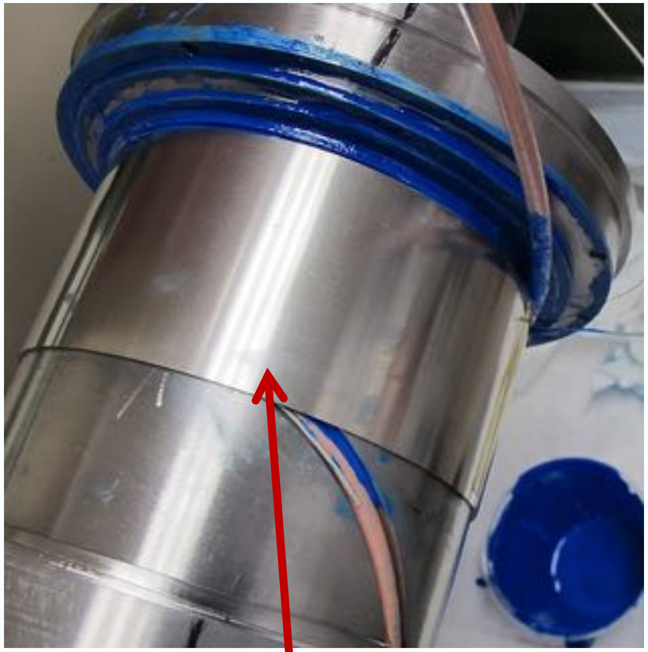


14 T LTS
(161 mm bore)



CORC® magnet winding



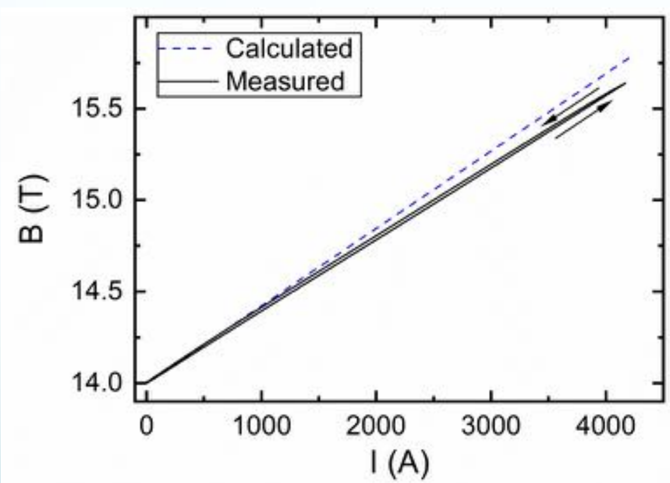


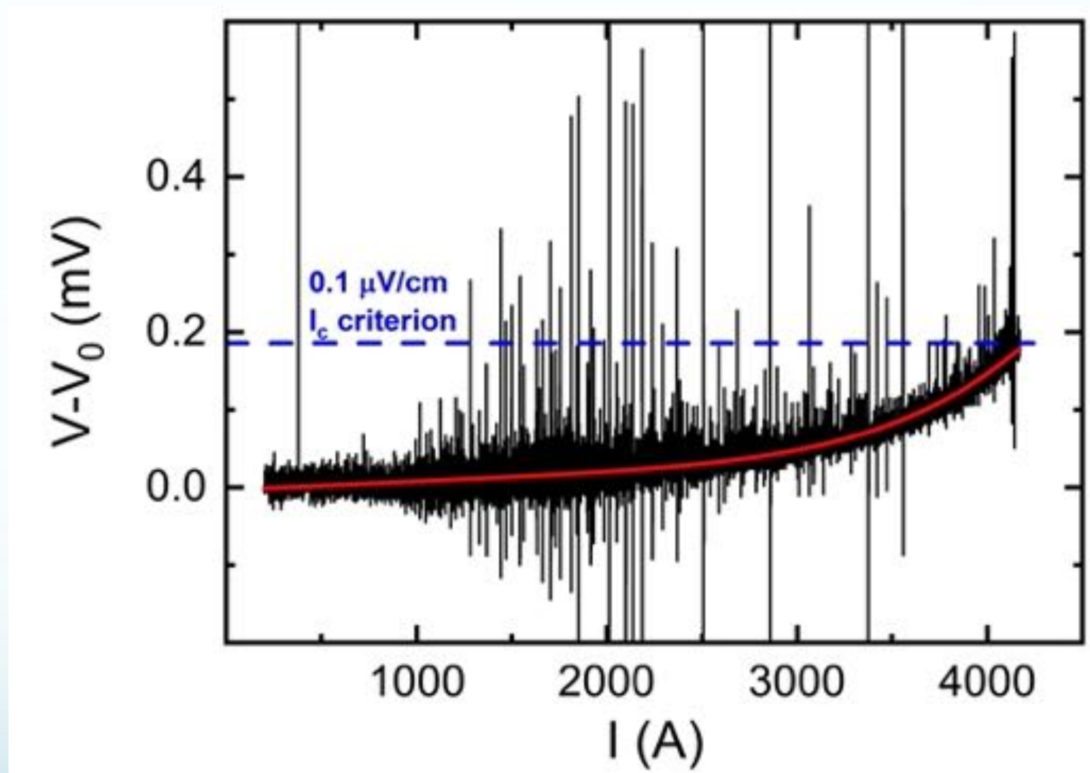
Interlayer stainless steel overbanding

CORC® magnet test: 14 T background field

Results 14 T background field

- Maximum current 4,200 A to avoid quench trigger
- I_c = 4,404 @ 0.1 μV/cm
- Contact resistance 11.1 nΩ
- 15.86 T central field
- 16.77 T on conductor
- JBr source stress 275 MPa





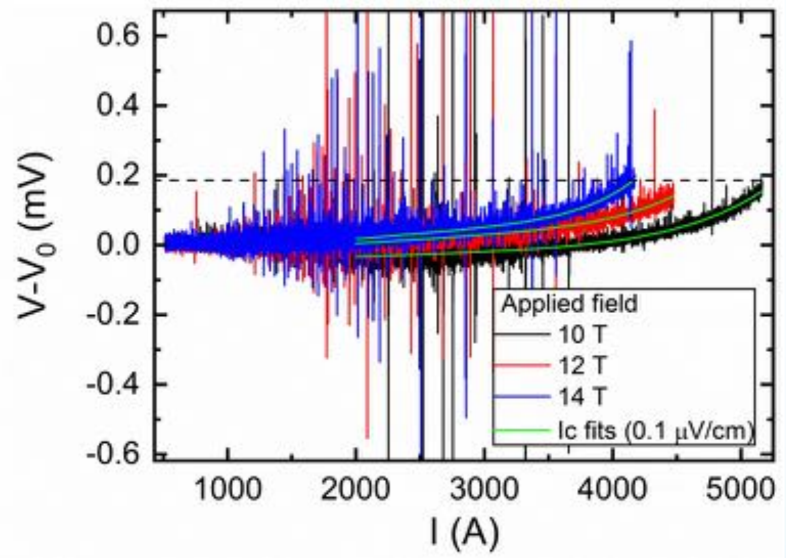
CORC® insert solenoid test: summary

CORC® insert impact

- **First HTS insert magnet tested at high current (>1 kA) in a background field**
- Stable operation likely due to current sharing between tapes in the CORC® cable
- Combination of high I, J_w and JBr demonstrated at 16.8 T peak field

Applied field [T]	Central field at I_c [T]	Peak field at I_c [T]	I_c (0.1 μV/cm) [A]	*n*-value [-]	J_w [A/mm²]	J_e [A/mm²]
10	12.25	13.35	5,315	7.9	203.9	340.3
12	14.08	15.09	4,908	9.1	188.3	314.2
14	15.86	16.77	4,404	10.5	168.9	281.9

D. C. van der Laan, et al.,
Supercond. Sci. Technol. (2020)
https://doi.org/10.1088/1361-6668/ab7fbe



Conductor challenges when going to higher field and larger coil diameters

- A Central Solenoid in a future compact fusion reactor may have a JBr of 200 A/mm² x 20 T x 0.2 m = 800 MPa (source stress)
- How to further optimize the CORC® conductor to allow higher hoop stress, but also a higher irreversible strain limit?

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Why is Nb-Ti the workhorse of superconducting magnets?

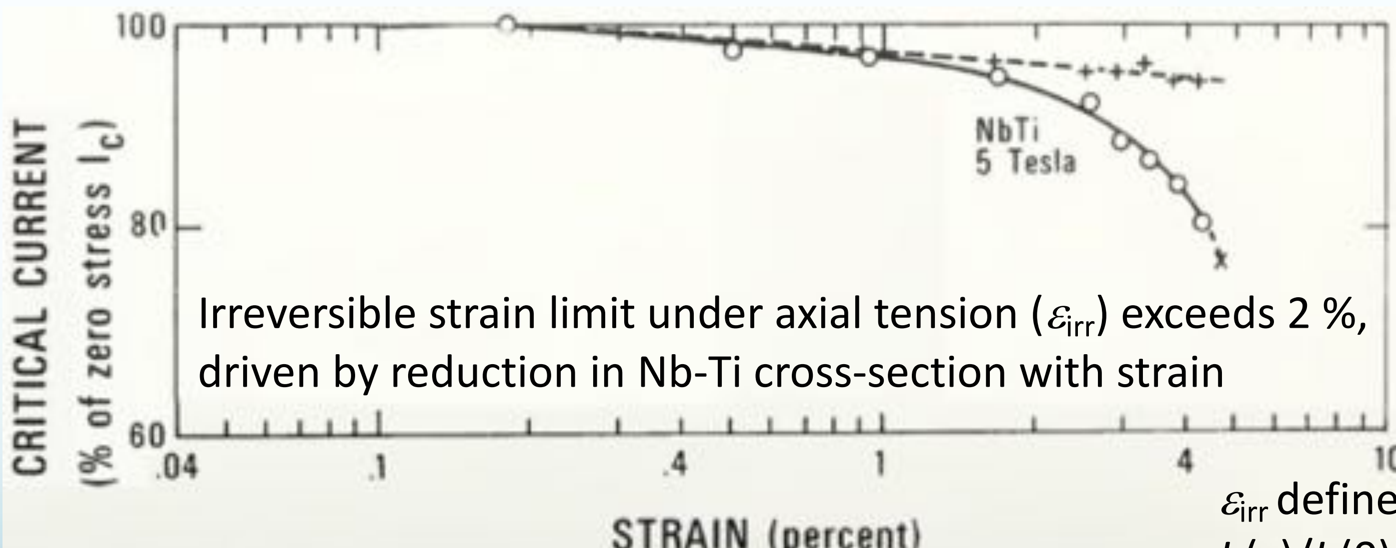
Nb-Ti is a superconducting magnet workhorse because

- 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)
✓ (Not too tight please!)

We know this, so what's new? To find out, let's consider this 44 year old plot:



Irreversible strain limit under axial tension (ε_{irr}) exceeds 2 %, driven by reduction in Nb-Ti cross-section with strain

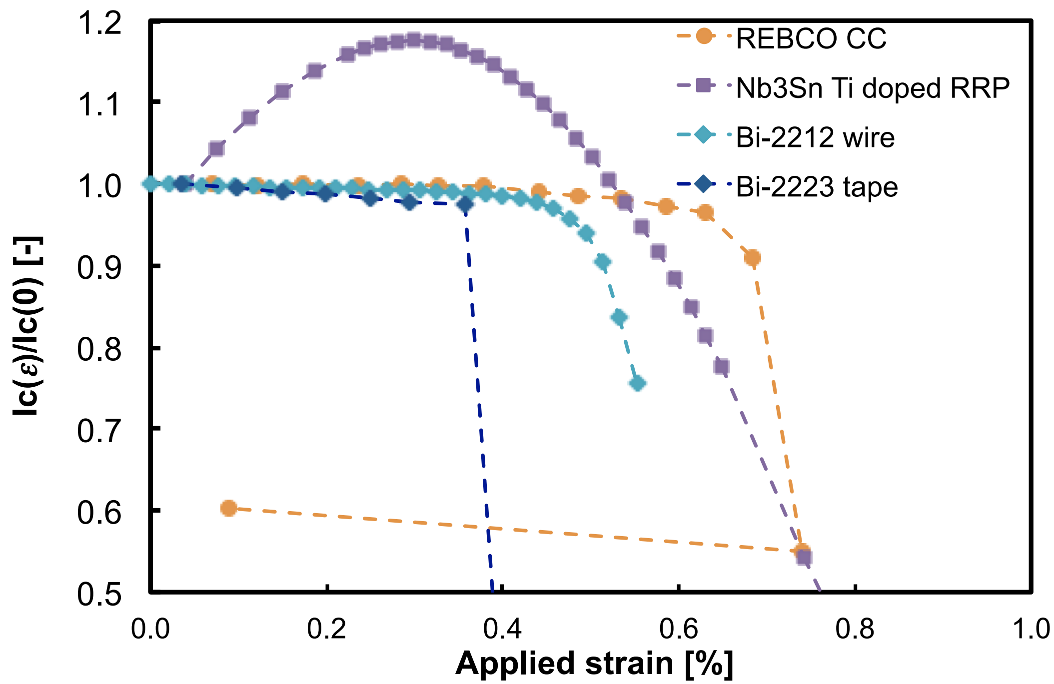
ε_{irr} defined at $I_c(\varepsilon)/I_c(0)$ < 97-98 %

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

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

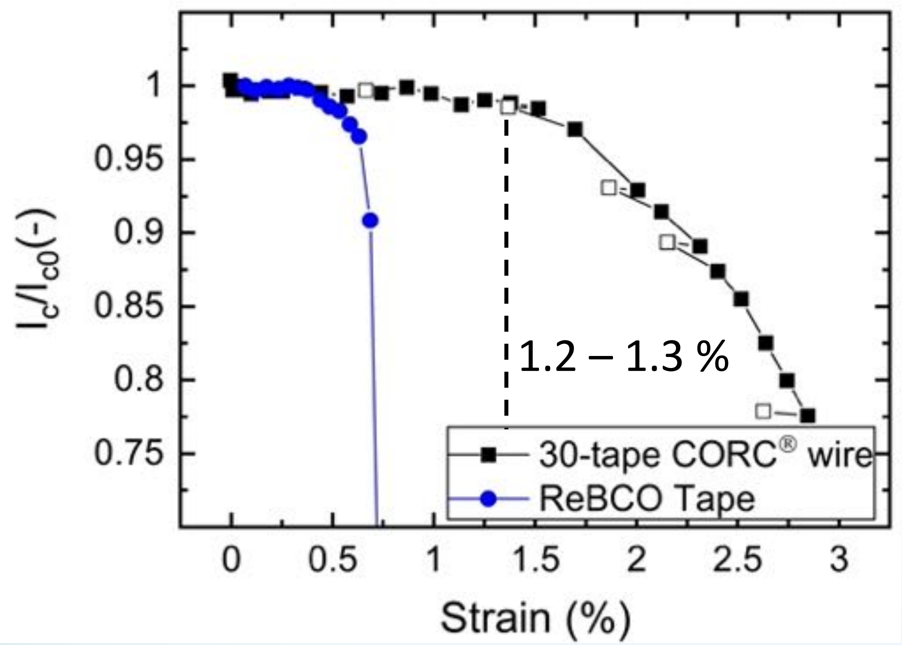
Testing CORC® wires under axial tension

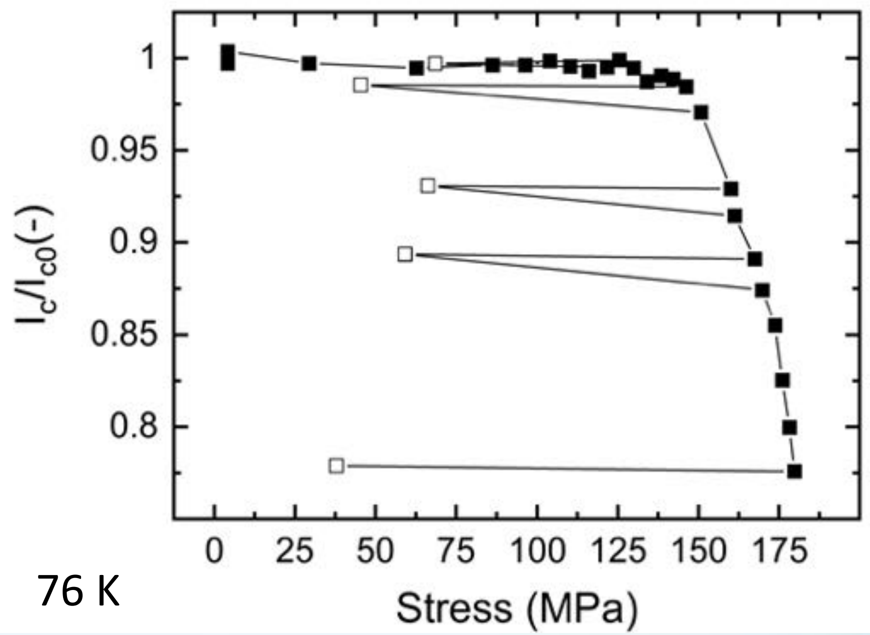
- Test performed in LN_2 at 77 K
- Maximum load of 13 kN applied to terminations
- Sample strain measured with pair of clamp-on extensometers

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**

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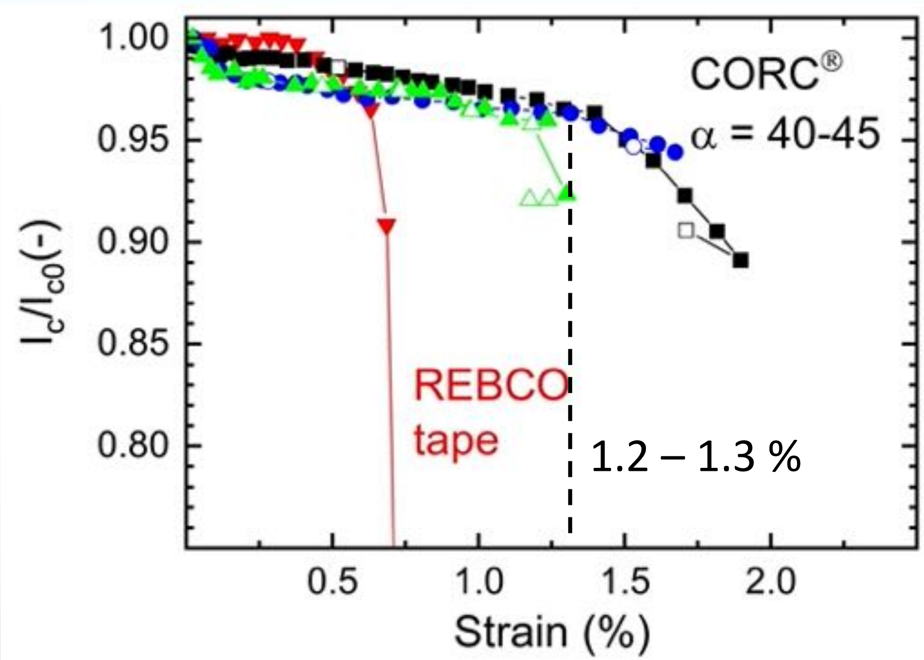
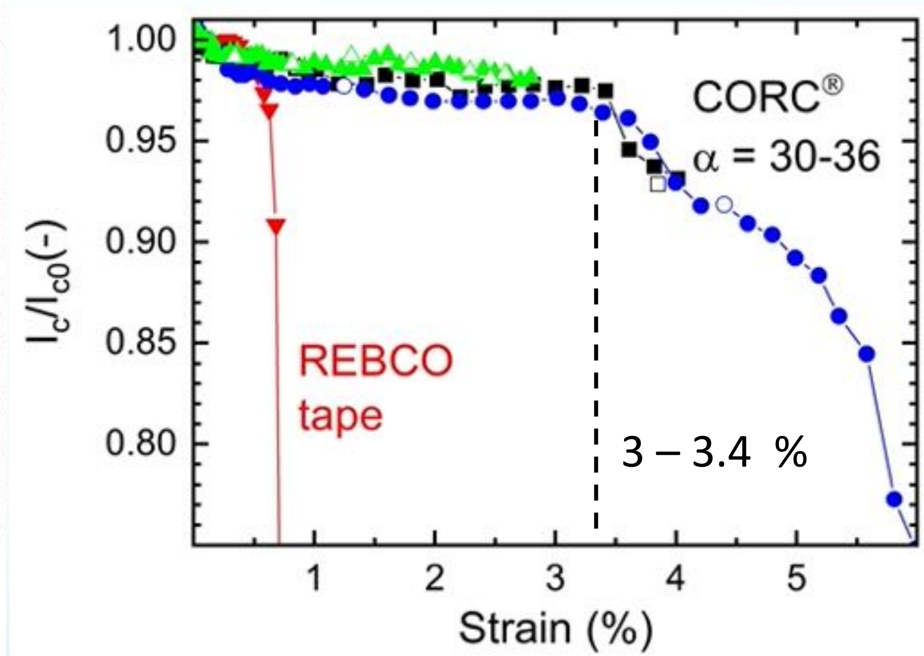
Effect of tape winding angle on ε_{irr}

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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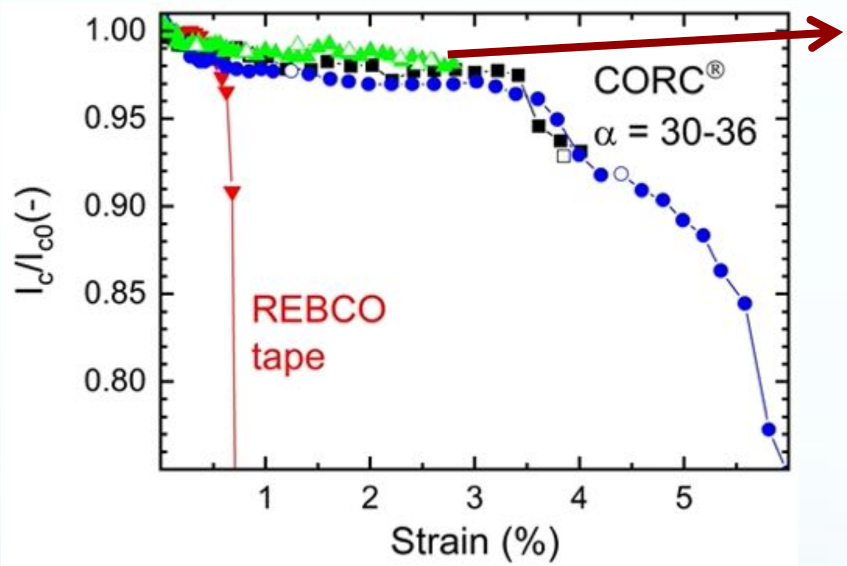
Verification of tape I_c retention after strain

Procedure

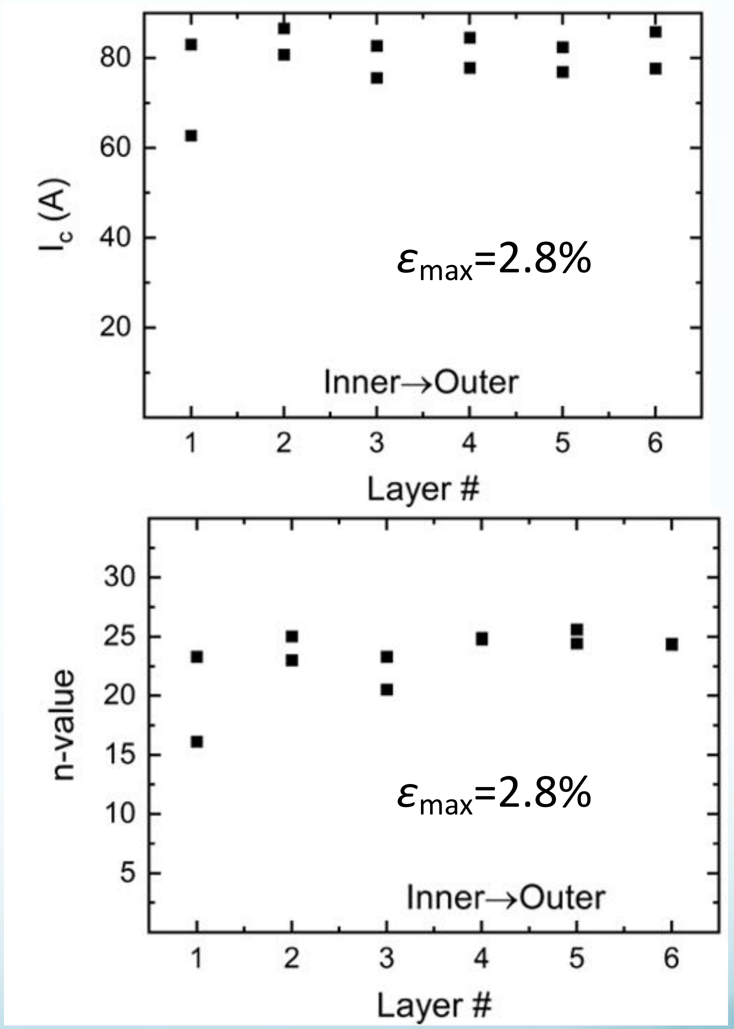
- Strain CORC® wire to 0.85 x ε_{irr}
- Extract tapes from CORC® wire
- Measure I_c from extracted tapes



Results

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

High ε_{irr} of 3.3 % is real!



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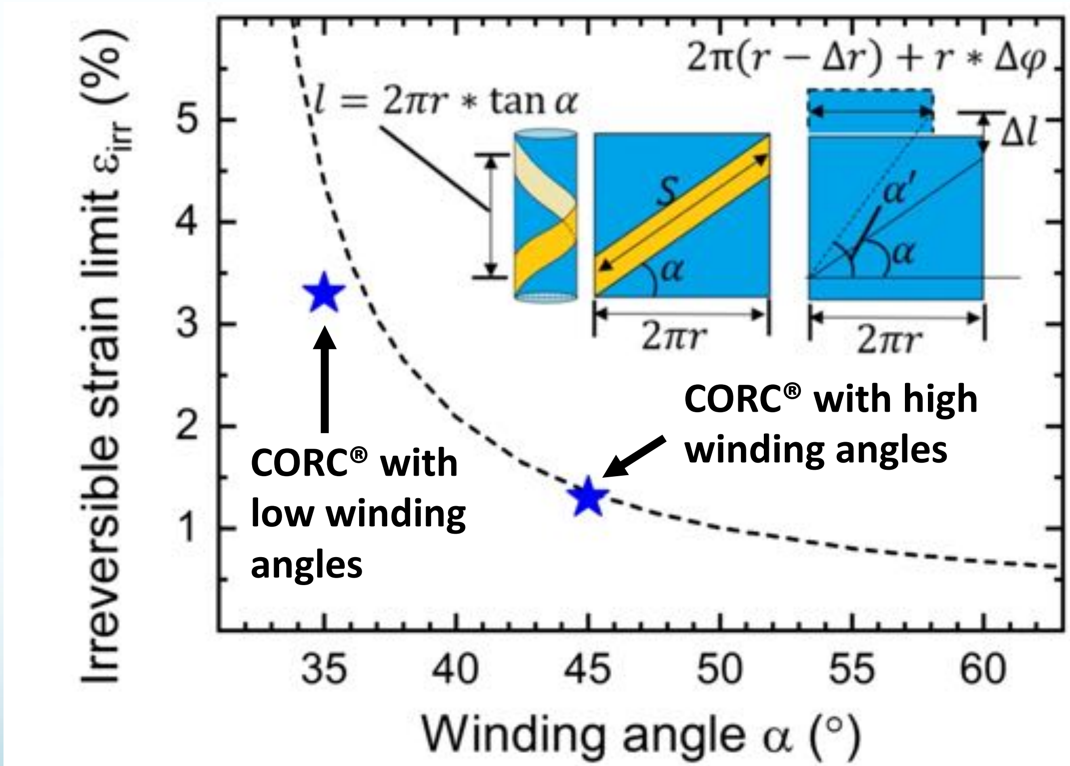
Analytical verification of strain results

Analytical approach

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

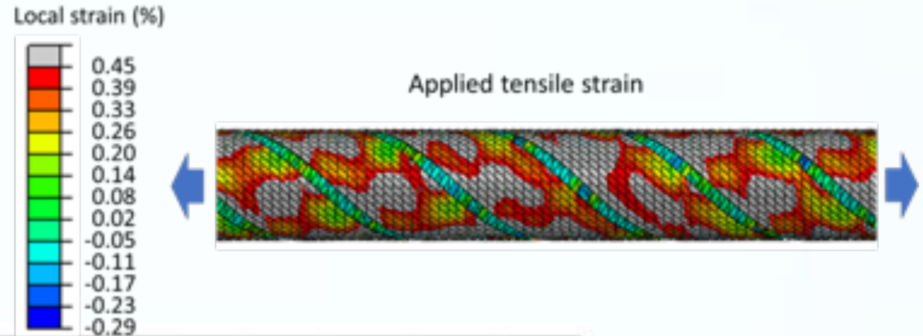
$$\varepsilon_{\text{tape}} = \frac{\Delta S}{S} = \frac{\frac{l+\Delta l}{\sin\alpha'} - \frac{l}{\sin\alpha}}{\frac{l}{\sin\alpha}} \approx \frac{\Delta l}{l}(sin^2\alpha - \nu cos^2\alpha)$$

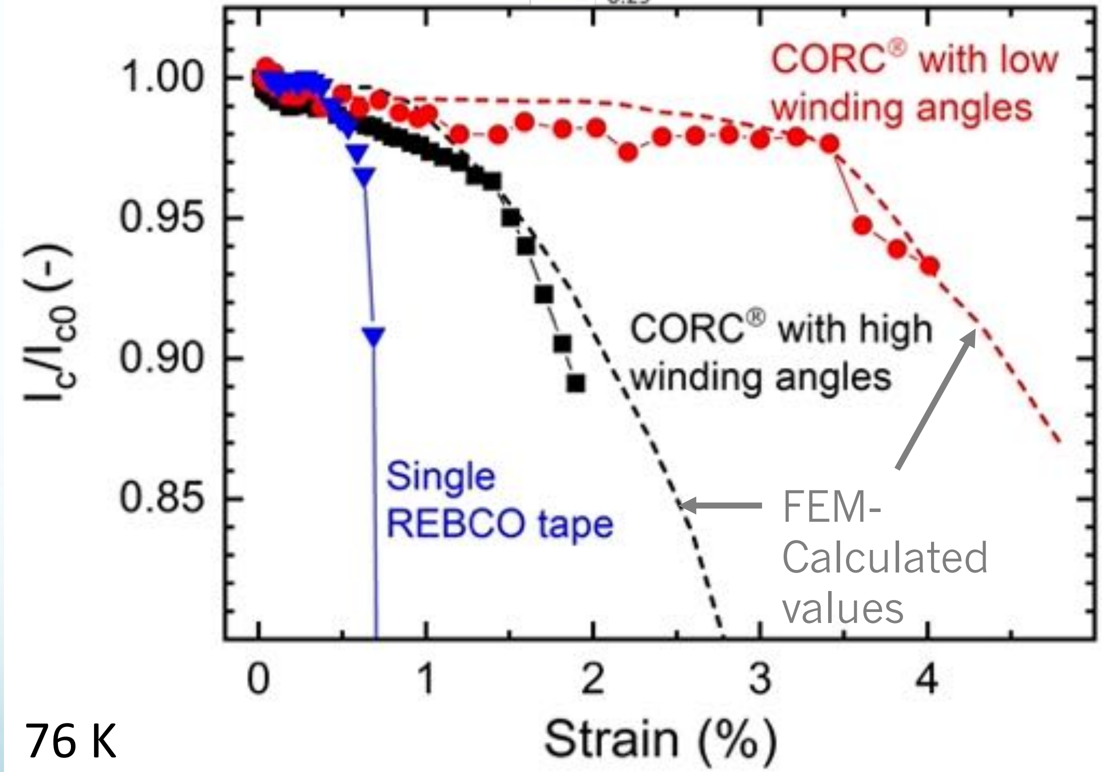


FEM verification of results

FEM approach

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

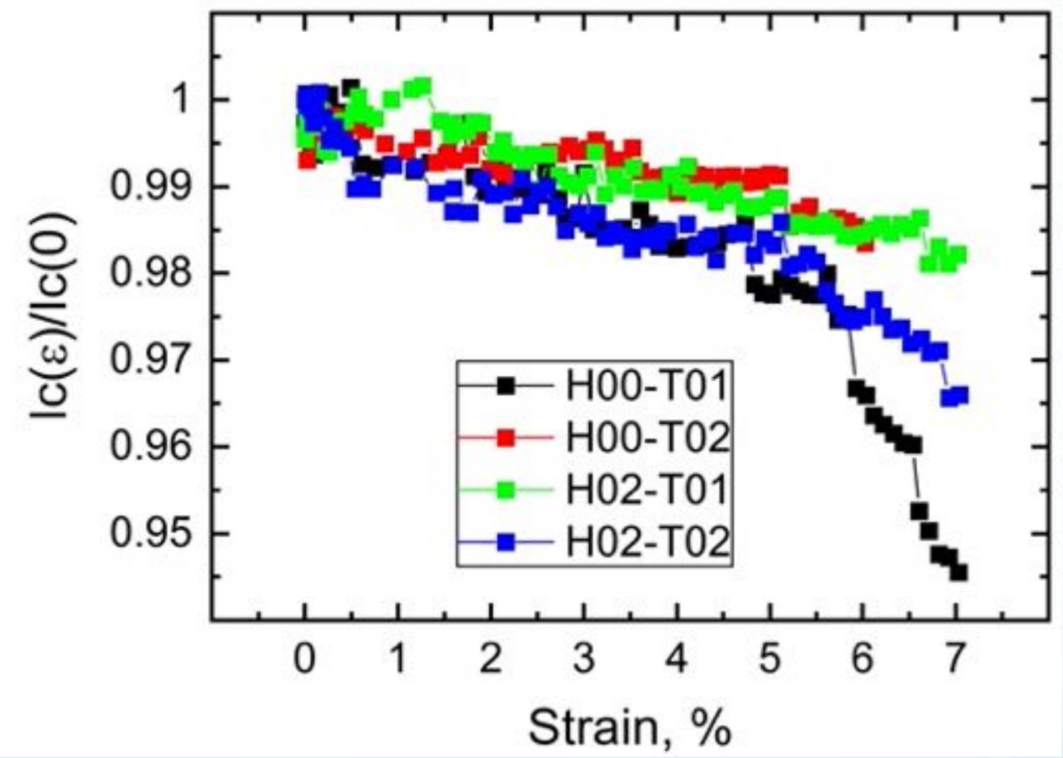




Extending ε_{irr} of high tape count CORC® wires

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

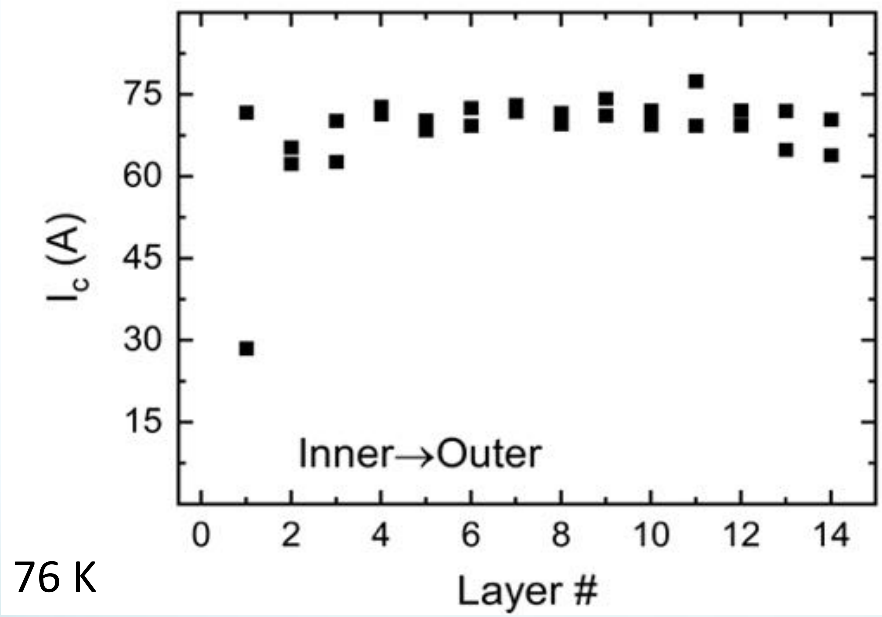


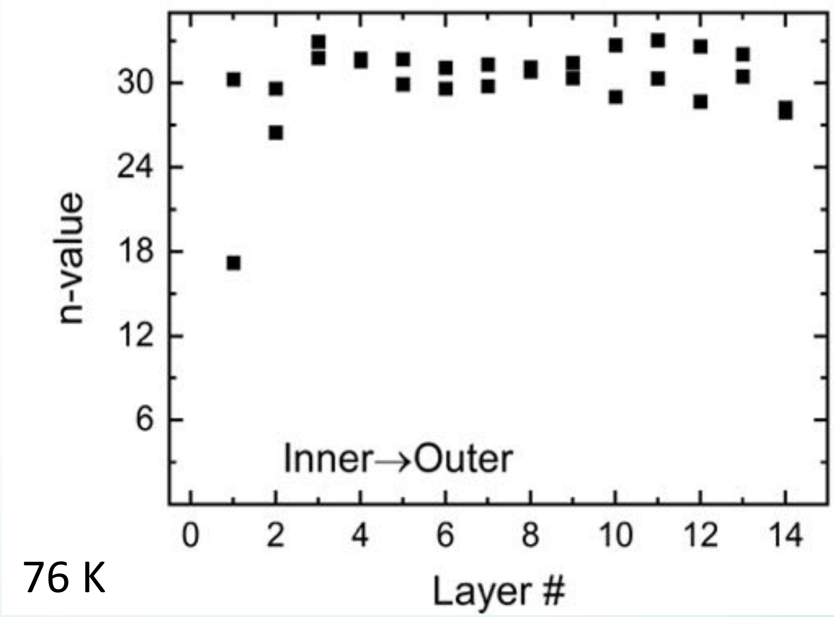
Optimized 28-tape CORC® wire : ε_{irr} = 6 – 7 %!!

Verification of tape I_c retention after high strain

Optimized 28-tape CORC® wire

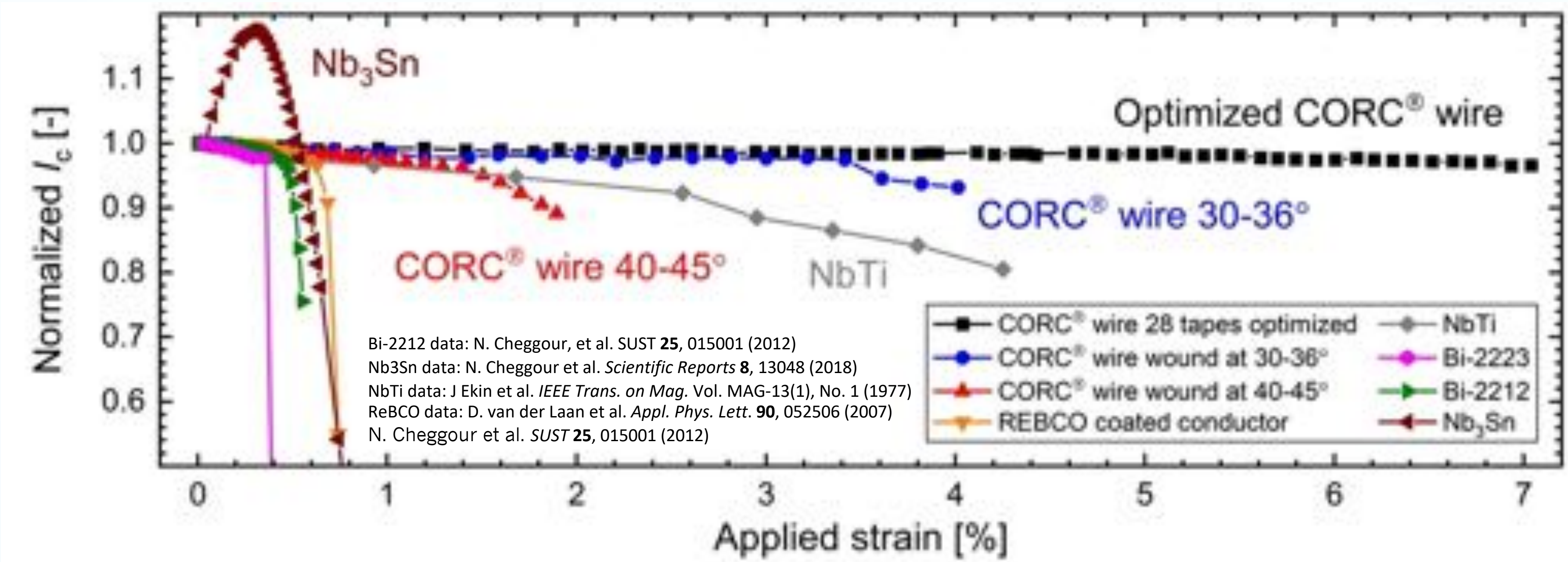
- CORC® wire I_c retention 98 % at 7 % strain
- Extracted tape I_c retention 99 %
- Only tapes in the inner layer are damaged





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

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**

Accepted for publication: van der Laan *et al.* “High -temperature superconducting CORC® wires with record-breaking axial tensile strain tolerance present a breakthrough for high-field magnets”
DOI https://doi.org/10.1088/1361-6668/ac1aae

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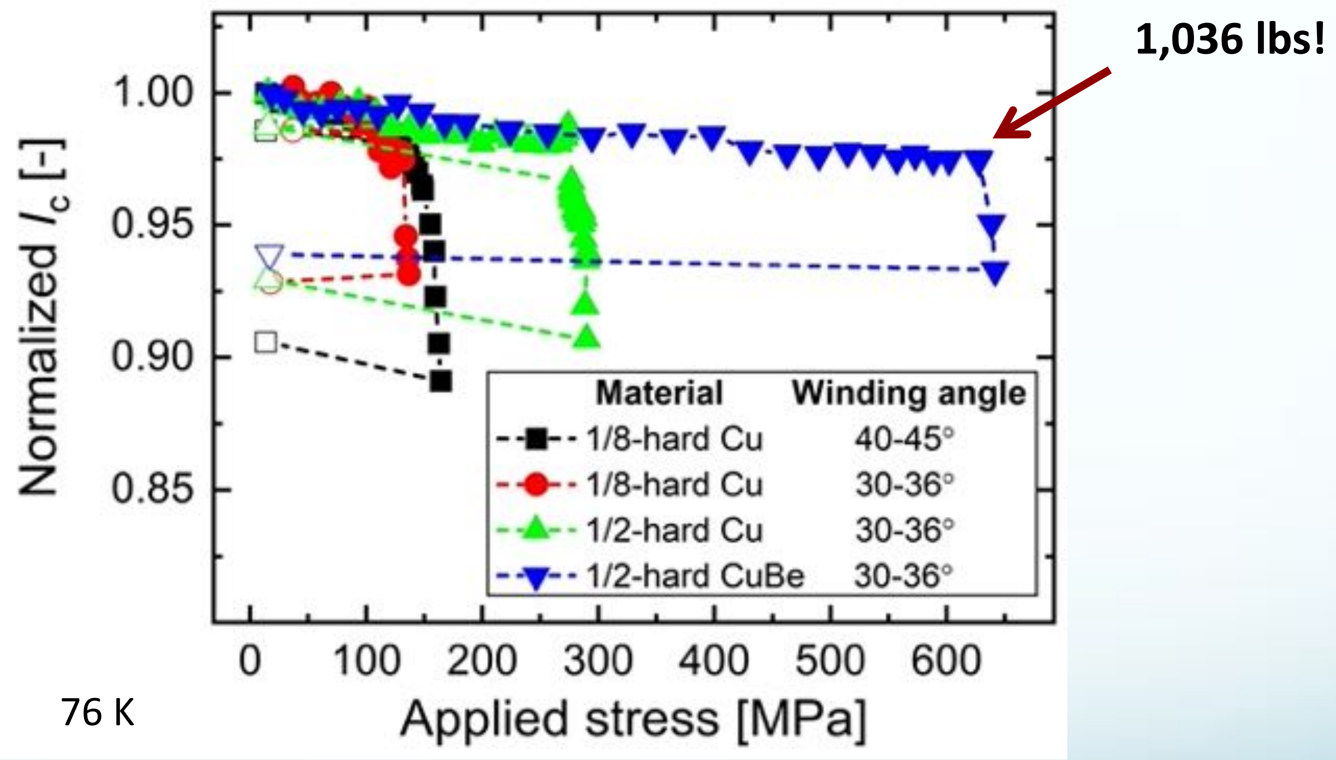
CORC® wires with improved mechanical tensile strength

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

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Summary

First high-current CORC® insert solenoid successfully tested

- Operation at over 4.4 kA in 14 T background field, generating a peak field of 16.77 T
- Operated at 282 A/mm^2 and 275 MPa JBr source stress at 14 T background field

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