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Invited presentation HF-5 was given at the virtual CCA 2021, October 11-15, 2021.

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

Danko van der Laan and Jeremy Weiss
Advanced Conductor Technologies & University of Colorado, Boulder, Colorado, USA

Kyle Radcliff
Advanced Conductor Technologies, Boulder, Colorado, USA

Shreyas Balachandran, Ulf Trociewitz, Dima Abraimov, Ashley Francis, James Gillman, Daniel Davis, Younjae Kim, Van Griffin, George. Miller, Lance Cooley, David Larbalestier
Applied Superconductivity Center, NHMFL, Tallahassee, Florida USA

Huub Weijers
Robinson Research institute, Victoria University of Wellington, New Zealand

Anvar V.A., Keyang Wang and Arend Nijhuis
University of Twente, Enschede, the Netherlands

CCA21, October 14th, 2021

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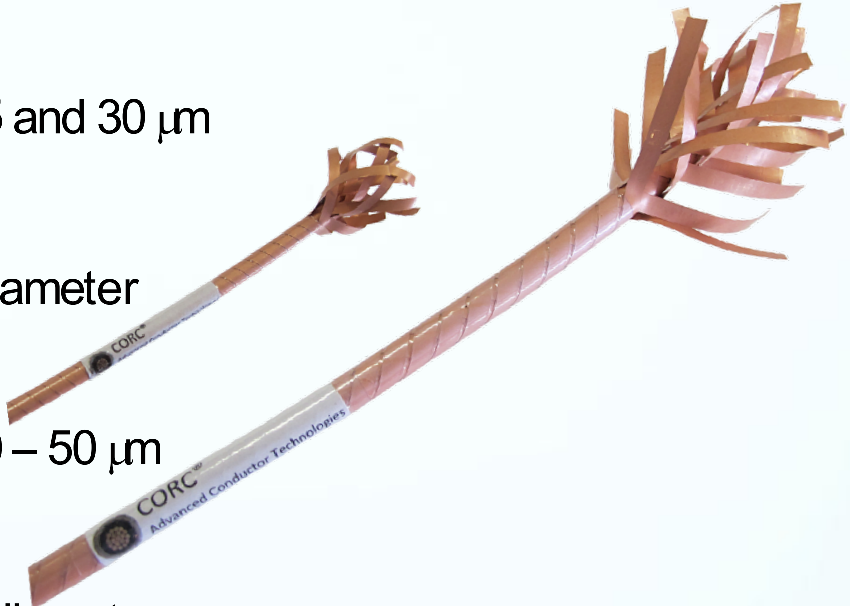
CORC® magnet cables and wires



CORC® wires (2.5 – 4.5 mm diameter)

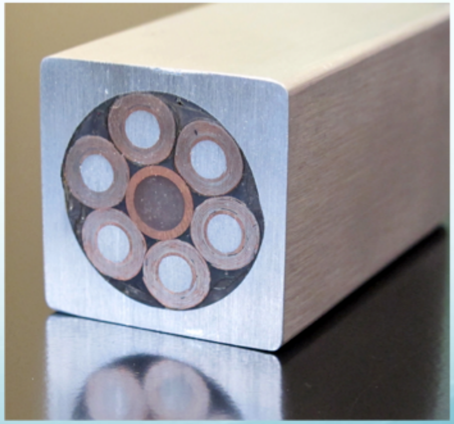
- Wound from 2 – 3 mm wide tapes with 25 and 30 μm substrate
- Typically no more than about 30 tapes
- Flexible with bending down to < 50 mm diameter

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



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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**

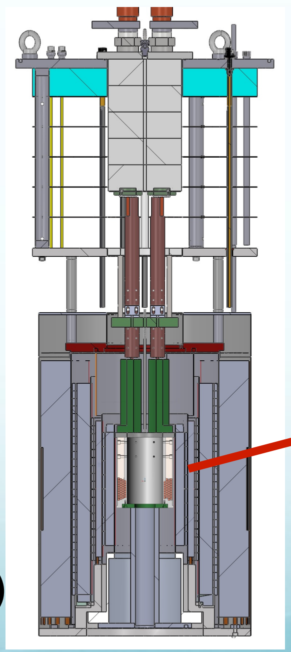
CORC® cable layout

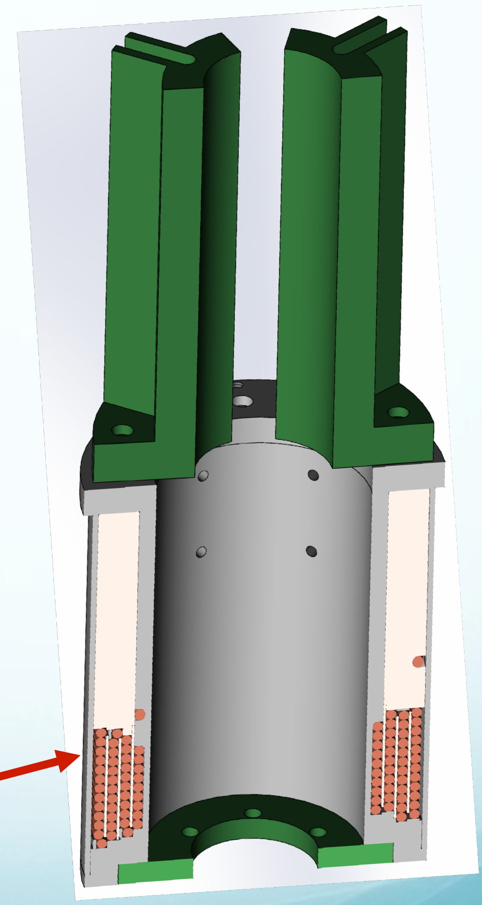
- 28 REBCO tapes of 3 mm width containing 30 μm substrates
- 4.56 mm CORC® cable outer diameter

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)





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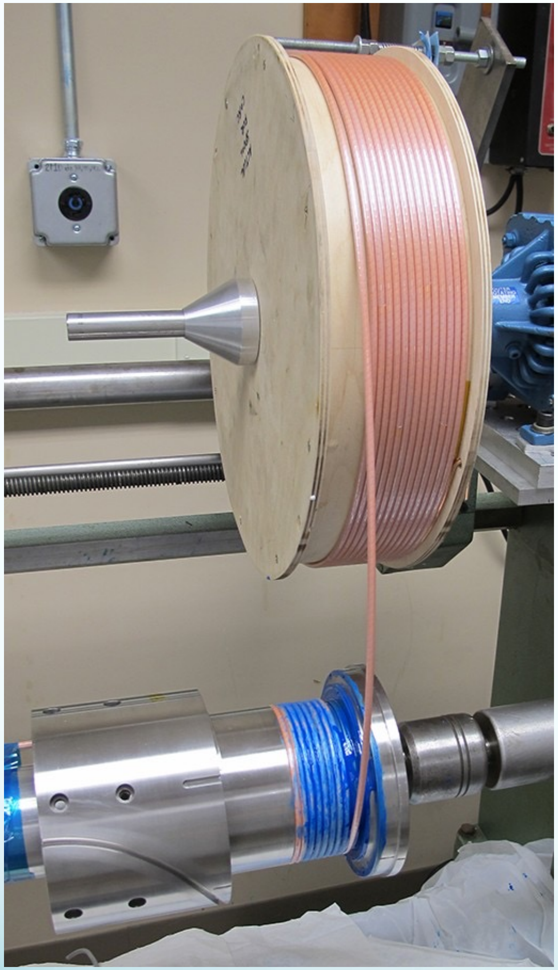
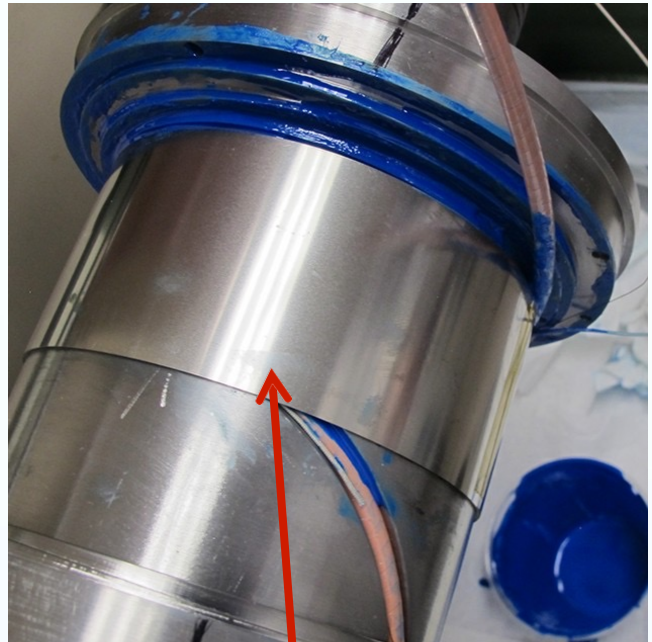
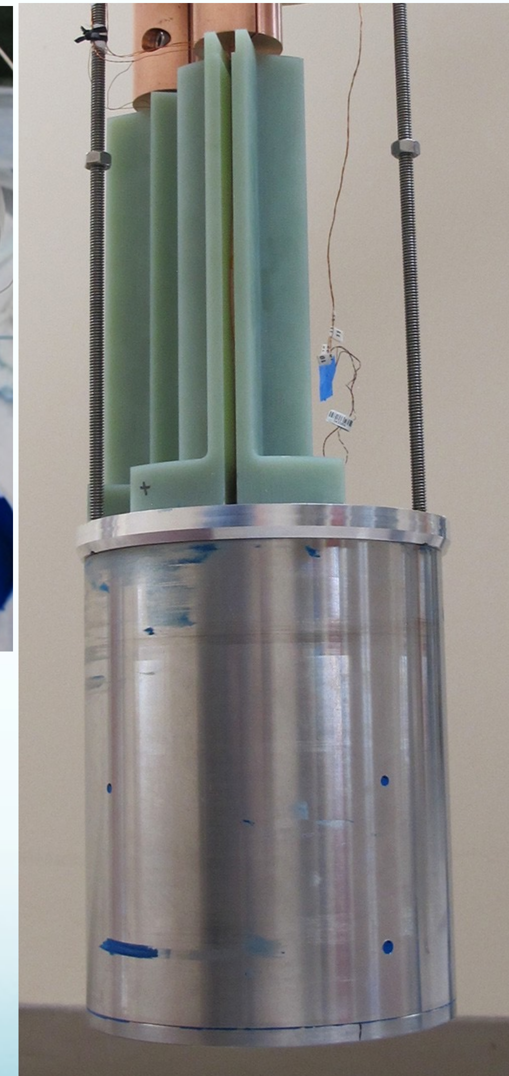
CORC® magnet winding





Interlayer stainless steel overbanding



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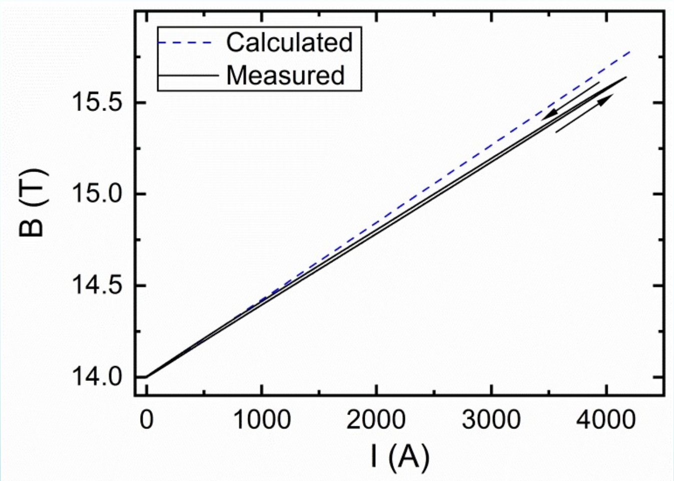
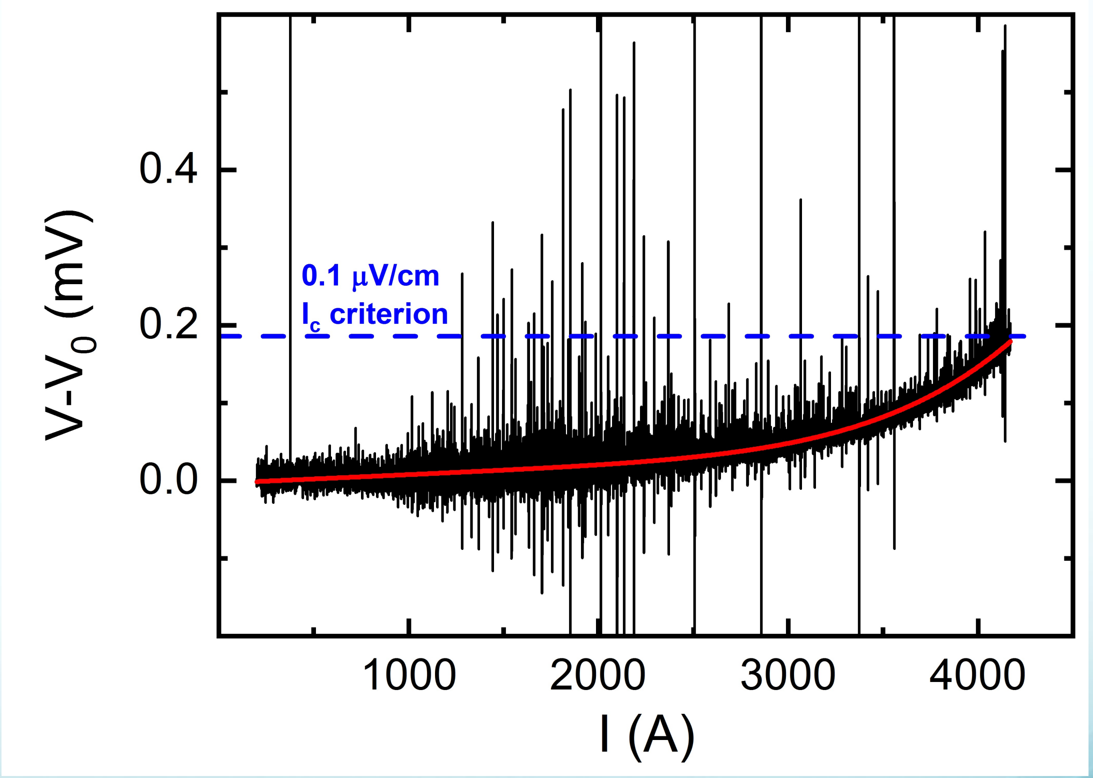
CORC® magnet test: 14 T background field

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





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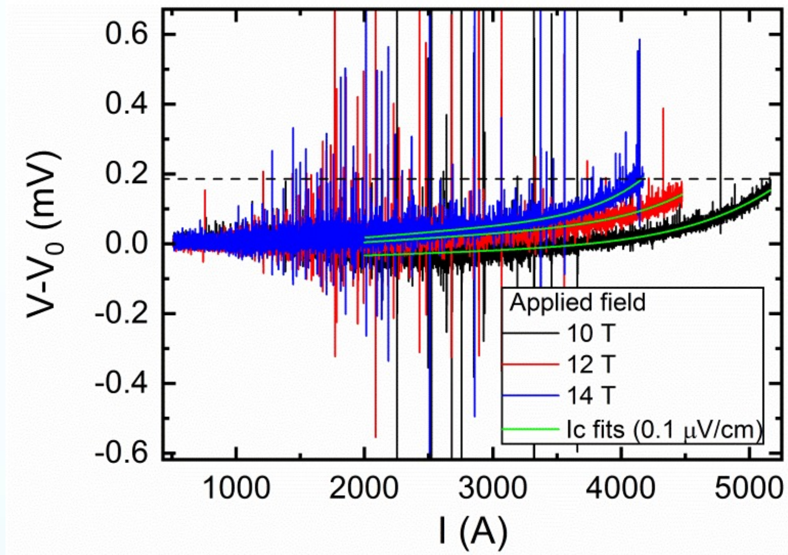
CORC® insert solenoid test: summary

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?

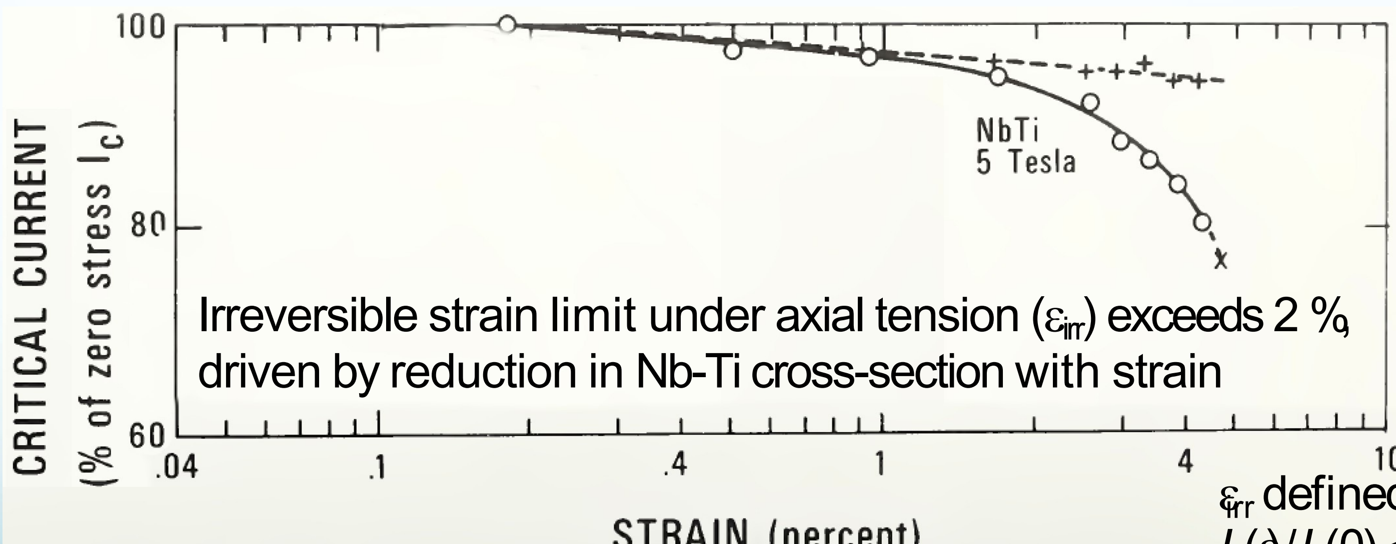
Nb-Ti is a superconducting magnet workhorse because

- 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

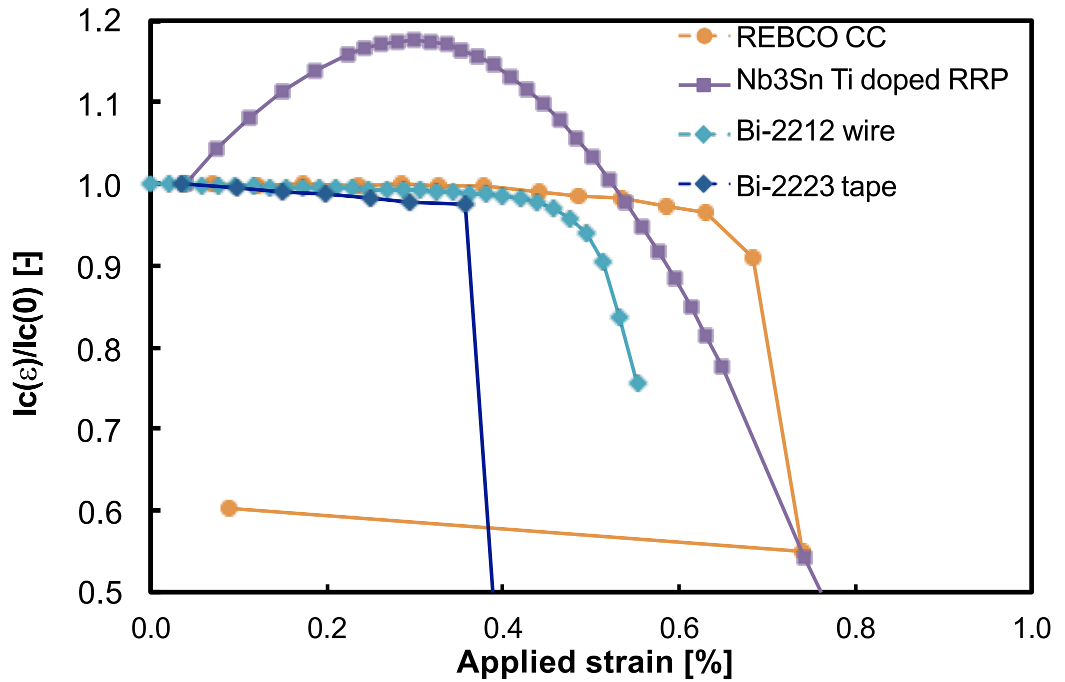
ε_{irr} defined at $I_c(\varepsilon)/I_c(0)$ < 97-98 %

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)

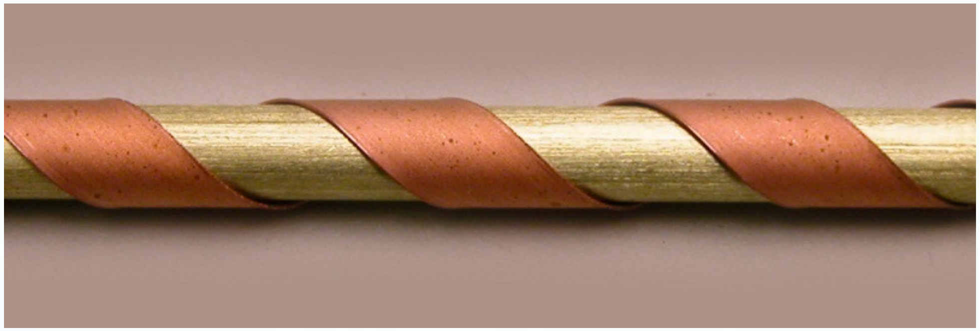
- Nb_3Sn: 0.65 % [1]
- Bi-2212 wires: 0.3 % [2]
- Bi-2223 tapes: 0.4 % [3]
- REBCO CC: 0.6 % [4]



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)
2N Cheggour, X F Lu, T G Holesinger, T C Stauffer, J Jiang and L F Goodrich, *Superconduct. Sci. Technol*. **25**, 015001 (2012)
3D.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

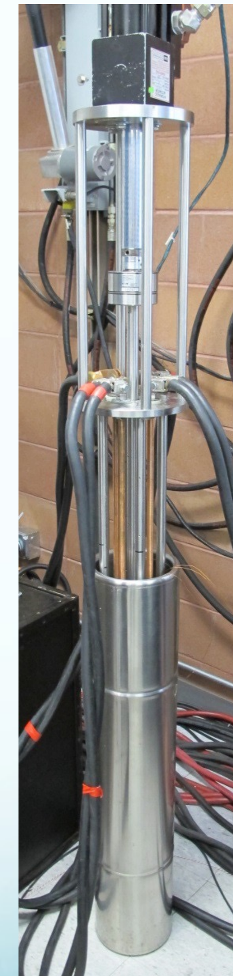


Simplified description of CORC® wire structure

- 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



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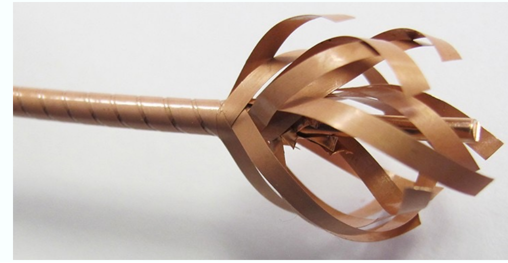
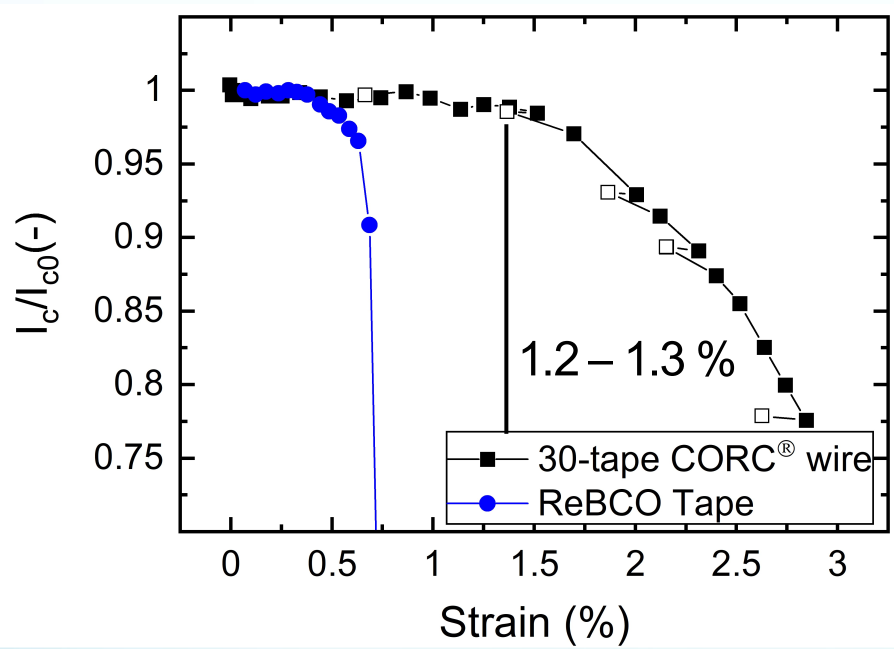
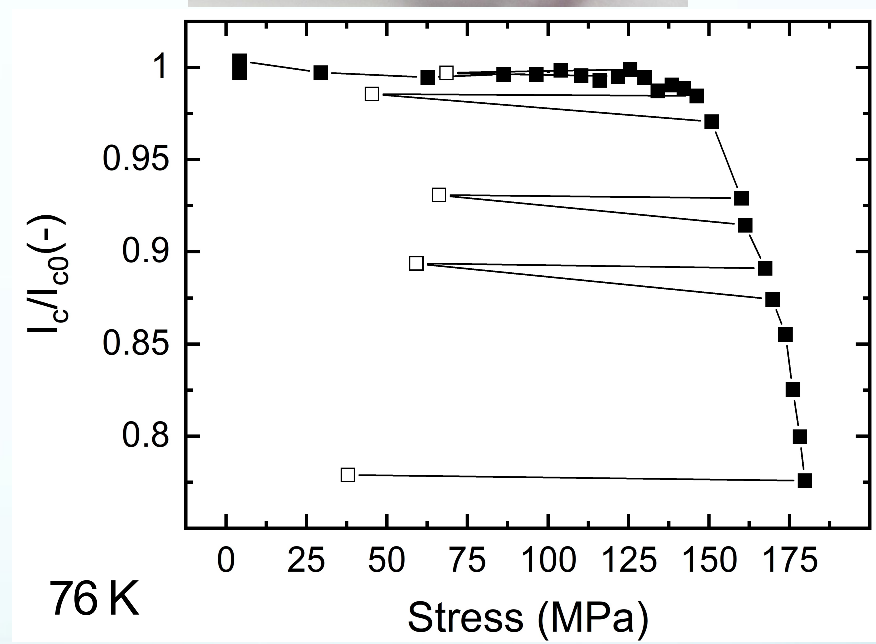
Performance of a standard 30-tape CORC® wire

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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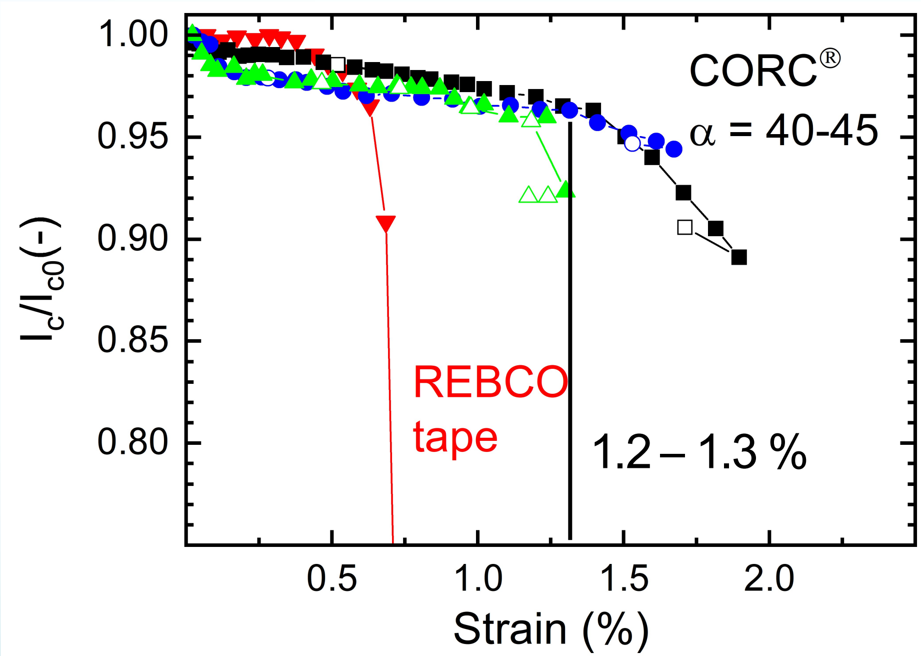
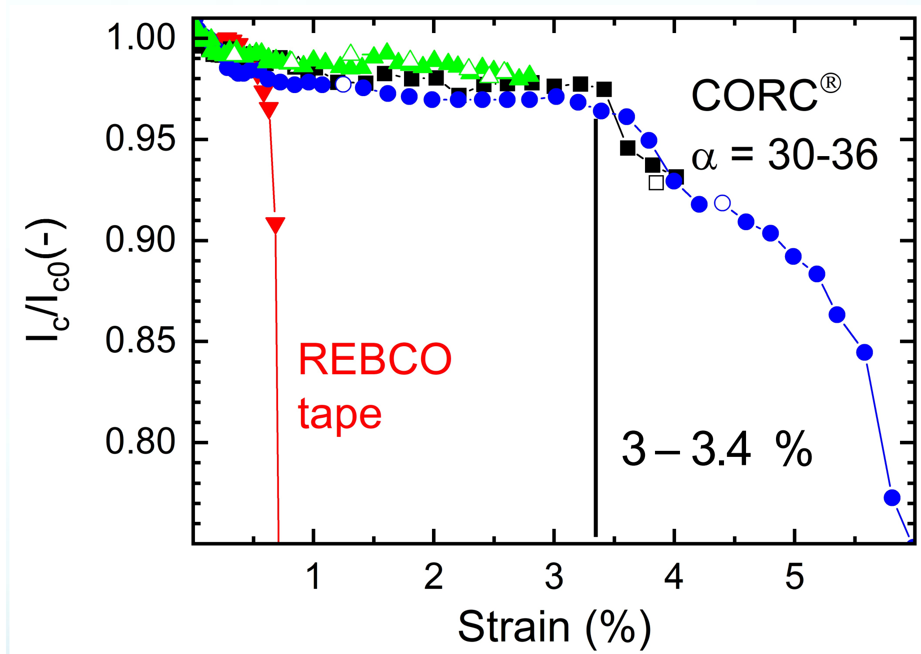
Effect of tape winding angle on ε_{irr}

High angle: α = 40-45º



Low angle: α = 30-36º



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

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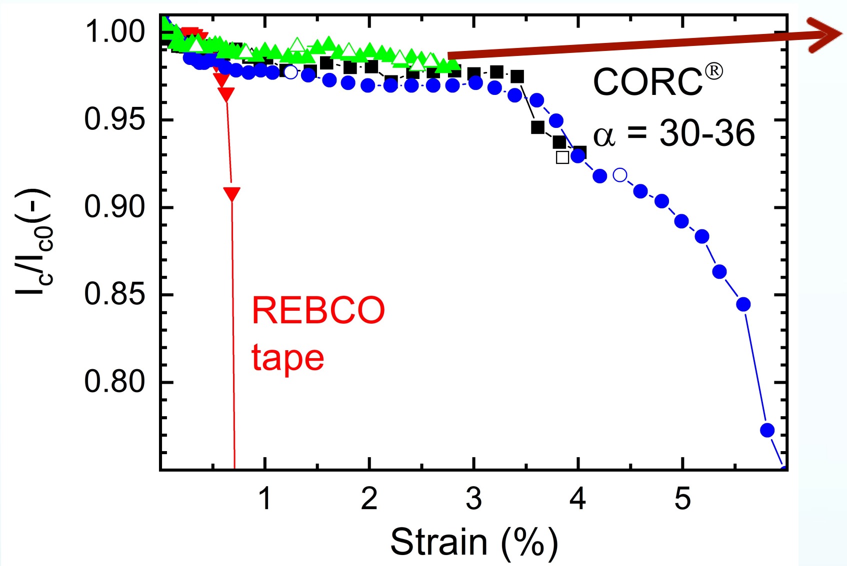
Verification of tape I_c retention after strain

Procedure

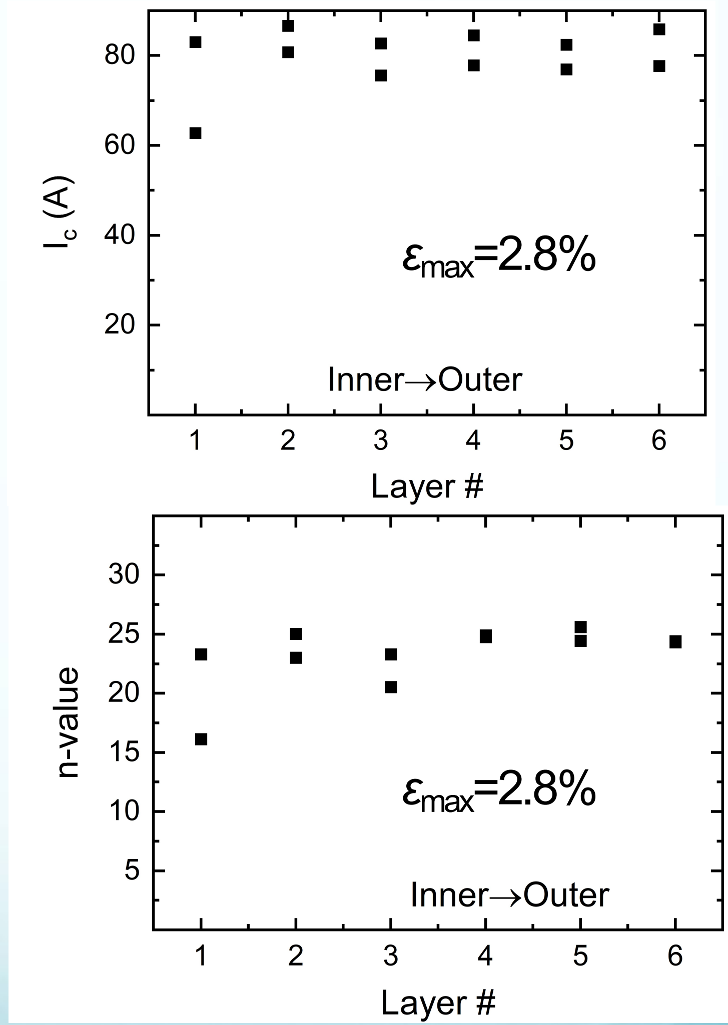
- Strain CORC®wire to 0.85 x ε_{irr}
- Extract tapes from CORC®wire
- Measure I_c from extracted tapes



Results

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

High ε_{irr} of 3.3 % is real!



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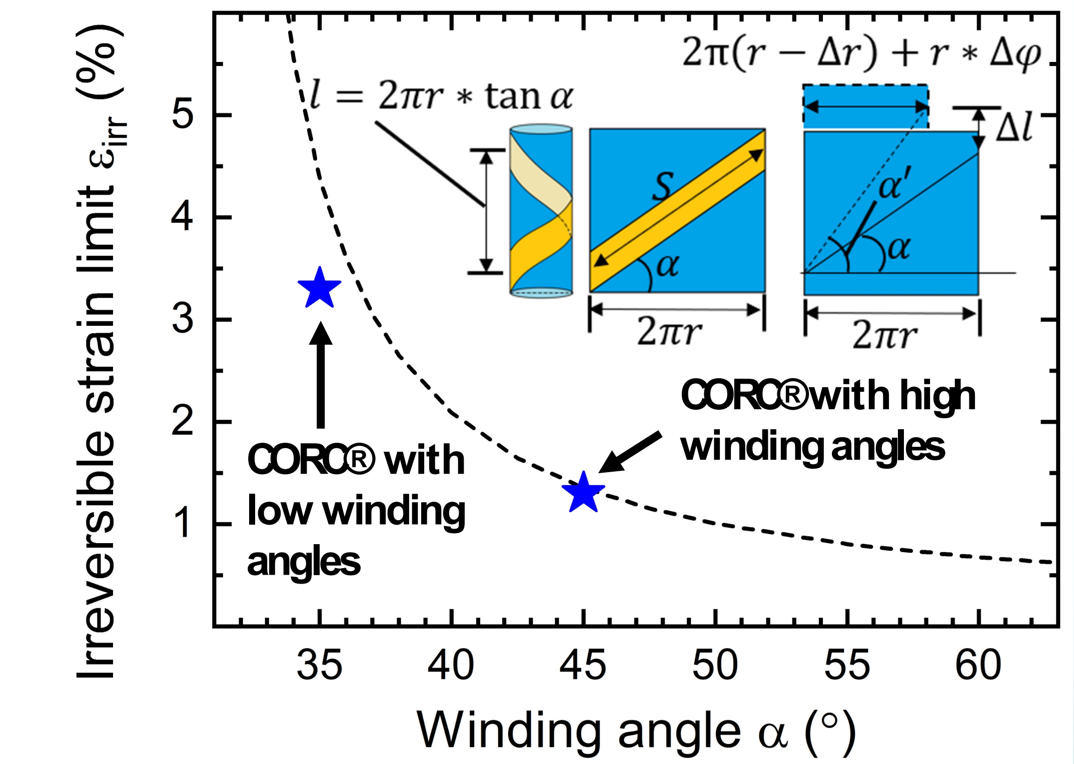
Analytical verification of strain results

Analytical approach

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

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



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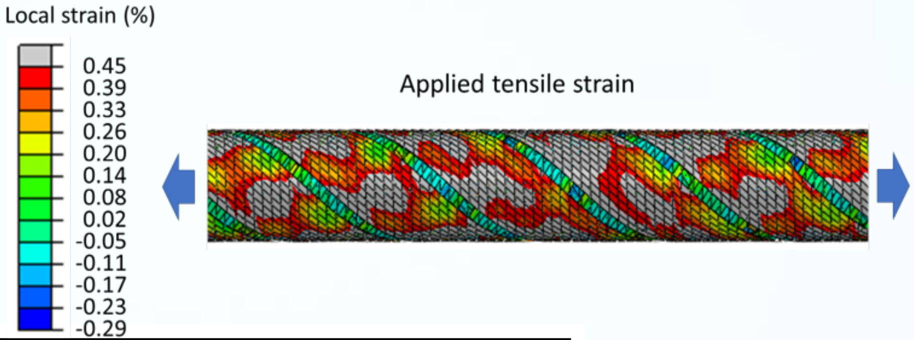
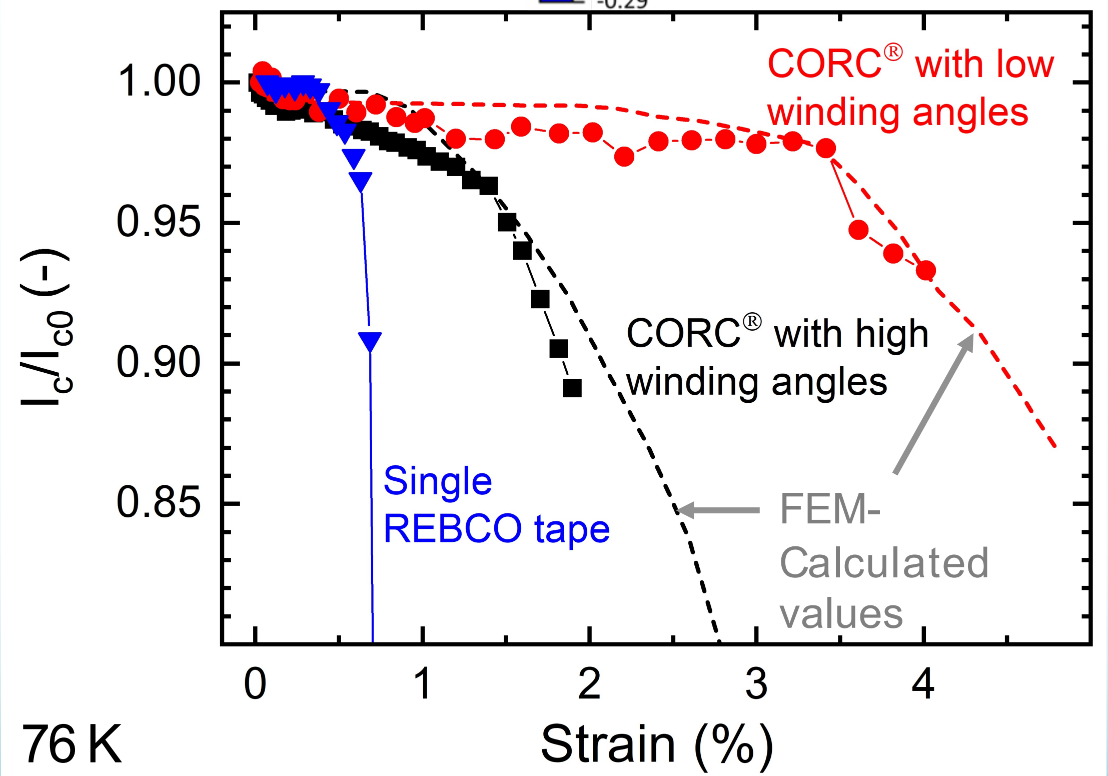
FEM verification of results

FEM approach

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





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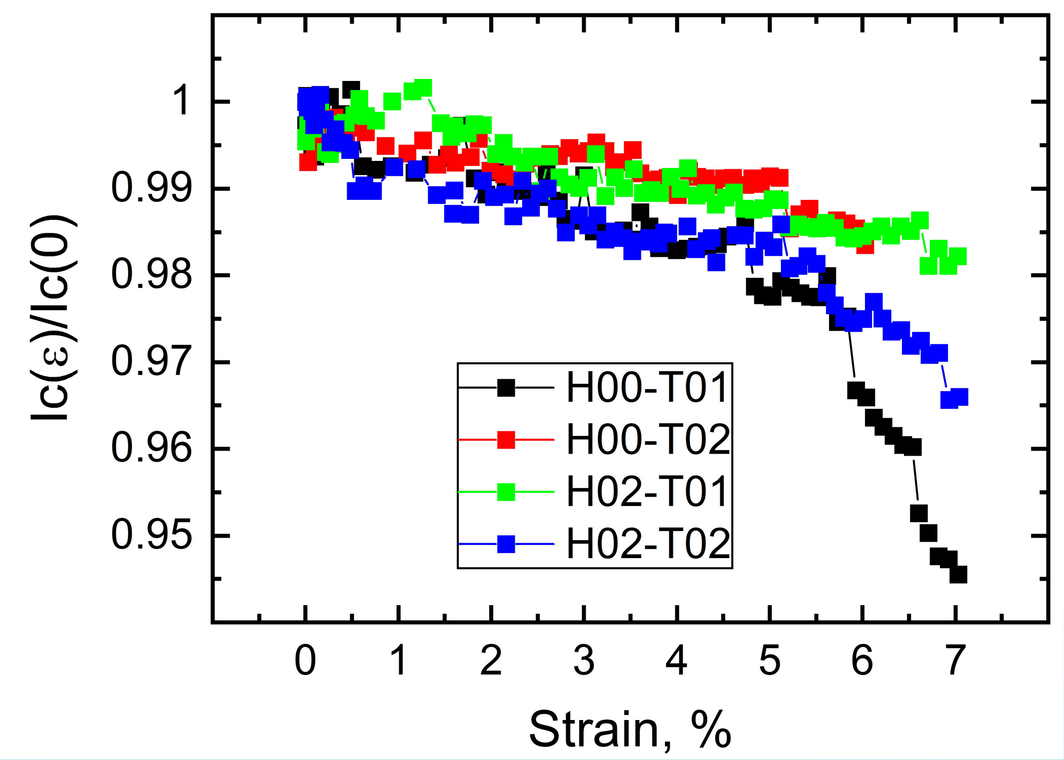
Extending ε_{irr} of high tape count CORC® wires

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 %!!

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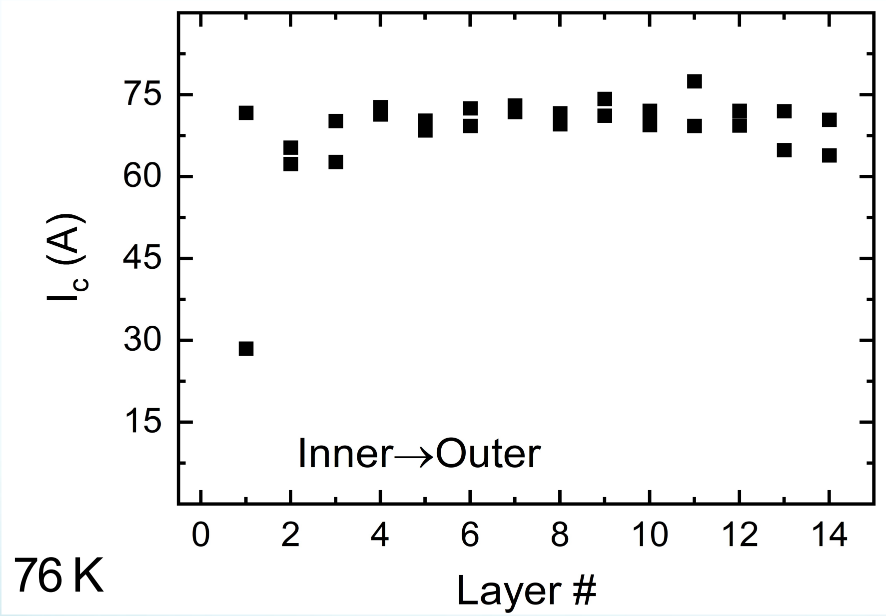
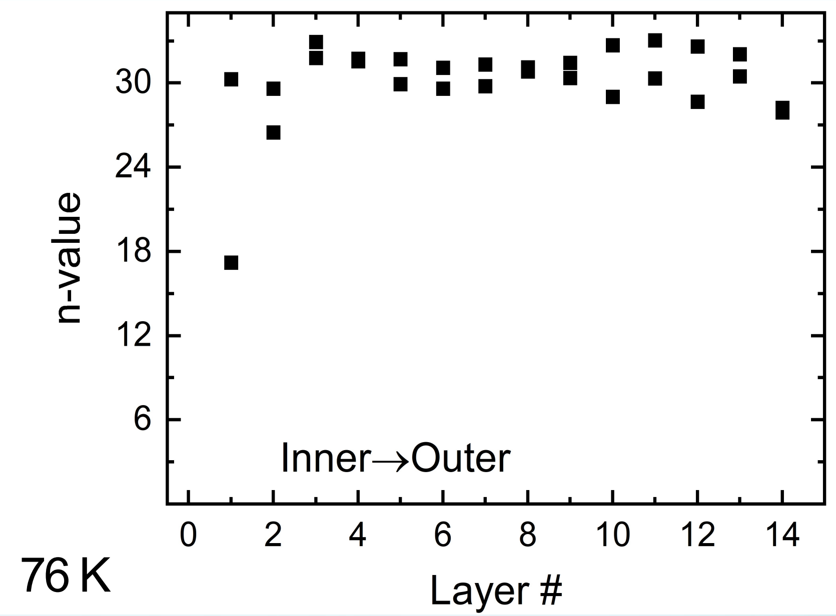
Verification of tape I_c retention after high strain

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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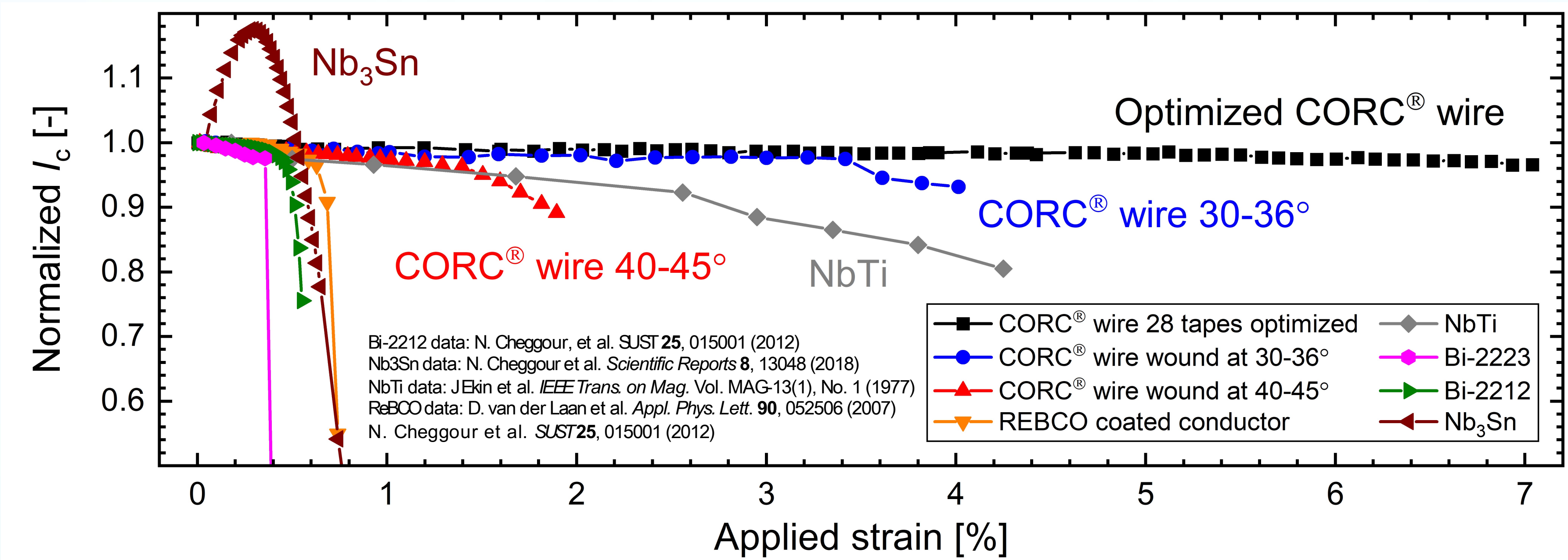
Axial strain practical superconductors Master Plot



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**

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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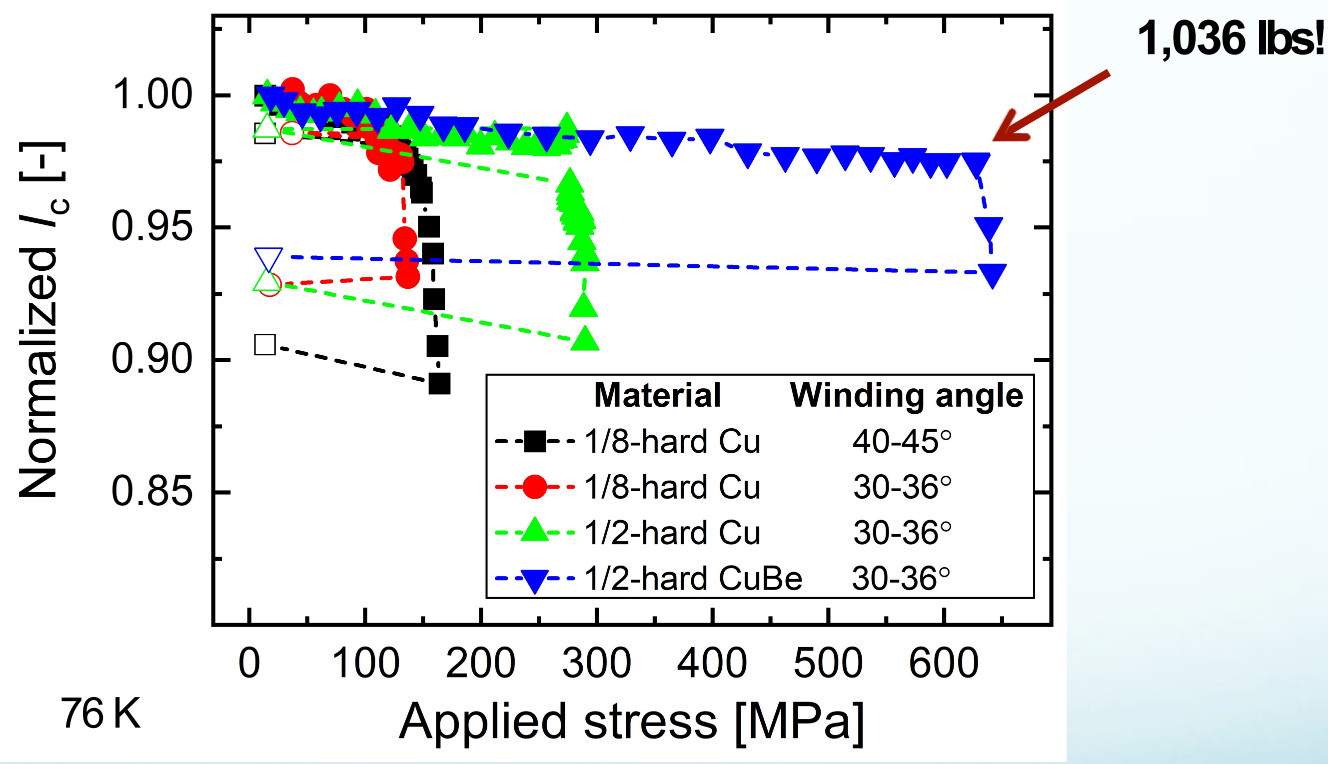
CORC® wires with improved mechanical tensile strength

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

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