Enhanced bending and high field performance of CORC® cables and wires for accelerator magnets

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

Sven Doenges & Kyle Radcliff
Advanced Conductor Technologies, Boulder, Colorado, USA

Anne de Jager
University of Colorado, Boulder, Colorado, USA

Xiaorong Wang & Hugh Higley
Lawrence Berkeley National Laboratory, Berkeley, California, U.S.A.

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LTSW 2024, Seaside California, April 3rd, 2024

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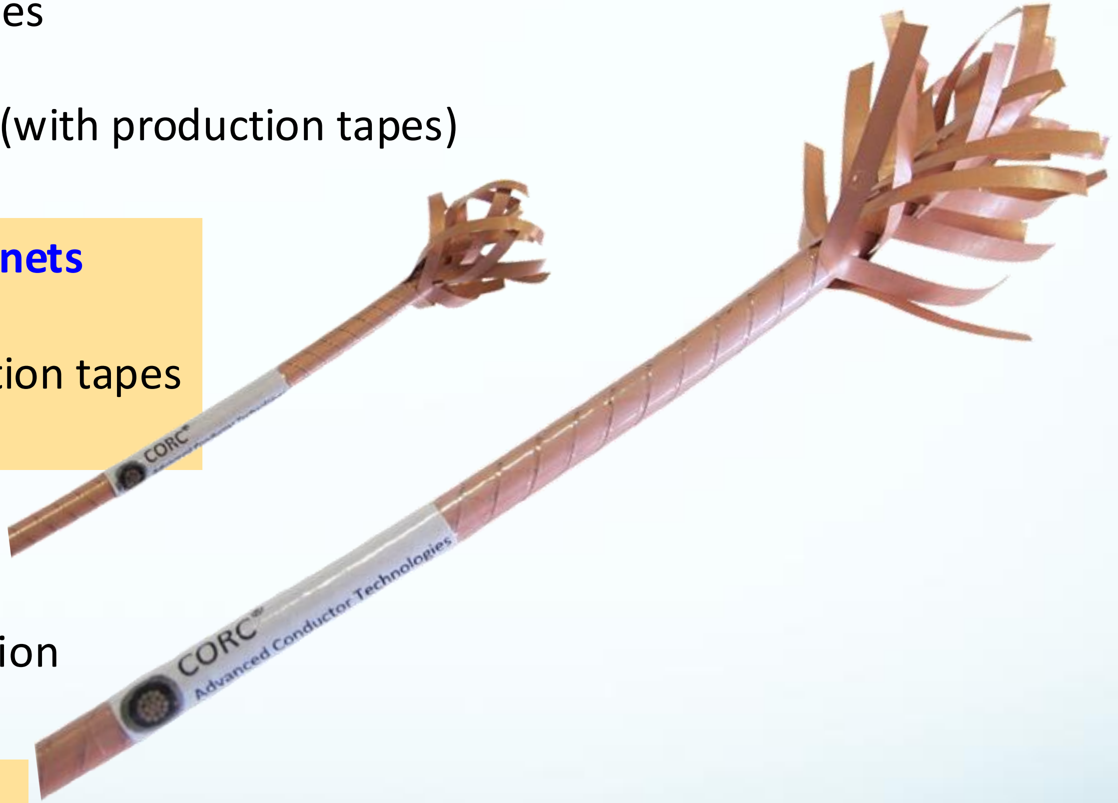
CORC® cables and wires: the previous generation

CORC® wires (2.5 – 4.5 mm diameter)

- Wound from 2 – 3 mm wide tapes with 25 and 30 μm substrates
- Allow bending to 30 mm radius at >80 % I_c retention
- J_e(4.2 K, 20 T) = 451 A/mm^2 (record R&D sample), 300 A/mm^2 (with production tapes)
- I_c(20 T) = 3,000 – 4,000 A

Inserts for 20 T canted-cosine theta accelerator magnets

- Require 20 mm radius at >90 % I_c retention
- Require J_e(20 T) of 500 – 600 A/mm^2 with production tapes
- I_c(4.2 K, 20 T) of 5,000 – 20,000 A



CORC® cable (5 – 8 mm diameter)

- Wound from 3 – 4 mm wide tapes with 30 – 50 μm substrates
- Allow bending to 50 – 70 mm radius, depending on configuration
- J_e(4.2 K, 10 T) = 600 – 800 A/mm^2 (production tapes)

Potential for large aperture CCT outserts

- CORC® CCT 10 – 12 T outsert operating at 4.2 K
- CORC® CCT stand-alone 8 – 10 T at 20 K

Development of the next generation of CORC® cable and wires for accelerators

The CCT magnet program at LBNL has been one of the major drivers for CORC® magnet wire development. Remaining shortcomings of CORC® wires need to be address to ultimately reach a 20 T dipole field.

1. Addressing the supply chain issues of REBCO tapes with 30 μm substrates

- Qualification of REBCO tapes from SuperOx (now Faraday Factory) and Shanghai Superconductor Technologies
- Working with High-temperature Superconductors Inc. to developing a robust domestic supply chain

2. Development of next generation CORC® wires and cabled with improved bending performance

- CORC® wires allowing for 20 mm bending radius, and possibly smaller
- CORC® cables allowing for 40 mm bending radius

3. Reaching new operating currents and current densities in CORC® wires

- Raising the in-field J_e and I_c values in CORC® wires to new heights
- Focusing on production REBCO tapes, no longer on record R&D samples

CORC® wire development for LBNL's CCT magnets

Program goal to reach 20 T dipole field by

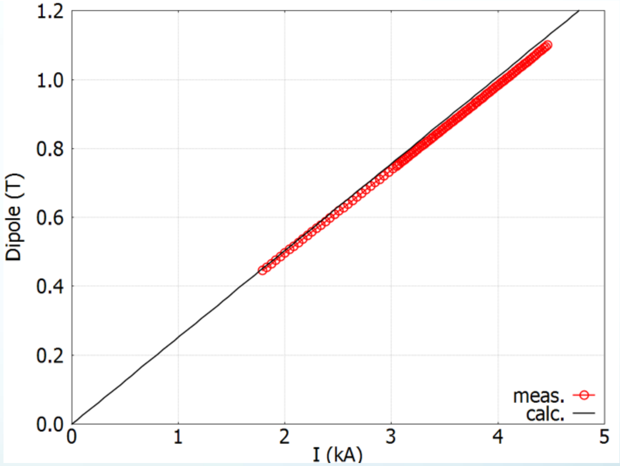
- Demonstrating stand-alone CCT magnets at 1 T, 3 T, 5 T and 8 – 10 T
- Combining a 12 – 15 T LTS CCT outsert with a 5 – 8 T CORC® CCT insert

A 1.2-T canted cos ϑ dipole magnet using high-temperature superconducting CORC® wires, X. Wang, et al., *Supercond. Sci. Technol.* **32**, 075002 (2019)

Successful demonstration of 1.2 T (CCT-C1)

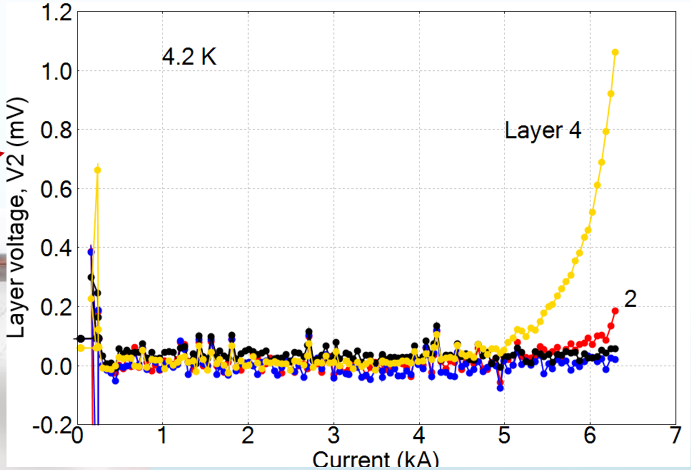
- First 2-layer coil wound from low-J_e 16-tape CORC® wire to learn the magnet winding procedures
- Generated 1.2 T at 4.5 kA

CORC® CCT-C1



Successful demonstration of 2.9 T (CCT-C2)

- 4-Layer coil wound from medium-J_e 30-tape CORC® wire resulting in significant stresses
- **Designed with 30 mm radius bend at poles**
- Generated 2.9 T at 6.5 kA



CORC® CCT-C2

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Development and performance of a 2.9 Tesla dipole magnet using high-temperature superconducting CORC® wires, X. Wang, et al., *Supercond. Sci. Technol.* **34**, 015012 (2021)

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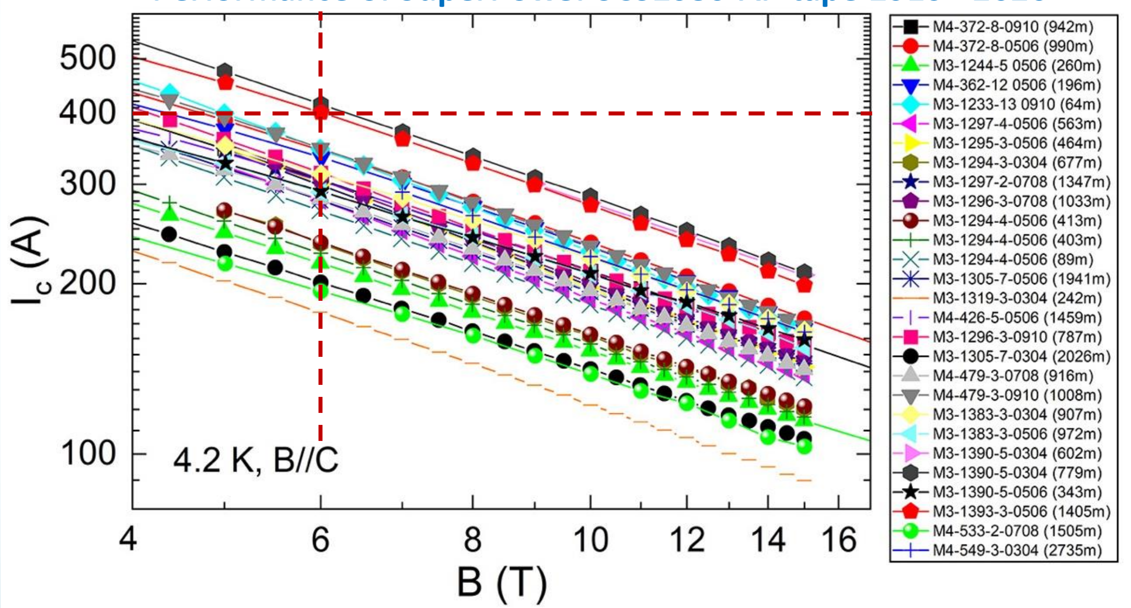
CORC® wire development for magnet CCT-C3 (5 T)

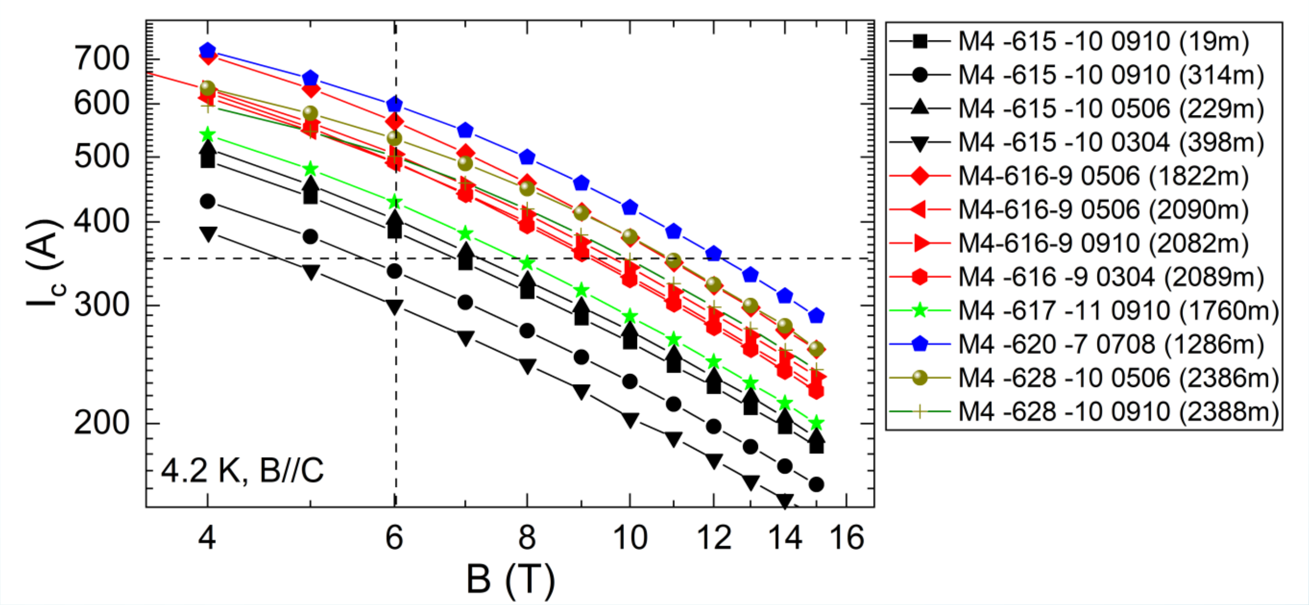
How to reach 5 T in CCT-C3?

- Magnet containing 6 layers with 40 turns each, requiring 145 meters of CORC® wire
- **Again using 30 mm bending radius at poles**
- Develop high-J_e CORC® wire from 30 tapes using SuperPower's new "HM" formulation

Performance of SuperPower SCS2030-AP tape 2016 - 2020



Performance of SuperPower SCS2030-HM tape 2021 - 2022



- Order placed March 2019 for 12 km of SCS-2030 HM tape with minimum I_c(4 K, 6 T) of 400 A
- REBCO tape order fulfilled in May 2022 => **3 years delivery time!**

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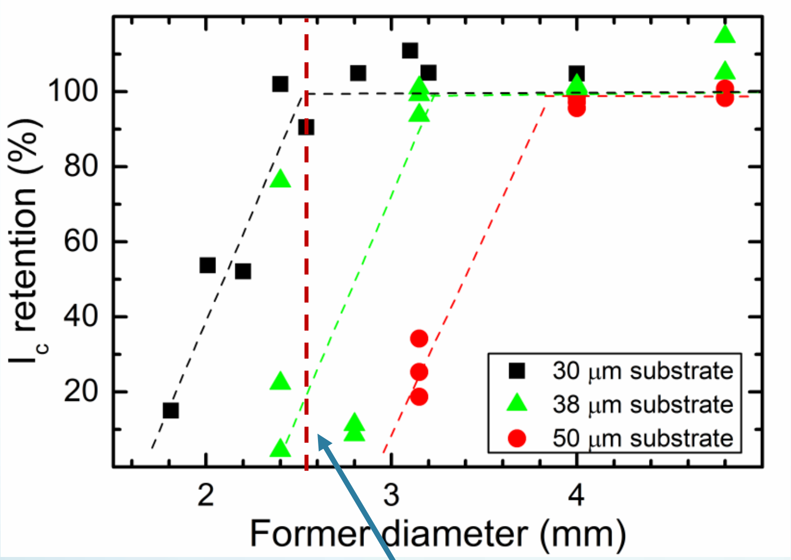
Challenges with SuperPower HM tape for cabling into CORC® wires

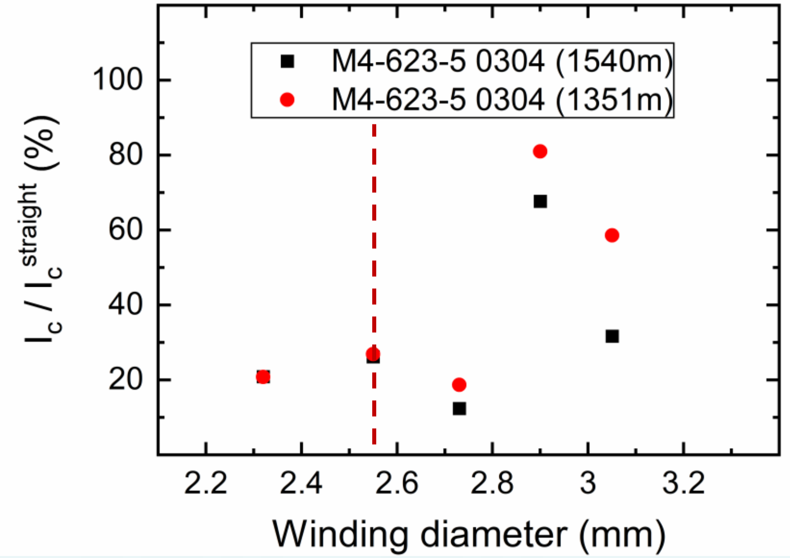
Sub-par mechanical robustness of many batched prevented cabling into CORC® wires with 2.55 mm core

- Substrate thickness determines the smallest core size of CORC® wires
- 30 μm substrates allow 2.3 mm thick cores, as long as the ceramic films are mechanically "robust"
- Many batches of SuperPower HM tape failed at much larger core size

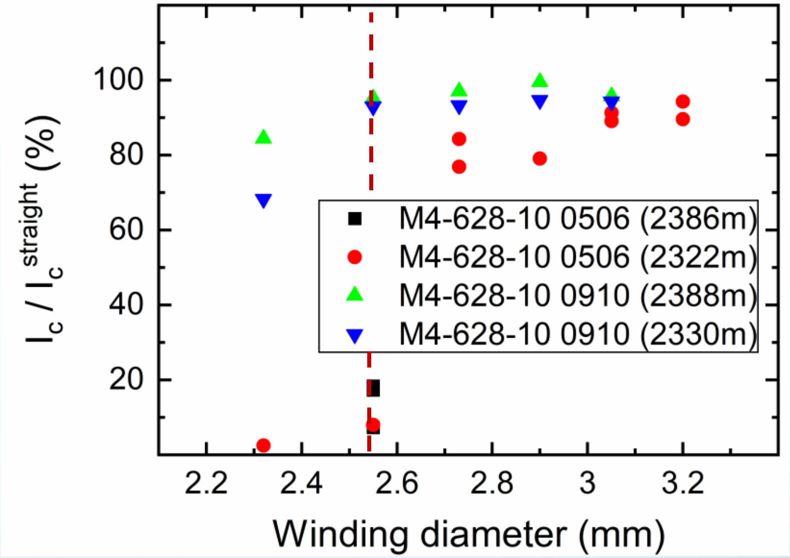
SuperPower AP tapes



SuperPower HM tapes



SuperPower HM tapes



Line indicates CORC® wire core size

Cause remains unknown. "Weak" tape batches were rejected and replaced by SuperPower

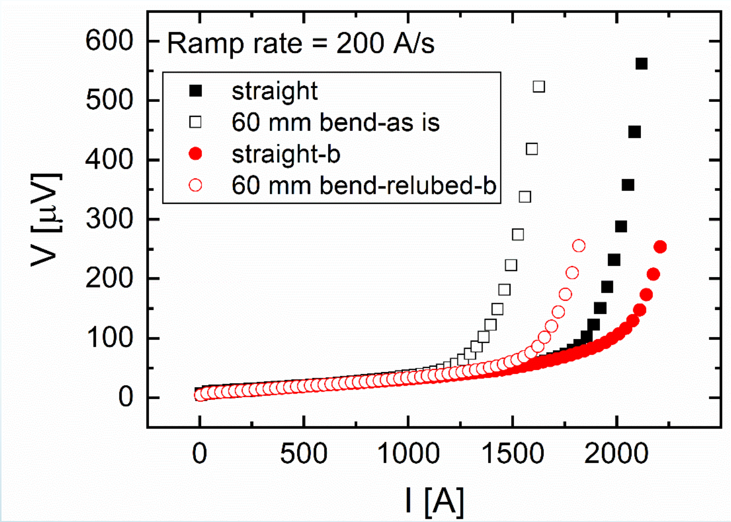
Challenges with SuperPower HM tape for cabling into CORC® wires (Cont.)

CORC® wires became less flexible due to very high surface roughness of latest SuperPower tapes

- CORC® wire bending performance is largely determined by friction between tapes
- CORC® wires wound from pre-2020 SuperPower tapes allow bending to 30 mm radius
- High surface roughness of post-2020 SuperPower tapes caused loss of CORC® wire flexibility

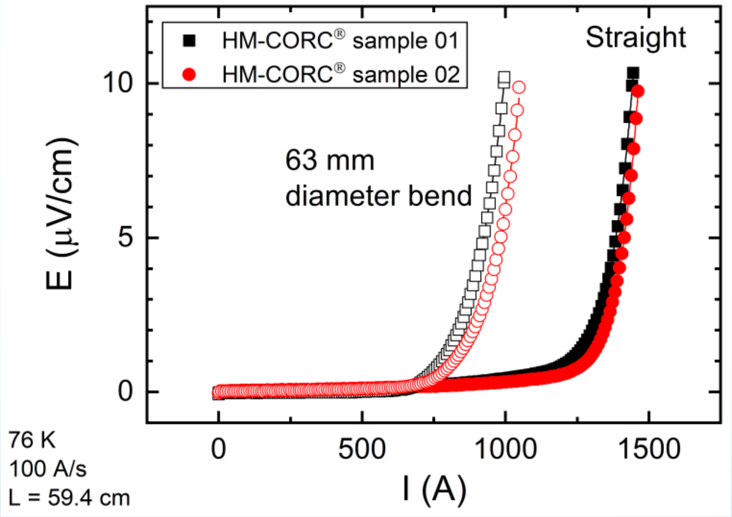
CCT-C2 (AP based) CORC® wire

- 70 – 80 % I_c retention at 30 mm radius
- Ok, not great



HM tape based CORC® wire

- 60 – 65 % I_c retention at 30 mm radius
- **Unacceptable!**



Flexibility ultimately restored (later slides) and CCT-C3 CORC® wire delivered December 2023

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REBCO tape qualification with 30 μm substrates from different vendors

1. SuperPower no longer selling REBCO tapes with 30 μm substrates

2. SuperOx (tapes purchased in 2019 before they became Faraday Factory)

- Reversible change in I_c of almost 20 % due to winding strain
- Standard tapes (2.5 μm thick REBCO layers): smallest core 3.0 mm
- Special batch (1.5 μm thick REBCO layers): Smallest core 2.55 mm

SuperOx tapes with 30 μm substrates

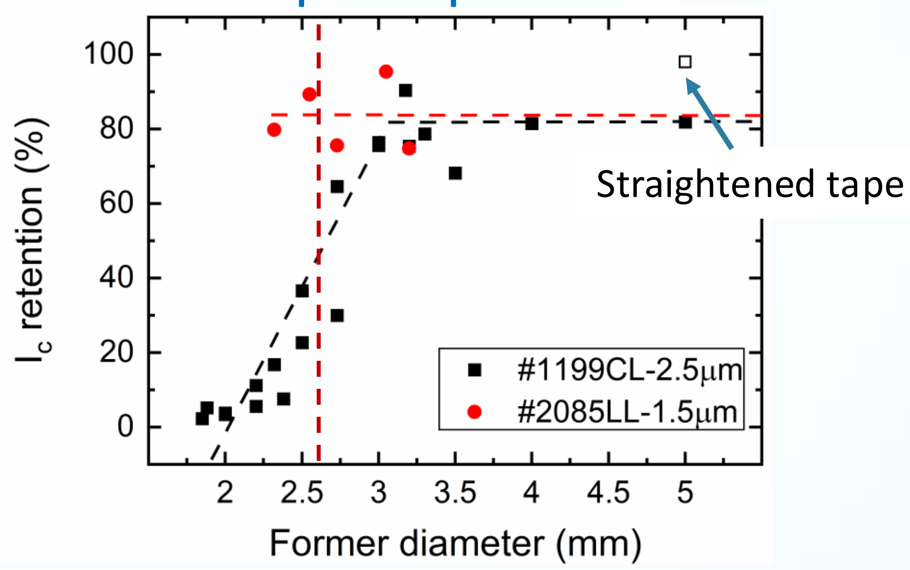
- Require larger cores that reduce J_e
- **Are no longer available**

3. Shanghai Superconductor Technologies

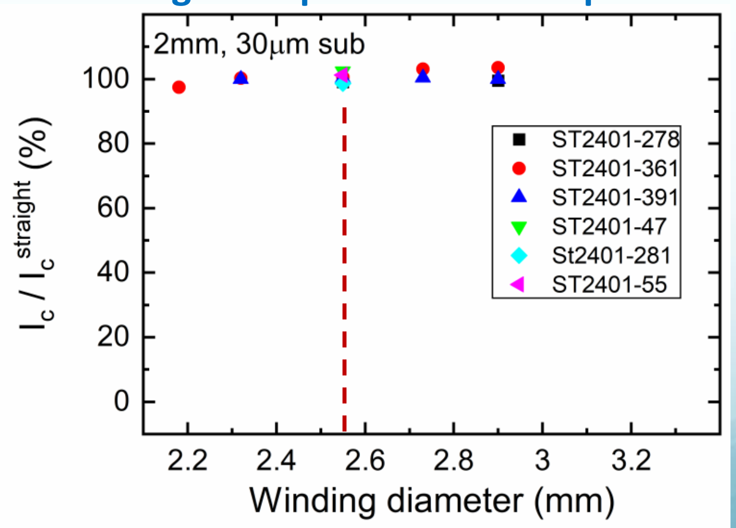
- Order of 5 km Shanghai Superconductor tape with 30 μm substrate was delivered within 4 months
- All batches measured so far allow winding onto 2.2 - 2.4 mm thick cores
- Pinning comparable to SuperPower AP tapes

Shanghai Superconductor remains the only vendor worldwide of REBCO tapes with 30 μm substrates

SuperOx tapes



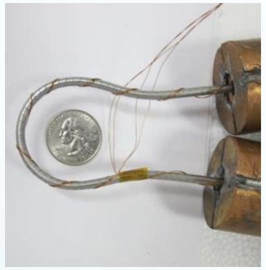
Shanghai Superconductor tapes



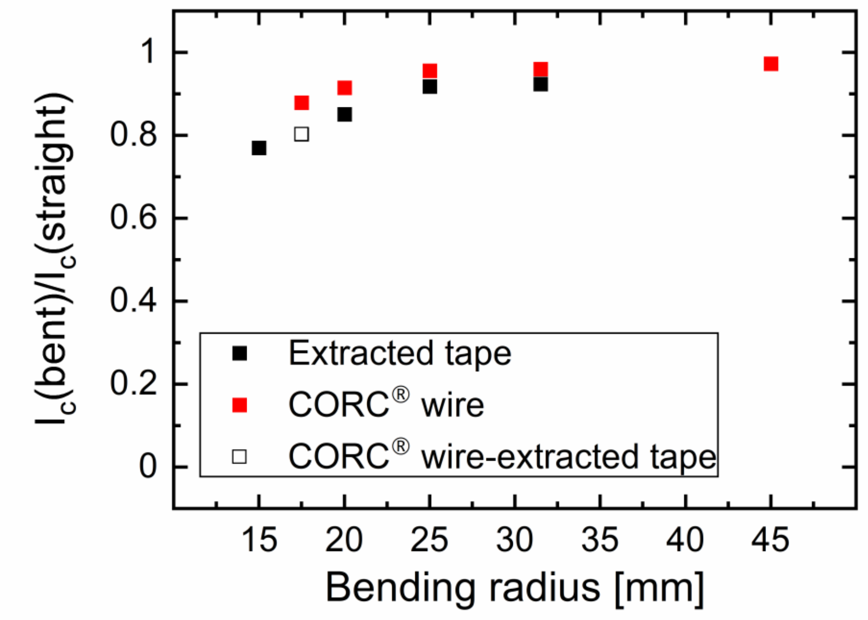
CORC® wires with improved bending flexibility: SuperPower HM tapes

New CORC® wire manufacturing process (P2)

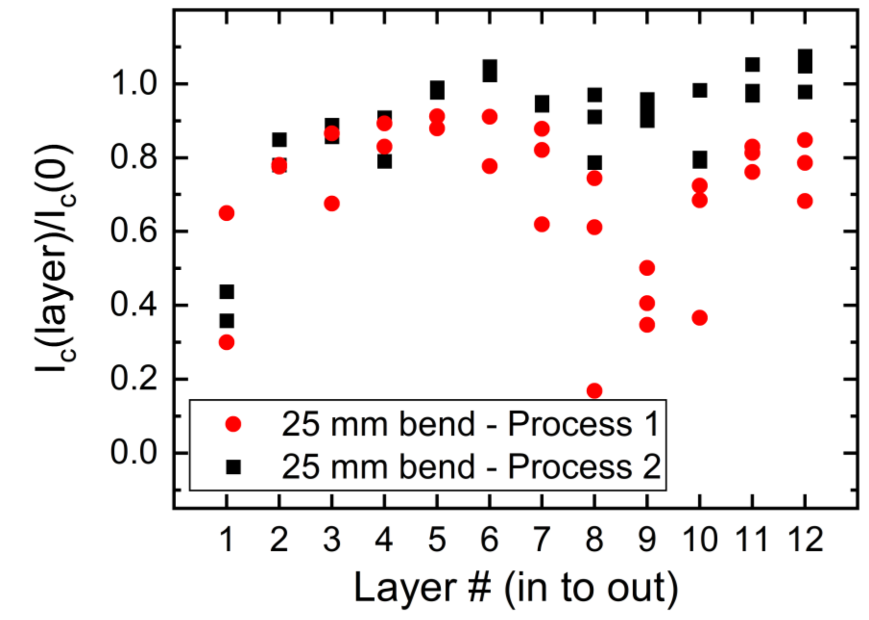
- Recovers bending flexibility when using “rough” tapes (such as latest SuperPower tapes)
- Allows for even smaller bending diameters than previous generation CORC® wires



SuperPower HM 30-tape CORC® wire



Extracted tape I_c after bending to 25 mm radius



Next generation 30-tape CORC® wire bending (SuperPower HM tapes)

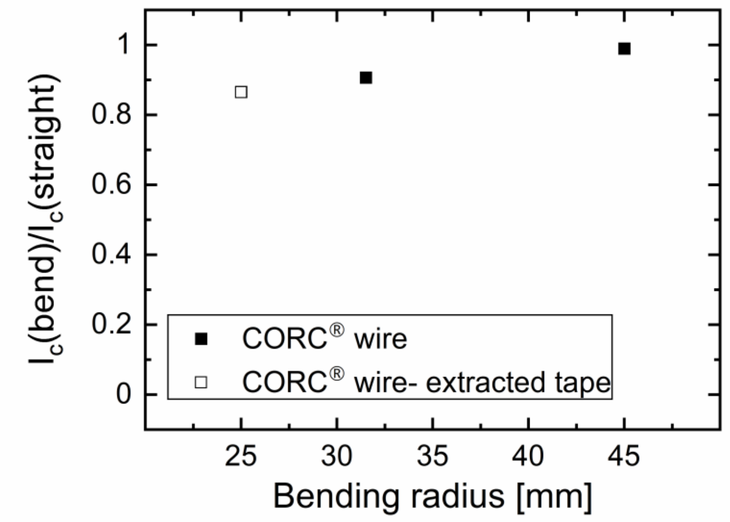
- I_c retention **91.8 % at 25 mm radius bend** and around **78 % at 17.5 mm radius bend**
- Should provide CCT-C3 with much larger margin in I_c than the 70 % used in its design

CORC® wires with improved bending flexibility: SuperOx tapes

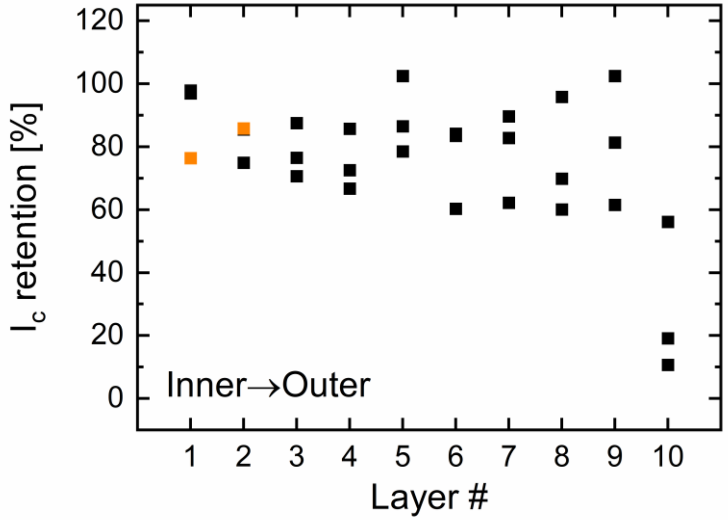
SuperOx tape CORC® wire details

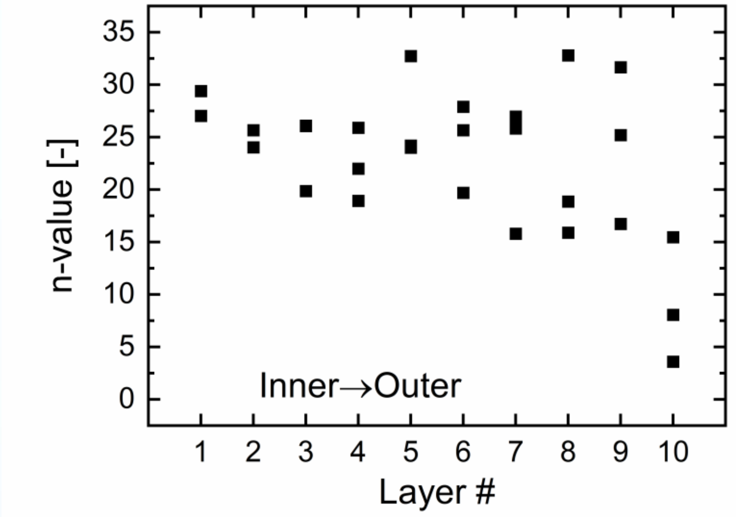
- Larger core of 3.2 mm thickness results in 4.15 mm thick CORC® wire
- Manufactured with process P2

SuperOx 30-tape CORC® wire



Extracted tape I_c after bending to 25 mm radius





Next generation 30-tape CORC® wire bending (SuperOx tapes)

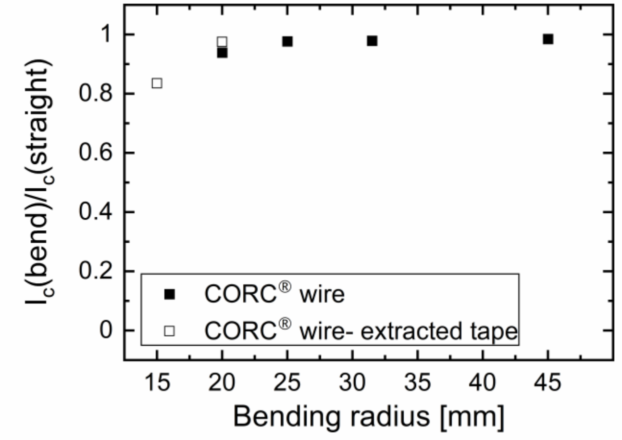
- I_c retention 86.5 % at 25 mm radius bend
- Lower mechanical resilience of SuperOx tapes likely also affect bending performance
- Larger core likely has an impact on bending performance (higher tape pressure during bending)

CORC® wires with improved bending flexibility: Shanghai Superconductor tapes

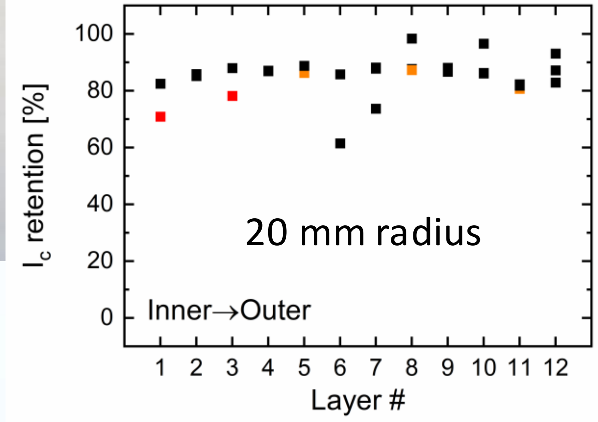
Shanghai Superconductor tape CORC® wire details

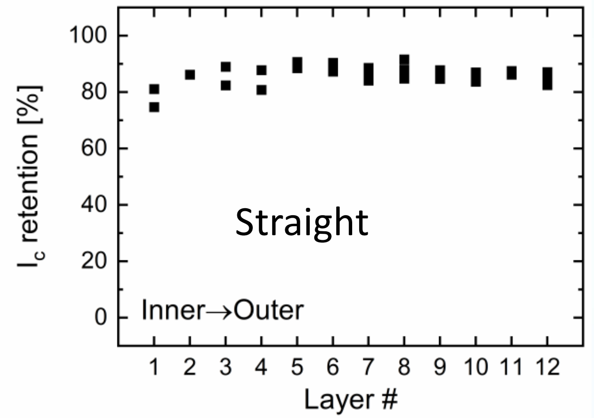
- Standard 2.55 mm core, same as in configuration with SuperPower tapes
- Manufactured with further improved **process P4**

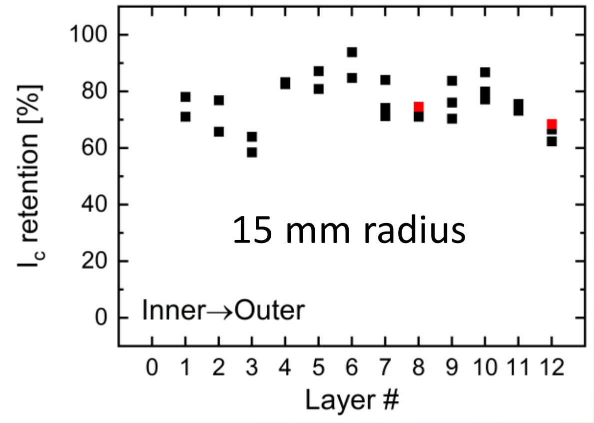
Shanghai Superconductor 30-tape CORC® wire



Extracted tape I_c







Next generation 30-tape CORC® wire bending (Shanghai Superconductor tapes)

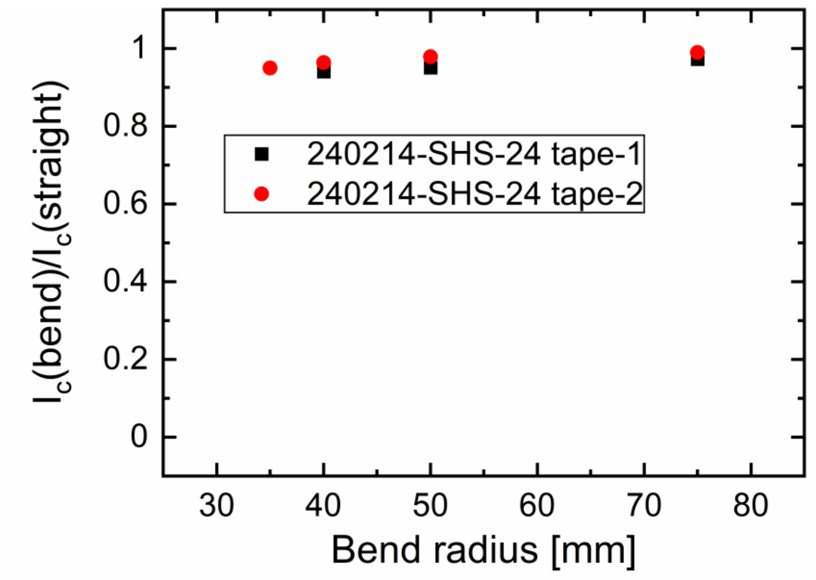
- I_c retention **97.5 % at 20 mm bend radius**, and 83.5 % at 15 mm bend radius
- **CORC® wires wound from Shanghai Superconductor tapes now allow CCT magnets with 20 mm radius bends**

CORC® cables with improved bending flexibility

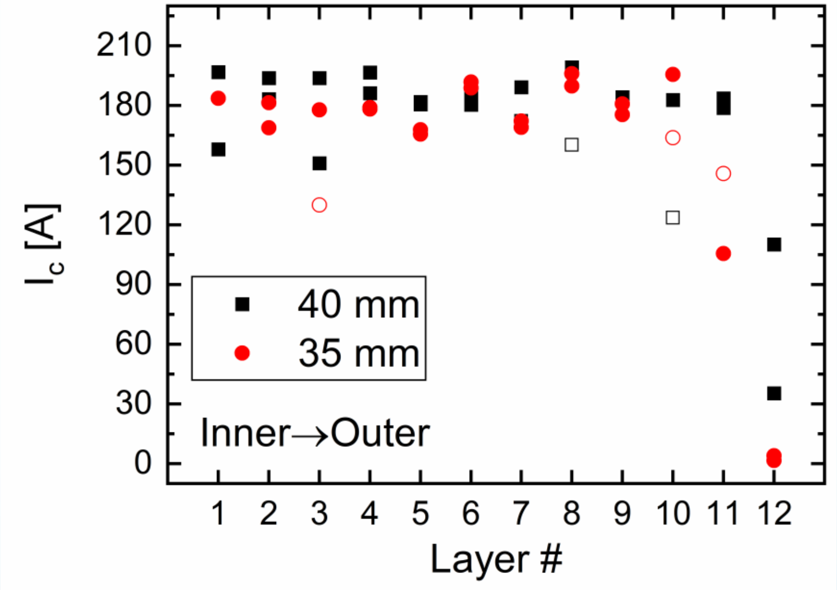
CORC® cable details

- Shanghai Superconductor CORC® cable made with procedure P4
- 4.2 mm core, 24 tapes of 4 mm width and 30 μm substrates
- Cable thickness 5.35 mm

Shanghai Superconductor 24-tape CORC® cable



Extracted tapes



Next generation 24-tape CORC® wire bending

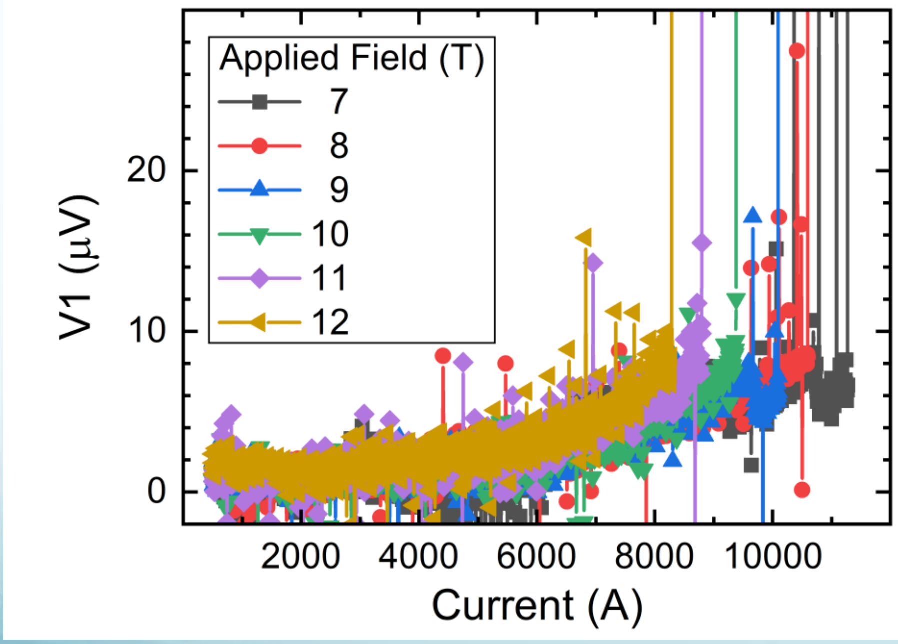
- I_c retention 85.9 % at 40 mm bend radius and 79 % at 35 mm bend radius
- **CORC® cables wound from Shanghai Superconductor tapes now allow CCT magnets with 40 mm radius bends**

In-field performance of CORC® wires: SuperPower HM tapes

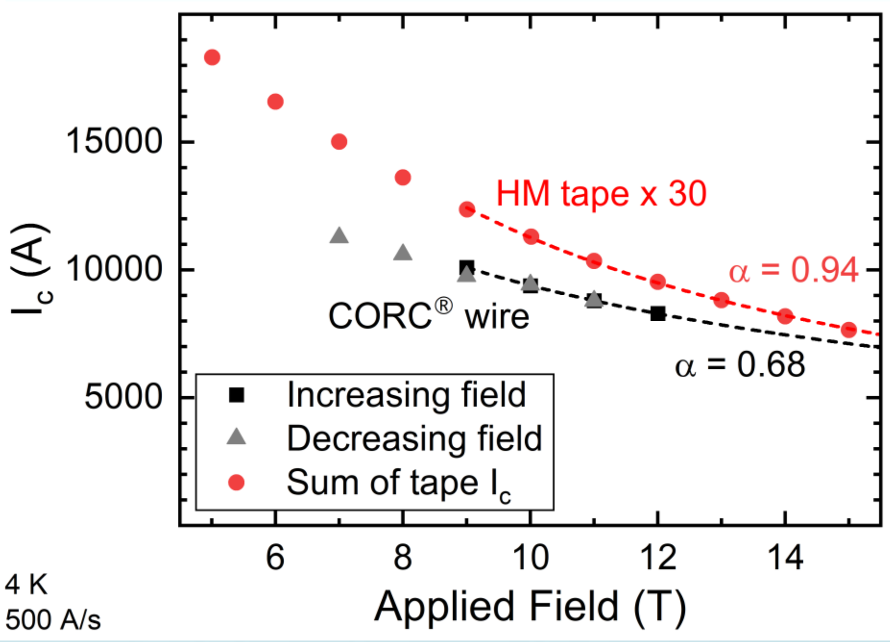
CORC® wire wound from SuperPower HM production tapes

- Bend into 31.5 mm radius hairpin
- Conductor movement resulted in wire quenching with minimal voltage rise
- **New record J_e(12 T) of 751 A/mm^2 and extrapolated J_e(20 T) of 530 A/mm^2**
- Peak current of over 8 kA at 12 T and extrapolated to over 5 kA at 20 T
- CORC® wire performance is 87 % of total tape performance at 12 T

B [T]	I_{quench} [A] 100 [A/s]	I_{quench} [A] 200 [A/s]	I_{quench} [A] 500 [A/s]	J_e [A/mm^2] 500 [A/s]
9	9,890	9,964	10,098	914
10	9,185	9,203	9,381	849
11	8,599	8,599	8,800	797
12		8,087	8,293	751
11			8,790	796
10			9,421	853
9			9,747	883
8	10,382	10,568	10,595	959
7			11,273	1,021
20			5,855*	530*



4 K
500 A/s

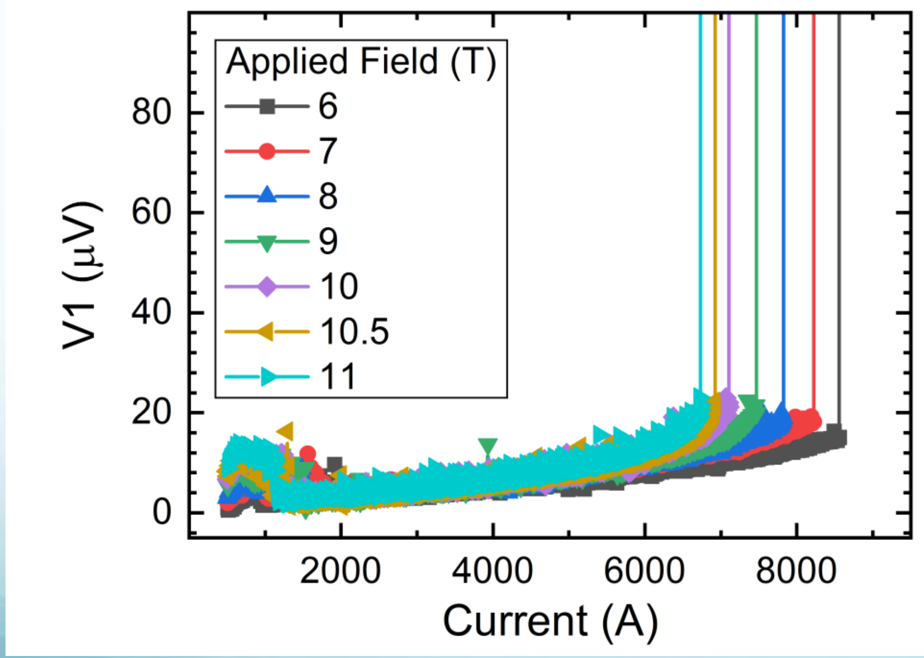


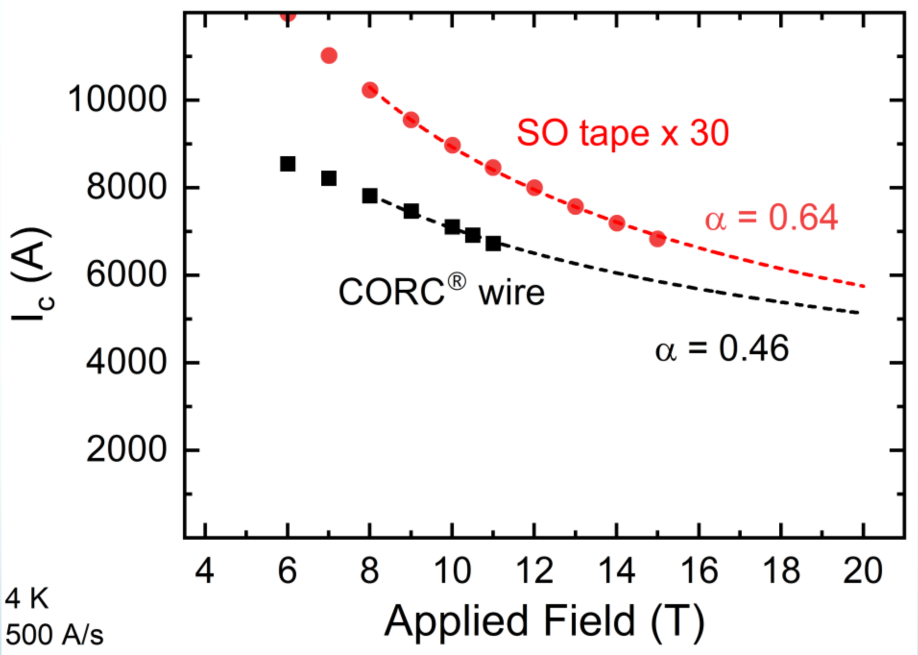
In-field performance of CORC® wires: SuperOx tapes

CORC® wire wound from SuperOx production tapes

- Using SuperOx-specific CORC® wire layout with 3.2 mm core
- Bend into 31.5 mm radius hairpin
- J_e(11 T) of 510 A/mm^2 and extrapolated J_e(20 T) of 388 A/mm^2
- Larger core results in lower J_e than in standard CORC® wires with 2.55 mm core
- CORC® wire performance is 79.6 % of total tape performance at 11 T

B [T]	I_{quench} [A]	I_c [A]	*n*-value	J_e [A/mm^2]
6	8,554	9,744	7.7	648
7	8,221	8,913	8.3	623
8	7,823	8,302	7.8	593
9	7,467	7,756	7.0	566
10	7,108	7,232	11.0	538
10.5	6,925	7,101	11.0	525
11	6,731	6,883	12.0	510
20	5,236*			388*



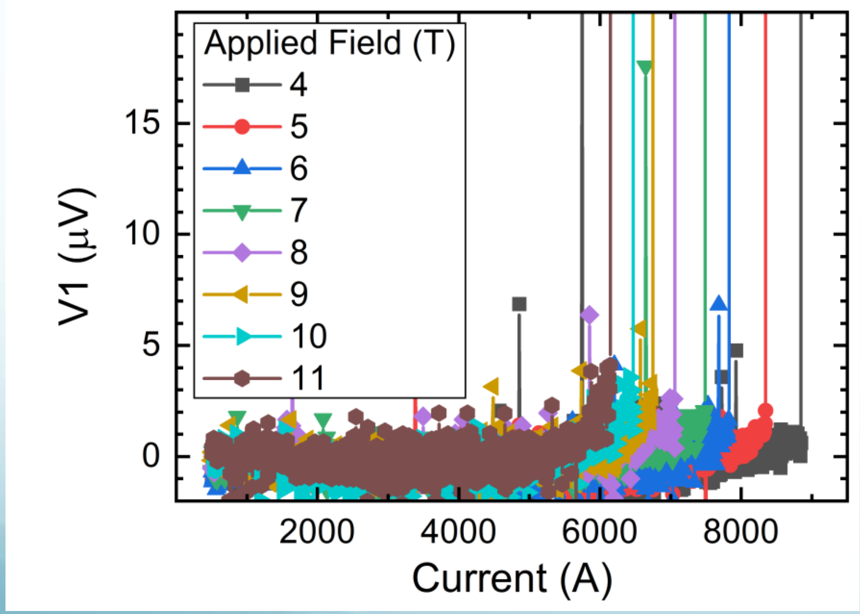


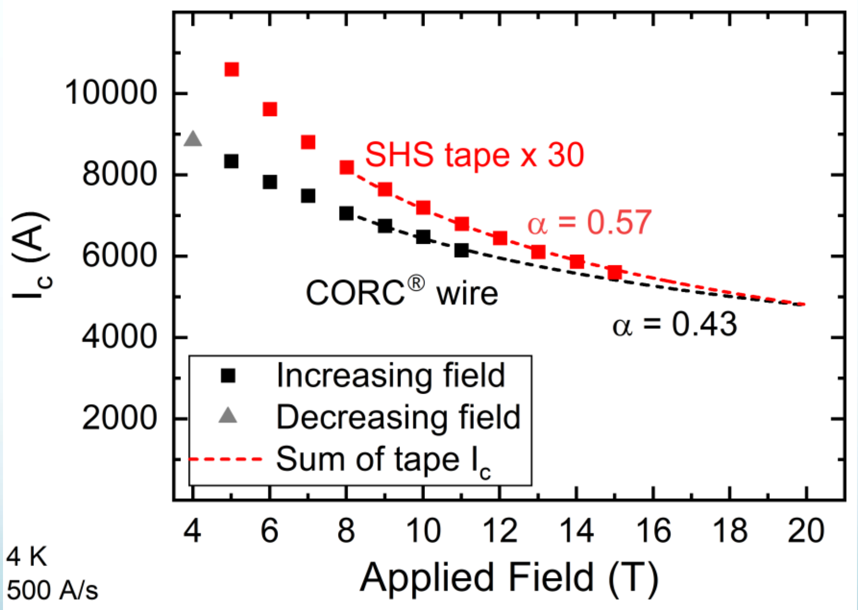
In-field performance of CORC® wires: Shanghai Superconductor tapes

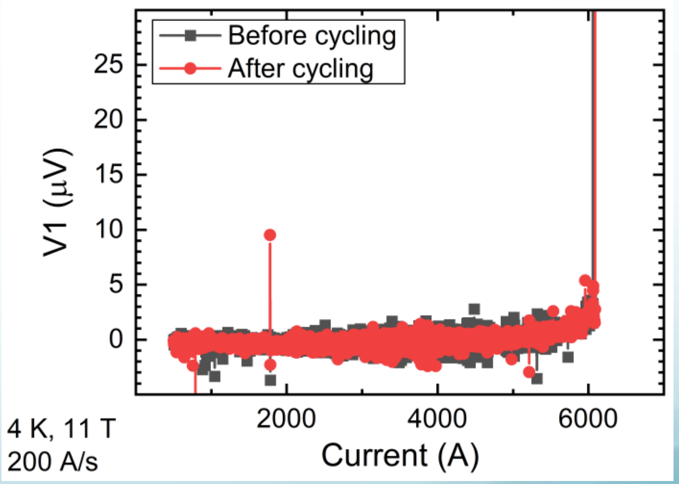
CORC® wire wound from Shanghai Superconductor production tapes

- Bend into **20 mm radius hairpin**
- High **J_e(11 T) of 584 A/mm²** and extrapolated **J_e(20 T) of 465 A/mm²**
- High J_e values considering tapes are not yet optimized for pinning
- Peak current of 6 kA at 11 T and extrapolated to almost 5 kA at 20 T
- CORC® wire performance is **90 % of total tape performance at 11 T**, similar to the I_c retention corresponding to the 20 mm radius bend test
- No performance degradation after 10 current cycles to 5.5 kA at 11 T

B [T]	I_{quench} [A] 100 [A/s]	I_{quench} [A] 200 [A/s]	I_{quench} [A] 500 [A/s]	J_e [A/mm²] 500 [A/s]
5	8,154	8,267	8,343	793
6	7,648	7,726	7,831	744
7	7,248	7,290	7,488	712
8	6,911	6,976	7,062	671
9	6,593	6,671	6,745	641
10	6,316	6,349	6,476	616
11	6,031	6,060	6,148	584
5		8,107		
4			8,842	840
20			4,895*	465*







CORC®-based hybrid high-field CCT magnets operating at 4 K

Next generation of CORC® wires enable potential magnet CCT-C4

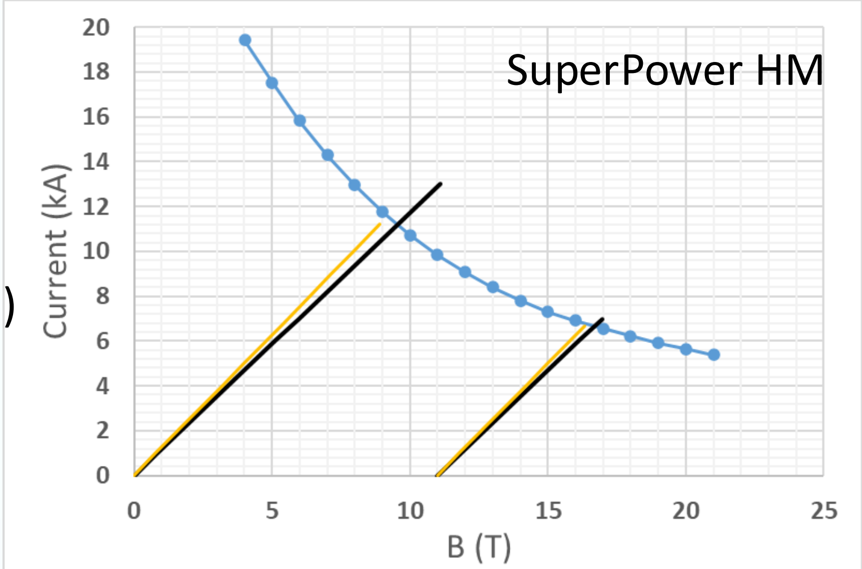
- Reduce the OD from 160 mm (CCT-C3) to less than 120 mm to fit future 11 T LTS CCT outsert
- 45 mm aperture, 6 layers, 40 turns per layer
- 20 mm bend radius at poles (compared to 30 mm radius for CCT-C3)

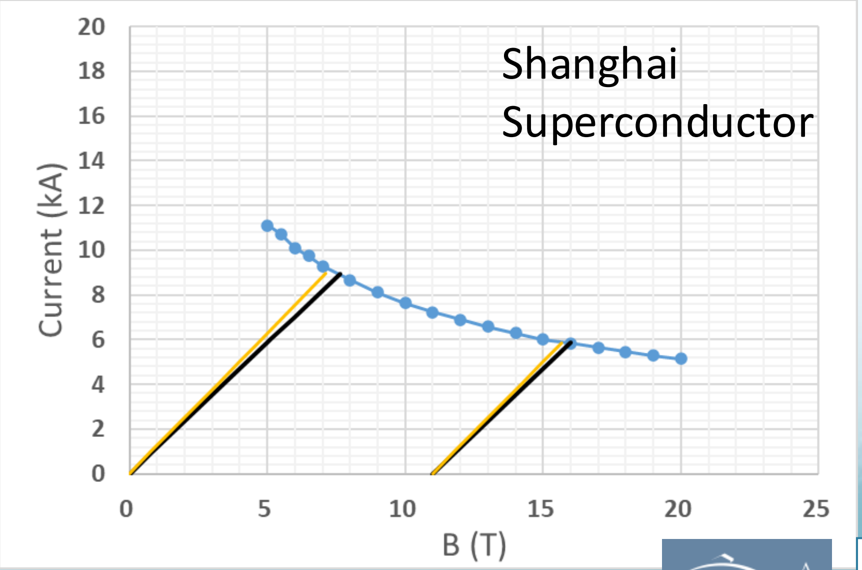
CCT-C4 SuperPower HM "option"

- Stand-alone dipole field of 8.9 T at 9.6 kA (100 % I_c)
- 5.3 T at 6.7 kA as insert within a 11 T outsert: 16.3 T total
- **Combined dipole field of 15.77 T at 90 % I_c retention**

CCT-C4 Shanghai Superconductor option

- Stand-alone dipole field of 7.1 T at 9 kA (100 % I_c)
- 4.7 T at 5.9 kA as insert within a 11 T outsert: 15.7 T total
- **Combined dipole field of 15.23 T at 90 % I_c retention**





Stand-alone high-field CORC® CCT magnets at 4.2 K

Combining a CORC® CCT outsert with a CORC® CCT insert

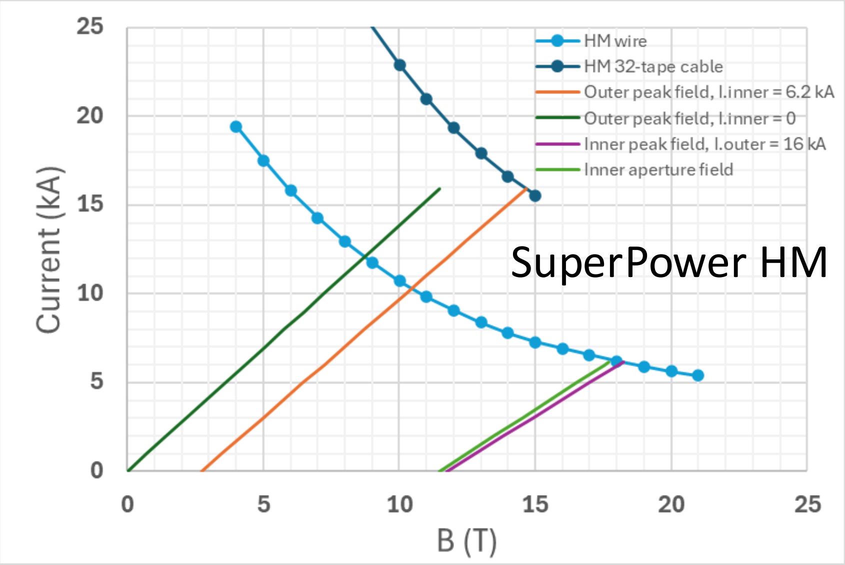
- CORC® CCT outsert aperture 155 mm, 8 layers of 32-tape CORC® cable with 45 mm bend radius
- CORC® CCT insert aperture 50 mm, 8 layers of standard 30-tape CORC® wire with 20 mm bend radius

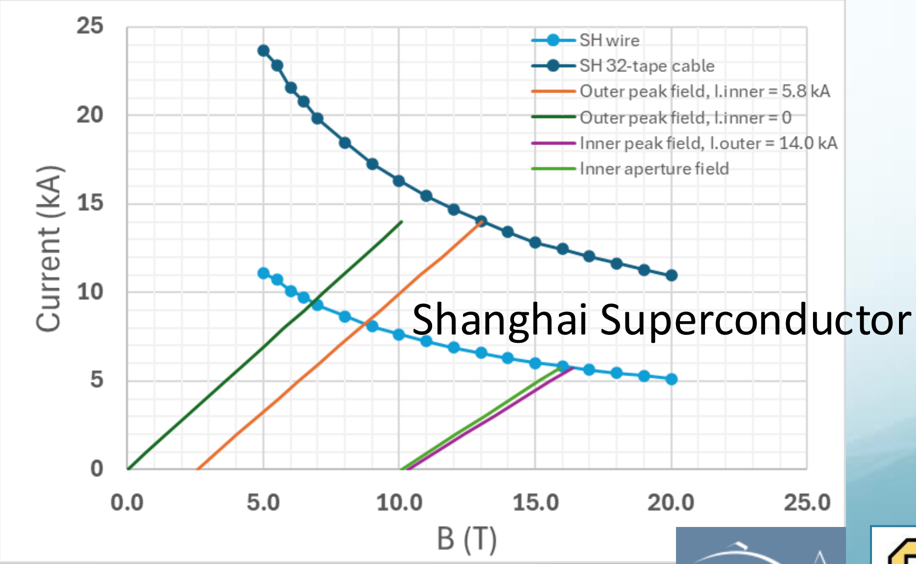
CORC® cable and wire based on SuperPower HM tape

- Insert: dipole field 6.2 T at 6.2 kA
- Outsert: dipole field 11.5 T at 15.9 kA
- **Combined field of 17.7 T**

CORC® cable and wire based on Shanghai Superconductor tape

- Insert: dipole field 5.8 T at 5.7 kA
- Outsert: dipole field 10.1 T at 13.3 kA
- **Combined field of 15.9 T**





Summary

Next generation CORC® cables wires addresses the main shortcomings of their previous generation

- CORC wires developed from REBCO tapes from different vendors
- Now have much better bending flexibility
- Have much higher J_e(20 T) using production tapes at more than 90 % expected I_c

Smallest bending radius of 30-tape CORC® wires reduced by factor of over 2

- I_c retention of 97.5 % at 20 mm radius improved from 78 % I_c retention at 30 mm radius
- I_c retention of 83.5 % at 15 mm radius

In-field performance of 30-tape CORC® wires increased by factor of 1.5 – 1.8

- New record J_e(20 T) of 530 A/mm^2 achieved in SuperPower HM based CORC® wire at 31.5 mm bending radius
- High J_e(20 T) of 465 A/mm^2 achieved in CORC® wire wound from Shanghai Superconductor production tape with 90 % I_c retention at 20 mm bending radius

Impact of next generation CORC® wires on accelerator magnet development

- Options for next CCT magnet with 7 – 8 T stand-alone, and 4 – 5 T in 11 T background field identified
- **Current CORC® cables and wires made from production REBCO tapes now allow manufacturing of low-inductance 15 – 17 T HTS-only CCT accelerator magnets!**