Development of the latest generation of CORC® wires and their implementation into high-field dipole magnets

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CORC® wire overview

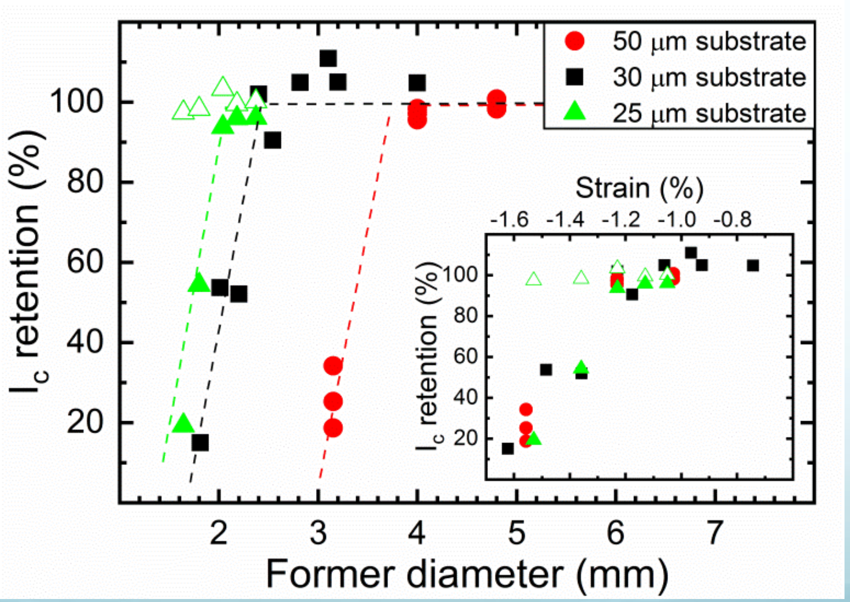
Future 20 T accelerator magnets require flexible high I_c and high J_e CORC® conductors

- Operating current > 10 kA, engineering current density (J_e) > 600 A/mm^2
- Bending to 20 mm radius without significant degradation

Route to achieve required performance

- Use of high-performance REBCO tapes of 2 mm width
- Minimize the CORC® wire core size by using REBCO tapes with thin substrates

Effect of substrate thickness on allowable core size



Minimum core 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

Typical CORC® wire (3.6 - 3.7 mm thick)

- Wound from tapes with 30 μm substrate
- Uses a 2.55 mm core
- Contains 30 tapes

Status of stand-alone CCT magnets based on CORC® wires

CCT magnet development based on CORC® wires

Achieve a dipole field of 20 T over several stages

1. Developing and demonstrating the CORC®-based CCT magnet technology
2. Improve the bending performance of CORC® wires to minimize winding degradation
3. Develop high-J_e and high I_c CORC® wires that allow operation at **10 kA at 20 T**

2017: Demonstration of 1.2 T (CCT-C1)

- 2-Layer coil, 40 turns per layer
- Low-J_e, 16-tape CORC® wire
- Generated 1.2 T at 4.5 kA

CORC® CCT-C1

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)

2020: Demonstration of 2.9 T (CCT-C2)

- 4-Layer coil, 40 turns per layer, **30 mm radius at poles**
- Medium-J_e, 30-tape CORC® wire
- Generated 2.9 T at 6.5 kA

CORC® CCT-C2

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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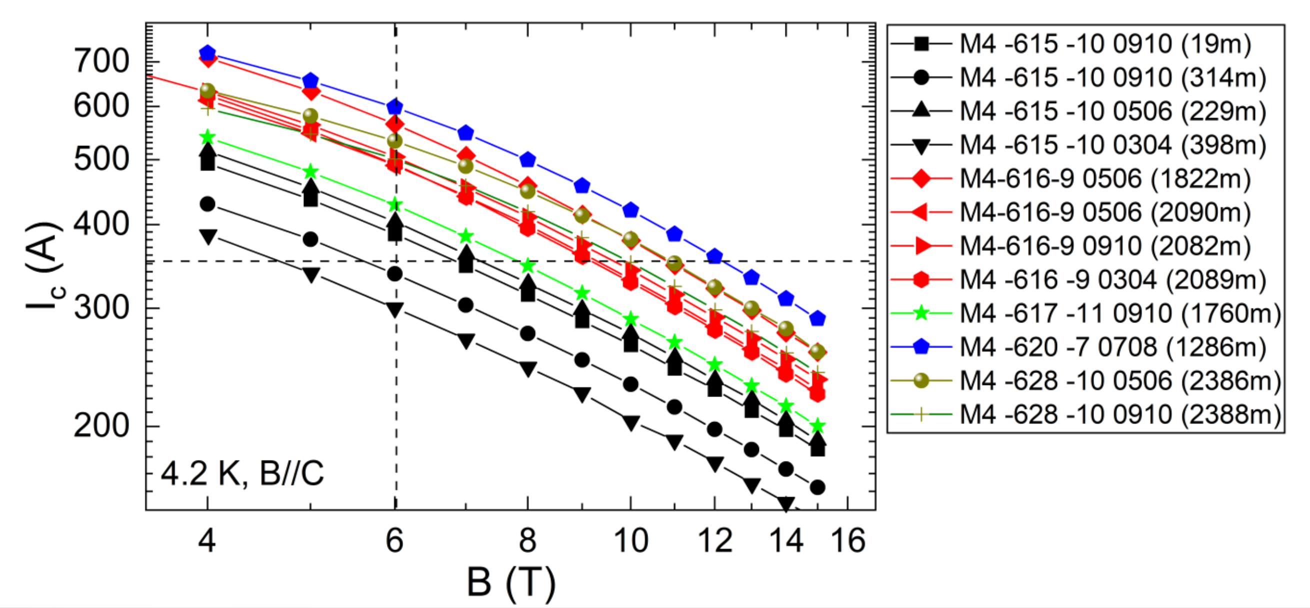
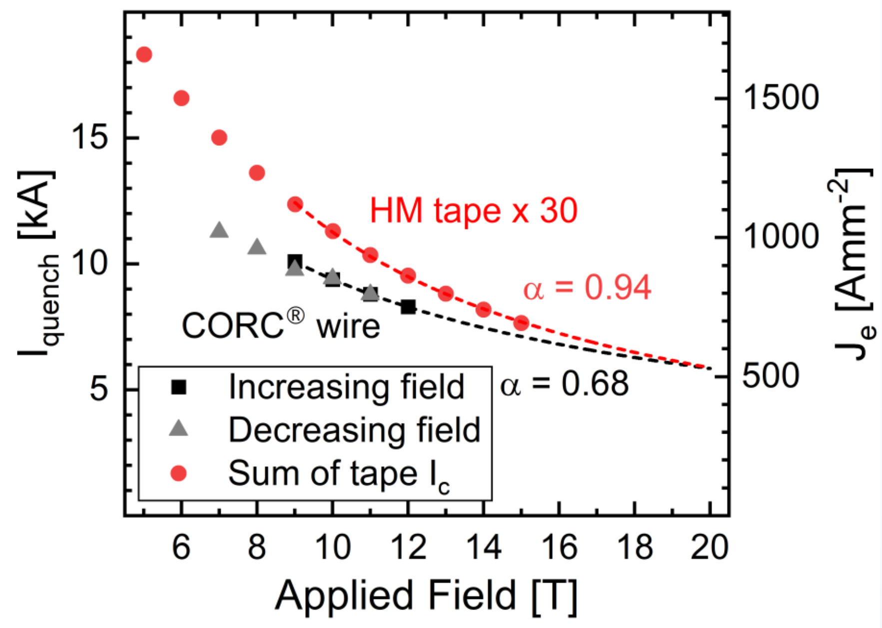
Development for magnet CCT-C3 to generate a 5 T dipole field

How to reach 5 T in CCT-C3?

- Magnet containing 6 layers with 40 turns each, requiring 145 meters of CORC® wire
- Keeping the 30 mm minimum bending radius at poles
- High-J_e 30-tape CORC® wires using SuperPower's HM tapes

Performance of SuperPower SCS2030-HM tape 2021 - 2022





CORC® wire (SuperPower HM tapes)

- Tested at 31.5 mm radius hairpin
- **Record J_e(20 T) of 530 A/mm² at I_c of 5 kA**
- 87 % of tape performance at 12 T

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Danko van der Laan, Jeremy Weiss, Kyle Radcliff and Dmytro Abraimov, *Supercond. Sci. Technol.* **37** 115007 (2024)

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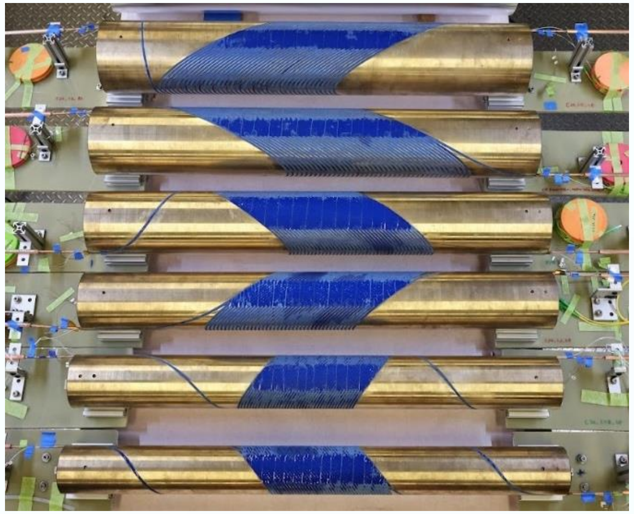
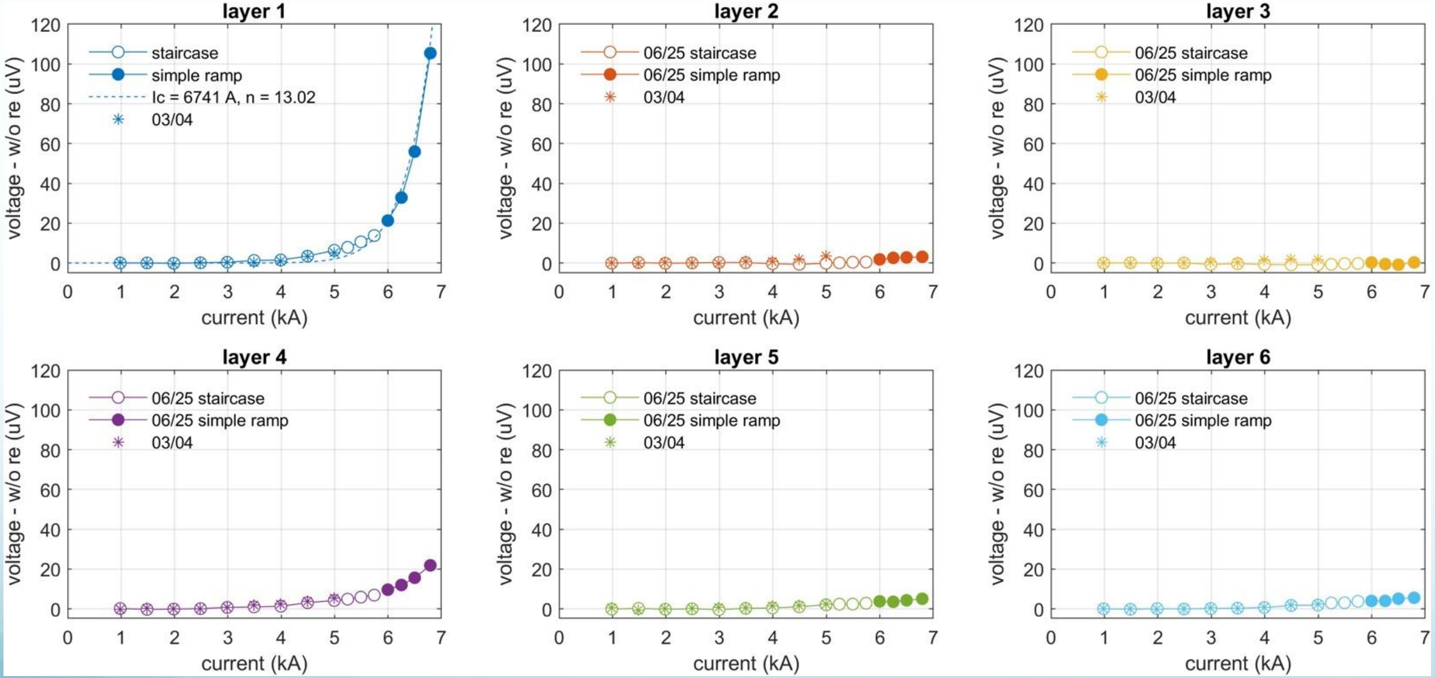
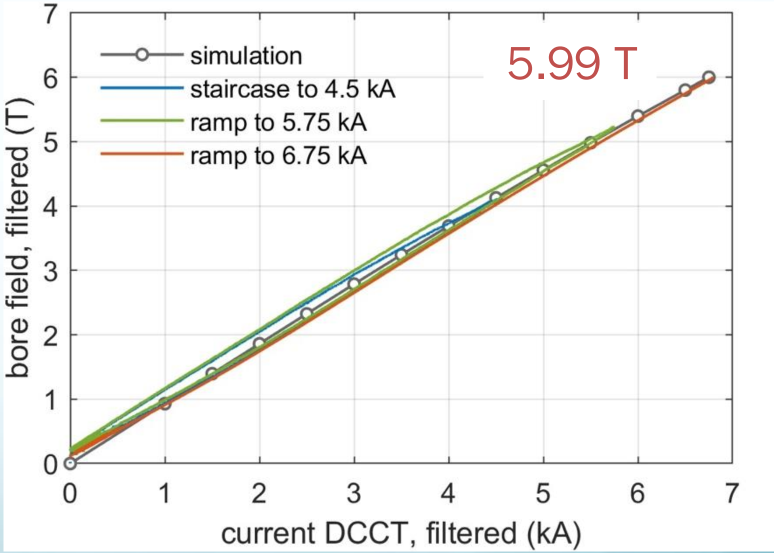
Dipole magnet CCT-C3 generates 5.99 T dipole field!

Magnet CCT-C3 exceeded its target of 5 T dipole field

- **Dipole field of 5.99 T achieved at 6.795 kA**
- Much lower CORC® wire bending degradation than 30 % as assumed in the original magnet design
- Inner layer (Layer 1) transition started and reached about 0.1 μV/cm but may have room to reach a dipole field of 6.2 – 6.3 T!







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Dmytro Abraimov, et al., *Phys. Rev. Accelerators and Beams.* **29** 083902 (2026)

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Development of the next CCT magnet

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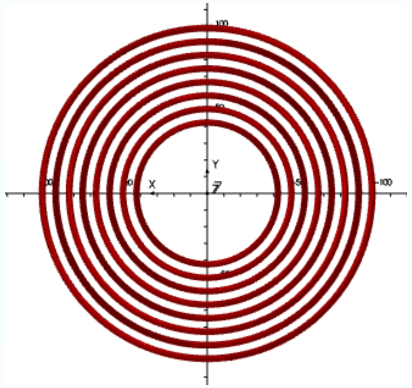
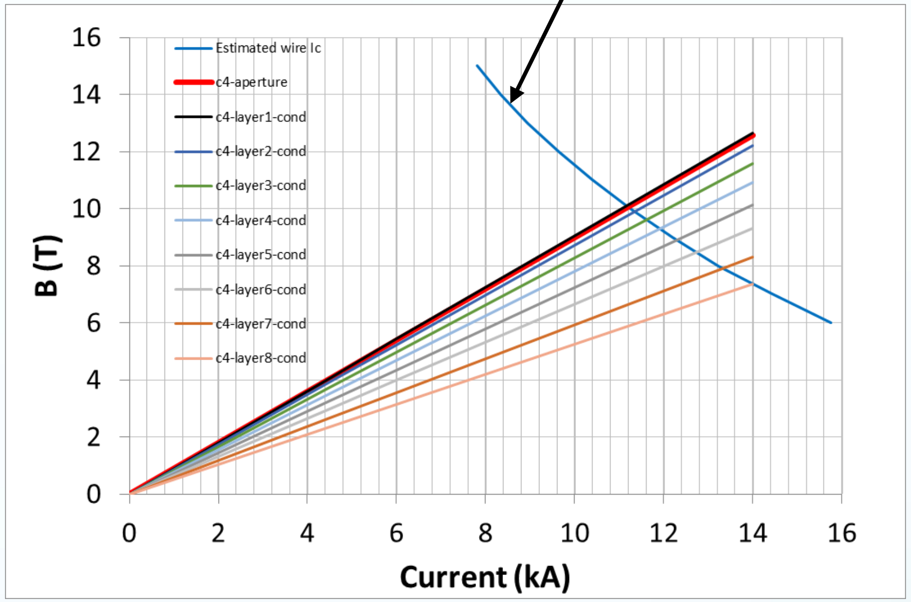
Development of magnet CCT-C4 generating 10 T dipole field

CCT-C4 magnet layout

- Target dipole field 10 T
- Magnet bore 65 mm, O.D. 225 mm
- Bending radius at pole 30 mm
- 8 layers
- Transfer function 0.898 T/kA (no iron)
- Transfer function 1.053 T/kA (with iron)
- Operating current 9.6 kA to generate 10 T (with iron)



CORC® wire performance (see later slide)



Conductor performance requirements a major step above CCT-C3

1. **CORC® wire capable of operating at 10 kA at 10 T instead of 5.66 kA at 5 T for CCT-C3**
2. **Operation at 100 kN/m instead of about 40 kN/m for CCT-C3**

CORC® wire requirements for a 10 kA, 10 T CCT dipole

Required electrical conductor performance for CCT-C4

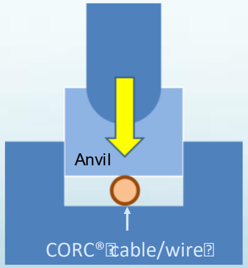
- Operating current of 10 kA at 10 T requires I_c of at least 13 kA
- Best SuperPower HM CORC® wire has I_c(10 T) of 9.2 kA
- **Over 40 % increase in tape performance needed**

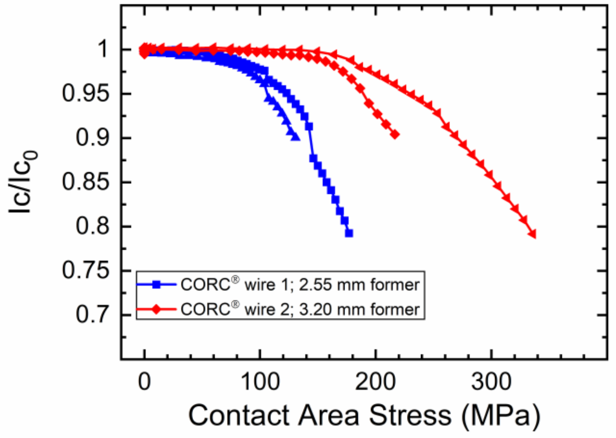
Mechanical resilience of CORC® wire

- **Transverse load on CORC® wire of 100 kN/m in CCT-C4**
- CCT-C3 operated at 40 kN/m transverse compression
- SuperPower HM based CORC® wire was tested at 99.5 kN/m without degradation, which may be near its critical limit

Critical transverse load of CORC® conductors

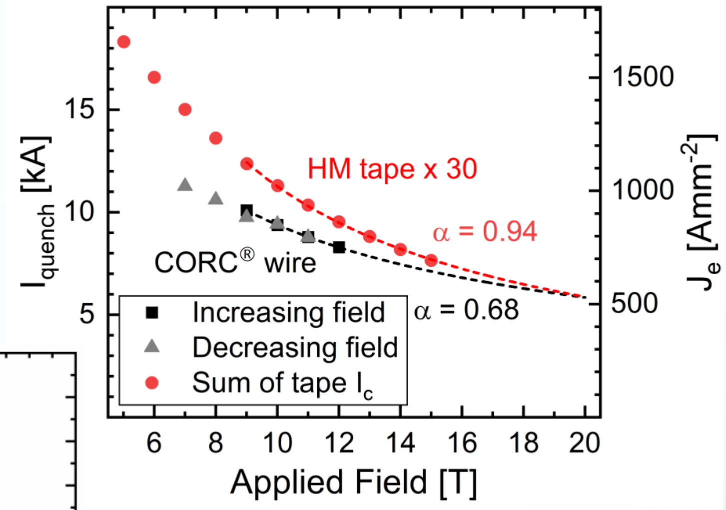
- Tested using two flat anvils (not Lorenz force driven)
- Depends on the CORC® core size:
  - 2.55 mm core: around 100 kN/m
  - 3.2 mm core: around 200 kN/m





CCT-C3 CORC® wire (SuperPower HM tapes)

- CORC® performance 87 % of tape
- Tested at 99.5 kN/m transverse load
- **Expected I_c at 10 T of 9.2 kA**



Danko van der Laan, Dustin Mc Rae & Jeremy Weiss, *Supercond. Sci. Technol.* **32** 015002 (2019)

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Developing a 10 kA (10 T) CORC® wire for CCT-C4

Availability of compatible tapes for use in CORC® wires: substrate thickness of less than 35 μm

2020: SuperPower HM

- Until recently the highest in-field performance
- 30 μm thick substrate
- Limited availability

2023: Shanghai Superconductor Technologies (SST)

- 30 μm thick substrates
- About 2/3 of SuperPower HM performance

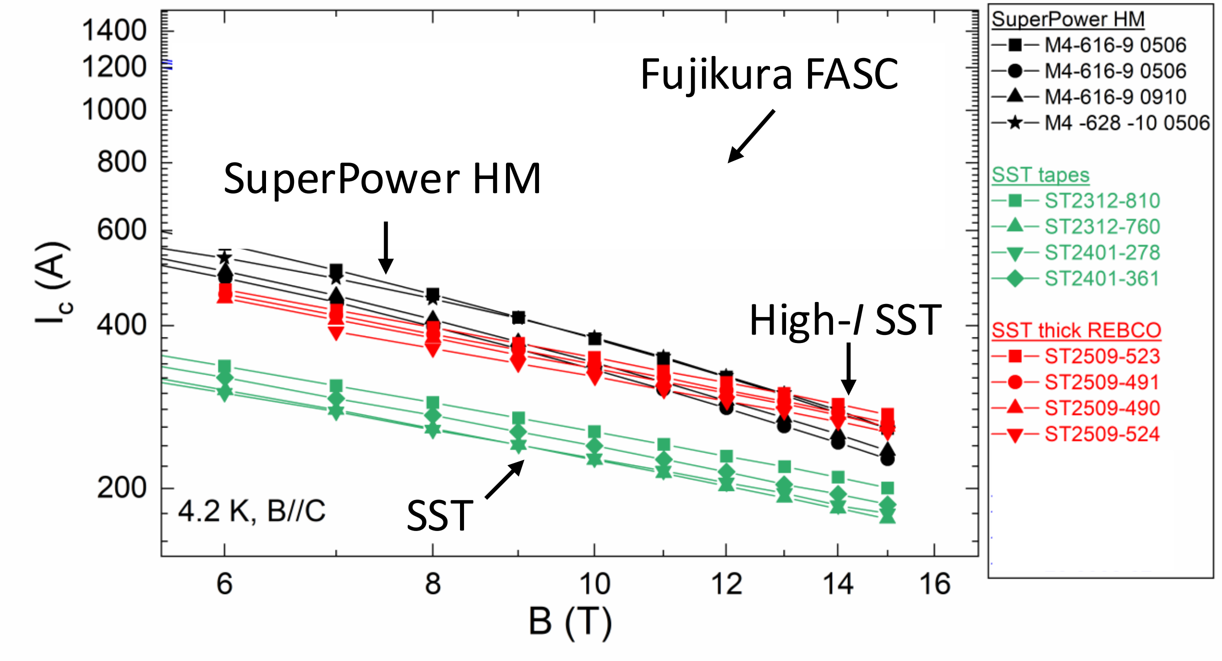
2025: High-*I* Shanghai Superconductor Technologies

- **23 μm thick substrates**
- Higher J_c and thicker REBCO film
- Performance comparable with SuperPower HM

2026: Fujikura FASC

- 35 μm thick substrates
- **Performance double that of SuperPower HM**

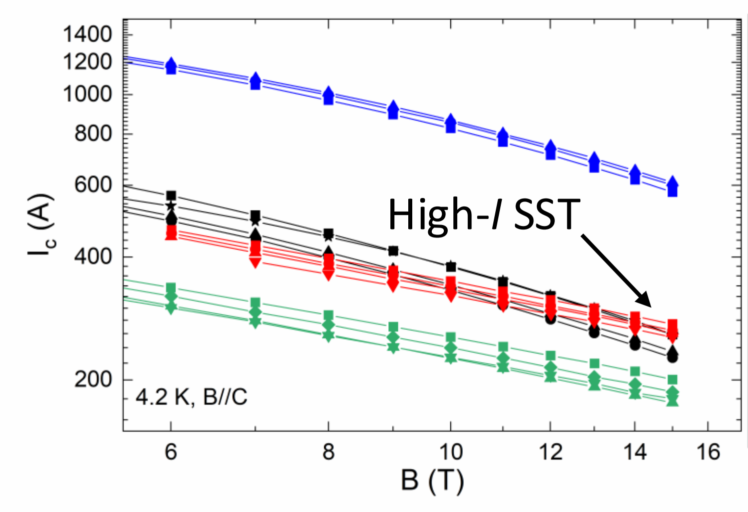
2 mm wide tape performance at 4.2 K



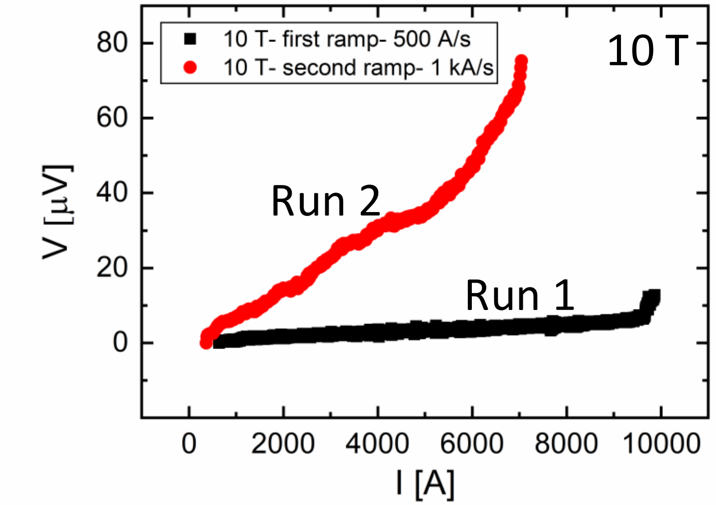
In-field performance of CORC® wires: High-*I* SST tapes

High-*I* SST CORC® wire layout

- Tapes with 23 μm substrate
- CORC® wire core 2.34 mm
- 34 tapes, O.D. 3.9 mm
- Expected transverse load limit <100 kN/m



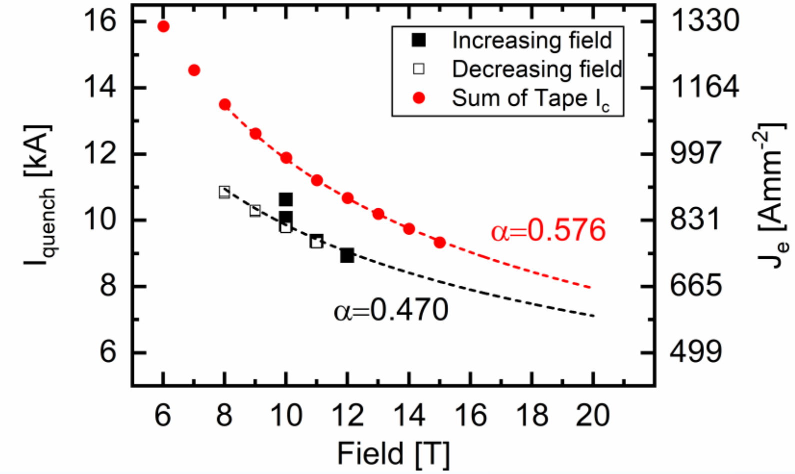
No reinforcement



CORC® wire (no reinforcement)

- Quenches at 10 T:
  - 1: 9,875 A
  - 2: 6,900 A
- Degradation of 30 % at 98.8 kN/m

Solder coated tapes



CORC® wire with solder coated tapes

- About 7 % degradation after initial 4 runs, after which it stabilized
- Final CORC® performance 87 % of tape
- **Peak transverse load: 107.4 kN/m at 12 T**
- **I_c at 10 T of 9,800 A**

Transverse load limit based on CORC® core size can be extended by additional CORC® wire reinforcement

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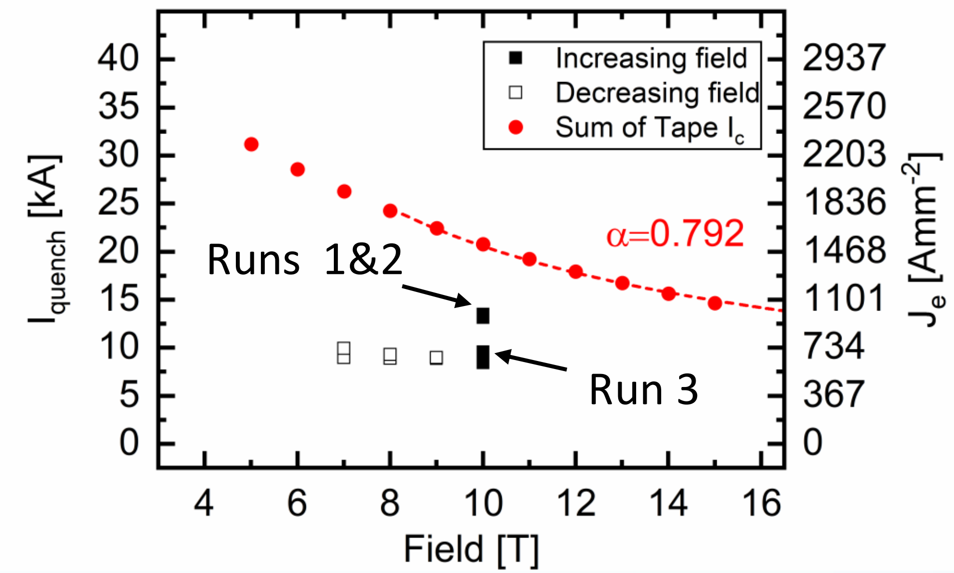
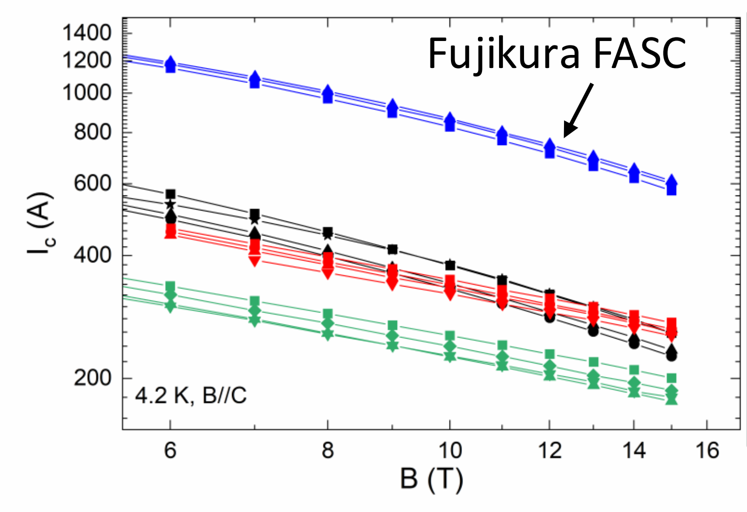
In-field performance of CORC® wires: Fujikura FASC

CORC® wire layout

- Tapes with 35 μm substrate
- **CORC® wire core 3.05 mm**
- 24 tapes, O.D. 4.2 mm
- Expected transverse load limit somewhere between 100 and 200 kN/m
- **Theoretical I_c at 10 T of 17.5 kA** (175 kN/m)
- Theoretical I_c at 20 T of 8.7 kA (174 kN/m)





CORC® wire performance

Quenches at 10 T:

1: 13,135 A (131.3 kN/m)

2: **13,489 A (134.9 kN/m)**

3: 8,700 A, …..

21: 8,659 A

Impact

- CORC® wire is not current limited, but stress limited
- Additional reinforcement (larger core, or solder coated tapes) may increase the transverse load limit towards 175 kN/m corresponding to the electrical CORC® wire limit

CCT-C4 can be wound from CORC® wire based on Fujikura FASC tapes without additional support

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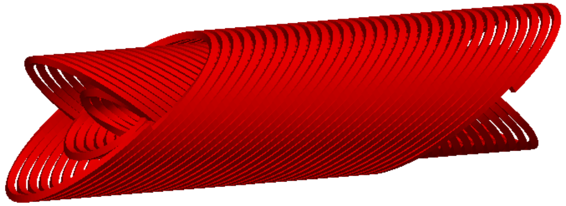
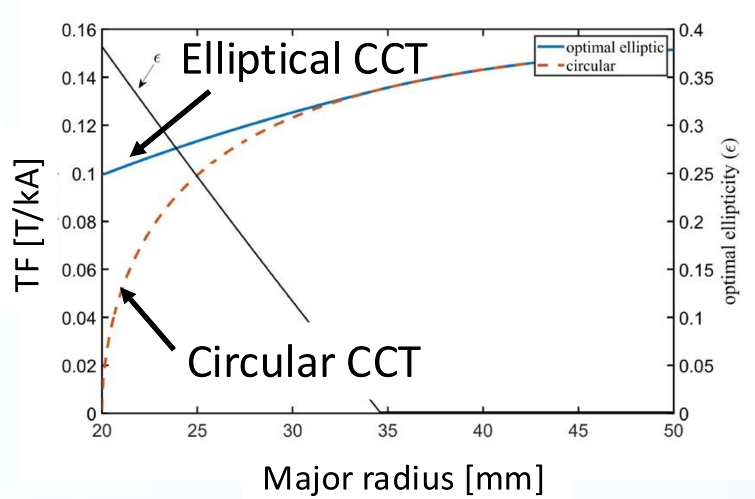
Inserts for LYS/HTS hybrid accelerator magnets based on CORC® wires

Elliptical CCT magnets wound from CORC® wires at 20 mm radius

CCT magnets with elliptical aperture

- Allow for smaller inserts than circular CCTs
- Allow ellipticity as additional design parameter
- Have a higher transfer function (T/kA) at smaller major radius than circular CCTs



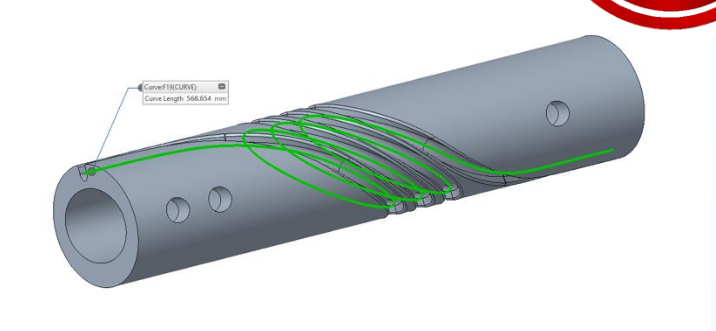


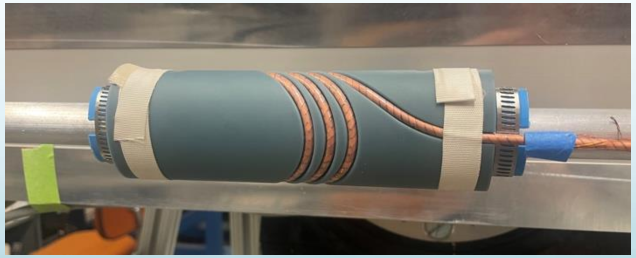
Concept verification at 20 mm CORC® bend radius

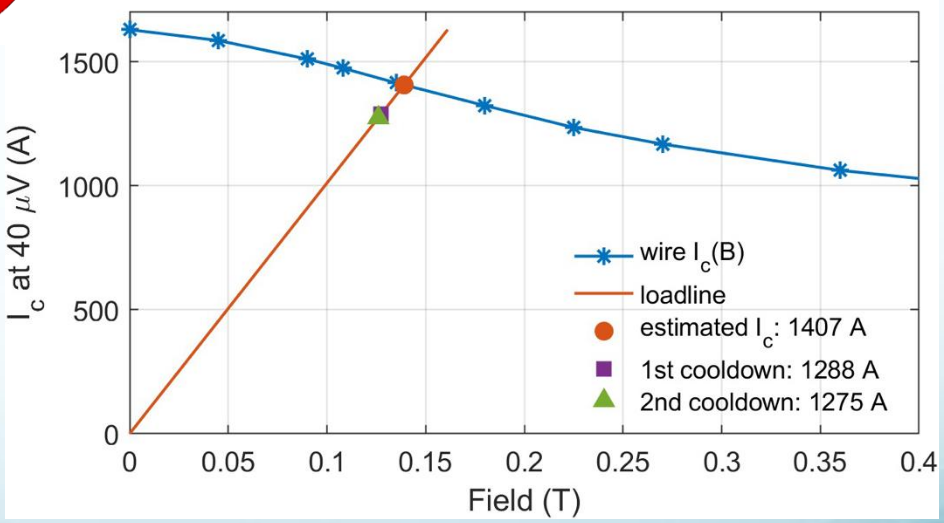
5 T (stand-alone), 3 T (in 10 T LTS outsert)

TABLE II
SUMMARY TABLE FOR THE HTS INSERT MAGNET DESIGN

parameter	value	unit
major aperture	36.3	mm
minor aperture	22.0	mm
min. bending radii	20/21/20/23	mm
wire piece lengths	4.0/5.9/11.3/13.7	m
total wire length	34.9	m
physical length	420	mm
Short sample: standalone (4.2 K)		
I_c	11.0	kA
B_1	4.88	T
conductor $\perp$ field	5.10	T
magnetic length	241.4	mm
Short sample: in 10 T background (4.2 K)		
I_c (HTS)	6.58	kA
B_1 (HTS)	2.92	T
B_1 (total)	12.92	T
conductor $\perp$ field (HTS)	13.05	T







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L. Brouwer, Y. Yan, X. Wang, J.F. Croteau, P. Ferracin, J.L Rudeiros Fernandez, and A. Saravanan, *IEEE Trans. Appl. Sup.* 36, 4600107(2026)

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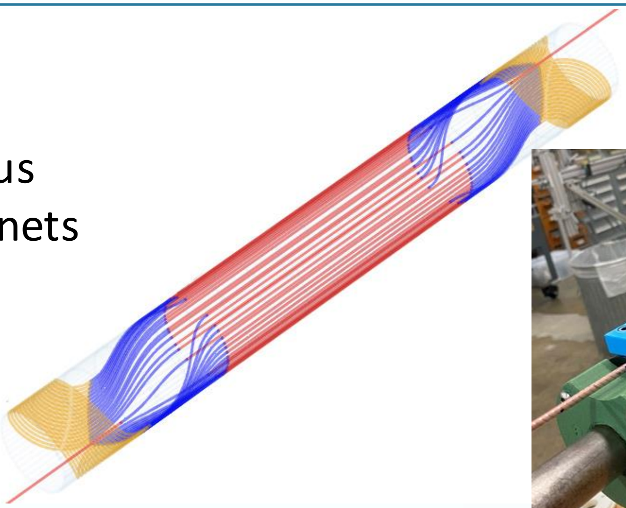
Uni-layer dipole magnets wound from CORC® wires at 20 mm radius



Uni-layer magnets have certain benefits

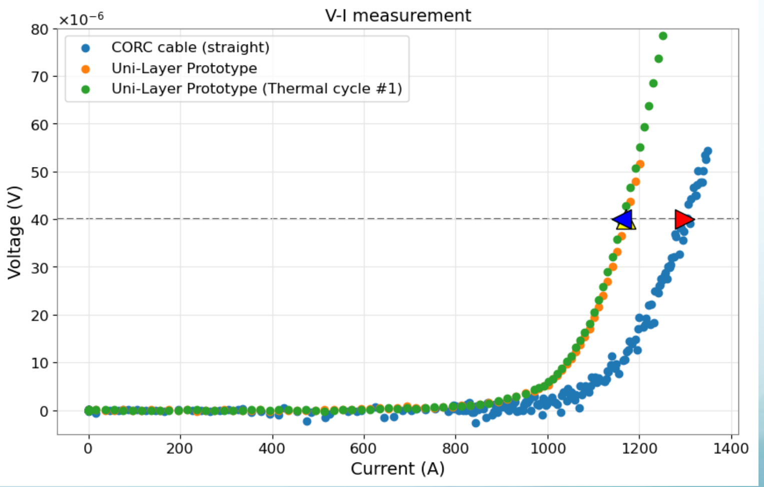
- More efficient use of conductor over others
- Allow for small aperture while limiting conductor bending radius
- Much higher transfer function than Cosine Theta and CCT magnets

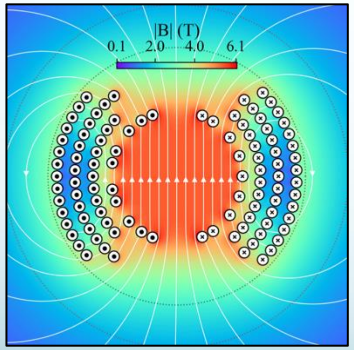
Concept verification

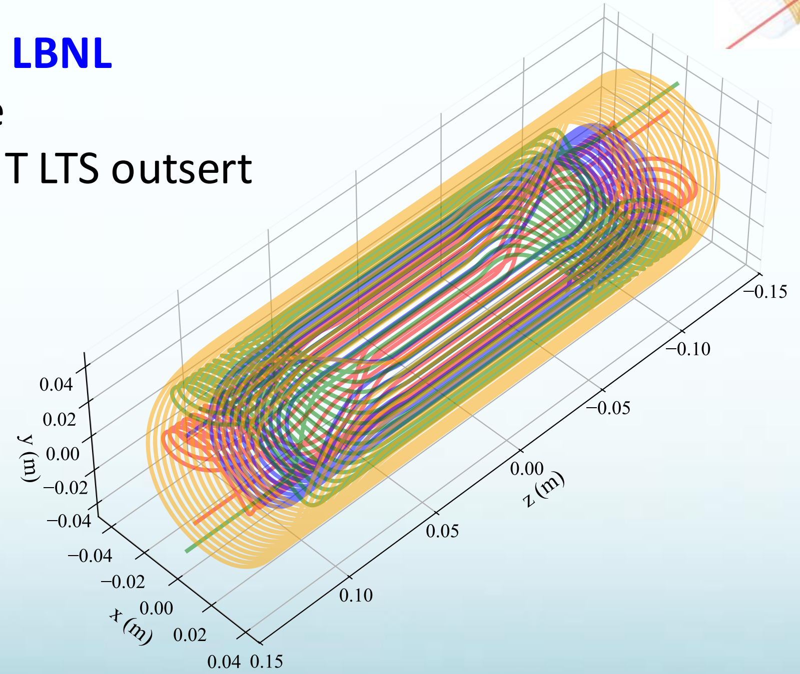
- 20 mm bend radius
- Performance 90 % after winding, not taking field into account

Uni-layer magnet program at LBNL

- 5.5 T at 9.8 kA stand-alone
- 12.1 T at 6.5 kA within 8.5 T LTS outsert







J.L Rudeiros Fernandez and P. Ferracin, *Superconduct. Sci. Technol.* **36** 055003 (2023)

Summary

Development of dipole magnets based on CORC® wires

- Canted-cosine-theta magnets have demonstrated 1.2 T, 2.9 T and 5.99 T dipole fields
- The improved bending performance of CORC® wires resulted in a dipole field of 5.99 T in the latest CCT magnet, overshooting its 5 T target by 20 %
- Improved bending flexibility of CORC® wires now allows compact and more efficient CCT magnets with minimum bending radius of 20 mm
- Magnet CCT-C4, generating a dipole field of 10 T at a current of 10 kA is planned

Development CORC® wires for CCT-C4 and beyond

- The electrical performance of CORC® wires can only be achieved with Fujikura FASC tapes, which have 50 % higher in-field performance than Superpower HM tapes used in CCT-C3
- CORC® wires based on Fujikura FASC tapes are stress limited under transverse compression at about 75 % of their theoretical electrical limit
- CORC® wires based on Fujikura FASC tapes are compatible with the transverse compressive load of 100 kN/m in CCT-C4
- An optimized CORC® wire design is required to allow operation at transverse loads of 200 kN/m in a 20 T dipole magnet operating at 10 kA