Development of high-field dipole and solenoid magnets using the latest generation of CORC® cables and wires

Danko van der Laan & Jeremy Weiss*
Advanced Conductor Technologies & University of Colorado, Boulder, Colorado, USA
* Now with High Temperature Superconductors Inc, Santa Barbara, CA, U.S.A.

Sven Dönges, Daniel Kwiatkowski & Kyle Radcliff
Advanced Conductor Technologies, Boulder, Colorado, USA

Dima Abraimov
Applied Superconductivity Center, National High Magnetic Field Laboratory, Tallahassee, Florida, U.S.A.

Xiaorong Wang, Yufan Yan, Lukas Brouwer, José Luis Fernandez, Hugh Higley & Soren Prestemon
Lawrence Berkeley National Laboratory, Berkeley, California, U.S.A.

Advanced Conductor Technologies
www.advancedconductor.com

EUCAS 2025, Porto, Portugal, September 24th, 2025

Fermilab
NATIONAL HIGH MAGNETIC FIELD LABORATORY
BERKELEY LAB

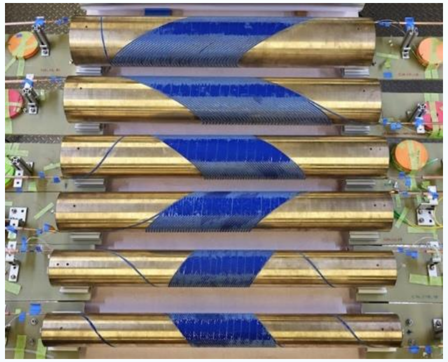
Outline

Accelerator dipole magnets under development using CORC® wires

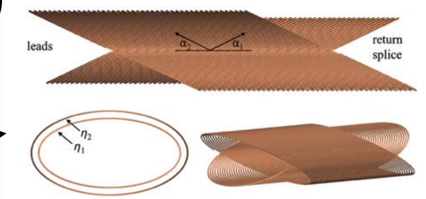
- Canted-Cosine-Theta (CCT) magnets with circular aperture (LBNL)
  - Earlier CCT magnets CCT-C1 (1.2 T) and CCT-C2 (2.9 T)
  - Latest CCT magnet CCT-C3 (6 T)
  - Future CCT magnets towards 10 T
- CCT magnets with elliptical aperture (LBNL)
- Uni-layer magnets (LBNL)

CCT-C1

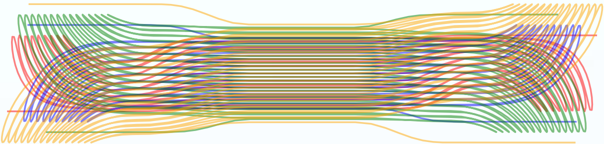
CCT-C2



CCT-C3



Elliptical CCT

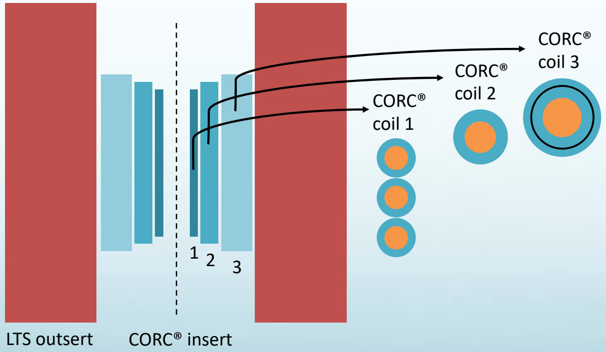


Uni-layer

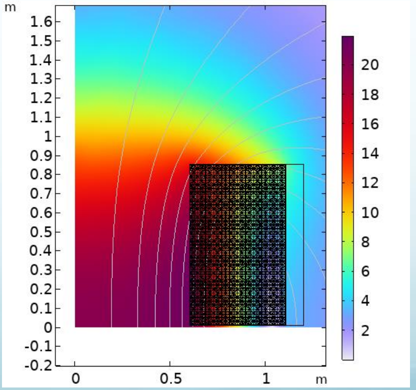
High-field CORC® solenoids

- 40 T series-connected CORC® solenoids
- 20 T, large-bore CORC® solenoids for the muon collider

40 T CORC® solenoid



20 T large-aperture solenoid



Advanced Conductor Technologies
www.advancedconductor.com

Development of CORC® dipole magnets

Circular CCT magnet development based on CORC® wires

Development of low-inductance 20 T dipole CCT magnet by

- Developing and demonstrating the CORC®-based CCT magnet technology
- Improve the in-field and bending performance of CORC® wires

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
- 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)

Advanced Conductor Technologies
www.advancedconductor.com

Fermilab
NATIONAL HIGH MAGNETIC FIELD LABORATORY
BERKELEY LAB

Improvement of CORC® wire bending flexibility

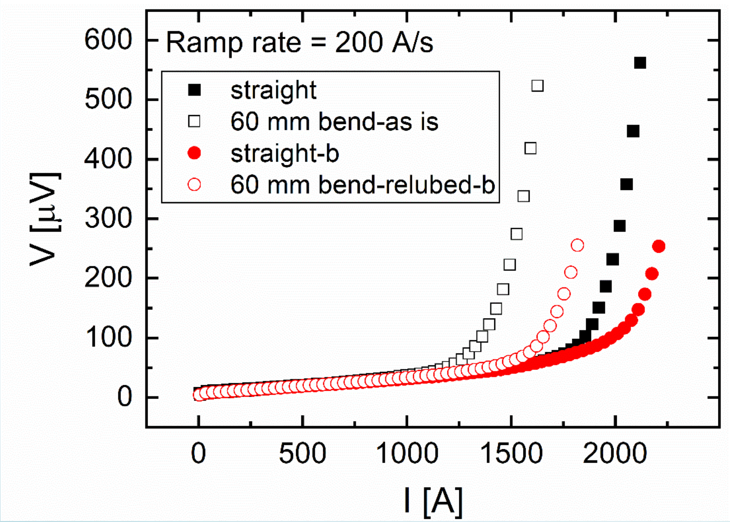
Improve bending flexibility of standard 30-tape CORC® wire

- Reduce bending degradation for 30 mm bending radius from 20 – 30 % as seen in CCT-C2
- Allow future CCT magnets to be based on 20 mm bending radius

CCT-C2 (AP based) CORC® wire

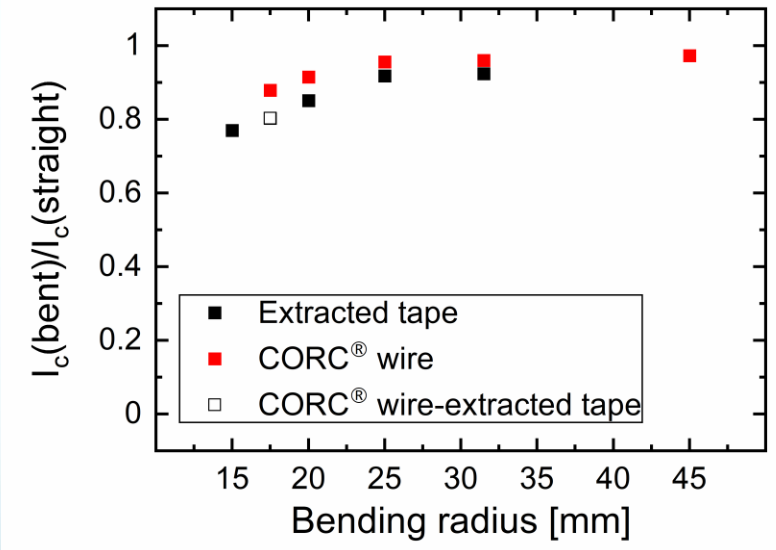
- 70 – 80 % I_c retention at 30 mm radius

Extensive optimization followed



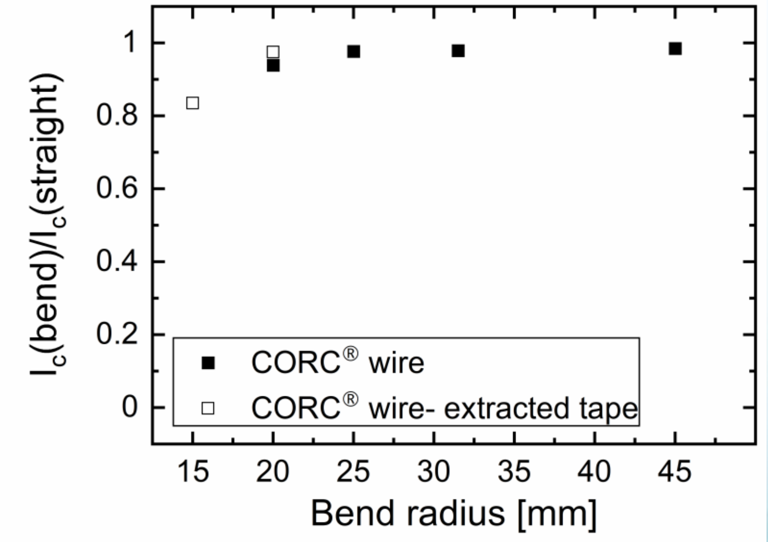
CORC® wire (SuperPower HM)

- 91.8 % I_c retention at 25 mm radius
- 80.3 % I_c retention at 17.5 mm radius



CORC® wire (Shanghai Superconductor)

- ~100 % I_c retention at 30 mm radius
- **97 % I_c retention at 20 mm radius**
- 83.5 % I_c retention at 15 mm radius



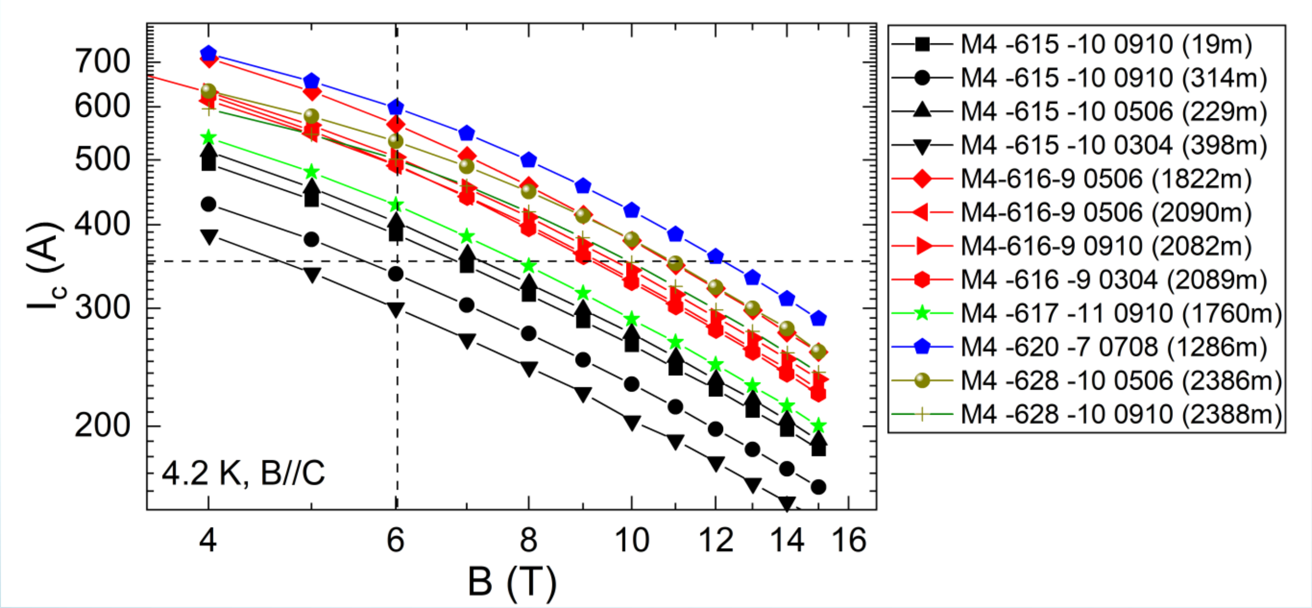
Danko van der Laan, Jeremy Weiss, Kyle Radcliff and Dmytro Abraimov, *Supercond. Sci. Technol.* **37** 115007 (2024)

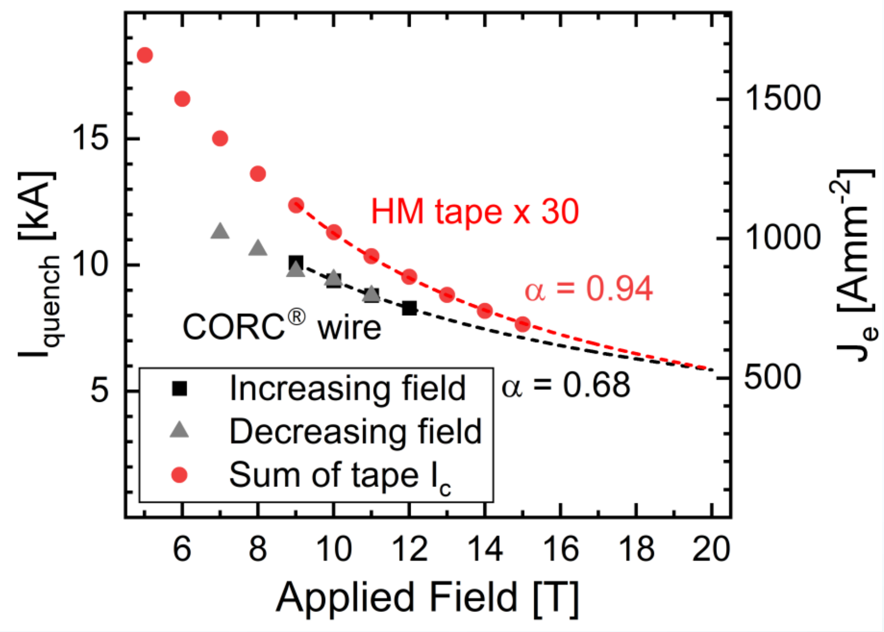
Development for magnet CCT-C3 with 5 T dipole field

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
- **New record J_e(20 T) of 530 A/mm²**
- 87 % of tape performance at 12 T

Advanced Conductor Technologies
www.advancedconductor.com

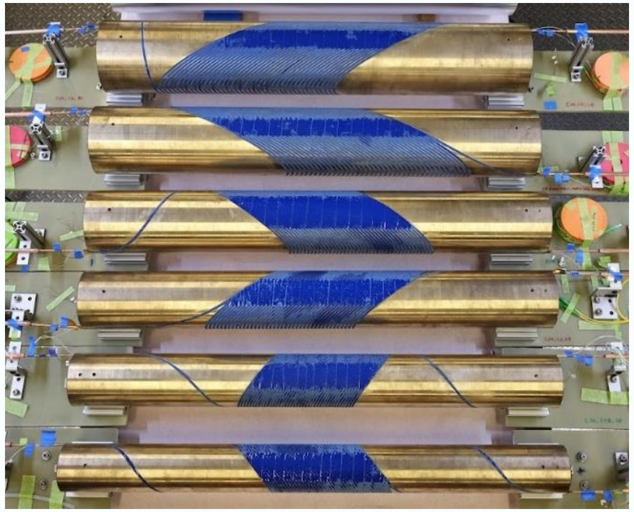
Danko van der Laan, Jeremy Weiss, Kyle Radcliff and Dmytro Abraimov, *Supercond. Sci. Technol.* **37** 115007 (2024)

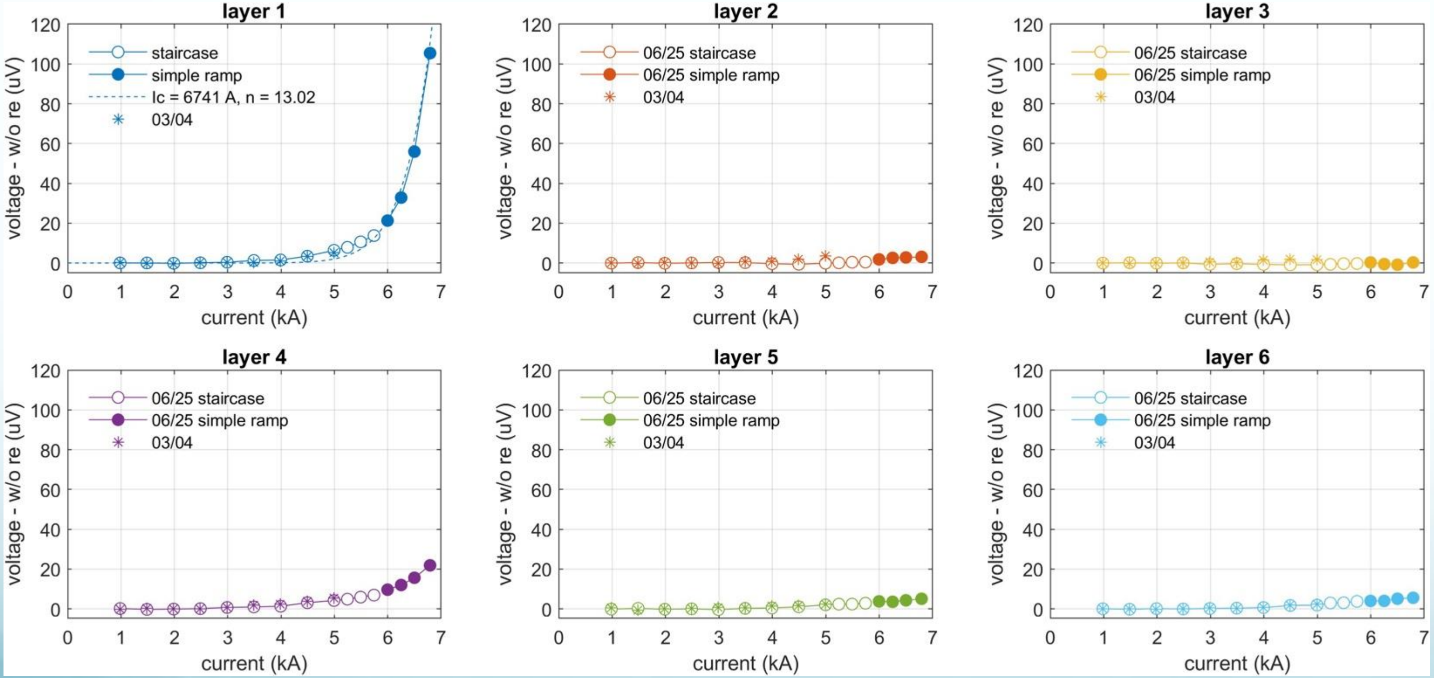
Fermilab
NATIONAL HIGH MAGNETIC FIELD LABORATORY
BERKELEY LAB

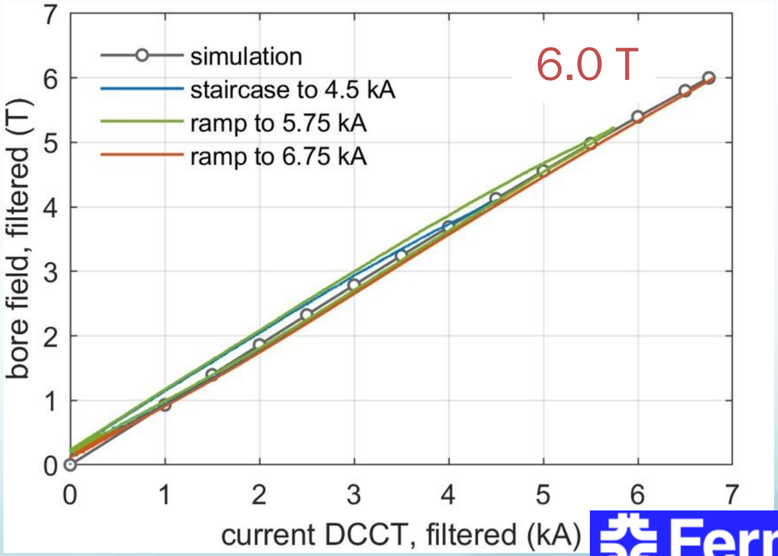
Dipole magnet CCT-C3 generates 6 T dipole field!

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

- **Dipole field of 6 T achieved at 6.75 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!







Advanced Conductor Technologies
www.advancedconductor.com

Fermilab

NATIONAL HIGH MAGNETIC FIELD LABORATORY

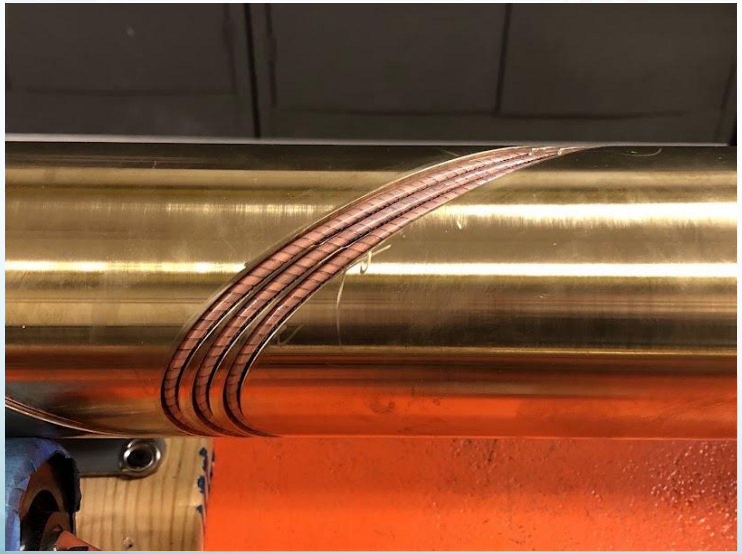
BERKELEY LAB

Next step towards 20 T CCT magnets: LTS/HTS hybrid?

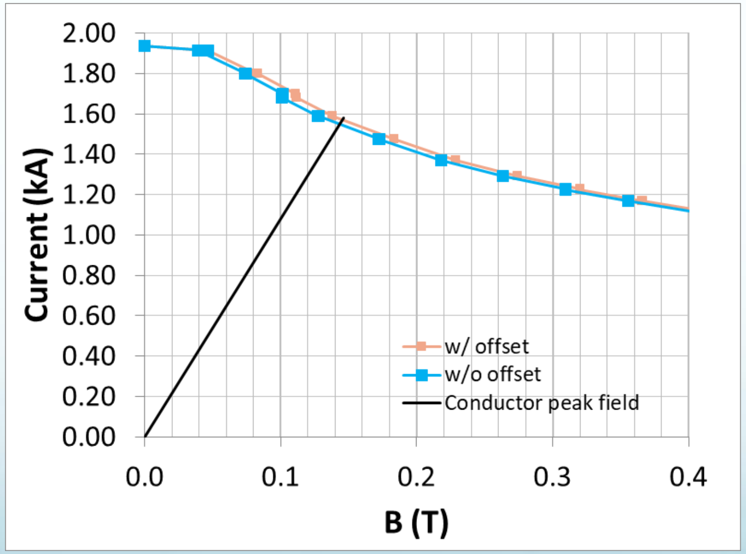
Higher bending flexibility of CORC® wires now enables more compact CCT magnets

- **20 mm bend radius at poles** (compared to 30 mm radius for CCT-C3)
- 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

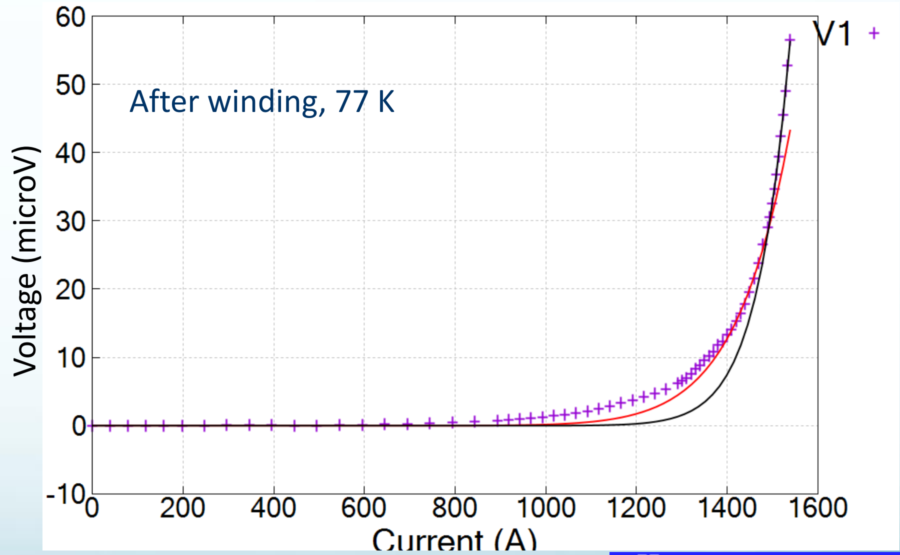
Next generation of CORC® wire based on Shanghai Superconductor tape retained 96 % of its I_c after being wound into a 3-turn CCT structure with 20 mm bend radius at poles.



CORC® wire I_c(B) at 77 K intersects the CCT load line at 1,578 A at 145 mT



CORC® wire in CCT structure has I_c of 1,514 A



Advanced Conductor Technologies
www.advancedconductor.com

Fermilab

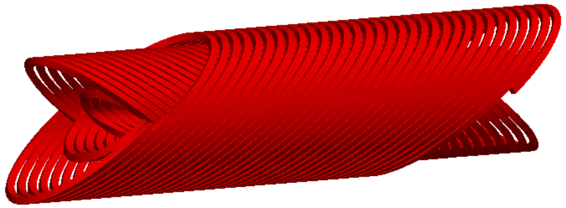
NATIONAL HIGH MAGNETIC FIELD LABORATORY

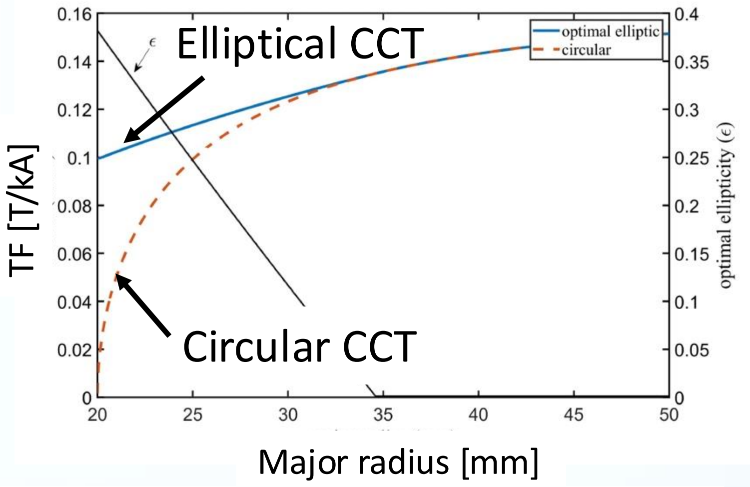
BERKELEY LAB

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



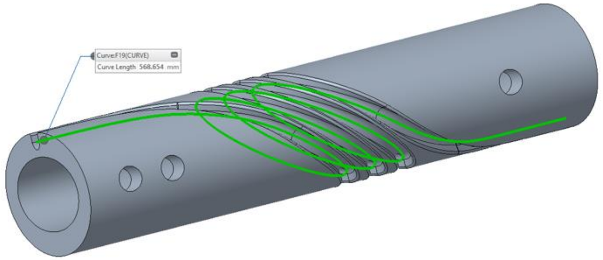


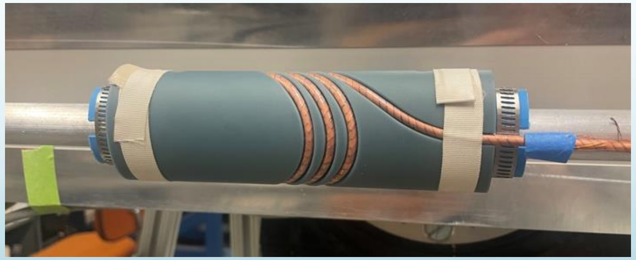
Concept verification at 20 mm CORC® bend radius

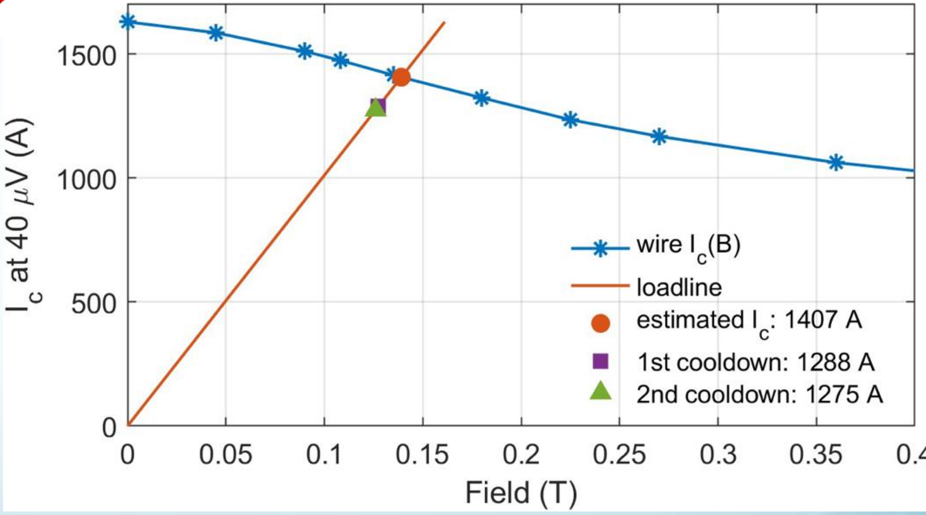
5 T (stand-alone), 13 T (in 10 T LTS outsert)

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 ⊥ 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 ⊥ field (HTS)	13.05	T







Advanced Conductor Technologies
www.advancedconductor.com

L. Brouwer, Y. Yan, X. Wang, J.F. Croteau, P. Ferracin, J.L Rudeiros Fernandez, and A. Saravanan, *accepted for publication in IEEE Trans. Appl. Sup.* (2025)

Fermilab
NATIONAL HIGH MAGNETIC FIELD LABORATORY
BERKELEY LAB

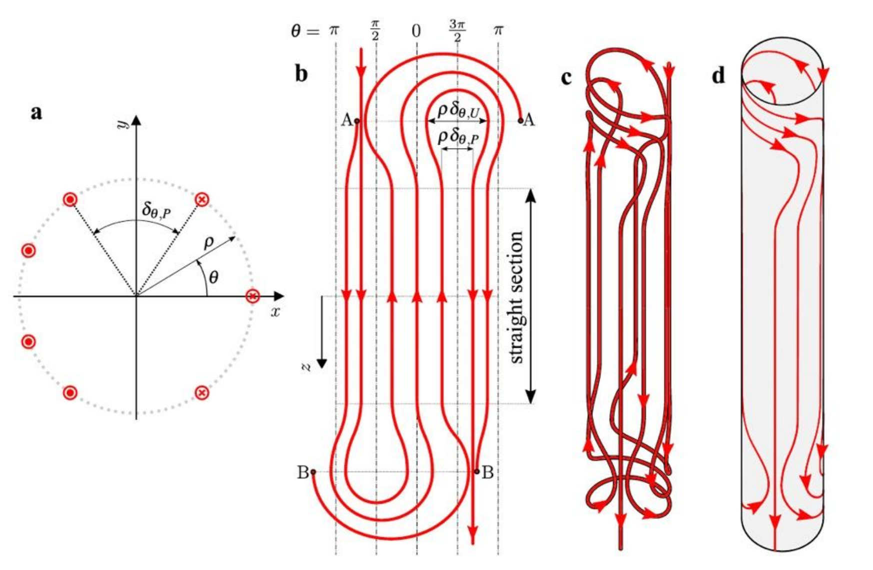
Uni-layer dipole magnets wound from CORC® wires at 20 mm radius

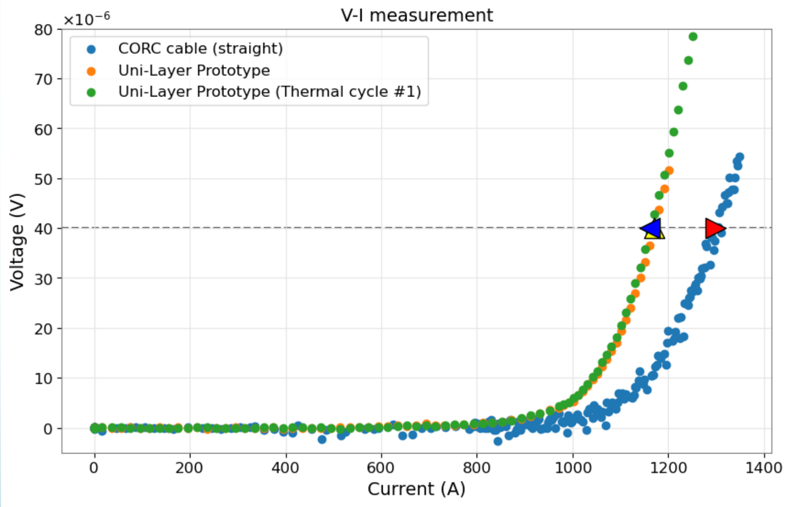
Uni-layer magnets have certain benefits

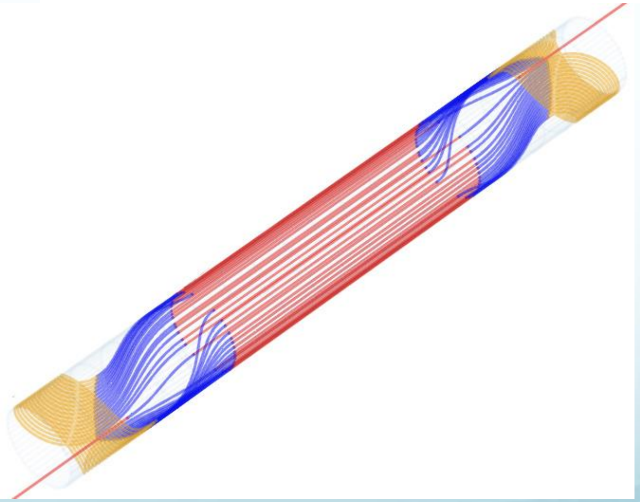
- More efficient use of conductor over others
- Allow for small aperture while limiting conductor bending radius
- Much higher transfer function than Cosine Theta and CCT magnets

Concept verification

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







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

Advanced Conductor Technologies
www.advancedconductor.com

Fermilab

NATIONAL HIGH MAGNETIC FIELD LABORATORY

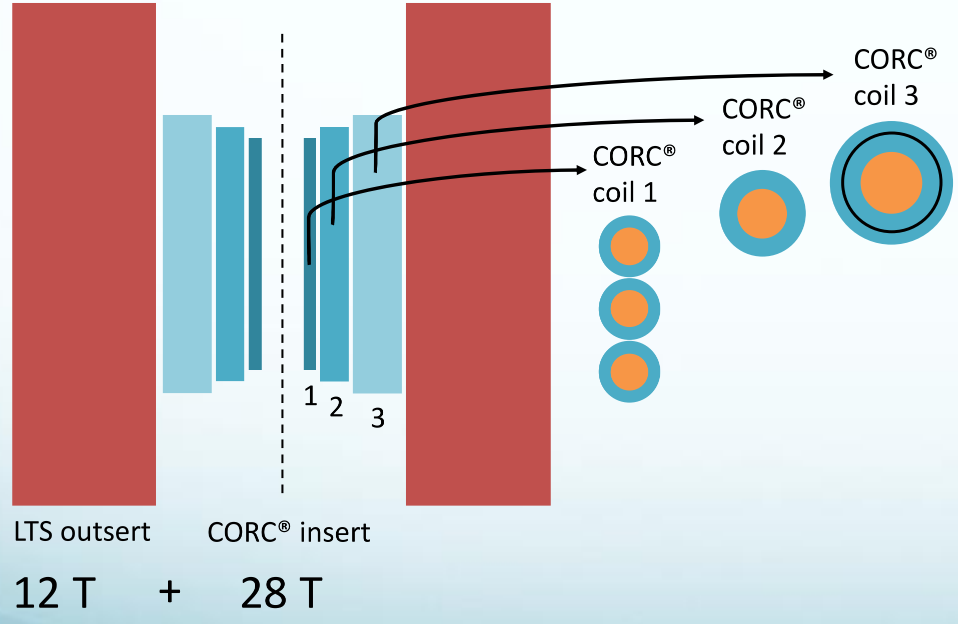
BERKELEY LAB

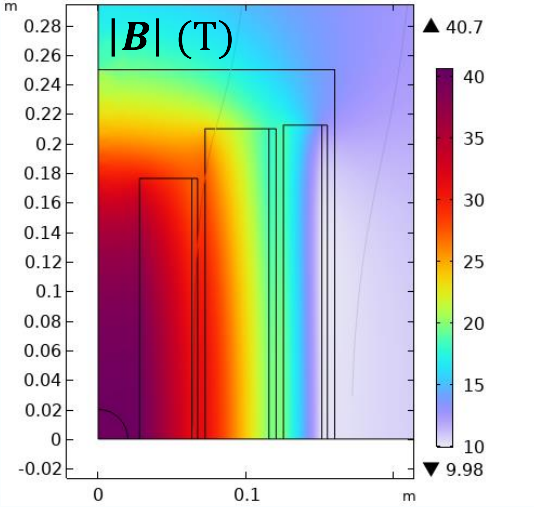
Development of high-field CORC® solenoids

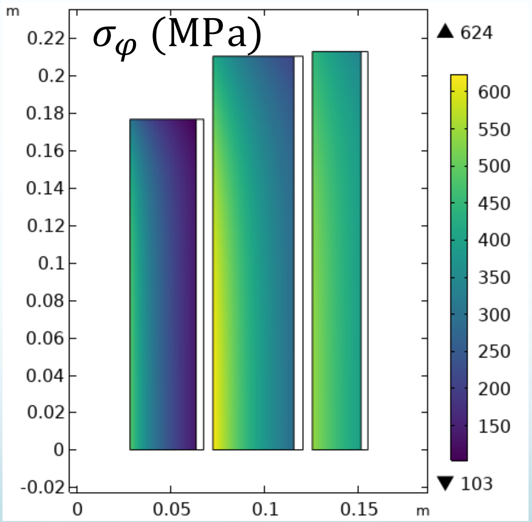
Series-connected 40 T low-inductance CORC® solenoids

Initial iteration of 40 T solenoid

- 50 mm bore
- 12 T LTS outsert (Oxford Instruments)
- Three CORC® coils connected in series
- Stainless steel overbanding over each coil
- Operating at 11.2 kA at 80 - 88 % of I_c







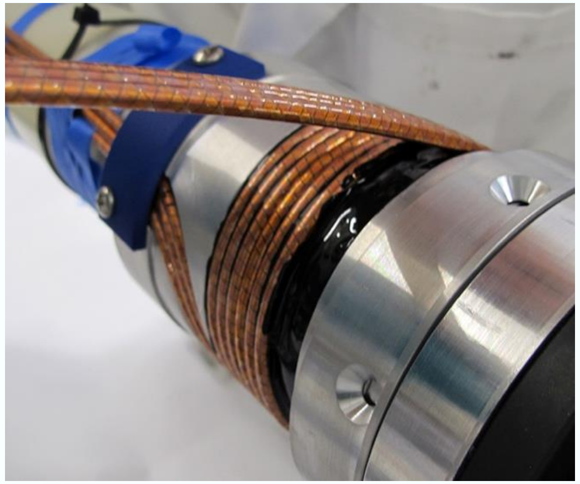
	unit	Coil 1	Coil 2	Coil 3
cable type		A-U x 3	B-V	C-U / 2
cables per layer		42	30	25
number of layers		8	6	3
height	mm	176.4	210	212.5
inner radius	mm	28.0	72.3	125.3
outer radius (sc)	mm	63.4	115.5	151.3
I_{op}	kA		11.2	
background field	T		12	
field contribution	T	8.65	11.0	8.33
I_{op}/I_{c0}	%	0.88	0.86	0.79
$\sigma_{r,max}$	MPa	39.8	6.5	0.1
σ_{hoop}	MPa	495	624	544
$\sigma_{overband}$	MPa	417	875	1117

Advanced Conductor Technologies
www.advancedconductor.com

Demonstration of series-connected CORC® solenoids

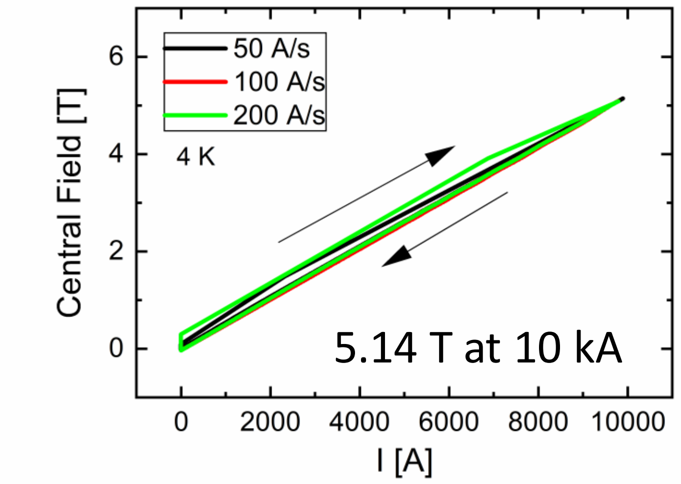
Series-connection of inner and middle coil

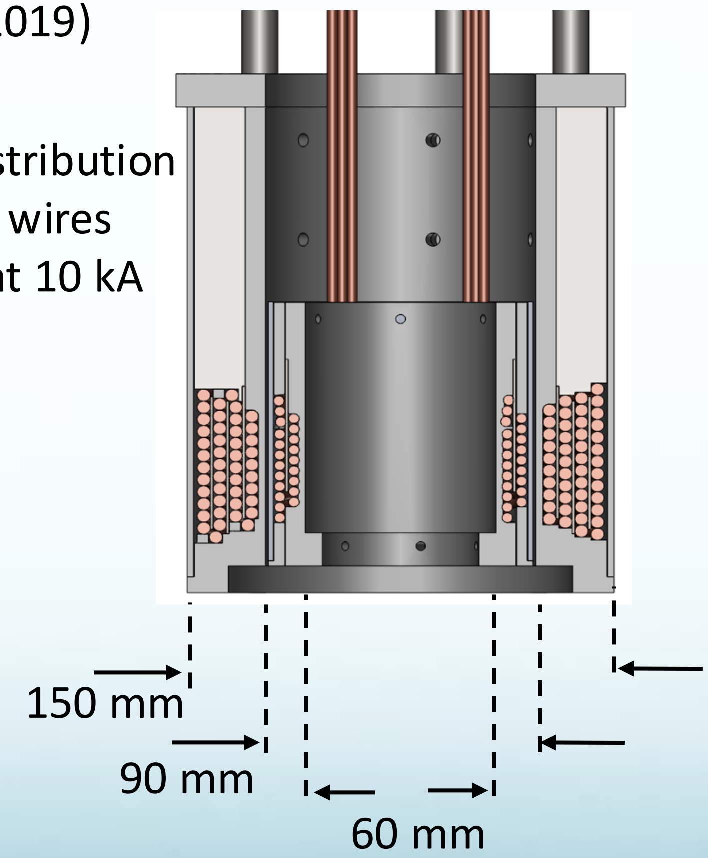
- Inner coil wound from three parallel CORC® wires
  3 turns per layer, 2 layers
- Middle coil based on a single CORC® cable
  46 turns, 4 layers (magnet from 2019)

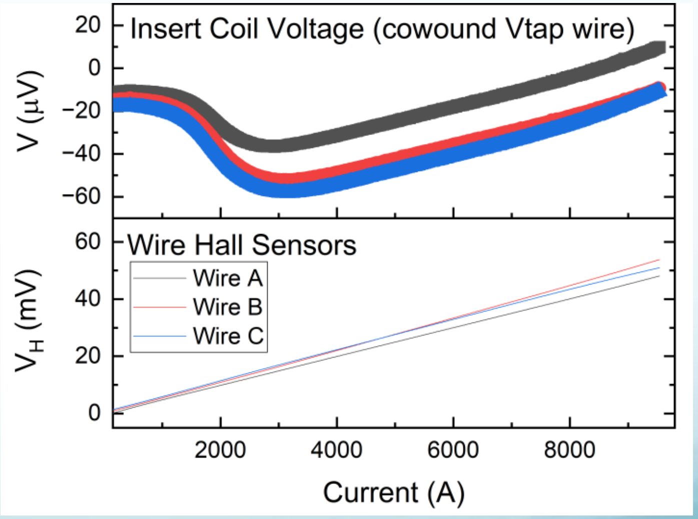


Results

- Hall sensors show even current distribution between the three parallel CORC® wires
- Peak axial field of 5.14 T reached at 10 kA







Advanced Conductor Technologies
www.advancedconductor.com

Fermilab

NATIONAL HIGH MAGNETIC FIELD LABORATORY

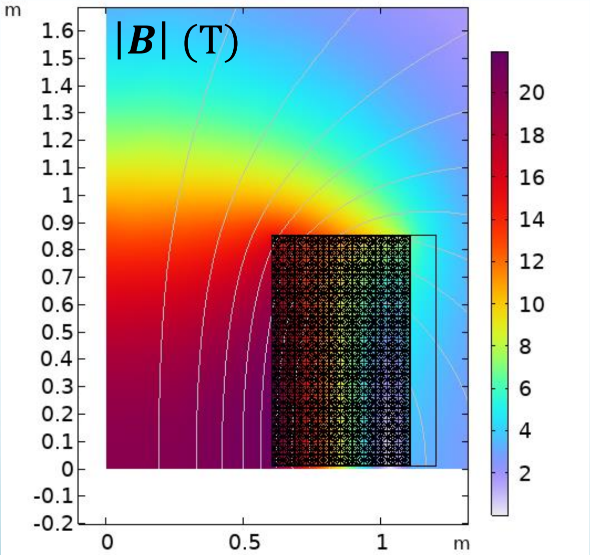
BERKELEY LAB

20 T Large-bore CORC® solenoids

Initial iterations of large-bore 20 T solenoids

- Single CORC® coil
- 1.2 m bore as needed for the muon collider target and capture solenoids

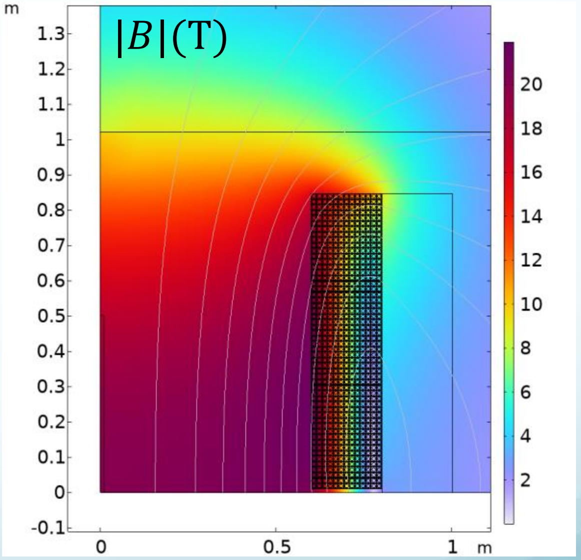
	unit	Value
number of layers (r)		12
turns per layer (z)		20
inner radius	m	0.60
outer radius (sc)	m	1.06
height	m	0.84
self inductance	H	0.0746
I_{op}	kA	80.0
max I_{op}/I_c @4.2 K		0.68
$\sigma_{hoop,cable}$	MPa	268
$\sigma_{r,cable}$	MPa	20.4
$\sigma_{mises,jacket}$	MPa	732



Two options are considered

1. 6-around-1 CORC®-CICC
2. Jacketed CORC® cable

	unit	Value
number of layers (r)		13
turns per layer (z)		54
inner radius	m	0.60
outer radius (sc)	m	0.80
height	m	0.837
self inductance	H	0.556
I_{op}	kA	25.2
max I_{op}/I_c @4.2 K		0.56
$\sigma_{hoop,cable}$	MPa	324
$\sigma_{r,cable}$	MPa	25
$\sigma_{mises,jacket}$	MPa	865



Advanced Conductor Technologies
www.advancedconductor.com

Fermilab

NATIONAL HIGH MAGNETIC FIELD LABORATORY

BERKELEY LAB

Summary

Development of circular CCT dipole magnets based on CORC® wires

- Canted-cosine-theta magnets have demonstrated 1.2 T and 2.9 T dipole fields
- The improved bending performance of CORC® wires resulted in a dipole field of 6 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

Development of other dipole magnets using CORC® wires

- Elliptical CCT magnets with higher transfer function than circular CCT magnets
- Uni-layer magnets with an even higher transfer function
- The feasibility of these three magnet concepts have been demonstrated using CORC® wires

A new program developing low-inductance, high-field solenoids from CORC® cables is about to start

- 40 T hybrid and stand-alone solenoids with 50 mm bore
- 20 T stand-alone solenoids with 1.2 meter diameter bore