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

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Low-inductance, high-field solenoids

Low-inductance, high-field solenoids
- Operating currents in the range of 5 – 100 kA to limit the magnet induction
- Allow for relatively high magnetic field ramp rates >> 1 T/s
- Potentially easier to protect during a quench

Benefits of CORC® conductors for use in high-field solenoids
- Compatible with a magnet bore of 50 mm in diameter of for instance a 40 T solenoid
- Tape transposition allows for high ramp rates at relatively low ramping losses
- Relatively straightforward coil winding without the need for solder impregnation
- The CORC® conductor performance can be verified before the magnet is wound

Examples of high-field CORC® solenoids
1. 50 mm bore 40 T hybrid LTS/HTS CORC® solenoid
2. 50 mm bore 40 T standalone CORC® solenoid
3. 1.2 m large-bore 20 T CORC® solenoid

Current status of CORC® solenoid development

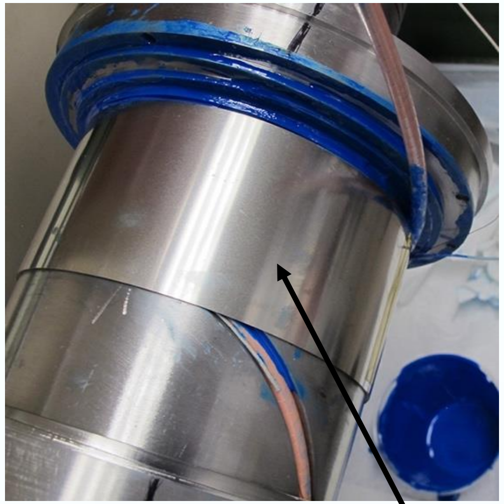
Overview of CORC® solenoids: 16.7 T insert solenoid

First CORC® insert magnet

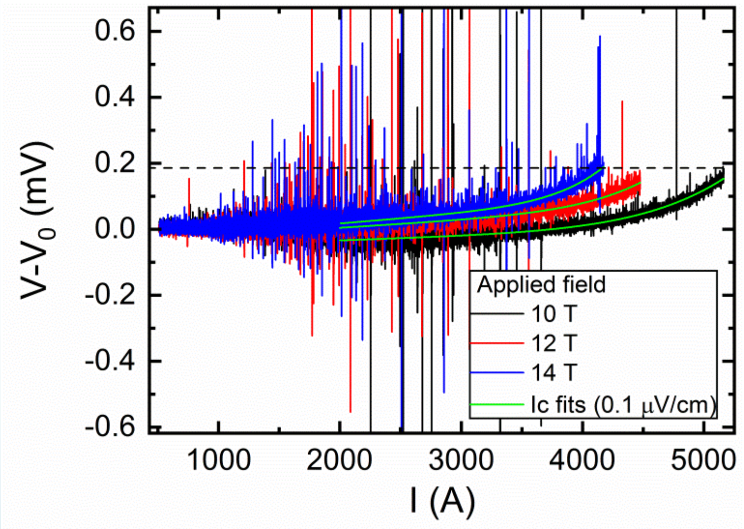
- Tested within a 14 T LTS outsert
- Critical current of 4,404 A at 16.77 T peak field
- High current density: J_e > 282 A/mm^2 at 16.77 T
- Peak JBr source stress of 275 MPa

CORC® insert layout

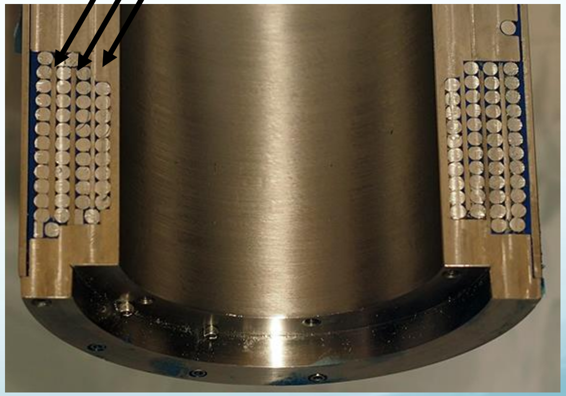
- 100 mm bore, 45 turns, 18.5 m of CORC® cable
- Wet-wound with Stycast 2850 Epoxy
- **Stainless steel overbanding between layers**



Applied field [T]	Central field at I_c [T]	Peak field at I_c [T]	I_c (0.1 μV/cm) [A]	J_e [A/mm²]
10	12.25	13.35	5,315	340.3
12	14.08	15.09	4,908	314.2
14	15.86	16.77	4,404	281.9



Stainless steel overbanding



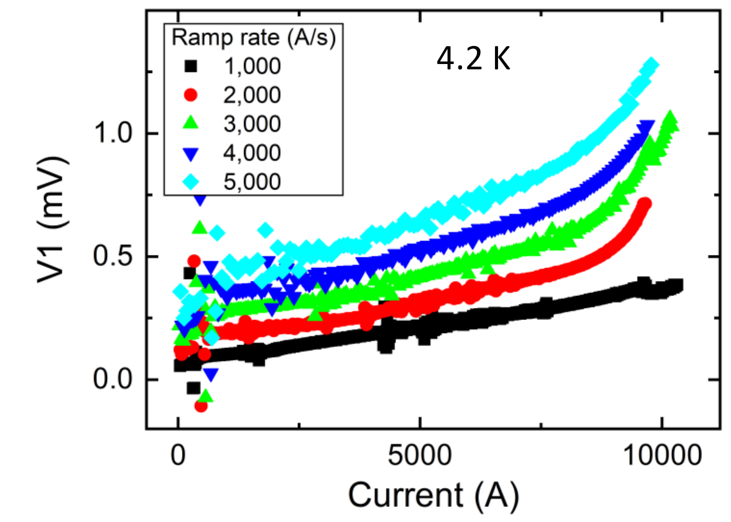
First HTS insert magnet tested at high current (>1 kA) within a meaningful background field

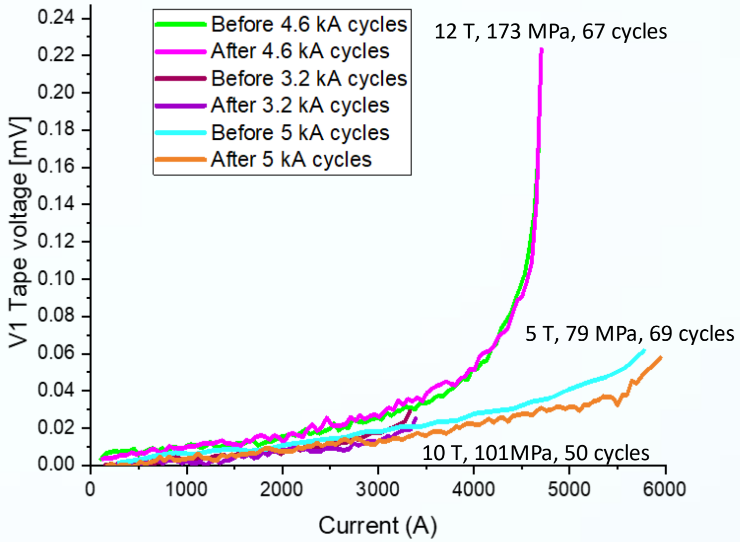
D.C. van der Laan, J.D. Weiss, U.P. Trociewitz, D. Abraimov, A. Francis, J. Gillman, D.S. Davis, Y. Kim, V. Griffin, G. Miller, H.W. Weijers, L.D. Cooley, D.C. Larbalestier, X.R. Wang, Supercond. Sci. Technol. **33**, 05LT03 (2020)

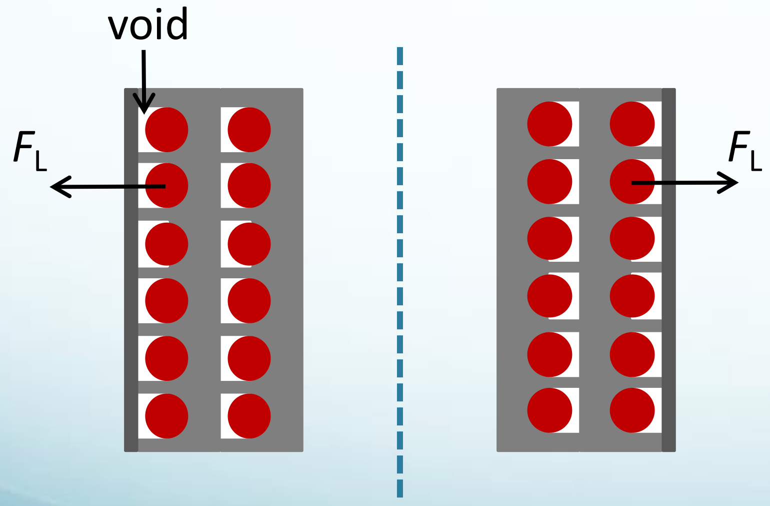
Overview of CORC® solenoids: fast ramping solenoid

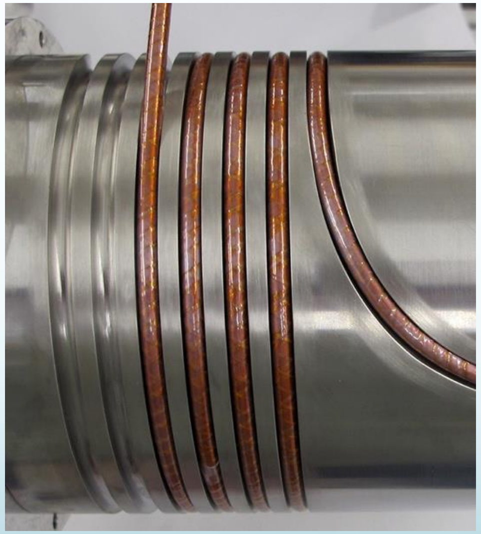
Unsupported CORC® coil

- 2-layers, 6 turns per layer, ID 119 mm,
- 6 mm thick cable in 7 mm groove
- Allows for 1 % radial cable expansion under hoop stress
- Integrated voltage tapes within the cable to minimize inductive pickup









Testing details

- Current ramp rates up to 5,000 A/s to 10 kA at 4.2 K
- Repeated current ramping into transition at 4.6 kA in 12 T background field
- J_e 200 A/mm^2, JBr hoop stress 185 MPa
- No degradation after 68 stress cycles

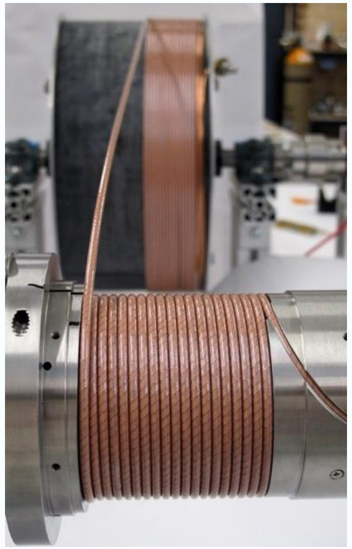
Overview of CORC® solenoids: current sharing around tape defects

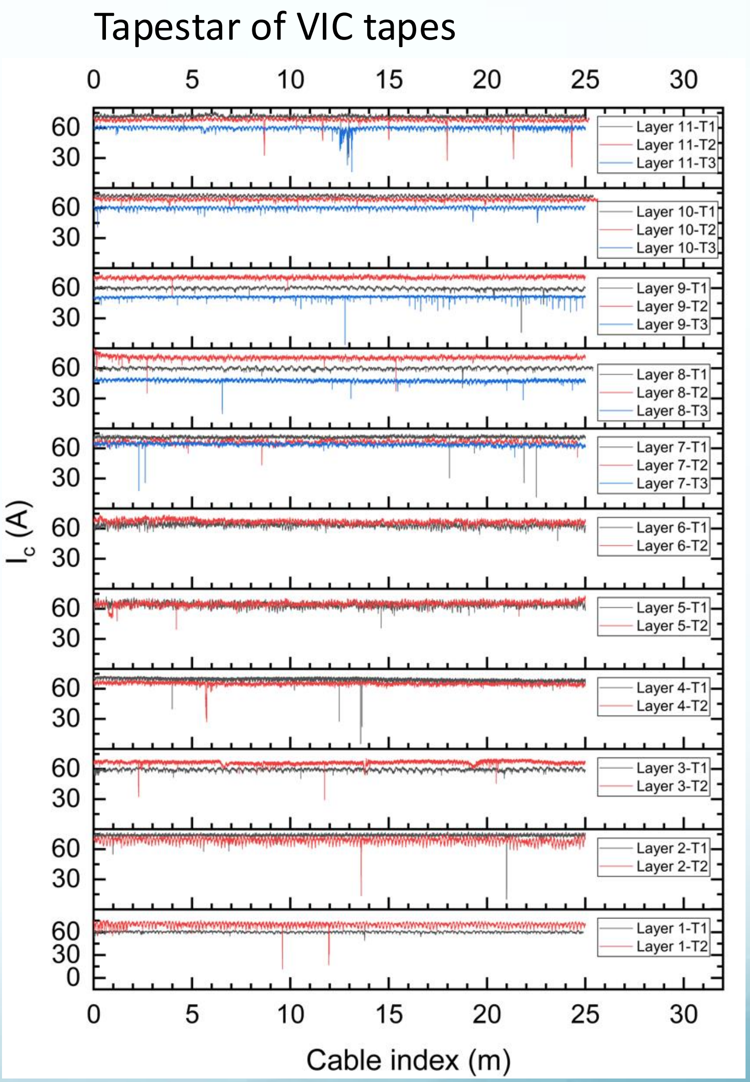
Coil details

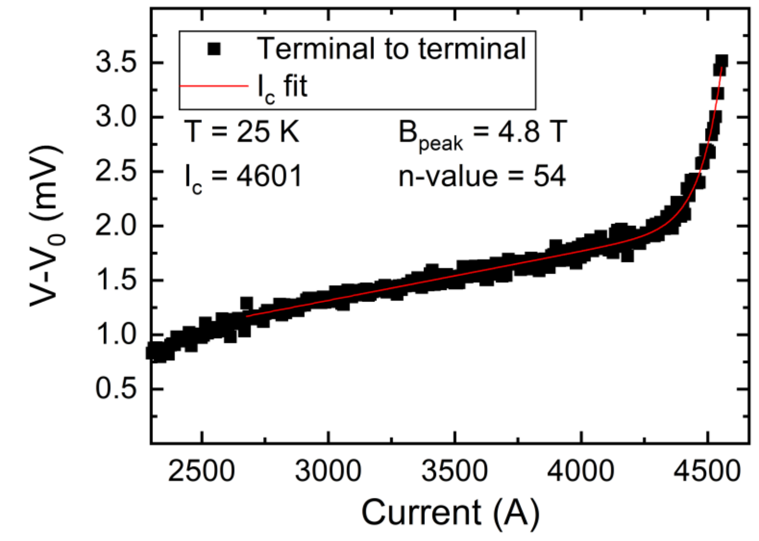
- CORC® wire wound from 27 "VIC" tapes, each containing several sharp dropouts
- 4-layer, 81-turn solenoid with 74 mm ID
- Tested at 25 K using helium gas cooling

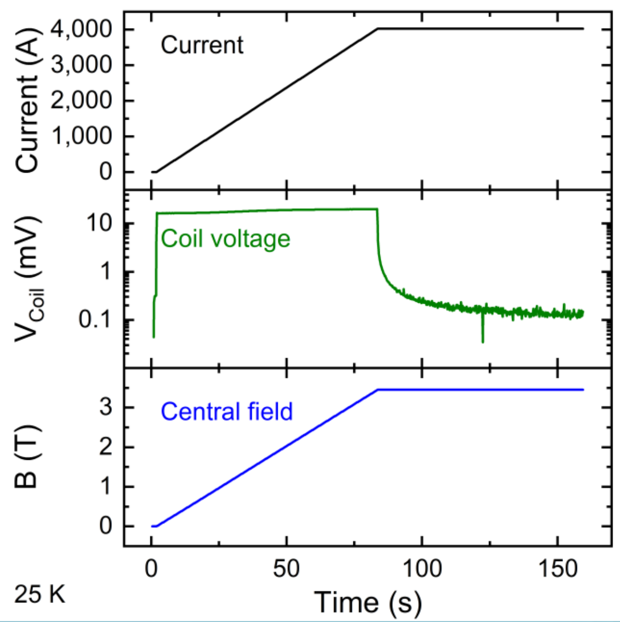
Results

- Peak magnetic field of **4.8 T at 25 K** (4,601 A)
- No effect of tape defects on CORC® wire performance
- **Current sharing in CORC® wires allows for tape defects**



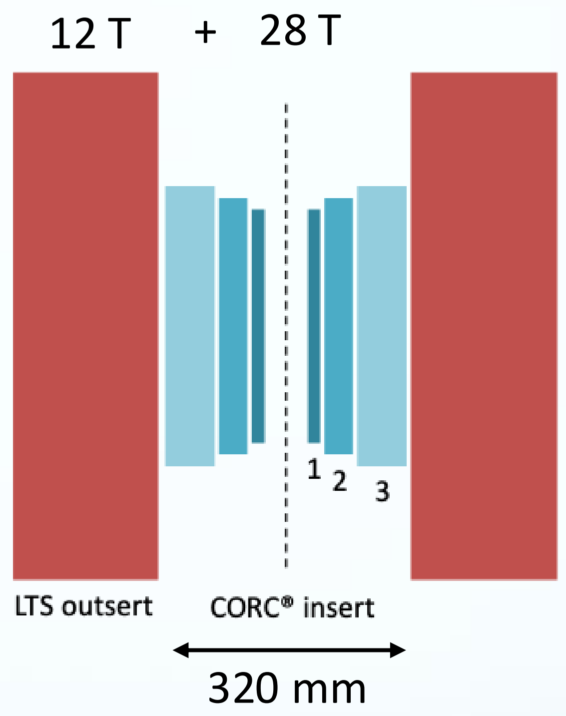






Conductor requirements for high-field solenoids

Development of a 40 T hybrid LTS/HTS solenoid



General layout of the 40 T LTS/HTS hybrid solenoid

- Use of an Oxford 12 T LTS outsert with 320 mm bore
- LTS outsert operates at 266 A (161 H, not low inductance)
- 50 mm inner diameter
- Several series-connected CORC® coils generating a total of 28 T
- CORC® insert operating at around 10 kA

Challenges in developing the CORC® insert

1. CORC® conductor electrical performance of the inner coil exposed to 40 T
2. Mechanical resilience of the CORC® conductor operating at high current and high field
3. Matching the operating current of the insert coils to allow series connection and use of a single power supply

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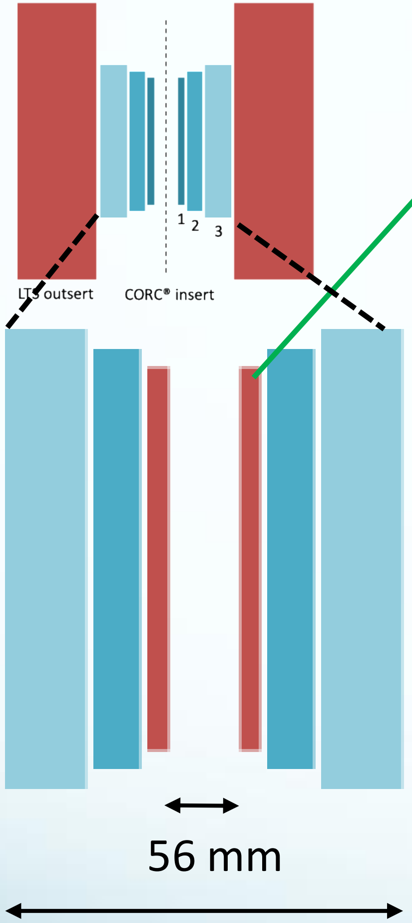
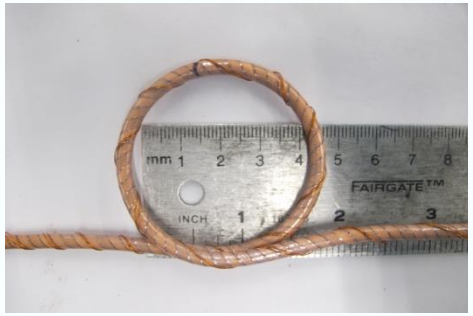
Inner coil wound from CORC® wires



Inner CORC® coil needs to be wound from CORC® wires

- Inner radius of around 28 mm
- CORC® wire is can be wound to 20 mm radius

20 mm radius



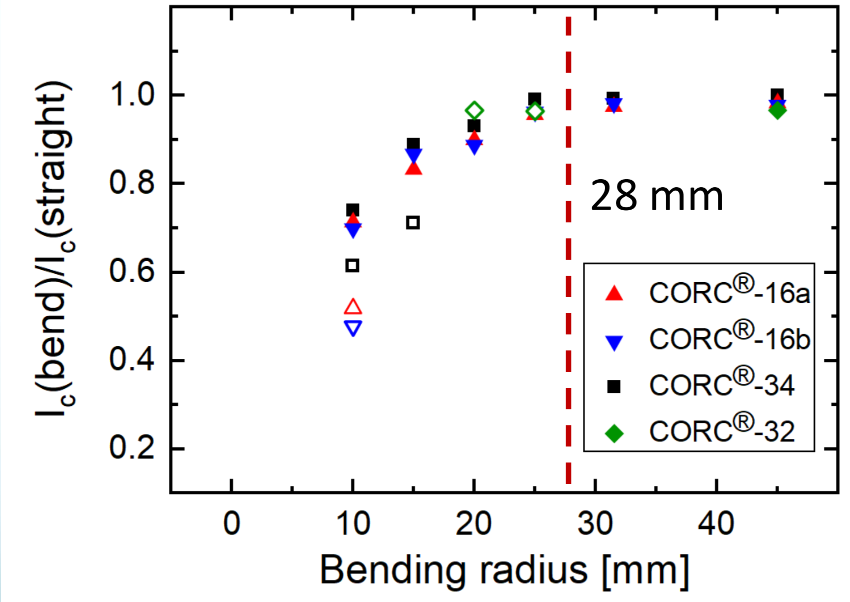
Inner coil needs to generate significant field

- Peak field of 40 T
- Requires a high winding current density
- Requires an operating current of >>1,000 A

CORC® wire size driven by core size

- 35 μm thick substrate => 3.0 mm core
- 30 μm thick substrate => 2.5 mm core
- 23 μm thick substrate => 2.0 mm core

CORC® wire bending performance



Availability of compatible tapes for use in CORC® wires

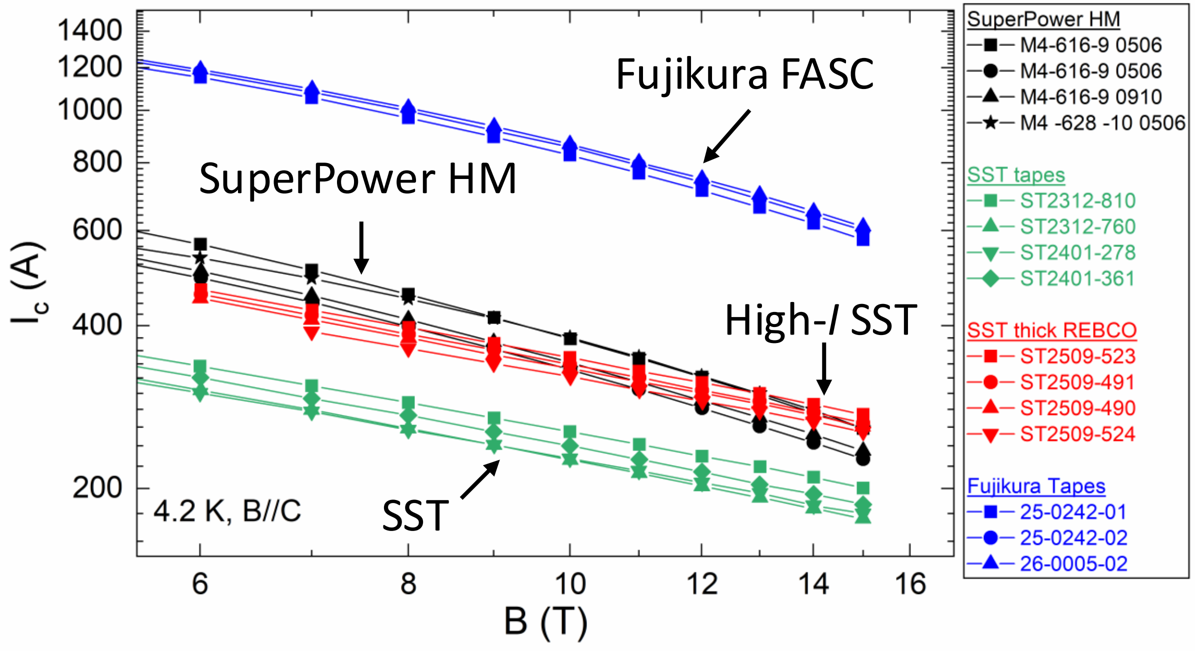
2020: SuperPower HM
- 30 μm thick substrate
- Until recently the highest in-field performance

2023: Shanghai Superconductor Technologies
- 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 to SuperPower HM

2026: Fujikura FASC
- 35 μm thick substrates
- Performance double that of SuperPower HM

2 mm wide tape performance at 4.2 K



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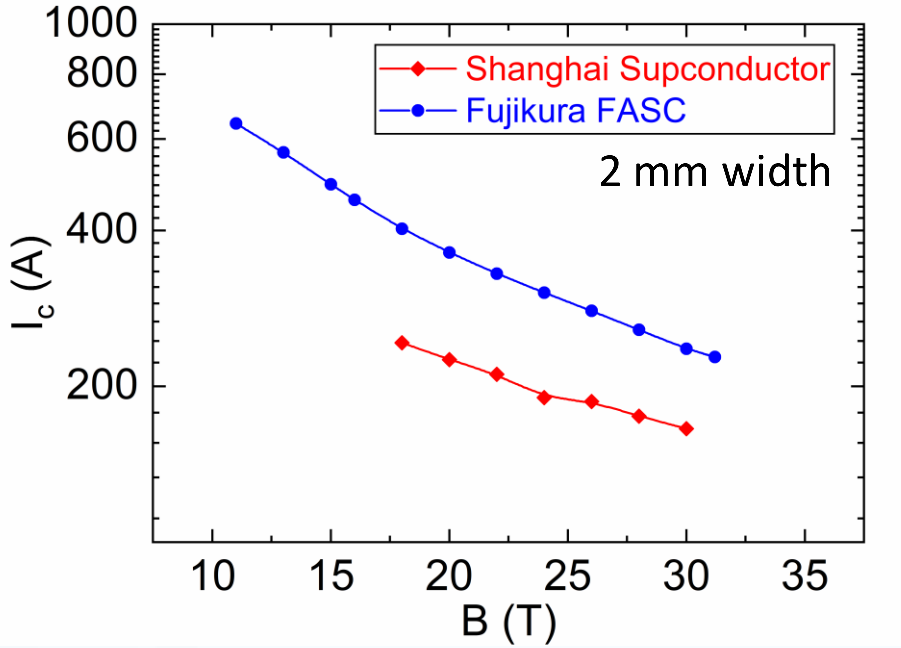
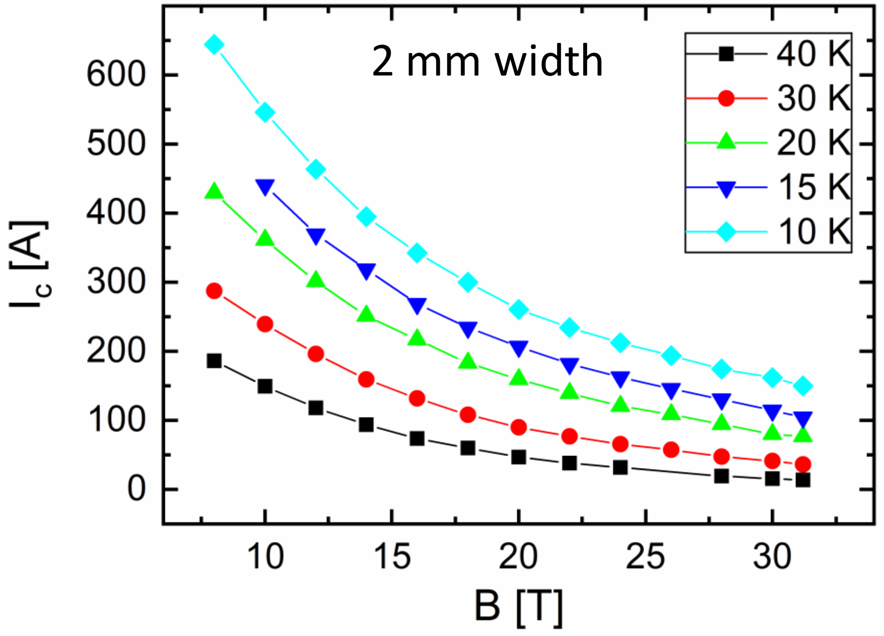
Characterization of REBCO tapes to 31.2 T at NHMFL

High-*I* SST and Fujikura at 4.2 K



Fujikura FASC



Extrapolated I_c at 4.2 K, 40 T (2 mm width)

- High-current SST: 135 A
- Fujikura FASC: 180 A

Theoretical CORC® wire I_c at 4.2 K, 40 T

- 30-Tape SST: 4,000 A
- 30-Tape Fujikura FASC: 5,400 A

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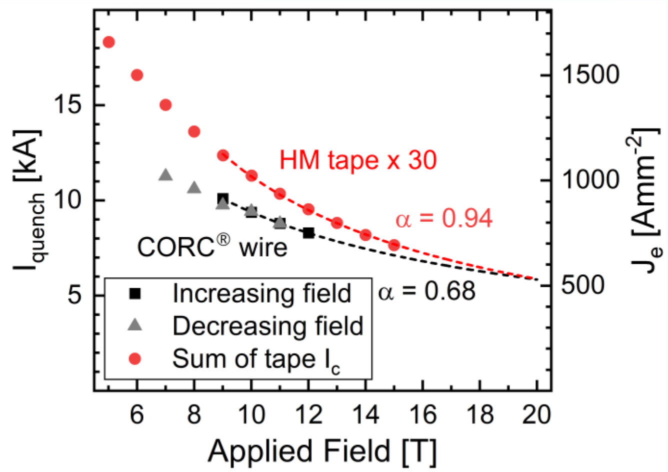
CORC® wire performance beyond the current status

30-tape CORC® wire (SuperPower HM)



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

Current CORC® wire with 2.55 mm core (SuperPower HM tapes)

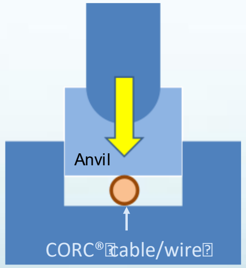
- Successfully applied in a 5.99 T canted-cosine-theta (CCT) magnet
- CORC® performance 87 % of tape in hairpin test
- **Tested at 99.5 kN/m transverse load**
- Expected I_c at 20 T of 5,900 A (118 kN/m)
- **Expected I_c at 40 T of 3,600 A (144 kN/m)**

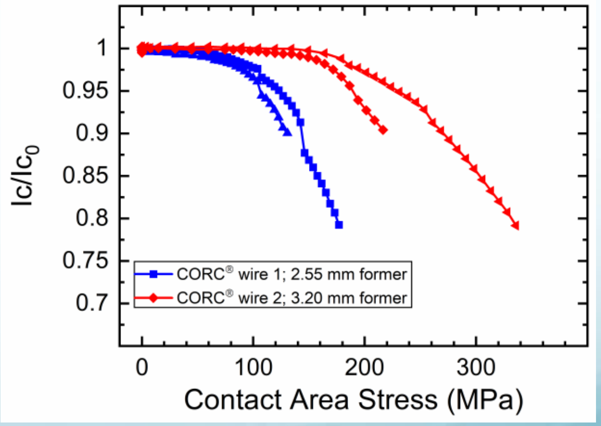
Unknown mechanical resilience of CORC® wires at very high fields

- Can CORC® wires survive the high Loren force?
- Can smaller cores be used to further increase J_e?
- Can we take full advantage of the performance of Fujikura FASC tapes?

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





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

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CORC® conductors experiencing high Lorenz force

Difference between anvil test and actual magnet operation

- Anvil test compresses both sides of the winding pack onto the core
- Actual Lorenz force driven load also pulls the tapes away from the core

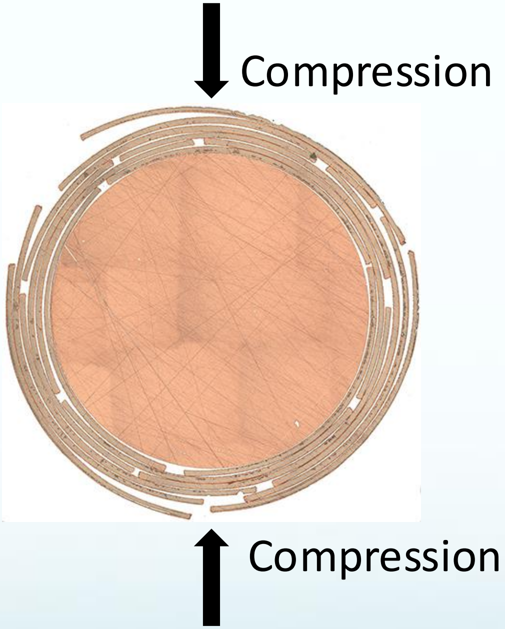
Possible consequences

- Compressive load on tapes is lower under Lorenz force
- Deformation of tapes being pulled from the core may cause additional damage
- The extend of the damage depends on what the tapes encounter when pulled away

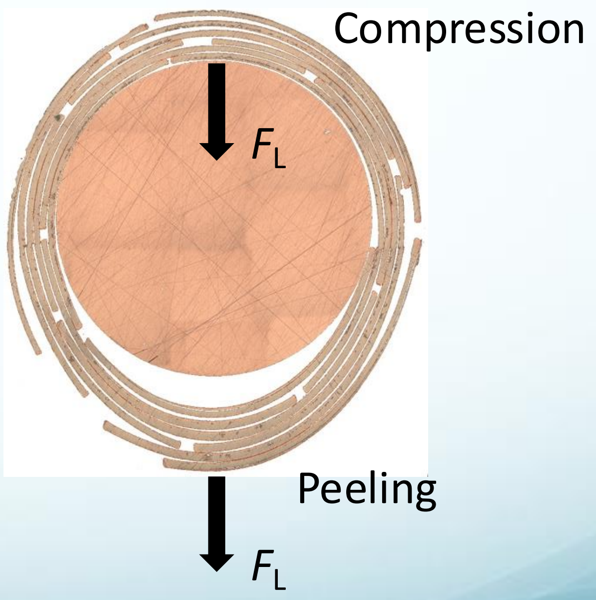
Possible solution to prevent tape deformation

- Encapsulate the magnet windings
- Provide the CORC® wire with an external "sleeve"
- Bond the tapes within the CORC® wire together
- Increase the number of tapes, reducing the Lorenz force experienced by each tape

Anvil test



Lorenz force

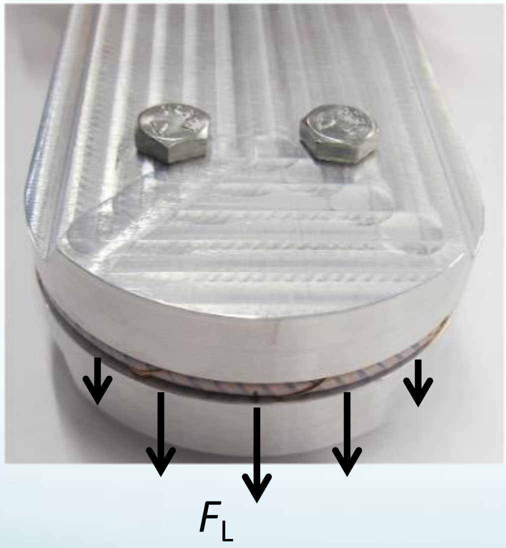


CORC® wire performance testing

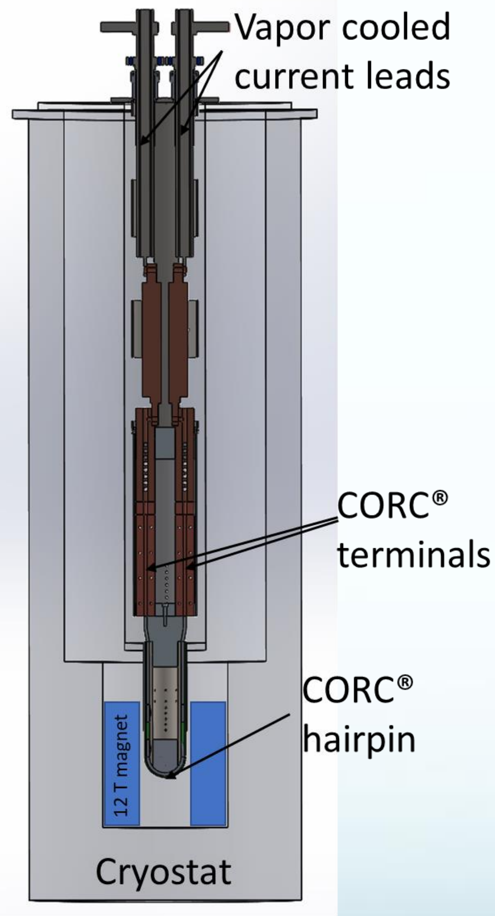
CORC® wire testing at 4.2 K

- CORC® wire mounted in 20 – 31.5 mm radius hairpin
- Secured with Stycast epoxy on holder
- Inserted within a 12 T 80 mm bore solenoid at ACT
- Current capacity 15 kA

CORC® wire mounted on sample holder



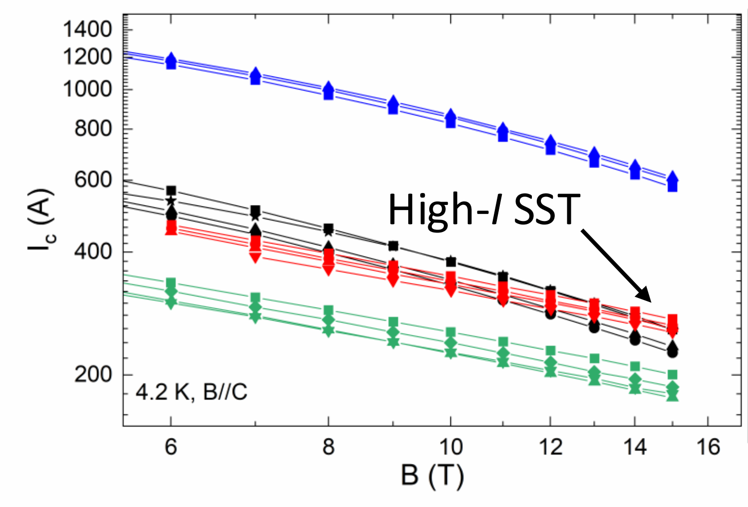
Lorenz force perpendicular to hairpin plane



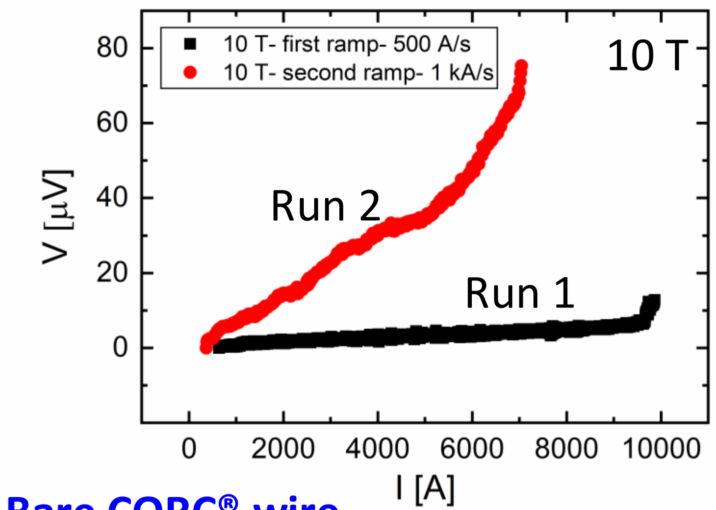
Effect of smaller cores on CORC® wire performance: High-*I* SST tapes

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



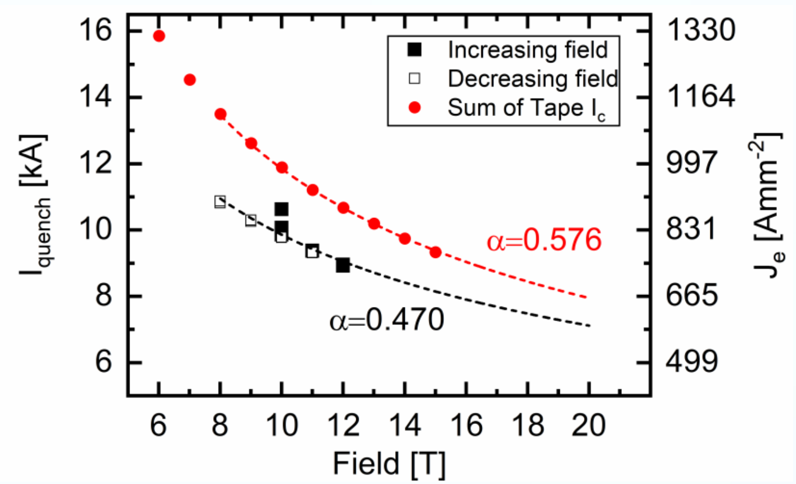
No reinforcement



Bare CORC® wire

- 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**
- **Expected I_c at 40 T of 4,000 A (160 kN/m)**

Transverse load limit based on CORC® core size can be extended by additional CORC® wire reinforcement, but will it be enough at 40 T?

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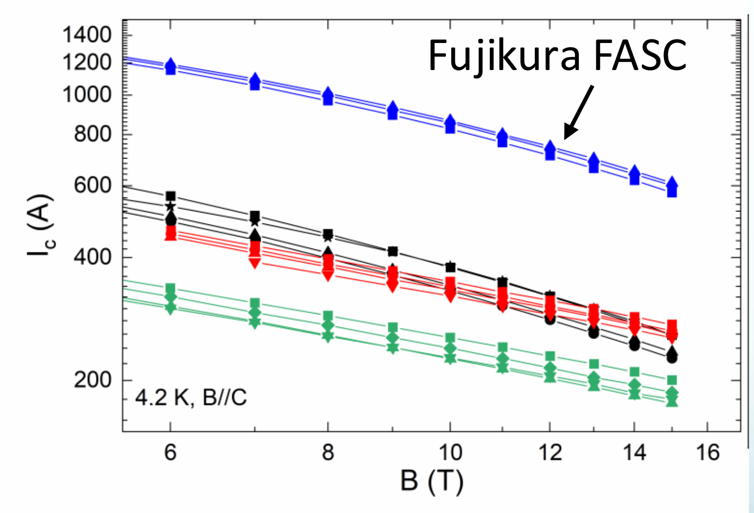
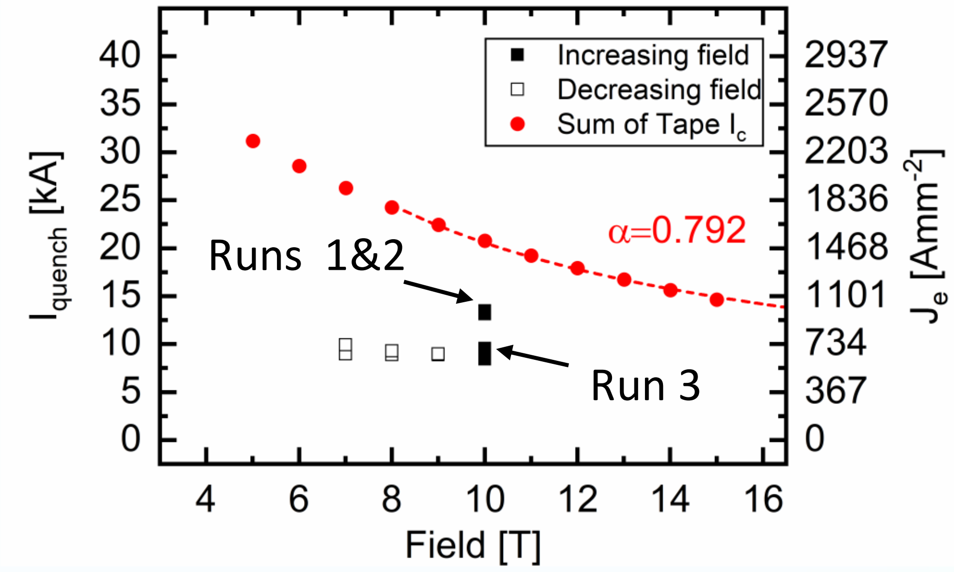
In-field performance of CORC® wires: Fujikura FASC

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 40 T of 4.3 kA (172 kN/m)





CORC® wire 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

Additional reinforcement (larger core, or solder coated tapes) may increase the transverse load limit towards 172 kN/m corresponding to the electrical CORC® wire limit at 40 T

Difference in transverse load between dipoles and solenoids

Solenoids

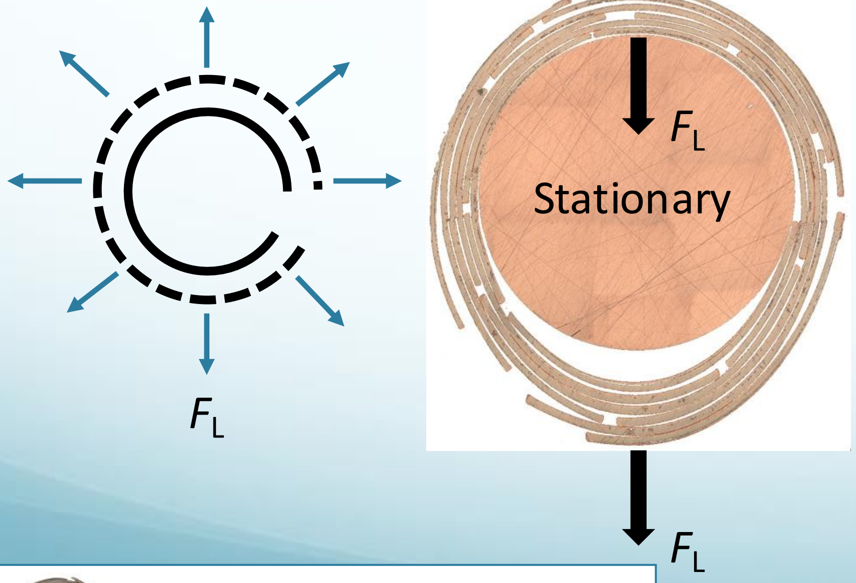
- Lorenz force results in hoop stress
- Hoop stress exerts axial stress on winding
- Force is reacted by the CORC® core (until it yields)
- CORC® core mechanically isolates both halves of the tape windings

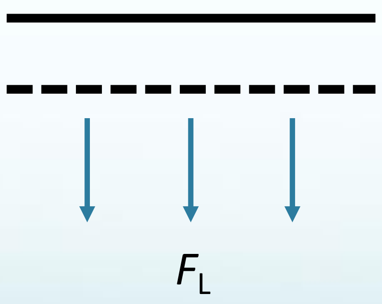
Dipoles

- Lorenz force represents a straight conductor case
- CORC® core isn't constrained in straight section of dipoles
- The CORC® core will compress the tapes that are being pulled away from the core

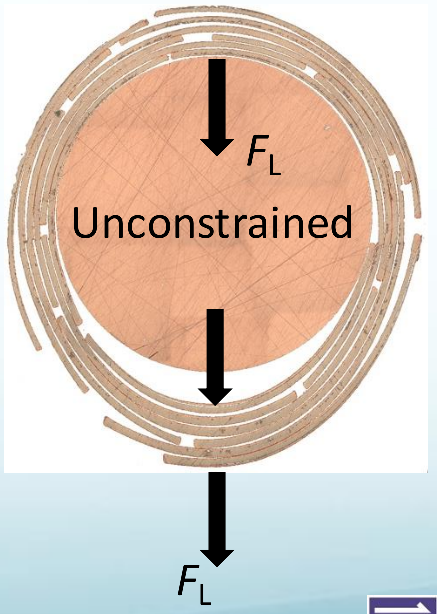
CORC® wires in dipoles and our hairpin test likely experience higher level of tape deformation than solenoids

Solenoid case

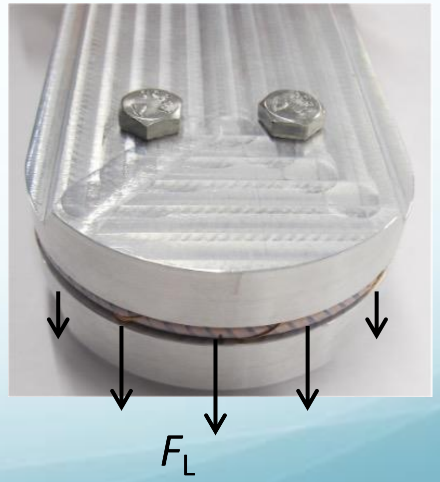




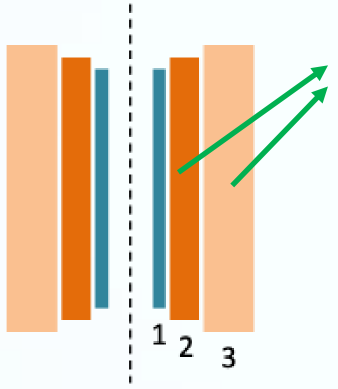
Dipole case



Our hairpin test represents the dipole case



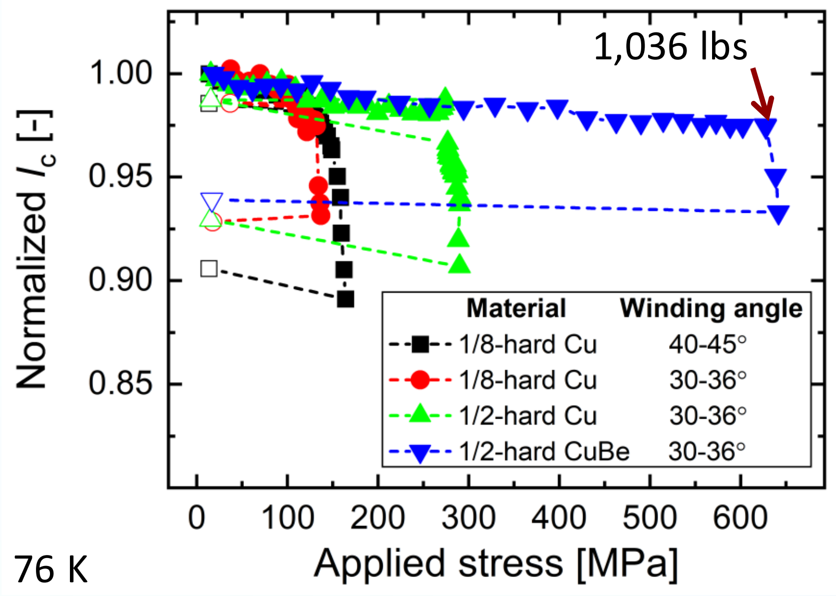
CORC® cables in coils 2 and 3



CORC® cables for coils 2&3

- Larger coil radius (>60 mm) makes CORC® cables the better choice over thinner CORC® wires
- Larger radius also results in high JBr hoop stress
- Larger core in CORC® cables offers more support against hoop stress

12-tape CORC® wire with 2.55 mm core



Resilience of CORC® conductors against axial stress/strain

- The helical wind of REBCO tapes results in a set of springs, largely isolating the tapes from axial stress
- Irreversible axial strain limit depends on tape winding angle and can be engineered to exceed 7%
- Tensile stress limit is mainly determined by the CORC® conductor former

Irreversible tensile stress limit of CORC® wires can be engineered to exceed 600 MPa at 77 K

Critical stress limit under tension at 76 K

- Soft annealed copper former: 134 MPa
- Half hard copper former: 280 MPa
- **CuBe former: 613 MPa**

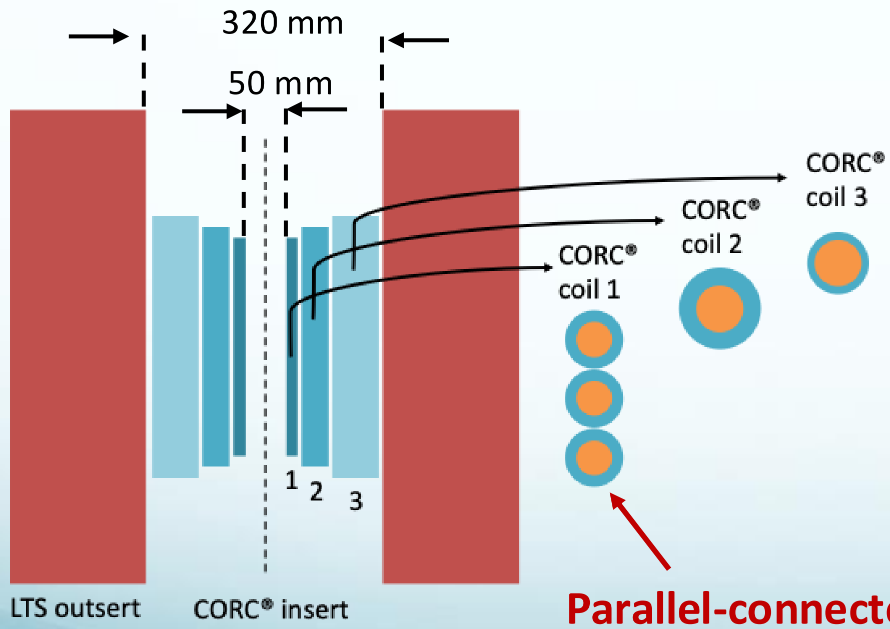
van der Laan *et al.* "High -temperature superconducting CORC® wires with record-breaking axial tensile strain tolerance present a breakthrough for high-field magnets", *Supercond. Sci. Technol.* **34**, 10LT01, (2021)

Preliminary high-field solenoid designs

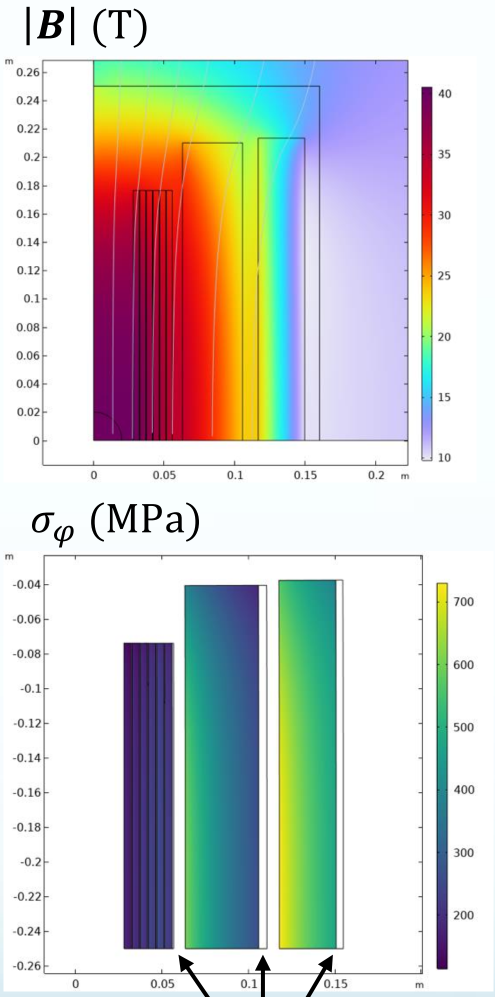
Series-connected 40 T hybrid LTS/HTS solenoid

Solenoid overview

- 50 mm bore
- 12 T LTS outsert (Oxford Instruments)
- Three CORC® coils connected in series
- Single power supply for CORC® insert
- Stainless steel overbanding over each coil
- Operating at 10.1 kA at 67 - 79 % of I_c



Parallel-connected CORC® wires



Stainless steel over banding

	unit	Coil 1	Coil 2	Coil 3
Cable type		3x wire	Cable	Cable
Tapes		3x 24	36	24
Tape width	mm	2	4	4
CORC® OD	mm	4.2	7	5.4
Turns per layer		84	60	79
Number of layers		6	6	6
Half height	mm	176.4	210	212.5
Inner radius	mm	28.0	62.4	115.4
Outer radius (sc)	mm	53.2	104.4	147.8
I_{opp}	kA		10.1	
Self-inductance	mH	0.39	6.1	26.0
Background field	T		12	
Field contribution	T	5.90	10.1	12.0
I_{op}/I_{c0}		0.79	0.67	0.67
$\sigma_{r,max}$	MPa	0.2	12.1	0
σ_{hoop}	MPa	266	610	591
$\sigma_{overband}$	MPa	673	803	1140
Peak *IxB*	kN/m	135	344	242

Operating at peak transverse limit of unsupported CORC® wire

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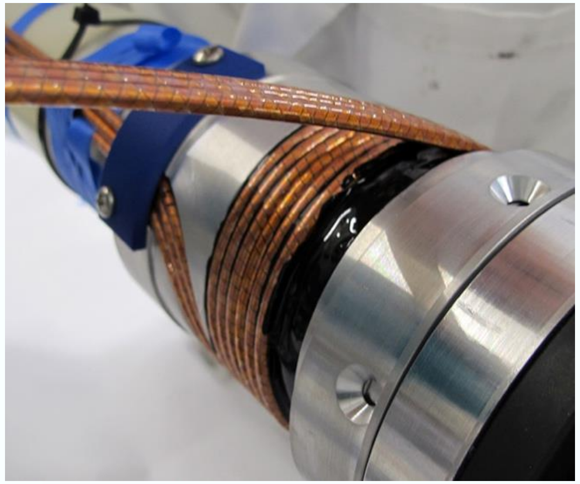
Demonstration of series-connected CORC® solenoids

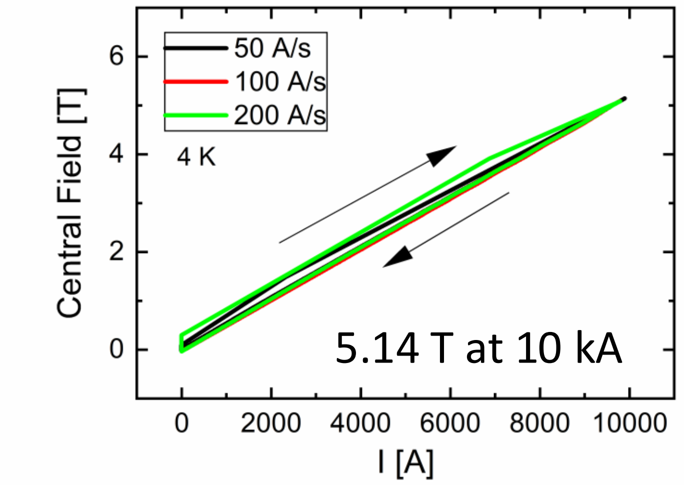
Series-connection of inner and middle coil

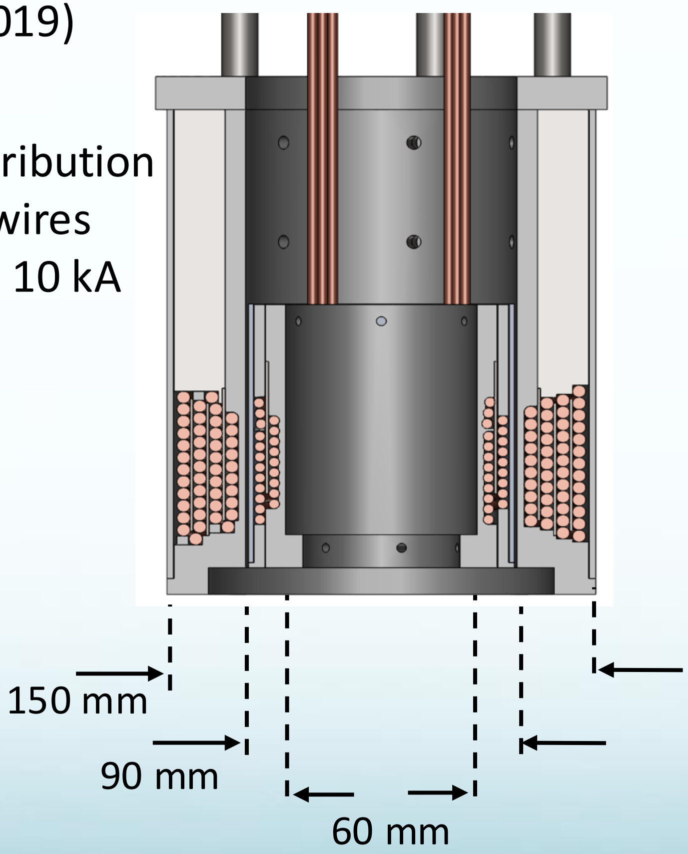
- Inner coil wound from three parallel CORC® wires
  3 turns per layer, 2 layers
- Outer coil based on a single CORC® cable
  46 turns, 4 layers (magnet from 2019)

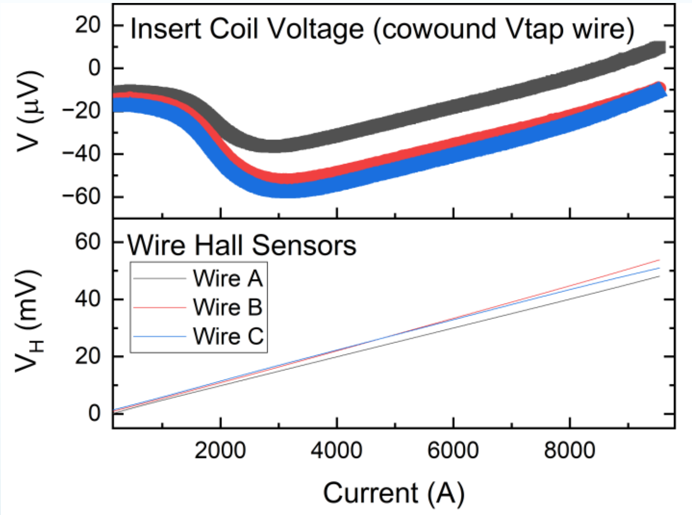


Results

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







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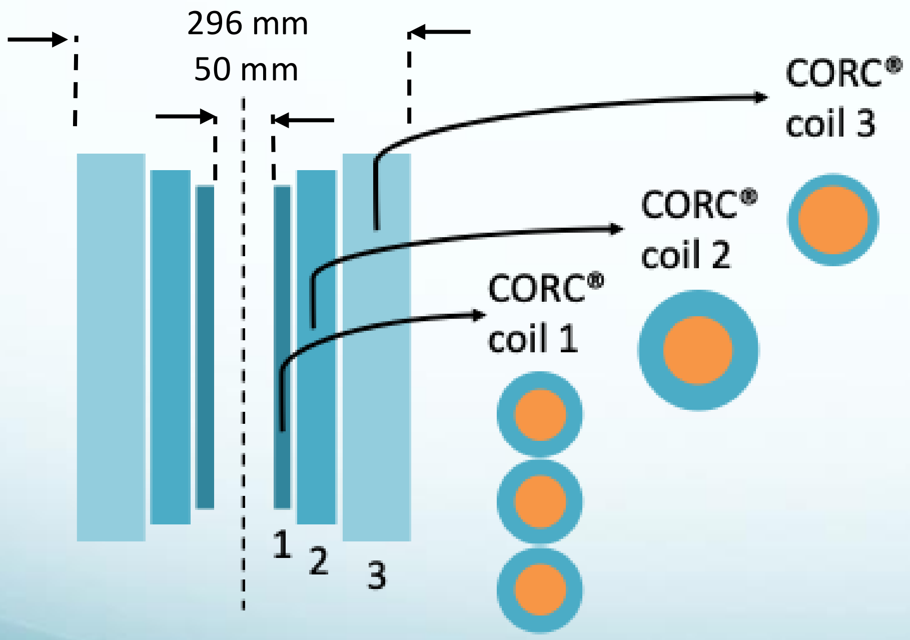
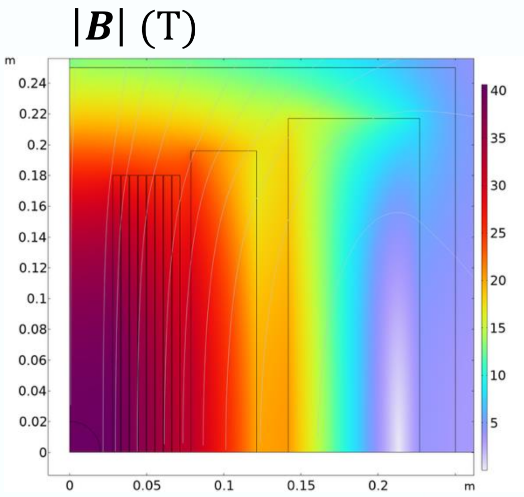
BERKELEY LAB

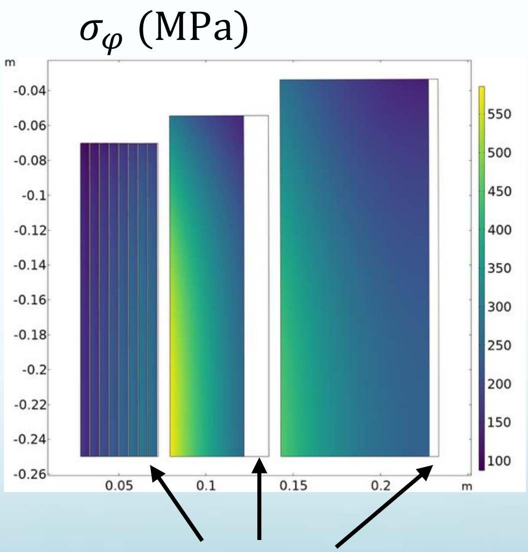
Series-connected 40 T CORC® stand-alone solenoid

Solenoid overview

- 50 mm bore
- Three CORC® coils connected in series
- Single power supply
- Stainless steel overbanding over each coil
- Operating at 12.37 kA at 73 - 77 % of I_c







Stainless steel over banding

	unit	Coil 1	Coil 2	Coil 3
Cable type		3x wire	Cable	Cable
Tapes		3x 30	36	24
Tape width	mm	2	4	4
CORC® OD	mm	5	7	7
Turns per layer		72	56	62
Number of layers		8	6	12
Half height	mm	180	196	217
Inner radius	mm	28.0	78.6	141.7
Outer radius (sc)	mm	72.2	135.3	232.2
I_{opp}	kA		12.37	
Self-inductance	mH	0.67	7.85	101.3
Field contribution	T	7.95	11.8	20.2
I_{op}/I_{c0}		0.77	0.77	0.73
$\sigma_{r,max}$	MPa	0.2	0	0
σ_{hoop}	MPa	296	586	456
$\sigma_{overband}$	MPa	763	848	736
Peak *IxB*	kN/m	165	396	250

A large-bore (280 mm) 20 T CORC® coil!

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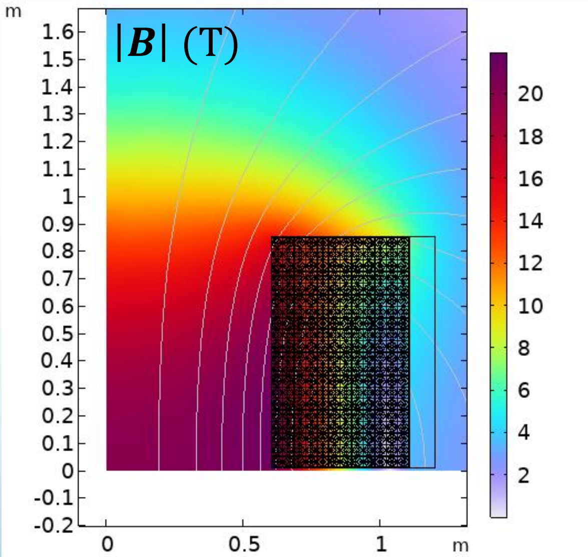
20 T Large-bore CORC® solenoids

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

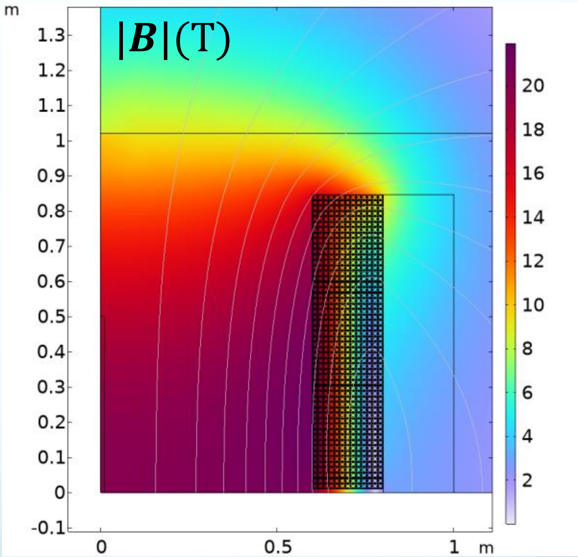
6-around-1 CORC®-CICC

	unit	Value
number of layers (r)		10
turns per layer (z)		20
inner radius	m	0.60
outer radius (sc)	m	1.02
height	m	0.84
self inductance	mH	67.8
I_{opp}	kA	93.9
max I_{op}/I_c @4.2 K		0.57
$\sigma_{hoop,cable}$	MPa	254
$\sigma_{r,cable}$	MPa	21.3
$\sigma_{mises,jacket}$	MPa	715



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	mH	556
I_{opp}	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



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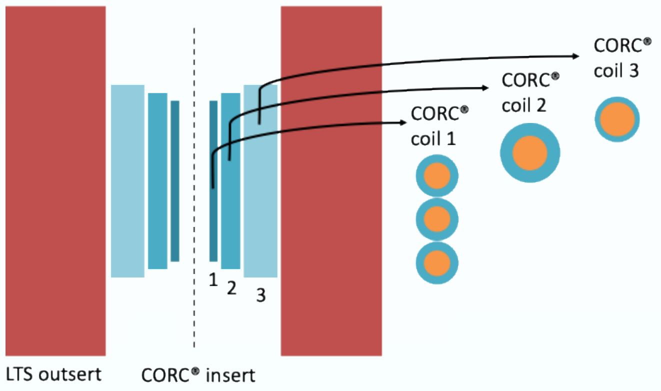
R&D to make 40 T CORC® solenoids a reality



	unit	Coil 1	Coil 2	Coil 3
Cable type		3x wire	Cable	Cable
CORC® core	mm	3.05	5.4	4.0
Inner radius	mm	28.0	62.4	115.4
I_{opp}	kA		10.1	
Peak field	T	40	34.1	24
σ_{hoop}	MPa	266	610	591
Peak *IxB*	kN/m	135	344	242

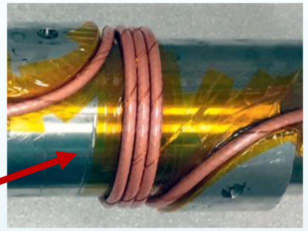
CORC® conductor testing at peak hoop stress and transverse load driven by Lorenz force is vital

Coil 1
- Hoop stress 266 MPa
- Transverse load 135 kN/m

Coil 2
- Hoop stress 610 MPa
- Transverse load 344 kN/m

Coil 3
- Hoop stress 591 MPa
- Transverse load 242 kN/m

12 T solenoid at ACT
- Test on ITER barrel type holder
- Transverse load of 180 kN/m possible
- Hoop stress of 350 MPa possible



Straight conductor testing within 12 T split pair at NHMFL
- Superconducting transformer 45 kA

2028: Large-bore resistive magnet at NHMFL
- Peak field of 22.5 T, warm bore 195 mm
- Requires at least 16 kA sample current

Thank you!