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Development of high temperature superconducting CORC® magnets, CICC, and low loss joints for fusion applications

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International Symposium on Superconductivity, Wellington, NZ, November 28th, 2023
WB-3-4_Jeremy Weiss

CORC® cables, wires and CICC

CORC® wires (2.5 – 4.5 mm diameter)

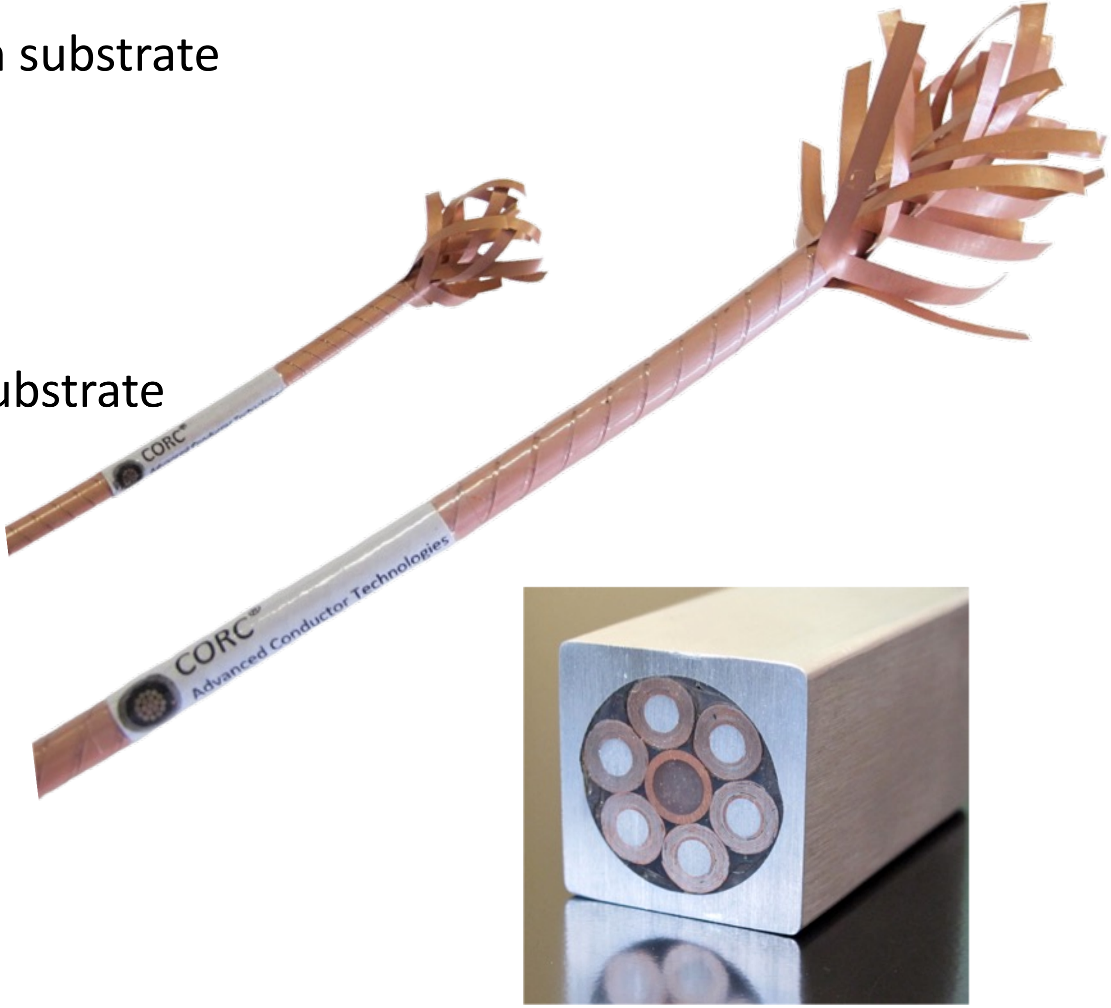
- Wound from 2 – 3 mm wide tapes with 25 and 30 μm substrate
- Typically, no more than about 30 tapes
- Flexible with bending down to > 40 mm diameter

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)

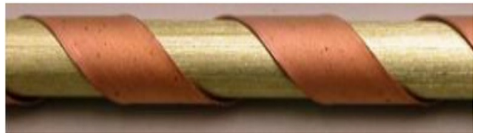
- Performance as high as 100,000 A (4.2 K, 20 T)
- Combination of multiple CORC® cables or wires
- Bending diameter about 0.5 – 1 meter

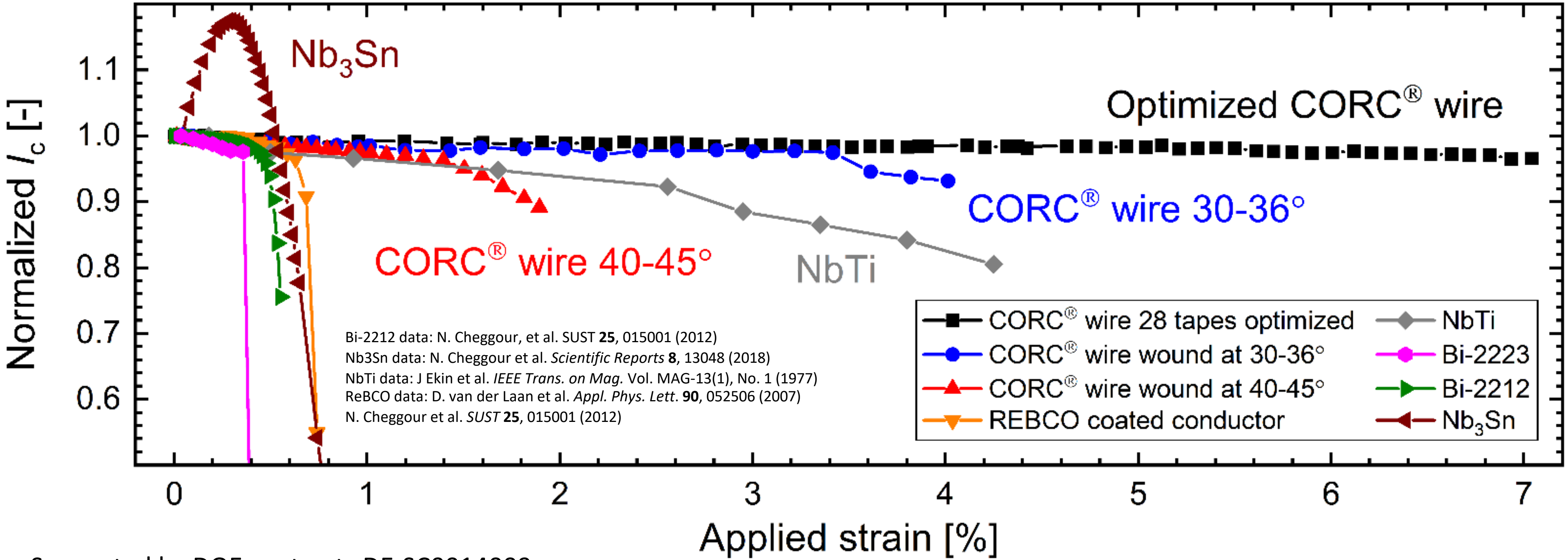


High axial strain tolerance of CORC® increases magnet design options

CORC® cables and wires can withstand very high axial strains

- Twice as high as low-temperature superconductor NbTi
- 10 times as high as REBCO coated conductors
- 20 times as high as Nb_3Sn, Bi-2212 and Bi-2223





Supported by DOE contracts DE-SC0014009, DE-SC0018125 and DE-SC0020710

van der Laan *et al. Supercond. Sci. Technol.* **34**, 10LT01, (2021)
Anvar *et* al. *Supercond. Sci. Technol.* **35**, 055002, (2022)
Wang *et* al. *Supercond. Sci. Technol.* **35**, 105012, (2022)

CORC® cable development for Ohmic Heating coils

Ohmic Heating (OH) and Central Solenoid (CS) coils in compact fusion reactors

PRINCETON PLASMA PHYSICS LABORATORY

Very narrow OH coils (NSTX-U-HTS at PPPL)

- Inner radius of 0.1 – 0.15 meters
- Peak magnetic field of > 15 T

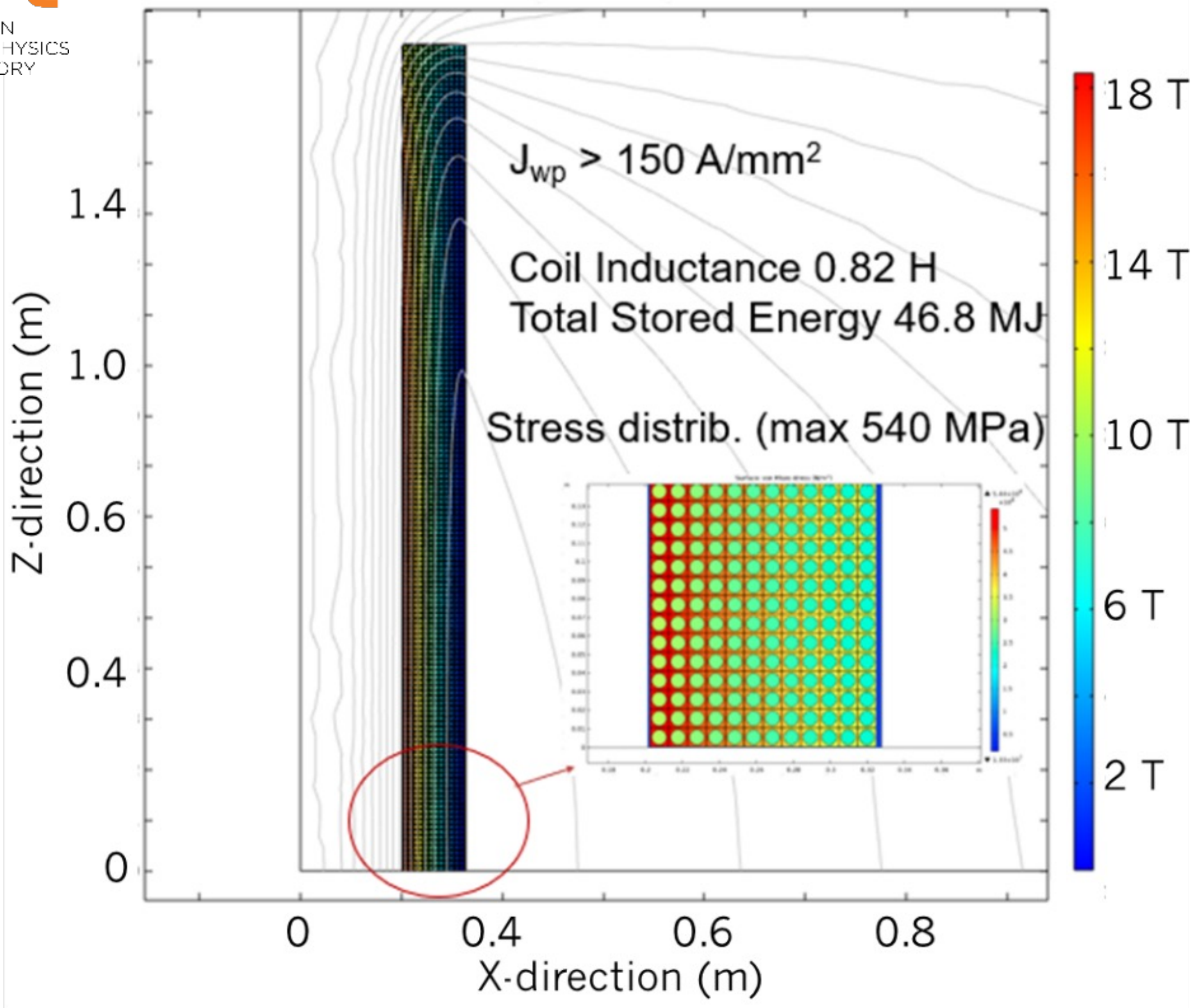
Fairly narrow OH/CS coils (SHPD)

- Inner radius of 0.2 – 0.3 meters
- Peak magnetic field of > 18 T

Overall OH coil conductor requirements

- **Operating current 10 – 20 kA**
- **Winding current density (J_w) 100 – 150 A/mm² (20 T)**
- **Conductor current density (J_e) 200 – 300 A/mm² (20 T)**
- JBr hoop stress over 500 MPa to > 1 Gpa !!

SHPD with CORC® Ohmic Heating Coil



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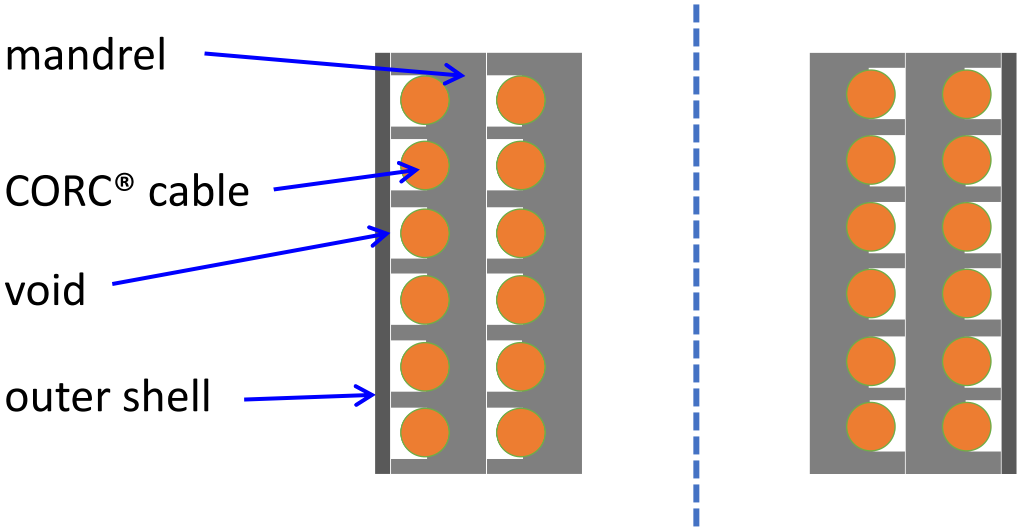
- Yuhu Zhai, et. al, IEEE Trans. Appl. Supercond. **32**, 4203005 (2022)
- Yuhu Zhai, et al, Fusion Engineering and Design **168**, 112611 (2021)
- Neil Mitchell, et al., Supercond. Sci. Technol. **34**, 103001 (2021)

Supporting the CORC® cable in OH coils against 0.5 – 1 GPa hoop stress

Options for winding Ohmic Heating coils

- Strengthen the CORC® core → **Sacrifices electrical stability and effects CORC® strain tolerance**
- Jacket the CORC® cable → **Need to scale the technology and retain conductor flexibility**
- Wind into High strength mandrel

Cable initially unsupported (also the case with a jacketed cable)



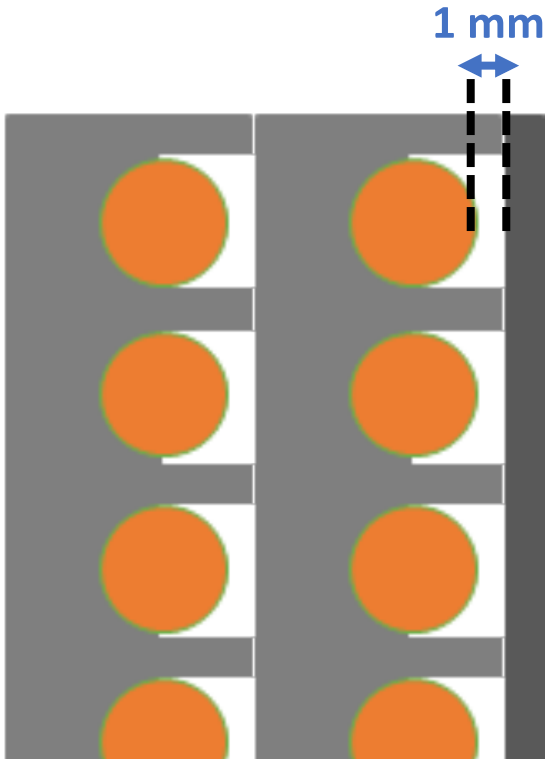
Questions to be answered regarding OH coils

- **Will the cable degrade at high cyclic operating loads?**
  - Axial tensile loads before the cable hits the wall
  - Transverse compressive loads once hitting the wall
- **Can the current be ramped at rates of about 10 kA/s needed to provide the flux swings?**
  - Does the current distribution remain homogeneous?
  - Will ramping losses overwhelm the cooling?

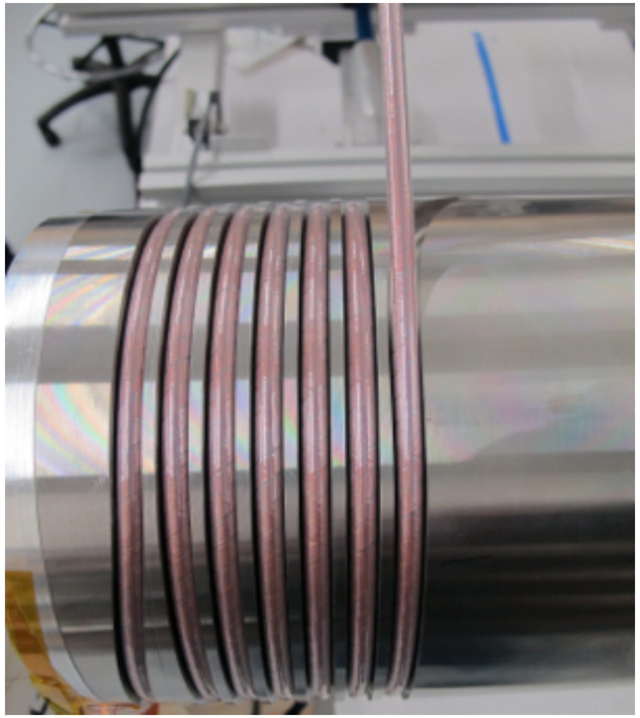
Development of prototype Ohmic Heating coil

First Ohmic Heating coil prototype based on CORC®

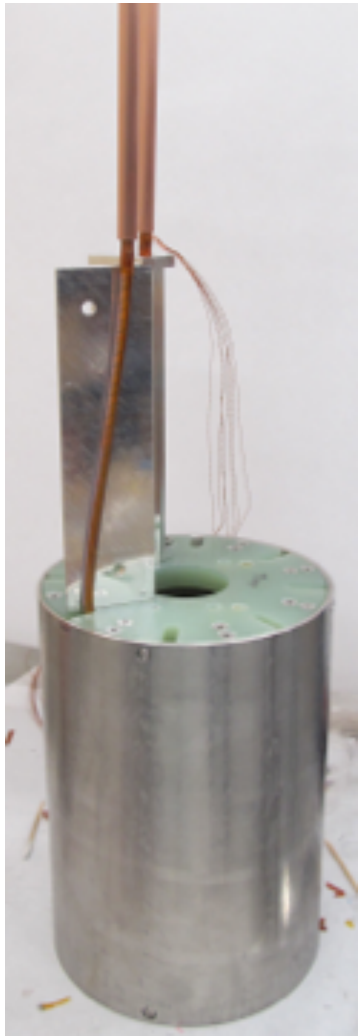
- Medium cable performance (I_c (16 T) 3.5 kA, J_e(16 T) = 150 A/mm^2
- Coil: 2-layers, 6 turns per layer, ID 119 mm, OD 159 mm, 60 mm height
- 6 mm thick cable in 7 mm groove
- Clearance of 1 mm results in about 1 % conductor strain



Coil winding at CU Boulder



Testing at PPPL and ASC-NHMFL

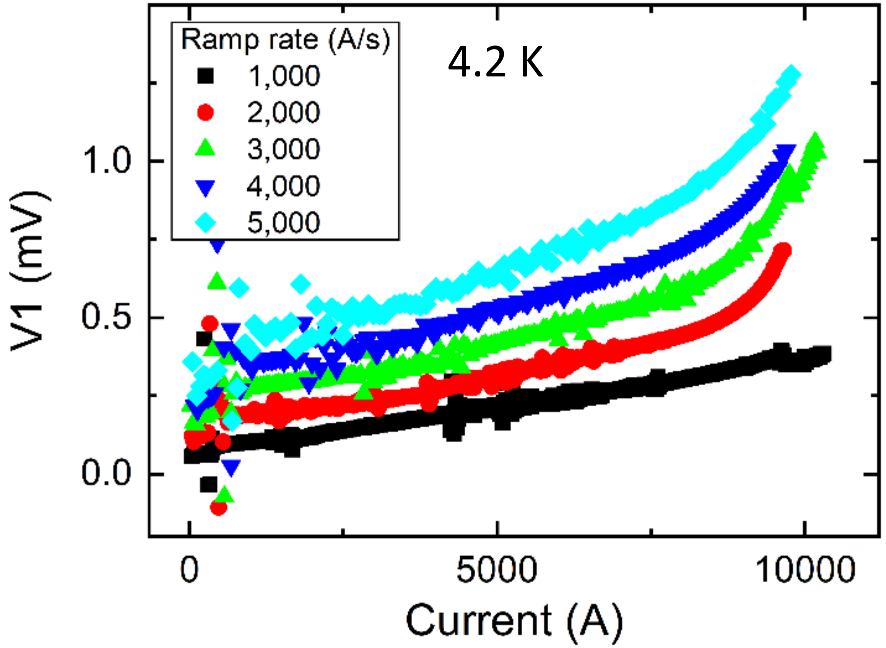


PRINCETON PLASMA PHYSICS LABORATORY

Testing of Ohmic Heating coil

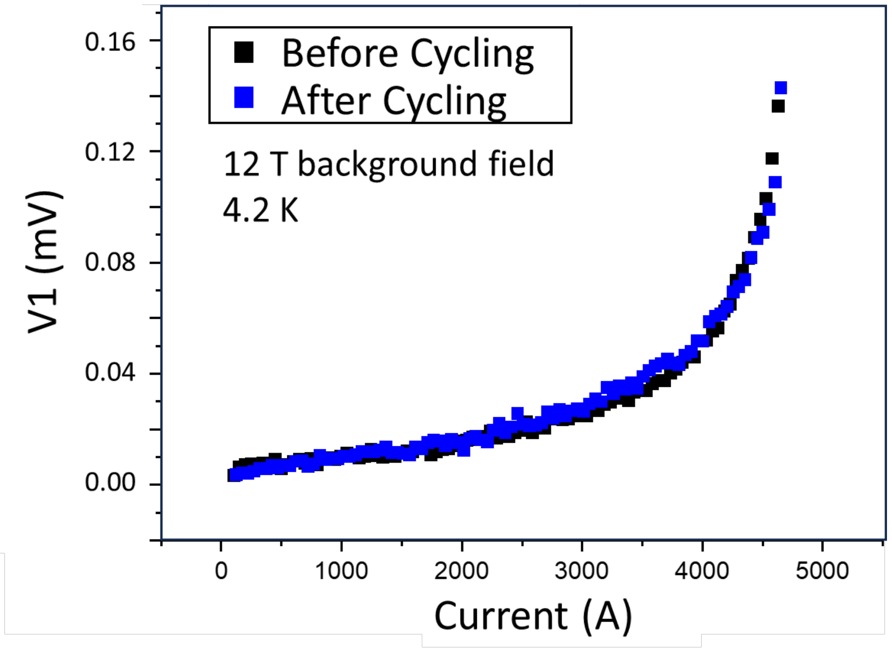
Testing done at ACT to high ramp-rates

- Current ramp rates up to 5 kA/s to 10 kA at 4 K
- Current distribution remained mostly homogeneous



Testing done at ASC-NHMFL: 14 T 160 mm outsert

- Repeated current ramping at 12 T into transition
- J_e 200 A/mm^2, JBr hoop stress 185 MPa
- No degradation after 68 stress cycles



Supported by DOE contracts DE-SC0014009, DE-SC0013723 and DE-SC0018125

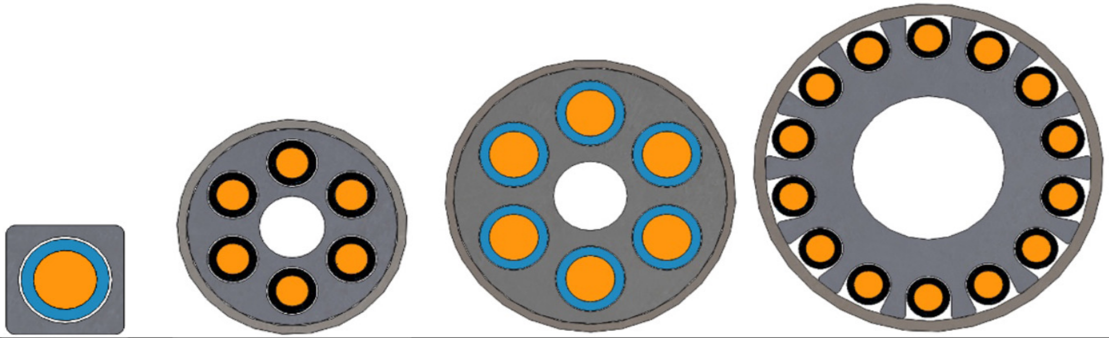
Next steps

- Prepare set of CORC® OH coils with higher current and current density to allow higher JBr stresses of 200 to 500 MPa
- Test higher elongation of cable: (1 – 2 % axial strain)

CORC®-CICC and joints for demountable Toroidal Field coils

CORC® CICC development

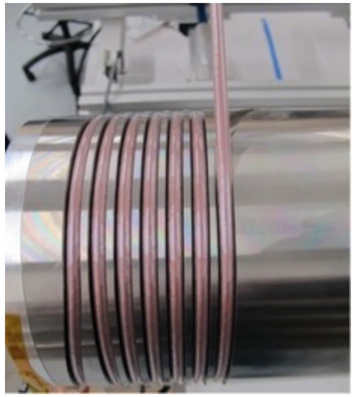
Layouts being developed for magnet systems: Central solenoid, Toroidal, etc



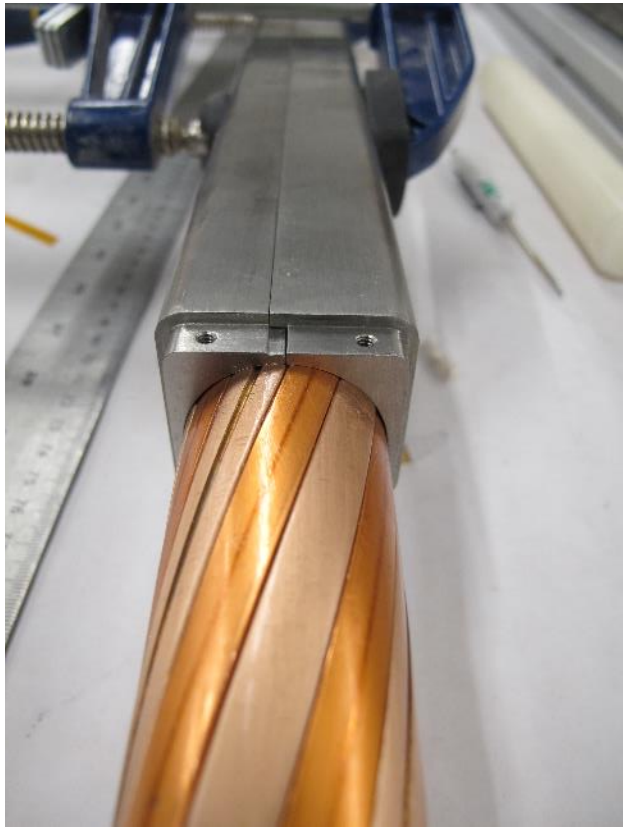
CORC®-CICC size	**[mm]**	10 x 10	22.23	31.75	38.1
CORC® conductors	**[-]**	1 cable	6 wires	6 cables	14 wires
Tapes per conductor	**[-]**	42	30	42	30
Tape width	**[m]**	4	3	4	3
I_c (4.2 K, 20 T)	**[kA]**	13.4	43.0	80.3	100.4
J_e (4.2 K, 20 T)	**[A/mm²]**	133.8	110.8	101.4	88.0
I_c (20 K, 20 T)	**[A]**	6.7	21.5	40.1	50.2
J_e (20 K, 20 T)	**[A/mm²]**	66.9	55.4	50.7	44.0

HTS Cable Conductor for Compact Fusion Tokamak Solenoids, Zhai et al.
IEEE doi: 10.1109/TASC.2022.3167343

- **Tests of straight samples in background field at SULTAN test facility**
- **subscale CS coil tests**



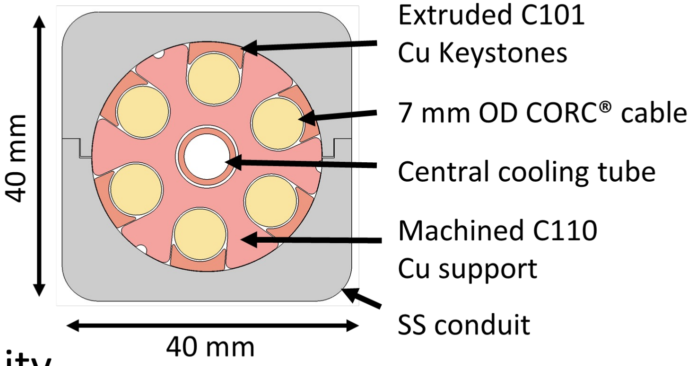
CORC® CICC tested in 10.9 T background field



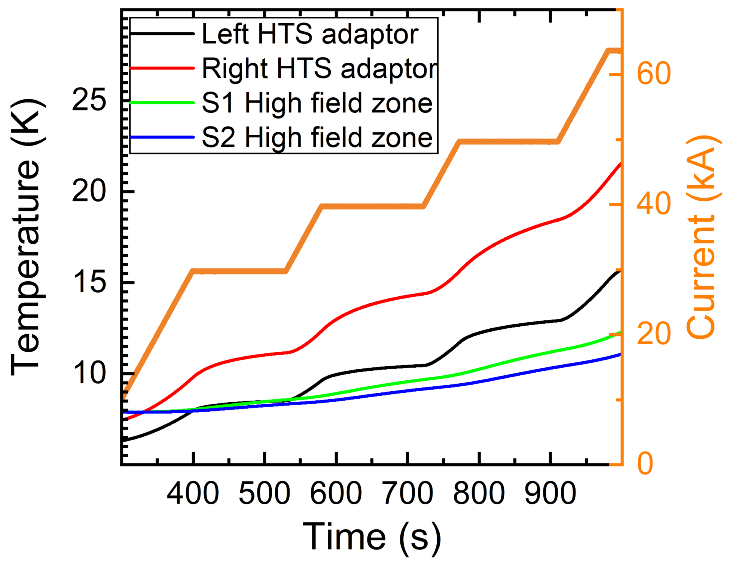
Preparation of two CORC® CICC (S1 and S2) with distributed conductor support

- **S1**: Six 36-tape CORC® cables (216 4 mm wide AP tapes)
- **S2**: Sample designed with the UKAEA
- Designed for 80 kA at 10 T and 4.2 K
- First week of testing November 2023 at SULTAN test facility

S1 Cross-section



Testing limited by high resistance in one side of HTS adaptors

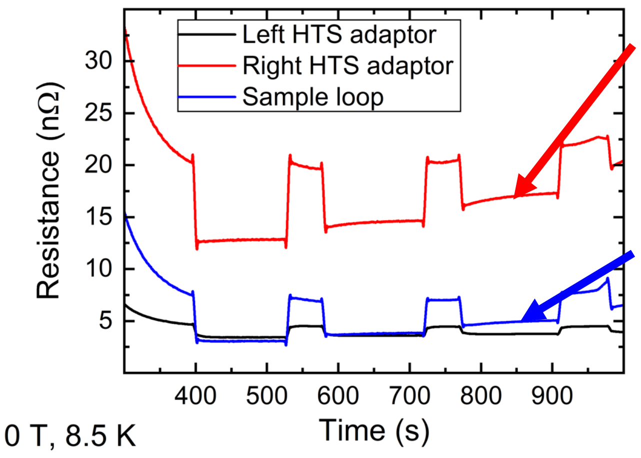


Testing at 0 T applied field

- Temperature rise in HTS adaptors
- High resistance in right side of HTS adaptor (connected to S2)

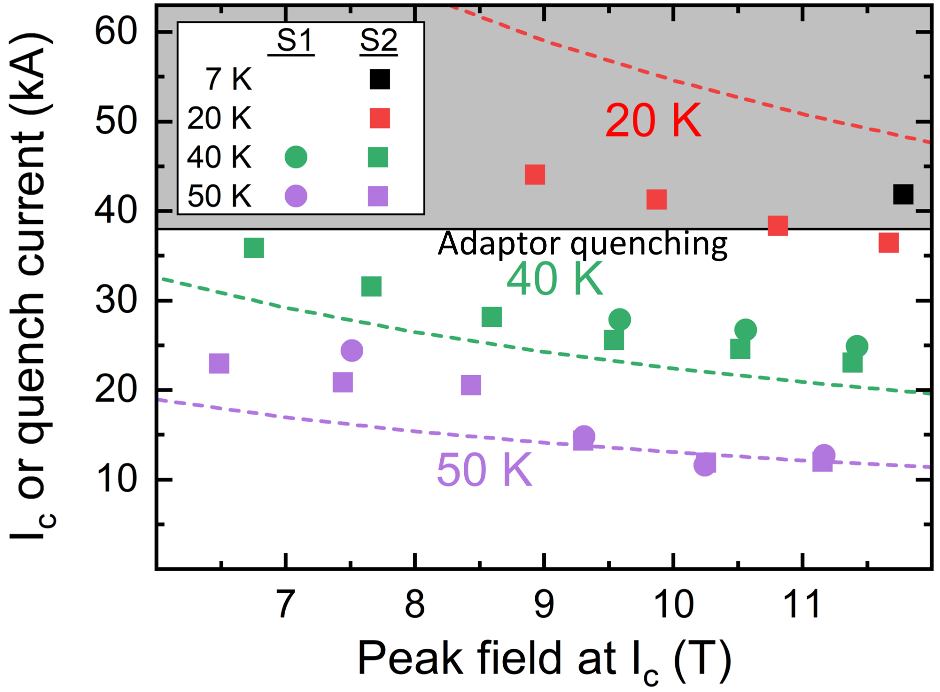
Testing in background field

- HTS adaptors quenched along with CORC® S2 at I > 38 kA
  - Limited I_c testing to elevated temperatures
  - Limited IxB loading to ~ 440 kN/m (700 kN/m cycling planned)



Part of HTS adaptor
R > 17 nΩ at 50 kA

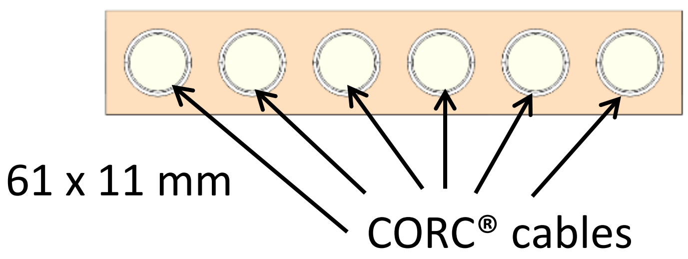
Total sample loop
R = 5 nΩ at 50 kA



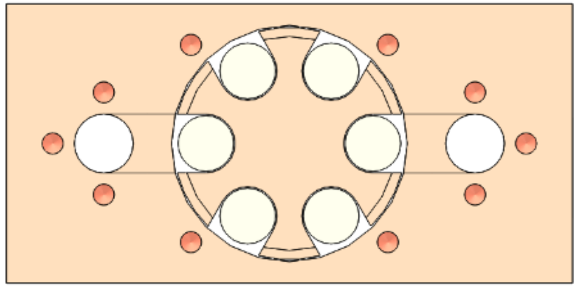
CORC®-CICC pressure joint between copper plates

Two CORC®-CICCs
- 6 CORC® cables in-plane
- 6-around-1 CORC®-CICC

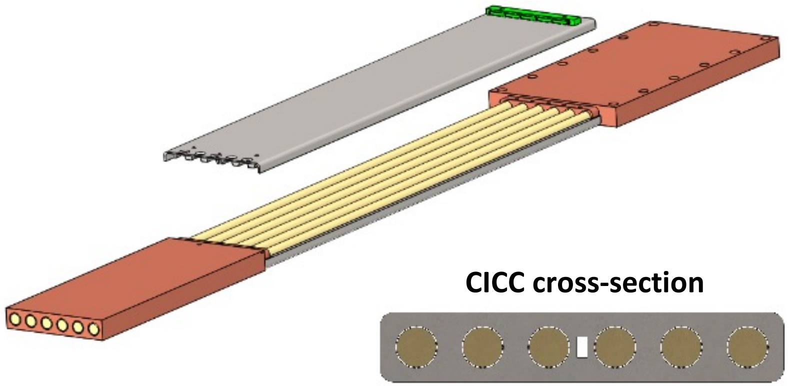
Termination cross-section

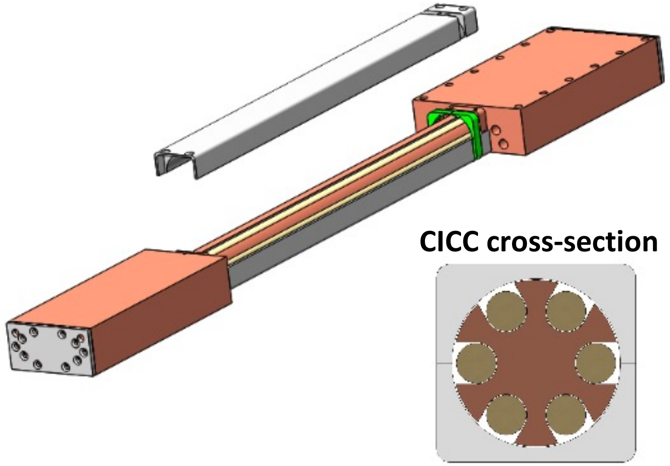


6x1 round CORC® CICC
(cables contain 12 tapes each)

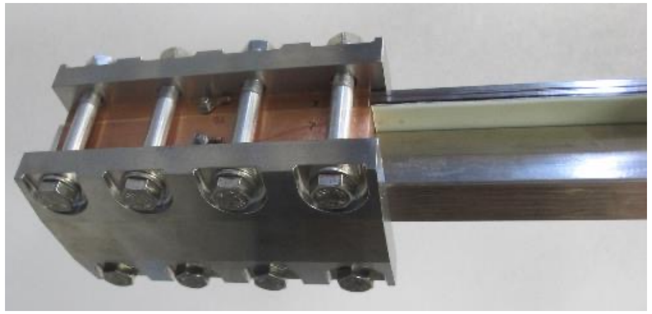


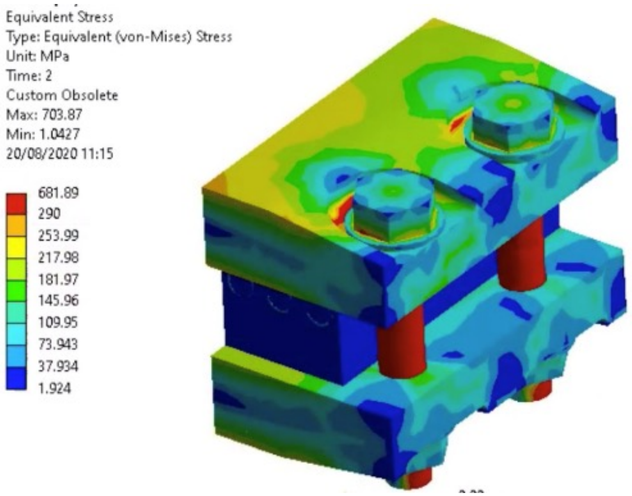
Joint: 61 x 30 mm
CICC: 30 x 30 mm





Joint design
- Annealed copper plates
- Clamping structure to ensure 10 MPa contact pressure



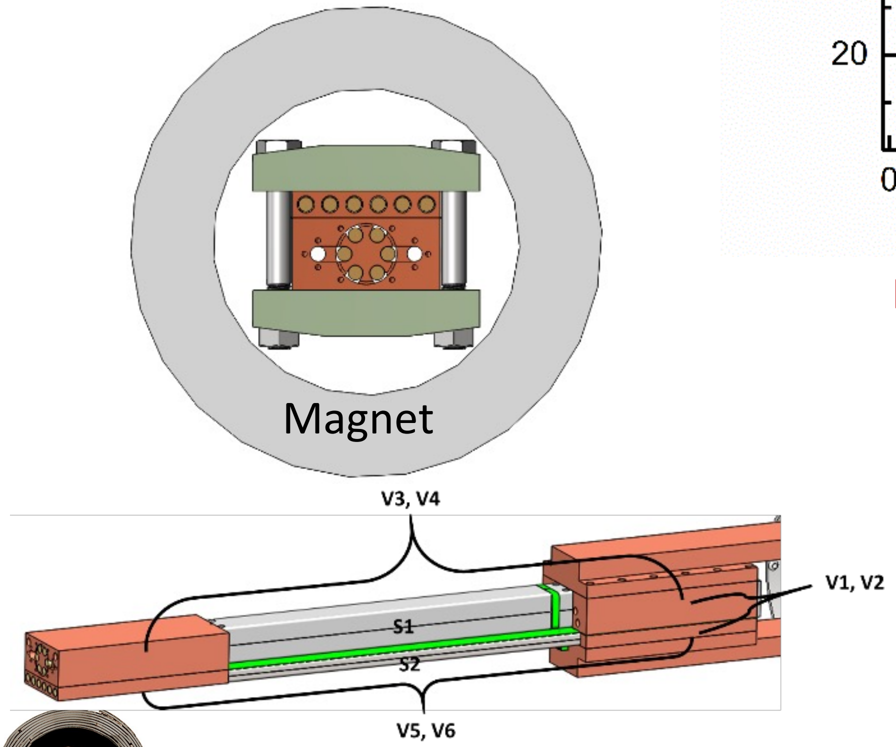


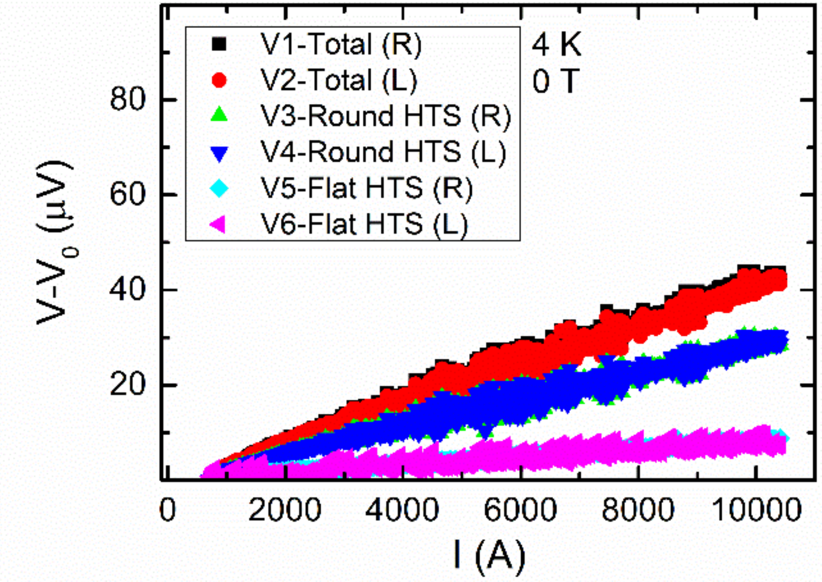
J.D. Weiss *et al* 2023 *Supercond. Sci. Technol.* **36** 085002 DOI: 10.1088/1361-6668/acdc59

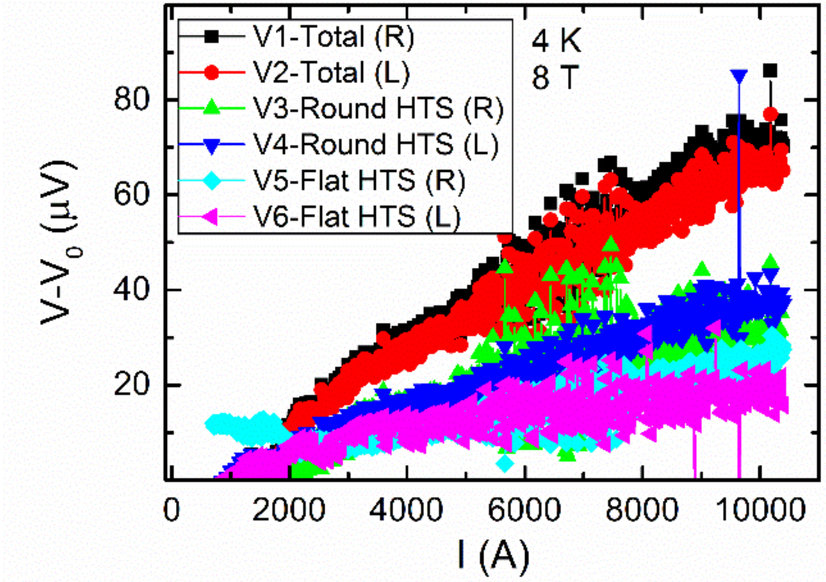
CORC®-CICC joint test results at 4 K

Joint test
- In liquid helium (4 K)
- Joint in superconducting magnets (8 T)

HTS 6x1 to HTS plate joint







Pressure joint resistance around 1 nΩ at 4 K at currents as high as 10 kA

B [T]	Average Resistance (4 K) [nΩ]			
	Total (V1,V2)	Round HTS (V3,V4)	Flat HTS (V5,V6)	Joint
0	4.1	2.8	0.8	0.5
4	5.2	3.0	1.3	0.9
6	6.1	3.4	1.5	1.2
8	6.9	3.6	1.9	1.4

J.D. Weiss *et al* 2023 *Supercond. Sci. Technol.* **36** 085002 DOI: 10.1088/1361-6668/acdc59

Thank you for your attention!

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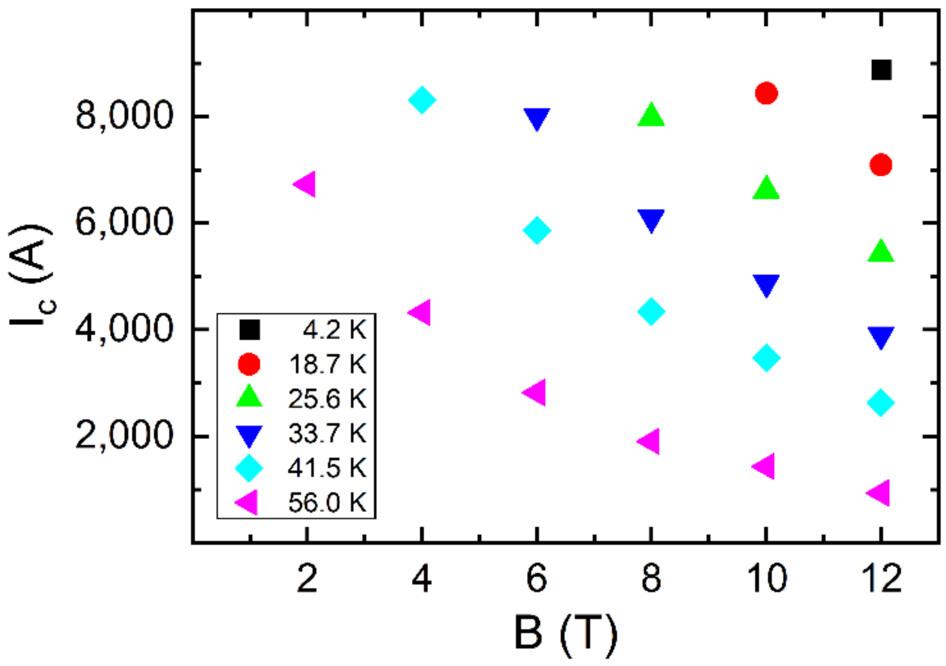
for technical information including presentations and published papers

In-field performance of CORC® cables using HM tapes

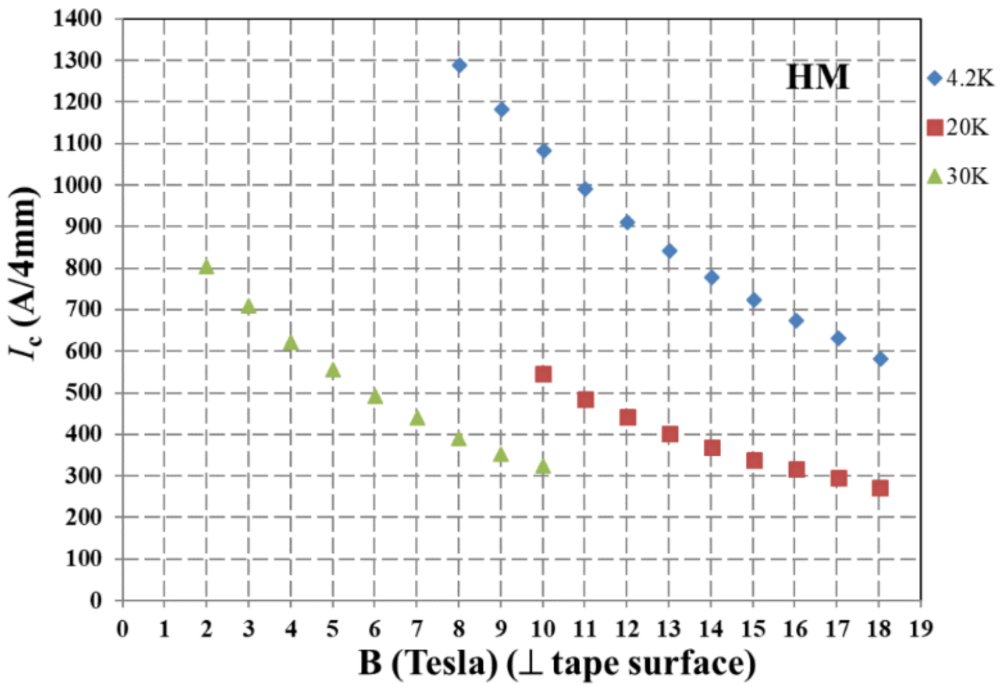
High-J_e CORC® cable from 4 mm wide HM tapes

- 42 tapes of 4 mm width: 42 x 500 A (15 T) = 21 kA
- 7.0 mm in thickness: J_e (15 T) = 545 A/mm^2
- **J_e(20 T) > 300 A/mm^2 is already possible with 30 % margin**

Previous CORC® cable with 30 “AP” tapes

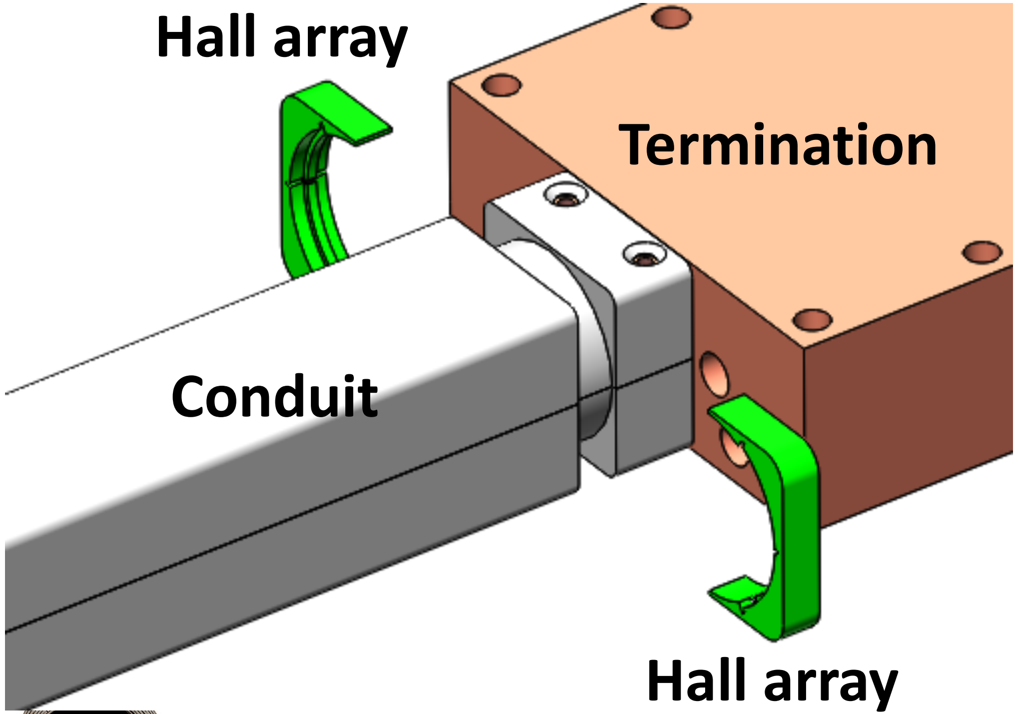


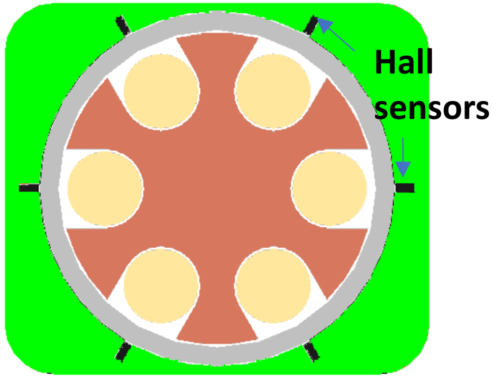
“HM” tapes offer 2x increase in performance



Hall probe array on 6x1 CICC

Hall sensors are mounted in holders that connect to outside of jacket to monitor current distribution and detect quenches





Computed peak self-field in CORC® 6x1 when current is (left) evenly distributed or (right) unevenly distributed in rightmost cable