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Development and testing of high temperature superconducting CORC® magnets and CICC for fusion applications

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ASC 2024
2LOr2C-01 (Invited)

Overview

Introduction to CORC® wires and CICC
Capabilities and unique properties

Cable development for Ohmic Heating coils
Winding magnets and validating their performance

Current sharing in CORC® cables
Strategies to mitigate performance loss due to defects or internal joints

CORC®-CICC development and testing
Performance evaluation of high-current cable architectures

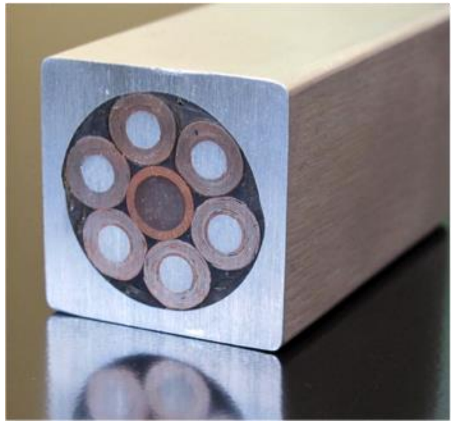
CORC® cable development for Ohmic Heating coils
Demonstrating fusion relevant performance

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

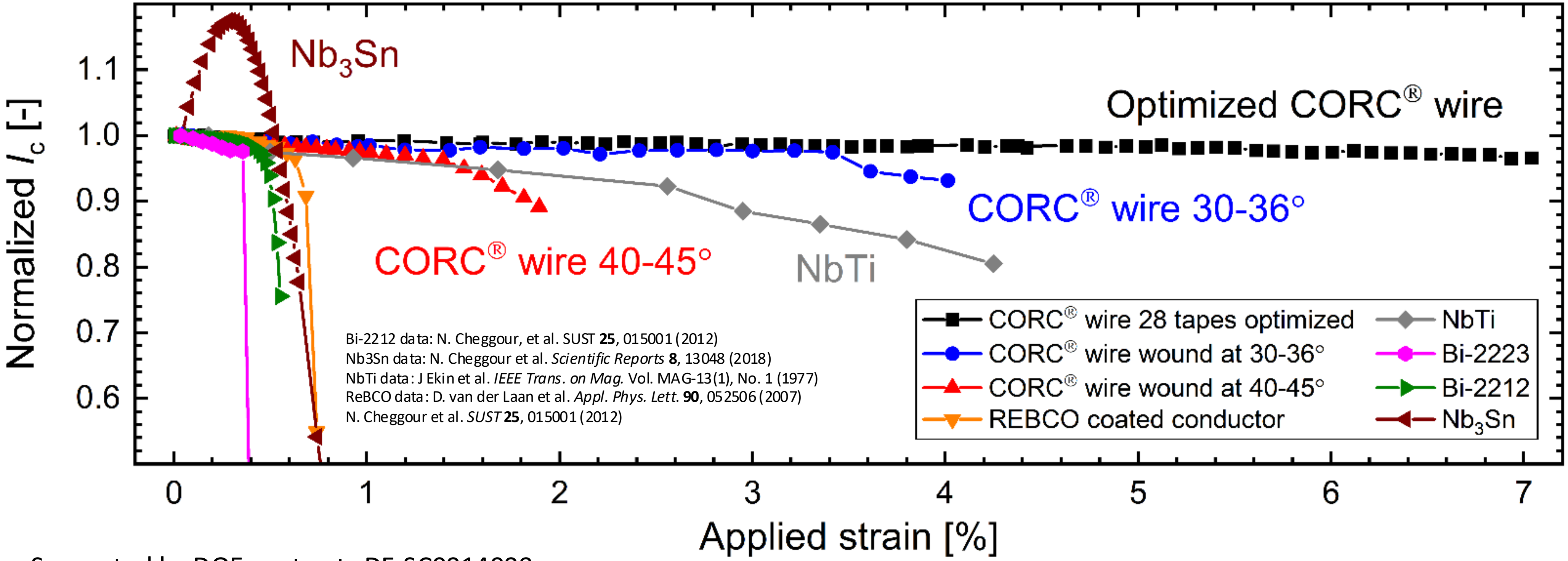
CORC®-Cable In Conduit Conductor (CICC)
- Performance as high as 100,000 A (4.2 K, 20 T)
- Combination of multiple CORC® cables or wires
- Bending diameter about 0.5 – 1 meter



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

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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

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

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

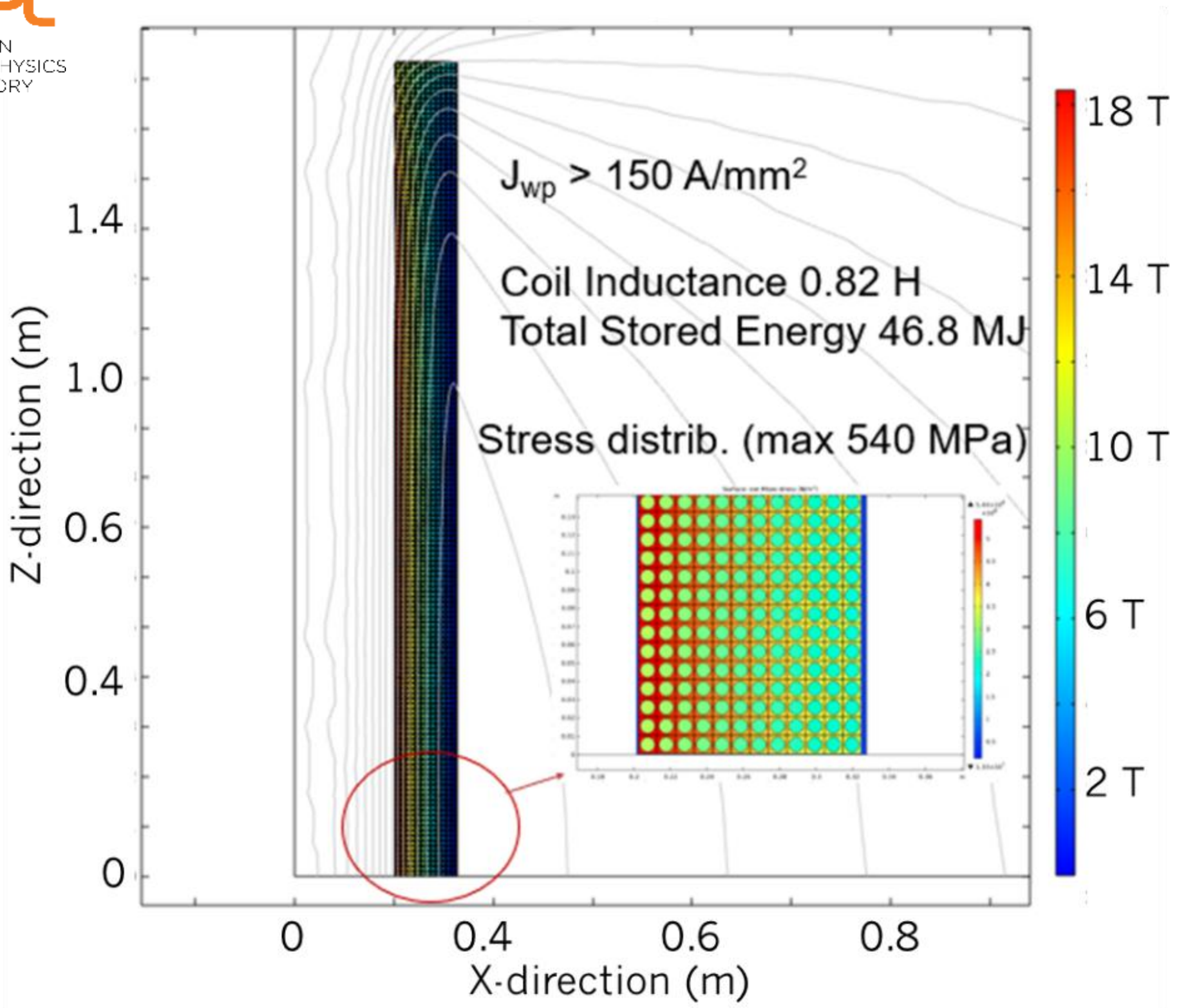
Fairly narrow OH/CS coils (SHPD)

- 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

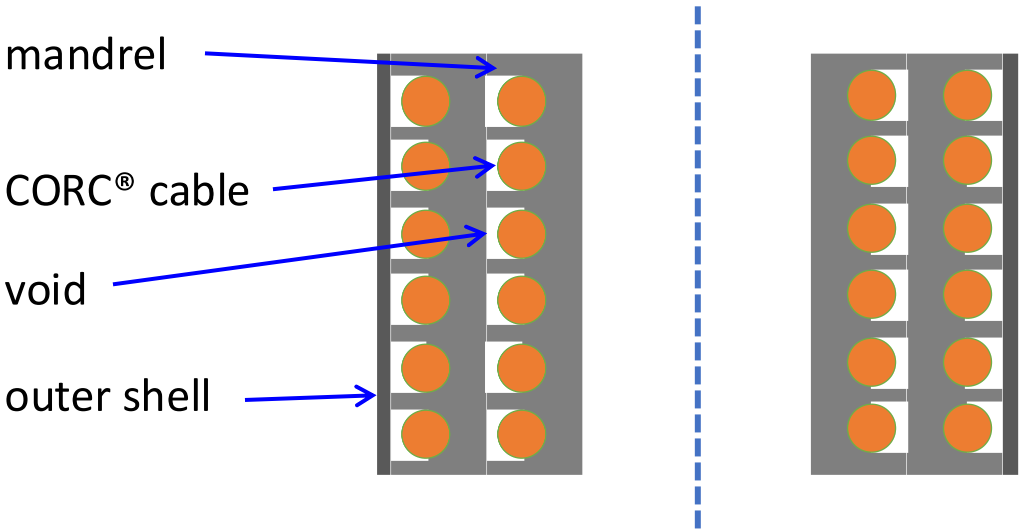


- Yuhu Zhai, et. al, IEEE Trans. Appl. Supercond. **32**, 4203005 (2022)
- Yuhu Zhai, et al, Fusion Engineering and Design **168**, 112611 (2021)
- Neil Mitchell, et al., Supercond. Sci. Technol. **34**, 103001 (2021)

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 to long lengths
- Wind into High strength mandrel → Approach we chose to make the first test coils



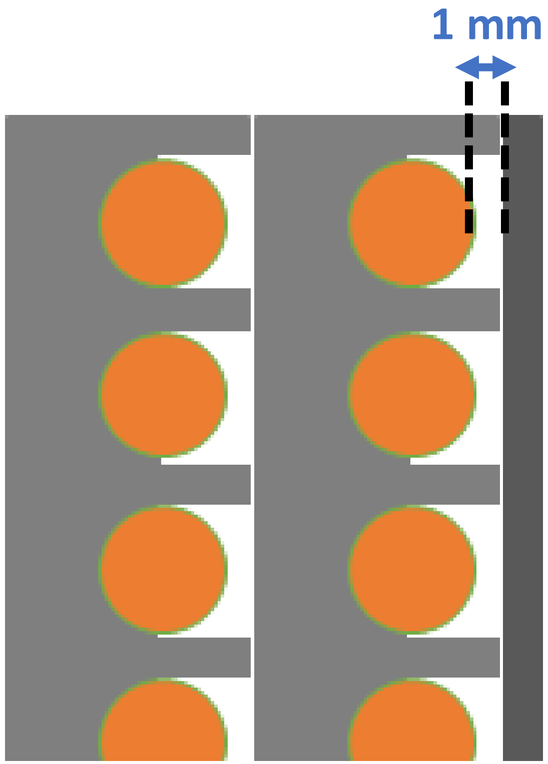
Questions to be answered regarding OH coils

- **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?

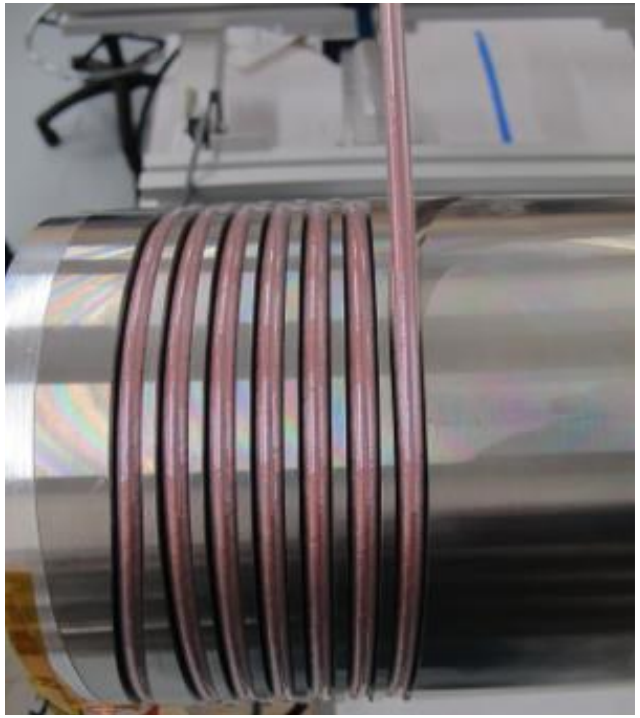
Development of prototype Ohmic Heating coil

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

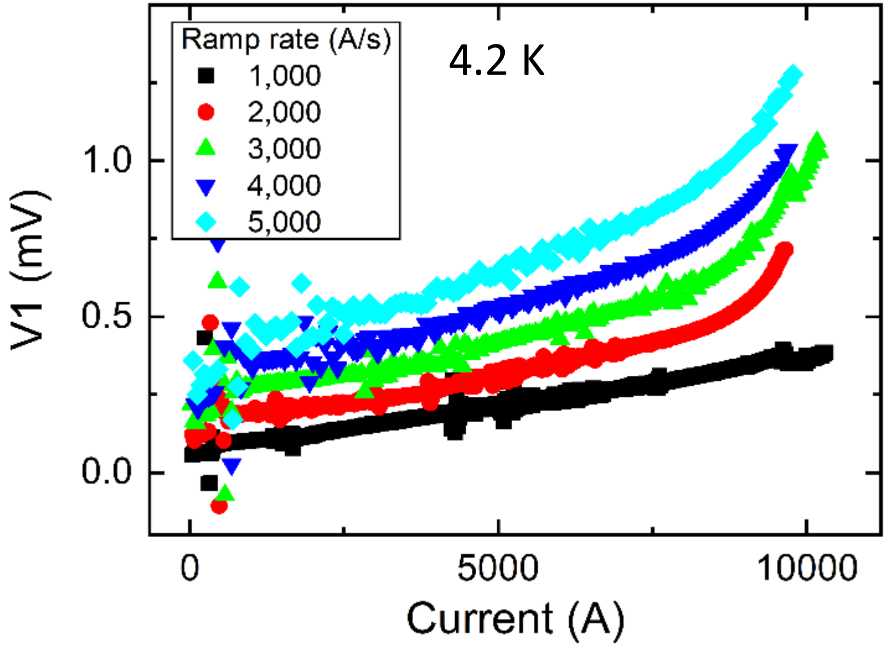


Testing at PPPL and ASC-NHMFL

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

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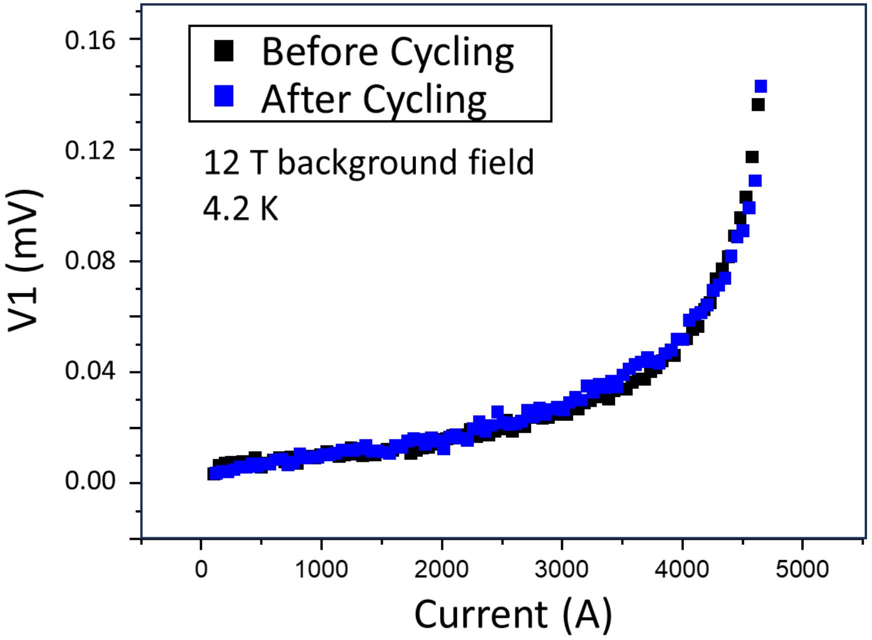


Supported by DOE contracts DE-SC0014009, DE-SC0013723 and DE-SC0018125

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)

Current sharing in CORC® cables

Can HTS cables with electrically coupled strands tolerate local strand-level dropouts, particularly when operated at elevated temperatures (20-77 K)?

See **Virgina Phiffer's** thesis:

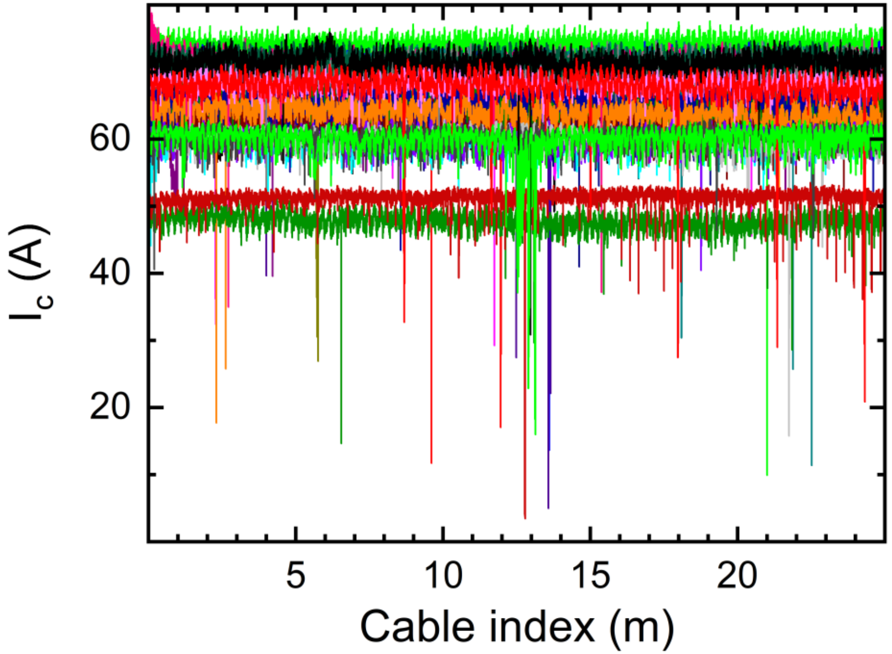
"EXPERIMENTAL INVESTIGATIONS OF TAPE-TO-TAPE CONTACT RESISTANCE AND ITS IMPACT ON CURRENT DISTRIBUTION AROUND LOCAL IC DEGRADATIONS IN CORC® CABLES" FSU 2023

Making use of REBCO tapes with variable I_c (VIC tapes)

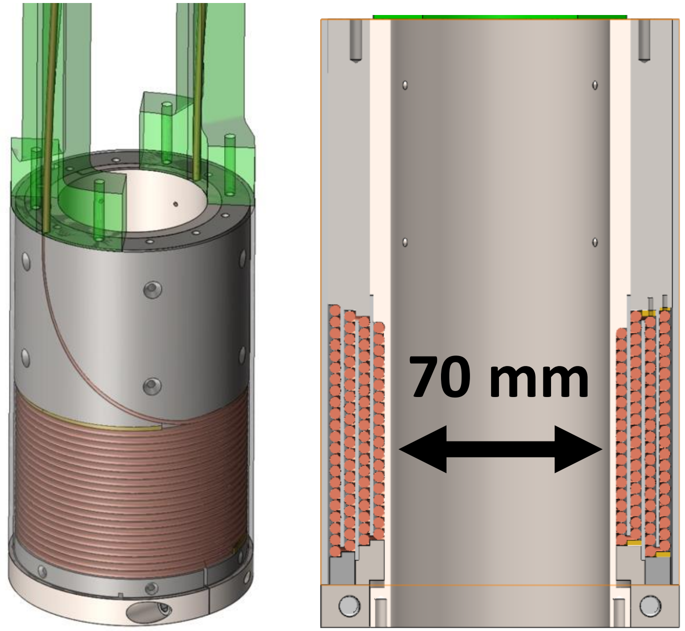
Office of Energy Efficiency and Renewable Energy (EERE) funded project:

Cost-effective Conductor, Cable, and Coils for High Field Rotating Electric Machines

I_c vs location in CORC® wire with 27 tapes (2 mm wide)

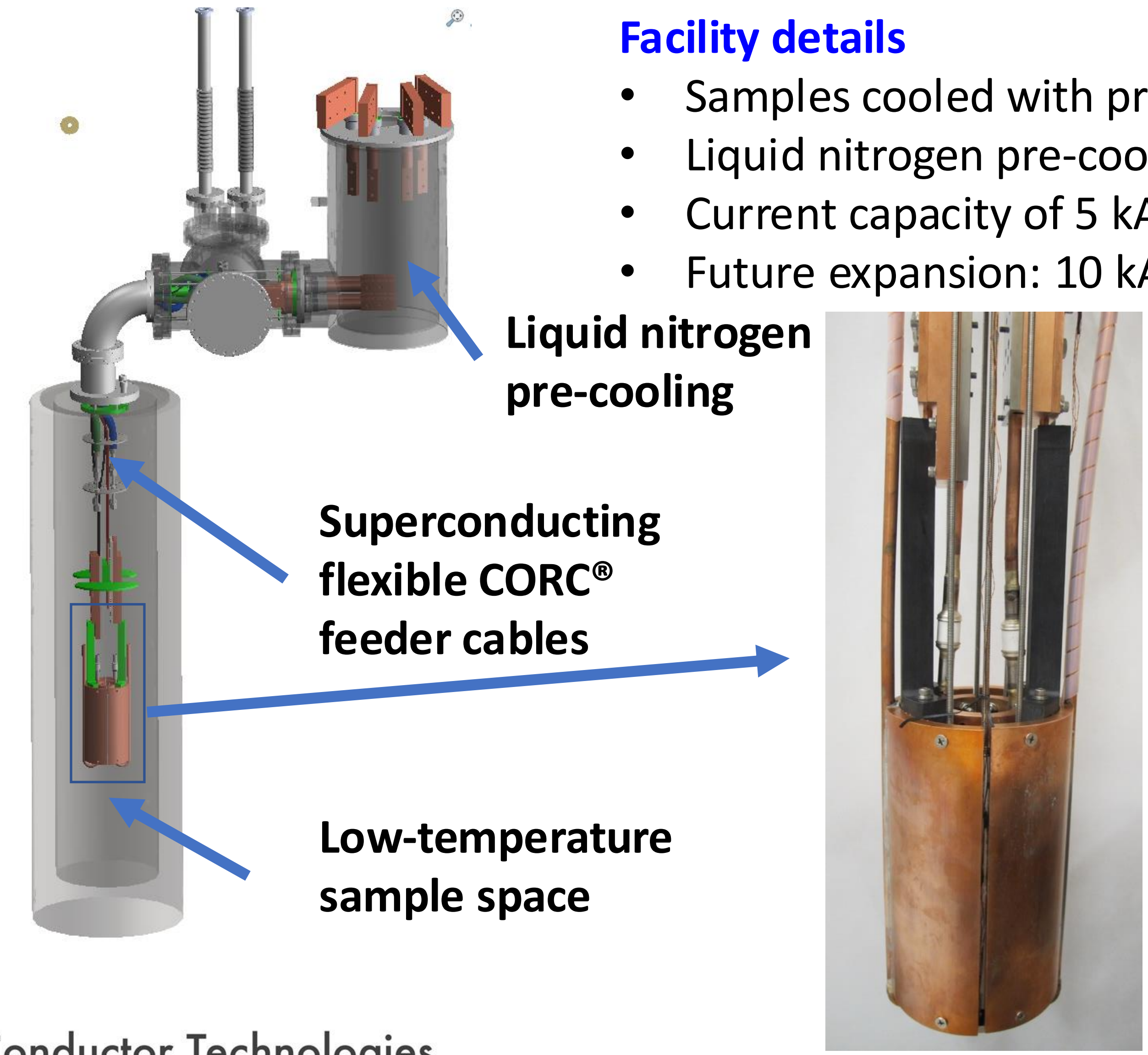


82 turn Coil design



Coil winding at CU

CU/ACT facility for high-current testing at 20 – 60 K

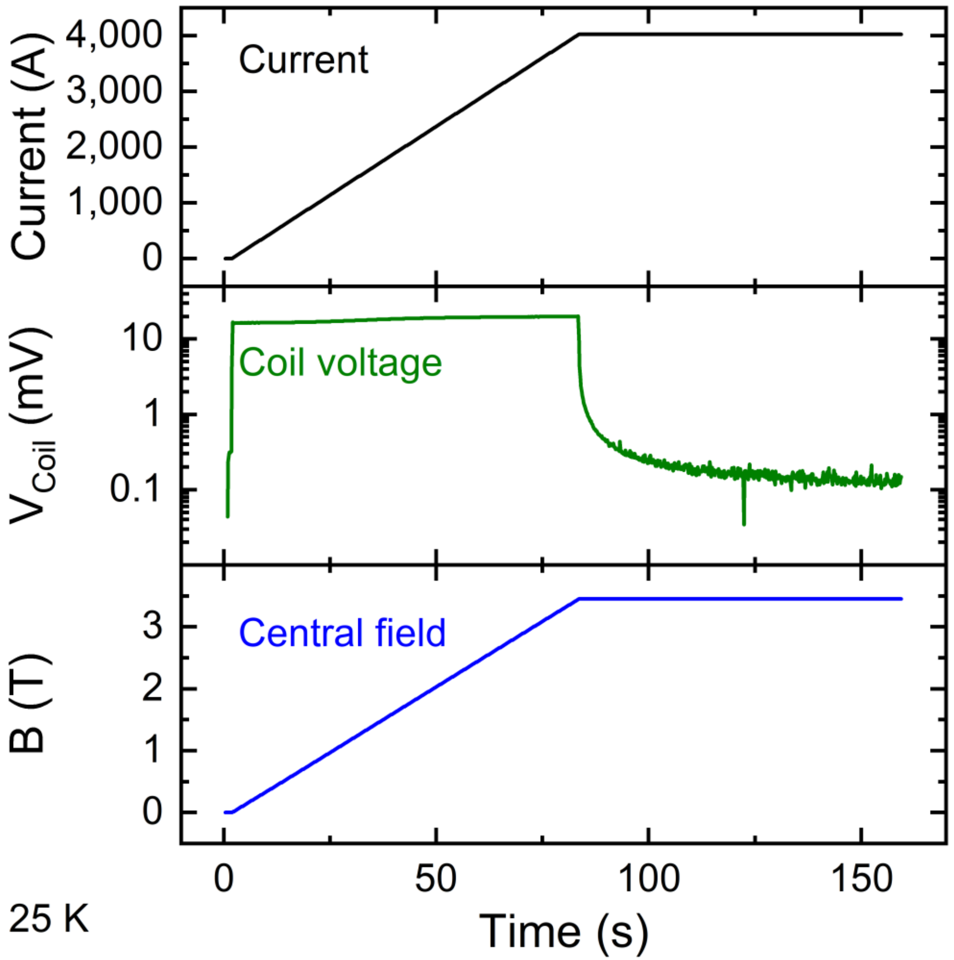


Facility details

- Samples cooled with pressurized supercritical helium gas
- Liquid nitrogen pre-cooling of feeder cables
- Current capacity of 5 kA (continuous)
- Future expansion: 10 kA and 8 T magnetic field

Cryogenic He gas is circulated through Copper cold-plates to cool down the magnet allowing us to do tests from 25-60 K

Steady state operation at 25 K close to I_c



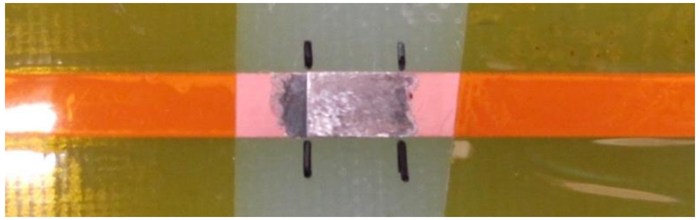
- Coil was ramped to 4021 A (87% I_c) and current was held constant
  - This is a current density of **395 A/mm²** (J_w = 243 A/mm²)
- Voltage over coil after inductive decay was 0.11 mV at held current of 4021 A
  - Power dissipation is 0.44 W as measured over the terminations
- Performance inline with average tape I_c

CORC® cables with internal tape-to-tape joints

DOE OFES PhI SBIR funded project:

long-length CORC® cables and cable-in-conduit-conductors for compact fusion reactors

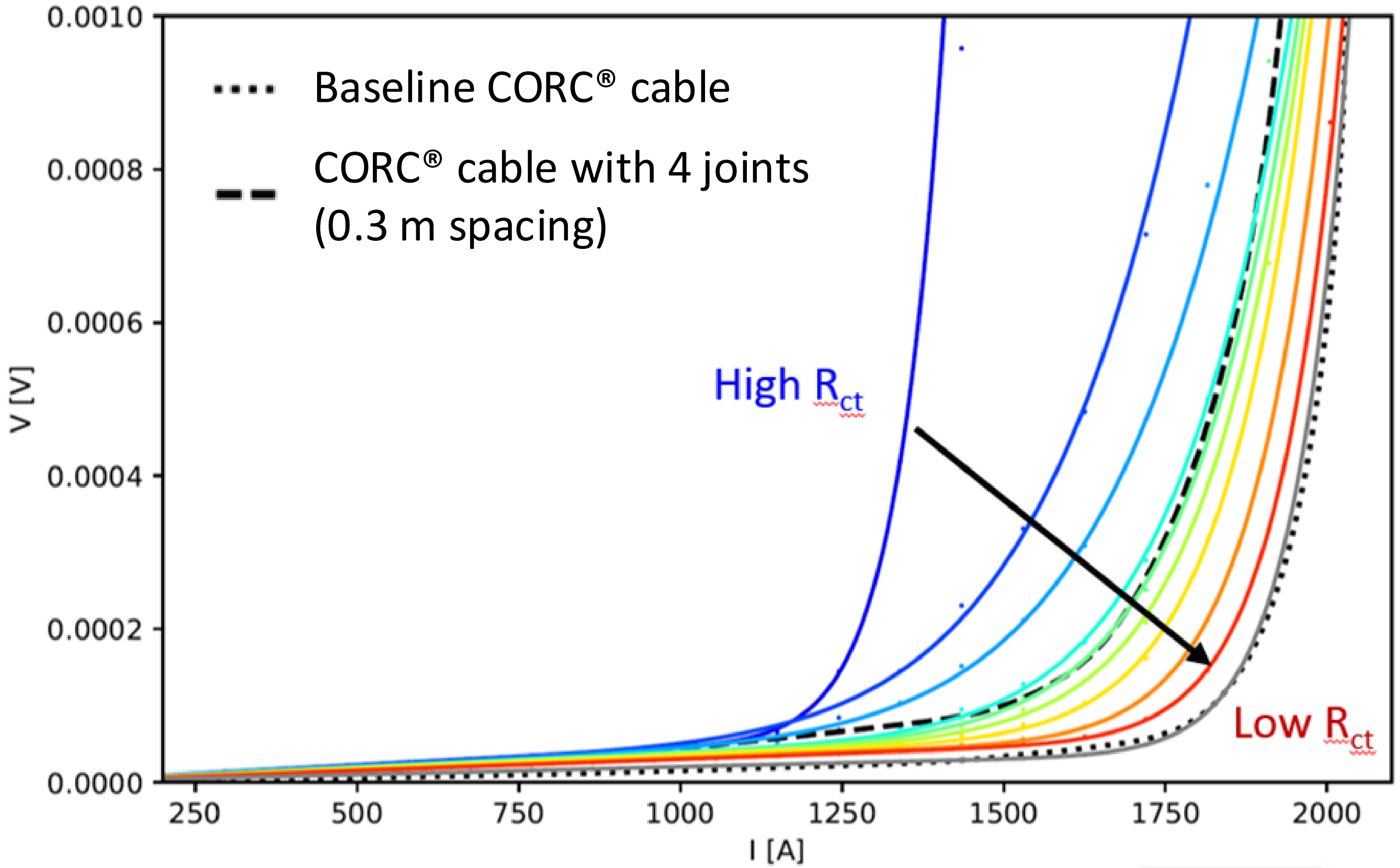
Welded joint between REBCO tapes



Welded joint wound into CORC® cable

12 tape CORC cable with 4 internal joints

Experiment vs network model[1] where contact resistivity is varied parametrically



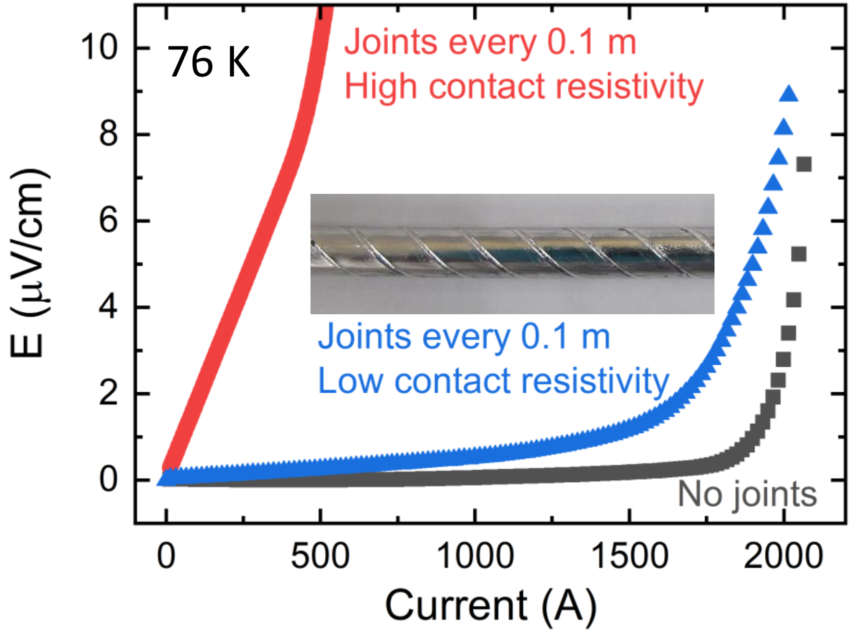
[1]Teyber, R. *et al.* Numerical investigation of current distributions around defects in high temperature superconducting CORC® cables. *Supercond. Sci. Technol.* **35**, 094008 (2022).

Two routes to lower contact resistance between tapes in CORC®

Vary contact resistivity between tapes

	76 K Contact resistivity ($\mu\Omega cm^2$)
CORC® ACT/LBNL experiments and modeling	50-460
CORC® with high-conductivity lubricant [1]	16-66
Single pressed REBCO tape front to back[3]	25-38
CORC® with PbSn coated tapes[1]	1.6-2.4
CORC® with PbSn coated tapes after melting[1]	0.3-1.1
Single soldered REBCO tape front to back[2]	0.4-0.9

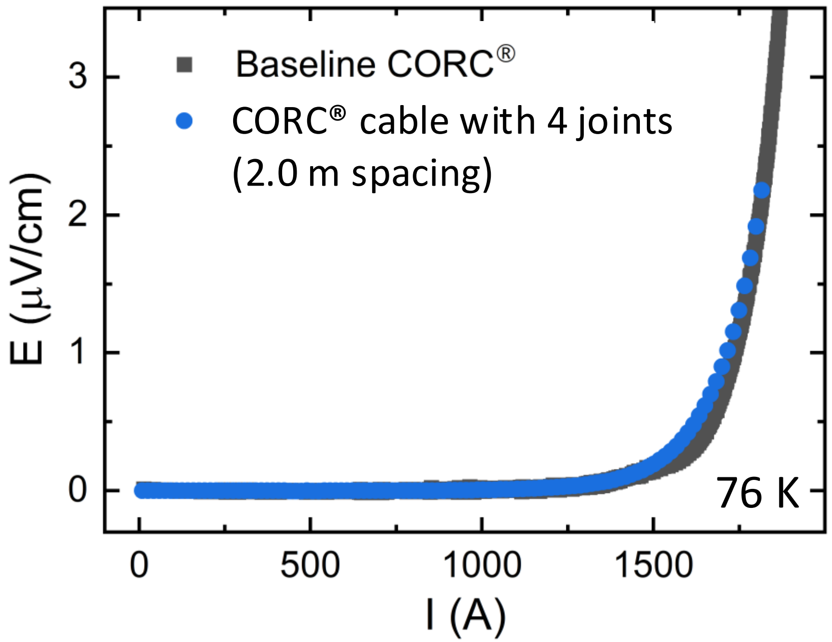
1.5 m long CORC® cable with 1 joint in each tape



Increase the contact area between tapes

Longer length between internal joints results in lower contact resistance between tapes

10 m long CORC® cable with 4 joints



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[1]Phifer, V. *et al. Supercond. Sci. Technol.* **35**, 065003 (2022).
[2]Fleiter, J. et al. *IEEE Transactions on Applied Superconductivity* **27**, 1–5 (2017).
[3]Lu, J et al. Contact resistance between two REBCO tapes under load and load cycles. *Supercond. Sci. Technol.* **30**, 045005 (2017).

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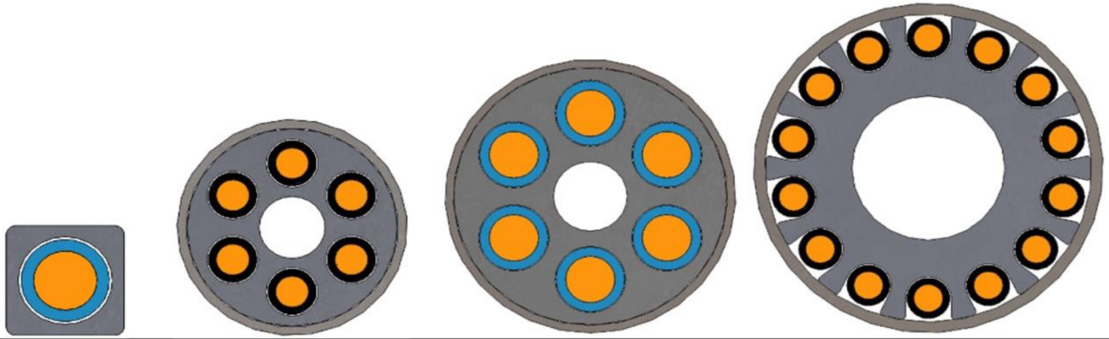
CORC®-CICC development and testing

Building on **Tim Mulder's** thesis:

"ADVANCING CORC-REBCO WIRE AND CABLE IN CONDUIT CONDUCTOR TECHNOLOGY FOR SUPERCONDUCTING MAGNETS" Twente 2018

CORC® CICC development

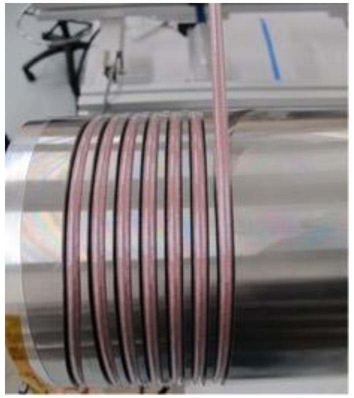
Layouts being developed for magnet systems: Central solenoid, Toroidal, etc



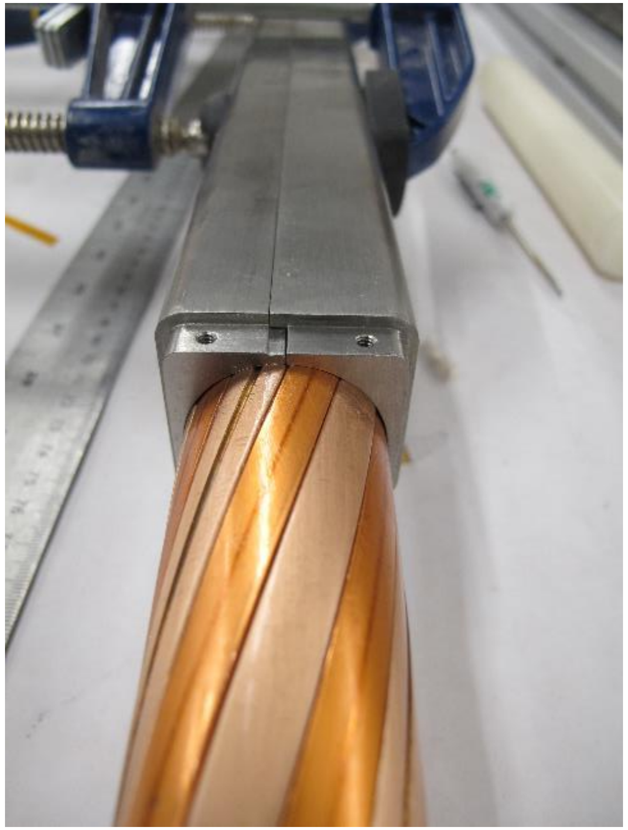
CORC®-CICC size	[mm]	10 x 10	22.23	31.75	38.1
CORC® conductors	[-]	1 cable	6 wires	6 cables	14 wires
Tapes per conductor	[-]	42	30	42	30
Tape width	[m]	4	3	4	3
I_c (4.2 K, 20 T)	[kA]	13.4	43.0	80.3	100.4
J_e (4.2 K, 20 T)	[A/mm^2]	133.8	110.8	101.4	88.0
I_c (20 K, 20 T)	[kA]	6.7	21.5	40.1	50.2
J_e (20 K, 20 T)	[A/mm^2]	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**



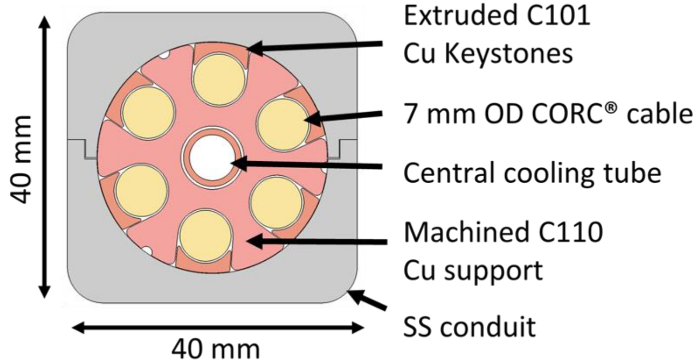
3 m long CORC® CICCs tested in 10.9 T background field at Sultan



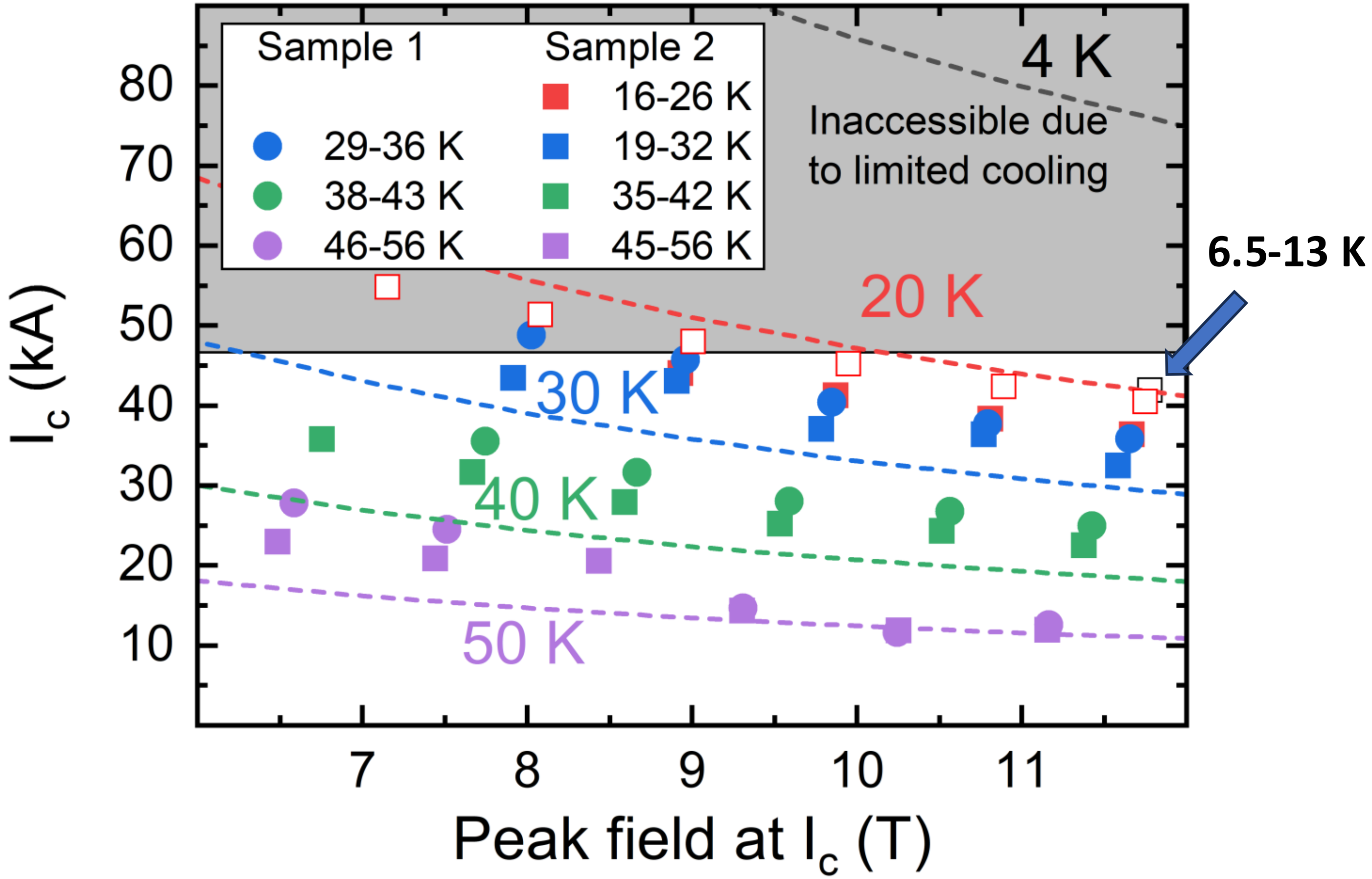
Preparation of two CORC® CICC (S1 and S2) with distributed conductor support

- **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
- Based on central copper support with grooves

S1 Cross-section

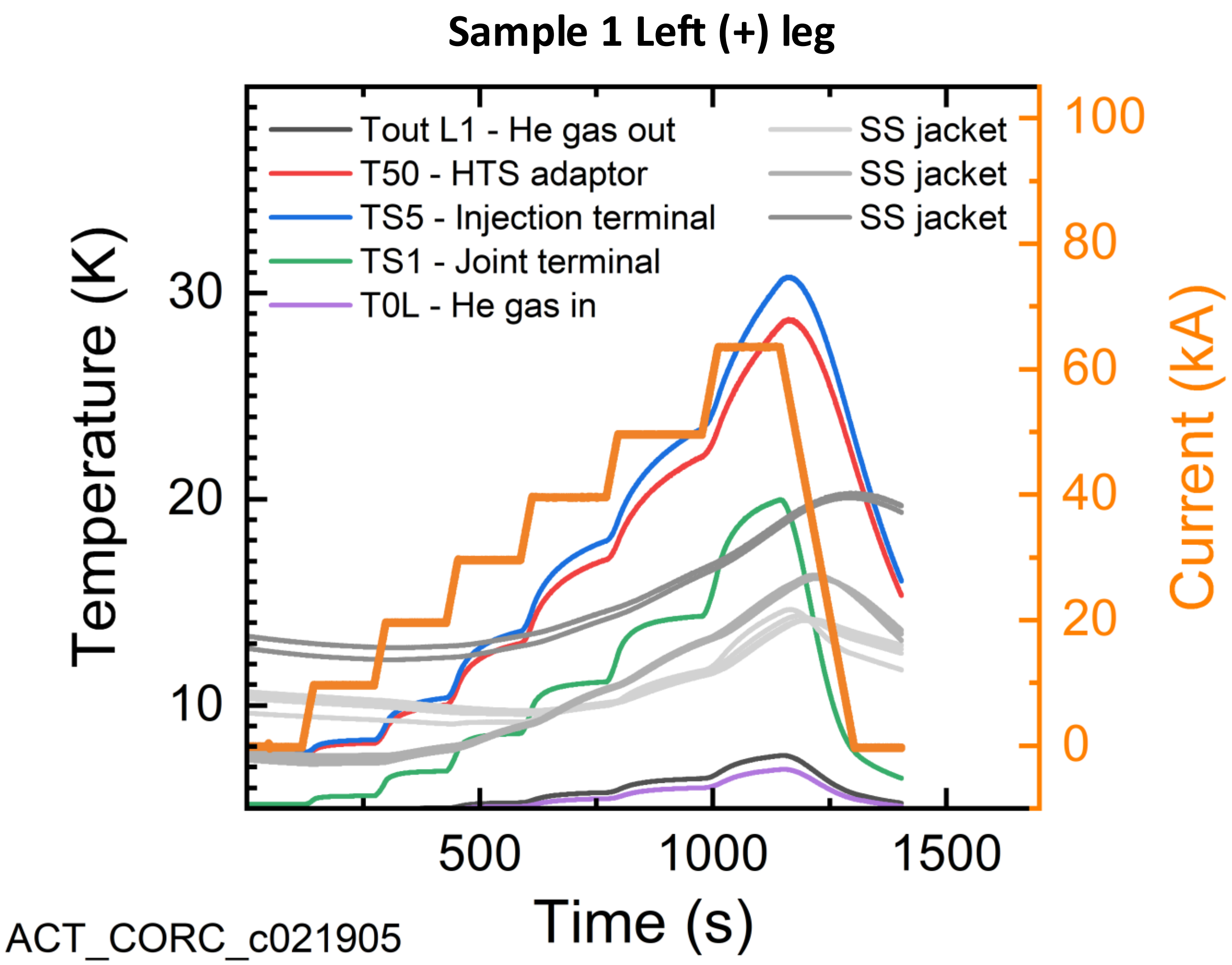


I_c (B, T) dependence within/above expectations at 30-50 K



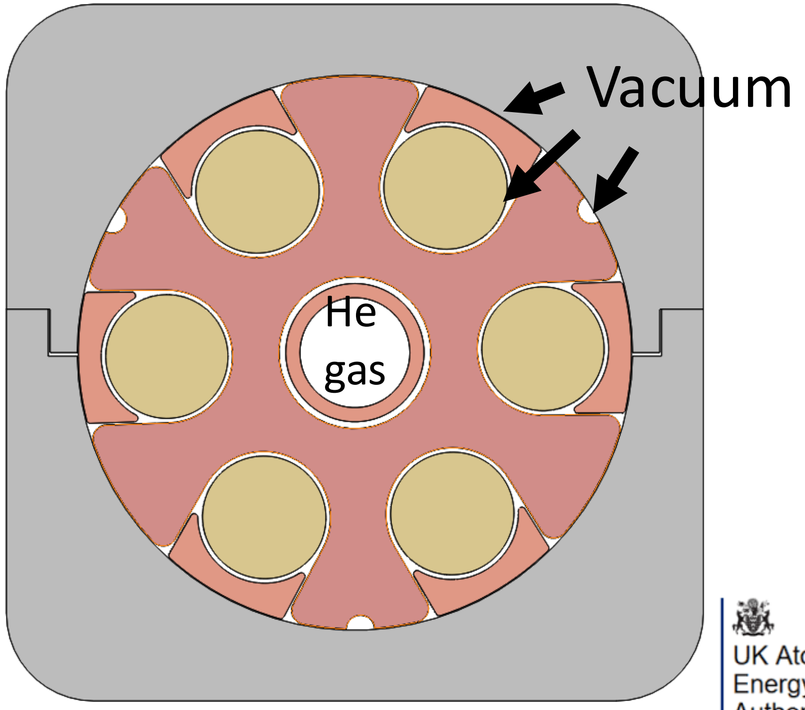
- **Dashed lines are 216 X 4 mm wide tape I_c (B) at 4.2 K scaled using SuperPower spec**
- **Below 20 K, sample 2 (S2) tended to quench well below expected I_c**
- **Not due to mechanical degradation**
- **Most infield measurements at or below 20 K showed quench in HTS adaptors (open symbols) around 38-44 kA**
- **<u>Temperature variations and current distribution plays a role in sample quenching</u>**

Large variation of temperatures across sample as current is ramped



He gas only routed through central tube

- **Design decision to allow instrumentation within jacket (voltage taps and Hall sensors)**
- **Gaps between support, cable, and jacket all contain vacuum**
- **Thermo-hydraulic design not optimized**
- **Resulted in an extremely valuable dataset**



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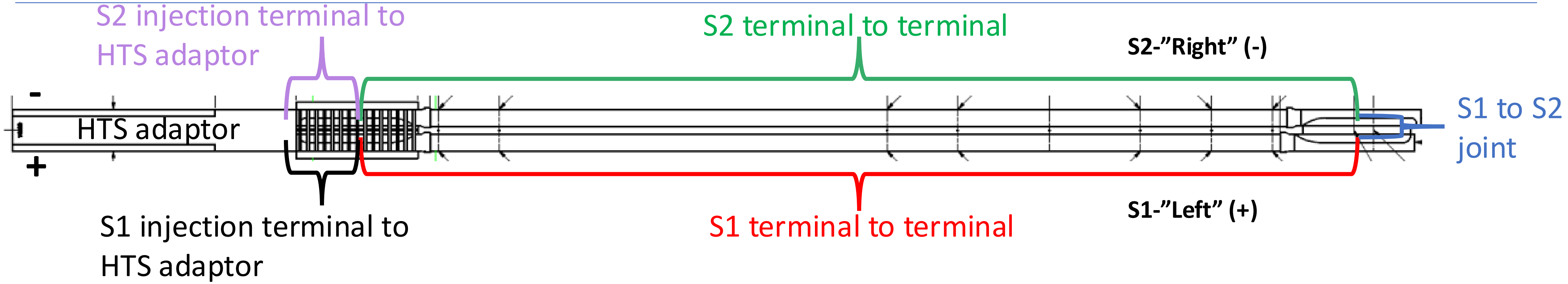
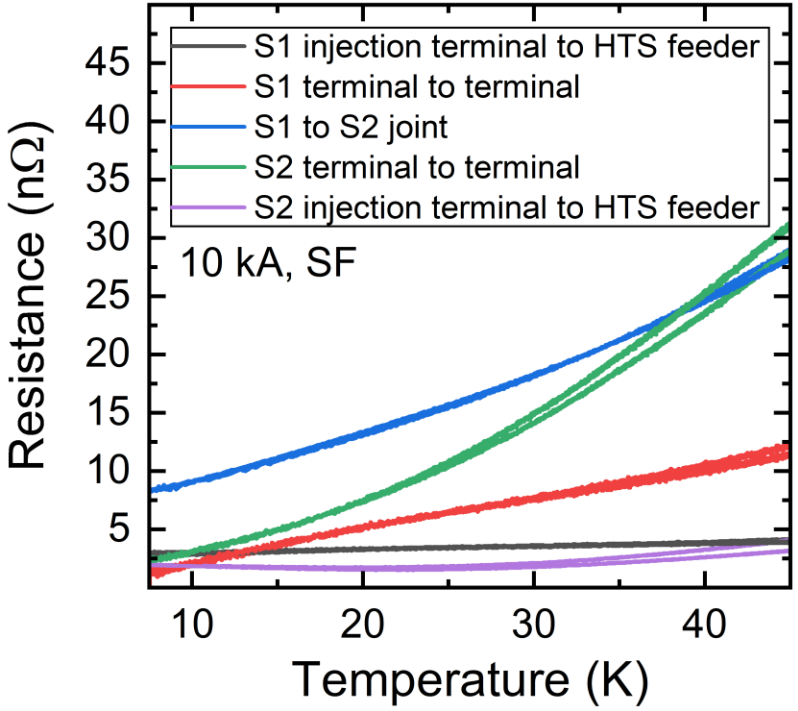
Evaluation of resistances vs temperature

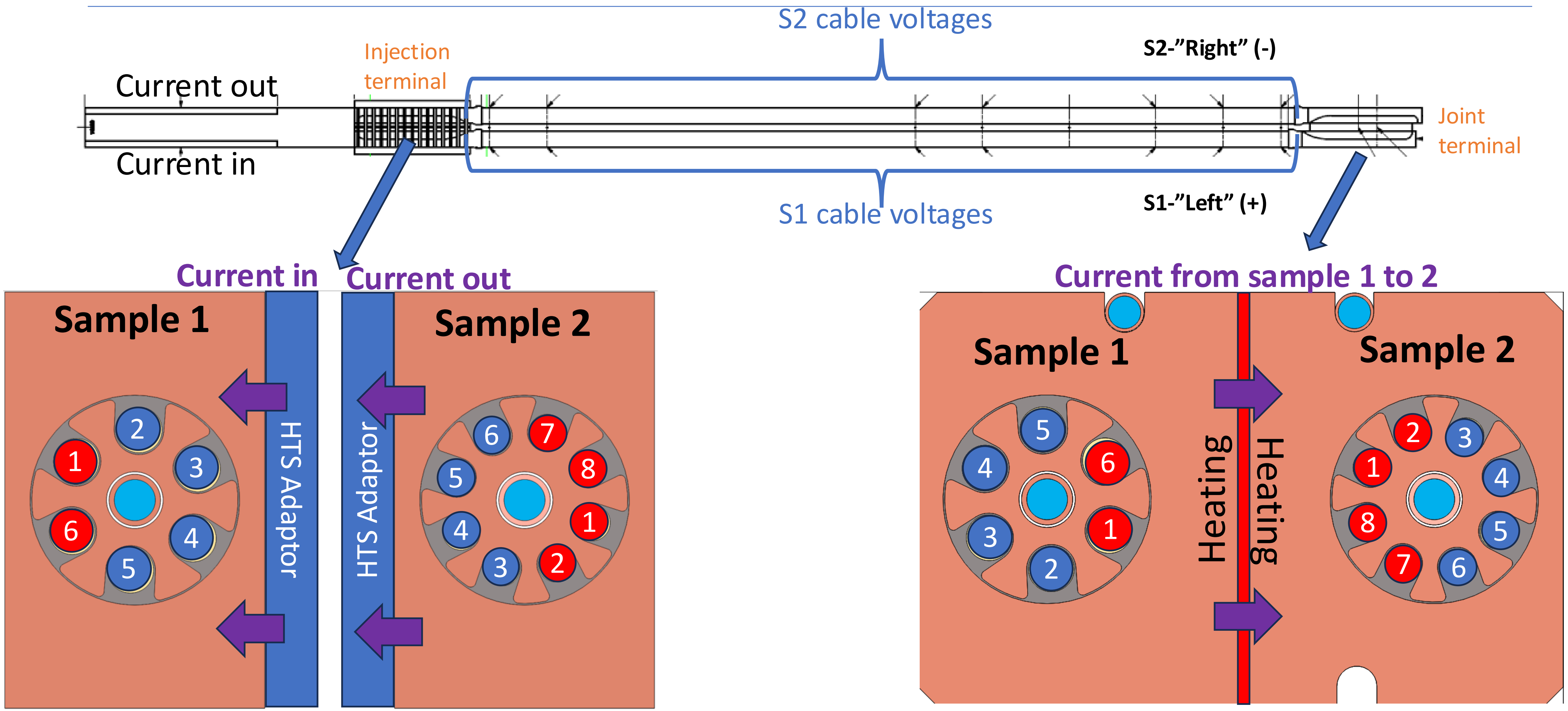




Most resistance comes from the joint terminals between sample 1 and sample 2

- **Expected resistance here of ~2 nΩ, actual resistance ~8 nΩ**
- **Post-mortem planned to determine origin of elevated joint resistance**
- **Sample 2 terminal-to-terminal resistance increases more with temperature than for sample 1**

Using voltage taps on every cable, we look for trends in voltage variations



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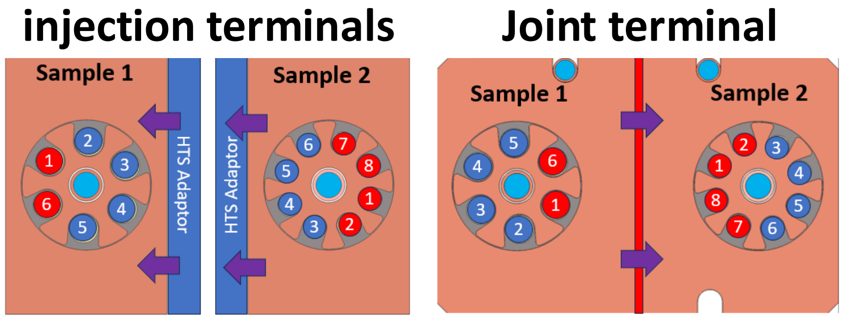
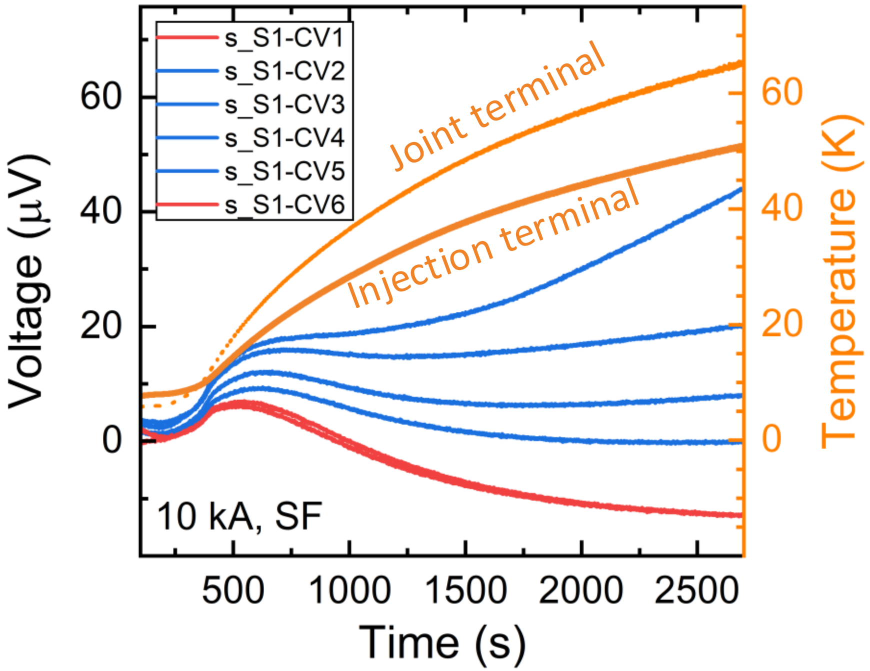
Voltages vary per cable depending on location of cables within terminations

Spread of voltages depending on cable location

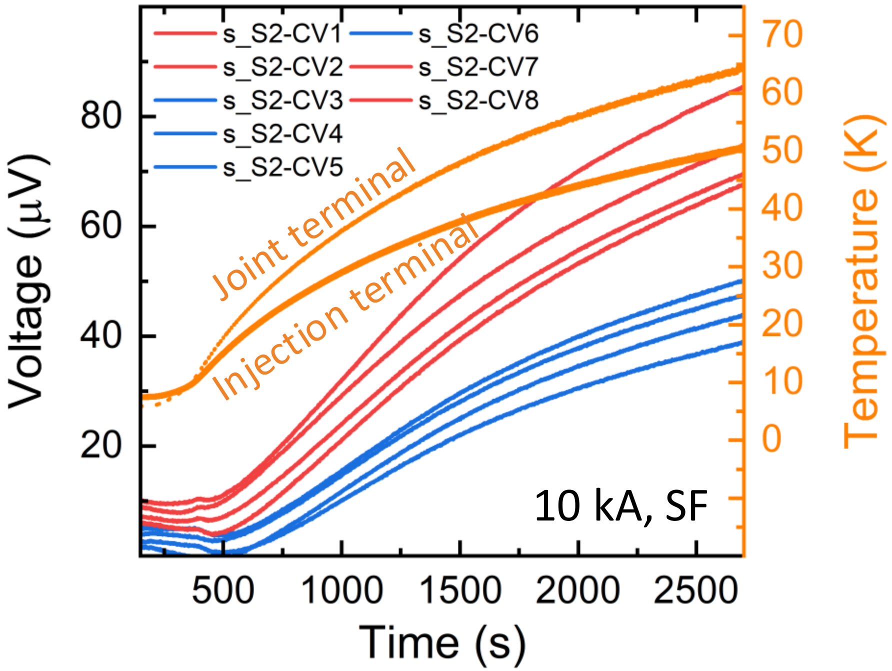
- Joint terminal warms faster than injection terminal
- Thermoelectric voltage influences cables closest to joint
- Voltage goes negative for cables 1 and 2 at t = 800 A!
- Thermoelectric voltages are driving current distribution
- Major implications for design of CICC, joints, and current leads



Sample 1: Negative thermoelectric voltage



Sample 2: positive thermoelectric voltage



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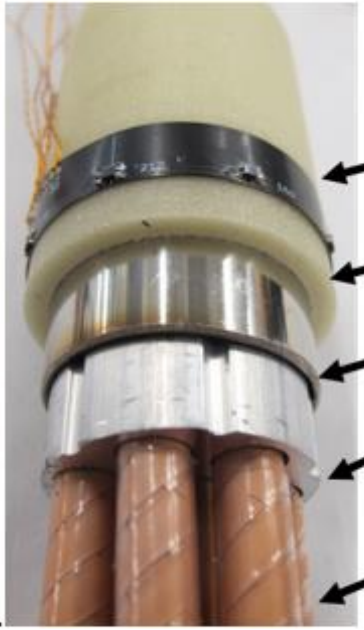
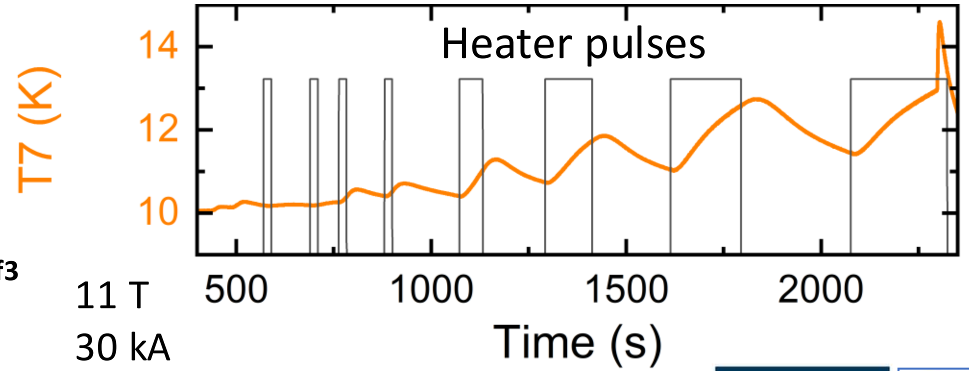
Quench detection in CORC® cables using Hall arrays

Limited current-sharing between CORC® cables in CICC allow us to monitor current redistribution

Hall array based quench detection for CICC

Flexible Hall array for CICC current distribution monitoring





J. D. Weiss, et al Quench detection using Hall sensors in CICC for fusion applications doi: 10.1088/1361-6668/abaec2.
R. Teyber, et al CORC® cable terminations with integrated hall arrays for quench detection doi: 10.1088/1361-6668/ab9ef3
R. Teyber, et al Current distribution monitoring in fusion magnets doi: 10.1038/s41598-022-26592-2.

Summary

There are advantages to keeping ReBCO tapes mechanically/electrically coupled, but unbonded

- Allowing tapes to slide when conductor is loaded is key to prevent strain concentrations above the critical strain limit of the tape
- Current sharing between many tapes has advantages when it comes to distributed drop-outs

Balanced current distribution within HTS CICC depends not just on balancing resistive and inductive voltages, but also thermoelectrical voltages

- Low resistance joints with even contact resistance required for every strand
- Transposition of tapes and twisting of cables remains important for ramped magnets
- Margin may allow for operation within a temperature gradient, but thermoelectrical voltages can be significant and can't be neglected

Thank you for your attention!

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