

# Development of high current CORC<sup>®</sup> cables, CICC, and low resistance demountable joints for fusion magnet applications

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 TYPE ONE ENERGY



Advanced Conductor Technologies  
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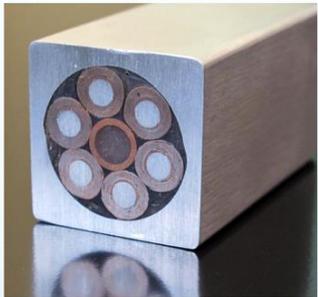
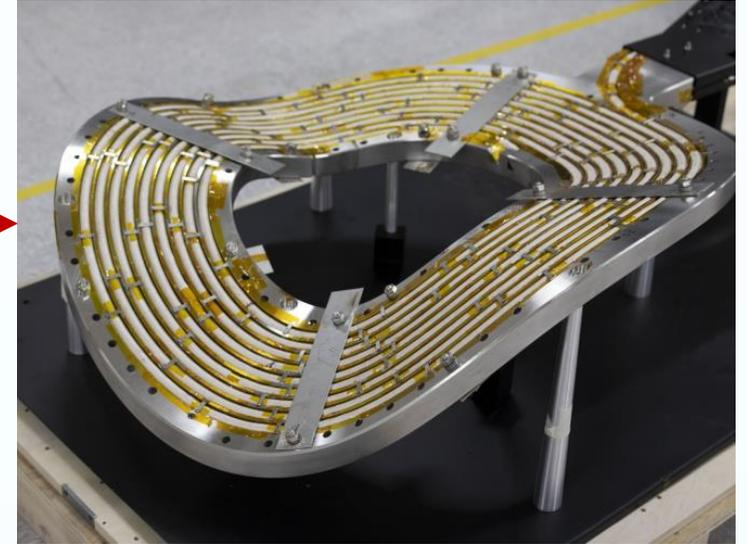


# Commercial development of CORC<sup>®</sup> cables for fusion applications

## High tape count CORC<sup>®</sup> cables

CEA Cadarache (DEMO):

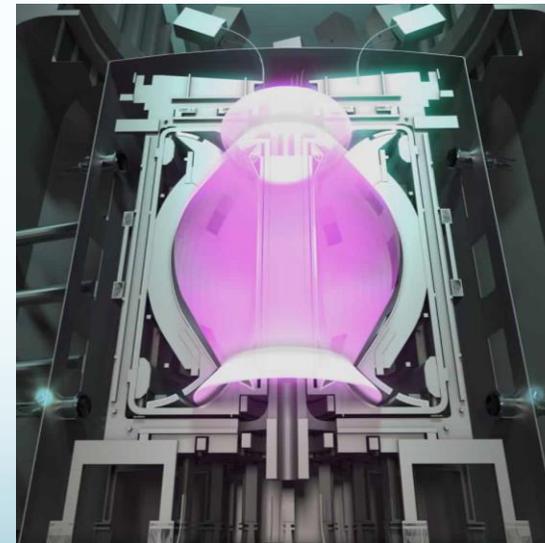
- 120-tape CORC<sup>®</sup> cable containing SnPb solder plating
- **Type One Energy Group (Stellarator magnets):** →
- 96-tape CORC<sup>®</sup> cable with bending flexibility down to 250 mm diameter



## CORC<sup>®</sup>-CICC

UKAEA (STEP):

- CICC layouts for various magnets
- Demountable joints between CORC<sup>®</sup>-CICC for TF coils



<https://typeoneenergy.com/type-one-energy-begins-testing-fusion-magnet/>

<https://step.ukaea.uk>

TYPE ONE ENERGY

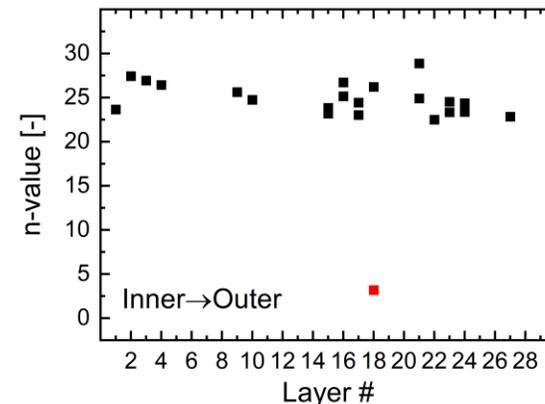
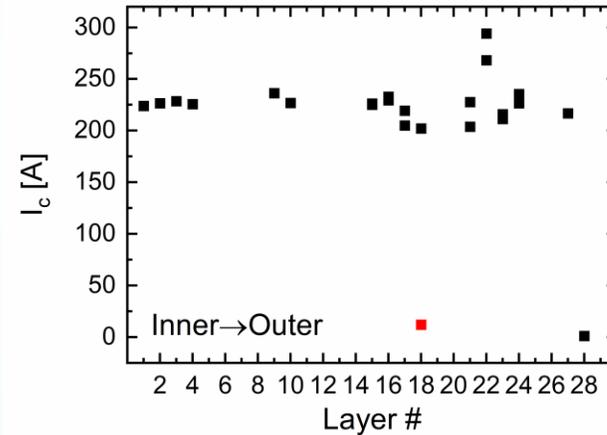
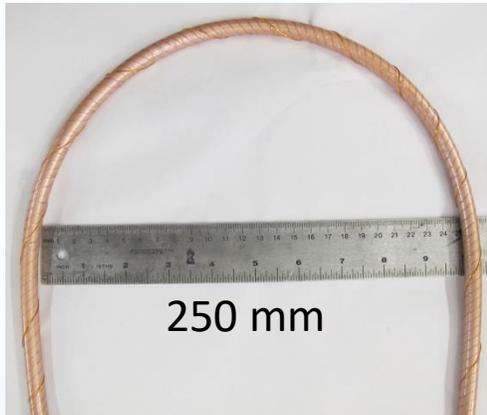


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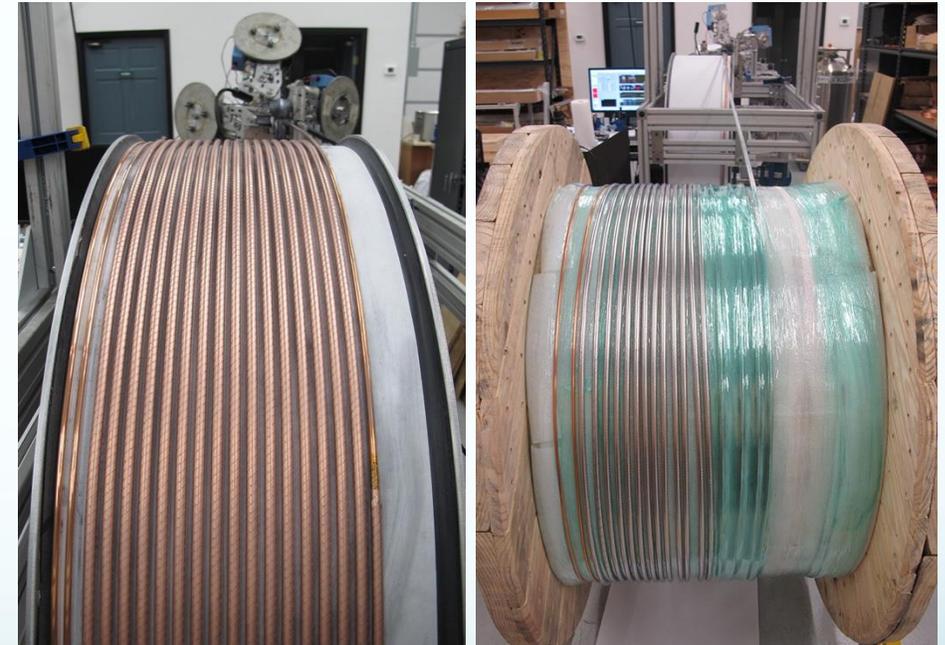
# 96-tape CORC<sup>®</sup> cable with high flexibility for Stellarators

## Type One Energy Group Stellarator magnets

- 96 tapes of 4 mm width wound into a 10.4 mm O.D. cable
- Continuous length of 56 meters
- Optimized for bending to 250 mm diameter
- **Extracted tape measurements show nearly 100%  $I_c$  retention**



56 meters of CORC<sup>®</sup> cable



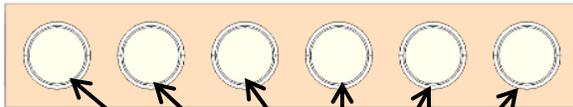
# CORC<sup>®</sup>-CICC demountable joints copper-to-copper joints

## Two CORC<sup>®</sup>-CICCs

- 6 CORC<sup>®</sup> cables in-plane
- 6-around-1 CORC<sup>®</sup>-CICC

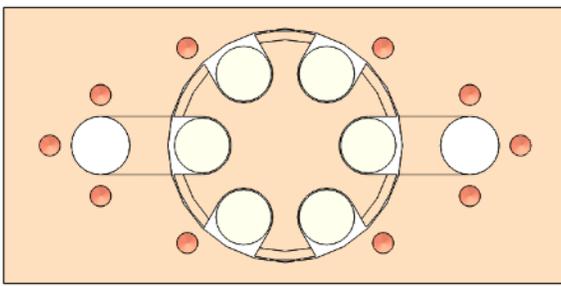
6x1 round CORC<sup>®</sup> CICC  
(cables contain 12 tapes each)

Termination cross-section



61 x 11 mm

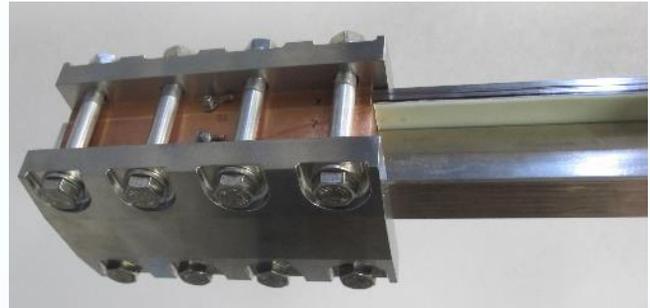
CORC<sup>®</sup> cables



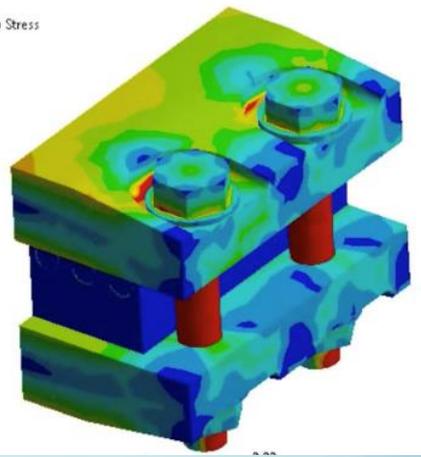
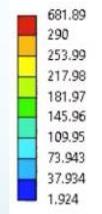
Joint: 61 x 30 mm  
CICC: 30 x 30 mm

## Joint design

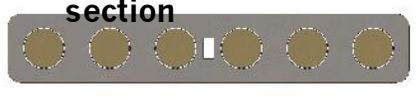
- Annealed copper plates
- Clamping structure to ensure 10 MPa contact pressure



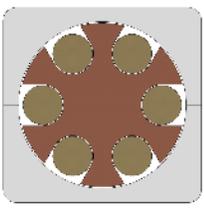
Equivalent Stress  
Type: Equivalent (von-Mises) Stress  
Unit: MPa  
Time: 2  
Custom Obsolete  
Max: 703.87  
Min: 1.0427  
20/08/2020 11:15



CICC cross-section



CICC cross-section

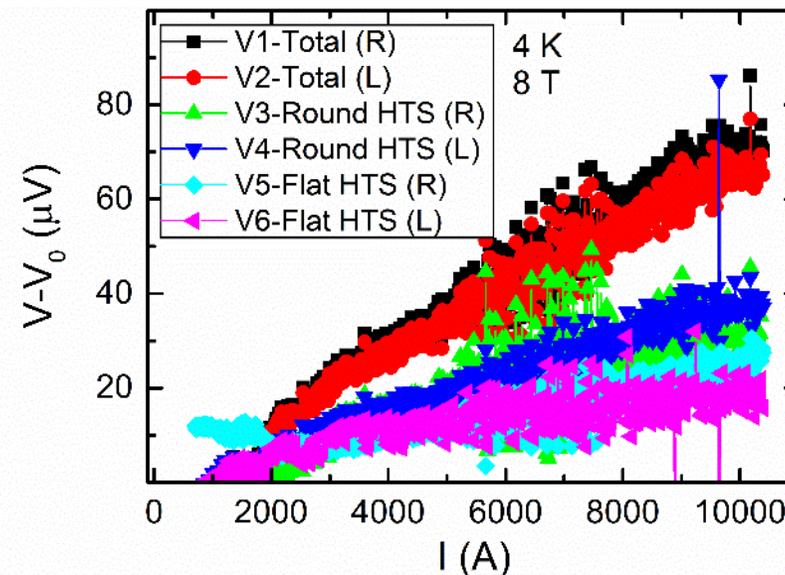
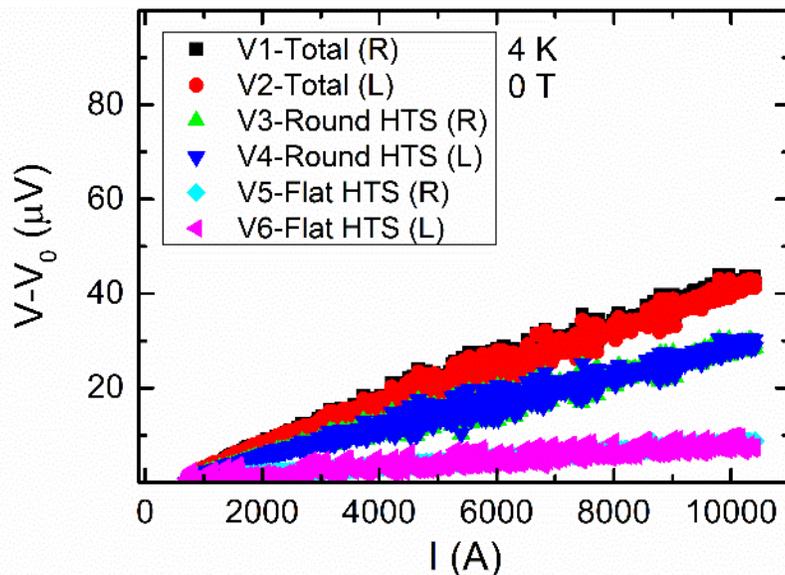
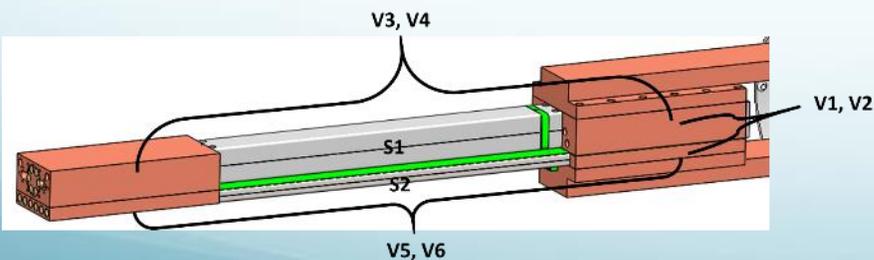
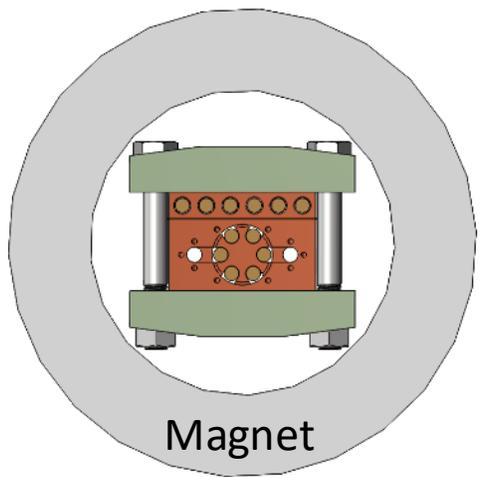


# CORC®-CICC copper-to-copper joint performance at 4.2 K

## 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**

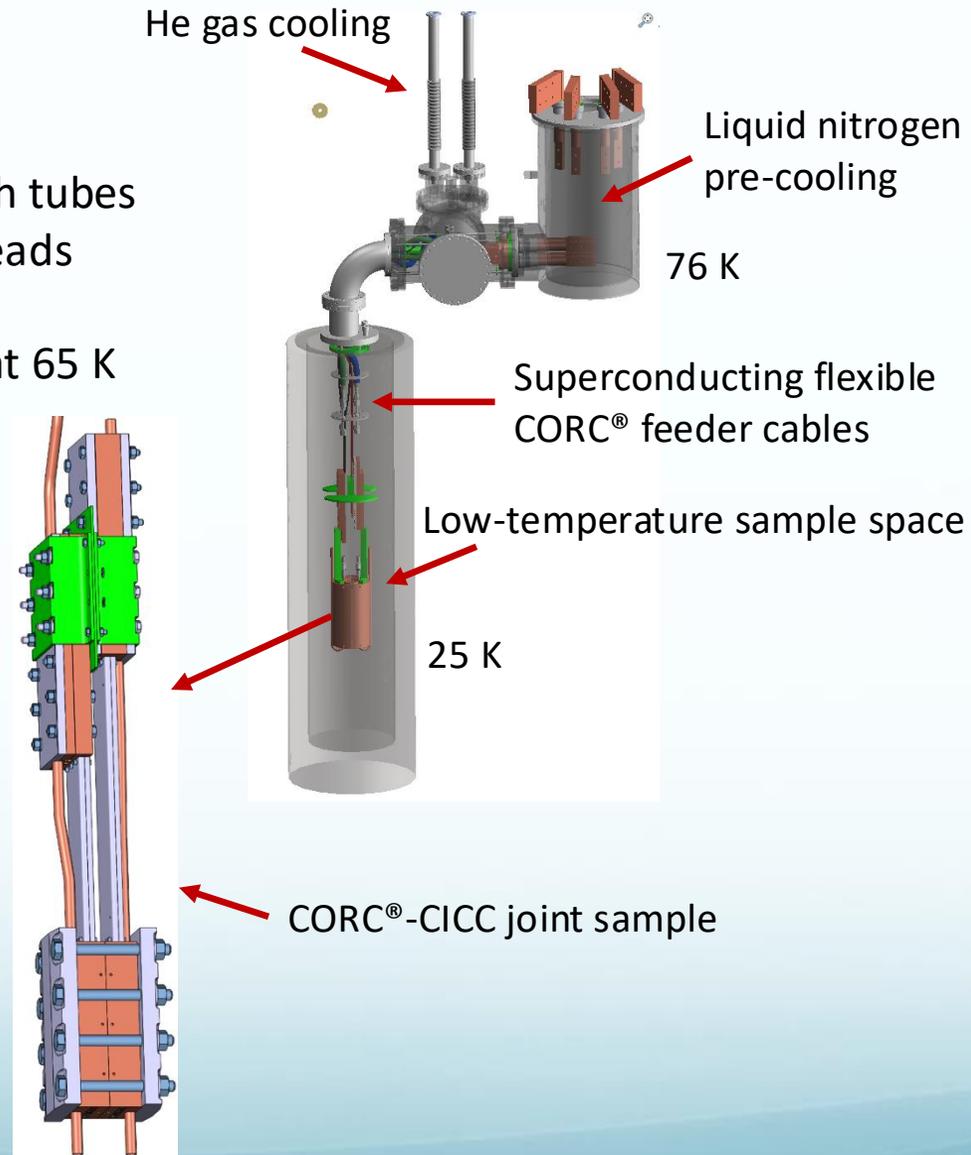
B [T]	Average Resistance (4 K) [nΩ]			
	Total (V1,V2)	Round HTS (V3,V4)	Flat HTS (V5,V6)	Joint
0	4.1	2.8	0.8	0.5
4	5.2	3.0	1.3	0.9
6	6.1	3.4	1.5	1.2
8	6.9	3.6	1.9	1.4



# Testing CORC<sup>®</sup>-CICC joints at 25 K

## Testing at up to 5 kA at 25 K

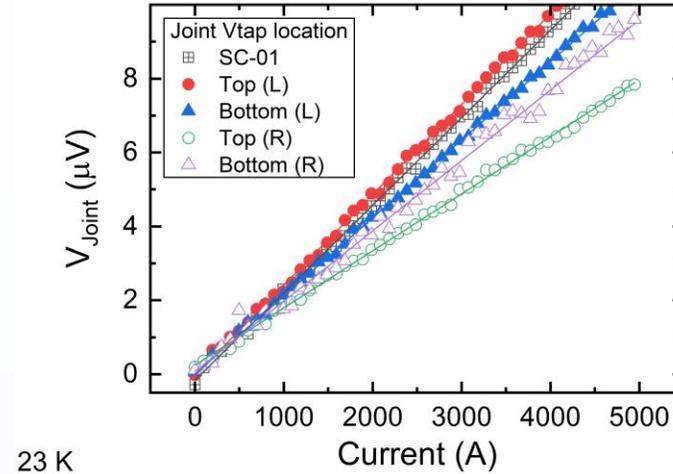
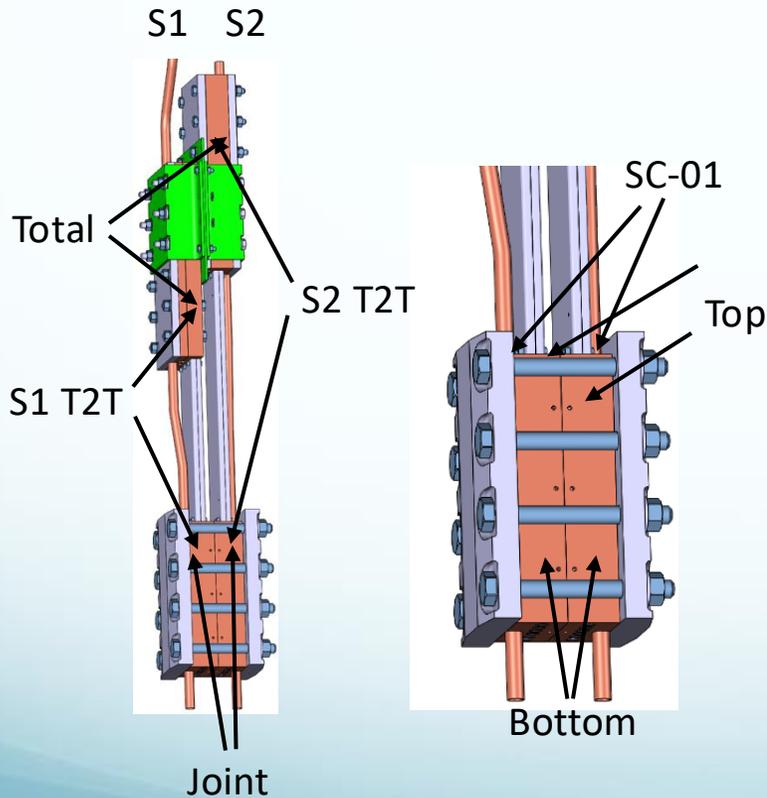
- Sample in vacuum space
- Cryogenic helium gas cooling through tubes
- Liquid nitrogen pre-cool of current leads from room temperature
- GHe CORC<sup>®</sup> feeder cables from LN<sub>2</sub> at 65 K to sample at 25 K



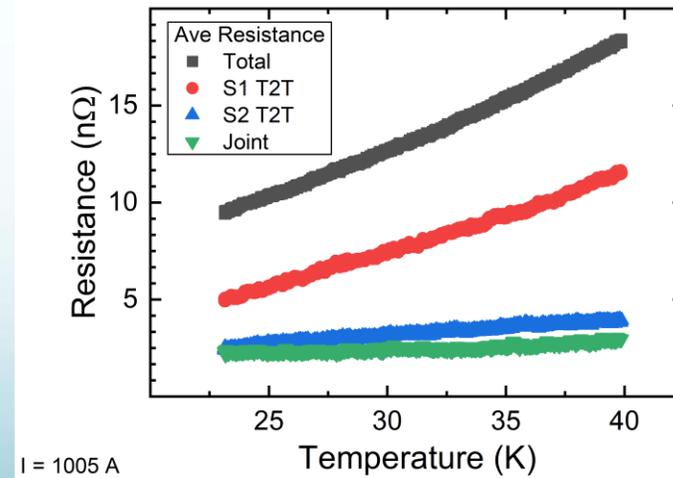
# Test results at 25 K: Silver-plated copper interface

## Sample details

- Two samples with 6 CORC® cables in-plane
- Silver plated copper interface
- Clamped at 15 MPa



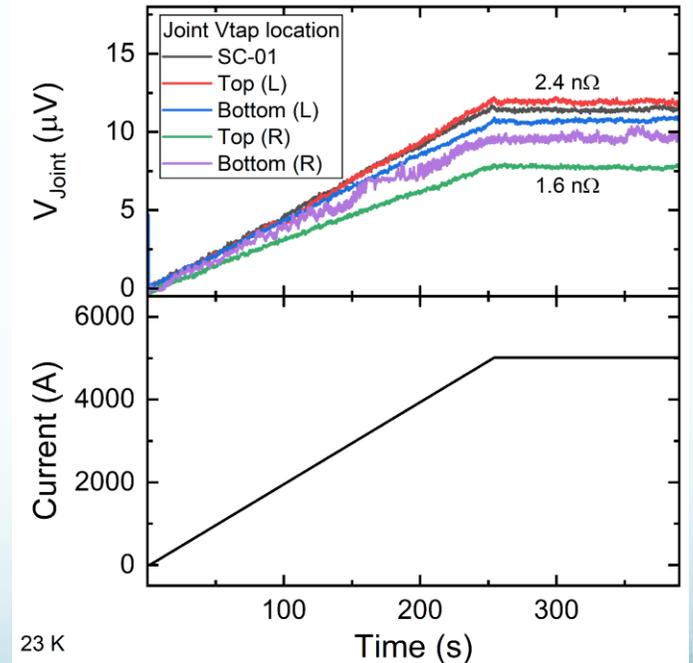
23 K



I = 1005 A

Name	Resistance (nΩ)
<b>SC-01</b>	2.4
<b>Top (L)</b>	2.4
<b>Bottom (L)</b>	2.1
<b>Top (R)</b>	1.5
<b>Bottom (R)</b>	1.9
<b>Calculated*</b>	2.3

\*R(total) - R(S1 T2T) - R(S2 T2T)



23 K



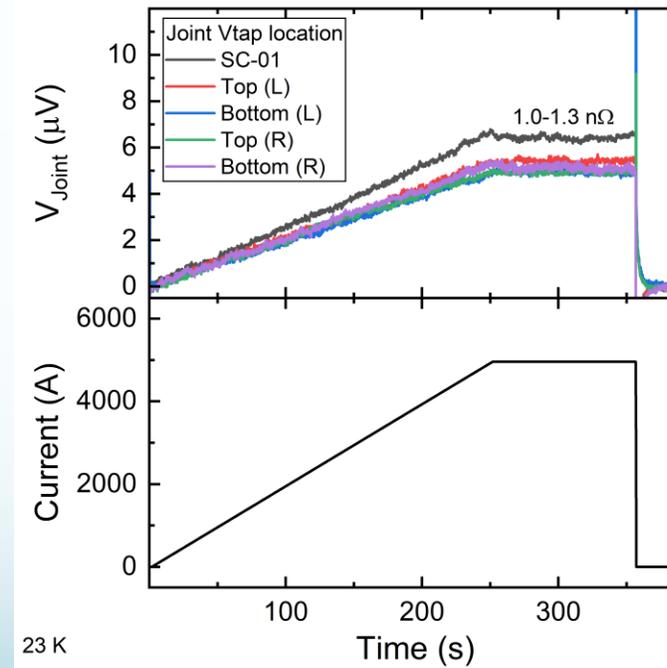
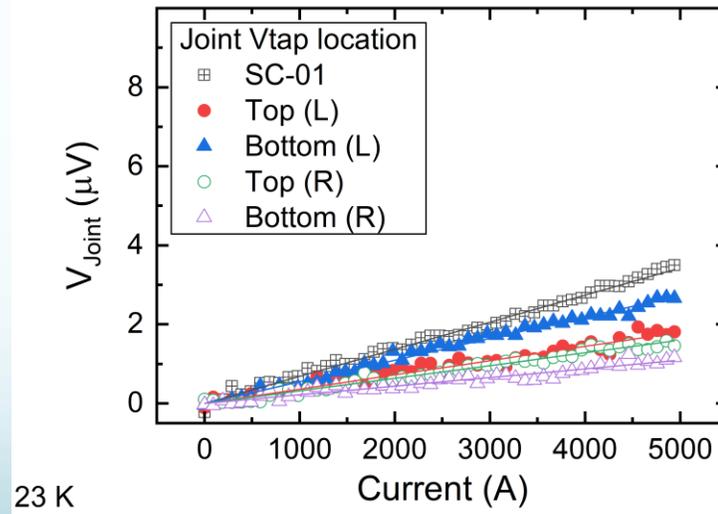
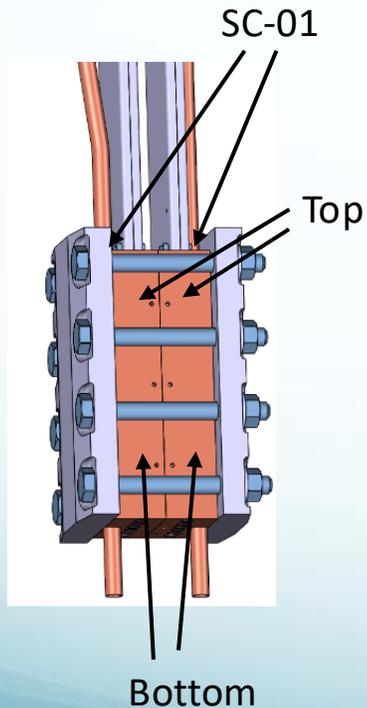
# Test results at 25 K: indium wire interface

## Sample details

- Two samples with 6 CORC® cables in-plane
- Silver plated copper / copper interface
- Indium wire
- Clamped at 15 MPa

Name	Resistance (nΩ)
<b>SC-01</b>	0.7
<b>Top (L)</b>	0.4
<b>Bottom (L)</b>	0.5
<b>Top (R)</b>	0.3
<b>Bottom (R)</b>	0.2
<b>Calculated*</b>	0.2

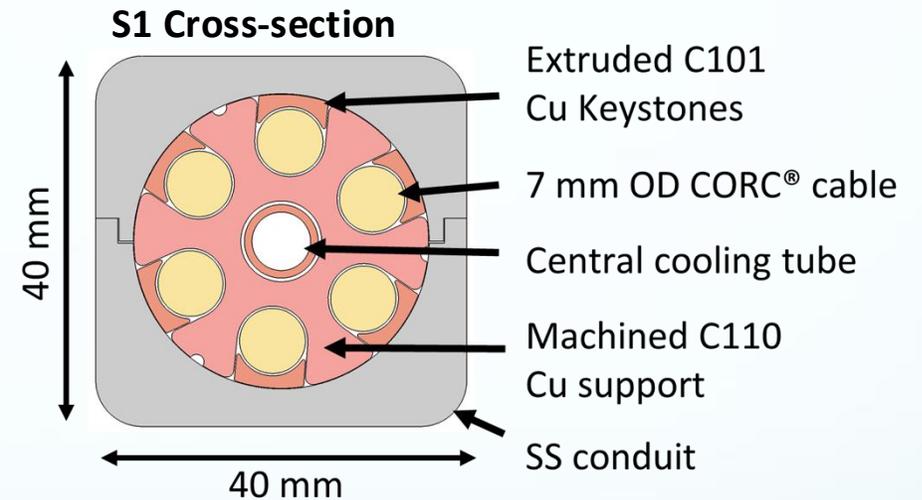
\*R(total) – R(S1 T2T) – R(S2 T2T)



# CORC<sup>®</sup>-CICC testing in SULTAN

## CORC<sup>®</sup>-CICC design with mechanically decoupled cables

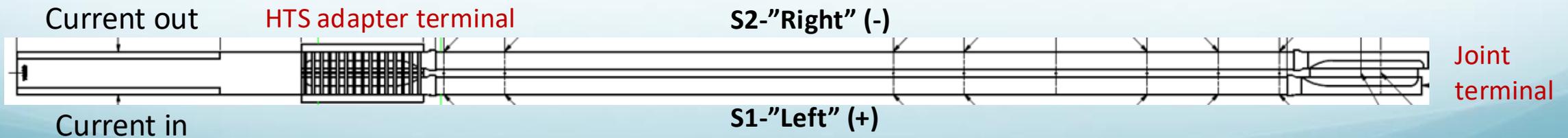
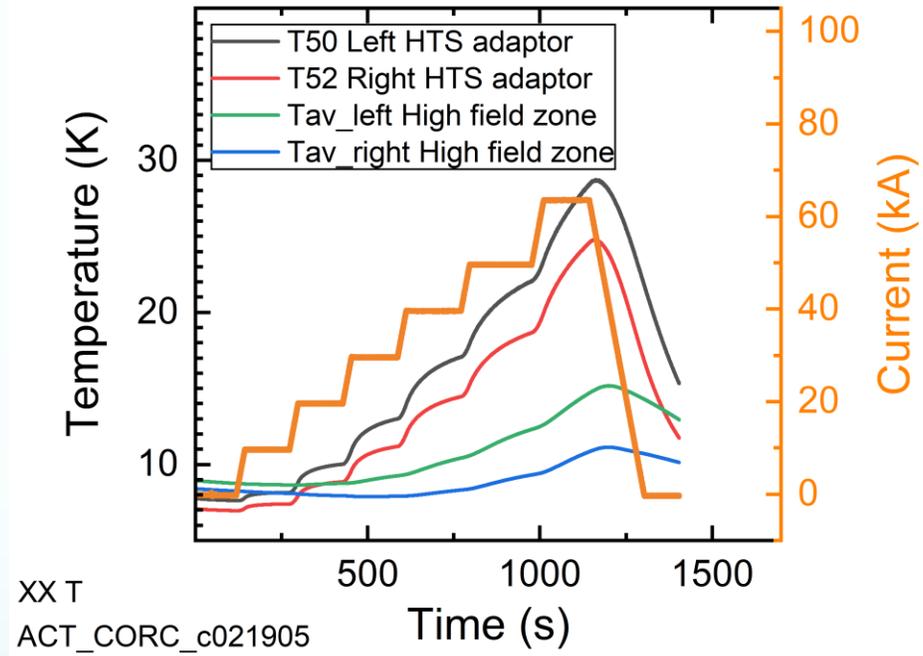
- **S1**: Six 36-tape CORC<sup>®</sup> cables (216 4 mm wide AP tapes)
- **S2**: Eight CORC<sup>®</sup> cables
- Each cable instrumented with voltage wires
- Designed for 80 kA at 10 T and 4.2 K
- Central copper support with grooves
- Single cooling central tube



# Temperature increase due to inadequate cooling

## High current operation in self-field

- Current increased stepwise to 60 kA
- Temperature of HTS adaptor increases significantly at high current



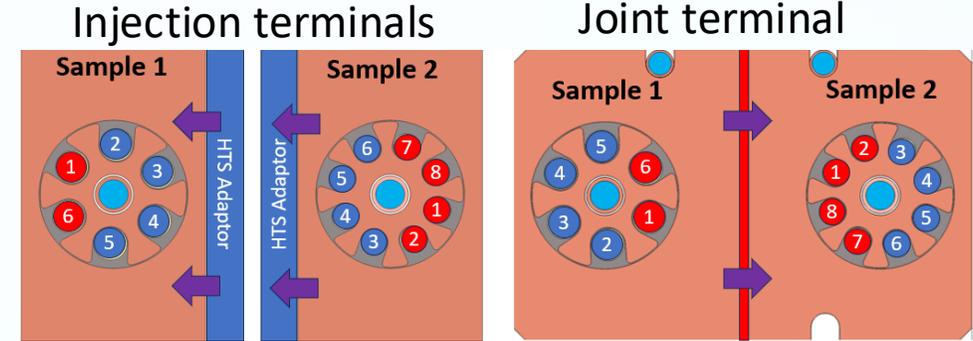
# Thermo-electric voltages drive current redistribution in Sample 1

## Thermoelectric voltages are driving current distribution

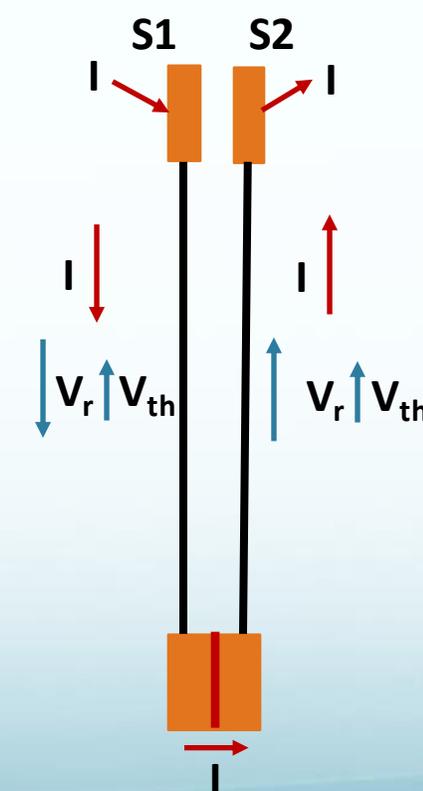
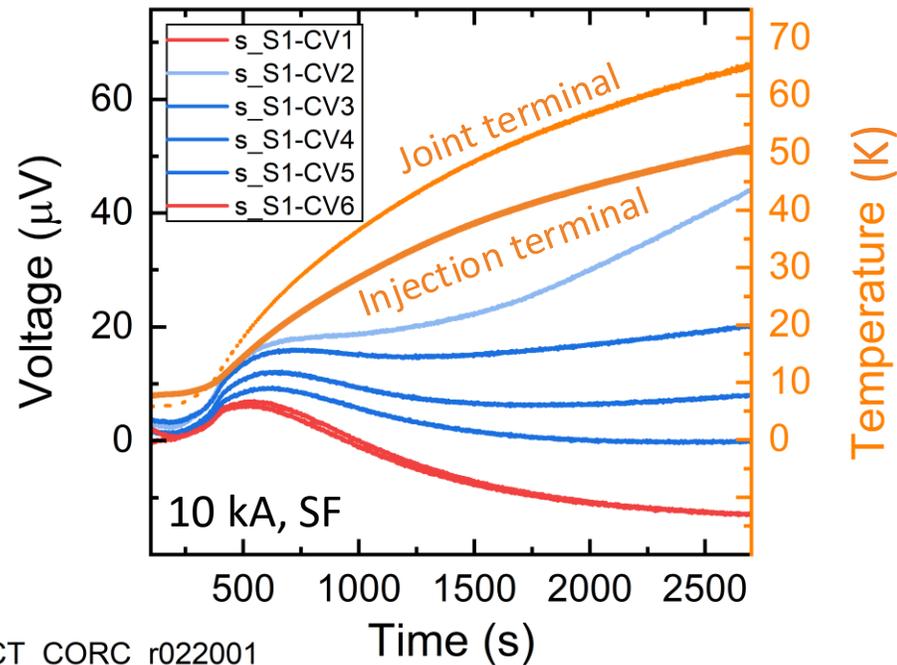
- Continuous current of 10 kA at 0 T field
- Increasing the temperature of both sample legs

### Sample 1

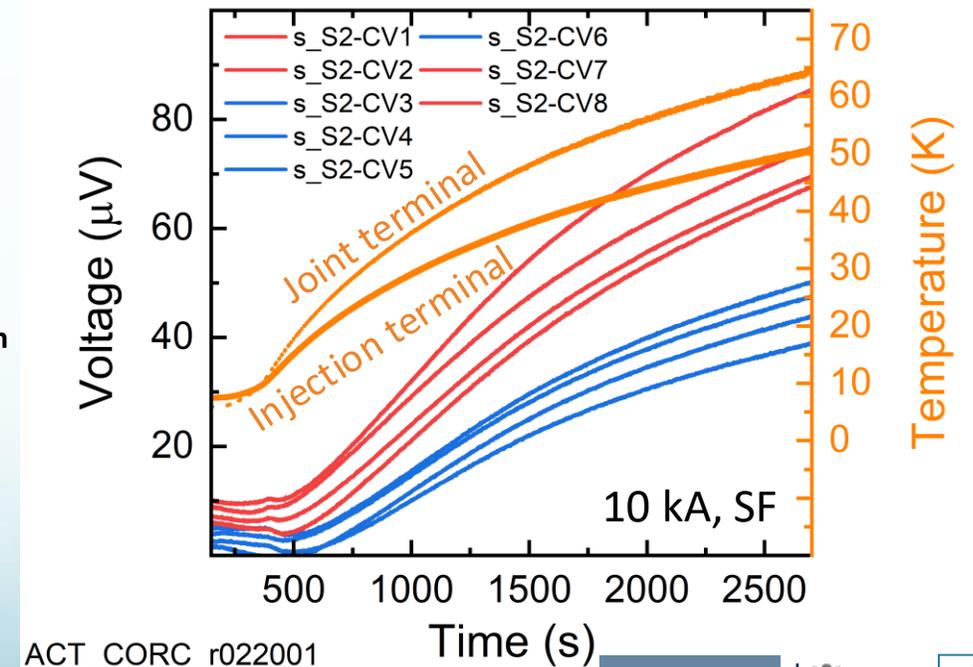
- Voltage goes negative for cables 1 and 6 at  $t = 800$  s
- **Current in CORC® cables 1 and 6 reverses direction!**



### Sample 1: Negative thermoelectric voltage



### Sample 2: positive thermoelectric voltage



ACT\_CORC\_r022001

ACT\_CORC\_r022001

Time (s)



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UK Atomic Energy Authority

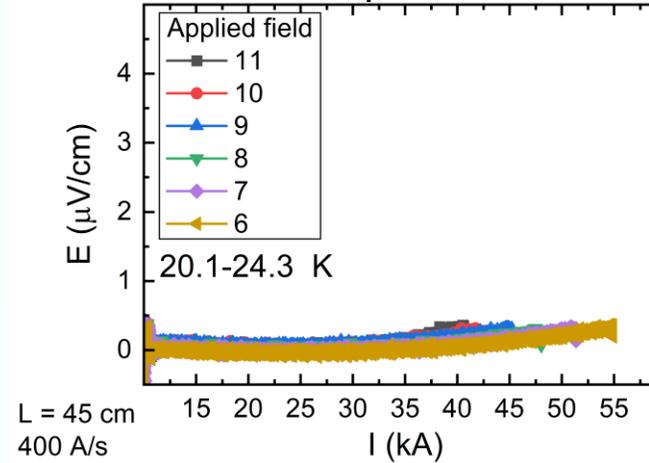


# CORC<sup>®</sup>-CICC SULTAN test results

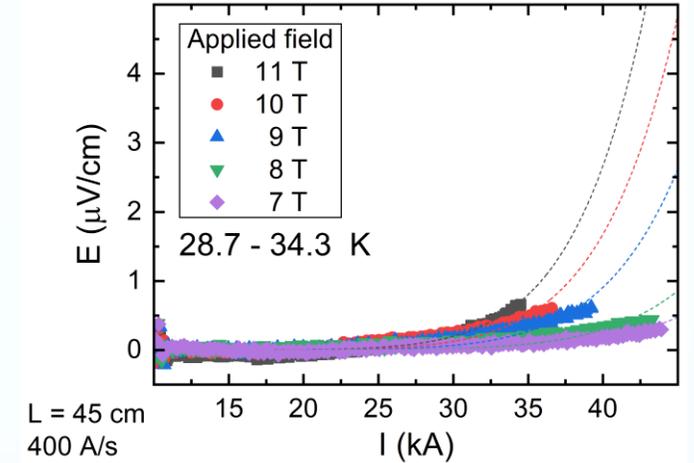
## Performance tests

- Sample 2 limits the performance due to higher level of heating
- Only at higher temperatures, both legs are transitioning at the expected current

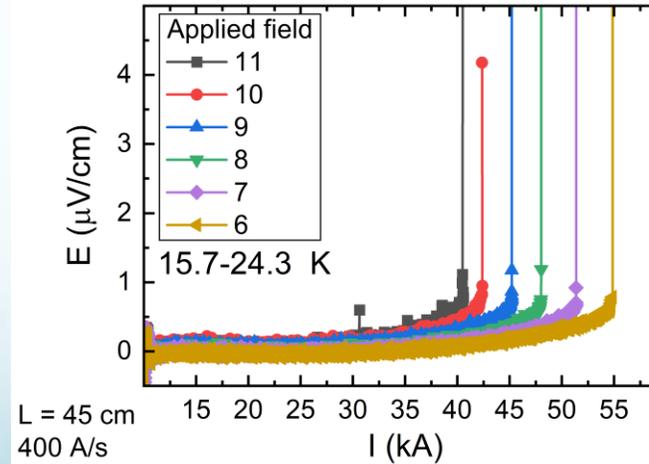
Sample 1



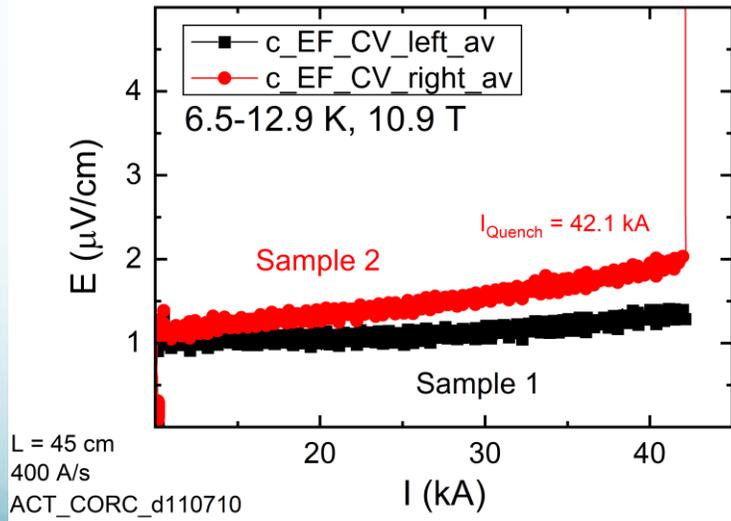
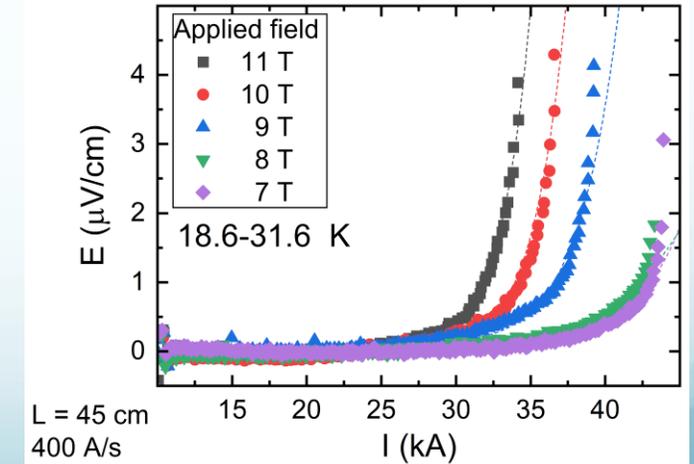
Sample 1



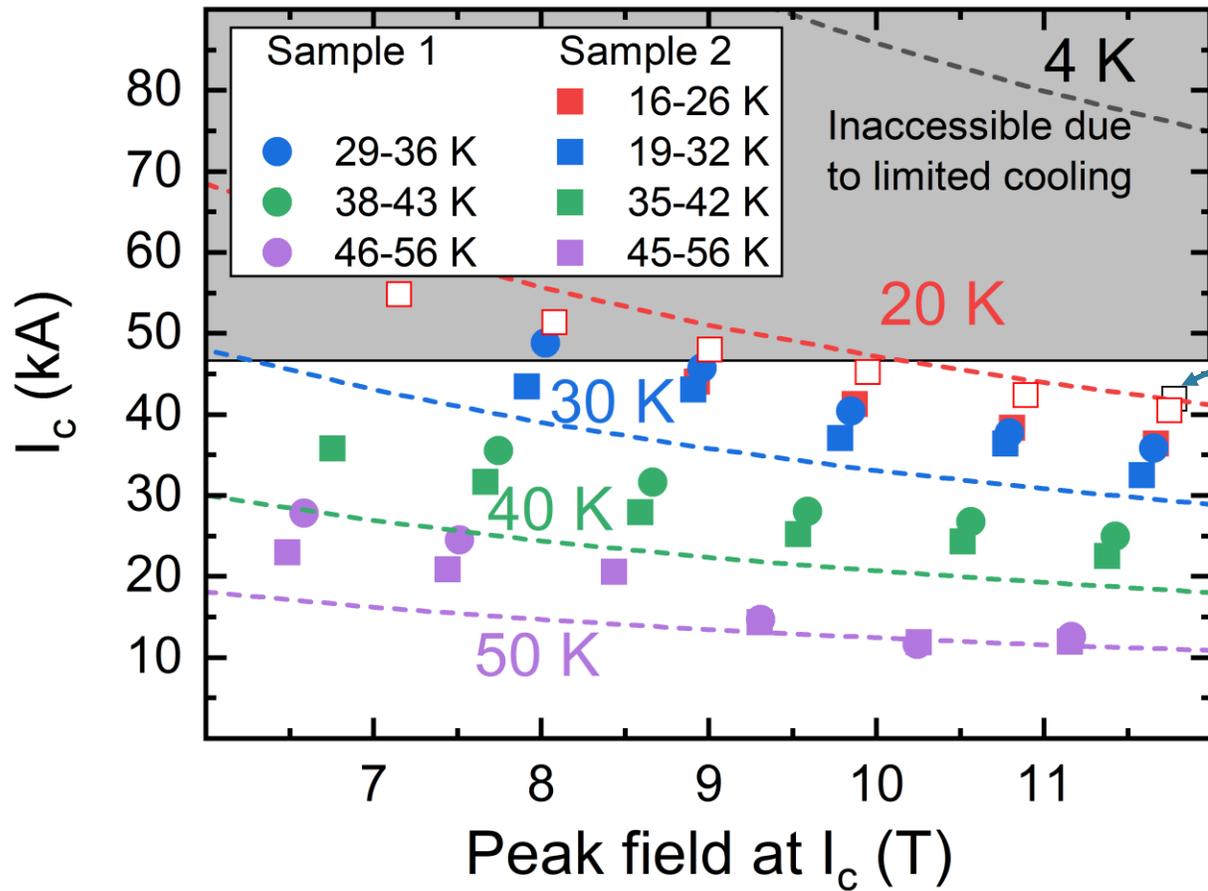
Sample 2



Sample 2



# CORC<sup>®</sup>-CICC SULTAN test results summary



## Results

- 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  $I_c$
- Quenches at low temperature due to inadequate cooling of sample
- Testing at 4 K not possible, because the current heated the sample to 6.5 - 13 K
- No mechanical degradation



# Summary

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## Expanding to high tape count CORC® cables

- 96-Tape CORC® cable with relatively high bending flexibility for Stellarator magnets
- 120-Tape CORC® cable wound from tapes with SnPb solder coating

## CORC®-CICC joint development

- Demonstrated joint resistance of pressed copper interface between CORC®-CICCs of around 0.5 nΩ at 4 K in self-field and 1-2 nΩ at up to 8 T
- Demonstrated joint resistance between silver plated copper terminals of around 2 nΩ at 25 K
- Joint resistance could be reduced to and less than 0.5 nΩ at 25 K by applying indium wires to the interface

## CORC®-CICC SULTAN test

- Performance of latest CORC®-CICC SULTAN sample limited by inadequate cooling due to poor thermal contact between cooling line and terminals
- Sample performed as expected at temperatures above 20 K
- Thermoelectric voltages drive current distribution in sample with very high temperature gradients
- Although only tested to about 50 % of design load, the sample showed no mechanical degradation

