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Development of low-resistance CORC®-CICC joints for use in demountable magnets for fusion and their performance up to 10 kA within a background magnetic field of up to 8 T

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UK Atomic Energy Authority

Conductor-On-Round-Core (CORC®) magnet cables and wires

CORC® cables and wires (2.5-8 mm diameter)

- Wound from 2-4 mm wide REBCO tapes that are helically wrapped around a small copper former
- Typically no more than 50 tapes
- Performance as high as 5-10 kA and 300-600 A/mm^2 at 20 T
- Flexible with bending down to 50-100 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 1 meter

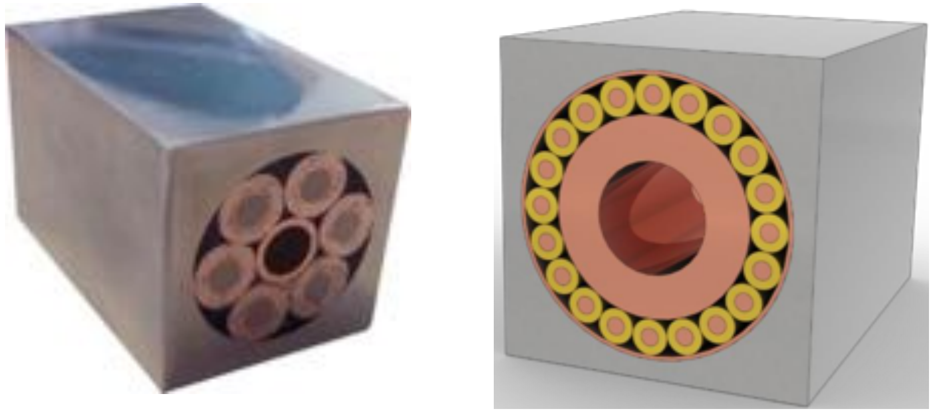


Image courtesy of T. Mulder

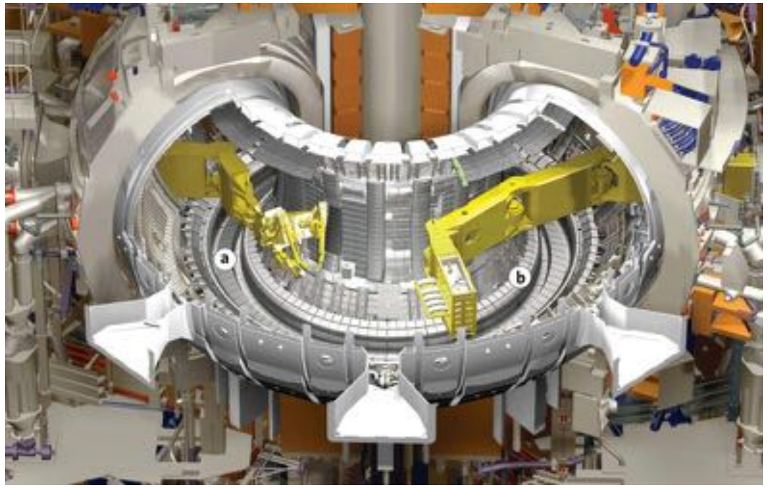
Motivation

Access to the internals of a fusion reactor is difficult with magnet windings in the way. Plasma facing components must be assembled within the magnet windings, like building a boat in a bottle, which complicates maintenance and impacts reactor down-time.

One solution is to incorporate low resistance (<5 nΩ) joints within each turn in the Toroidal field coils, allowing them to be disassembled.

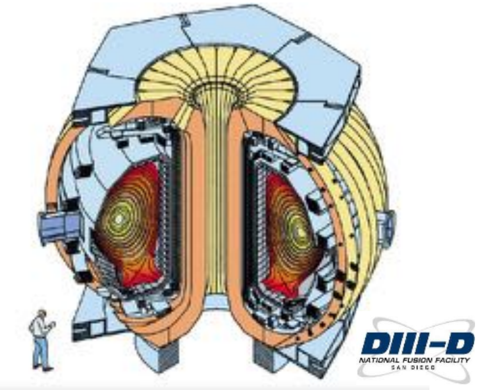
Terminations and joints are being developed for CORC® that are compact, robust and easy to incorporate into magnet designs

Schematic of robotic maintenance of JET facility

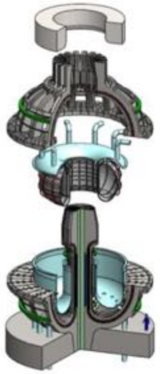


https://www.nature.com/articles/nphys3755/figures/1

Demountable joints allow better access to experiment



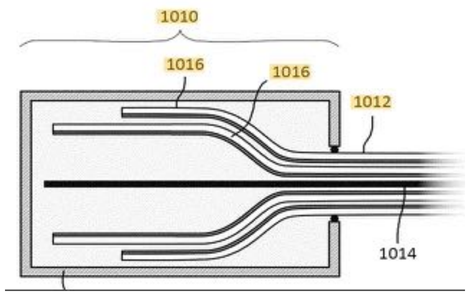
Alcator C-Mod



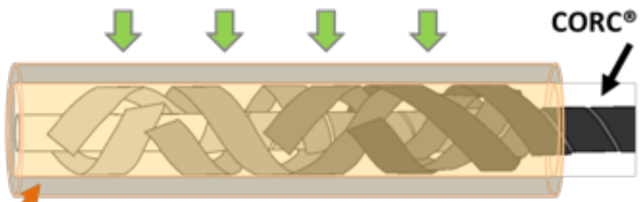
ARC concept

Route to demountable HTS magnets for fusion

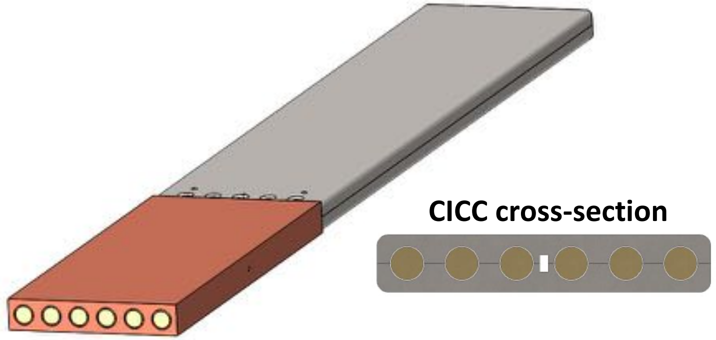
Ensure even contact resistance where tapes are terminated

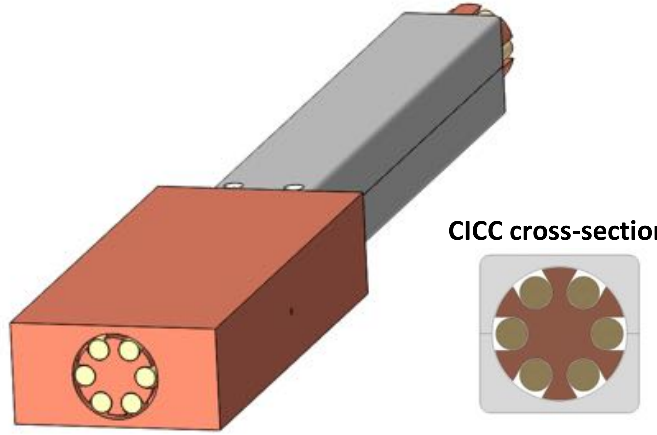


Patent: Van der Laan: US9755329B2

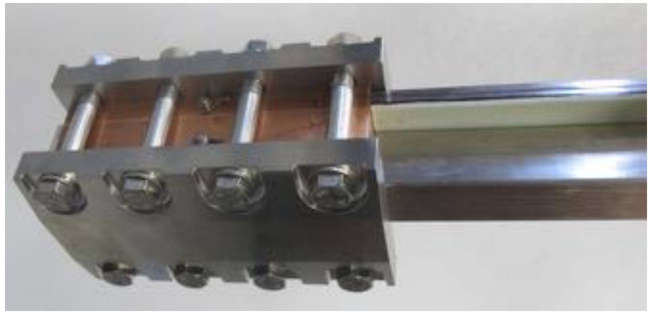


Terminate several CORC cables into joint structure





Simple joint test: Cu-to-Cu dry pressed contact between two flat samples (aiming for < 5 nΩ at 8 T)



An actual toroidal field coil could have 40-100 such joints. Example: 84 turns at 48 kA ~387 W given 1 nΩ resistance per joint

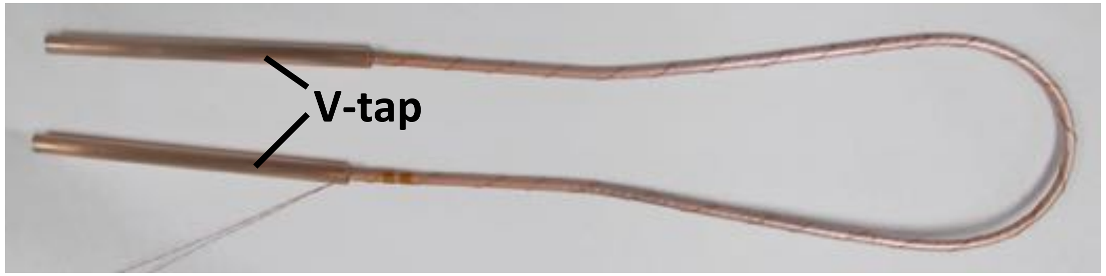
Measurement on joint between two CORC® cables

What are the V(I,B) characteristics of a joint between two individual CORC® cables?

In-field joint test between CORC® cables

- Hairpin 30-tape CORC® cable sample is tested at 4.2K, followed by cutting the sample, adding a joint, and retesting in a background field
- Voltage measured over terminations to capture entire voltage over the cable (not just the voltage over a single tape)

Initial measurements on bent sample to get the terminal's contribution to resistance



Terminal resistance

$$V = IR^{\text{term}}$$

Second measurements on sample after cutting and adding a joint to get the Joint + terminal's contribution to resistance

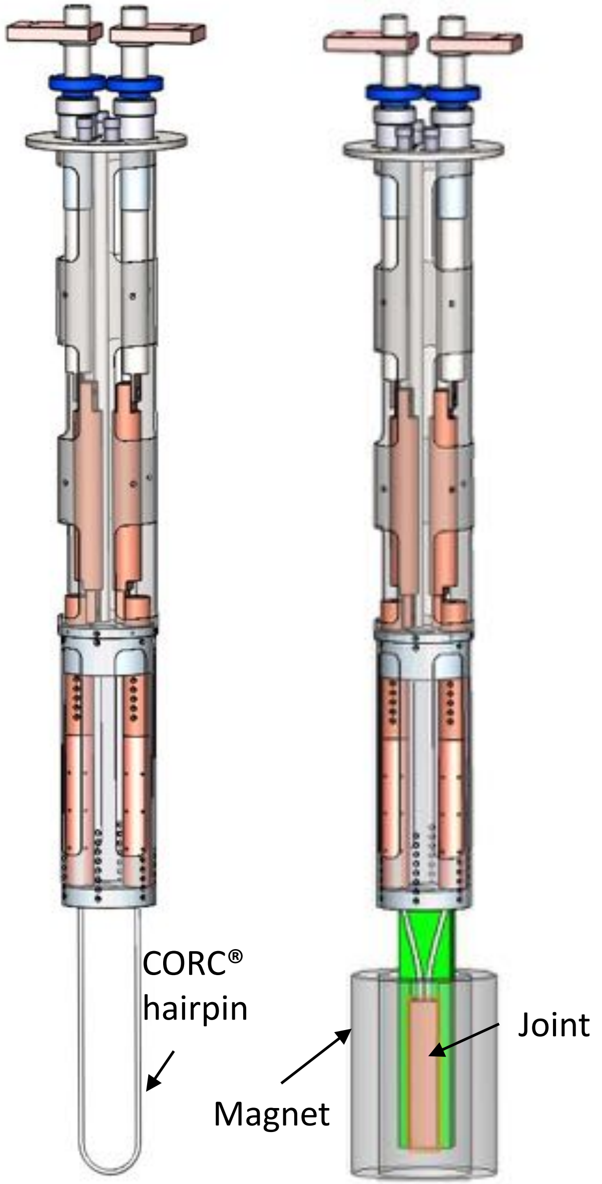
OFHC Cu joint (ρ = 0.13 nΩ-m)

Joint resistance

$$V = IR^{\text{term}} + IR^{joint}$$

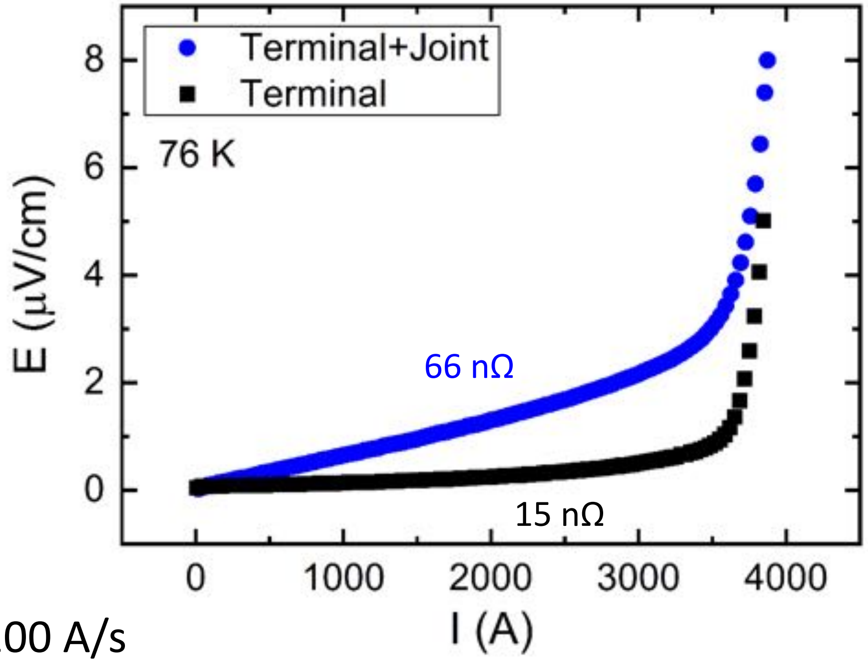
First test w/o joint

Second test w/ joint



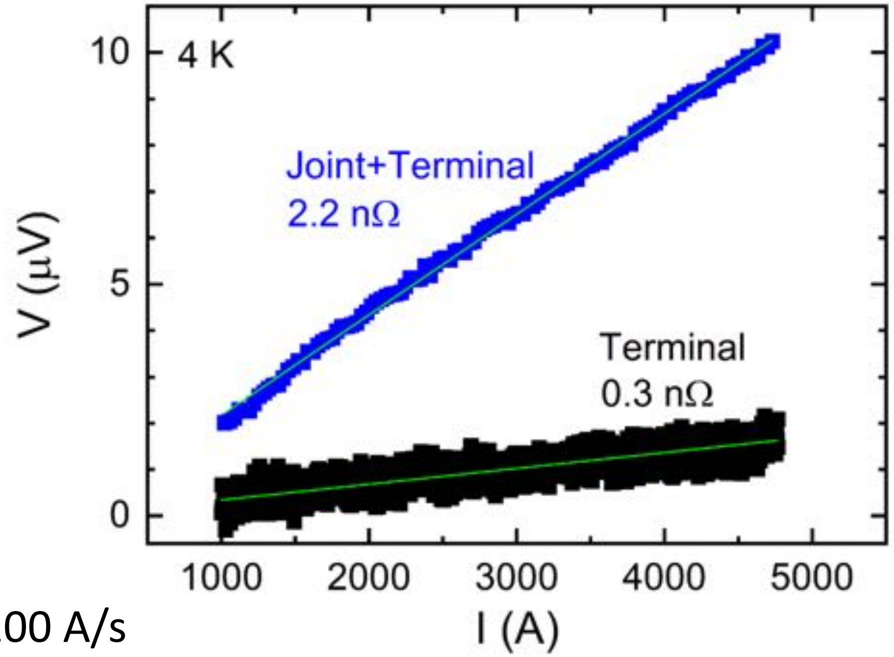
V(I) before and after adding joint

76 K



200 A/s
L = 93 cm

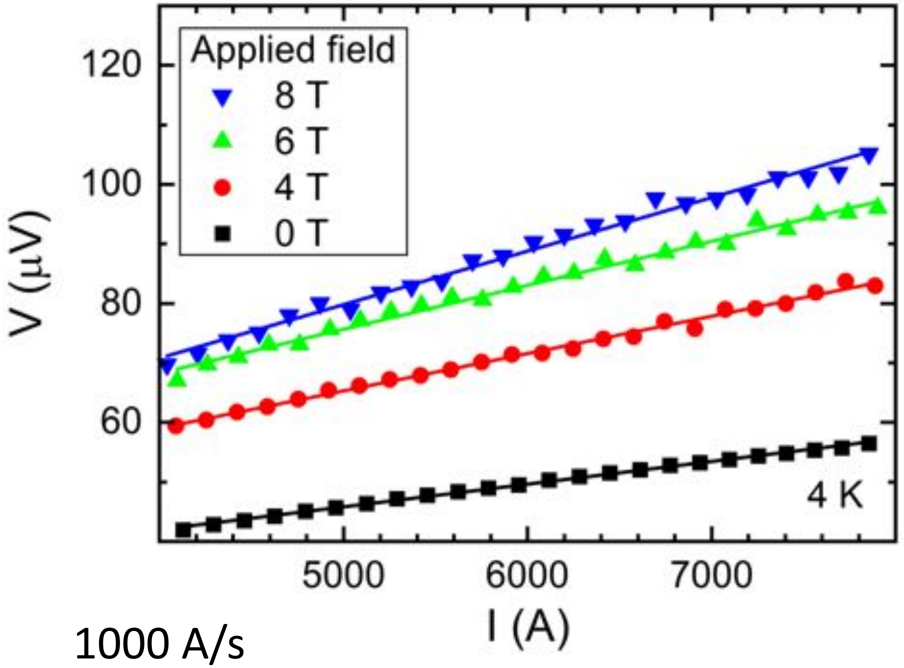
4 K



200 A/s

V(I) of joint tested in-field at 1000 A/s up to 8 kA

Magneto-resistance effects exist and must be considered in demountable TF coils that will be operated within relatively large magnetic fields



1000 A/s

Summary

		CORC® cable joint
Conductor ID		170404
Joint dimensions [TxWxL]	mm	16x38x200
77 K Terminal resistance	nΩ	14.7
77 K Joint resistance	nΩ	51.4
4 K, 0 T Terminal resistance*	nΩ	0.3
4 K, 0 T Joint resistance*	nΩ	1.9
4 K, 8 T Joint resistance**	nΩ	8.3

*Determined at 200 A/s ramp rate

**Determined at 1000 A/s ramp rate

Development of demountable CORC® joints

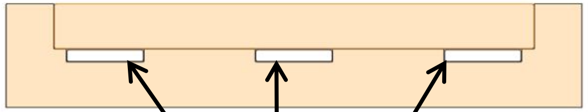
What are the characteristics of demountable HTS joints in significant applied fields?

Three CICC sample layouts tested

Rated for >20 kA operation at 7 T

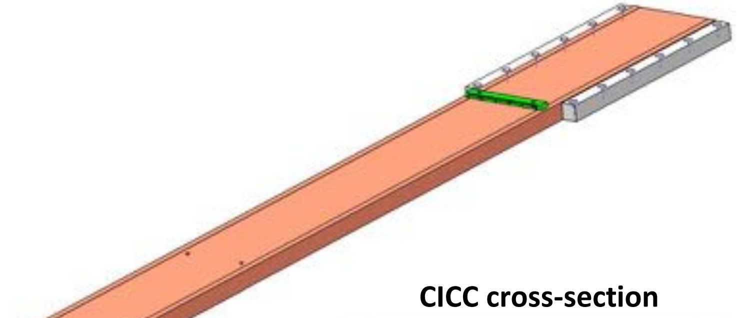
3 X LTS NbTi Rutherford cable-based CICC

Termination cross-section

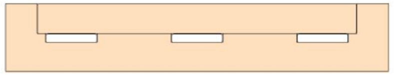


61 x 11 mm

NbTi Rutherford cables



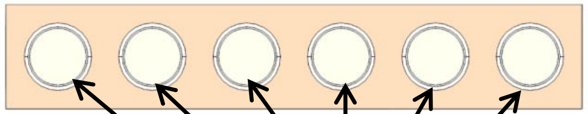
CICC cross-section



6x plate CORC® CICC

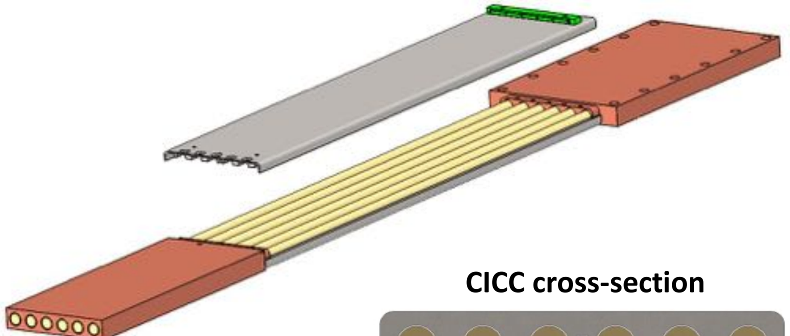
(cables contain 12 tapes each)

Termination cross-section

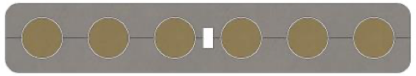


61 x 11 mm

CORC® cables



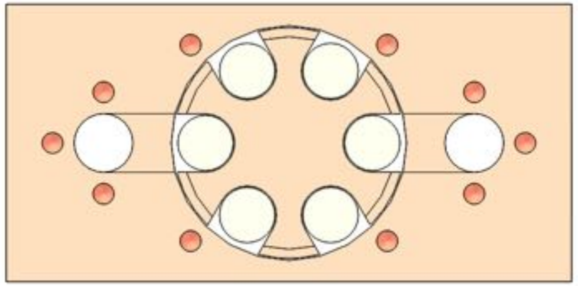
CICC cross-section



6x1 round CORC® CICC

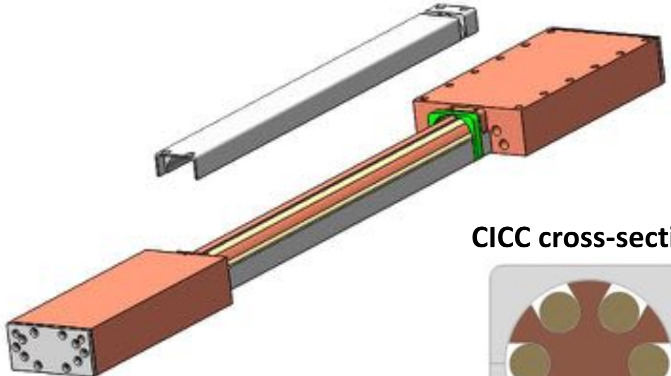
(cables contain 12 tapes each)

Termination cross-section



Joint: 61 x 30 mm

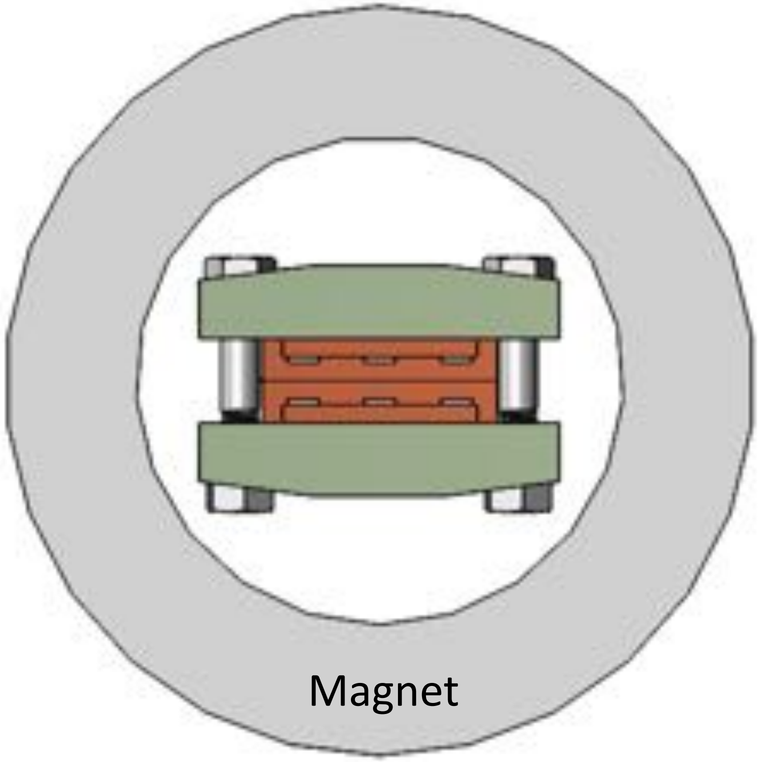
CICC: 30 x 30 mm



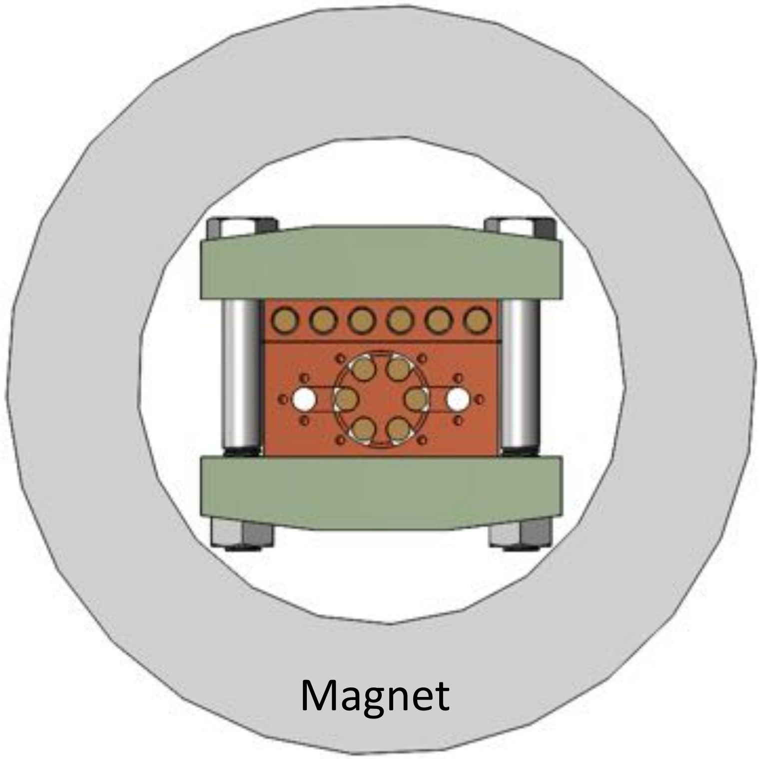
CICC cross-section

Samples connected in series with dry contact Cu-to-Cu joint in 8 T solenoid magnet

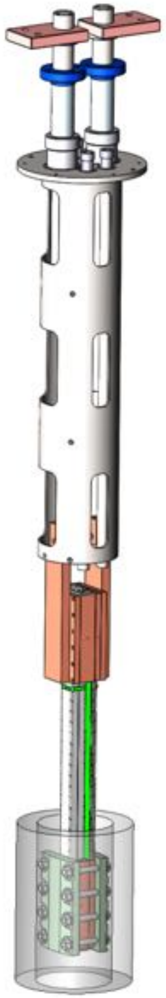
LTS to LTS joint



HTS 6x1 to HTS plate joint

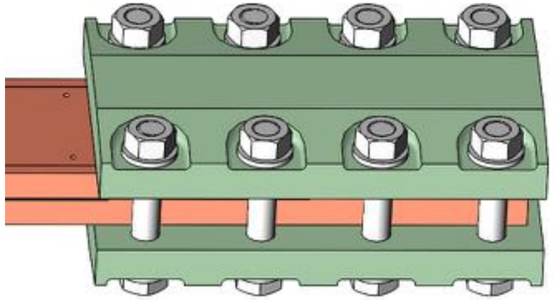


Model and picture of assembled sample probe

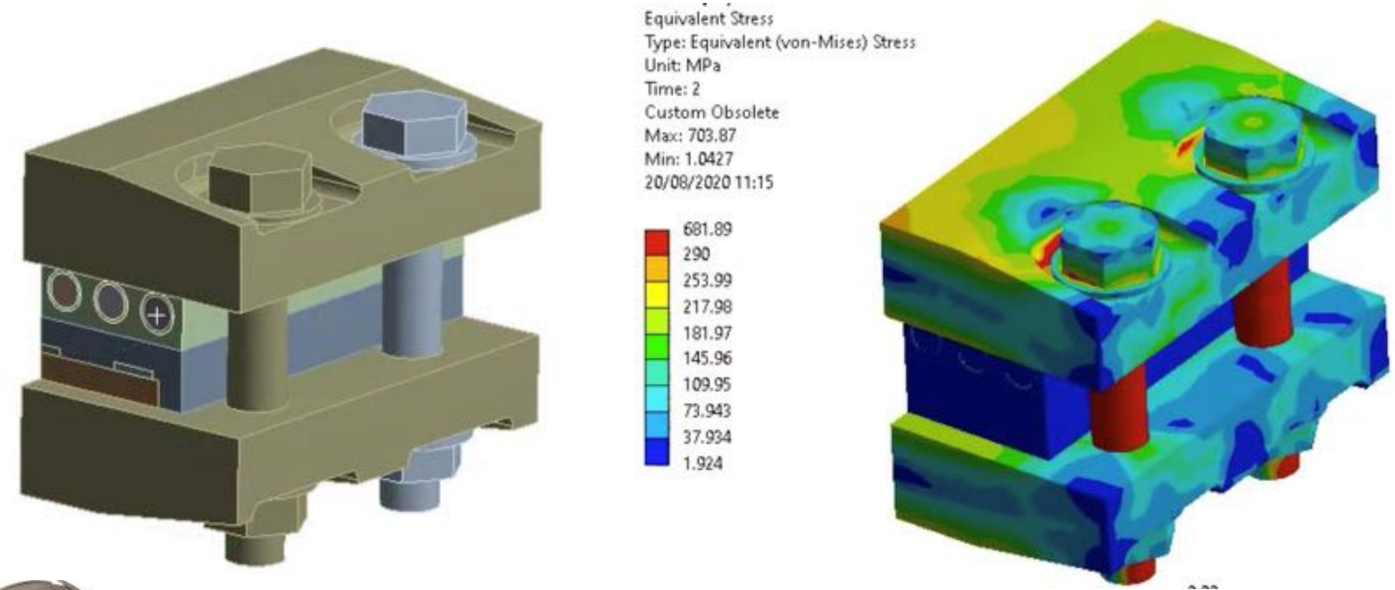

Magnet

UK Atomic Energy Authority

Modeling and testing to verify contact pressure exceeds 10 MPa

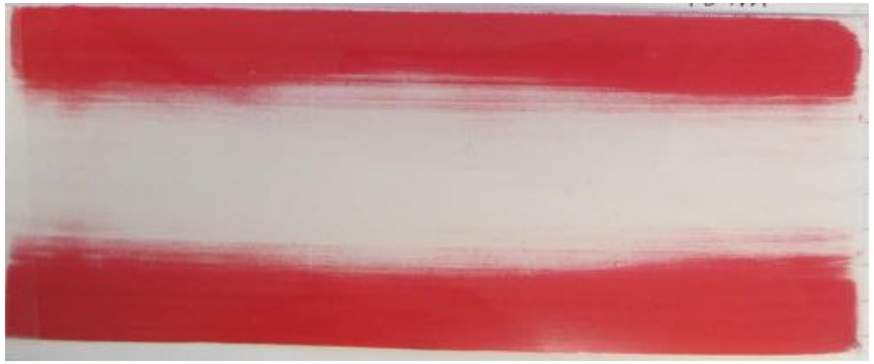


FEM simulations to determine stresses in clamping structure and contact pressure within joint



Fuji-film pressed between copper joint
Red shows > 10 MPa pressure

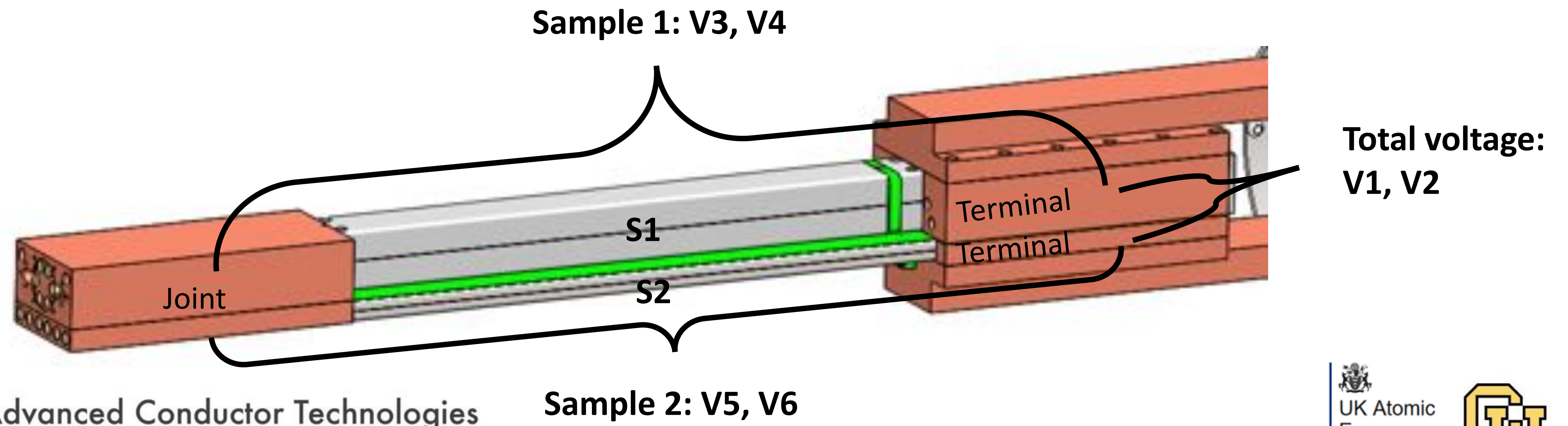
Using unannealed copper



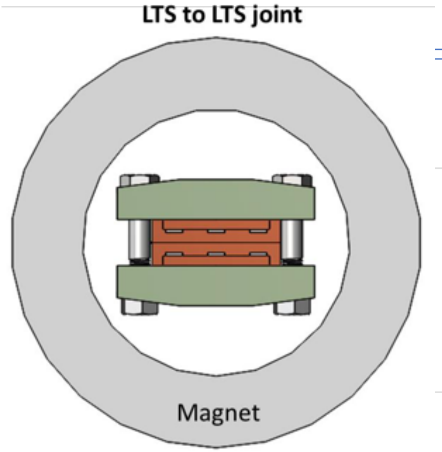
Using annealed copper (2h @ 575 ^{o}C)

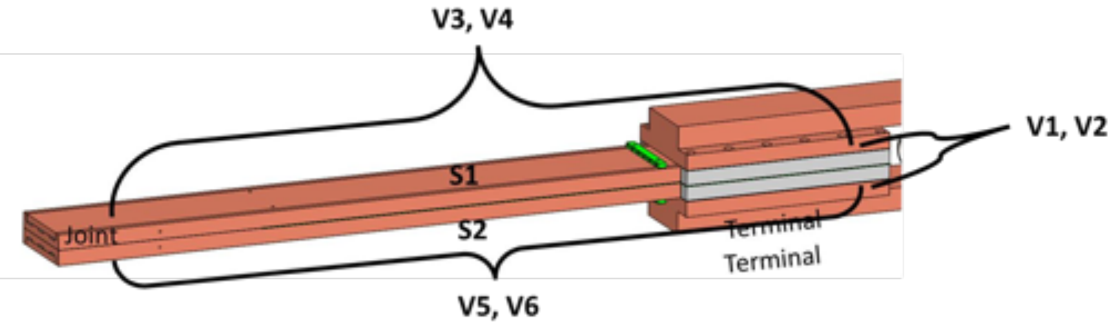
Instrumentation summary

Voltage contact	Location
V1	Overall sample voltage (left side)
V2	Overall sample voltage (right side)
V3	Voltage sample 1 (left side)
V4	Voltage sample 1 (right side)
V5	Voltage sample 2 (left side)
V6	Voltage sample 2 (right side)

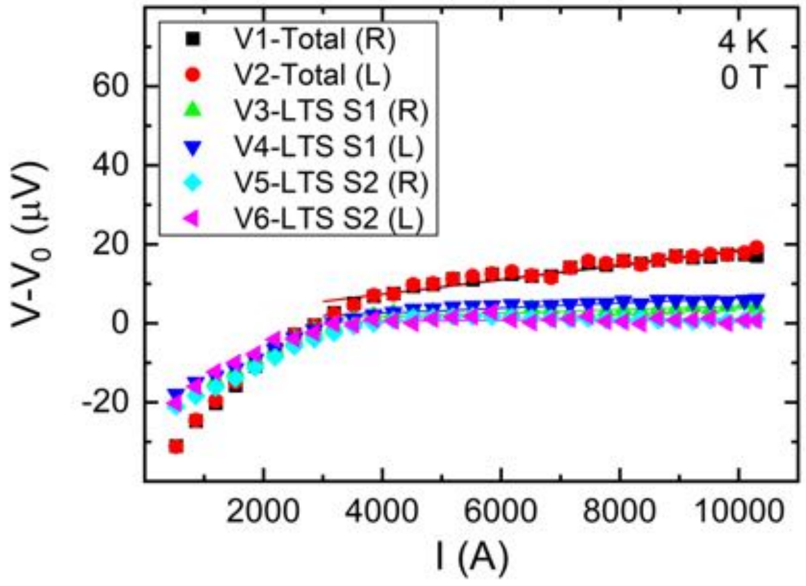


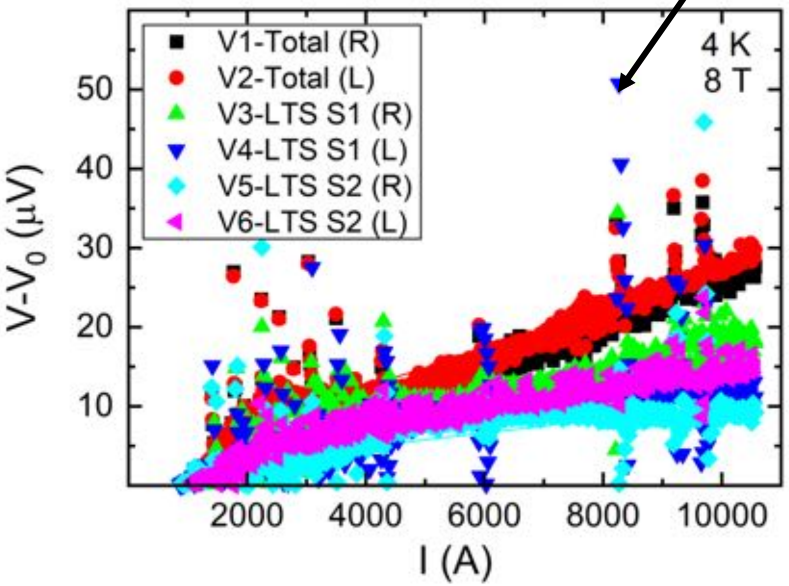
V(I) of LTS sample pair at 4 K





Voltage spikes appear in applied field. Could be from sample movement or instabilities from being close to LTS critical surface

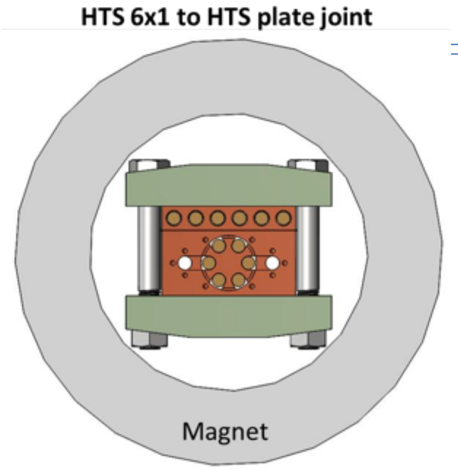


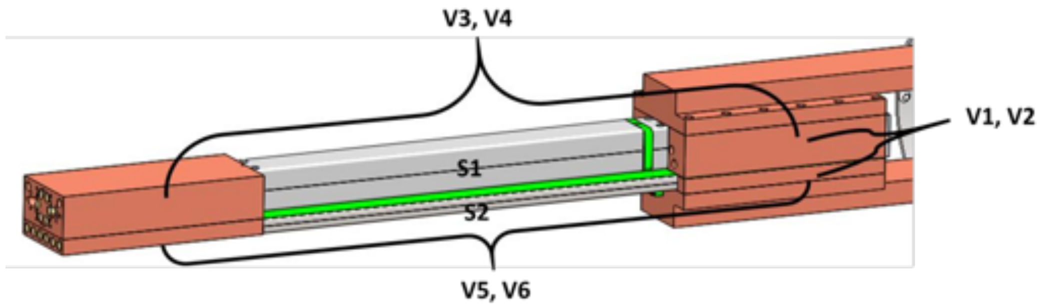


B [T]	Average Resistance (4 K) [nΩ]		
	Total (V1,V2)	LTS-1 (V3,V4)	LTS-2 (V5,V6)
0	1.8	0.5	0.1
4	2.2	1.0	0.8
6	2.4	1.1	0.9
8	2.3	1.3	1.0

1000 A/s

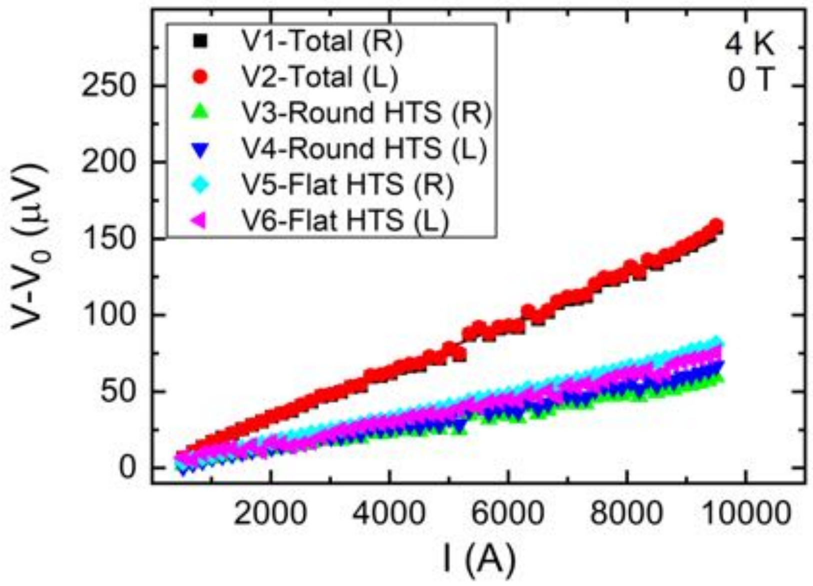
V(I) of HTS sample pair at 4 K

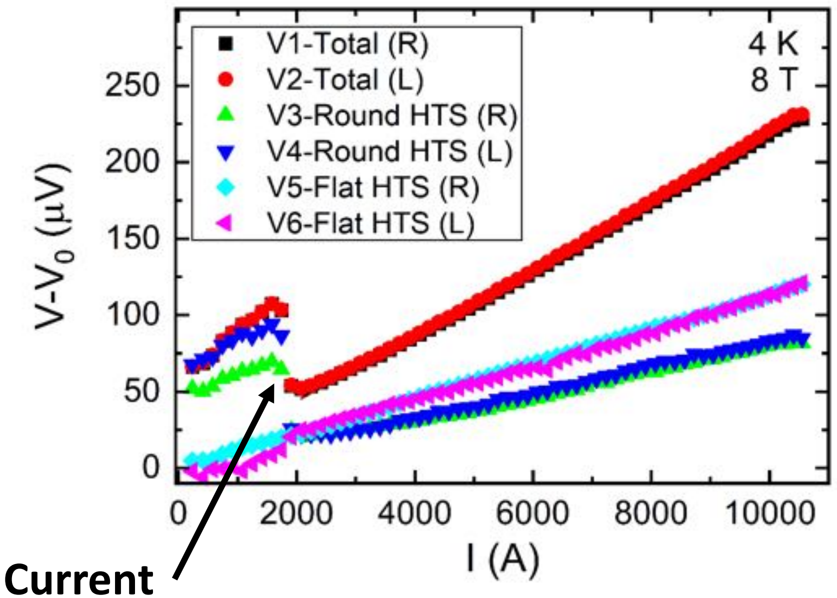




Higher than expected resistance!

Led to study on joint heating effects





B [T]	Average Resistance (4 K) [nΩ]		
	Total (V1, V2)	Round HTS (V3,V4)	Flat HTS (V5,V6)
0	15.8	6.2	7.8
4	18.6	6.7	9.8
6	19.9	7.2	10.4
8	21.7	8.0	11.3

1000 A/s

Current redistribution!

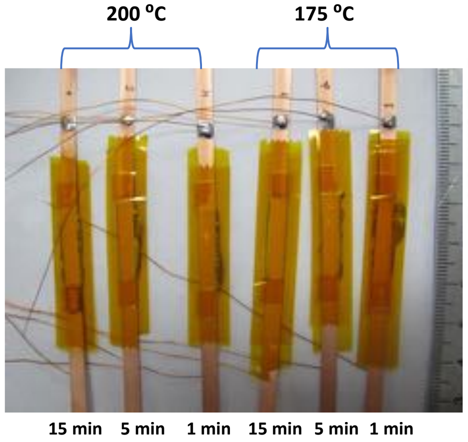
Exploring the cause of the high contact resistances in the HTS-to-HTS joint

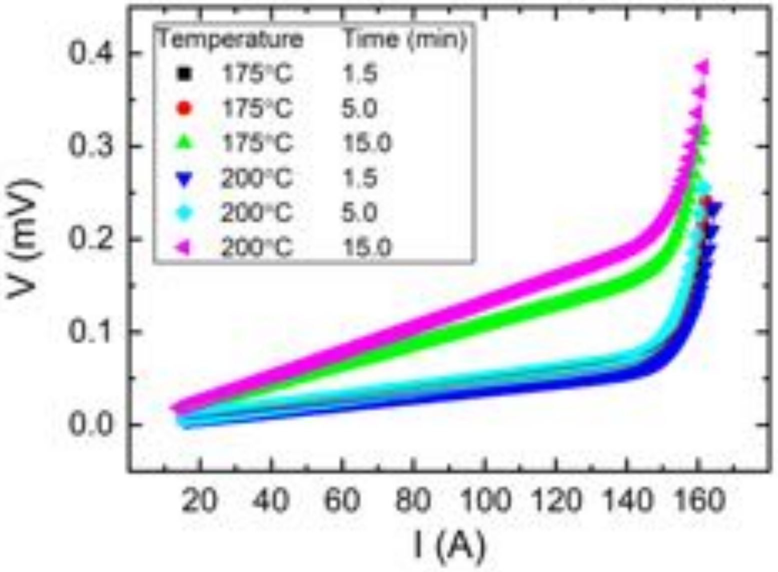
Copper used by machine shop to make joint, not pure copper!

		Resistivity			
Part	**Temper**	**293 K (nΩ*m)**	**76 K (nΩ*m)**	**4 K (nΩ*m)**	**RRR (293K/4K)**
annealed copper wire	H00 (1/8 CW)	17.08	1.93	0.08	225
half-hard copper wire	H02 (1/2 CW)	16.73	2.15	0.20	85
round CORC® CICC-01	As-received	19.36	4.55	2.61	7
round CORC® CICC-01	Annealed	18.14	4.30	2.38	8
plate CORC(r) CICC	As-received	18.20	2.19	0.20	90
plate CORC(r) CICC	Annealed	17.90	2.02	0.06	305
LTS CICC -01	As-received	17.83	2.25	0.22	83
LTS CICC -01	Annealed	17.52	1.96	0.07	257
LTS CICC-02	As-received	18.19	2.28	0.23	79
LTS CICC-02	Annealed	16.82	1.93	0.06	269

Soldering time strongly influences contact resistance in tape-to-tape lap joints made using indium solder

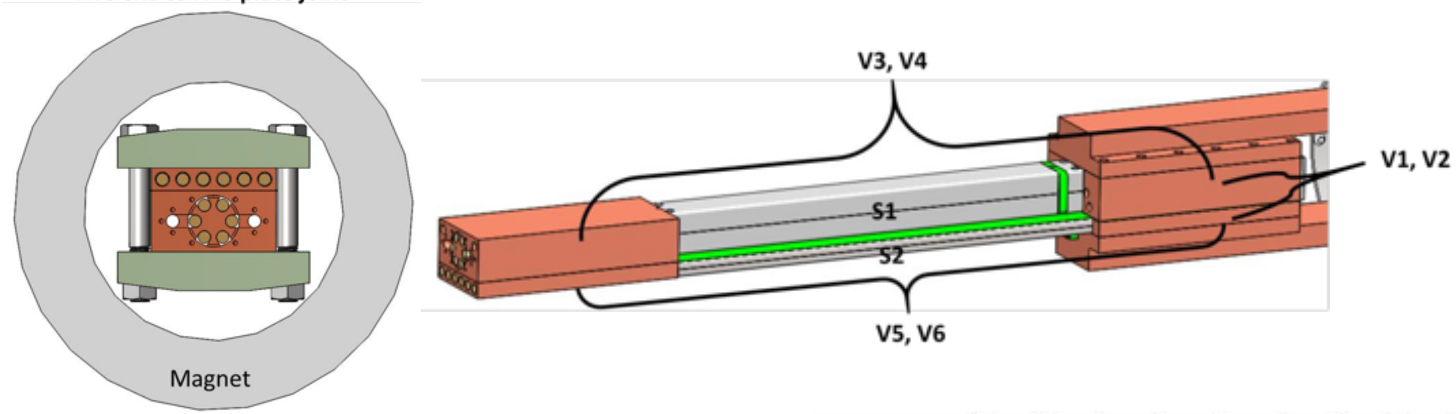
R_c increases by a factor of 2-4 between heating for 5 minutes and heating for 15 minutes – Likely mechanism is oxygen diffusion out of REBCO surface





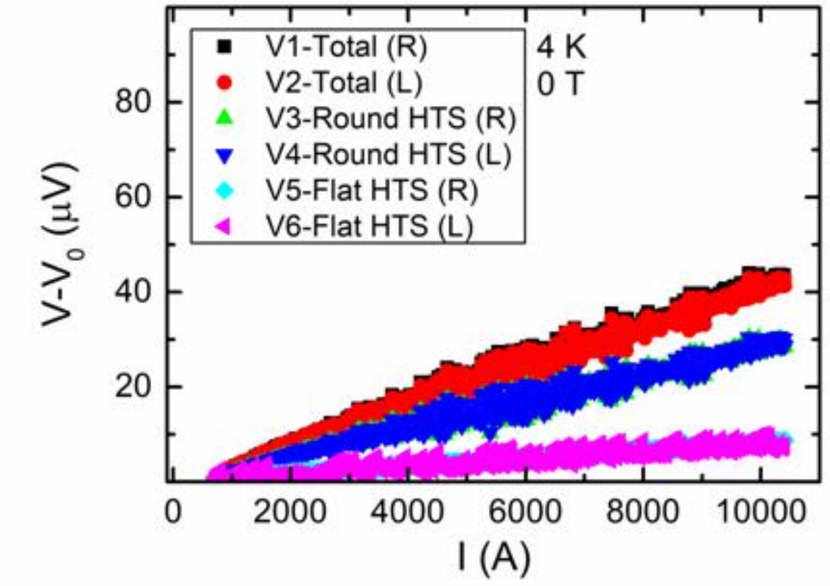
V(I) of second HTS sample pair using pure copper and short heating time

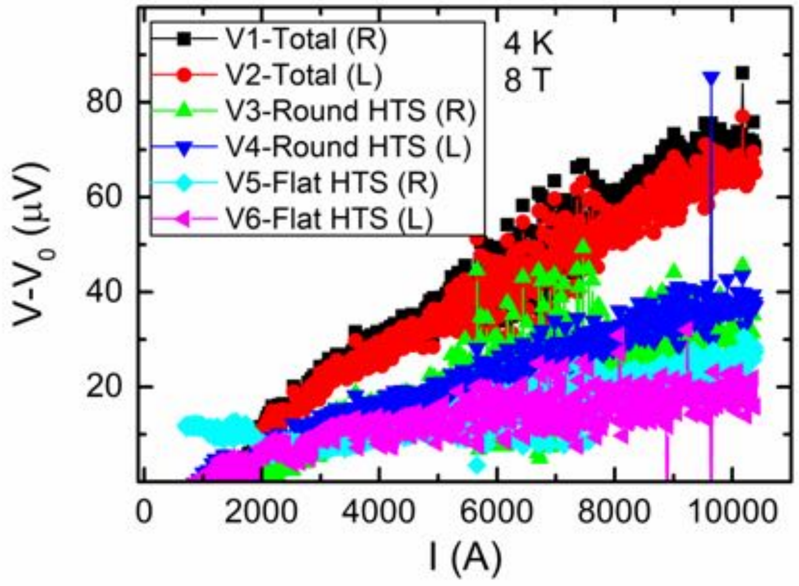
HTS 6x1 to HTS plate joint



3 kW heater block used to decrease soldering duration to < 10 minutes

Loop resistance decreased significantly compared to first HTS pair from 15.8 nΩ to 4.1 nΩ at 4.2K, 0 T



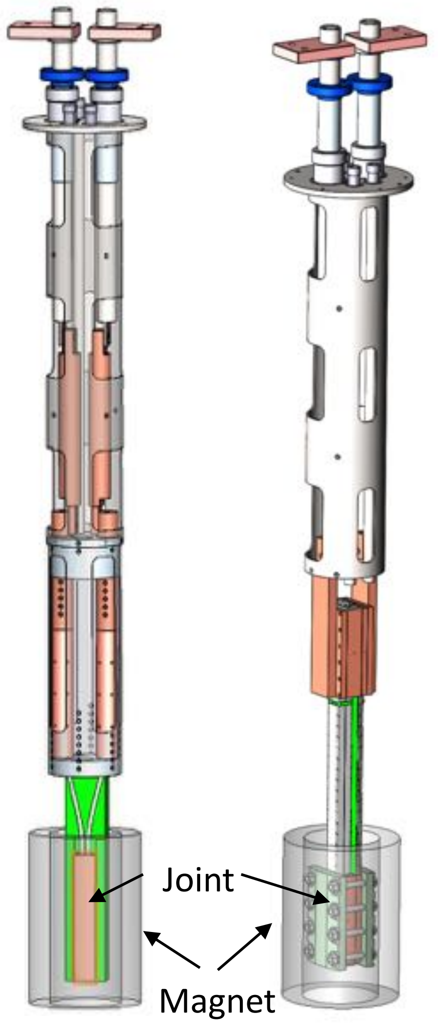


B [T]	Average Resistance (4 K) [nΩ]		
	Total (V1,V2)	Round HTS (V3,V4)	Flat HTS (V5,V6)
0	4.1	2.8	0.8
4	5.2	3.0	1.3
6	6.1	3.4	1.5
8	6.9	3.6	1.9

1000 A/s

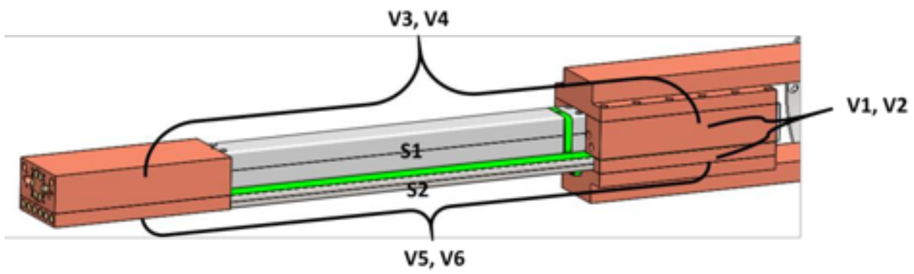
Summary

- **Development of cable-to-cable CORC® joints**
  - **77 K:** ~50 nΩ per joint (terminal resistance subtracted)
  - **4 K:** ~2 nΩ per joint (terminal resistance subtracted)
- **Demonstration of demountable HTS CORC® CICC joints**
  - Joint resistance at 4 K**:** ~4 nΩ for total sample loop consisting of 4 SC-to-Cu interfaces and a dry Cu-to-Cu joint!
    - Depended on solving key issues that came up during R&D test campaigns:
      - Joint surface temper
      - Copper quality
      - HTS cable heating time when terminating
  - Flat HTS sample performed similar to LTS CICC conductor 1-2 nΩ terminal to terminal resistance measured up to 8 T

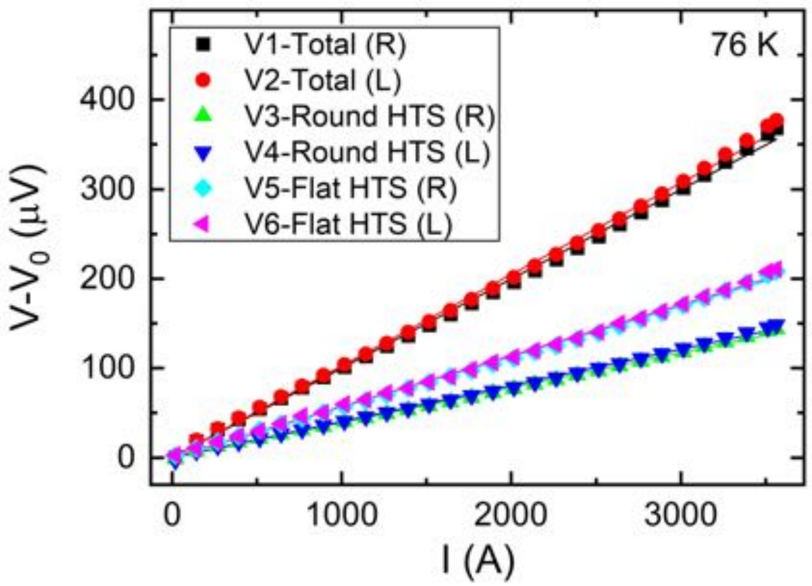


Work supported in part by
U.S. Department of Energy awards numbers DE-SC0013723 and DE-SC0014009

Extra slide - V(I) of HTS sample pairs at 76 K



First HTS sample pair



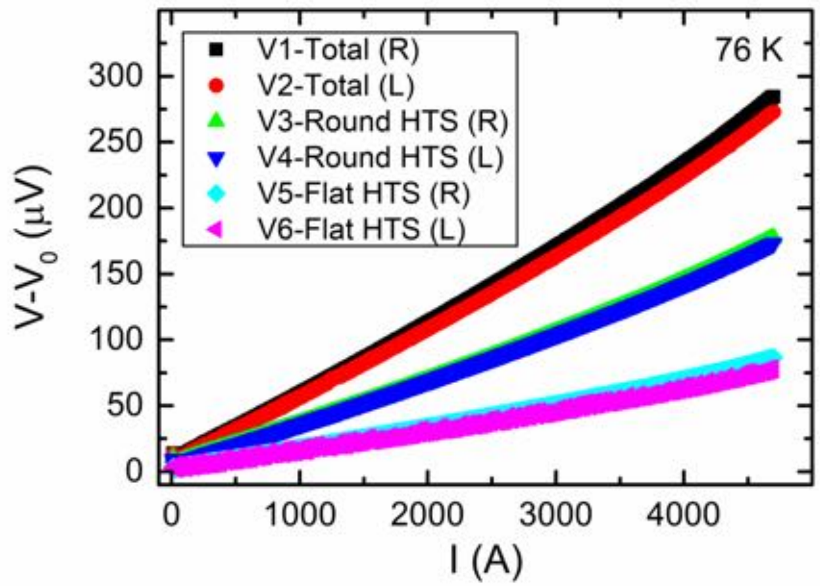
102 nΩ

40 nΩ

56 nΩ

500 /

Second HTS sample pair with improved soldering duration



58 nΩ

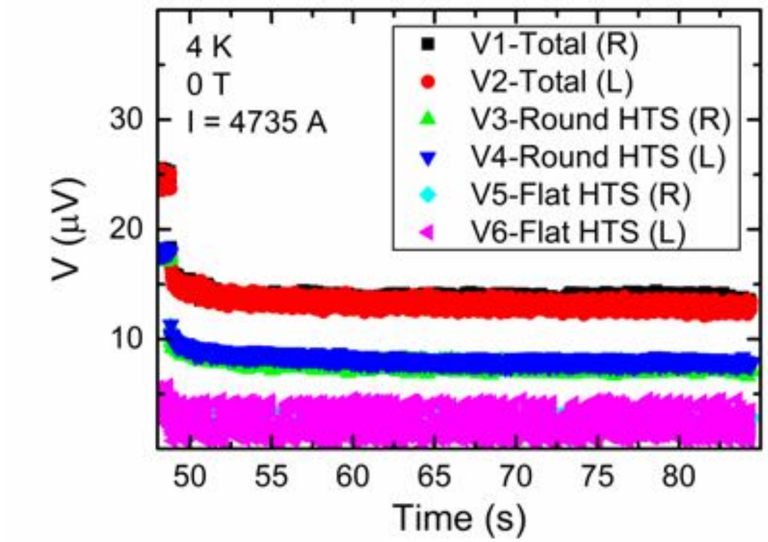
36 nΩ

16 nΩ

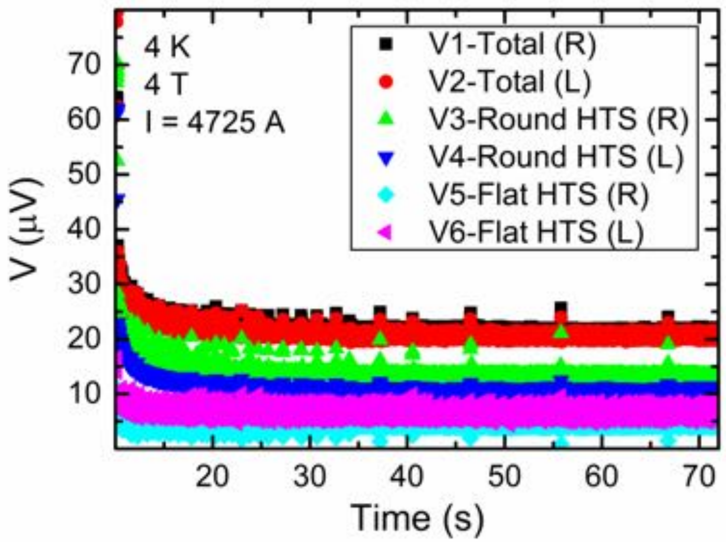
Extra slide - Steady state operation of HTS sample pair at 4 K

- Current was ramped and then held constant to let transients die out and to demonstrate steady state operation of joint.
- Max power dissipation of entire sample circuit (4K, 8T, 4605 A) is < 140 mW
  - Current for steady-state test limited by vapor-cooled-leads

0 T



4 T



8 T