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Development of CORC® Cable Terminations and low-loss Joints for use in Magnets for Fusion

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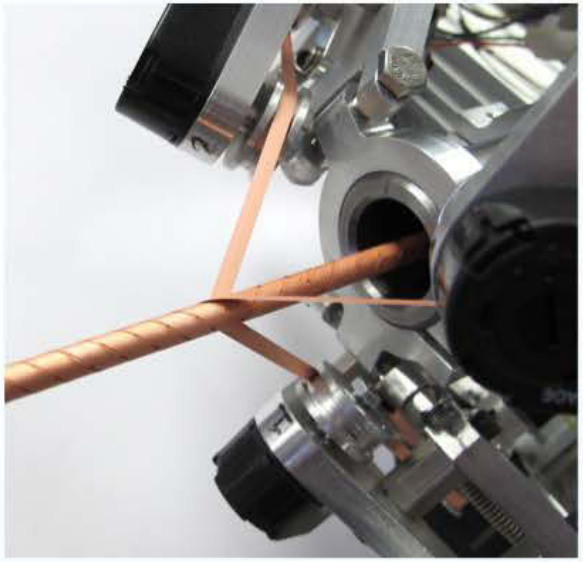
Overview

- **Motivation**
- **Development of CORC® terminations**
  - Evolution of CORC® terminations
  - Compact low resistance terminations
- **Development of CORC® joints**
  - Cable to cable connections tested to 9 kA
  - Current injection at high ramp-rates
- **CICC joints for currents of 50 kA to 100 kA**
- **Development of demountable CORC® joints**
- **Summary**



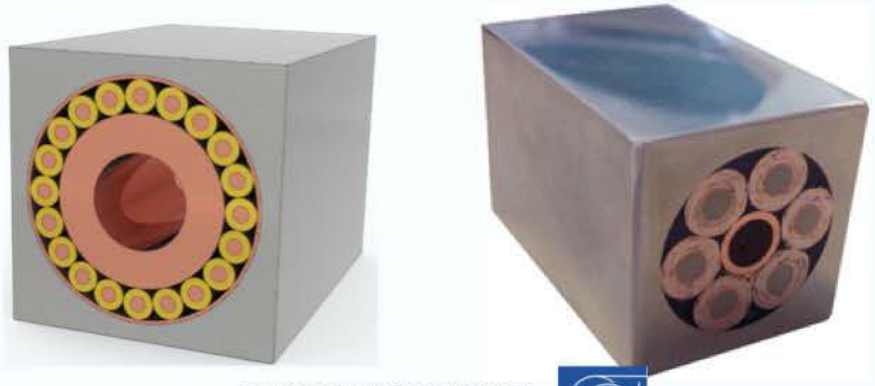
Motivation

CORC® CICC concepts offer current densities, high levels of transposition, and flexibility needed to make HTS fusion a reality

Benefits of magnets made from HTS include higher tolerance to EM stresses and higher temperature margins than available with LTS

One of the biggest challenges of using HTS cables is developing the ability to inject current homogeneously into every strand at sufficiently low contact resistances

Terminations and Joints need to be developed that are compact, robust and easy to incorporate into magnet designs



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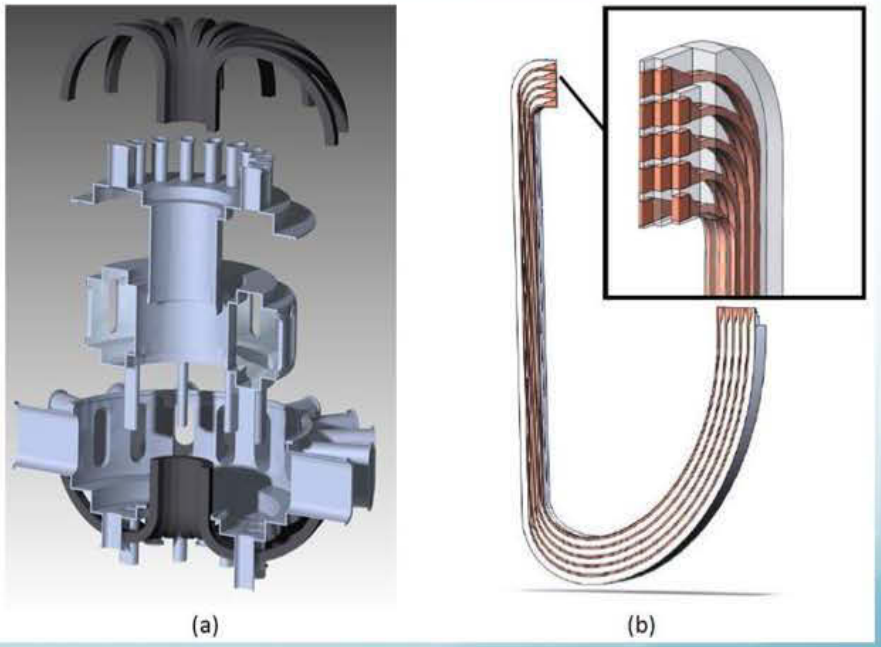


Development of CORC® terminations

Evolution of CORC® terminal designs

Conical terminals

Solder-filled terminals

Solder-filled terminals with copper insert

	Advantages	Disadvantages
Conical terminals	• Current injected on REBCO side of tape	• Difficult for large tape count. • Prone to tape kinking. • Tests revealed signs of current redistribution
Solder-filled terminals	• Easier to solder than conical terminals	• Bulky • Tests revealed signs of current redistribution
Solder-filled terminals with copper insert	• No signs of current redistribution • Current injected on REBCO side of tape	• Bulky • Complicated implementation

Compact low resistance terminations

Tube terminals: R (76K) = 5 to 50 nΩ

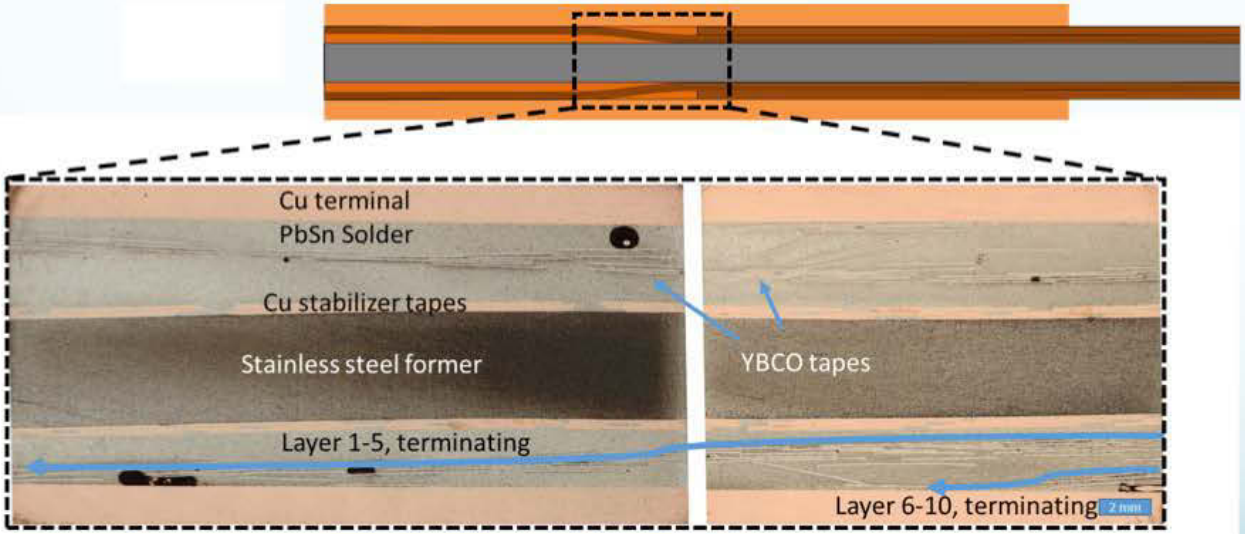
Advantages

- Extremely compact
- Controlled tapering of tapes possible
- Very even current injection

Disadvantages

- Current injected on back side of tape

Example of tapering tapes within a tube terminal



Tapes spring out to contact copper tube

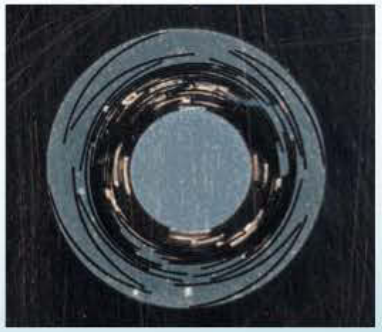
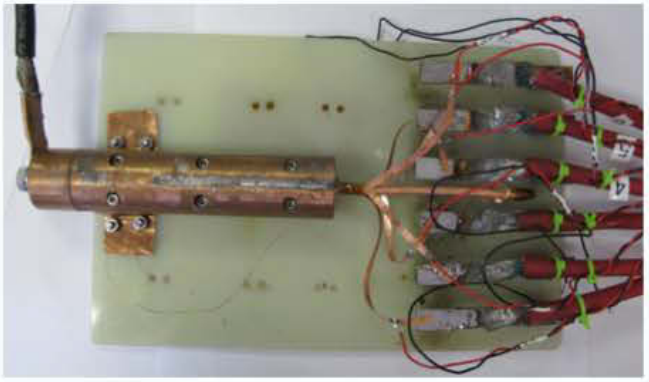


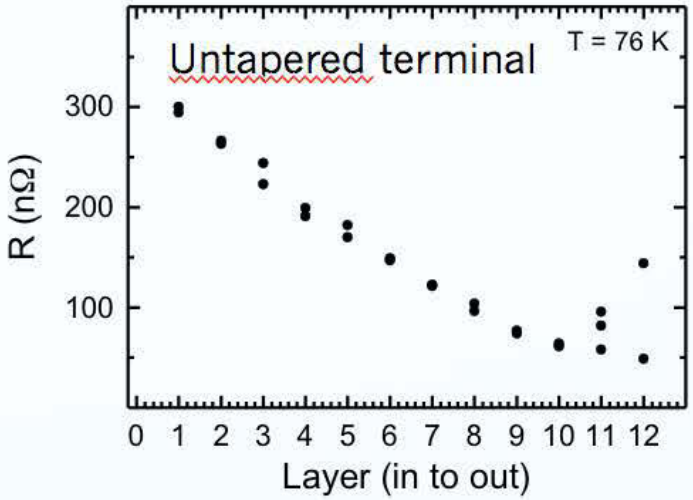
Image courtesy of T. Mulder

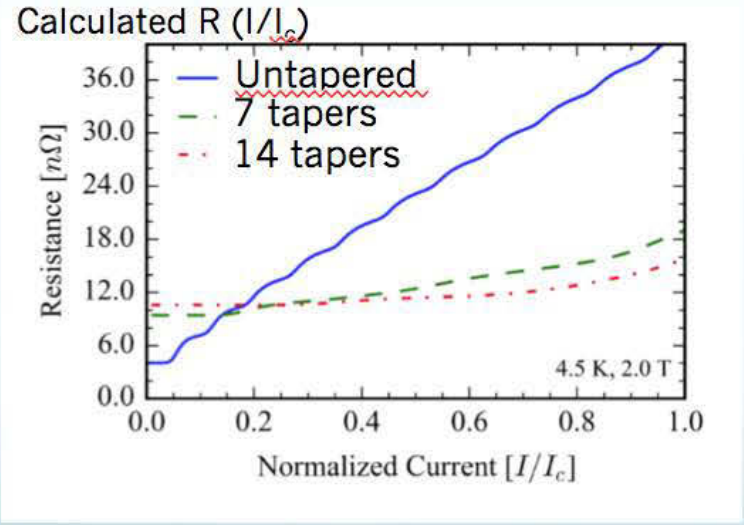
Importance of tapering

Each tape unwound from central Cu former and energized individually



Contact resistance increases from outermost layer to innermost layer



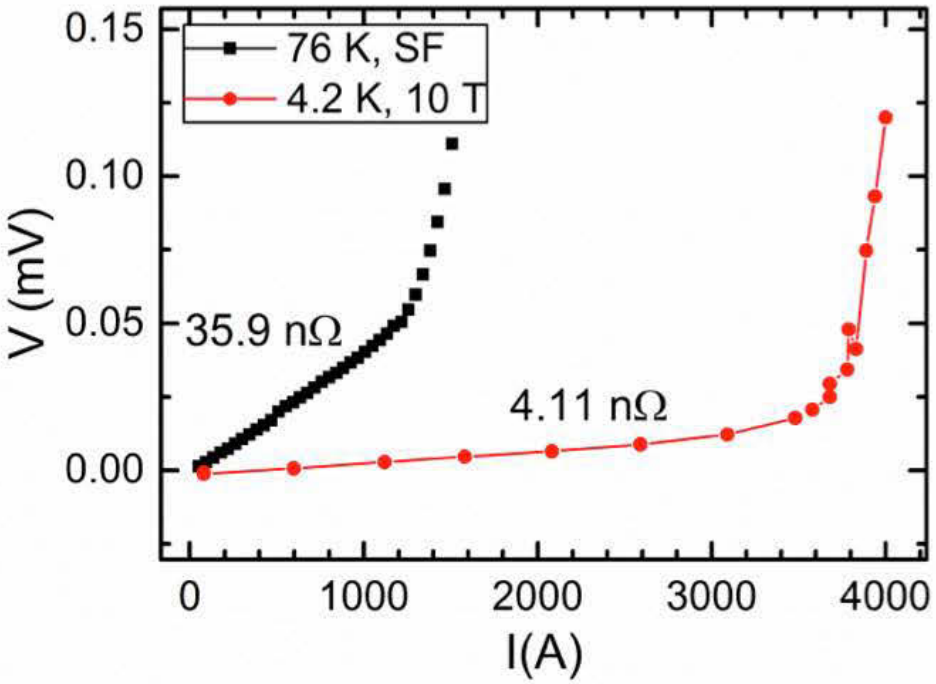


As a result of inhomogeneous current injection, overall resistance changes as a function of current

T Mulder et al 2015 IOP Conf. Ser.: Mater. Sci. Eng.102 012026

V(I) from properly tapered tube terminations

Voltage from termination to termination of a 29 tape CORC® wire for a 4-turn coil of 60 mm inner diameter

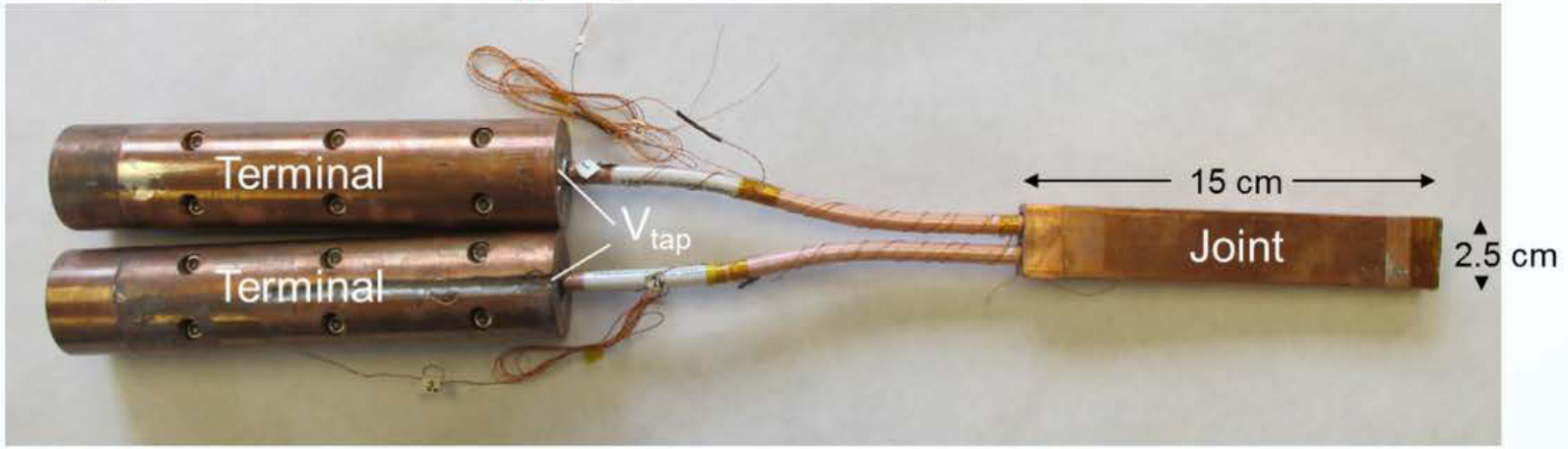


Courtesy of T. Mulder

Development of CORC® joints

Simple copper block joints tested with and without tapering

Sample before mounting on probe

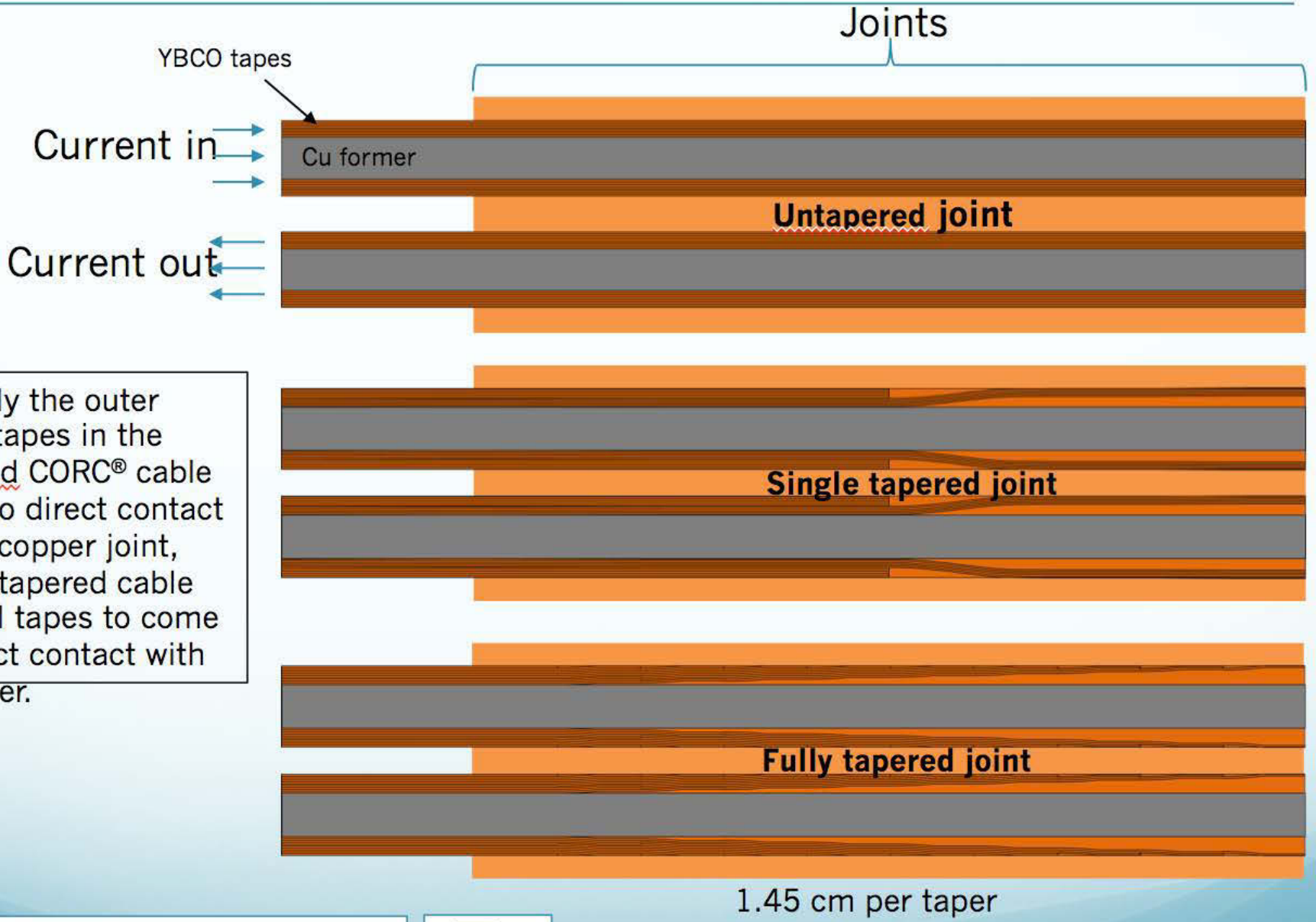


ACTs high current test facility

Cable contains 30 tapes arranged in 10 layers

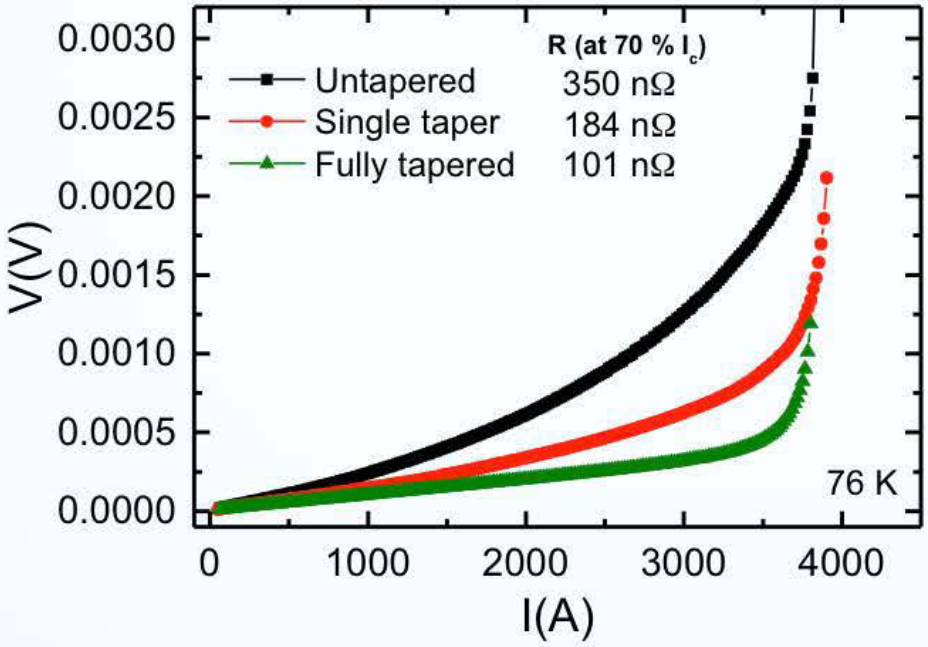
76 K I_c of cable tested ~3500 A
4.2 K I_c expected ~30,000 to 45,000 A

Schematics of joints tested



While only the outer layer of tapes in the untapered CORC® cable come into direct contact with the copper joint, the fully tapered cable allows all tapes to come into direct contact with the copper.

Measurements of joints in LN_2



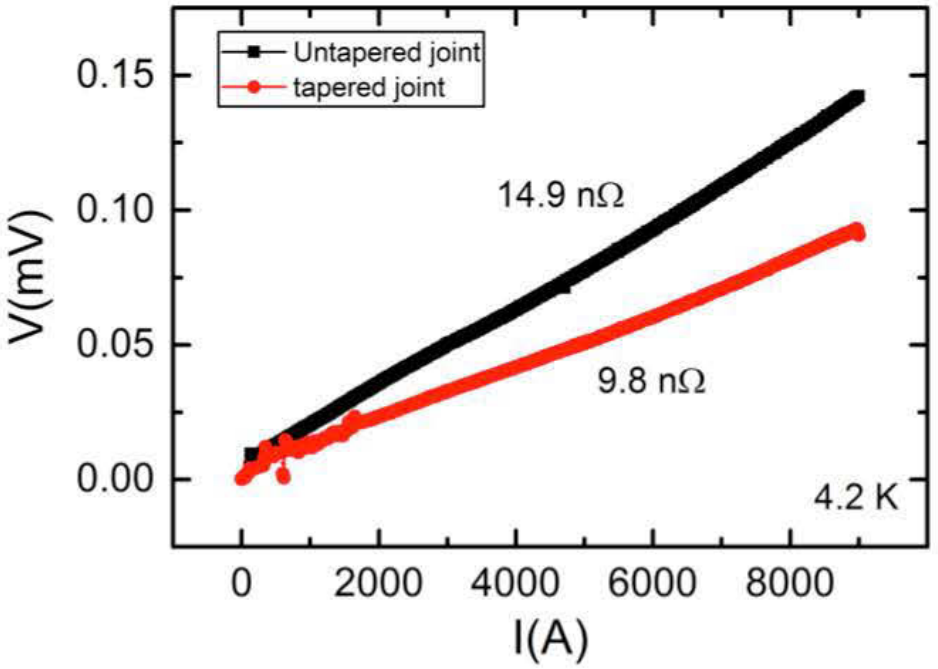
- **Untapered terminals result in uneven current injection evidenced by non-linear V(I) behavior below I_c**
  - N-value not even obtainable
- **For single taper, N-value is 17.8 and increases to 28.9 for the fully tapered joint (similar to individual tapes)**

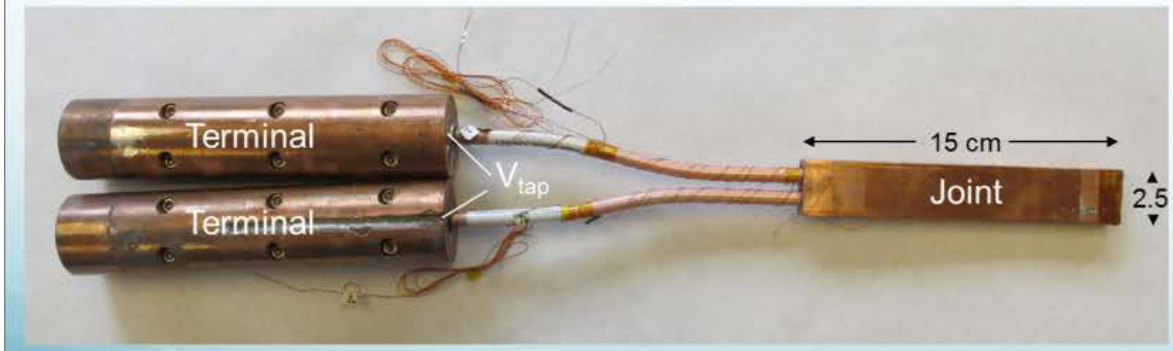
$$V = IR + V_c (I/I_c)^N \text{ value}$$

Terminal resistance

Superconducting to normal transition

Measurements of joints at 4.2 K

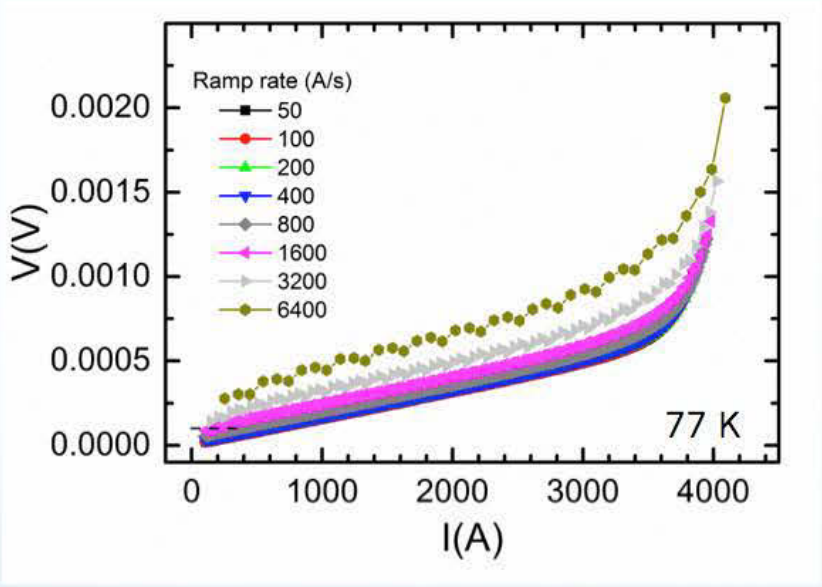




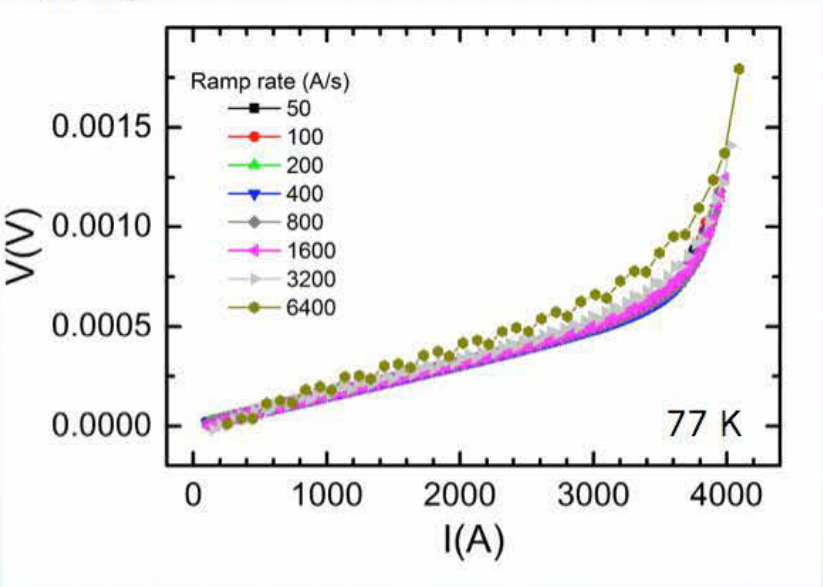
- **Resistance includes contribution of the terminals**
  - Terminals contribute to 20-40% of the resistance measured.
  - We estimate that the tapered joint has a resistance of about **6 nΩ** while the untapered joint has a resistance of about **11.6 nΩ**.
- **Current measured up to 9000 A, which is only about 20 % of I_c at 4.2 K**
  - For the untapered joint, judging by the nonlinear V(I) behavior at 76 K when current exceeds 10-20% of I_c, V(I) behavior at 4.2 K likely also digresses from being linear if we measure to higher currents.

Test of fully tapered joint at high ramp-rates

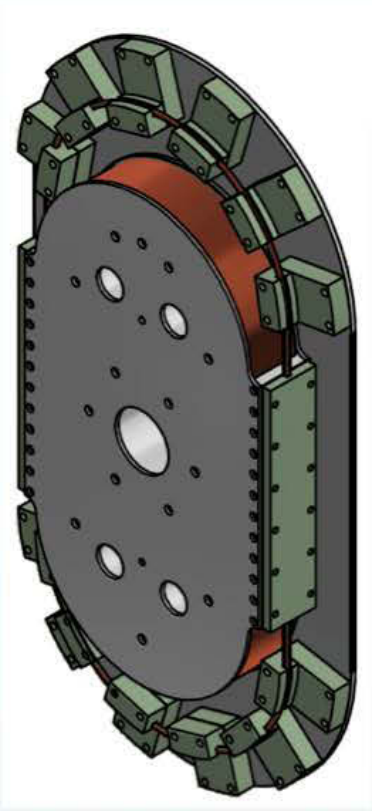
I_c does not change with increasing ramp-rate

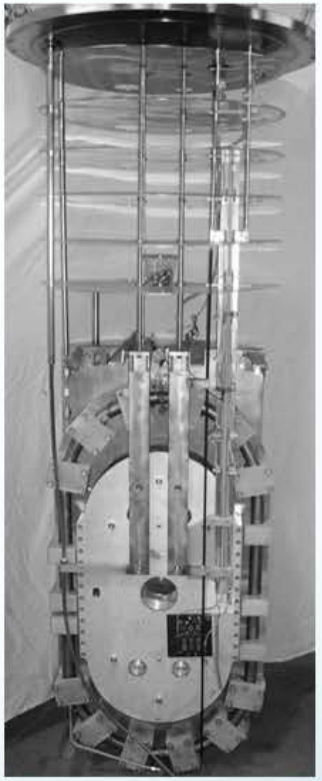


After removing inductive voltage component, slight change of resistive slope observed at very high ramp-rates. I_c remains the same



Upcoming inductive test of CORC® joint at NHMFL



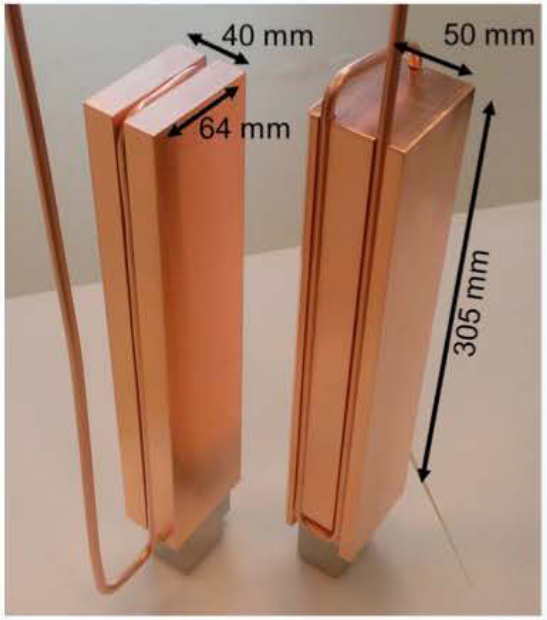


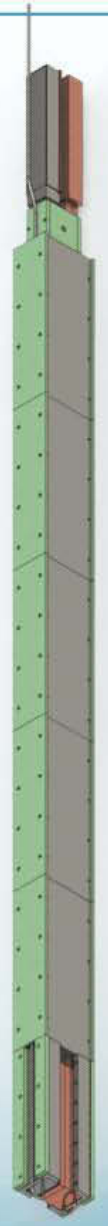
CICC joints for currents of 50 kA to 100 kA

6x1 CORC® CICC terminations

CORC® CICC Joint terminals developed at CERN and University of Twente

- Solder filled
- Tapered strands
- Embedded conduction cooling





Top terminals

Bottom terminals

Temperature (K)	Expected Bottom Terminal Resistance (nΩ)	Expected Top Terminal Resistance (nΩ)	Expected Loop Resistance (nΩ)
5	1.7	1.5	6.4
10	2.0	1.7	7.5
30	4.0	3.0	14
50	6.5	5.4	24

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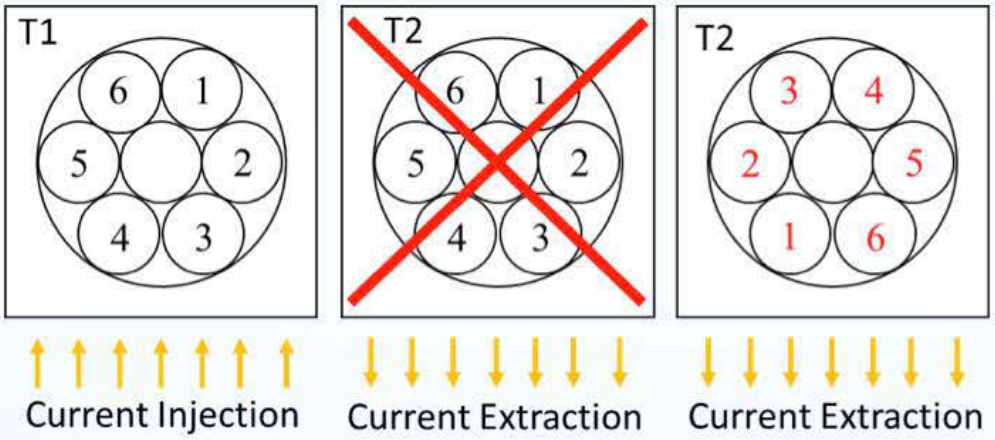
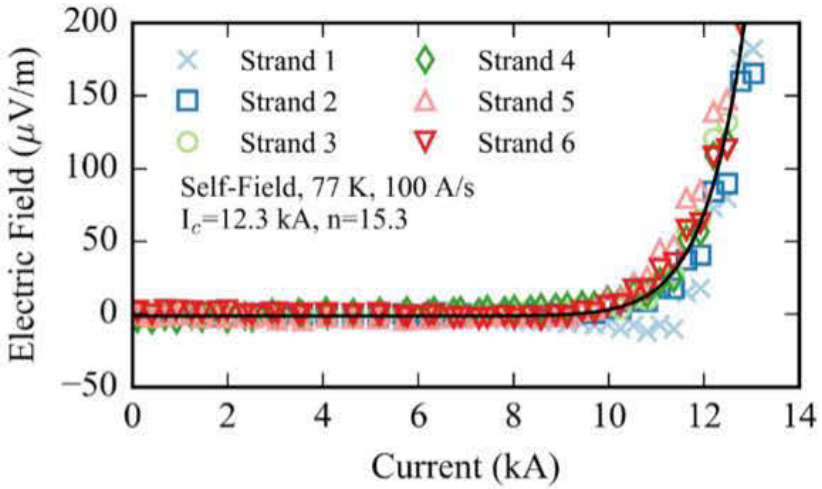
Can inject current on one side if cables are transposed

½ turn transposition of cables at termination evens out resistances so current distribution is homogeneous



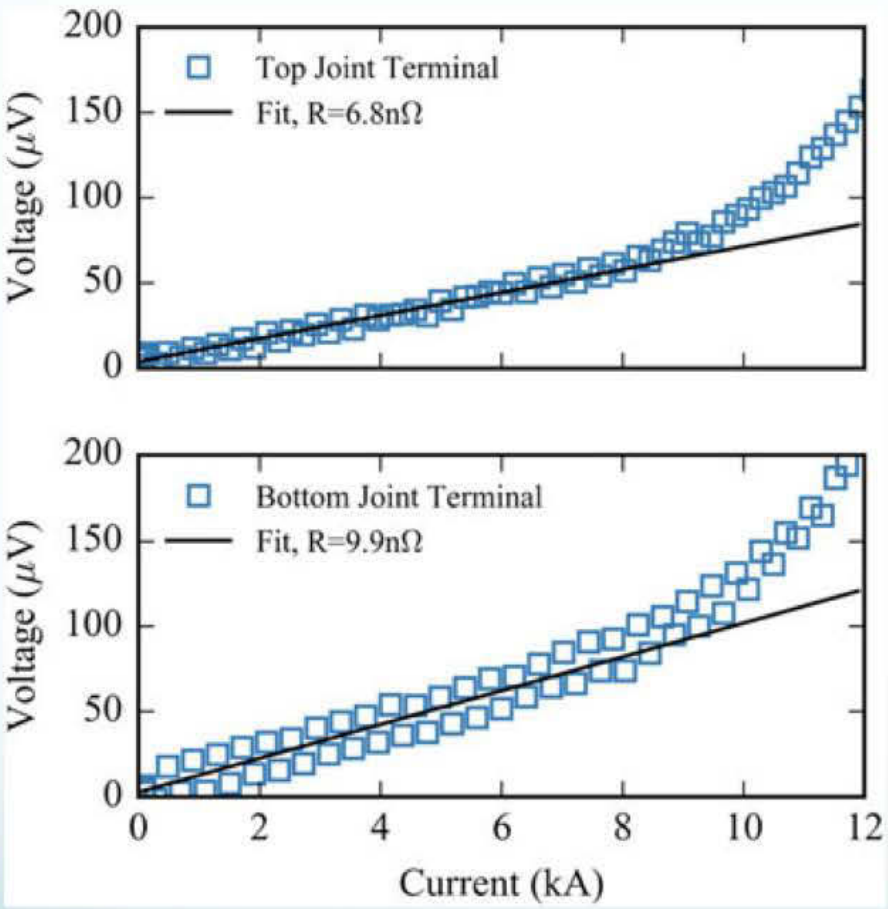
Experiment shows all 6 strands transition at once



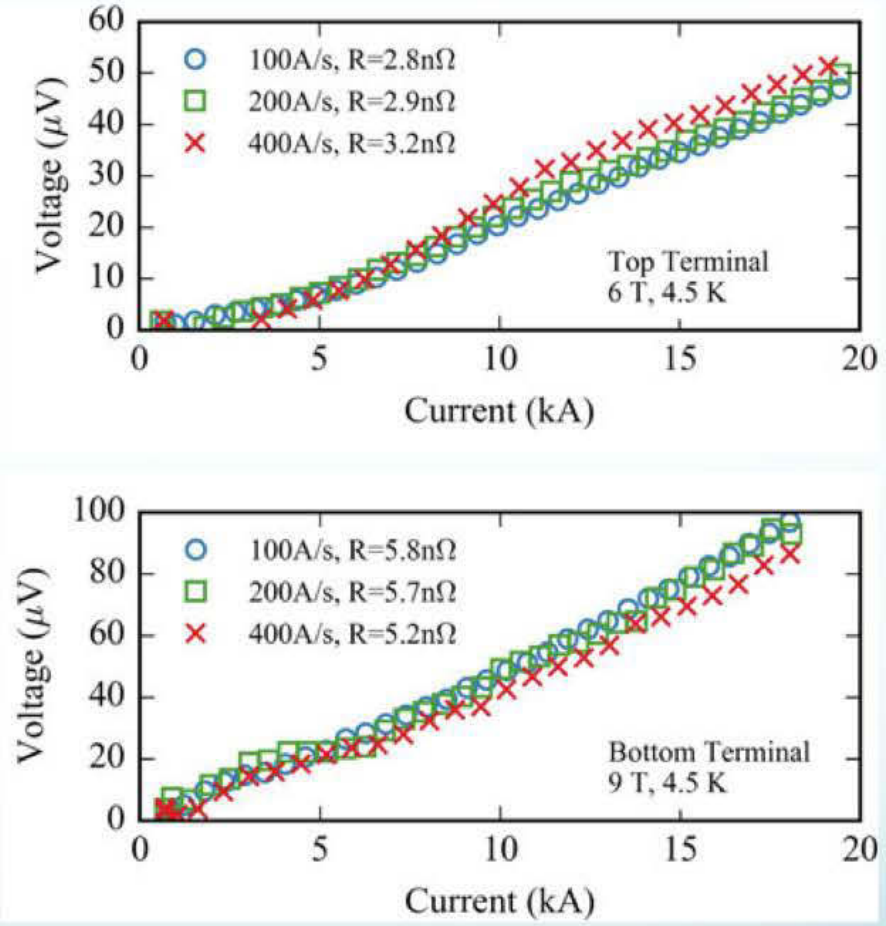
FRESCA test sample

Joint resistances of CORC® CICC conductor

77 K



4.5 K



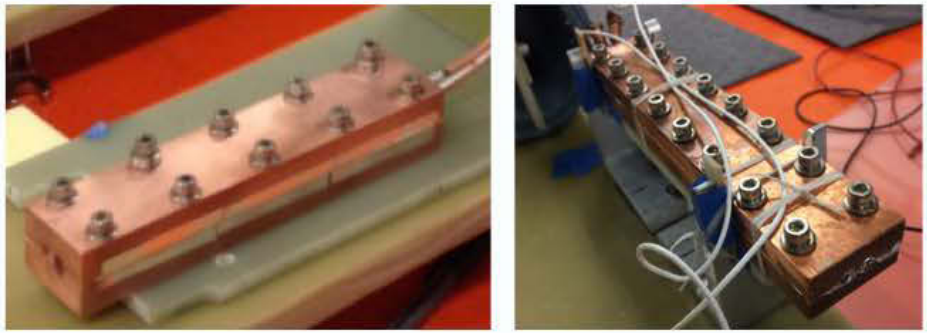
Mulder, T. *et al.* Demonstration of the ReBCO CORC 47kA@10T/4.2K Cable-In-Conduit-Conductor and its Joint Terminals at 4.5 and 77 K. *IEEE Transactions on Applied Superconductivity* **27,** 1–4 (2017).

Development of demountable CORC® joints

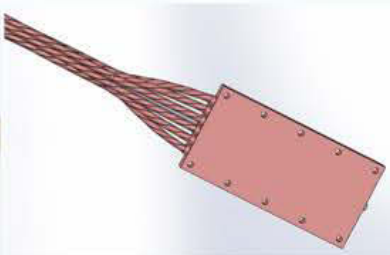
CORC® connector designs

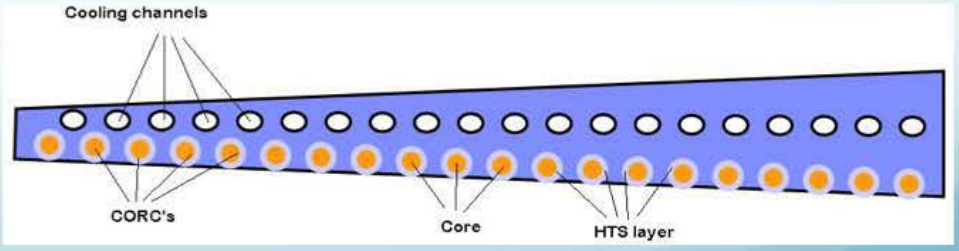
Male to female connectors:
R (76K) = 465 nΩ

Clamped praying hands joint between tube terminals: R (76K) = 194 nΩ



Both concepts expandable to several cables in parallel

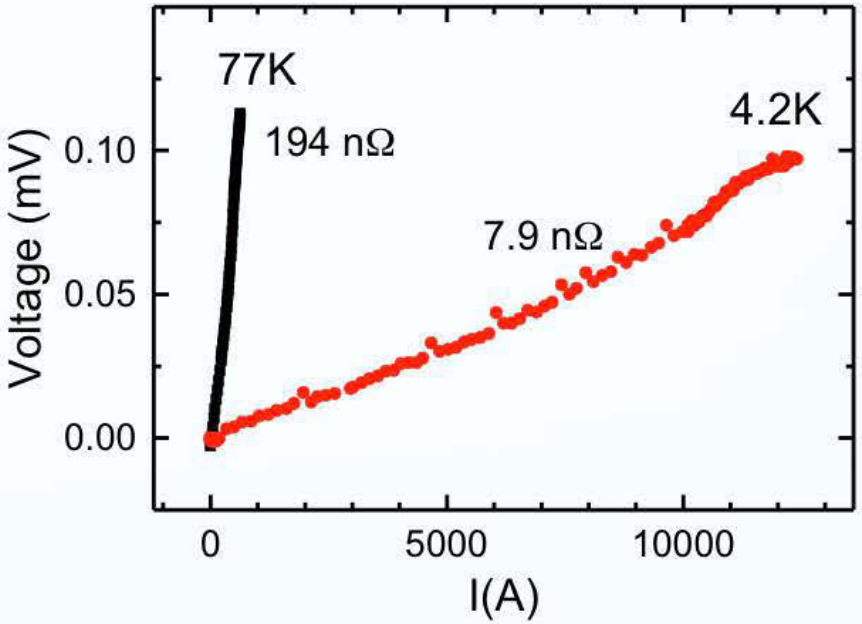




Simple praying hands joint connecting two CORC® wires

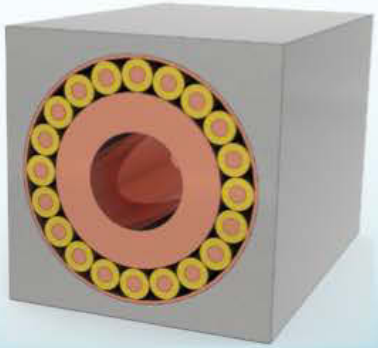
20 cm long praying hands joint

Courtesy of Xiaorong Xu



Several routes to lower resistance further

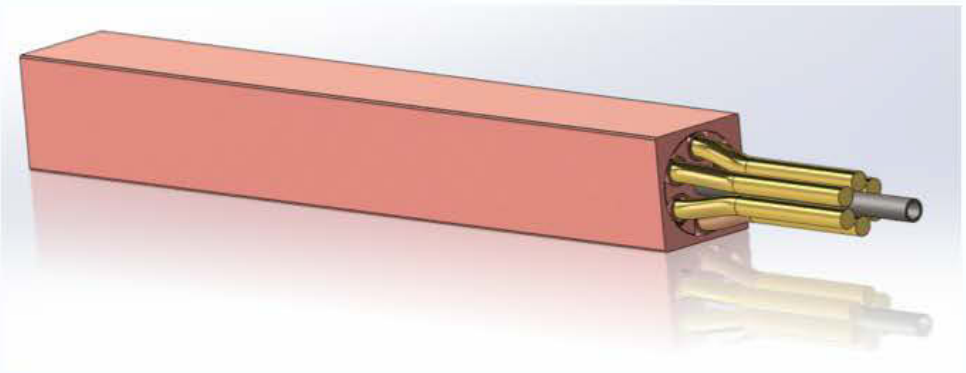
- Longer terminations
- Higher RRR copper
- More wires in parallel (relevant for high operating currents)

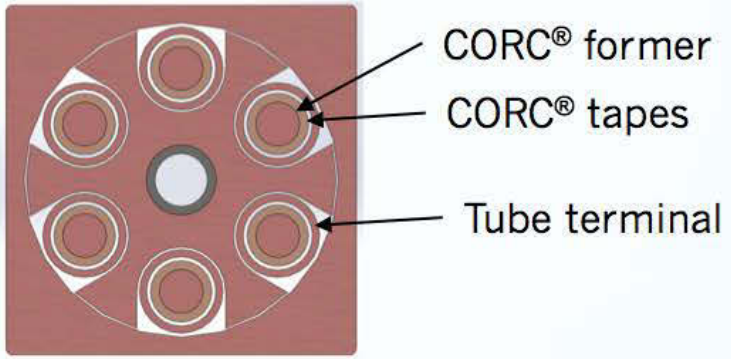


Courtesy of T. Mulder

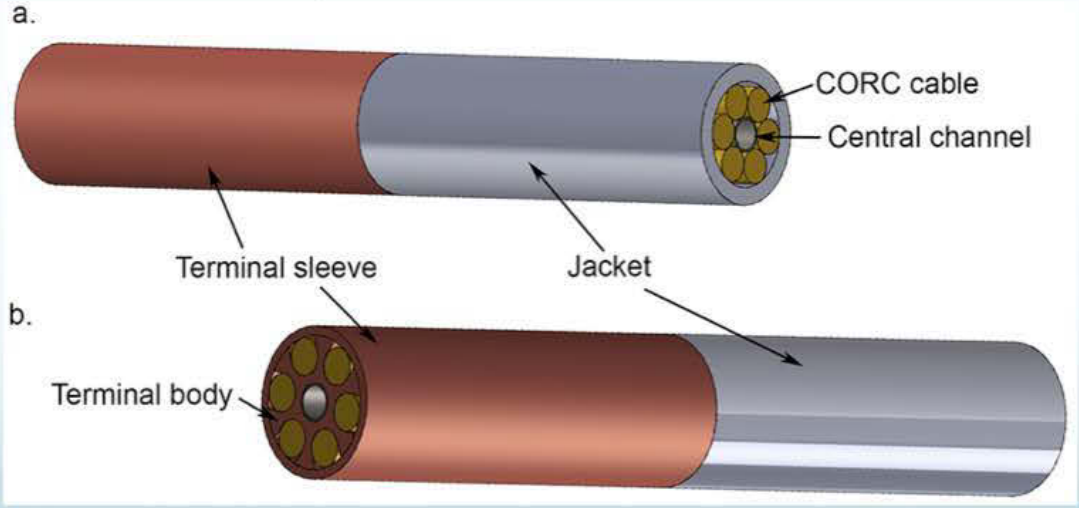
Concepts for terminating 6x1 CORC®-CICC

Rectangular cross-section





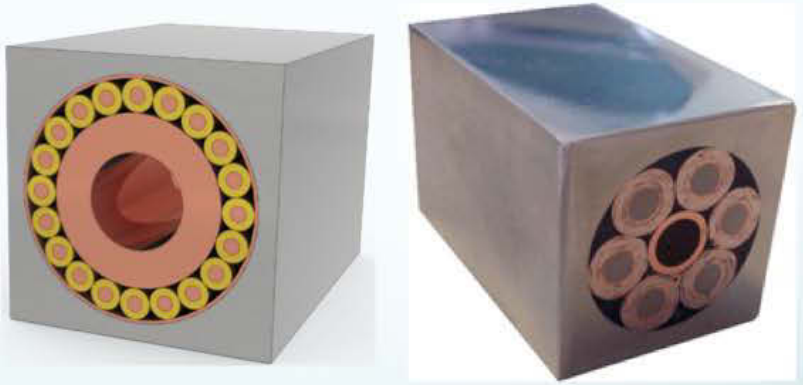
Cylindrical cross-section



Summary

- **Multi-year development of low resistance CORC® terminations**
  - Tube-type terminals are extremely compact
  - Tapering is key to homogeneous current
  - **77 K:** 10-50 nΩ per terminal
  - **4.2 K:** < 5 nΩ per terminal

- **Development of cable-to-cable CORC joints**
  - **77 K:** ~100 nΩ per joint
  - **4.2 K:** < 10 nΩ per joint
- **6x1 CICC joints for currents of 50 kA to 100 kA**
  - **77 K:** < 10 nΩ per joint
  - **4.2 K, 6-9 T:** 2-6 nΩ per joint
  - Clear path to < 1 nΩ joints
- **Development of demountable joints**
  - Several optional designs being considered
  - Simple clamped praying hands joint: < 8 nΩ at 4.2 K



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