Work supported by
U.S. Department of Energy awards numbers DE-SC0009485, DE-SC0013723, and DE-SC14009

Development of HTS CORC® Cables and Joints for use in Magnets for Fusion

Jeremy Weiss, D.C. van der Laan
Advanced Conductor Technologies
and University of Colorado
Boulder, Colorado, USA

T. Mulder, H. ten Kate
CERN, Geneva, Switzerland & the University of Twente, Enschede, the Netherlands

Advanced Conductor Technologies
www.advancedconductor.com

EUCAS 2019, Glasgow

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

CORC® wires (2.5-4.5 mm diameter)
- Wound from 2-3 mm wide tapes with 30 μm substrate
- Typically no more than 30 tapes
- Highly flexible with bending down to < 50 mm diameter

CORC® cables (5-8 mm diameter)
- Wound from 3-4 mm wide tapes with 30-50 μm substrate
- Performance as high as >10 kA and 300-600 A/mm² at 20 T
- Typically no more than 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 1 meter

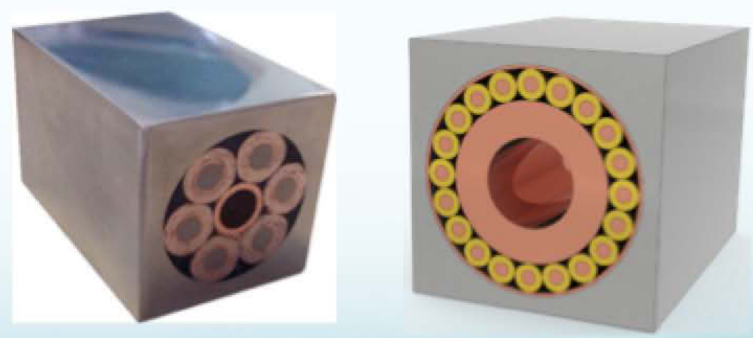


Image courtesy of T. Mulder

Motivation

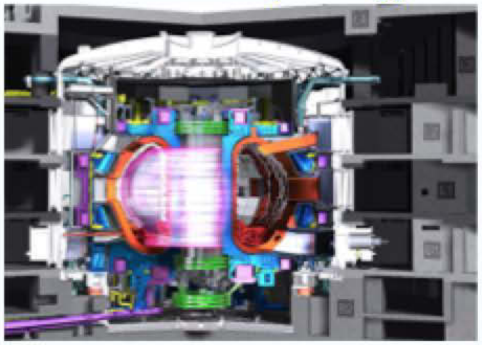
CORC® based concepts offer current densities, high levels of transposition, and flexibility needed to make compact HTS fusion a reality

Other 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

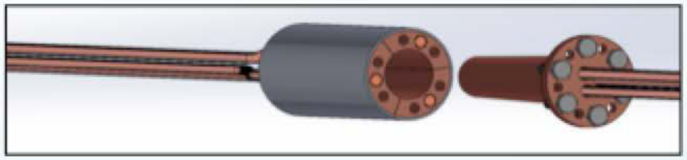
Terminations and Joints are being developed that are compact, robust and easy to incorporate into magnet designs

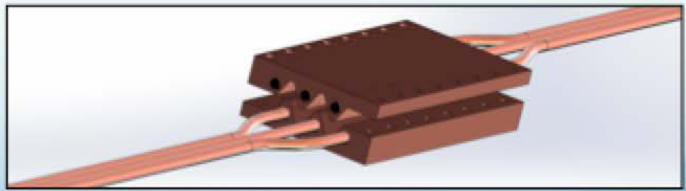
5-story $24bn ITER fusion prototype based on LTS



https://www.iter.org/doc/www/content/com/Lists/WebText_2014/Attachments/230/tkm_cplx_final_plasma2013-07.jpg

Demountable joints between CORC® cables





Advanced Conductor Technologies
www.advancedconductor.com

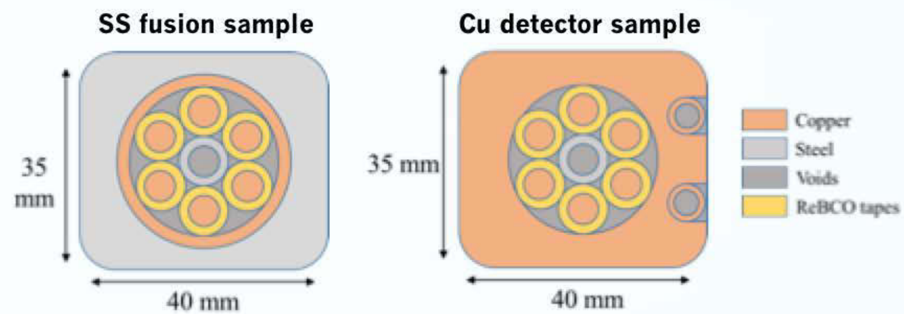
J. D. Weiss

Development of CORC® CICC

80 kA (10 T) CORC®-CICC test in SULTAN

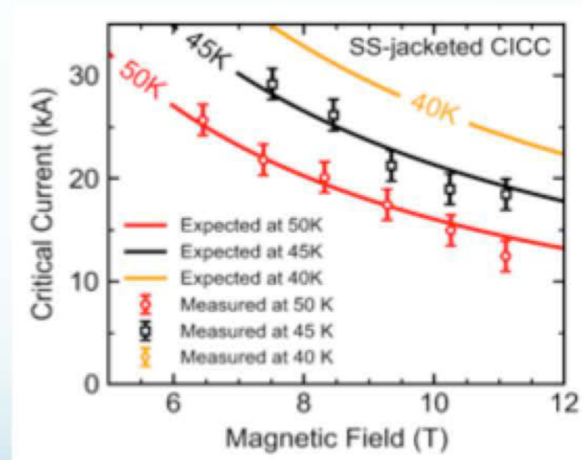
80 kA (4.2 K, 12 T) 6x1 CORC®-CICC built at CERN

- 6 CORC® cables of 7.7 mm diameter
- 42 tapes per CORC® cable
- Two layouts tested in series
  - Stainless steel jacketed sample for Fusion applications
  - Copper jacketed sample for Detector magnets and bus-bars, conduction cooled



CORC®-CICC test results

- SS fusion sample performed as expected
  - I_c(45 K, 11 T) = ~18 kA
  - Temperature range of measurements limited by the Cu detector sample in series with the SS fusion sample
- Cu detector sample degraded
  - I_c(45 K, 11 T) = ~7.5 kA

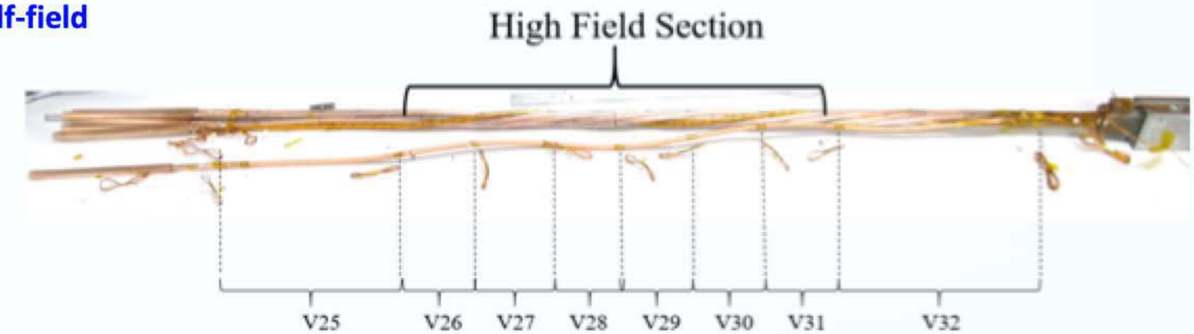


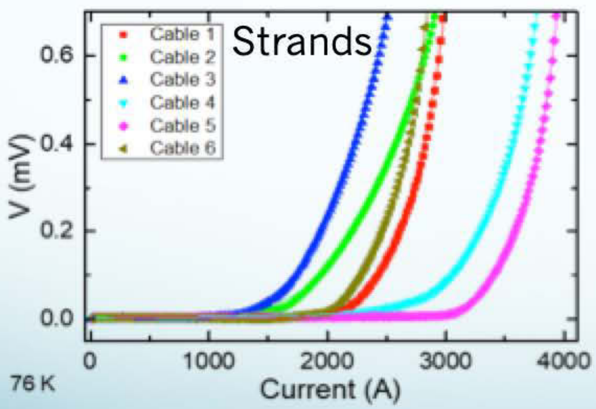
T. Mulder et al, *IOP Conference Series: Materials Science and Engineering*, vol. 279, p. 012033

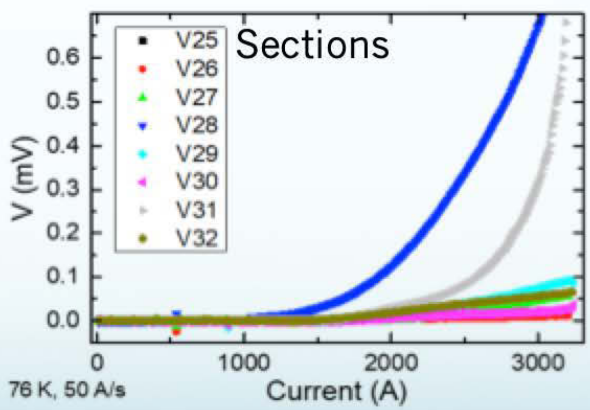
Postmortem of degraded SULTAN sample

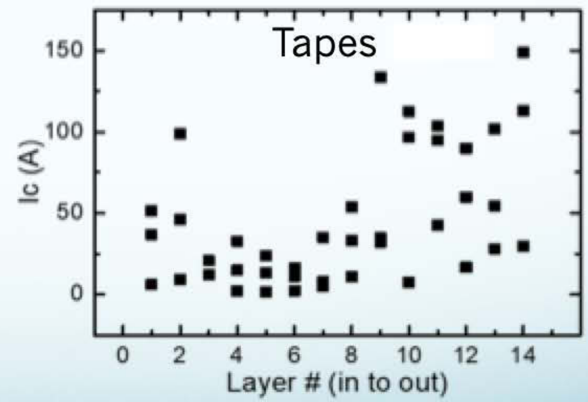
Single strands were extracted tested at 76 K in self-field

- Major degradation in high-field region of Cu-jacketed CICC.
- Single tapes from extracted from the worst performing strand.
- Most damage to tapes in the inner layers.









J. D. Weiss

Advanced Conductor Technologies
www.advancedconductor.com

UNIVERSITY OF TWENTE.

CERN

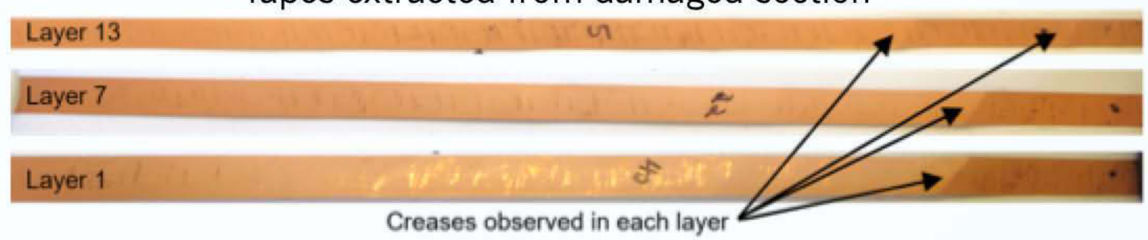
Postmortem of degraded SULTAN sample

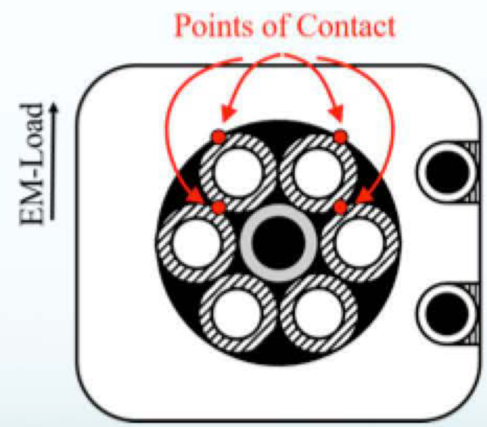
Cause of the degradation:

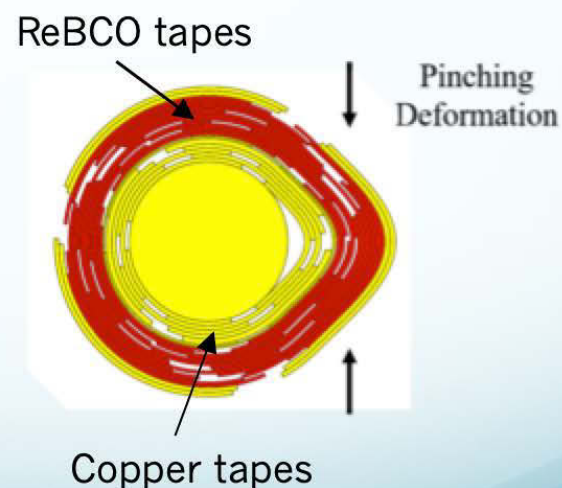
- Primary failure mode is a pinching effect.
- Specific for CORC® strand layout/winding parameters of the Cu-jacketed CICC.

The test showed that copper tapes pre-wound around the core, or a soft core in general, do not provide sufficient mechanical support.

Tapes extracted from damaged section





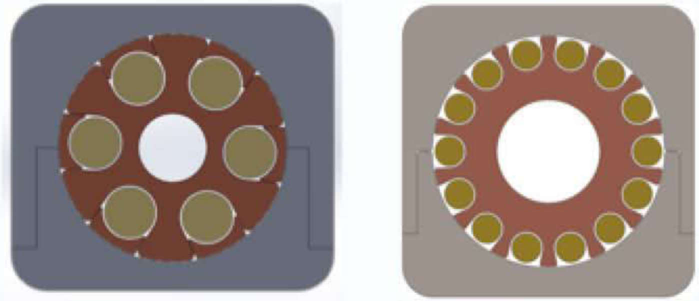


T. Mulder Thesis: https://doi.org/10.3990/1.9789036546164

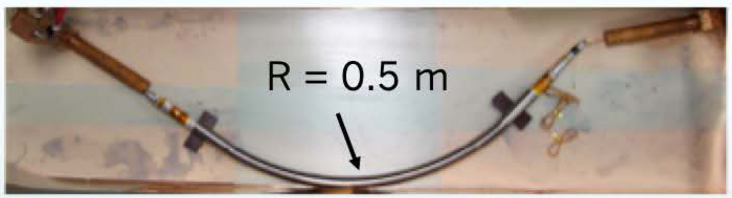
Next steps for CORC® CICC development

- **Distributed CORC® strand support structures**
- **Demountable joints with R(4.2 K) < 1 nohm**
- **Developing more flexible CICC using CORC® wires**
    - Relevant for compact fusion magnets
    - Shorter transposition length
    - Dummy and Subscale CICC tested as a function of bending as part of a phase I SBIR with LBNL

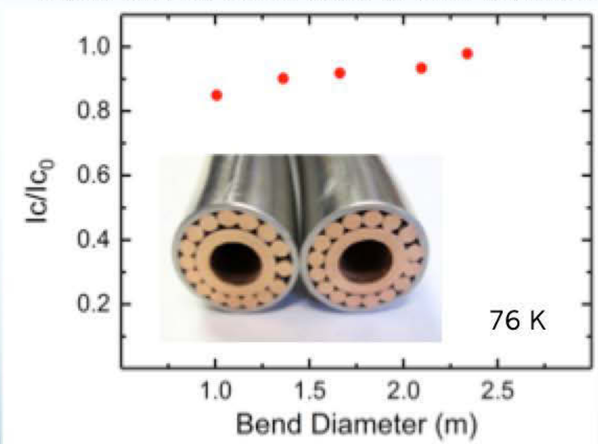
CICC concepts with mechanically decoupled conductors



CICC with one CORC® strand



Multi-strand CICC bent to 1 m diameter



Development of CORC® terminations and joints

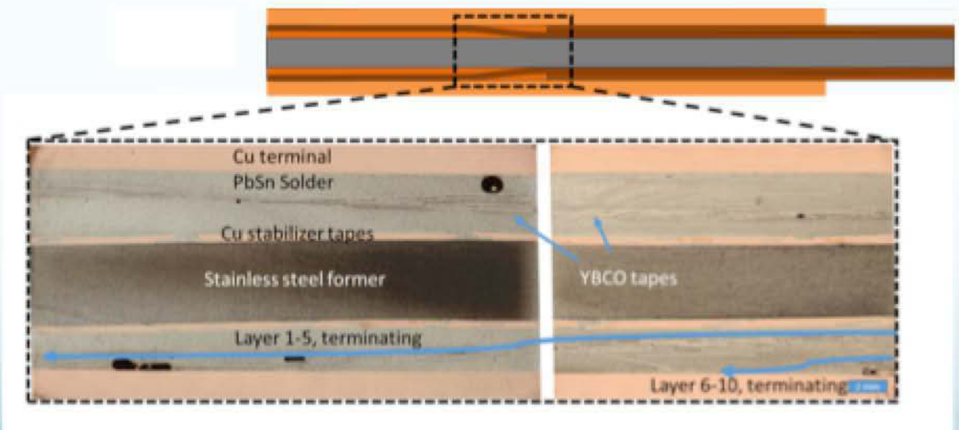
Compact low resistance terminations

Tube terminals: R (76 K) = 5 to 50 nΩ

Advantages

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

Example of tapering tapes within a tube terminal



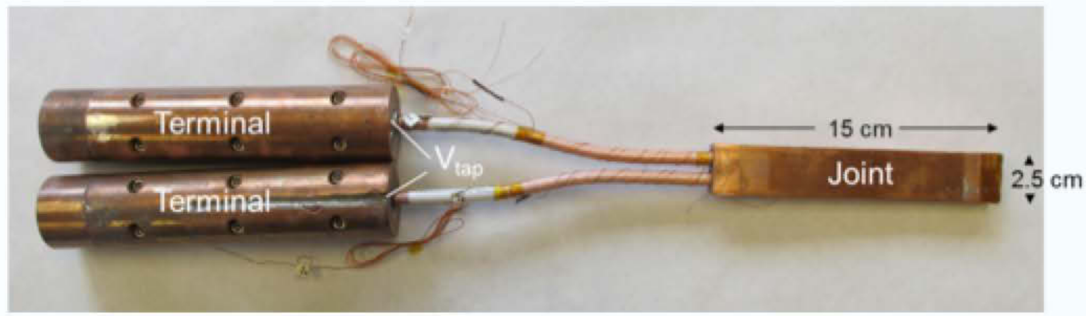
Tapes spring out to contact copper tube

Image courtesy of T. Mulder

Simple copper block joints tested with and without tapering

ACTs high current test facility

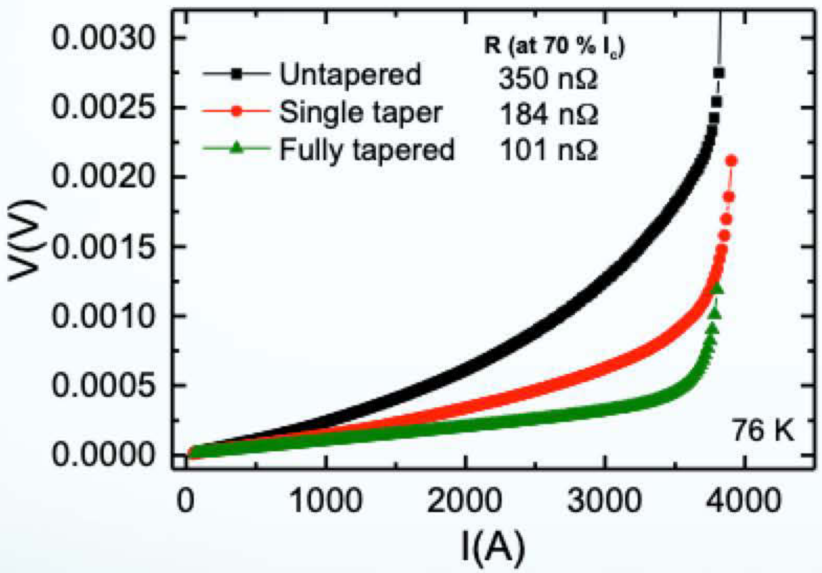
Sample before mounting on probe



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

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

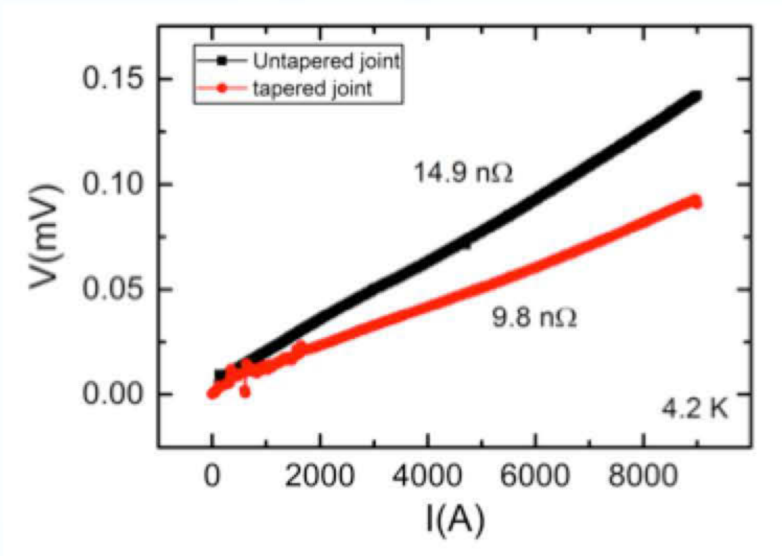
- **For single taper, N-value is 17.8 and increases to 28.9 for the fully tapered joint (similar to individual tapes)**

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

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.

Advanced Conductor Technologies
www.advancedconductor.com

Development of demountable CORC® joints

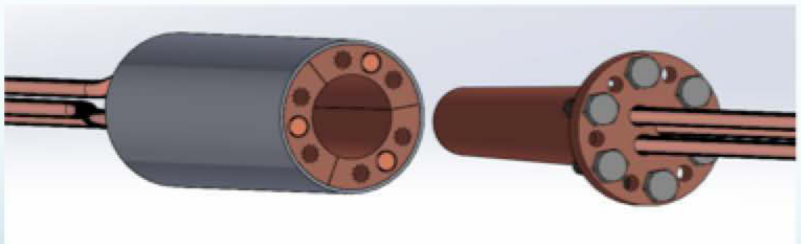
CORC® connector designs

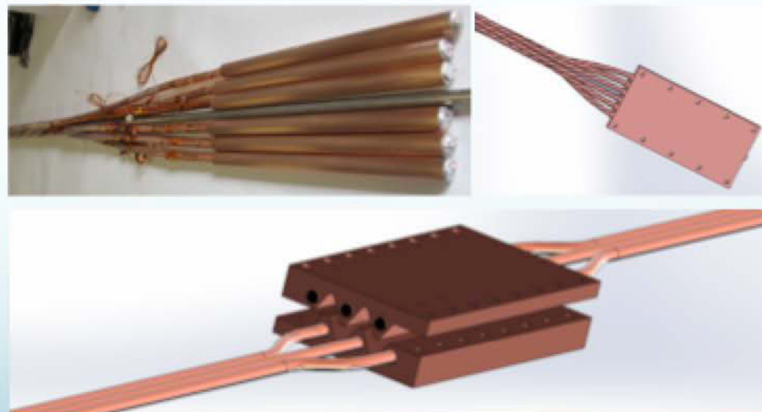
Male to female connectors:
1st generation design (>5 years old): R (76 K) = 465 nΩ

Clamped praying hands joint between tube terminals: R (4.2 K) = 7.9 nΩ

Image courtesy of X. Wang

Both concepts expandable to several cables in parallel





Summary

- **Development of CORC® CICC concepts**
  - Ongoing testing at the SULTAN facility at PSI
  - Soft core and tape pinching effect led to degradation in one sample
  - Improved designs, including mechanically decoupling strands being considered
- **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