*Re*BCO CORC Cable-In-Conduit Conductors and *Re*BCO CORC-Wire for High-Field Magnets

Herman H.J. ten Kate, Tim Mulder and Alexey Dudarev

Special thanks to Danko van der Laan & Jeremy Weiss of ACT-Boulder

But first, a unique ReBCO application, the EcoSwing Wind turbine as Appetizer…..!

WAMHTS 2019, Budapest, April 11, 2019

Appetizer using ReBCO: EcoSwing

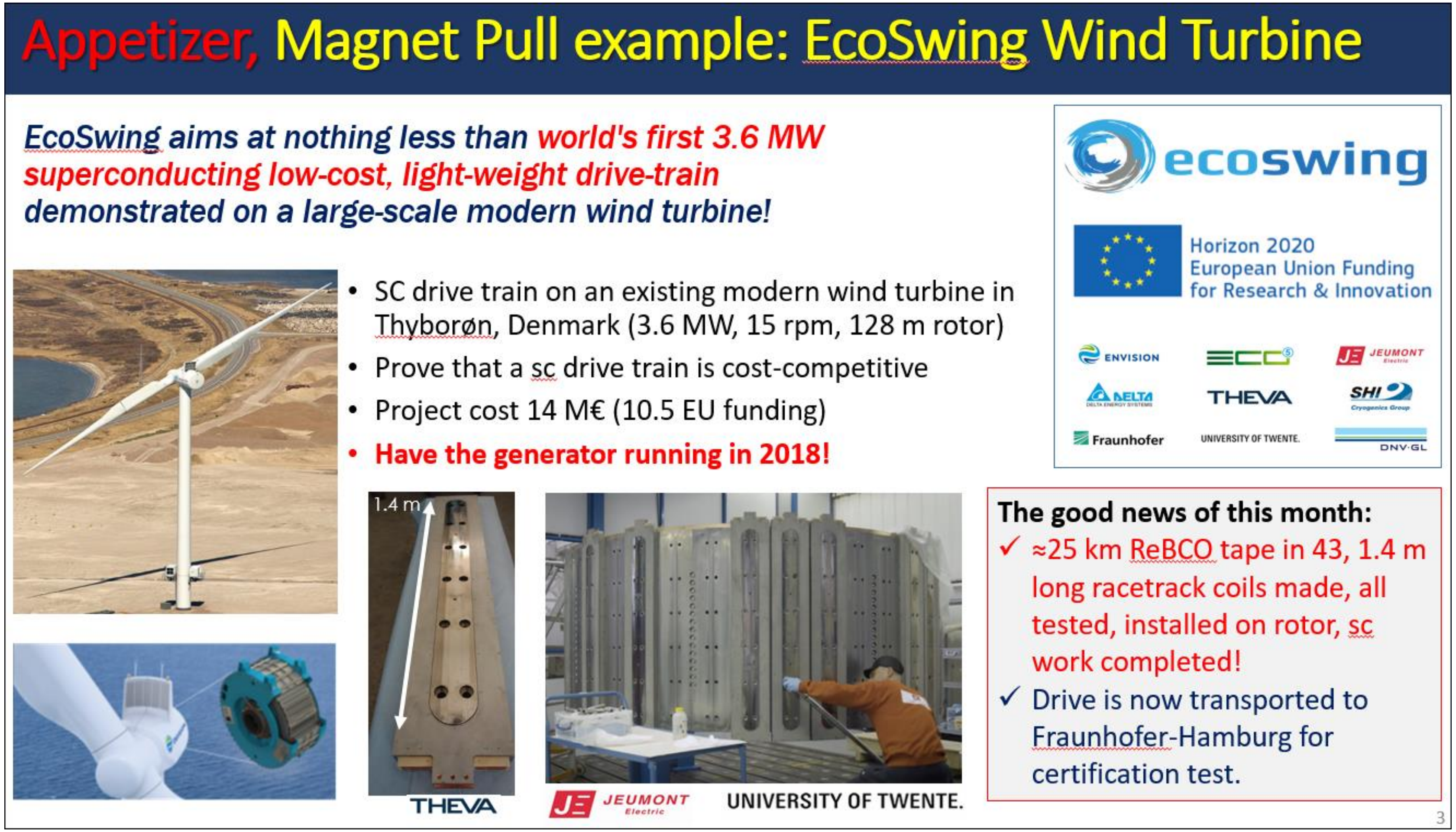
UNIVERSITY OF TWENTE.

✓ **A MW class superconducting wind turbine is turning on its pole since autumn 2018…..**

And it works!

- **2.8 MW achieved!**
- Connected to the grid!
- Earning €.
- Collecting field experience.
- Projects ends soon.

✓ **Remarkably successful,**
Who, where is next?



Appetizer - EcoSwing Wind Turbine

UNIVERSITY OF TWENTE.

World's first superconducting generator successfully operated on a real wind turbine!

- Compact and 'simple' use of high temperature superconductive technology.
- HTS technology and cryocooling is stable and robust (after few months…..).

✓ HTS technology yields 40% mass reduction. EcoSwing shows a generator diameter reduction from 5.4 to 4 m diameter.

✓ For the 1st time ever we are getting real field experience with a sc wind turbine, essential for easing follow-up projects

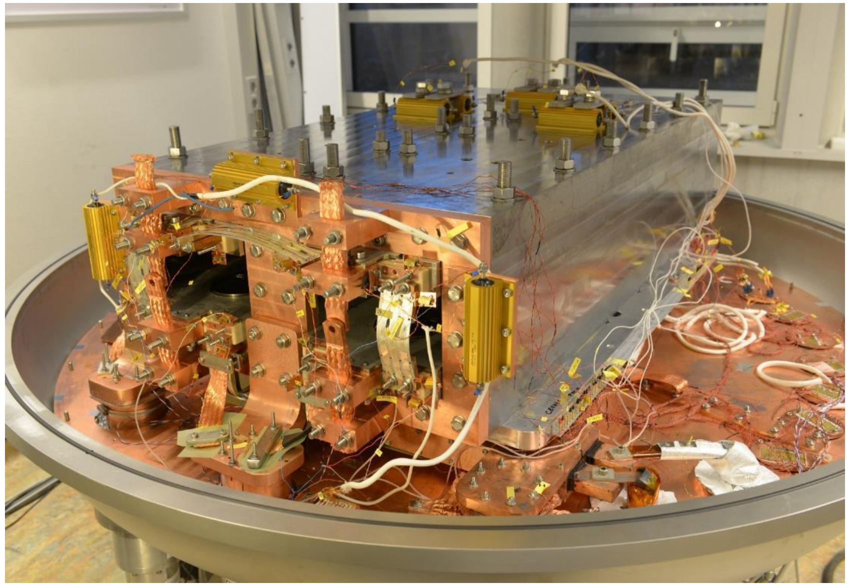
✓ Properties & cost are now better understood, paving the road towards 'reliable' and cost-efficient HTS generators.

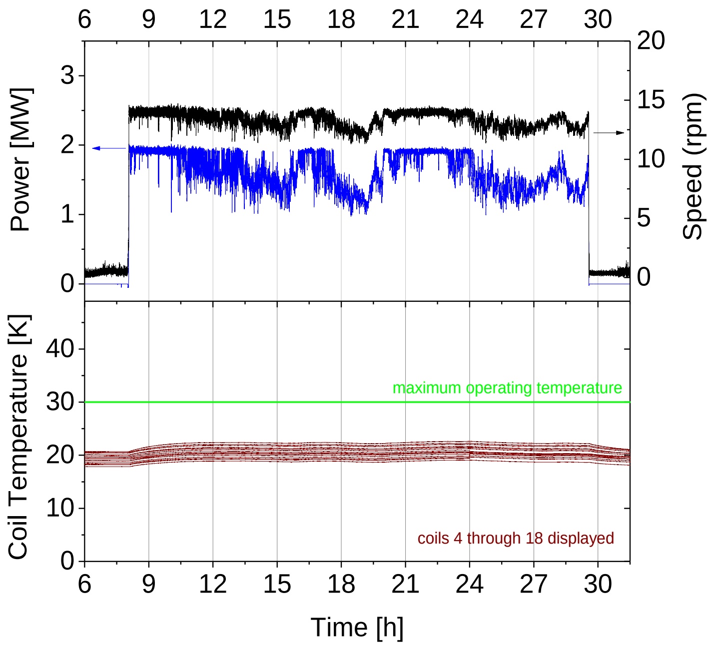
Test at Fraunhofer Institute

Old and new generator in same casing

Appetizer - EcoSwing Experience……

UNIVERSITY OF TWENTE.

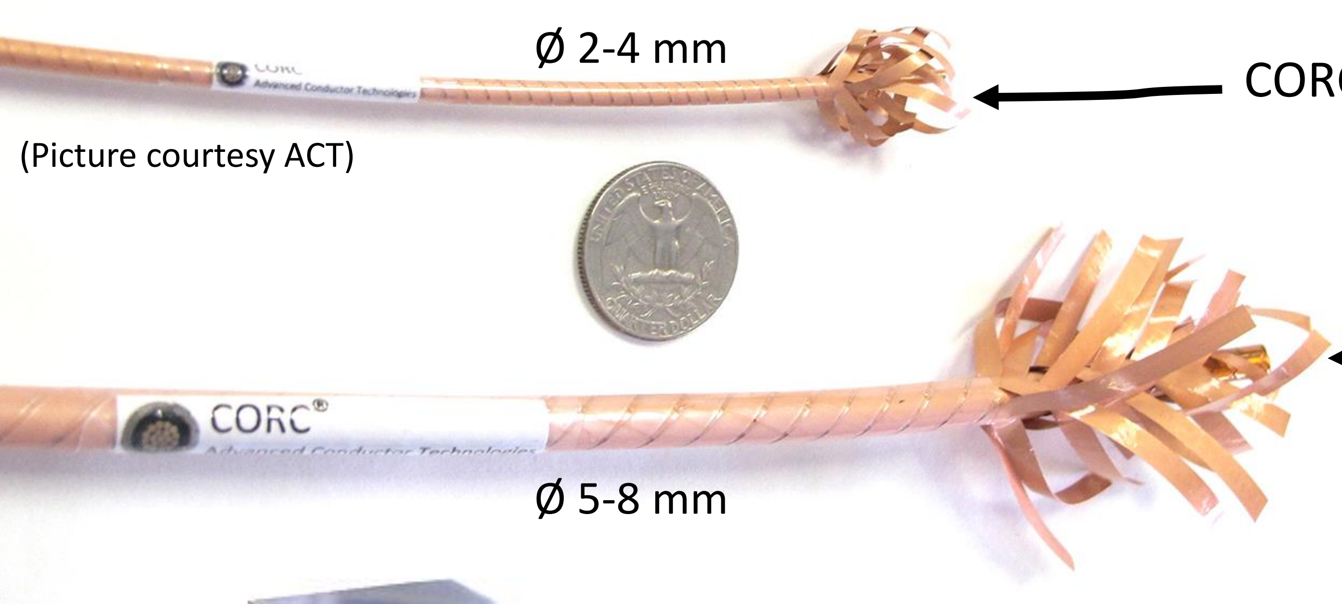




Stability test:

21.5 h operation with
1.6 MW mean power generation
during commissioning at Thyborøn.
In total 169 h the generator was in
operation during commissioning
tests in January 2019.

CORC - Wires, Cables and CICCs



(Picture courtesy ACT)

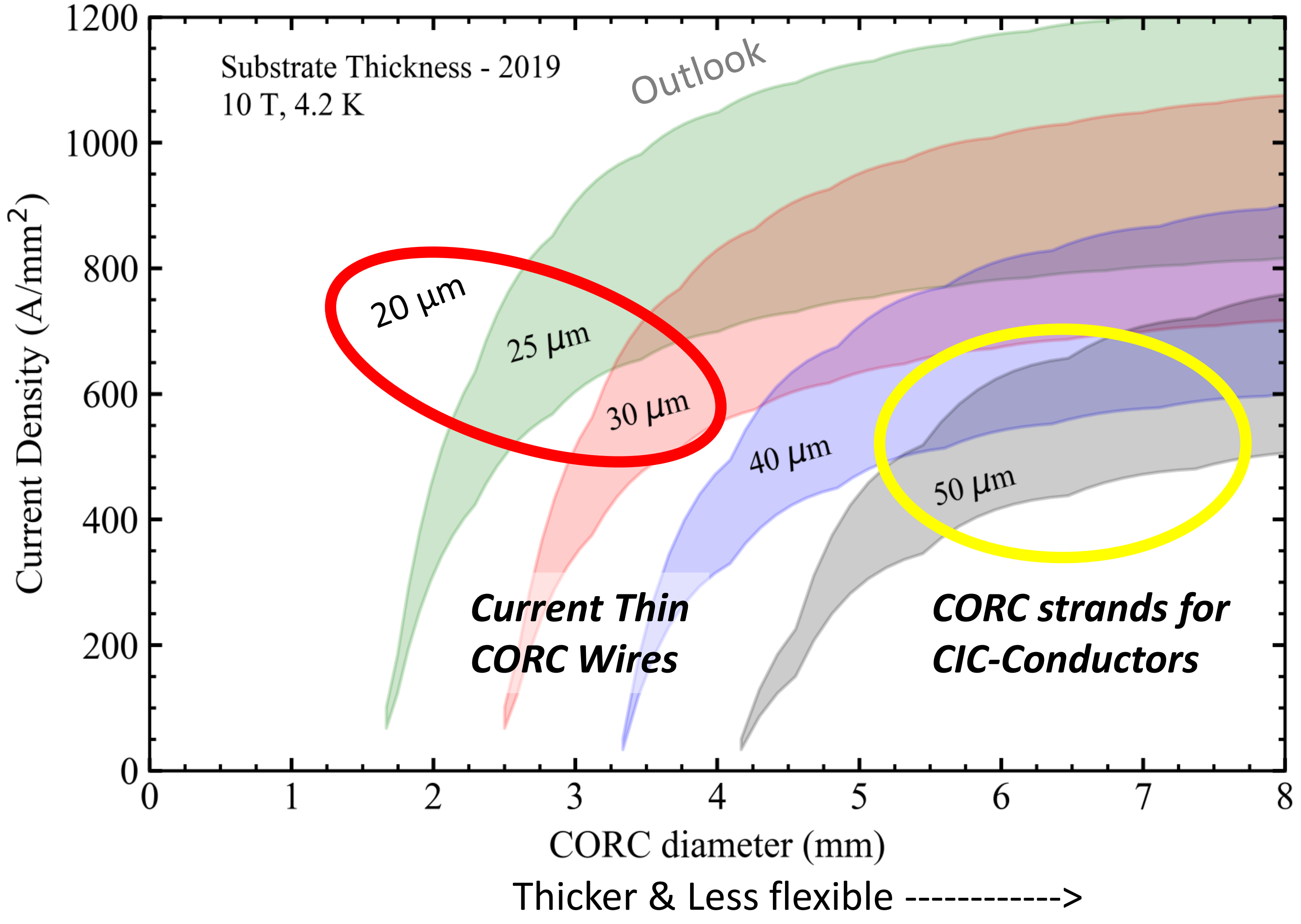
CORC strand based Cable-In-Conduit Conductor

CORC Wire: *accelerator magnets, high-field insert coils or standalone solenoids.*

CORC Cable: *general purpose, stable SC magnets and power transmission.*

CORC Cable-In-Conduit Conductor (CICC): *high current, high-field magnets and HTS bus bars / sc links.*

Substrate Thickness – Towards thinner ReBCO wires



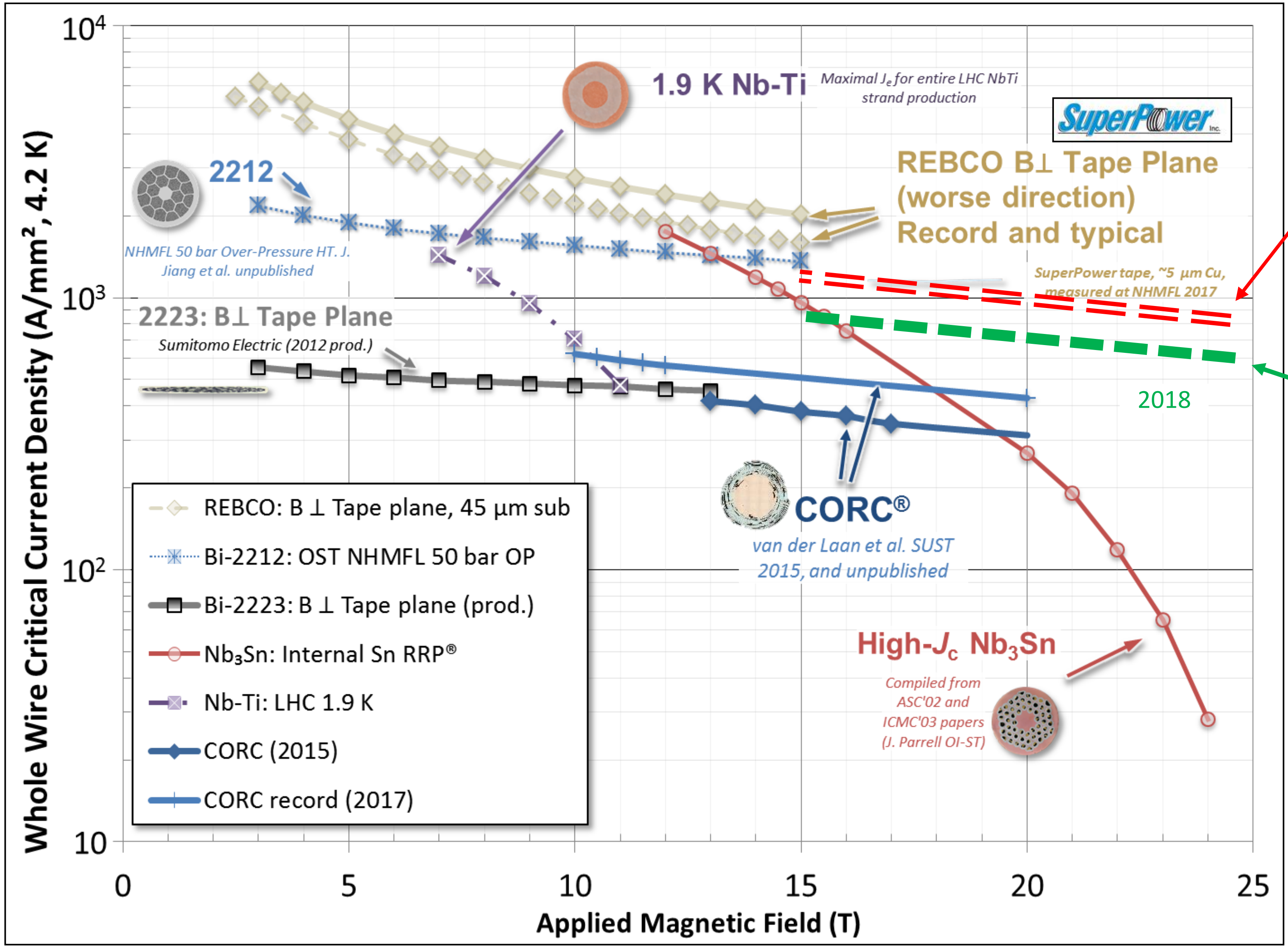
CORC *Wires*:

- Made possible by the reduction in substrate thickness from 50 to 30 µm.
- Now 25 µm and next 20 µm.
- Designed for high-field magnets.
- Several CORC demonstrator magnets are currently developped at CERN.

CORC *Strands*:

- Thicker medium-current cables.
- Designed for large high-field magnets, requiring high thermal/electrical stability.
- Several CORC CICC samples currently in development at CERN in collaboration with ACT.

CORC J_e vs high-field magnet wires – What CORC can do



Data from https://nationalmaglab.org/magnet-development/applied-superconductivity-center/plots

CORC® Potential using tapes with 20 um substrates and lift-factor over 2

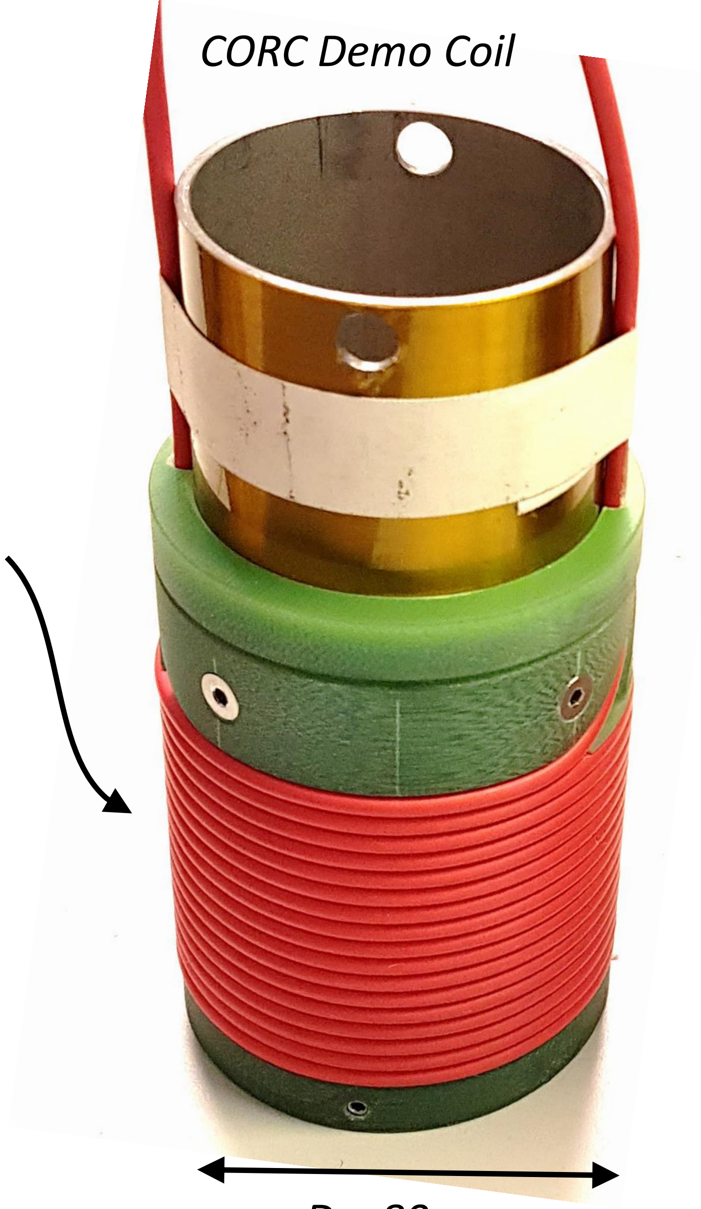
CORC® Possible with tapes currently available

- ✓ Step by step increasing current density and technology reaching 1000 A/mm² at 20T,4.2K enabling robust and industrial high-field magnets far beyond 20 T.

CORC-Wire Coil Technology – Series of demo coils

- A series of compact 2-layer CORC solenoids under development at CERN to demonstrate practical handling, winding technology, and high performance of CORC wires for magnets.
- CORC Wire in 1st coil: 27 ReBCO SCS2030, 2 mm wide, 30 μm substrate.
- **1st demo coil is being manufactured now for test in self-field in liquid nitrogen in May and in 11T background field in Twente in summer 2019.**
- Others to follow….

Two layers, each 16.5 turns



Design Self-Field Performance

*	High-field I_c	Overall I_c	Unit
77 K	785	805	A
60 K	2438	2500	A
50 K	3405	3494	A
4.2 K	**9517**	**9755**	**A**

** 100 μV/m criterion*

**	Peak field	Central field	Unit
77 K	0.47	0.39	T
60 K	1.47	1.20	T
50 K	2.05	1.68	T
4.2 K	5.73	**4.69**	T

*** Using the Overall I_c*

CORC Solenoids - Test in high field

CORC solenoid as high-field insert:

- Tested as insert in the 11 T Nb_3Sn magnet at University of Twente at 4.2 K.
- In background field of 10 T, generating an additional 2.5 T.

Calculated in-field performance at 4.2 K:

Bext (T)	Ic (kA)	Peak field (T)	Center field (T)
0 T	9.76	5.7	4.7
4 T	7.39	8.3	7.6
8 T	5.83	11.4	10.8
10 T	**5.20**	**13.1**	**12.5**
12 T	4.74	14.8	14.3

✓ This CORC solenoid is the first of several demo coils and will be followed by a higher-performance CORC solenoid with more layers and higher-J_e tapes.

✓ In parallel, development of CORC dipole magnet winding technology.

Wet wound and strengthened with epoxy

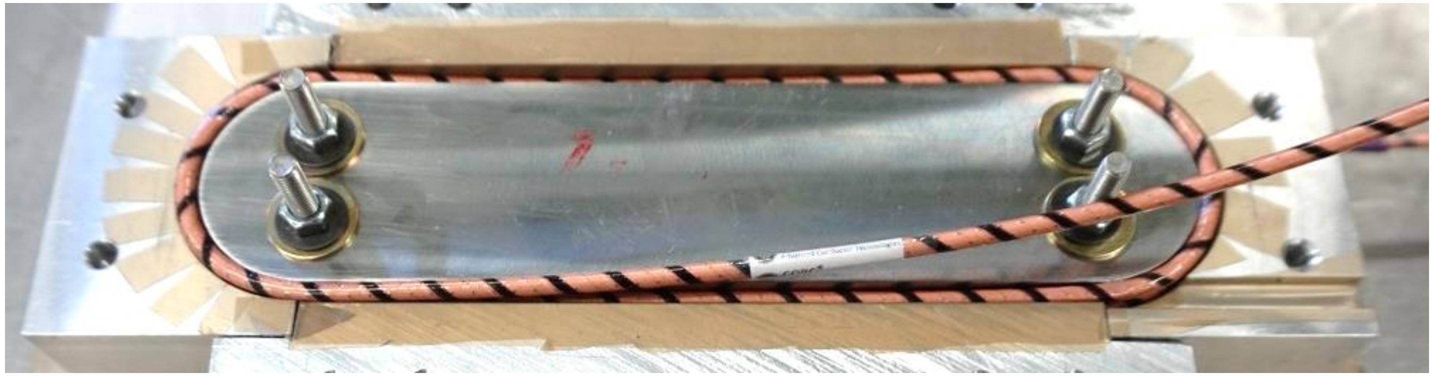
CORC Coils – Racetracks Development

CERN CORC Demonstrator Racetrack Coil:

- Layout: 2 layers with each 8 turns
- Minimum bending diameter of 40 mm
- Coil inductance ≈ 50 µH, 0.38 T per kA
- I_c of ≈ 4.5 kA at 10 T and 4.2 K

✓ First demonstrator coil using ‘dummy’ CORC wire made using a ⌀3.3 mm wire with tapes comprising 30 µm substrate, still too thick for such bending.

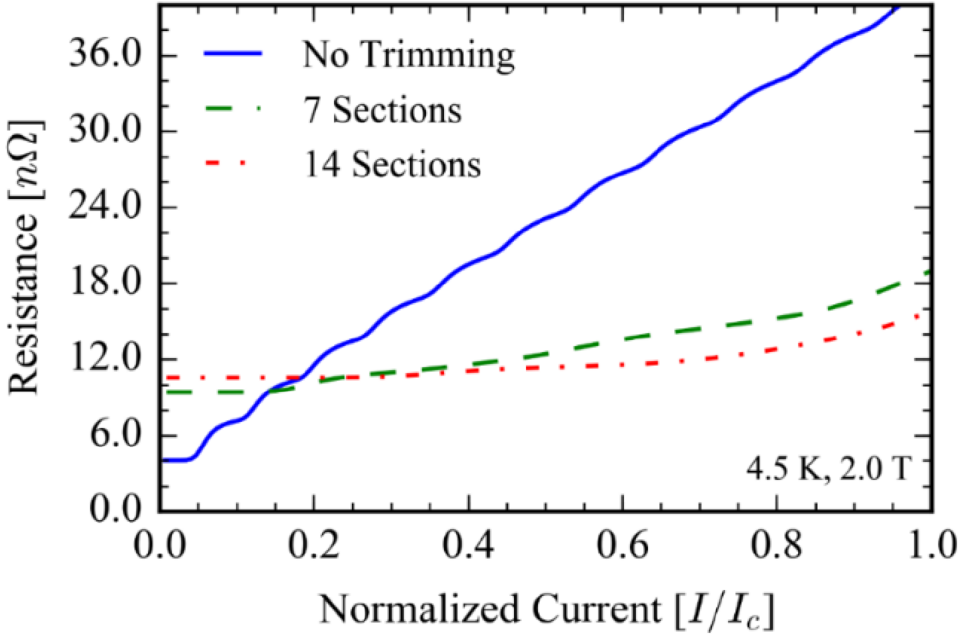
✓ New ⌀2.0 to ⌀3.0 mm CORC wires with 25 µm substrate tapes are awaited from ACT.

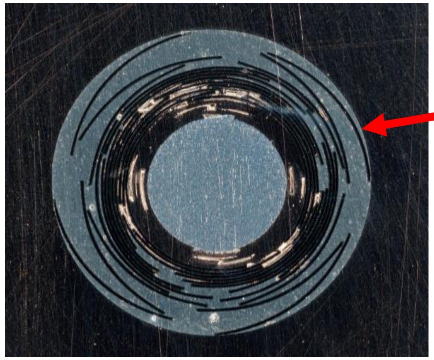


CORC Joint Terminals - Resistance and current sharing

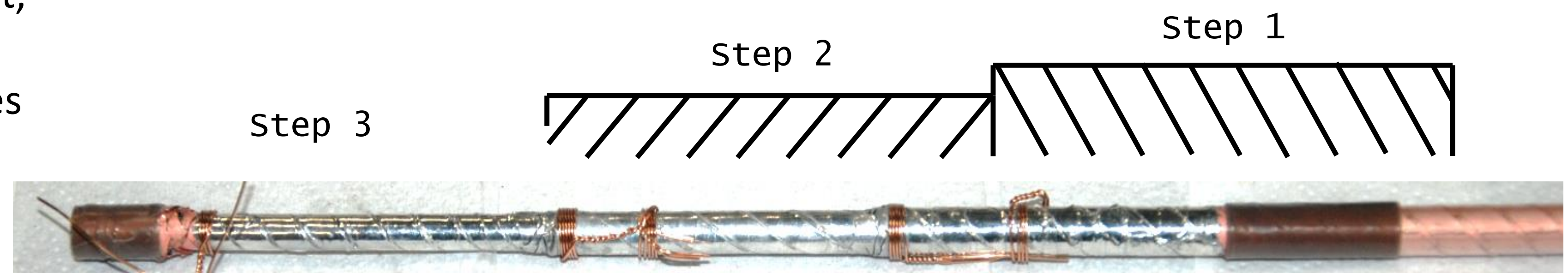
Joint technology developed for low resistance:

- Need current transfer to all (sets of) layers, how?
- --> Taper the CORC cable for good current sharing and joint terminal performance.
- Practical and scalable method.
- Yields low resistance of 0.7 to 2 nΩ.m for 6-o-1 CICC.
- And good current distribution.





Tapes spring out, solder flows inbetween tapes

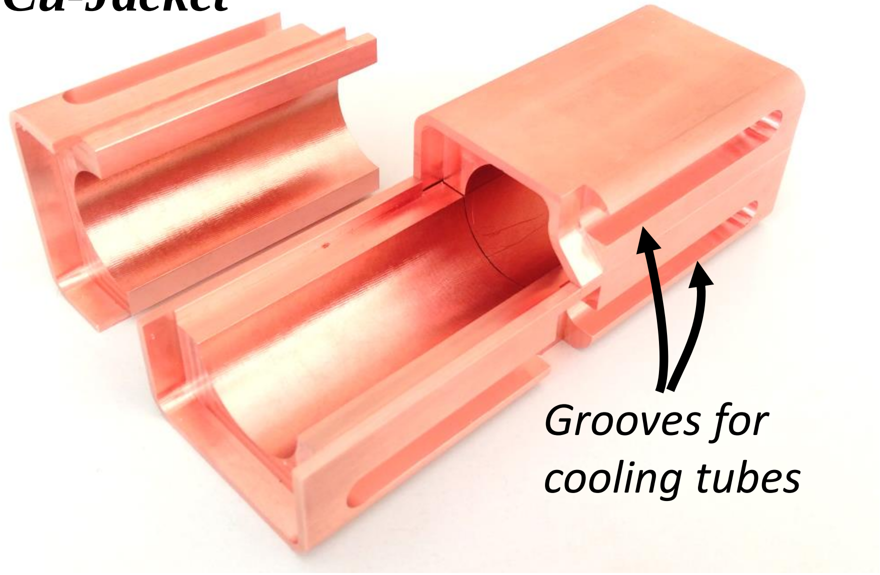


✓ **Good joints** when using staging technique, insertion in soft Cu sleeve/bus & filling with low-resistivity solder!

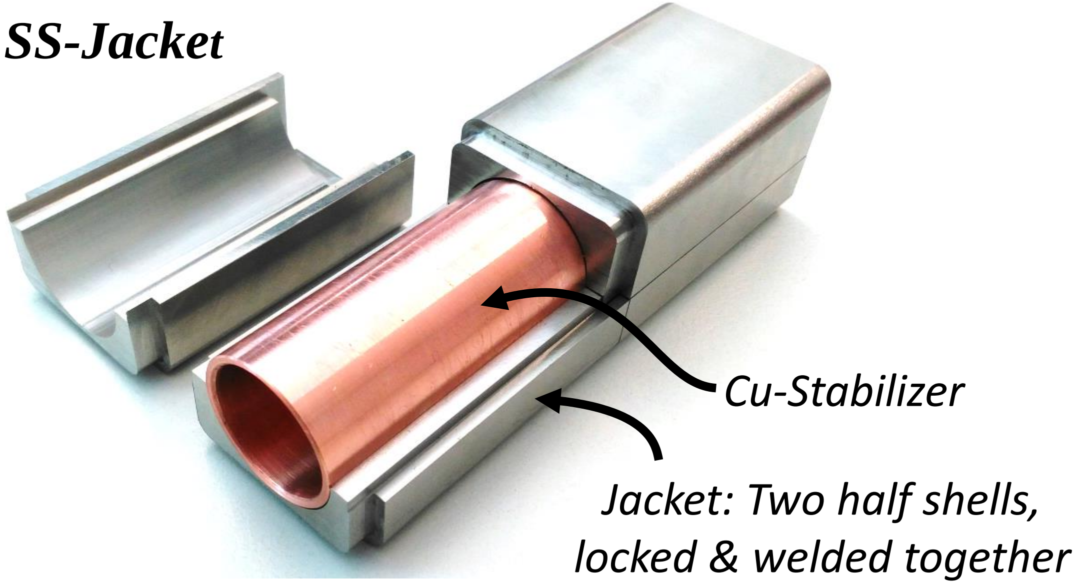
CORC Cable-in-Conduit Conductors - Development

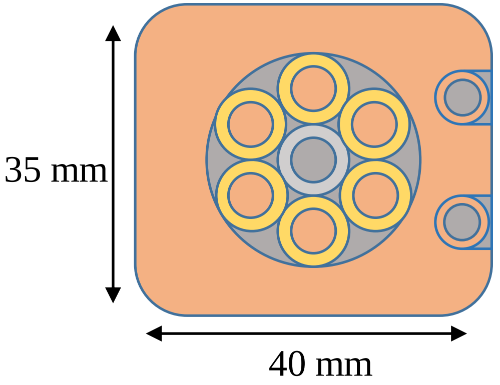
CICCs are 2.8 m long and designed for 80 kA at 12 T and 5 K.

Cu-Jacket



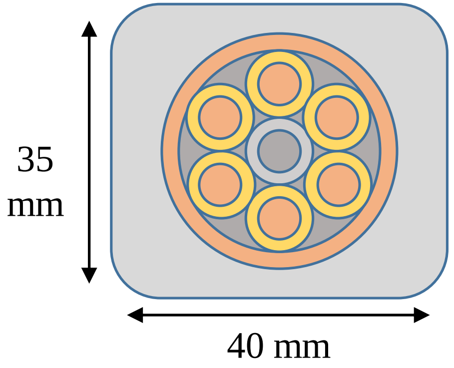
SS-Jacket





For Detector Magnets & Bus Bars:

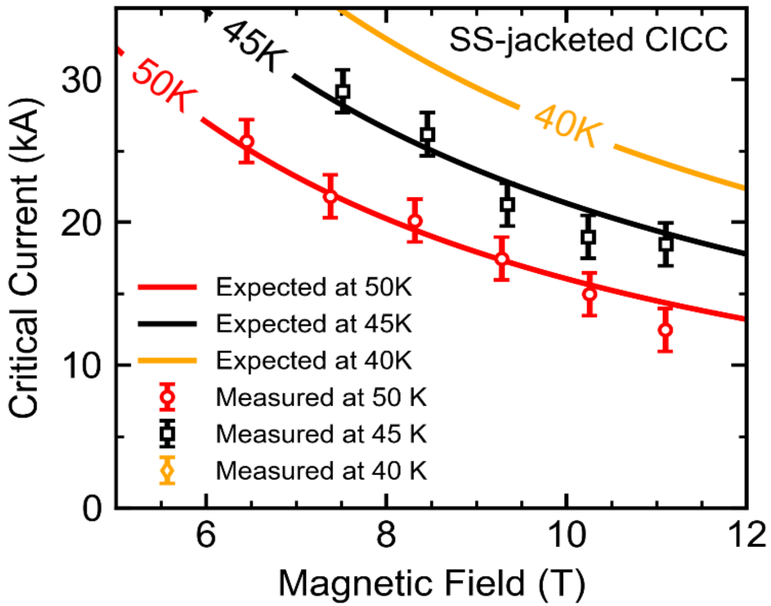
- High thermal & electrical stability
- Practical conduction cooling

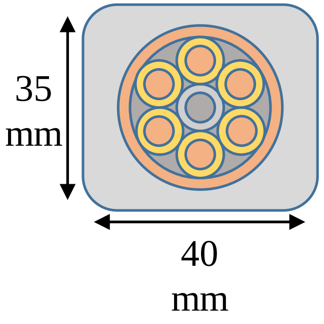


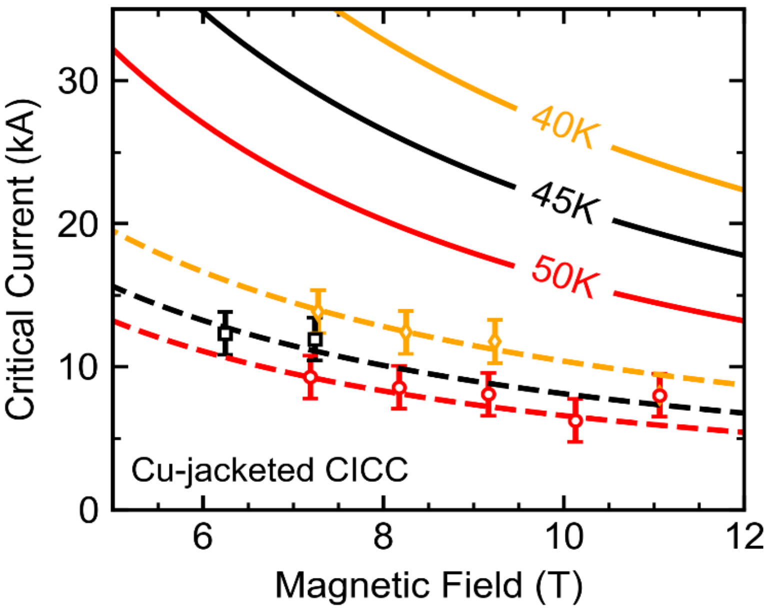
For Fusion type magnets:

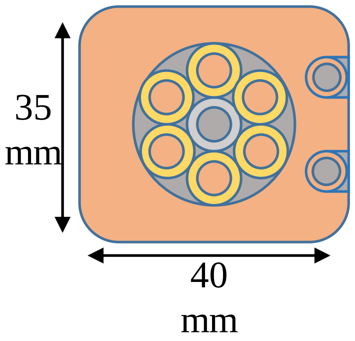
- Can sustains high stress
- Can cope with large heat load
- Internal forced-flow cooling

Test Result of these two first-of-its-type full-size CICCs









SS-jacketed CICC for Fusion Magnets:

- Performed **according to prediction** at 40 to 60 K
- N-value of **14±3** (similar to 2016 sample).

Cu-jacketed CICC for Detector Magnets & Bus Bars:

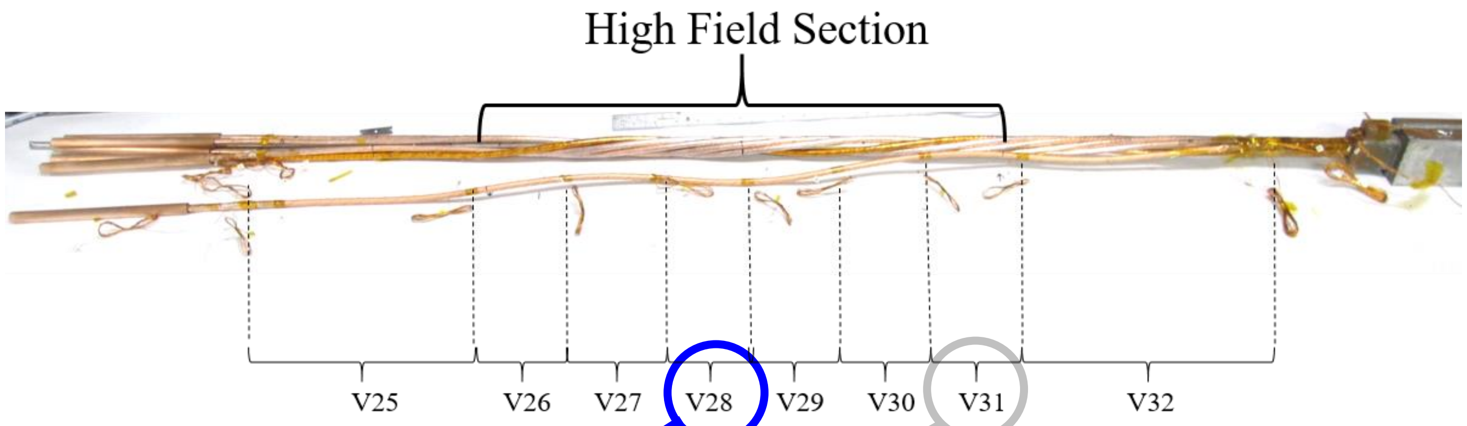
- Limited to **30 - 40 %** of predicted I_c
- **Low n-value of 5±2** in the 40 to 60 K range
- **Degradation occurred only in the Cu-jacketed CICC.**

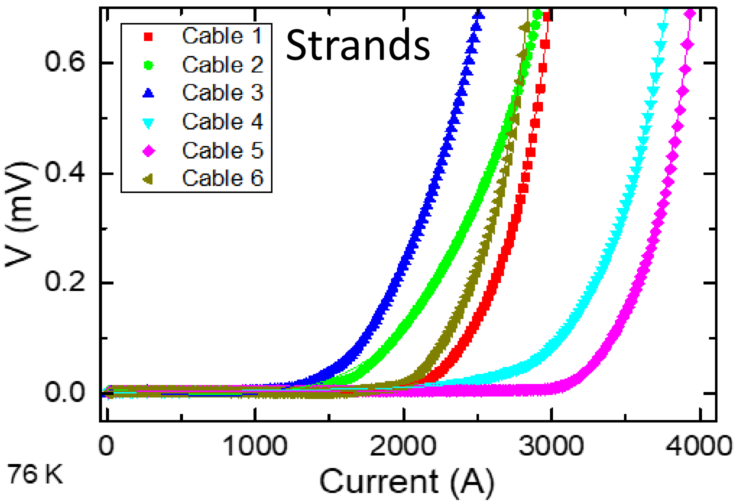
✓ **Both: <u>Conduction</u> and <u>Forced-flow Convection</u> cooling proved efficient for such conductors.**

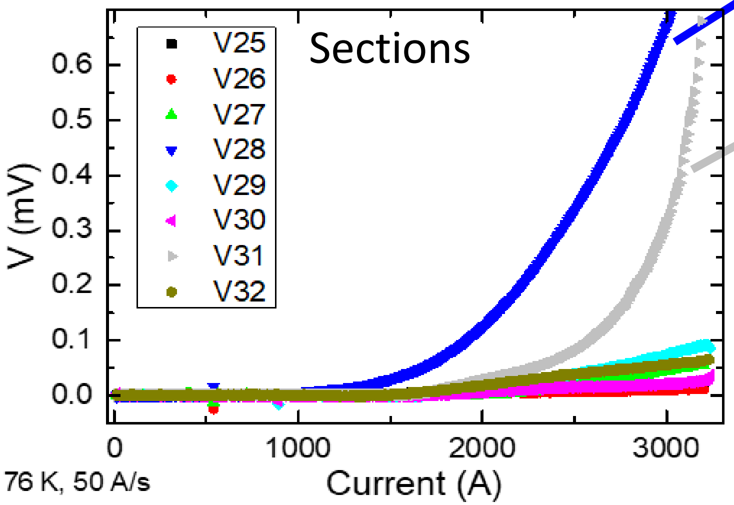
Finding the degraded spots…

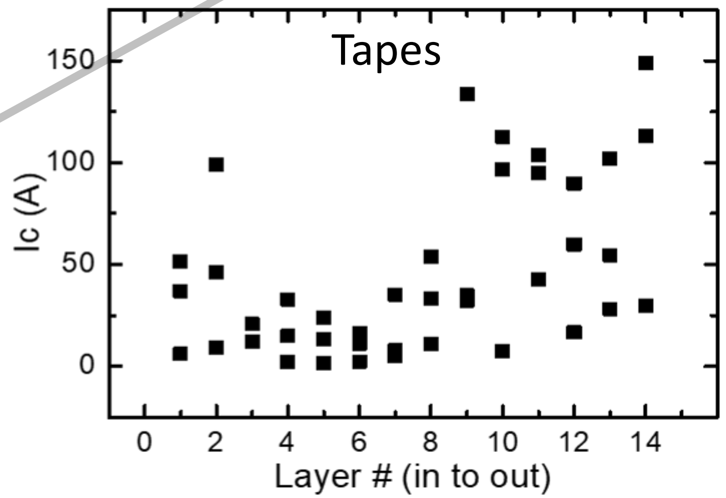
Single strands were extracted tested at 76 K in self-field at ACT

- 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.







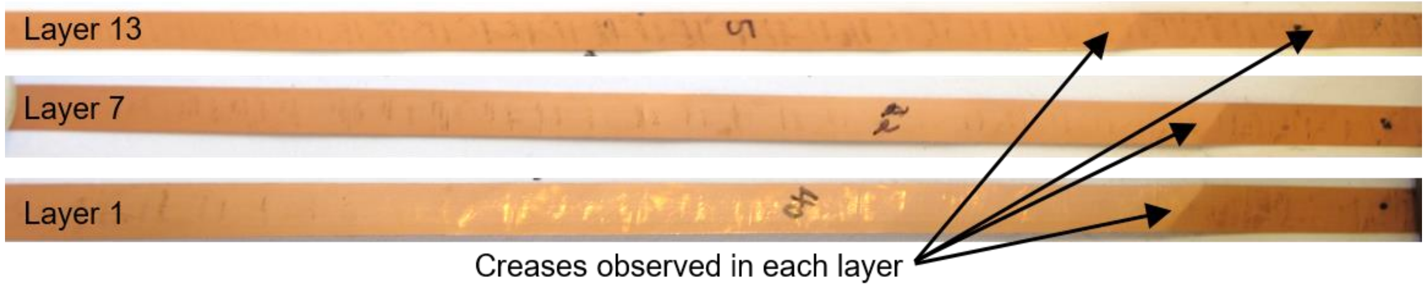


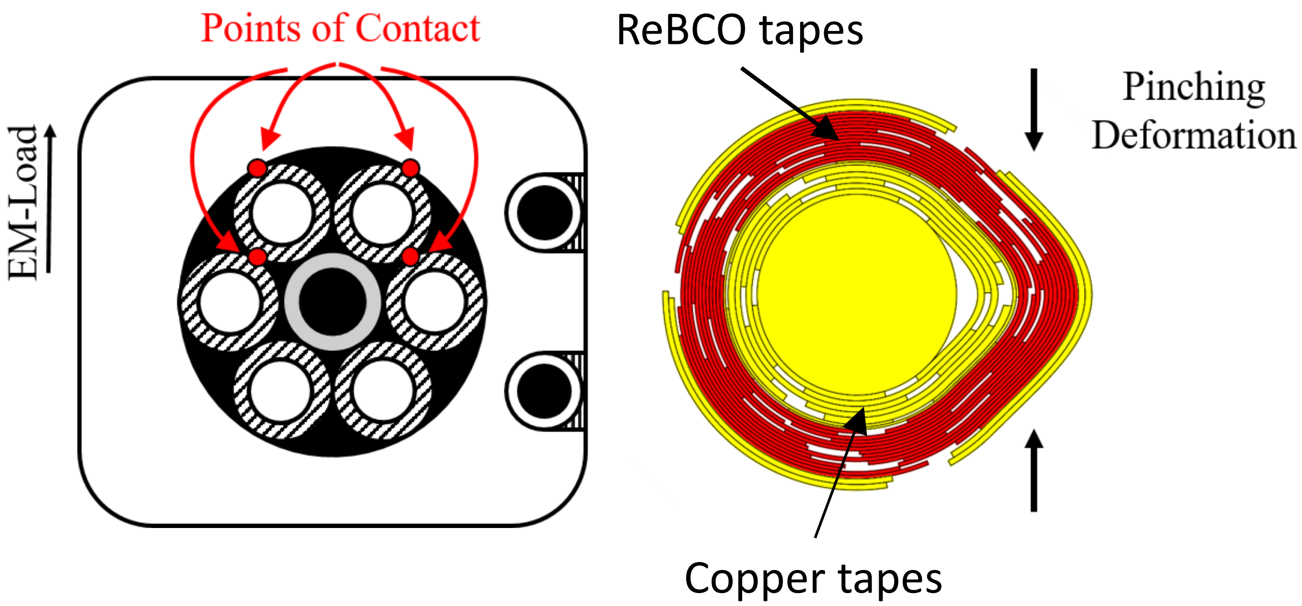
Cause of degradation

Likely 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 a soft core, like copper tapes pre-wound around a core, does not provide sufficient mechanical support.*



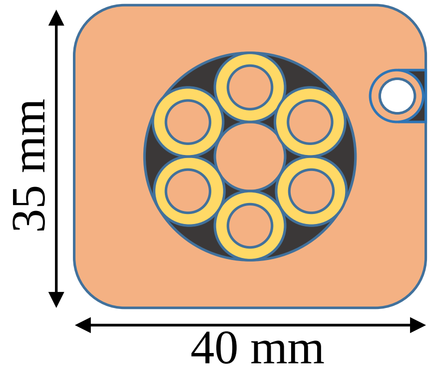


Next step:

- New CORC CICC prepared replacing the degraded Cu-jacketed CICC.
- New strand layout with a thicker core.
- Improved mechanical support of CORC strands

New Cu-jacket CORC CICC Sample (May 2019)

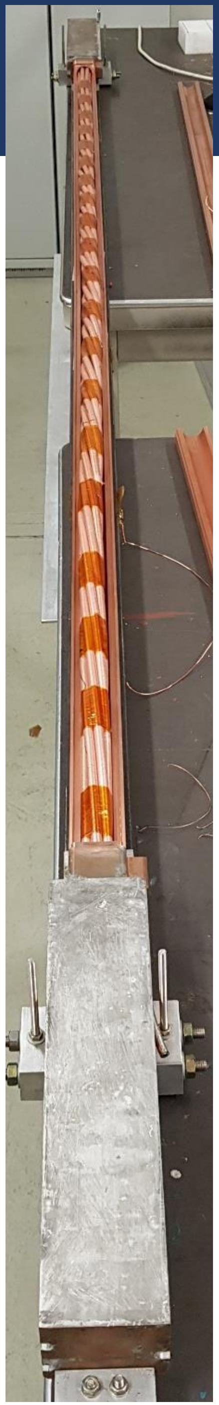
- Project in Collaboration with ACT
- Similar high-I_c tape layout in the CORC strands as the previous sample
- Solely cooled by conduction cooling via its jacket
- Improved electrical and mechanical performance
- Solder filling inside the jacket.

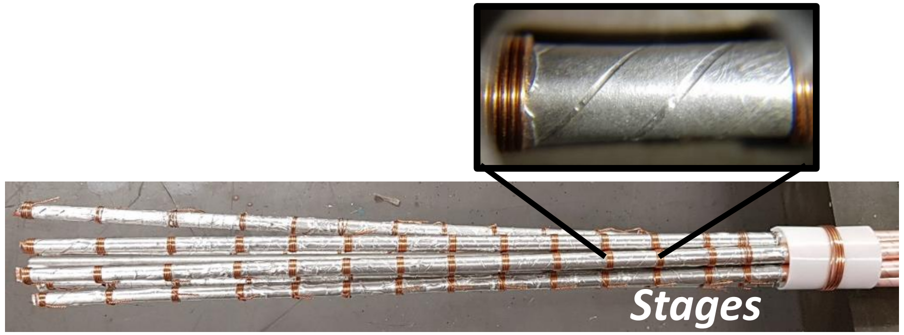


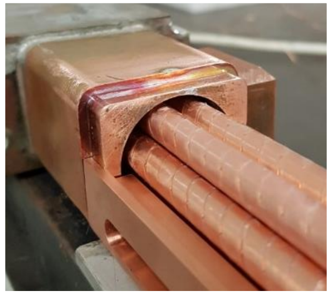
	Trial (2016) CICC #1	Fusion Sample (2017) CICC #2	Detectors Sample (2017) CICC #3	Detector Sample (2019) CICC #4
Number of tapes	38	42	42	42
Number of layers	12	14	14	14
Tape type	SCS 4050	SCS 4050	SCS 4050	SCS 4050
Copper plating [μm]	40	10	10	10
Core material	Aluminum	Copper	Copper	Copper
Solid core diameter [mm]	4.0	5.0	4.0	5.0
Outer diameter [mm]	7.6	7.7	7.7	7.7
Critical current (4K, 10T) [kA]	48	90	90	100

Design, Assembly & Sultan Test (May 2019)

- 6 new CORC strands, cable-pitch ≈ 400 mm, 4.5 pitches in total, strands are straight in the terminal sockets.
- Voids filled with BiPbSn solder (96°C) over the entire length for mechanical stability. Solder also yields heat transfer between strands and cooling channel.
- In the joints the CORC strands are made staircase like allowing current to be directly and homogeneously injected in each ReBCO layer.
- R100 Cu sockets, Indium filled (160°C), best, 1.4 nΩ/terminal expected, 0.4 nΩ.m (30% better than with PbSn).
- Jacket closed by EB-welding.
- **Sample tested in series with the earlier SS-jacket CICC.**



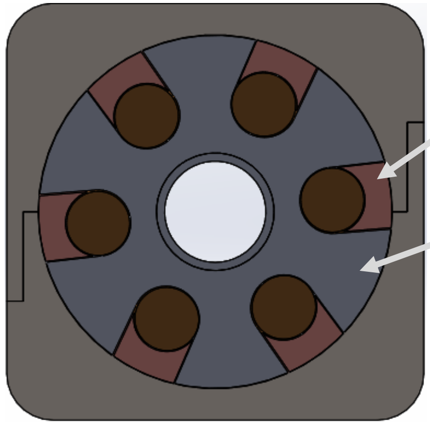




Next: another two CICC variants to build and test in 2019

Fusion type CORC-CICC #5, test in SULTAN

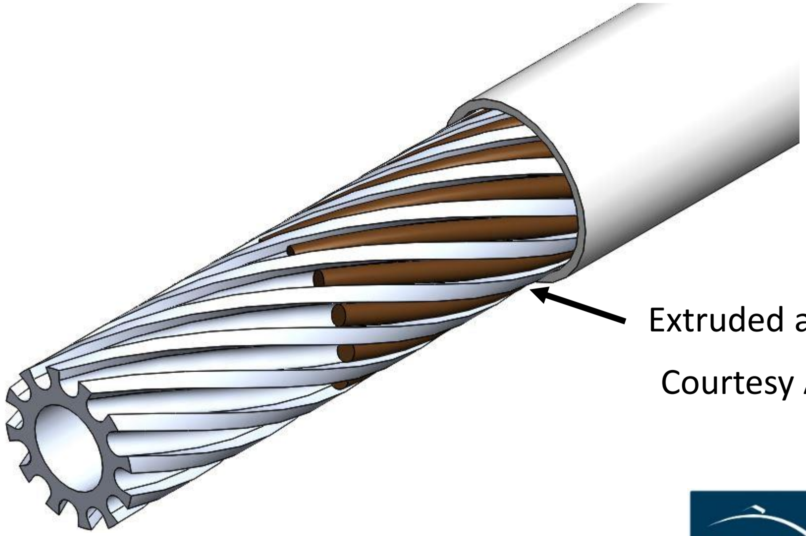
- USA funded, testing in collaboration ACT, CERN, UT
- 6-around-1 CICC based on CORC® cables
- Goal is 80 kA at 10.8 T background field
- Using internal support to decouple CORC® strands
- Improved CORC®-CICC terminals
- SULTAN test expected early autumn 2019.



Courtesy ACT/J.Weiss

Fusion type CORC-CICC #6, test in SULTAN

- USA funded, collaboration ACT, LBNL, CERN, UT
- Based on CORC® 12 – 14 wires for higher degree of transposition and better flexibility
- Goal is 80 kA at 10.8 T background field
- Using internal support to decouple CORC® strands
- SULTAN test by end of 2019.



Courtesy ACT/J.Weiss

UNIVERSITY OF TWENTE. BERKELEY LAB CERN

Conclusion – CORC wire based devices

- **Development of CORC-wire and multi-strand conductors actively pursued in cooperation with ACT and associated partners.**
- Series of CORC wire based demonstrator coils are developed at CERN and tested at Uni. Twente, mastering the technology.
- A 1st CORC solenoid being prepared for test in summer 2019.
- Two 2.8 m long 80 kA class CORC CICCs were tested in Sultan.
- Degradation in the Cu-jacketed CICCs observed, localized and explained. Learned a lot, valuable feedback for optimizing CORC.
- A new Cu-jacket CORC CICC prepared, test in Sultan in May 2019.
- Another 2 CICC variants are planned for testing in Q3&4 2019.

✓ **Imminent: test of the new Cu-jacket CICC at 4-50 K in SULTAN including extensive cycling tests…., stay tuned!**