

Development of ReBCO-CORC Conductors and Magnet Technology at CERN

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ReBCO Multi-Tape Conductors

ReBCO Multi-Tape Cables:

- Large magnets require currents beyond the capacity of a single ReBCO tape.
- Multiple tapes combined to a high-current ReBCO cable.
- Increased stability, single tape defects are less pronounced.
- Reduction of inductive and coupling losses.
- Three main designs: Roebel, Twisted Stacked Tape Cable (TSTC) and Conductor on Round Core (CORC).



TSTC:

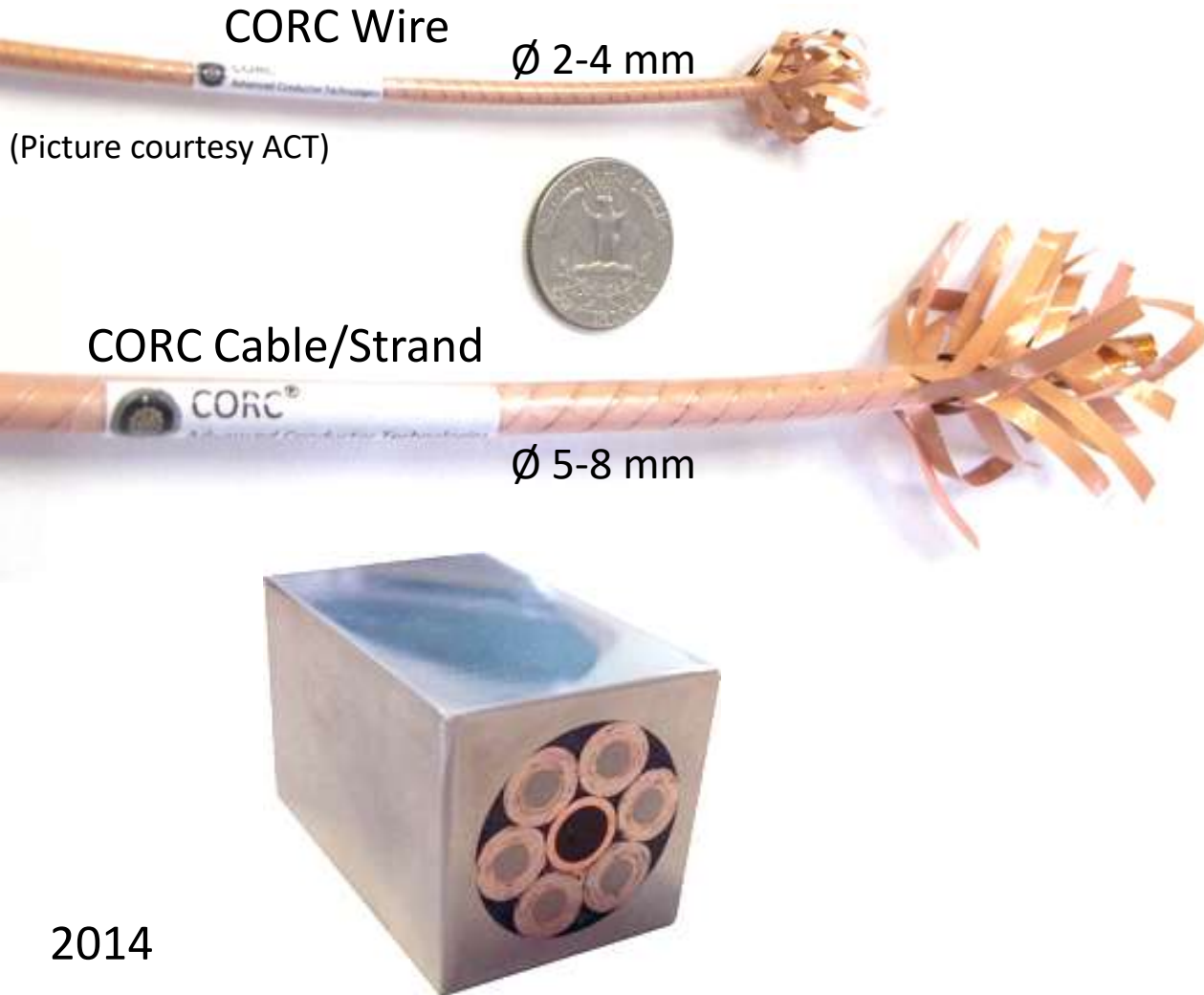
- Tape stack with high current density.
- Difficult to bend and long twist pitch.
- Copper shell for practical handling during magnet winding.
- Mainly designed for large-scale magnets for fusion reactors.



Roebel:

- High current density.
- Flexible in the 'out-of-plane' bending direction.
- Fully transposed.
- Designed for compact high-field magnets.

CORC Wires, Cables and Cable-In-Conduit Conductors



CORC:

- High omni-directional flexibility.
- Round shape resilient towards transverse loads.
- Internal core stabilized.
- No tape lost during production.
- For compact high-field magnets and large magnets (detector and fusion) and bus bars.

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.*

Quest for CORC-wire optimized *ReBCO* tape

CORC Wires:

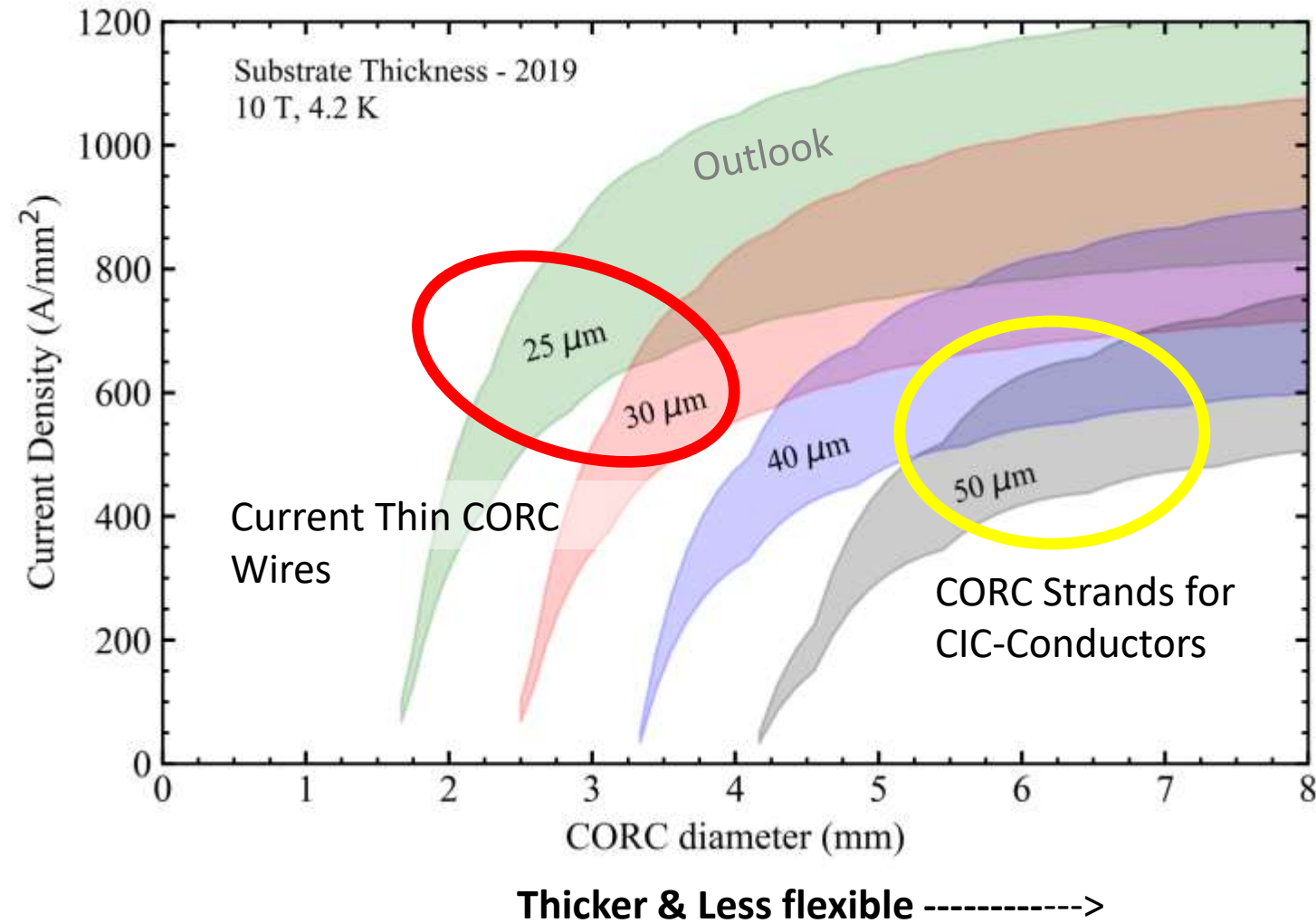
- Made possible by the reduction in substrate thickness from 50 to 30 μm .
- Narrower tapes of 2 mm wide.
- Designed for high-field magnets.

CORC Strands:

- Thicker medium-current cables.
- Designed for large high-field magnets, requiring high thermal/electrical stability.

Further Cable & Wire Optimization:

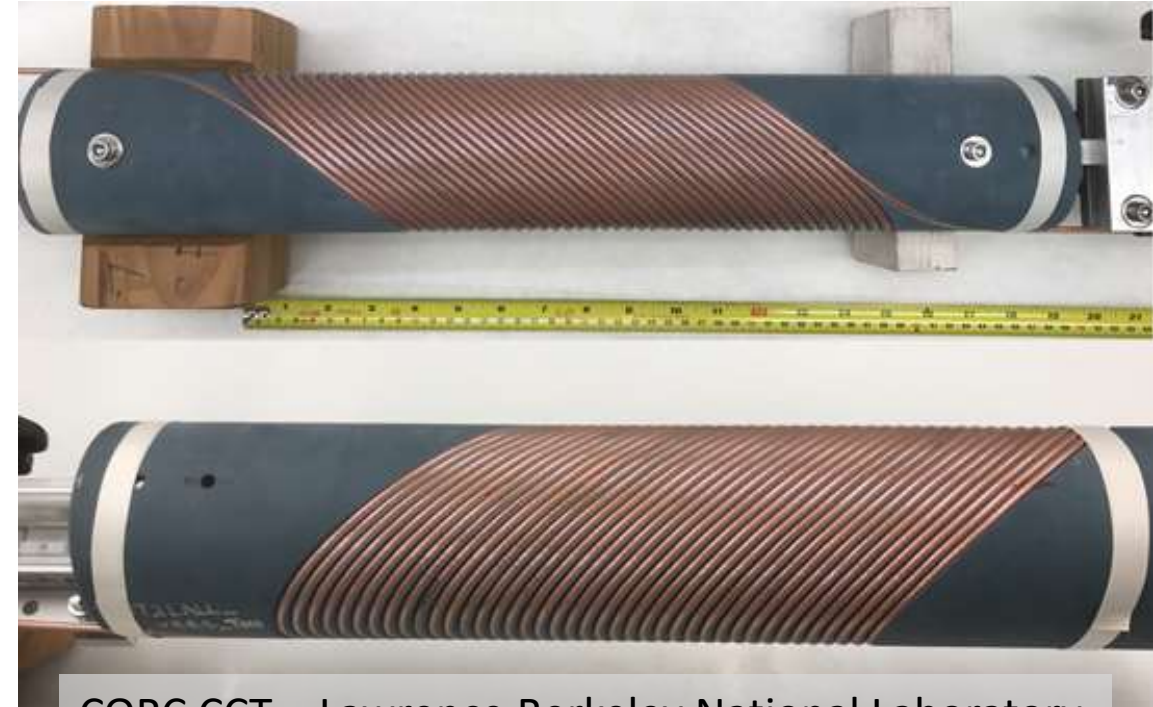
- Thinner substrate of $25 > 20 \mu\text{m}$.
- Narrower tapes of $1.5 > 1.0 \text{ mm}$.
- Higher I_c by increasing *ReBCO* layer thickness to 2 or 3 μm (or even more!).



ReBCO High-Field Magnets - Examples

Benefits of *ReBCO* for High Field Magnets:

- *ReBCO* conductors by far surpass common LTS conductors in I_c and B_{c2} at 4.2 K.
 - User magnetic field far beyond 20 T in 4 to 30 K range.
 - Extreme thermal and electrical stability!
 - Hybrid HTS/LTS solutions available.
- ✓ Several *ReBCO* Roebel and CORC demonstrator coils have been exercised in the last years.
- ✓ CORC's round shape allows multi-directional bending, thus practical coil winding, i.e. the CCT of LBNL.



CORC CCT – Lawrence Berkeley National Laboratory

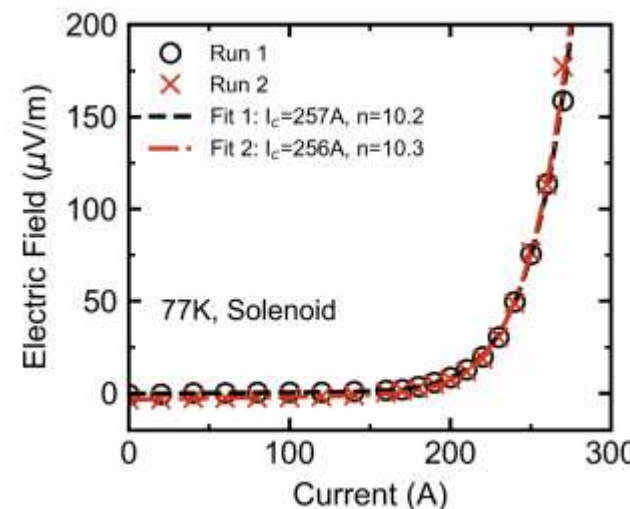
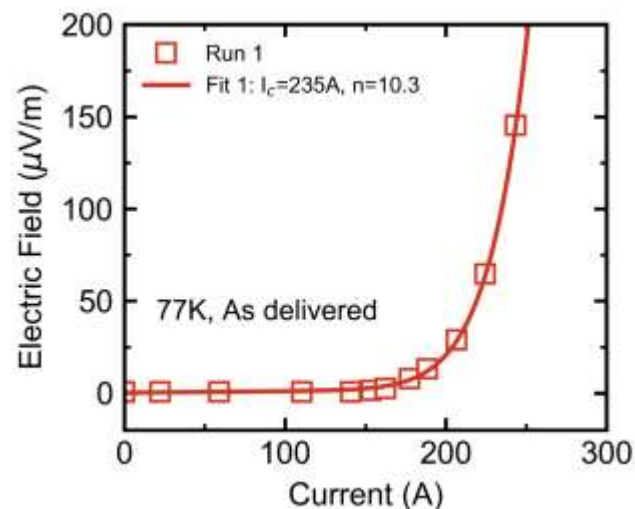


Roebel cable based dipole magnet – CERN

CORC Racetrack Coil Development at CERN

CERN CORC demonstrator racetrack coils:

- Layout: 2 layers with each 8 turns
 - Minimum bending diameter of 40 mm
 - Coil inductance $\approx 50 \mu\text{H}$, 0.38 T per kA
 - I_c of around 4.5 kA at 10 T and 4.2 K
- ✓ First prototype using 'dummy' CORC wire demonstrated using a $\varnothing 3.3 \text{ mm}$ wire with tapes comprising $30 \mu\text{m}$ substrate are still too thick for such bending.
- ✓ New $\varnothing 2.0 - \varnothing 3.0 \text{ mm}$ CORC wires with tapes comprising $25 \mu\text{m}$ substrate are under development.



CORC Race Track Coil

Practice coil using dummy wire with 4 *ReBCO* tapes.

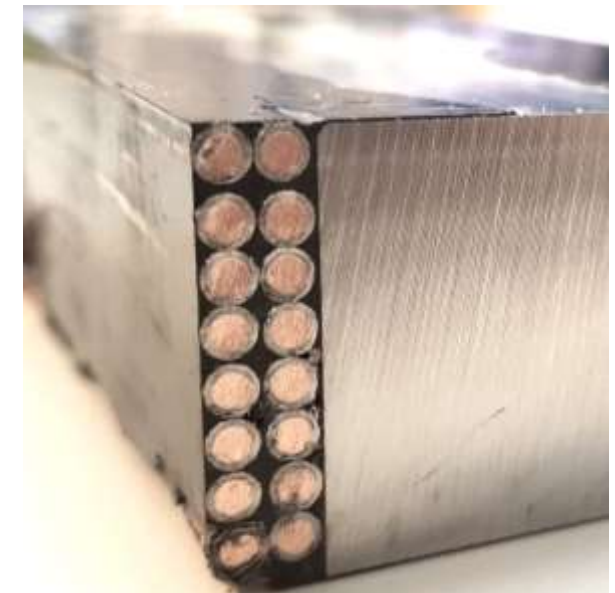
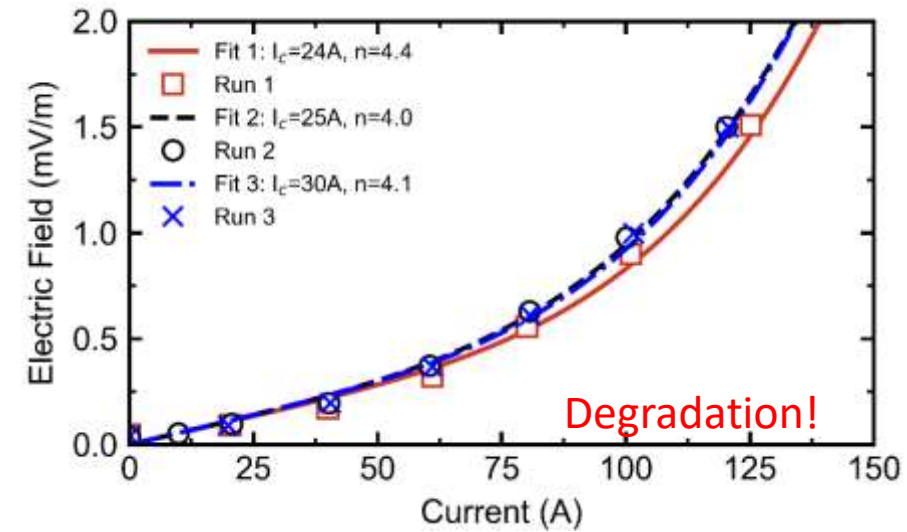
- Dummy wire: $I_c = 250$ A, $n = 10$ @ 77 K before winding

Racetrack wet wound with Stycast 2850FT epoxy resin.

- **Racetrack: $I_c = 30$ A, $n = 4$ @ 77 K**

Bending diameter of 40 mm appeared to be too small for the tapes.

- ✓ **Narrower tapes with thinner substrate required!**



CORC Race Track Coil

What is next?

Designs are in preparation for a new prototype CORC dipole.

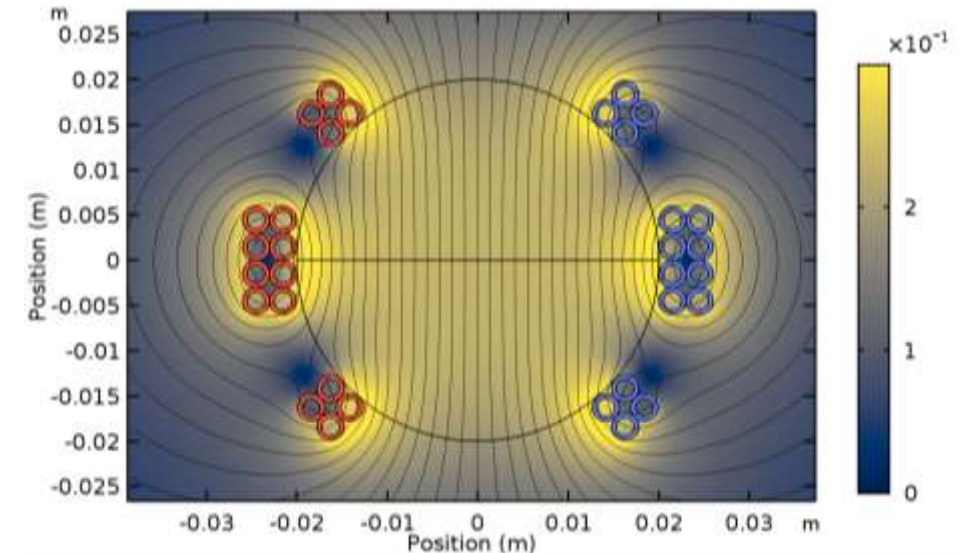
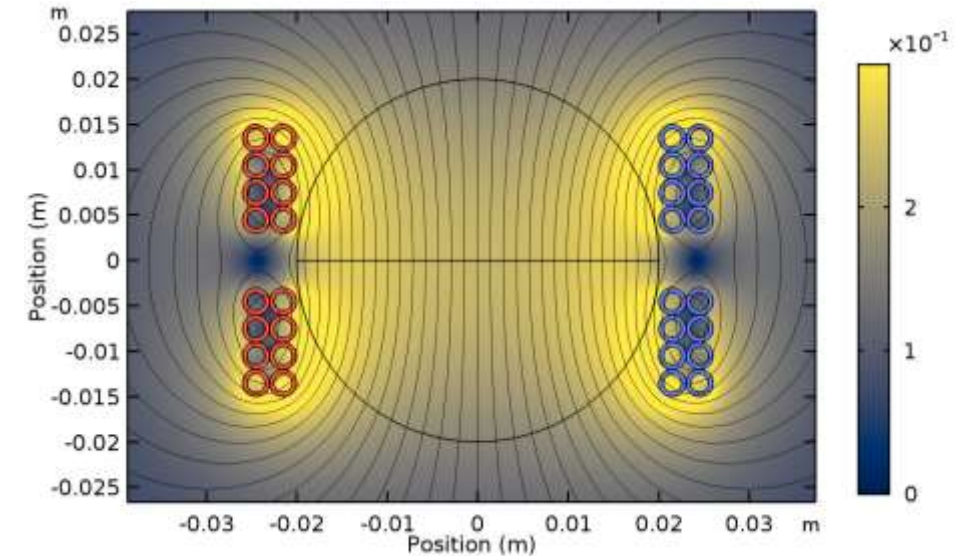
New CORC Racetrack

- Similar design as the first demonstrator
- Minimum bending radius of 20-25 mm (depends on wire)
- Two individual racetracks of 2 layers and 4 turns
- Intermediate connection between coils
- ~ 0.3 T/kA

A 1st CORC 'Block' Coil

- More complex design
- Minimum bending radius of 20-25 mm (depends on wire)
- Allows relatively homogenous magnetic field in the center over 20 mm and 0.3 T/kA

✓ **Thinner and narrower tape requires for small bore, $d < 50$ mm, CORC based magnets.**



CORC solenoid – Series of demonstrators

- A series of compact 2-layer CORC solenoids developed at CERN to demonstrate practical handling, materials choices, conductor robustness, and high performance of CORC wires for magnets.
- CORC wire: 27 ReBCO SCS2030 tapes, 2 mm wide, 30 μm substrate.
- Minimum bending radius of 30 mm.
- Magnet scheduled for testing in self-field in liquid nitrogen in Q3-2019, followed by a 4.2K test in background of 15 T at Uni Twente.

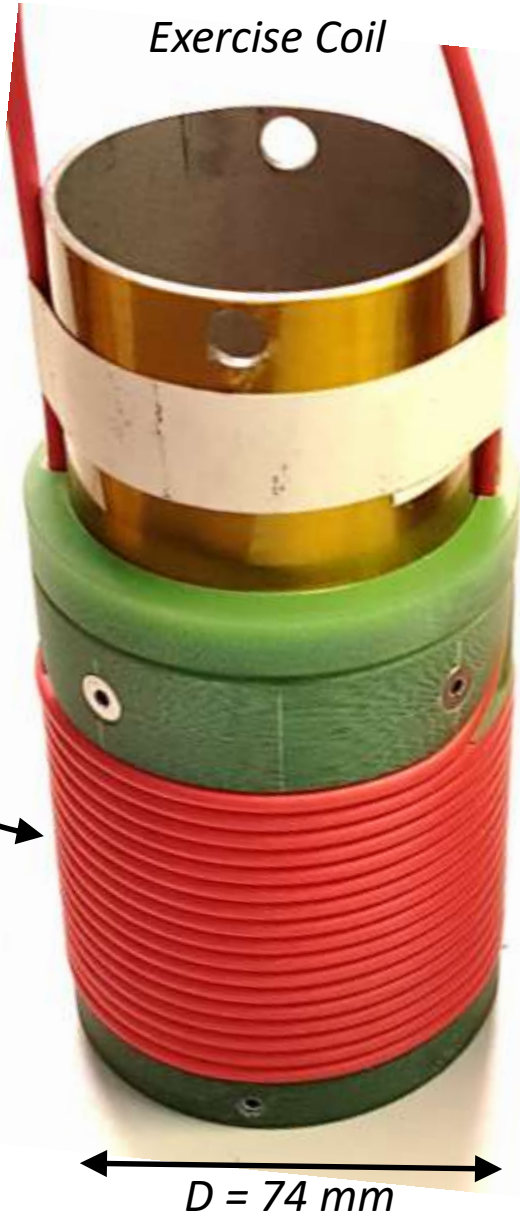
Design Self-Field Performance

T (K) *	High-Field I_c (T)	Overall I_c (A)	T (K) **	Peak Field (T)	Central Field (T)
77	785	805	77	0.47	0.39
70	1467	1505	70	0.88	0.72
65	1968	2019	65	1.19	0.97
60	2438	2500	60	1.47	1.20
50	3405	3494	50	2.05	1.68
4.2	9517	9755	4.2	5.73	4.69

* 100 $\mu\text{V/m}$ criterion

** Using the Overall I_c

Two layers, each 16.5 turns



CORC Solenoids – High-field test

- CORC coils are tested as insert in a 15T Nb₃Sn magnet at the University of Twente at 4.2 K.
- In 10 T background, the coil is expected to generate an additional 2.5 T.

Calculated in-field performance at 4.2K

BG (T)	I _c (kA)	Peak field (T)	Central field (T)
0	9.76	5.73	4.69
2	8.56	7.02	6.12
4	7.39	8.34	7.55
6	6.50	9.81	9.13
8	5.83	11.4	10.8
10	5.20	13.0	12.5
12	4.74	14.8	14.3

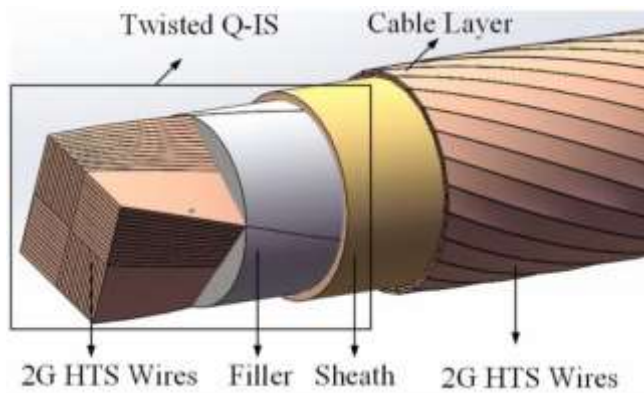
- ✓ This CORC solenoid is the first of several CORC demonstrator coils. It will be succeeded by higher-performance CORC solenoid with more layers and higher-I_c tapes and by a CORC dipole magnet.



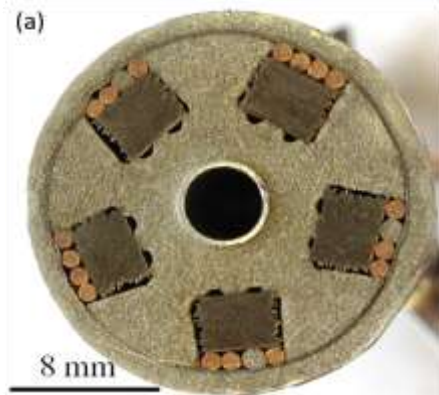
ReBCO Cable-In-Conduit Conductors

- Superconducting **Cable-In-Conduit Conductors (CICCs)** are commonly designed for large-scale, high-current magnets such as used in experimental fusion reactors and particle detectors.
- *NbTi* and *Nb₃Sn* conductor development are close to their limits, and quest of higher temperature, and no-helium operation ---> ***ReBCO based CICCs to be developed!***
- **ReBCO** based conductors offer a further increase in current density, stability and allows (optional) operation above liquid helium temperatures.

Examples of several *ReBCO* based CICCs are in development around the globe:



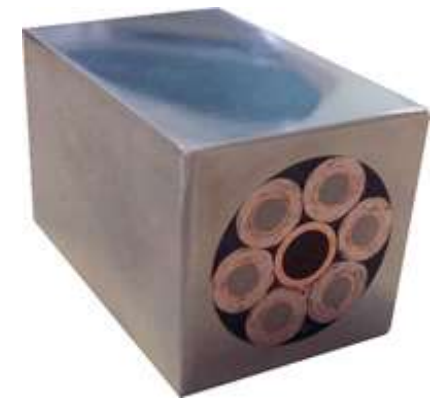
North China Electric Power University
Quasi-Isotropic Conductor



ENEA: Twisted Stacked
Round CICC



Swiss Plasma Center:
Twisted Stacked Rectangular CICC



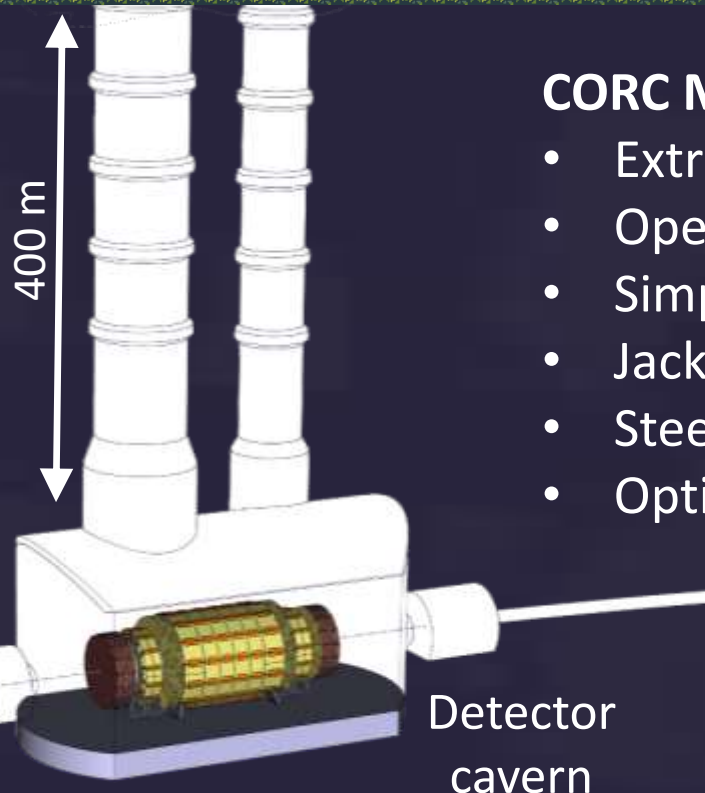
CERN & ACT: CORC 6-a-
1 CICC

CORC CICC for Bus Bars and Large Scale Magnets

Bus bars based on CORC CICC conductor, lighter, taking less space.

CORC Bus Lines:

- Reduce weight
- Reduce volume
- Reduce power converter requirements
- Allow power convertor placement on surface



CORC Magnets:

- Extremen thermal & electric stability
- Operation at 20 to 50 K
- Simpler cooling with helium gas
- Jacket material application dependent
- Steel for fusion, Aluminum for detectors.....
- Options for internal or external cooling

CORC CICC Development Timeline



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- Test of two CORC CICC
- Stainless steel jacket + internal cooling
 - Copper jacket + external conduction cooling

Test of new solder-filled CICC with copper jacket

2017

2019

2016

Test of 1st CICC with Aluminum jacket



2018

Design & Preparation of new sample

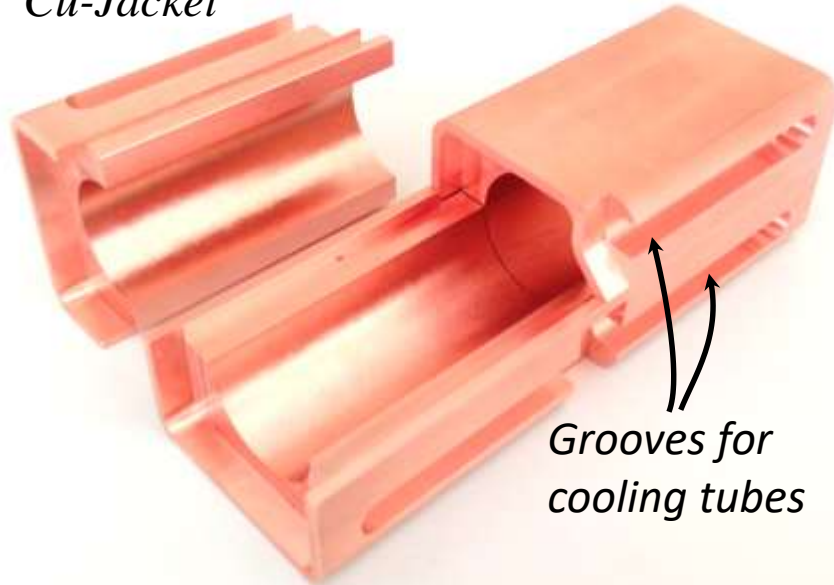


2020

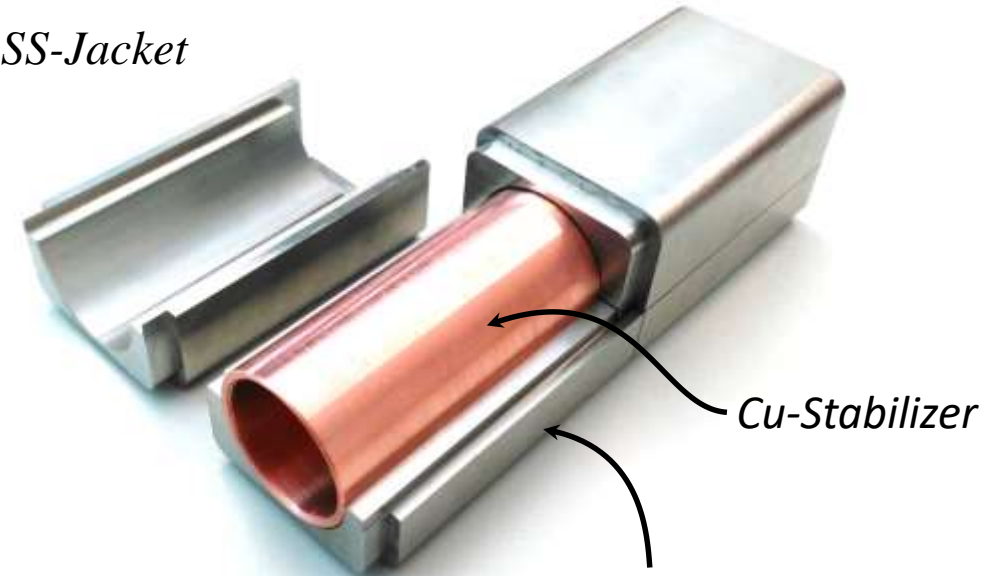
Testing new layouts of internally cooled CORC CICC

CORC Cable-In-Conduit Conductor Design

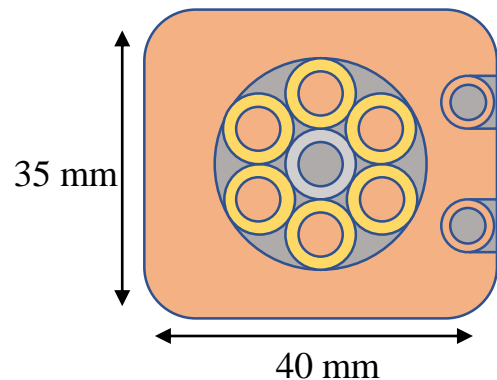
Cu-Jacket



SS-Jacket



Jacket: Two half shells, locked & welded together

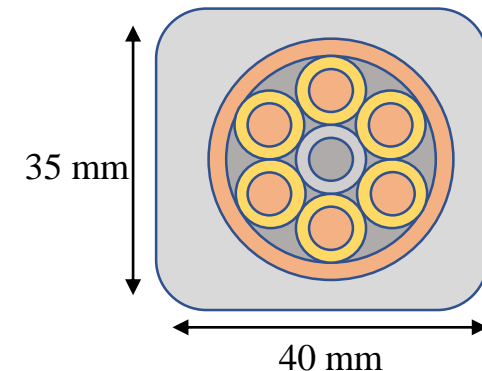


Detector magnets & Bus Bars:

- High thermal & electrical stability
- Practical conduction cooling

Fusion type magnets:

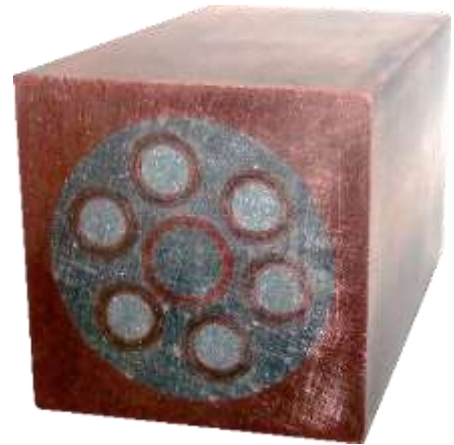
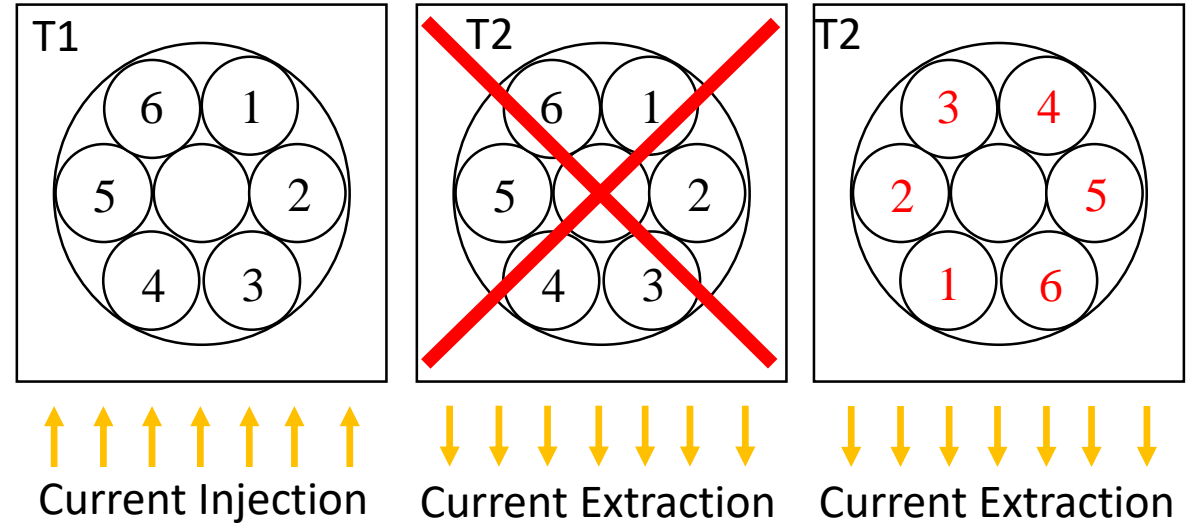
- Can sustain high stress
- Can cope with large heat loads
- Internal forced-flow cooling



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

CORC CICC - Joint terminal design

- Short sample current is distributed in terminals.
- Strands are tapered, allows current to flow evenly into each layer of each CORC strand.
- Strands are straight inside the terminal.
- Half a cable pitch difference between terminals improves current distribution among strands.
- Terminals filled with solder, SnPb or Indium (best).
- Design resistance of $0.6 \text{ n}\Omega\text{m}$.



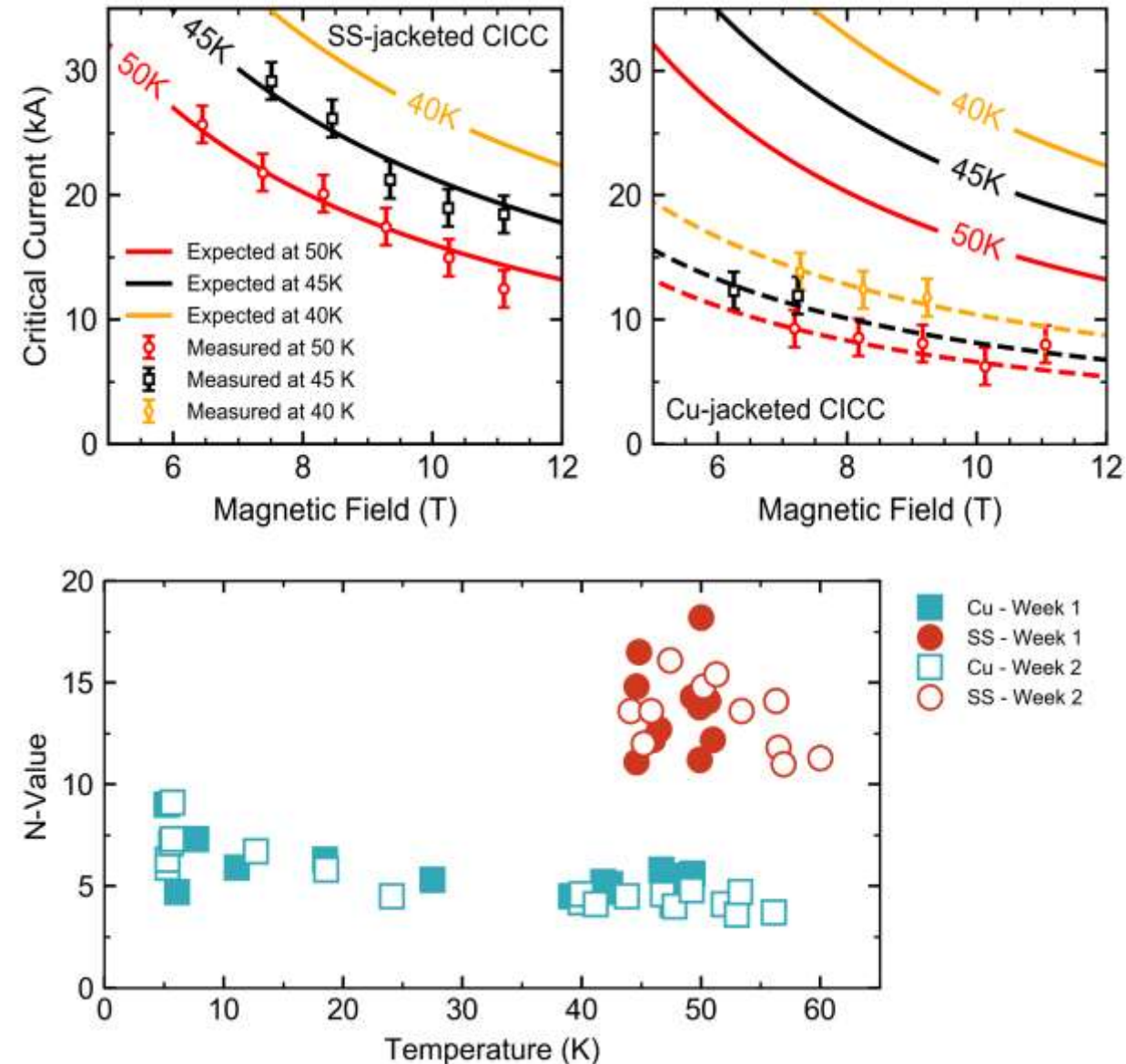
SS and Cu jacketed CORC CICC samples – test results

SS-jacketed CICC for Fusion Magnets:

- Performed **according to prediction** at 40 to 60 K
- N-value of **14 ± 3** (similar to the 2016 sample)
- Low AC-loss of 7 mJ/cycle/cm³

Cu-jacketed CICC for Detector Magnets & Bus Bars:

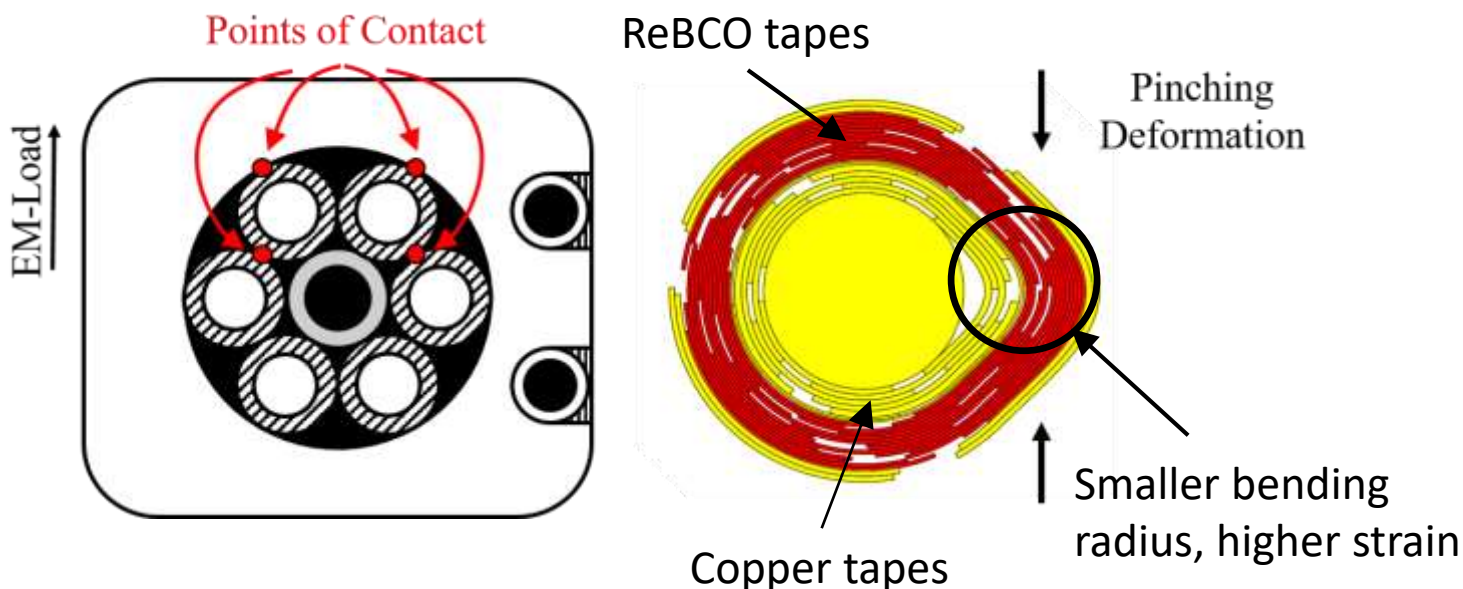
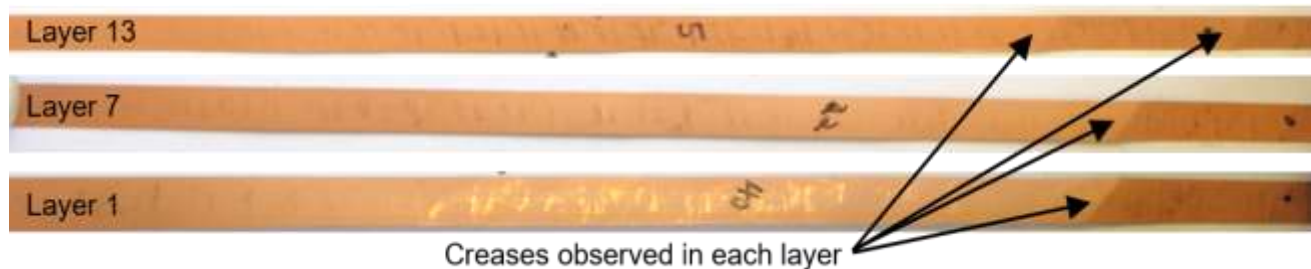
- Only **30 to 40 %** of predicted I_c
 - **Low n-value of 5 ± 2** in 40 to 60 K range
 - Degradation occurred only in the Cu-jacketed CICC.
- ✓ Both conduction and forced-flow convection cooling **proved valid** for such conductors.



2017 tested CORC CICC samples

Likely cause of the degradation:

- Primary failure mode is a pinching effect.
- Specific for CORC strand layout/winding parameters of the Cu-jacketed CICC.
- ✓ Copper tapes layers around the core do not give sufficient mechanical support.

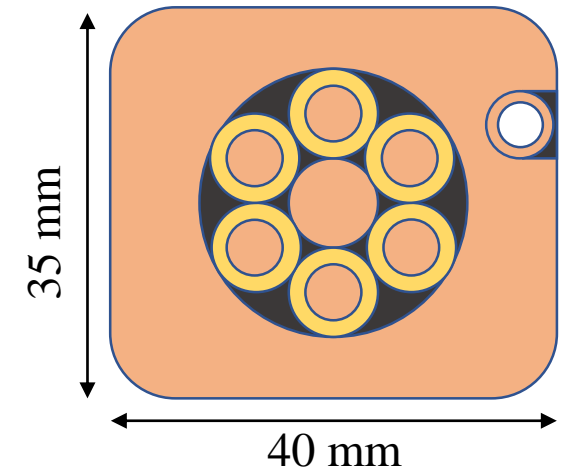


Next steps:

- New CICC to replace the degraded Cu-jacketed CICC.
- New strand layout is used with a thicker core.
- Mechanical support of CORC strands by solder filling of the voids between strands.

Latest CORC CICC Sample (2019)

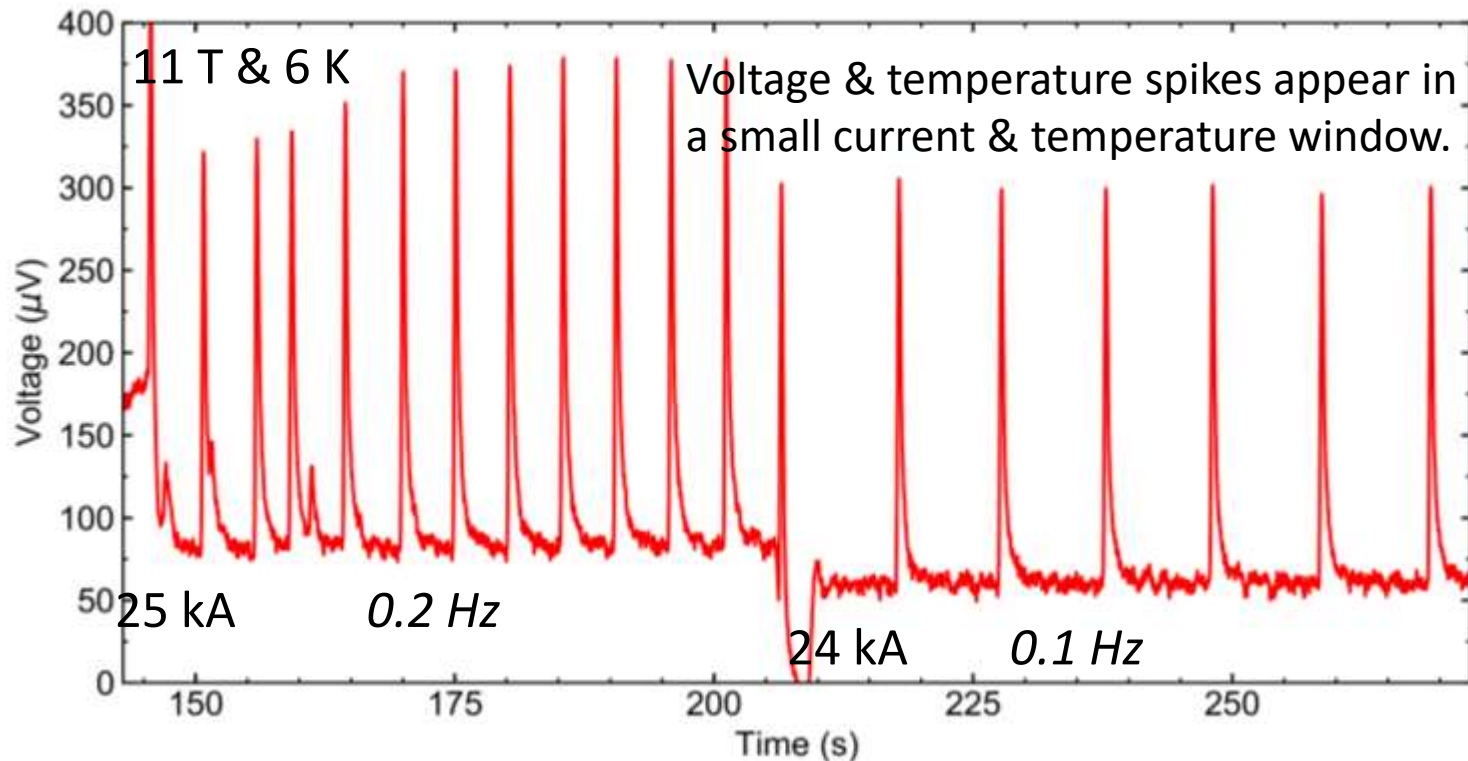
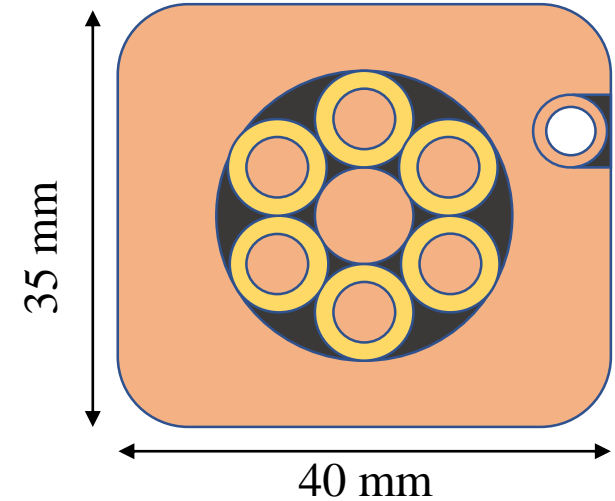
- Project in collaboration with ACT
- Similar high- I_c tape layout in the CORC strands as in the previous sample
- Solely cooled by conduction cooling via its jacket
- Improved electrical and mechanical performance by solder filling of conduit.



	Trial (2016)	Fusion Sample (2017)	Detectors Sample (2017)	Detector Sample (2019)
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	5	4	<u>5</u>
Outer diameter [mm]	7.6	7.7	7.7	7.7
Critical Current (4K, 10T) [kA]	48	90	90	<u>100</u>

Unfortunately, odd current sharing seen, surprise

- Issues with the new sample that prevented accurate I_c measurements.
- Bad current distribution measured leading to oscillating sharing of current, likely resulting from solder alloying in the joint regions (now being tested).



- Seen only in this CICC, error!
- Spikes were reproducible.
- Frequency depends on current.
- Frequency depends on temperature.
- Only occurs within a small current and temperature range.

Odd behavior, what we learnt (2019)

What we know:

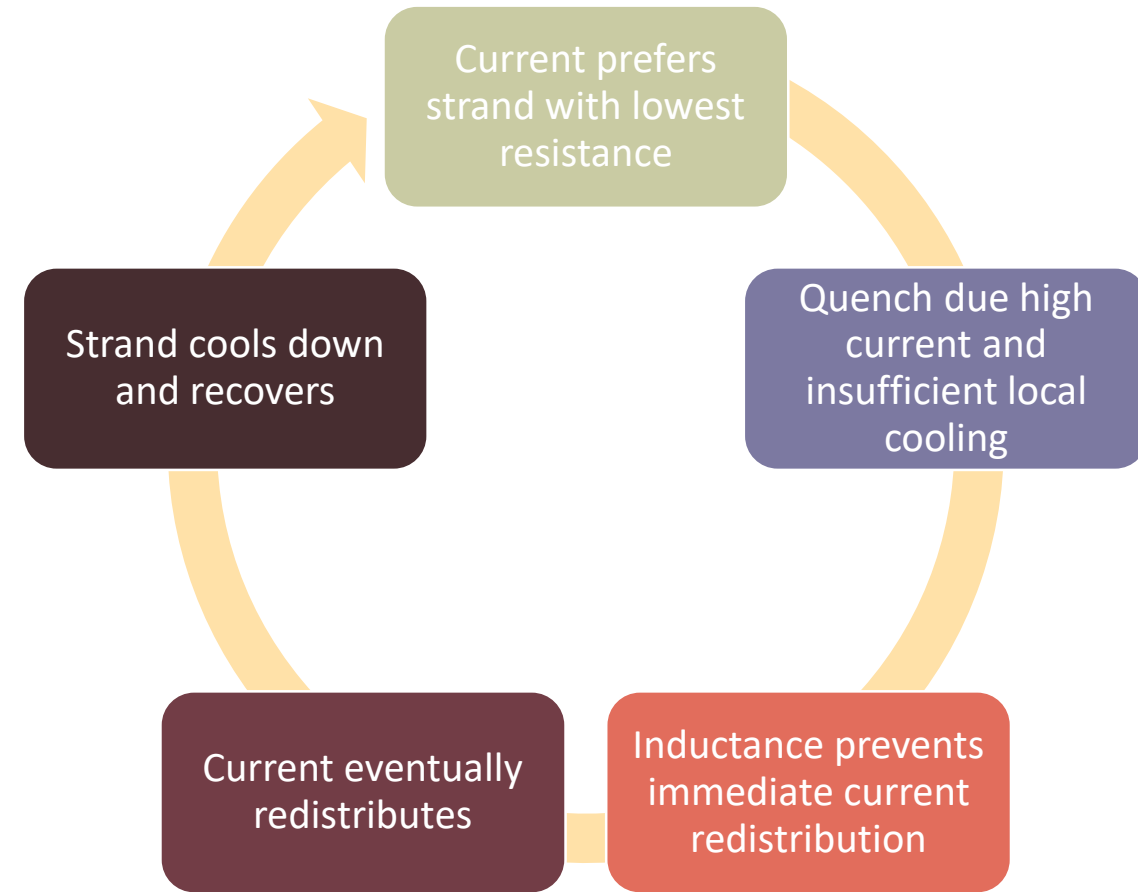
- Model is able to reproduce similar voltage spikes.
- Small window of parameters where such behavior occurs.
- Unique to HTS multi-strand conductors.
- Model & measurements suggest current distribution issue.
- No direct evidence of strand degradation.
- New joints may resolve the issue.

Next steps (already in progress):

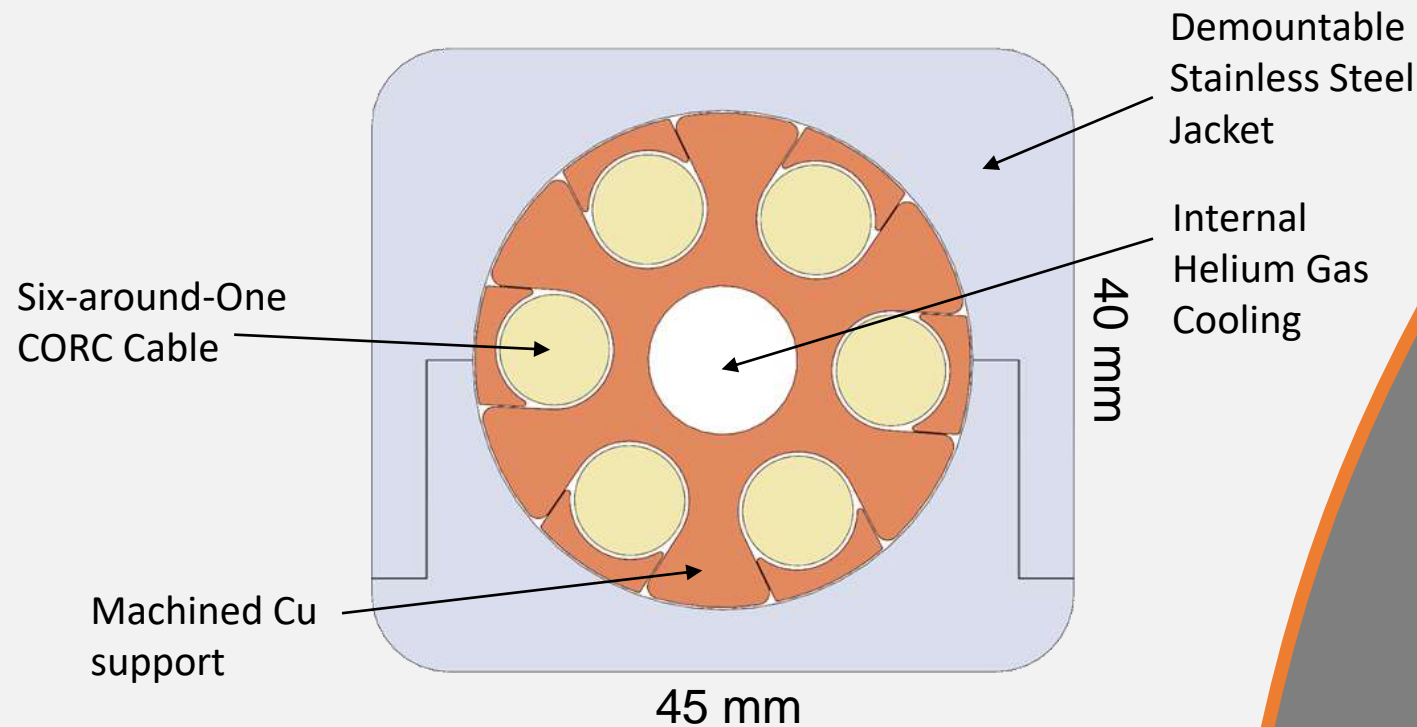
- Extracting all solder from the sample.
- Refilling the joint and sample with indium.
- Test again in autumn 2019.

✓ Each measurement iteration increases our knowledge and experience of CORC CIC conductors.

- It is still a work in progress, more new CORC CICC's are in development.



New CORC CICC's > 2020 and beyond



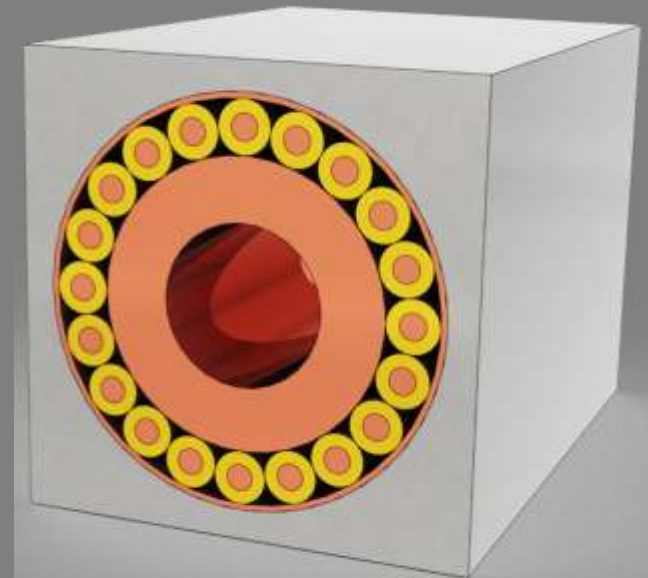
- **Next sample in preparation right now, mainly designed and prepared at ACT, instrumented and integrated at CERN and tested in Sultan early 2020.**



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- Currently in design: X-around-1
- Thinner more flexible CORC strands.
 - Shorter twist pitch.
 - Internal gas cooling.
 - More flexible CICC depending on jacket and core design.



Conclusion

- ✓ Series of CORC wire based demonstrator magnets are under development at CERN
- ✓ A 1st compact CORC Solenoid prepared now for test later this summer
- ✓ Research on CORC Cable-In-Conduit Conductors is ongoing in collaboration with ACT
- ✓ Odd joint-introduced current sharing seen in last simple, lessons learnt and next test of refilled CICC in fall this year
- ✓ Another few CICC variants to come, next version test early 2020, more in coming years.....



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