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Development of *Re*BCO-CORC Cable-In-Conduit Conductors for Large-Scale Magnets

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CERN

Advanced Conductor Technologies LLC
www.advancedconductor.com

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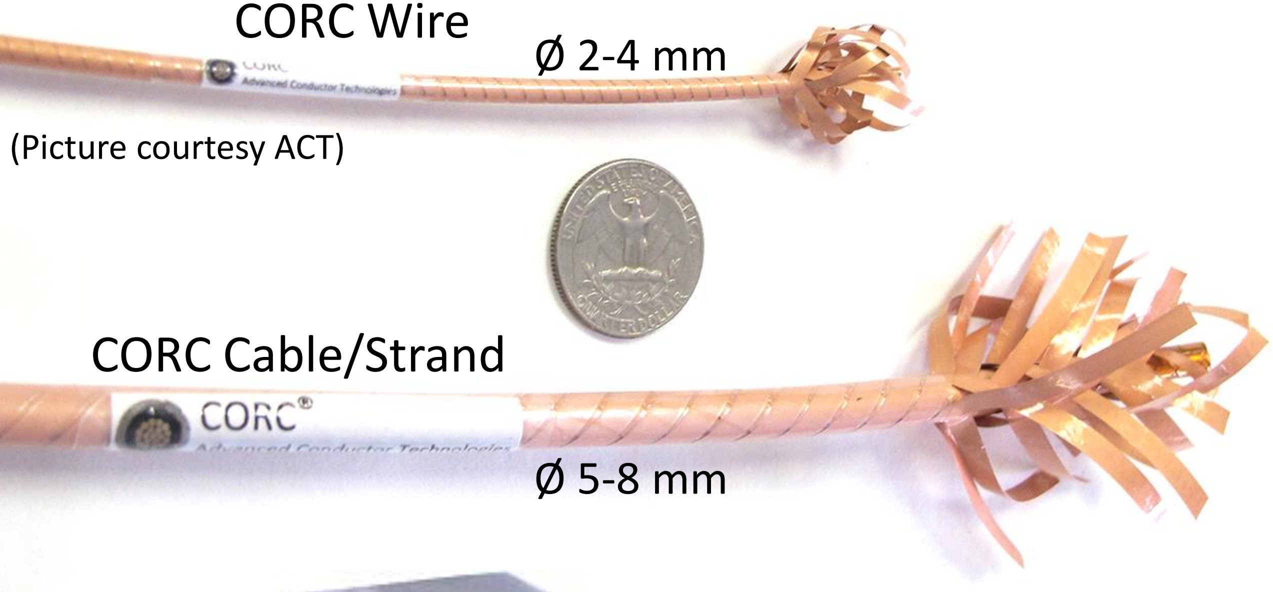
CORC Wires, Cables and Cable-In-Conduit Conductors



(Picture courtesy ACT)

2015

1st CORC Al-jacketed Cable-In-Conduit Conductor.

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.*

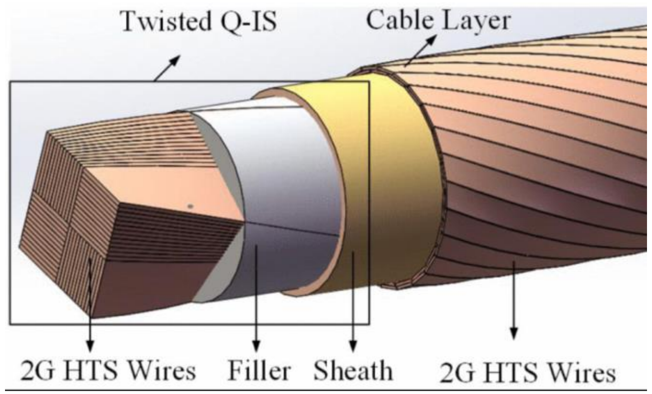
CORC Cable: *general purpose, stable SC magnets and power transmission.*

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

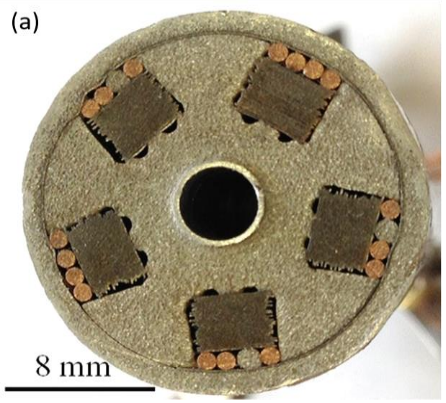
*Re*BCO Cable-In-Conduit Conductors

- 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 *Nb_3Sn* 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.

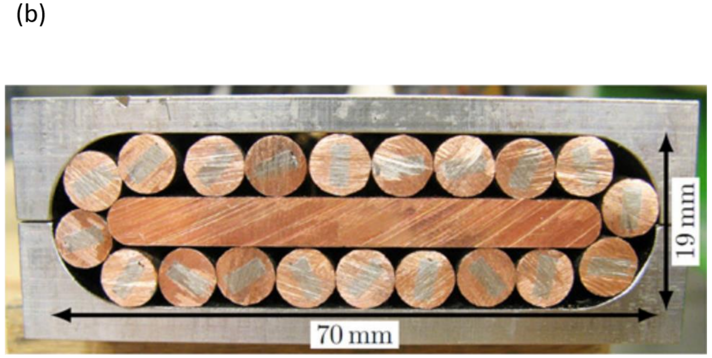
Examples of several *Re*BCO based CICCs are in development around the globe:



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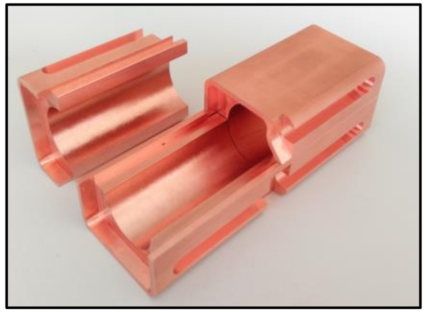
Test of two CORC CICCs
- Stainless steel jacket + internal cooling
- Copper jacket + external conduction cooling

Test of new solder-filled CICC with copper jacket

2016

Test of 1st CICC with Aluminum jacket

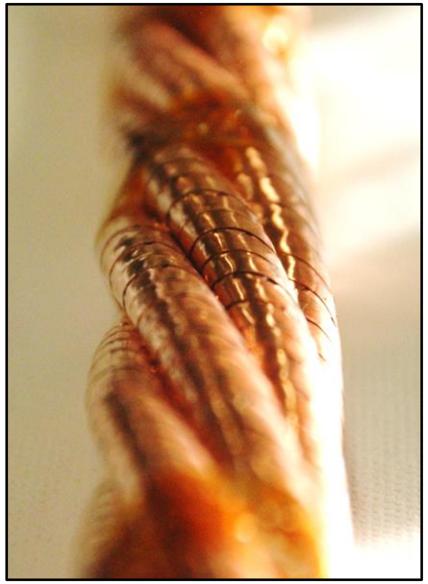
2017



2018

Design & Preparation of new sample

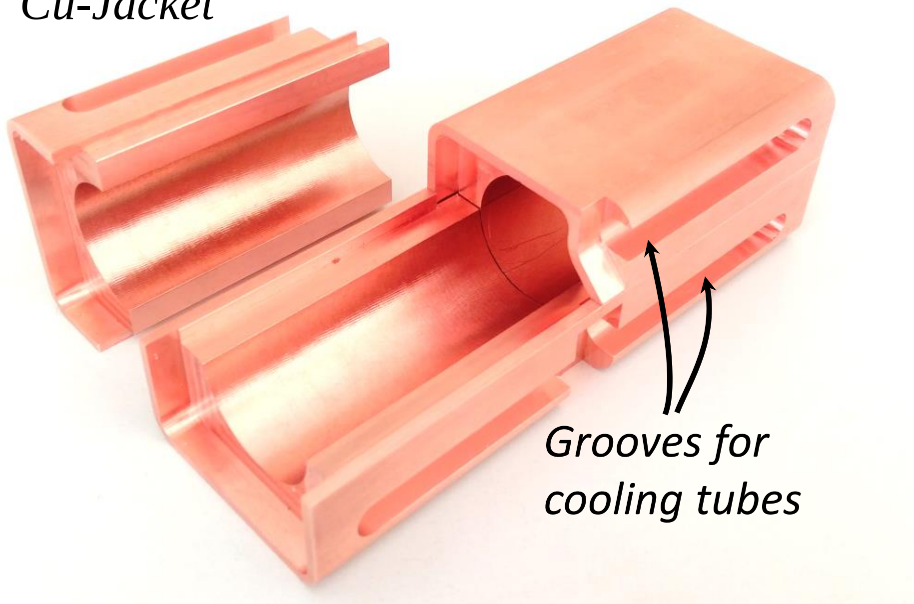
2019

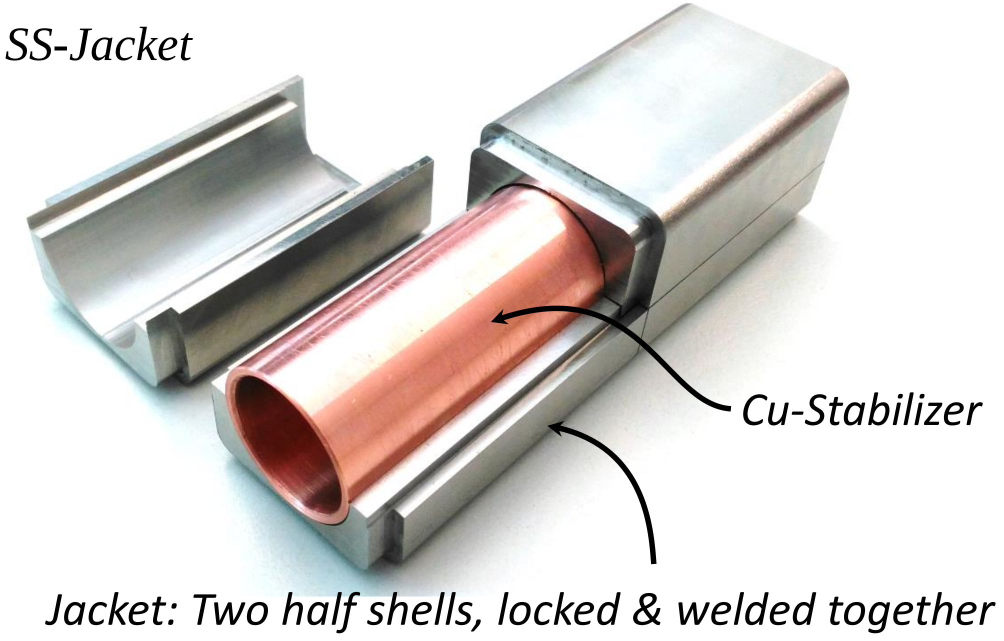


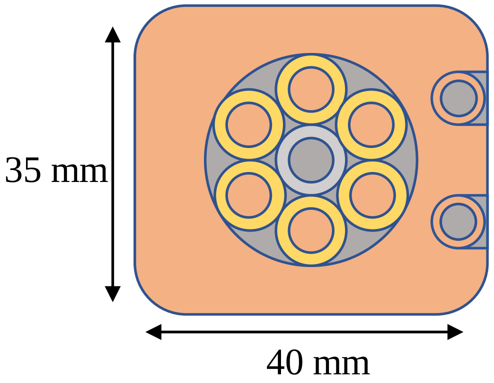
2020

Testing new layouts of internally cooled CORC CICCs

CORC Cable-In-Conduit Conductor Design





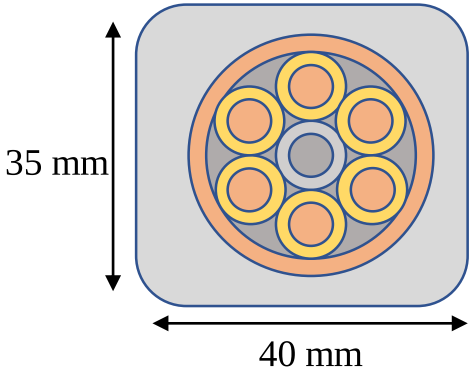


Detector magnets & Bus Bars:

- High thermal & electrical stability
- Practical conduction cooling

Fusion type magnets:

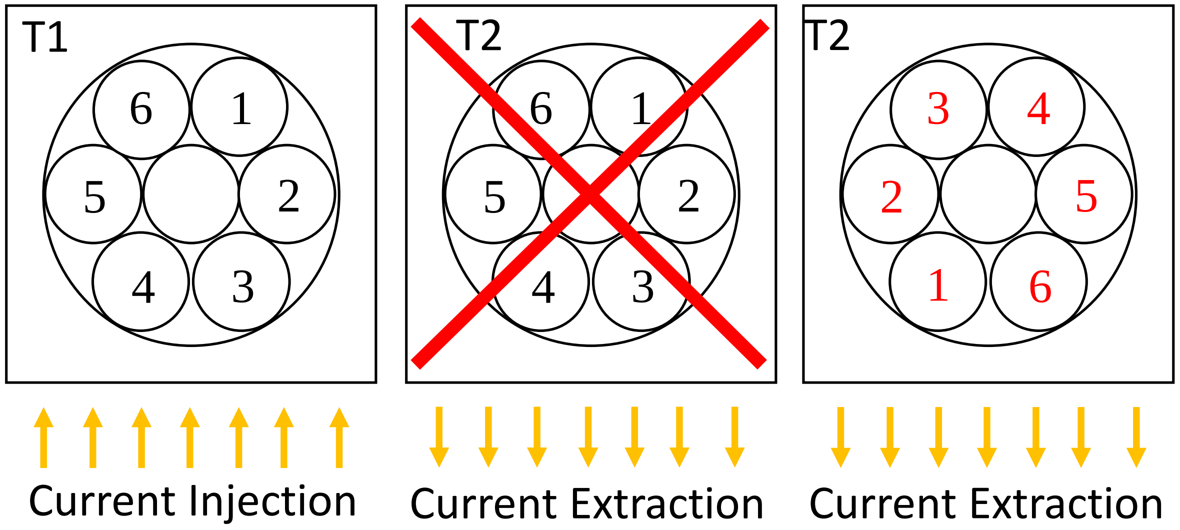
- Can sustains high stress
- Can cope with large heat loads
- Internal forced-flow cooling

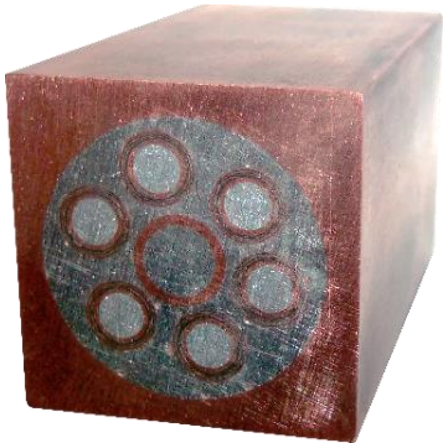


CICCs are 2.8 m long and designed for 80 kA at 12 T and 5 K.

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 nΩm.





SS and Cu jacketed CORC CICC samples – test results

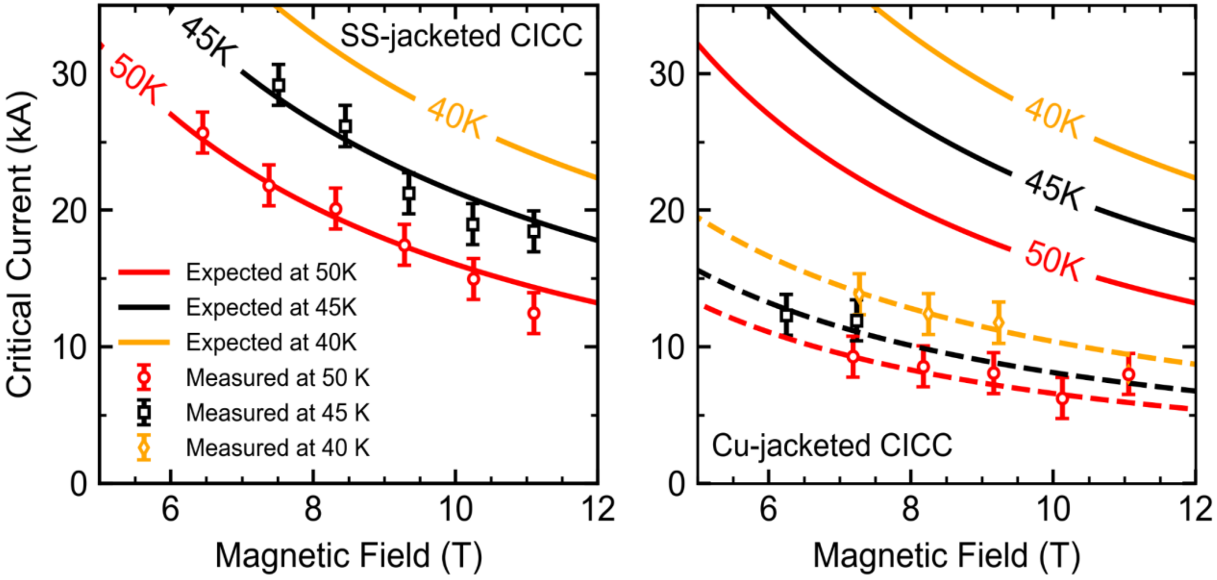
SS-jacketed CICC for Fusion Magnets:

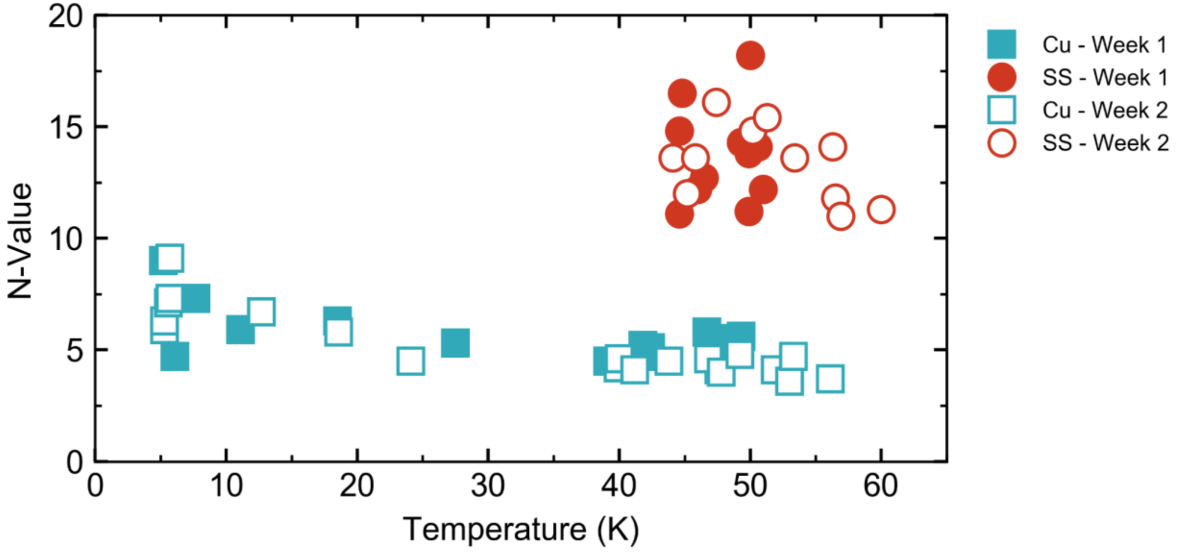
- Performed **according to prediction** at 40 to 60 K
- N-value of **14 ± 3** (similar to the 2016 sample)
- Low AC-loss of 7 mJ/cycle/cm^3

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 occured only in the Cu-jacketed CICC.

✓ Both <u>conduction</u> and <u>forced-flow convection</u> cooling **proved valid** for such conductors.



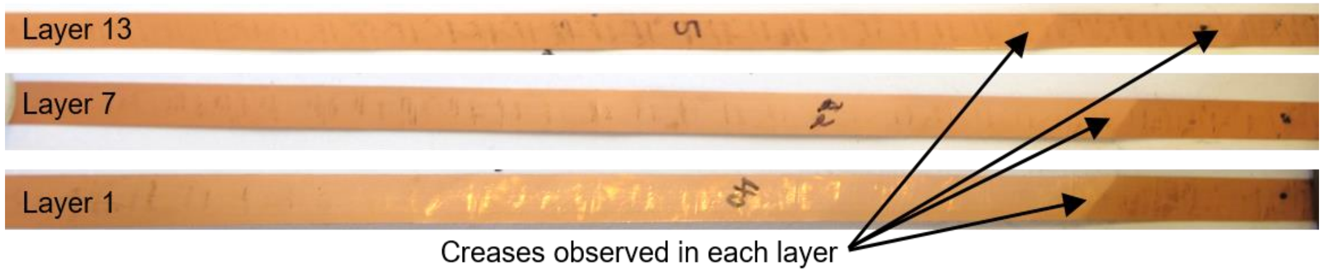


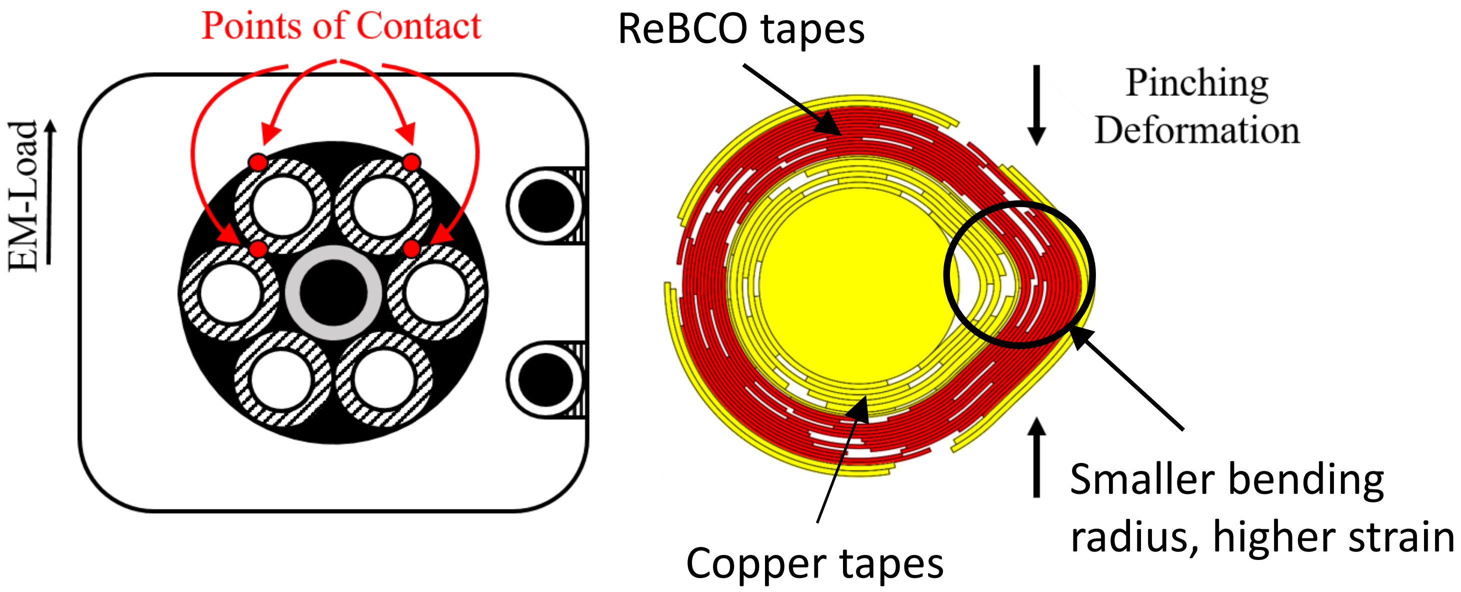
2017 tested CORC CICC samples

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.

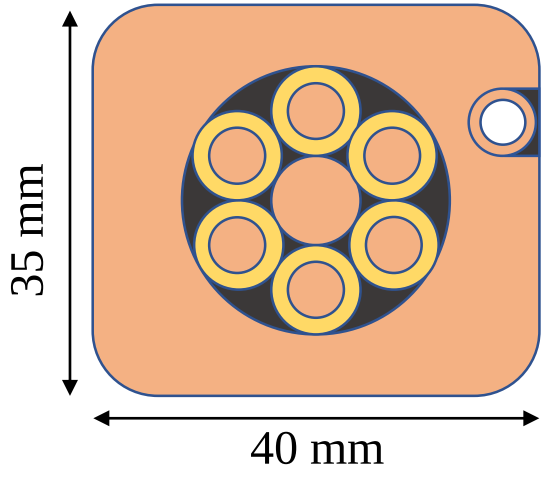




Next steps:

- 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)

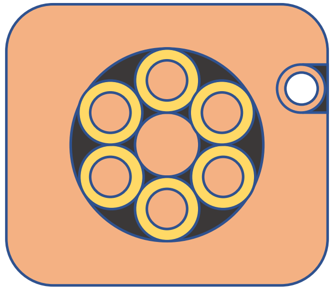


- Project in collaboration with ACT.
- Similar high-I_c tape layout in the CORC strands as in the previous sample.
- Solely cooled by conduction cooling via its jacket.
- Improved electrical and mechanical performance by solder filling of conduit.

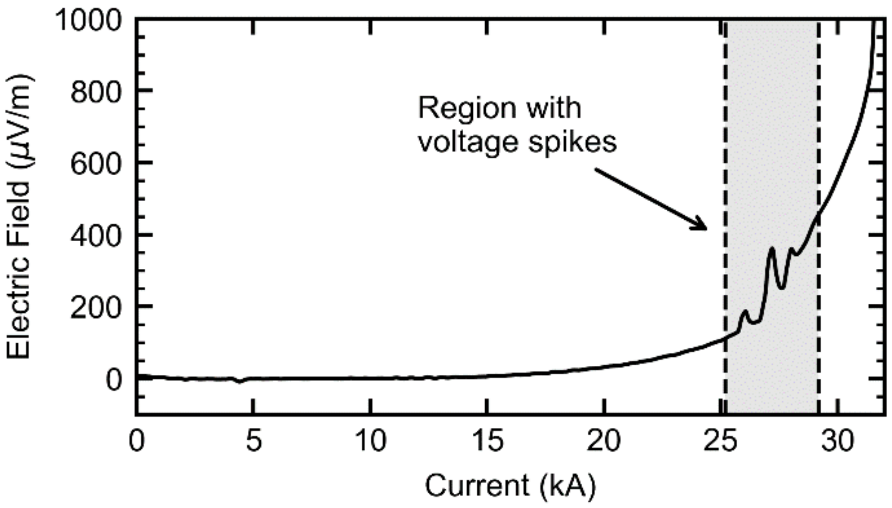
	Trial (2016)	Fusion Sample (2017)	Detectors Sample (2017)	Detector Sample (2019)
Number of tapes	**38**	**42**	**42**	**42**
Number of layers	**12**	**14**	**14**	**14**
Tape Type	**SCS 4050**	**SCS 4050**	**SCS 4050**	**SCS 4050**
Copper plating [µm]	**40**	**10**	**10**	**10**
Core material	**Aluminum**	**Copper**	**Copper**	**Copper**
Solid core diameter [mm]	**4**	**5**	**4**	**5**
Outer diameter [mm]	**7.6**	**7.7**	**7.7**	**7.7**
Critical Current (4K, 10T) [kA]	**48**	**90**	**90**	**100**

Unfortunately, odd current sharing seen, surprise

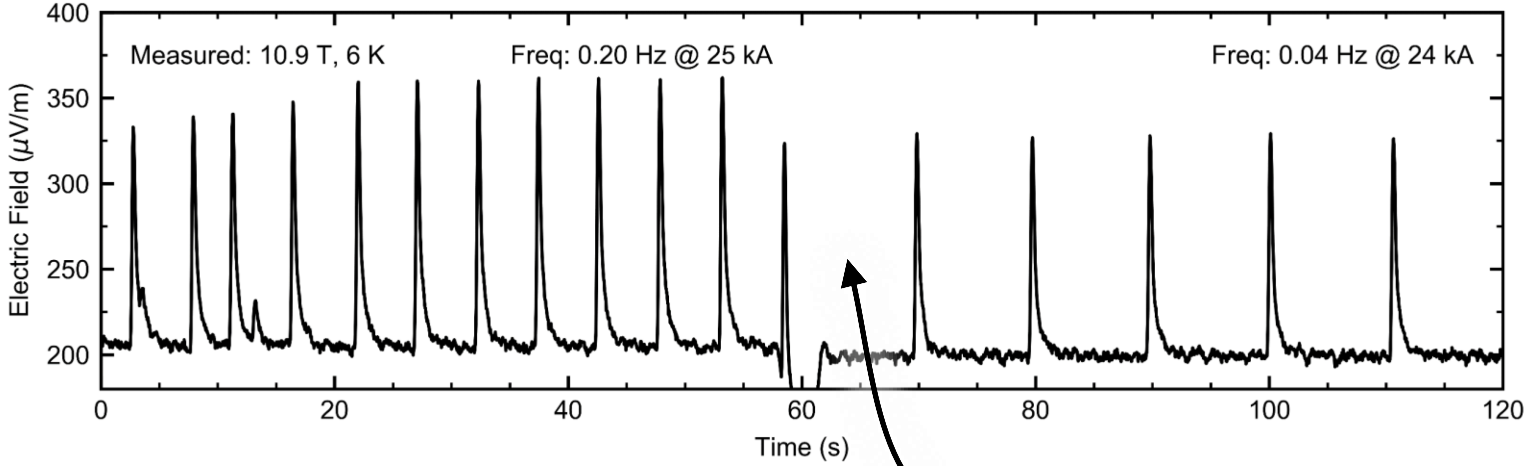
- Issues with the new sample that prevented accurate I_c measurements.
- Bad current distribution measured leading to oscillating sharing of current, likely resulting from solder alloying in the joint regions.

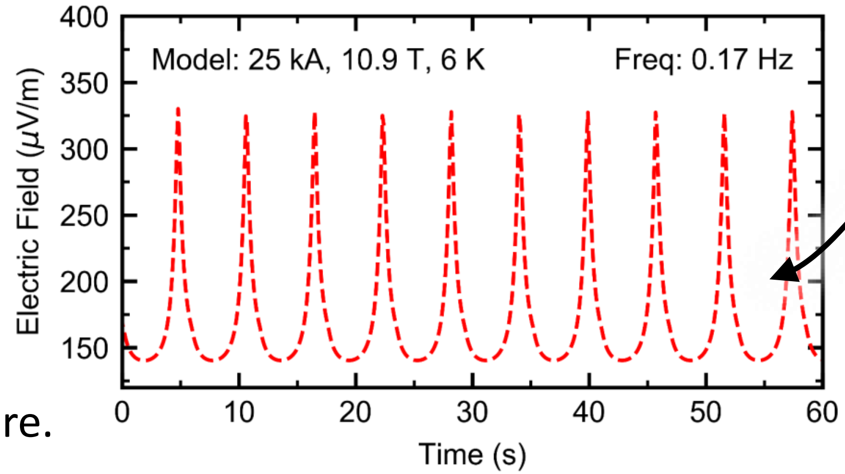


Voltage & temperature oscillations appear in a small current & temperature window.



- Seen only in this CICC, error!
- Spikes were reproducible.
- Frequency depends on current and temperature.





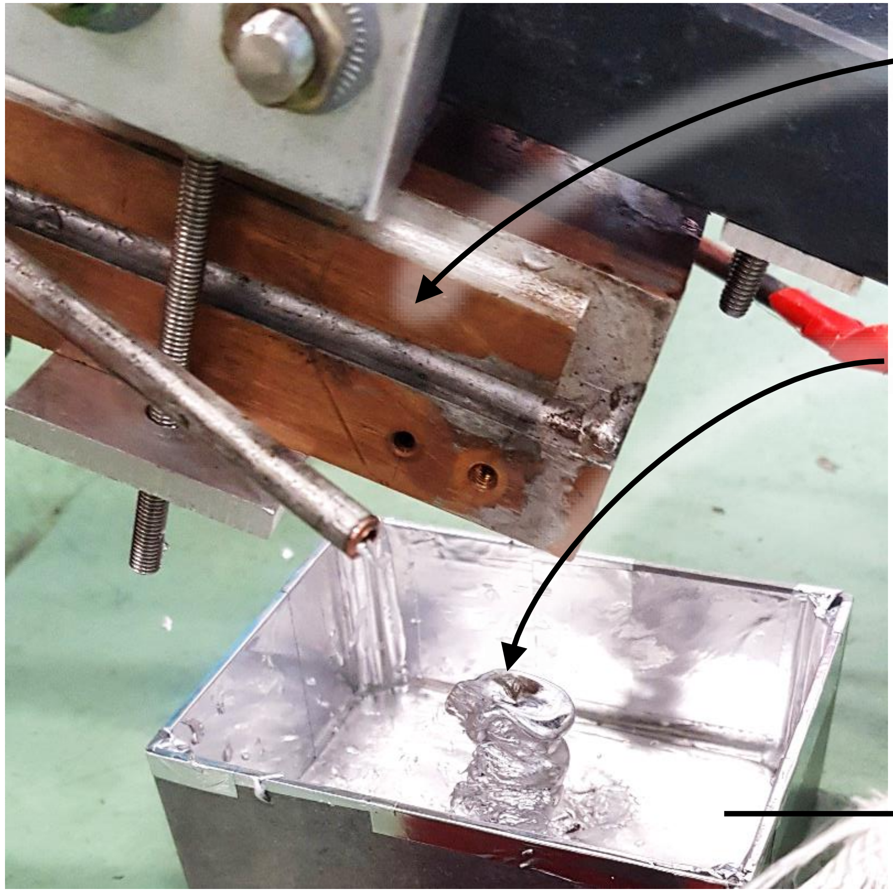
Measured

Model

Model:
- Same order of magnitude of frequency and amplitude
- Slightly different shape of the spikes

Test of solder metal of the joint terminals

- Solder was extracted from the extremities of the joint terminals.
- Test of the solder confirms suspicions: alloying throughout the entire terminal.
- Result is some In-Bi-Sn-Pb alloy with a highly non-eutectic melting temperature of 60 to 80 °C.



CICC-joint terminal

Pillar of solder

Pillars were divided to sections

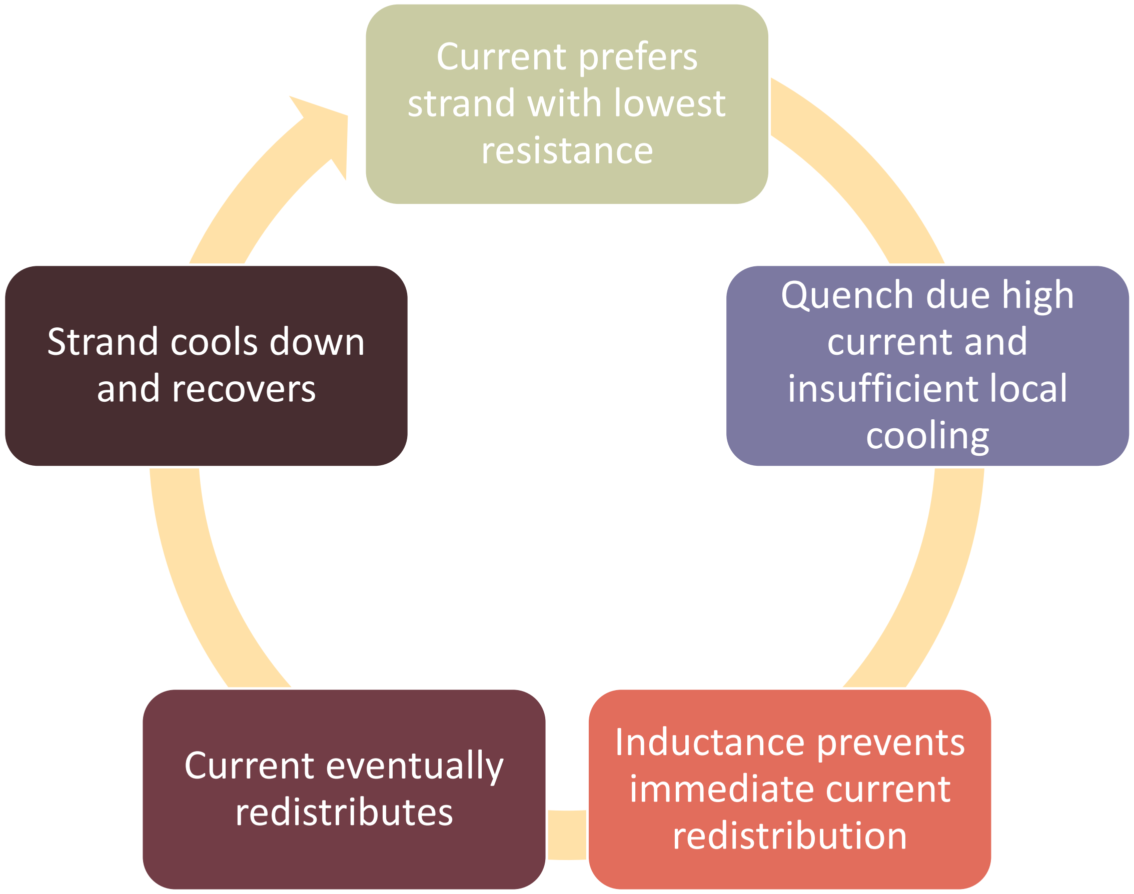
Odd behavior, what we learnt (2019)

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):

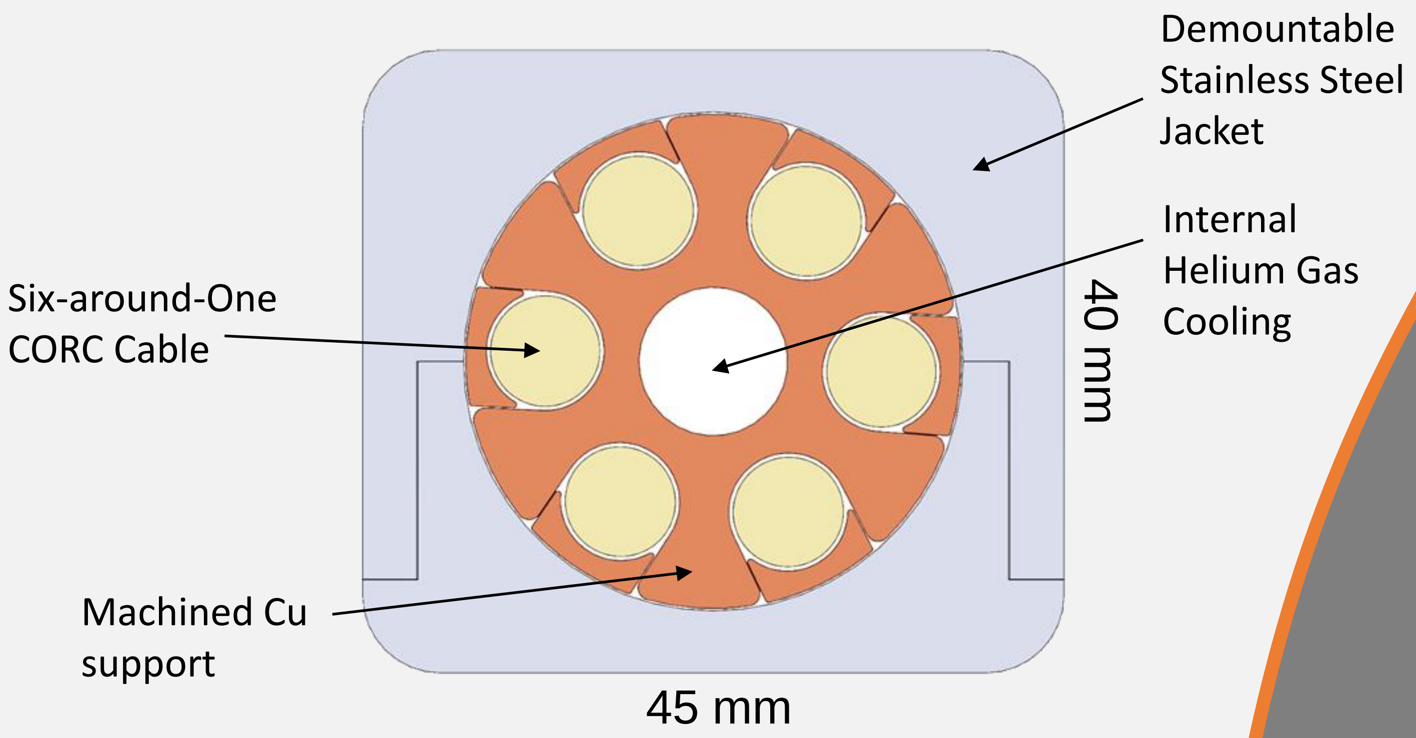
- Extracting all solder from the sample. (✓ Done)
- Refilling the joint and sample with indium. (✓ This week)
- Test again in autumn 2019.



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

- **It is still a work in progress, more new CORC CICCs are in development.**

New CORC CICCs > 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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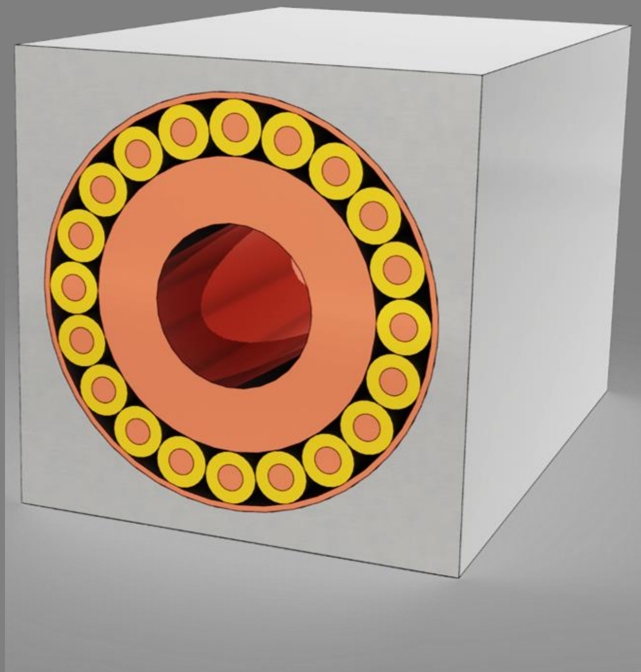
CERN

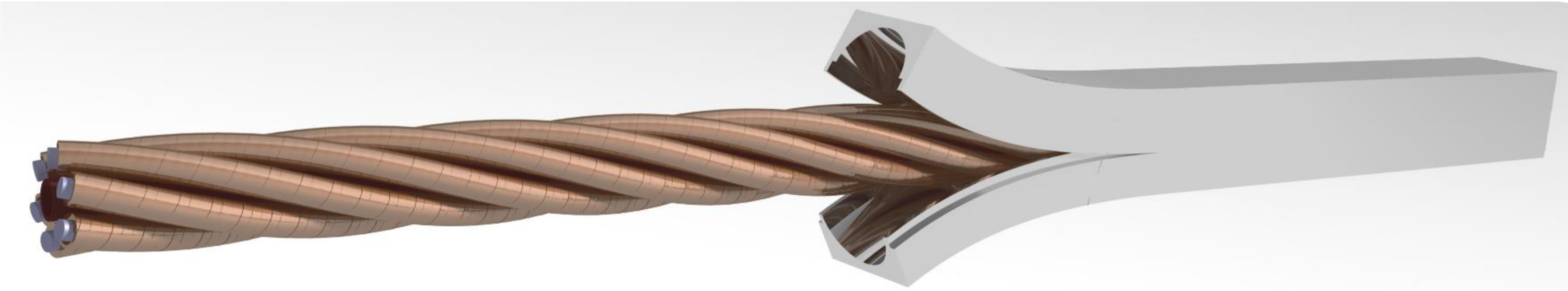
Currently in design: X-around-1

- Thinner more flexible CORC strands.
- Shorter twist pitch.
- Internal gas cooling.
- More flexible CICC depending on jacket and core design.



Conclusion

- ✓ Research on CORC Cable-In-Conduit Conductors is ongoing in collaboration with ACT
- ✓ Each measurement iteration increases our knowledge and experience of CORC CICCs.
- ✓ Odd joint-introduced current sharing seen in last sample.
- ✓ Latest CICC is being refilled this week and will be tested in the coming month.
- ✓ Another few CICC variants to come, next version test early 2020, more in coming years………



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