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COMB progress and preliminary CORC wire test results in LN_2

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General MDP Meeting

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COMB/REBCO development goals

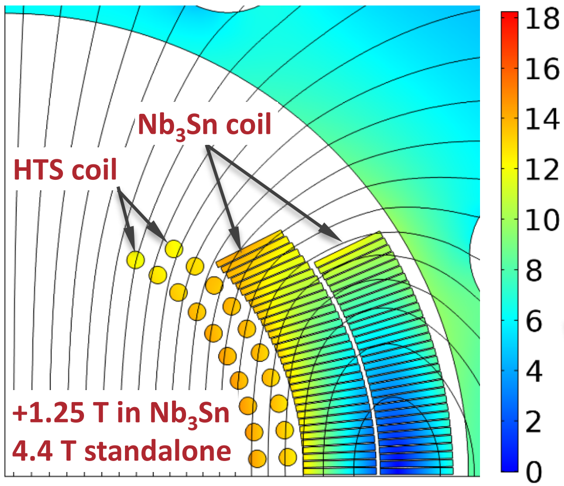
The project objectives are twofold:

- development of the Conductor on Molded Barrel (COMB) magnet technology and its initial demonstration (proof of principle) with an average-performance CORC® cable made of REBCO High Temperature Superconductor (HTS);
- performance demonstration of the HTS accelerator magnet compatible with operation in a hybrid LTS/HTS magnet using the CORC® cable made of the state-of-the-art REBCO tapes (expected dipole self-field over 5 T) to meet the U.S. MDP goal (#2).

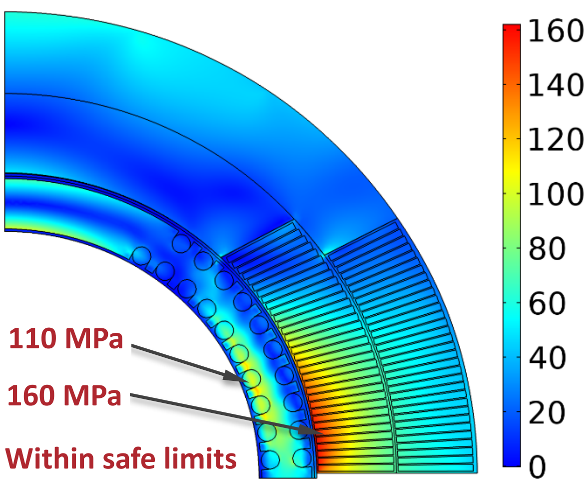
This technology is well suited for round conductors - including CORC® and STAR cables based on the latest generation of REBCO tapes and round Bi-2212 strands and cables. It offers an elegant solution for producing HTS inserts to boost the magnetic field strength in the superconducting accelerator magnets.

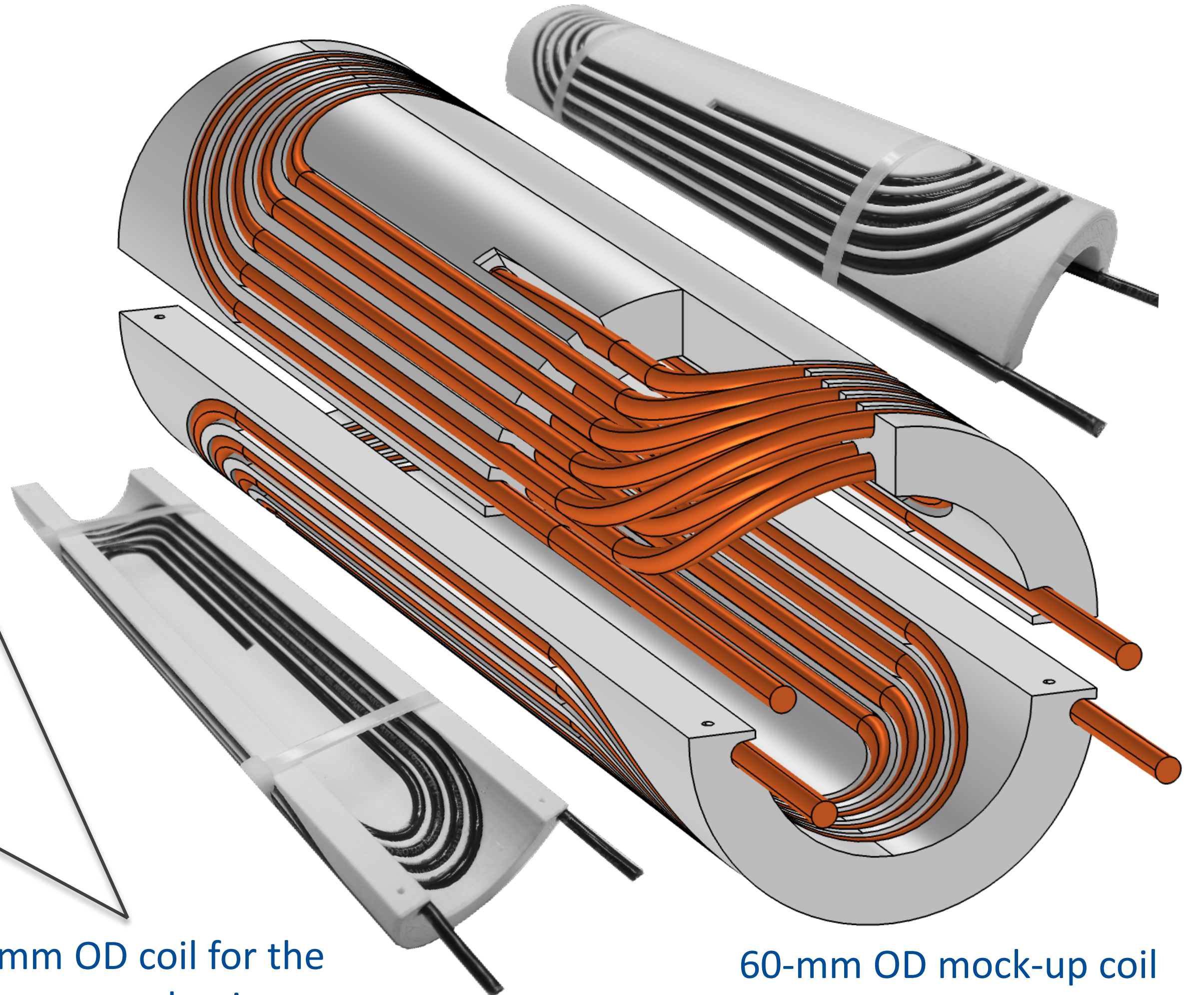
Conductor On Molded Barrel (COMB) magnet technology

Magnetic field (T)



Equivalent stress (MPa)

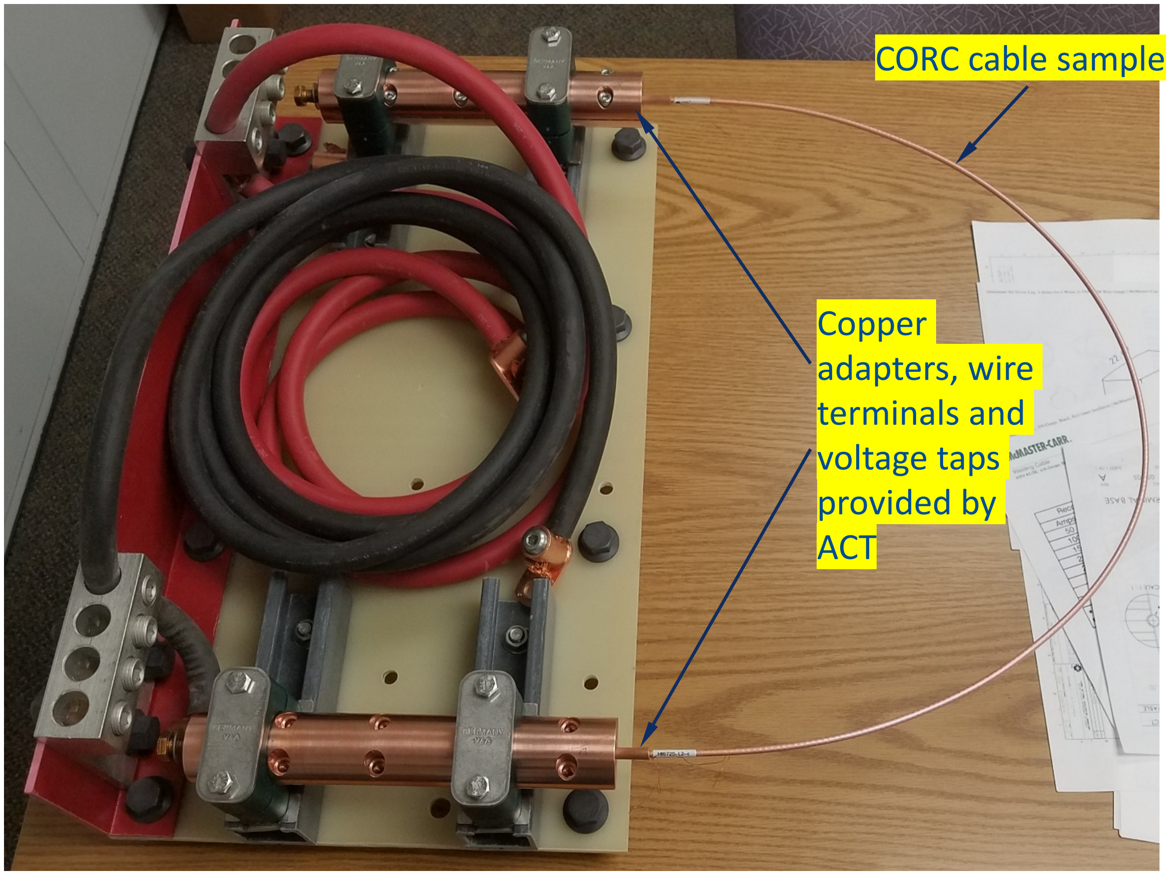




120-mm OD coil for the first superconducting model

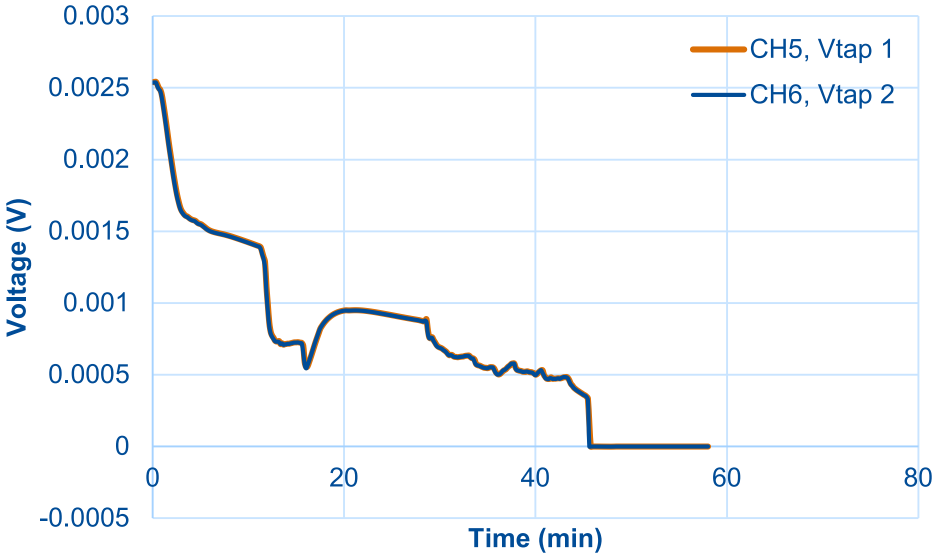
60-mm OD mock-up coil built to demonstrate manufacturability

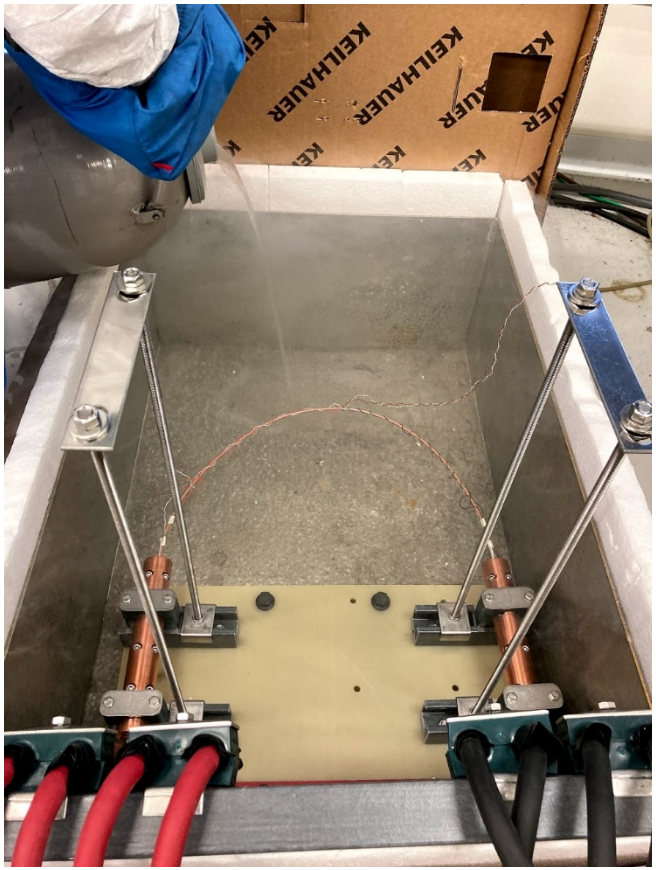
Short-sample tests



- Prior to the final magnet design and fabrication, a series of short sample tests is performed:
  - use short lengths or CORC cable provided by LBL to get a hands-on winding experience of CORC cable into the COMB structure;
  - assess the cable degradation due to winding.
- Procedure:
  - Each piece is first tested in a large U-shape (~0.5 m bending diameter) to measure the undisturbed wire performance.
  - Then ~1.5 turns are wound into the inner/outer groves of the COMB structure (~52 mm minimum bending diameter) and retested.
- The I_c test results before and after winding are compared.

First “controlled” cool down





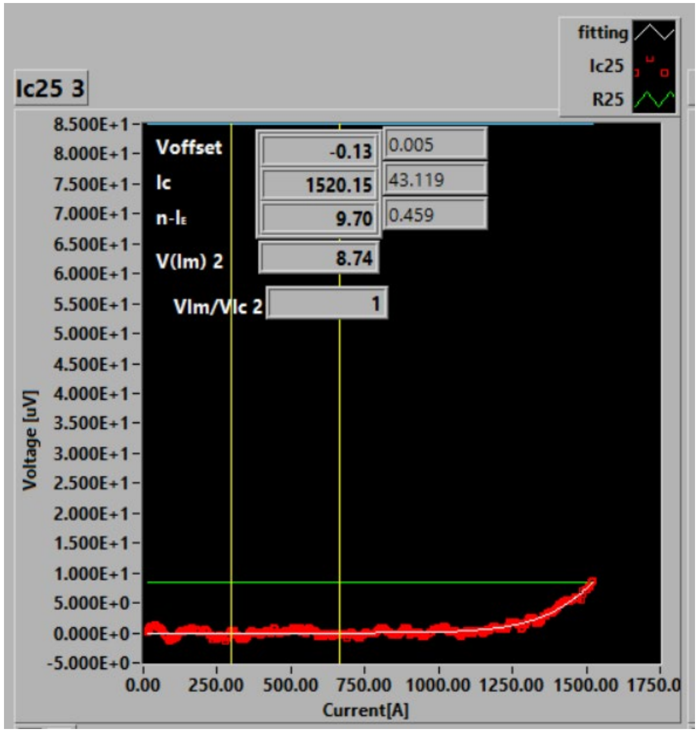
Procedure: run a small current through the wire; slowly pour LN_2 into the container; monitor the voltage across the sample

Took ~45 minutes to reach the superconducting state on the first cool down

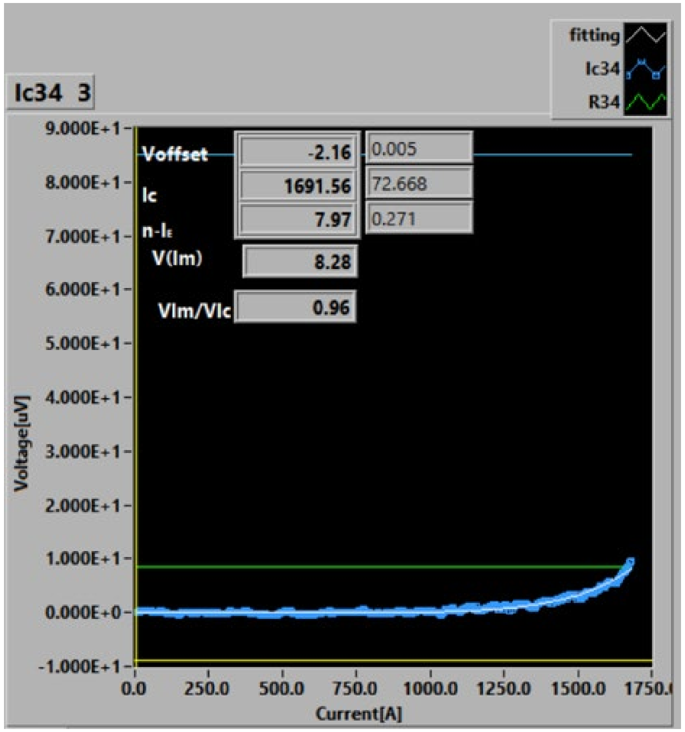
Cut that time by a factor of ~2 on subsequent runs after consultation with the CORC vendor

Sample 1 and 2 after the resistive correction

CORC Sample 1



CORC Sample 2

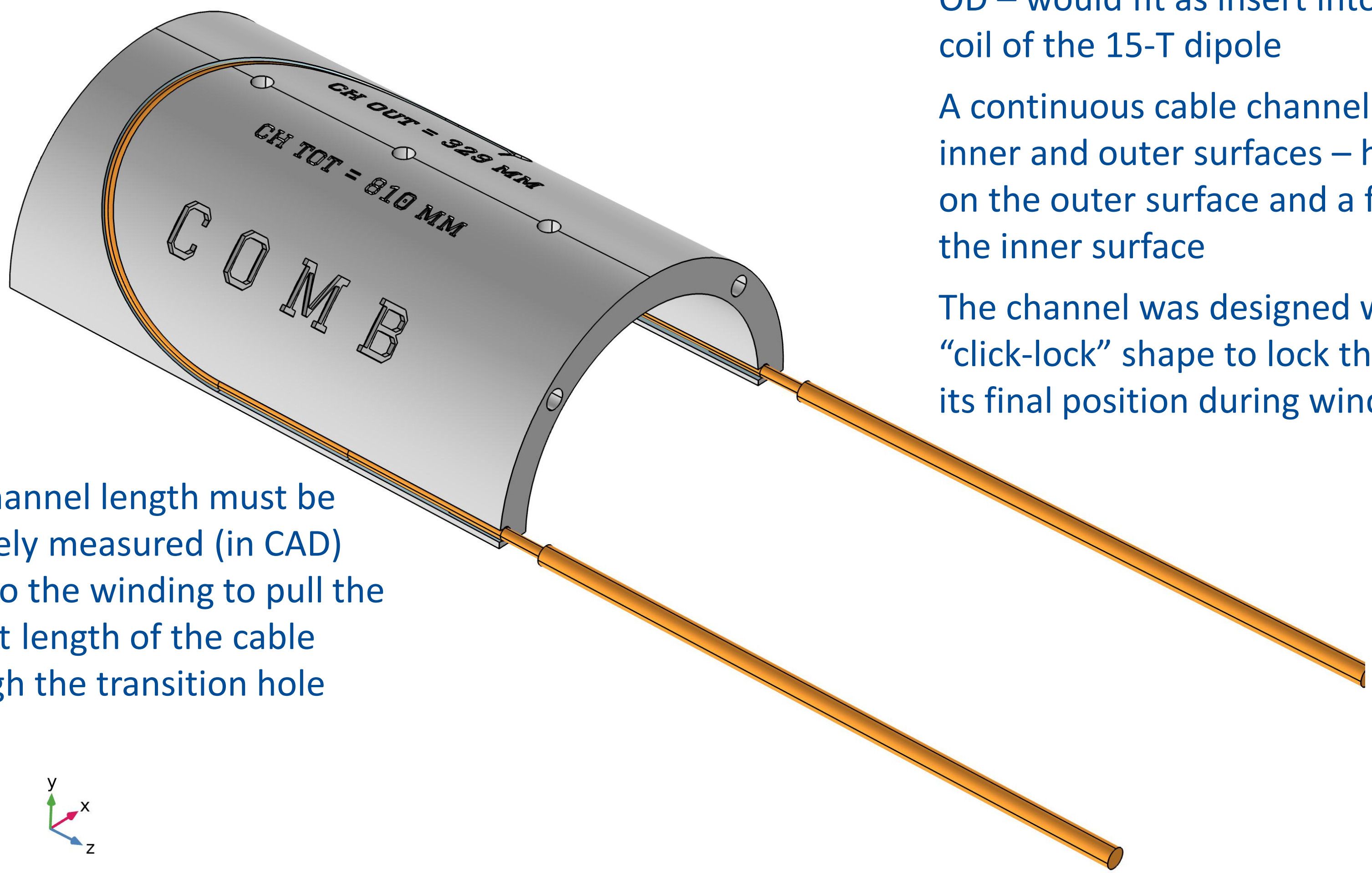


Data corrected for resistive component, I_c @ 0.1 μV/cm over 850mm length between the taps

Samples showed self-field I_c of 1520-1700 A.

Sample 2 was used for subsequent winding and testing.

Test model, top view



Mandrel with 100 mm ID and 121 mm OD – would fit as insert into the outer coil of the 15-T dipole

A continuous cable channel in the inner and outer surfaces – half a turn on the outer surface and a full turn on the inner surface

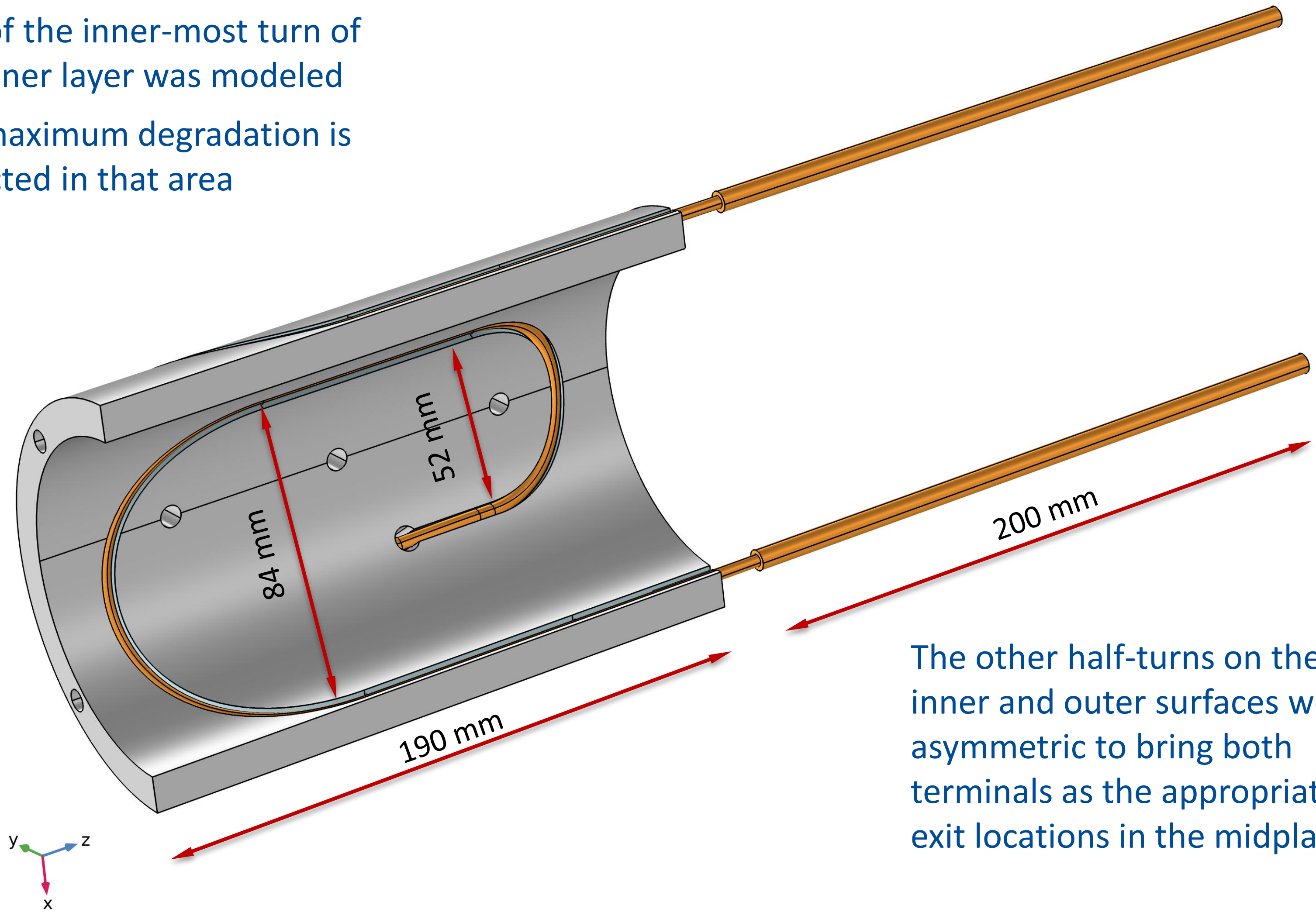
The channel was designed with a "click-lock" shape to lock the cable in its final position during winding

The channel length must be precisely measured (in CAD) prior to the winding to pull the correct length of the cable through the transition hole

Test model, bottom view

Half of the inner-most turn of the inner layer was modeled

The maximum degradation is expected in that area



The other half-turns on the inner and outer surfaces were asymmetric to bring both terminals as the appropriate exit locations in the midplane

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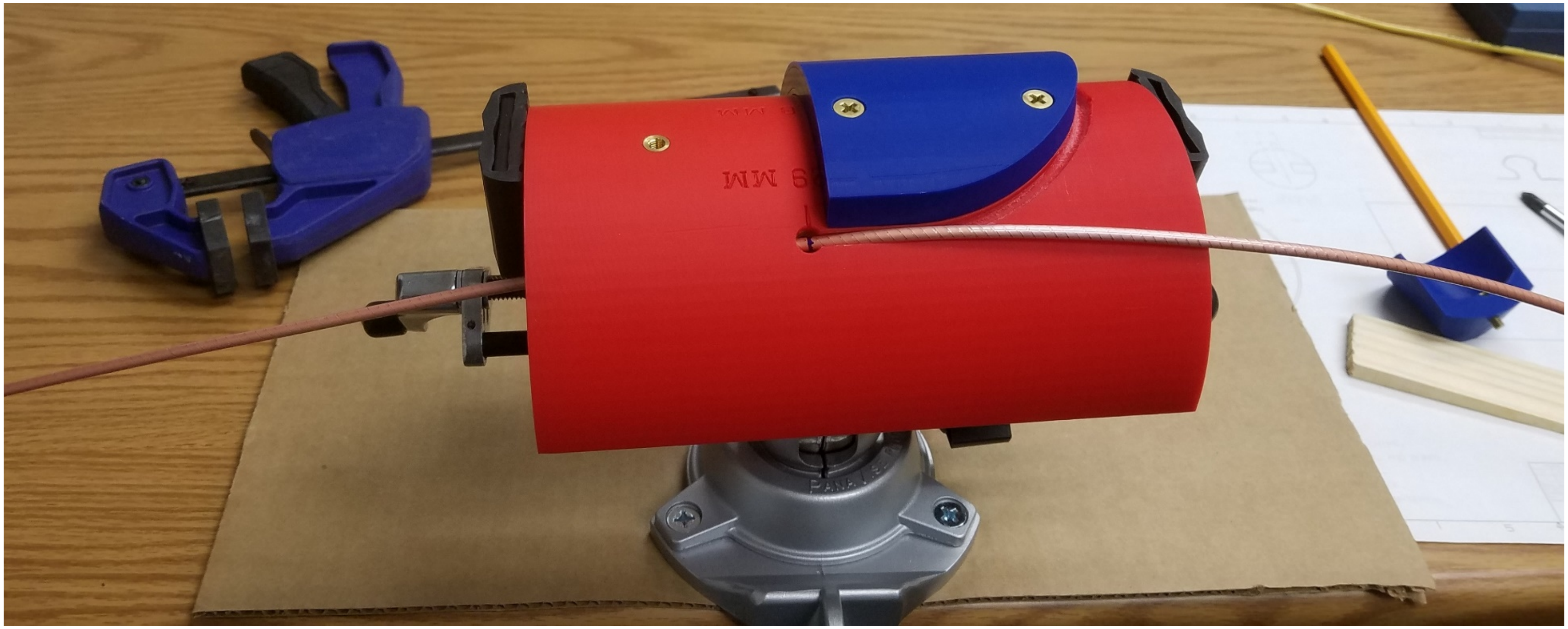
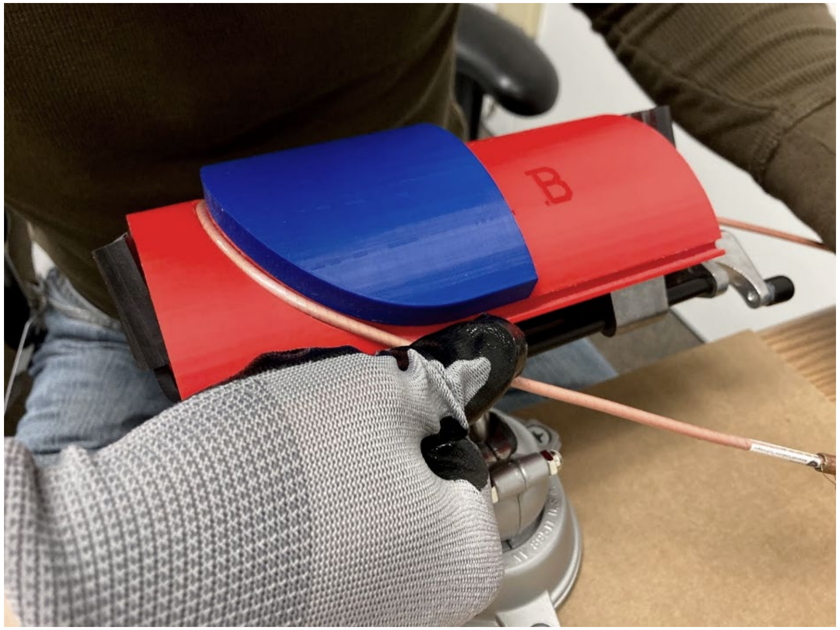
Cable positioning



The structure was 3D printed from PLA material

The cable was pulled through the transition hole in the structure prior to winding making sure the “middle” marks on the cable and the structure match

Outer layer winding

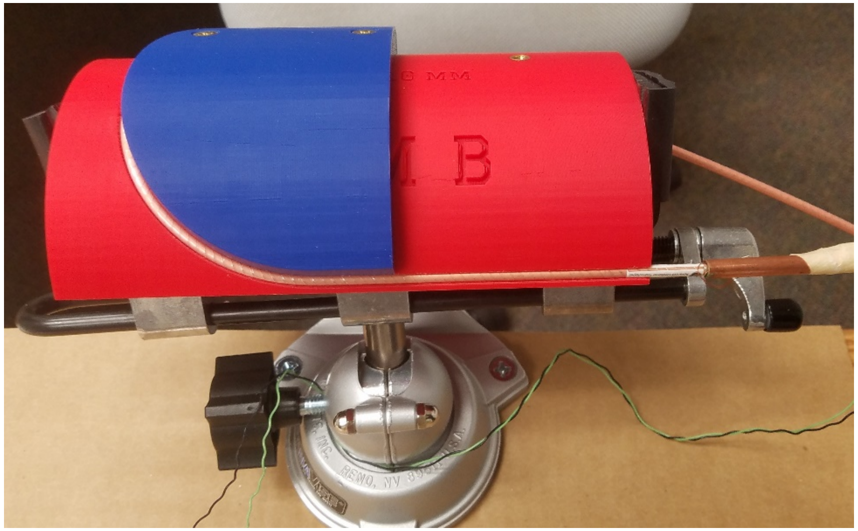


A single-step process:

The cable is pre-bent around the auxiliary spacer and pushed into the channel at the same time

The spacer was there mostly as a visual aid

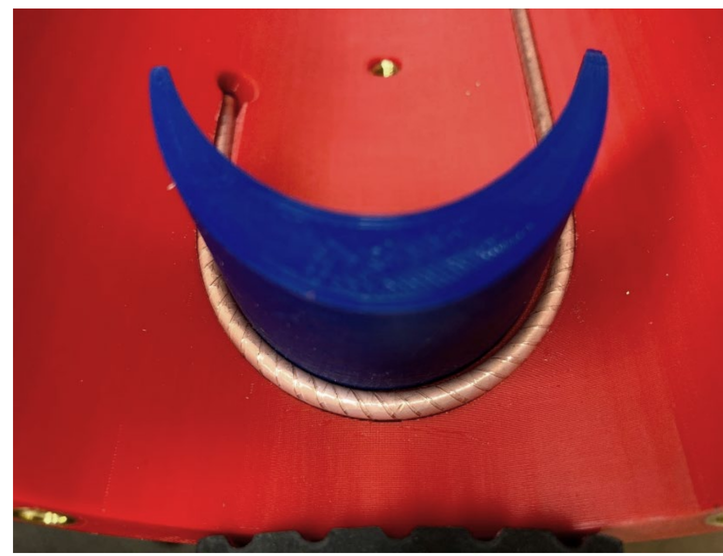
If a sufficient tension is applied to the cable, it follows the channel by itself



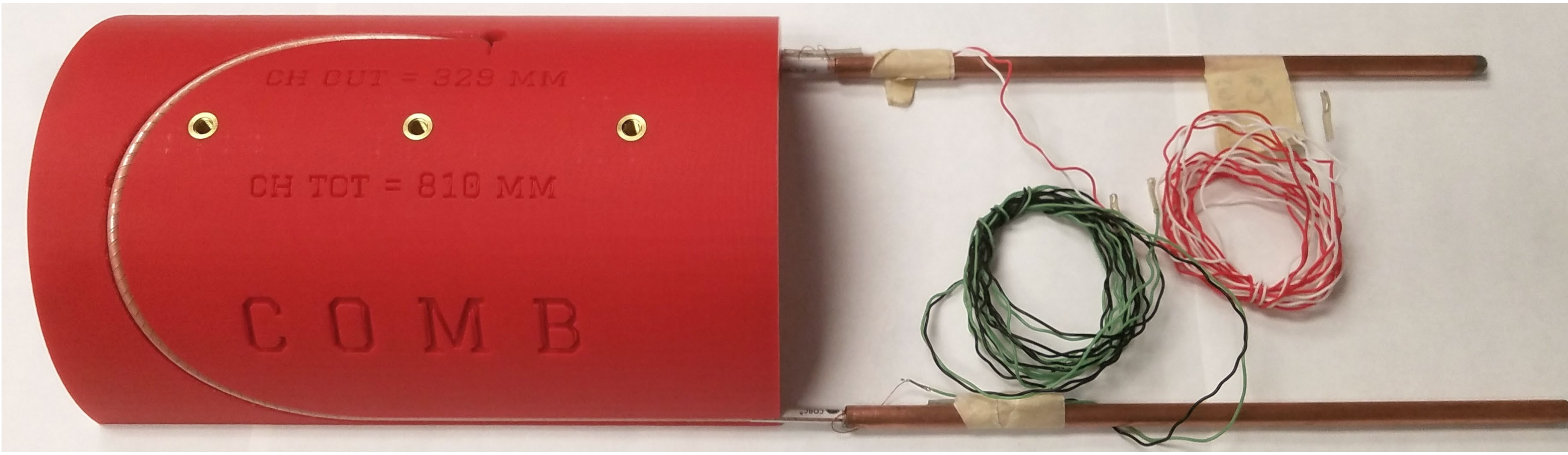
Inner layer winding

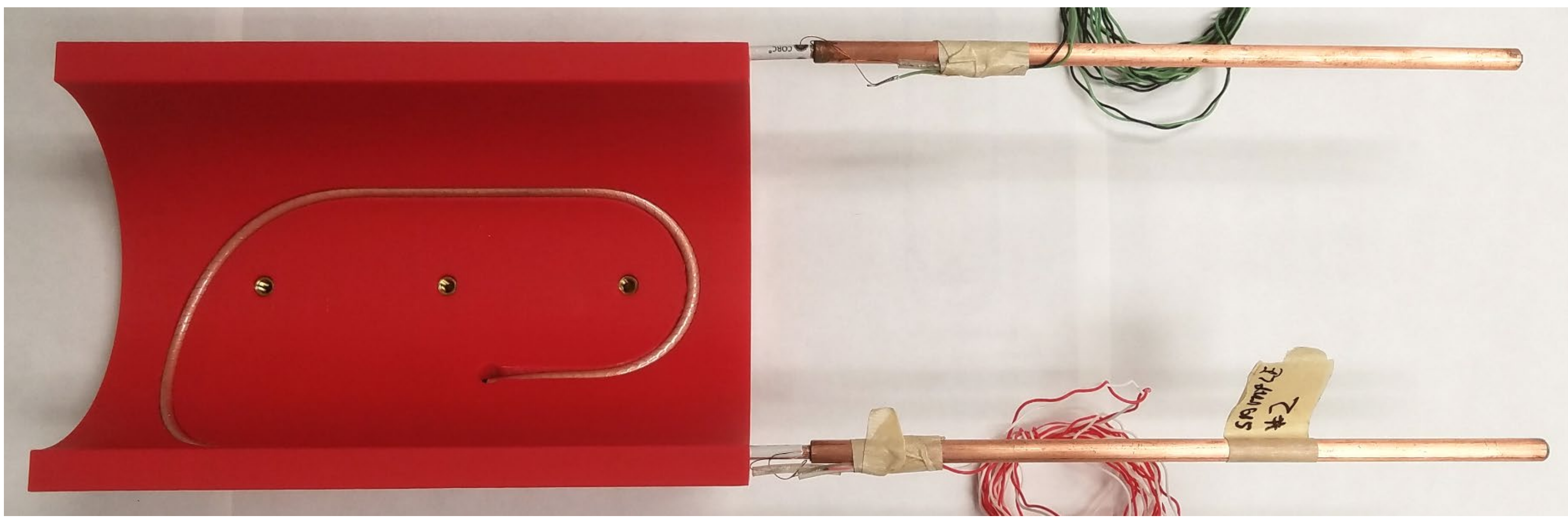
A two-step process:

the cable is pre-bent around the auxiliary spacer at the first step and then pushed into the channel at the second step

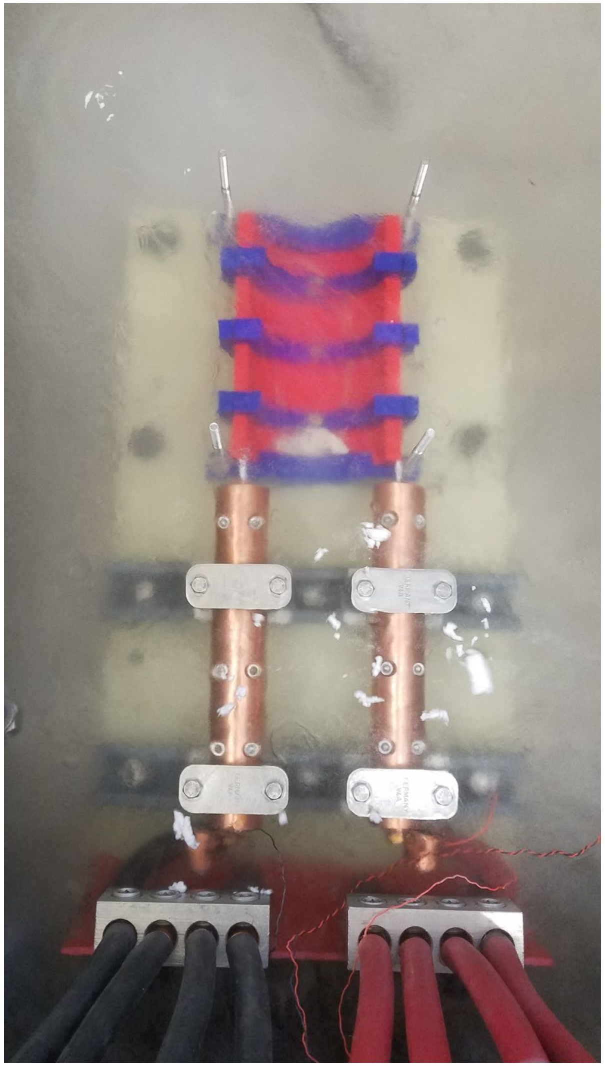


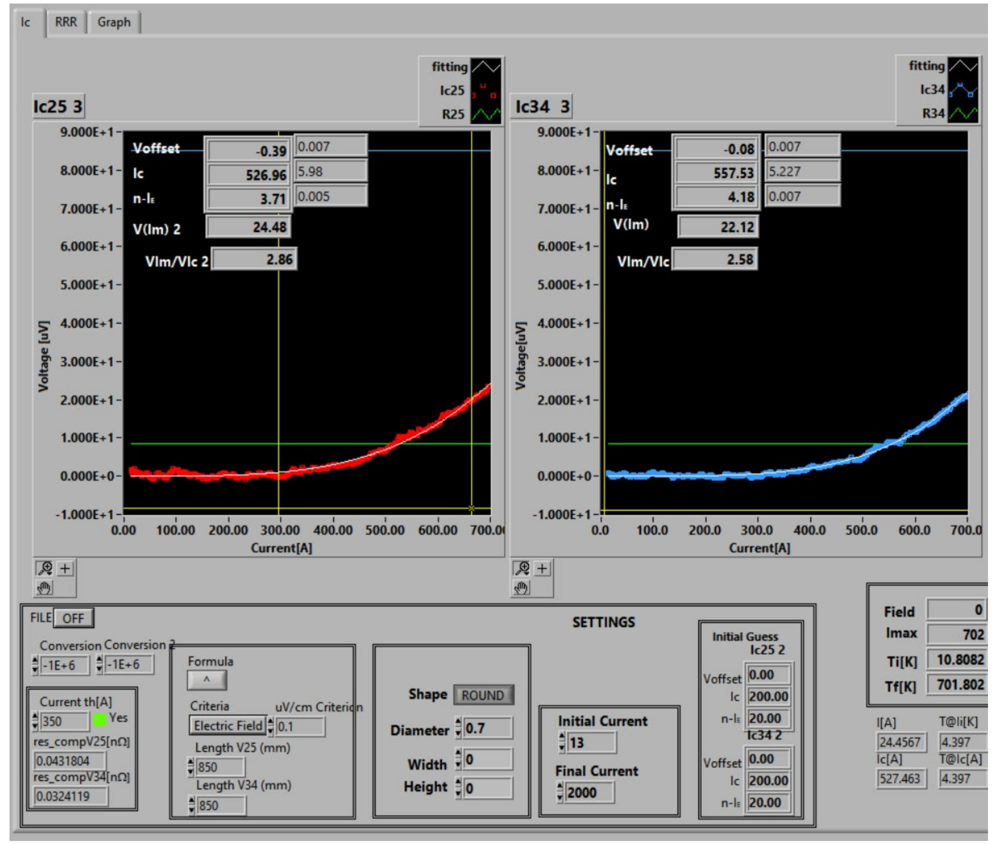
A complete model





First LN_2 test of the model



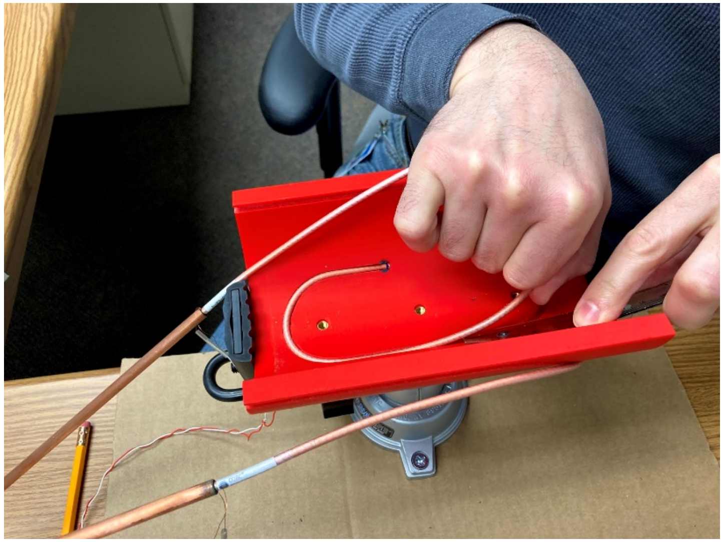


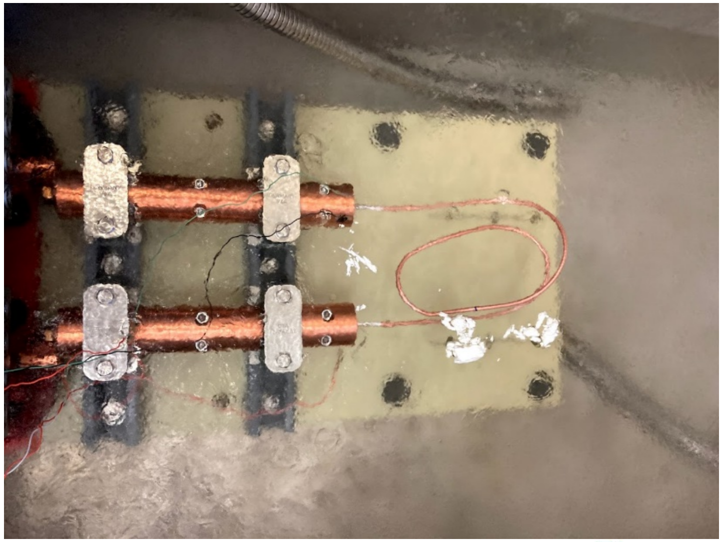
A large I_c reduction was observed after winding (no SF correction - it will be discussed later)

Also, there was a factor of 2 reduction in n-value

Possible causes of the I_c reduction

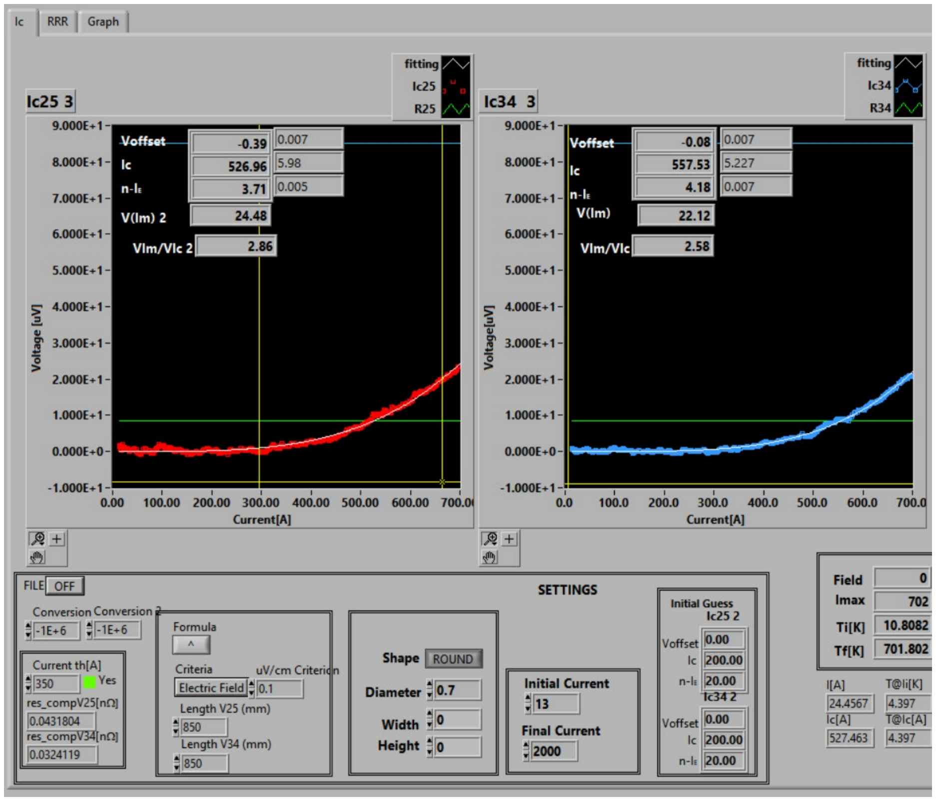
- Damage to the superconducting layer due to excessive bending strain.
- Effect of the self-field from the tight bending radii.
- Additional strain due to cool-down of the structure:
  - The cable was locked in the channel. The large thermal contraction of the plastic structure could induce additional strains in the cable, in particular, at the inner layer
  - That strain could potentially have a reversible component – to test that hypothesis, the cable was extracted from the structure without unbending it and retested.



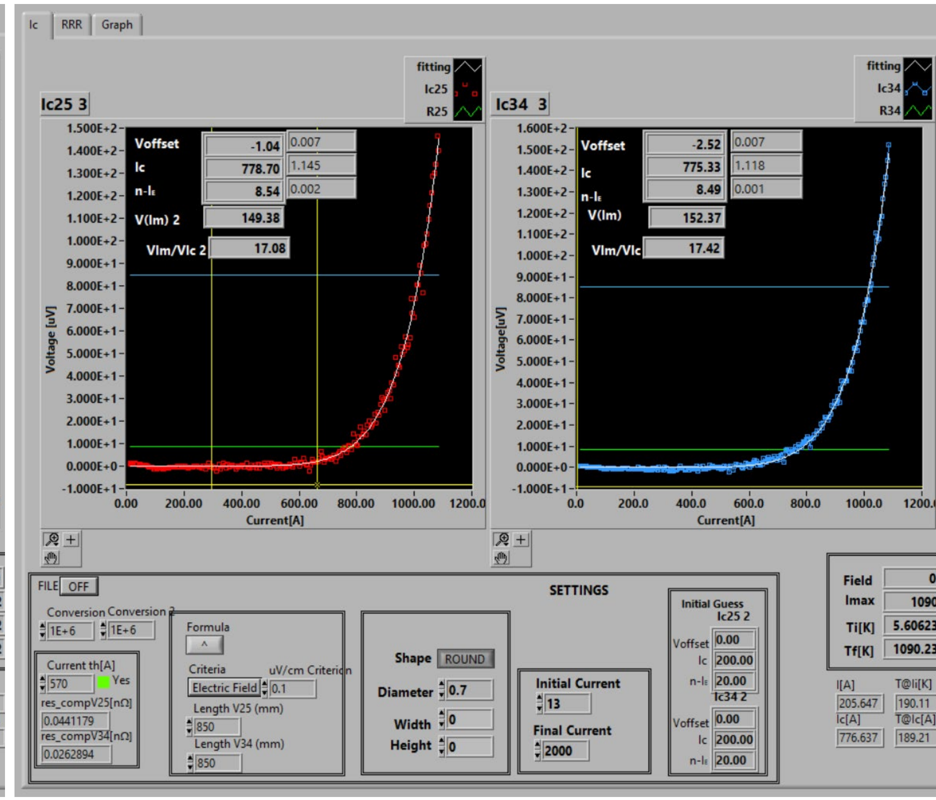


LN_2 test in/out of the structure

In the plastic structure



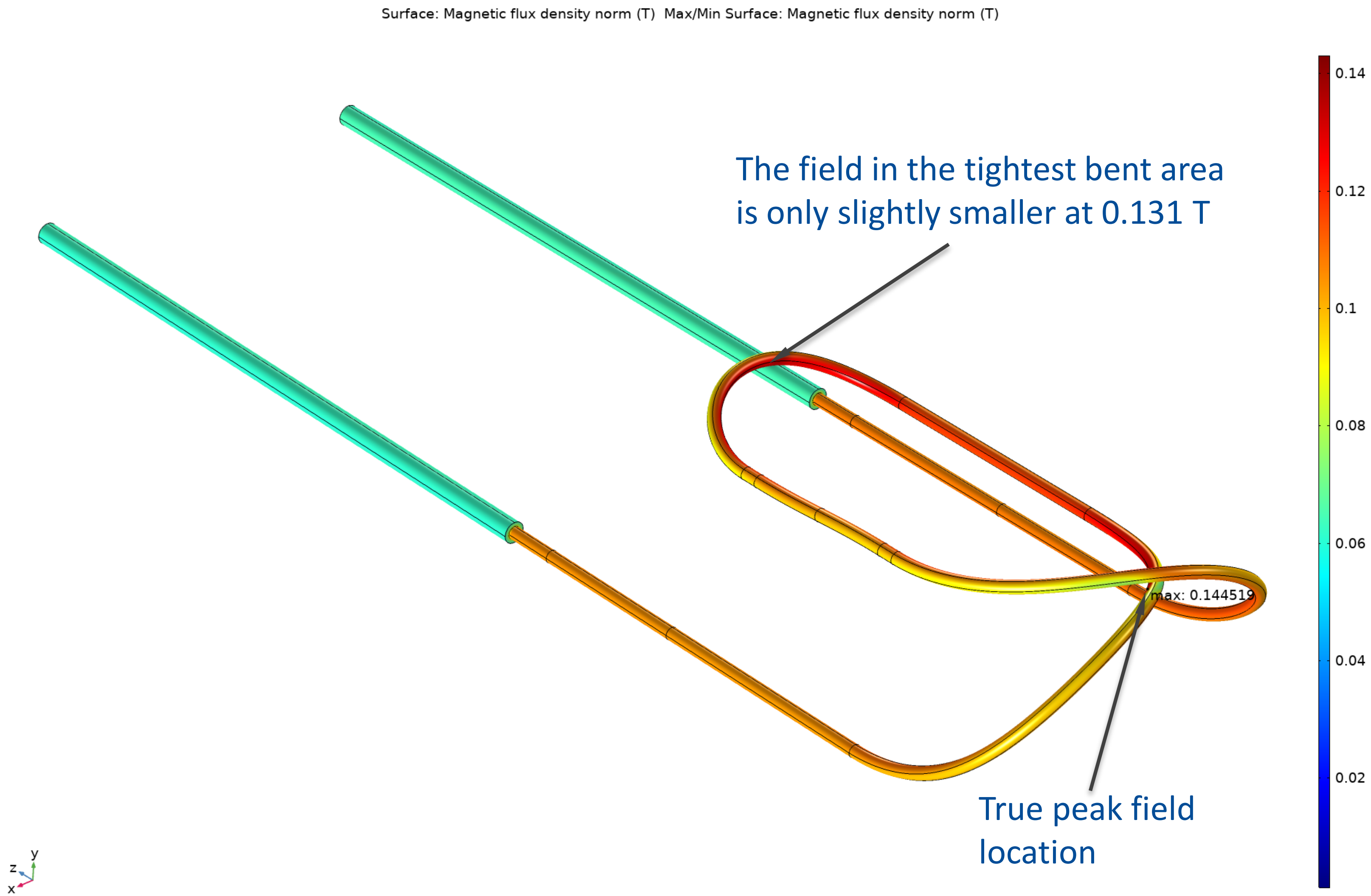
Extracted from the plastic structure



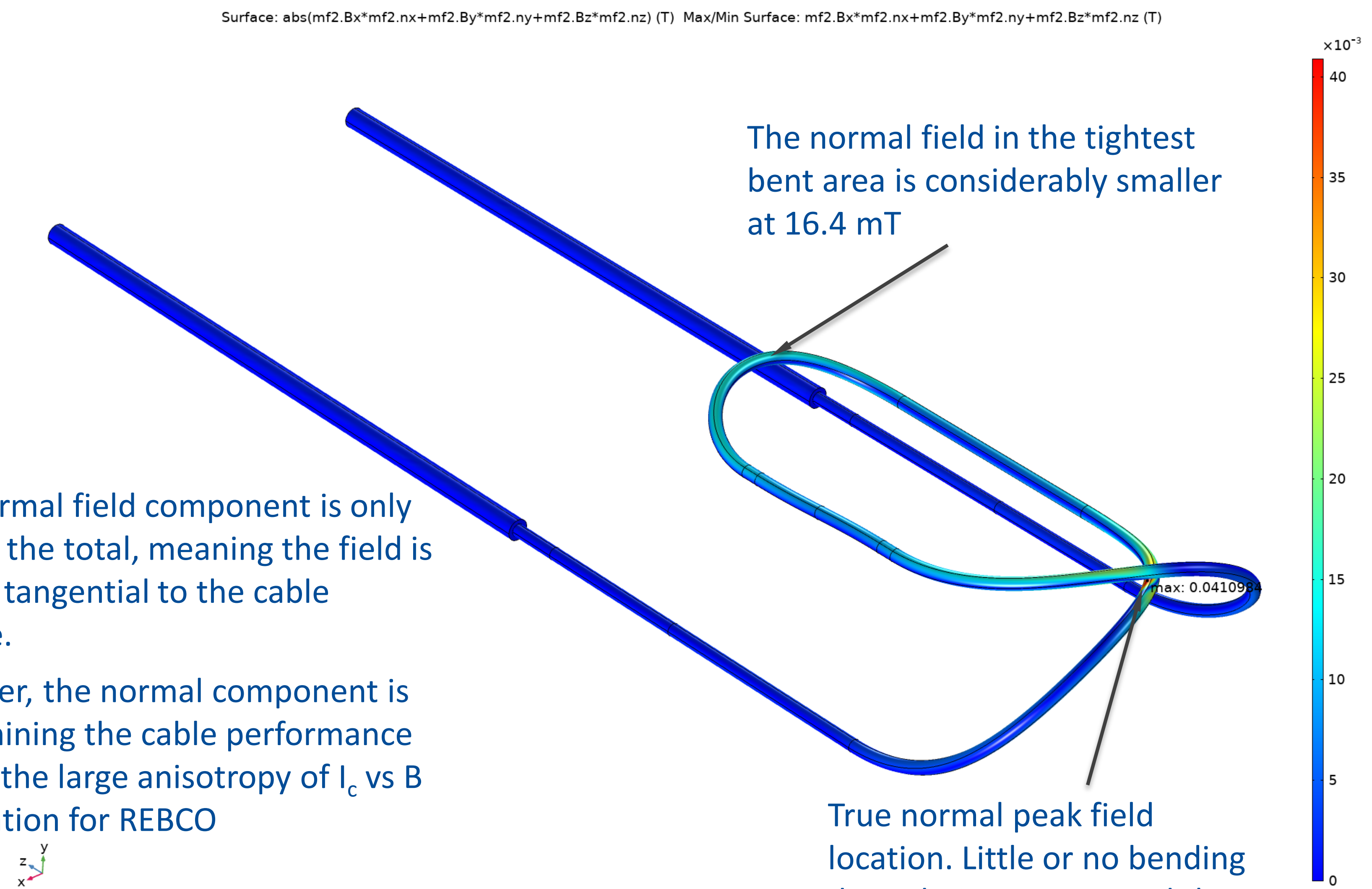
A 43% increase in I_c was observed in the extracted sample

Also, the n-value recovered to the original number

Self-field at 1000 A – total field



Self-field at 1000 A – normal component



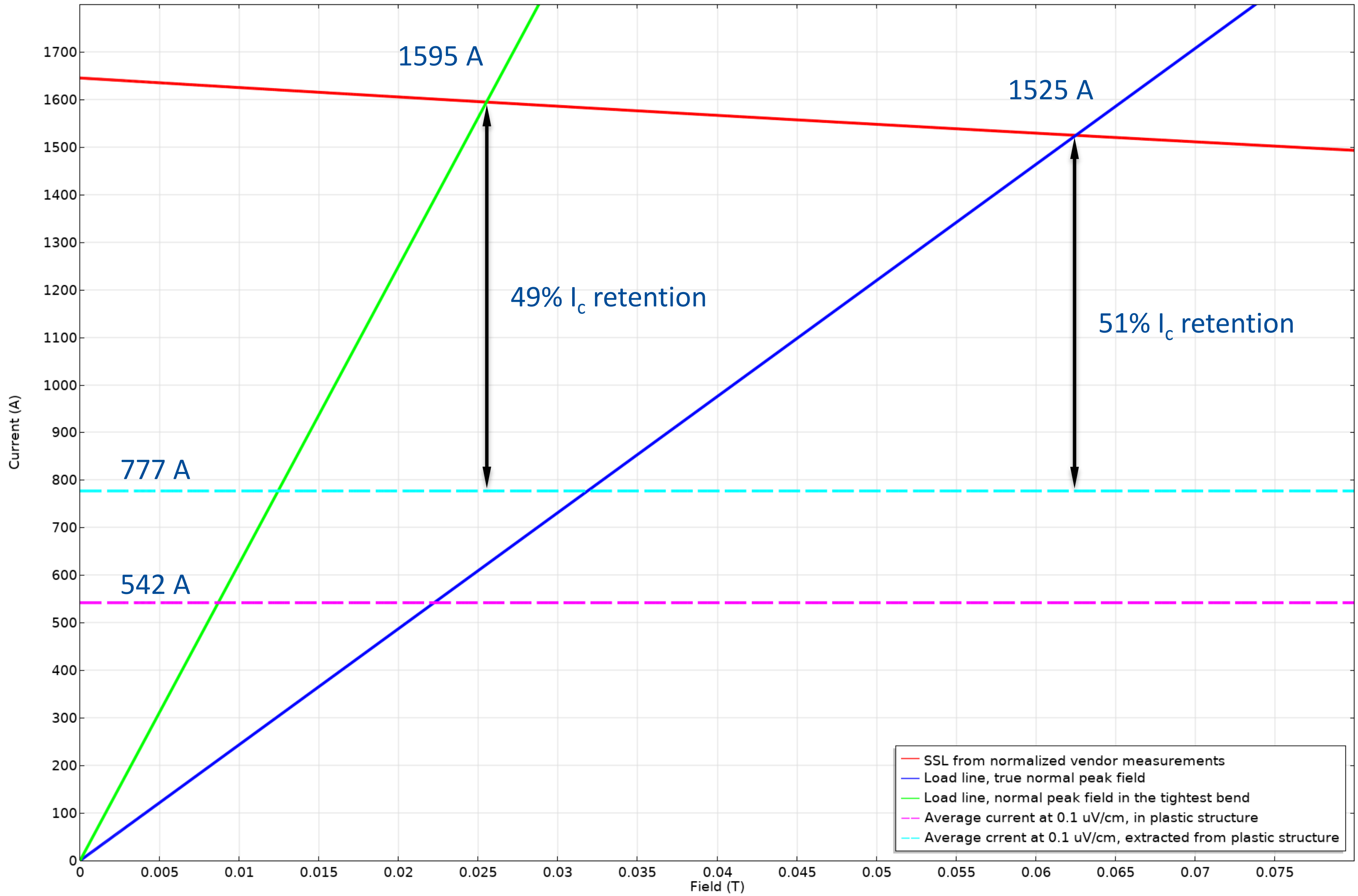
The normal field in the tightest bent area is considerably smaller at 16.4 mT

The normal field component is only 30% of the total, meaning the field is mostly tangential to the cable surface.

However, the normal component is determining the cable performance due to the large anisotropy of I_c vs B orientation for REBCO

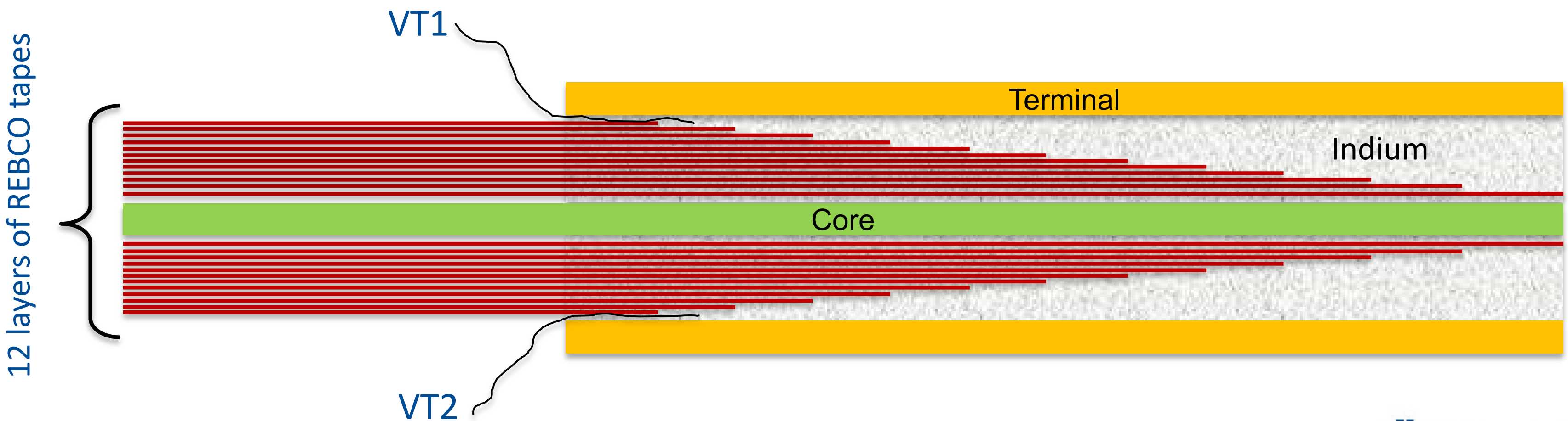
True normal peak field location. Little or no bending degradation is expected there.

Self-field effect



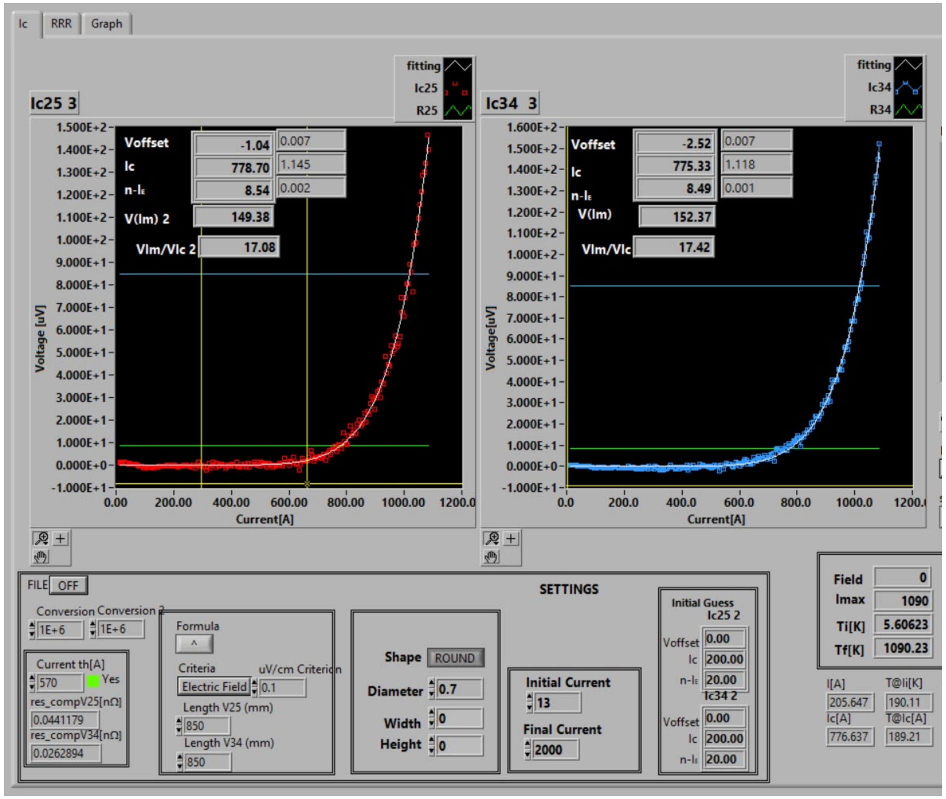
Current injection scheme

- The current is injected radially into the whole 20 cm length of the terminals. The voltage taps are installed a few cm from the cable exit locations. Inside of the terminals, the layers of REBCO tapes are tapered in a stairstep pattern to ensure a uniform direct current injection into each layer.
- Due to this layout, the VTs pickup the signal mostly from the outer layer(s) of the tapes. If the bending degradation is non-uniform – i.e. outer layers are degraded more than the inner layer(s) then it is possible that the resistive criteria is reached before all the layers are at 100% saturated with the current.
- To check this hypothesis, the terminals were pulled out of the copper adapters by 5 cm, which prevented a direct current injection into the 3 outermost layers and the I_c measurement was repeated.

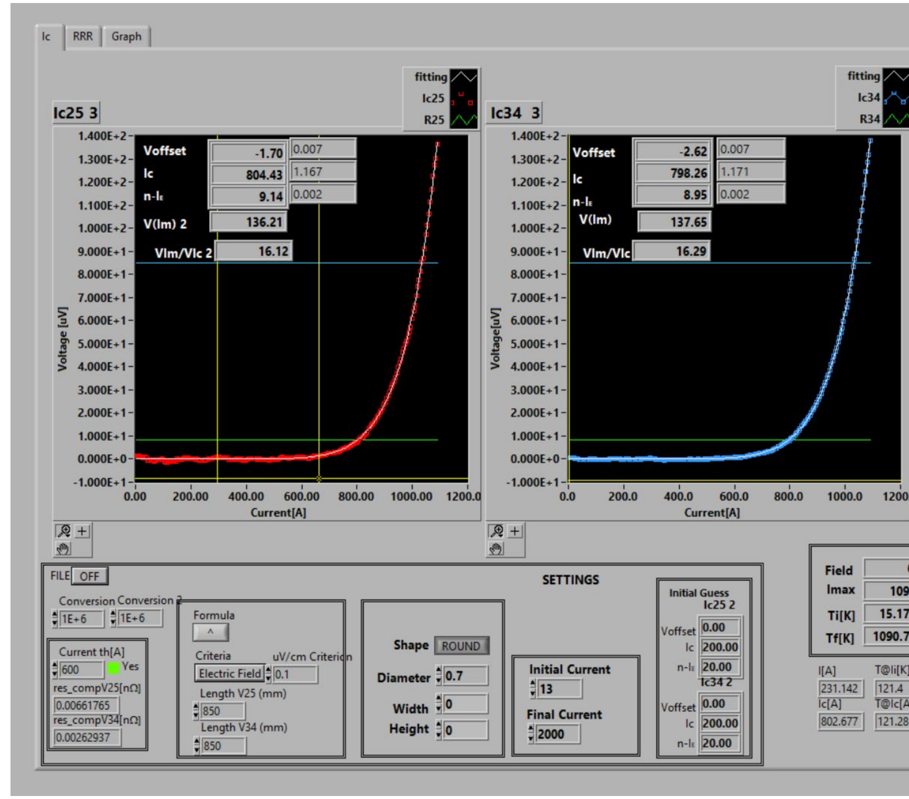


LN_2 test with reduced current injection length

Original (full) injection length



Reduced injection length



There was a small (~3%), but consistent I_c increase in both channels in case of the reduced current injection length

Also, there was an increase in the n-value

It supports the hypothesis of a non-uniform I_c degradation between the layers

Summary

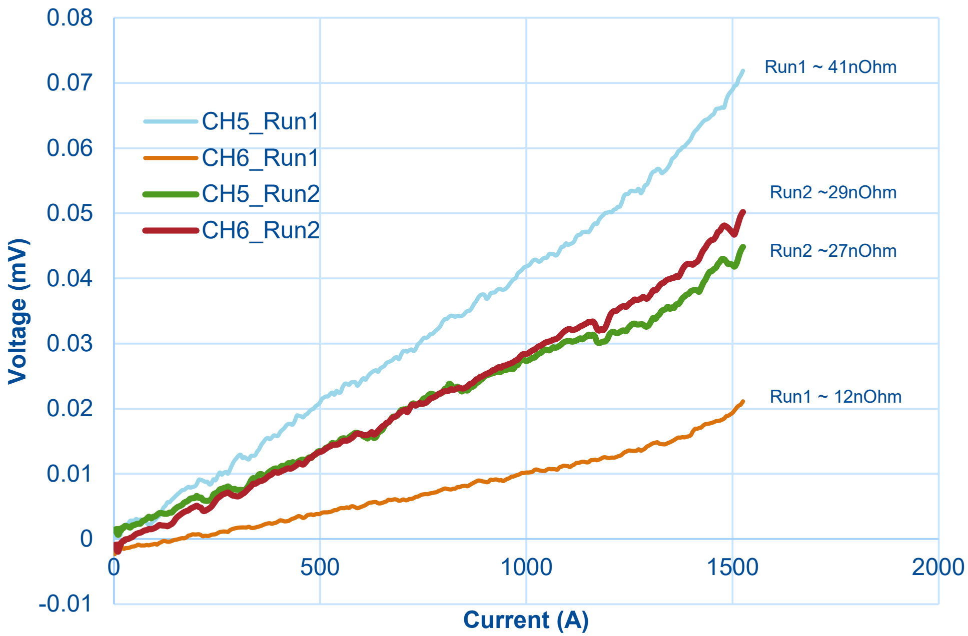
- A large I_c reduction was observed after winding the cable into the plastic structure.
- The majority of the reduction is expected to be related to the primary bend of the cable around the 52 mm pole spacer.
- The secondary bend around the 100 mm ID when the cable was pushed into the channel might have a compound effect on the bending strain and degradation.
- A part of the degradation is likely related to the thermally induced strains due to the differential thermal contraction between the cable and the structure. This can be eliminated by designing the structure that allows the cable motion in the channel.
- There is an indication of a non-uniform current degradation between the layers, which may obscure the actual cable performance.

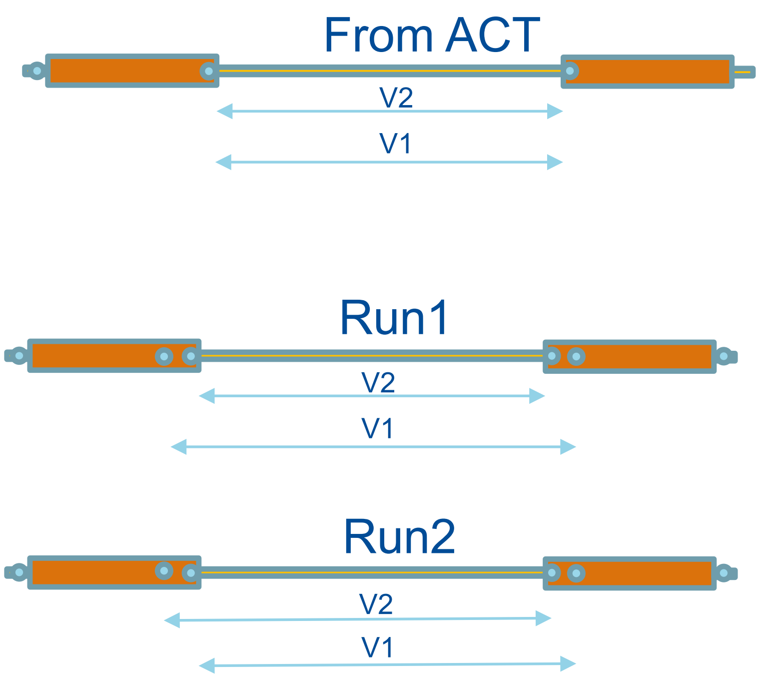
Next steps

- Understand the actual cable performance by reconstructing it from I_c vs. B measurements in transverse field on all the layers:
  - ACT has a setup and offered to perform these measurements;
  - It is expected that the I_c will be higher than during the cable tests, but still likely substantially degraded.
- In the meantime, work on increasing the minimum bending diameter and use a single-step bending process instead of the two-step, which means winding from the outside. There are at least 3 possible outer winding schemes (all have pros and cons). Stay with the present OD constraint to fit into Nb_3Sn coil (for now).
  - Pushing the structural material to the inside of the mandrel will allow to gain a few mm of the radial space for the turns to increase the pole width;
  - Eliminating the two-step bending process will avoid a possible compound strain effect.
- Repeat the short sample measurements with the redesigned structure considering the lessons learned from the previous tests.

Backup information

Sample 1 - Raw data from the first 2 runs, no resistive correction





Two pairs of voltage taps were installed by the vendor inside of the terminals a few cm from the inner ends (optimum location where all the REBCO tapes are soldered together)

The location of redundant VTs is supposed to be the same, but there was a considerable difference in resistances

Tried two combinations, however the difference in Ic was negligible after the resistive correction