# Fabrication of long-length cable-in-conduit for superconducting magnets

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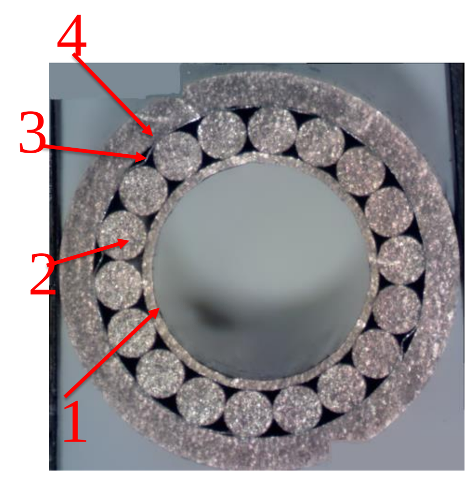
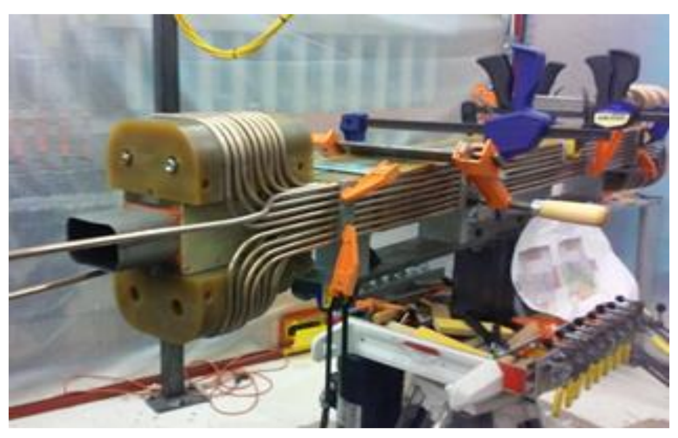
## Abstract

*Cable-in-conduit (CIC) conductor has particular benefits for superconducting magnets. It is rugged and provides cable-level stress management, it has internal flow of cryogen, flared ends can be formed readily and are self-stable once formed. Fabrication of long-length cable presents several challenges: cabling >125 m of CIC; the cable must be pulled through a long length of seamless sheath tube and then the sheath must be drawn down to compress the wires against the center tube and immobilize them.*

## Introduction

The CIC has four main elements:
1) a thin-wall high-strength perforated center tube provides helium flow to the
2) superconducting wires (NbTi, $MgB_2$ or $Nb_3Sn$).
3) Thin stainless steel foil provides a slip plane between the superconductors. 1-3 defines the core.
4) The wrapped cable is pulled through an outer sheath. The outer sheath is drawn down to compress the wires against the center tube and immobilize them.

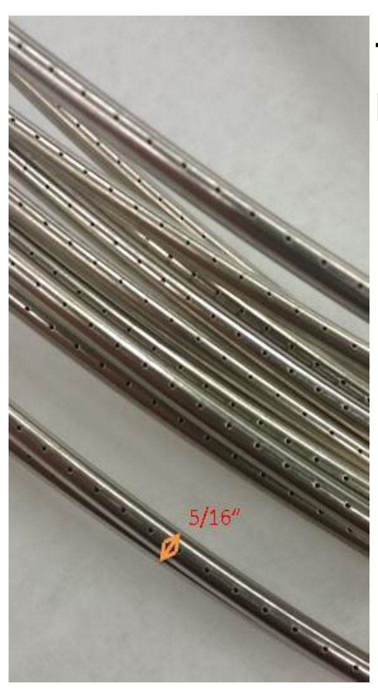


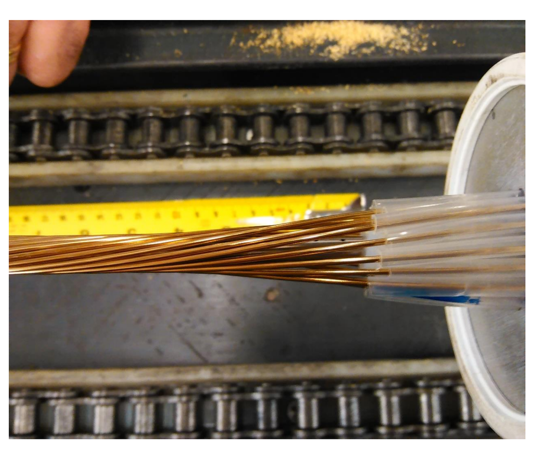
Although CIC can have many applications, this CIC is being developed for use in a dipole magnet for Jefferson Lab's JLEIC project.

## In-lab Development

### CIC short sample R&D (~10 m)




To the left is the *perforated center tube* used in the production of the CIC.



*Center*: Hand-stranding device. The 15 wires being stranded onto the center tube. *Right:* the stranding process in which the wires are laid down with a specific twist pitch.


The 7.5 cm twist pitch is periodically verified for consistency. Cabling longer lengths will be done using a planetary stranding machine.

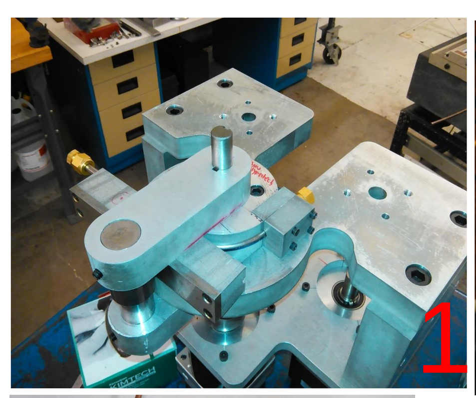
Once the superconducting wires are wound onto the perforated tube, stainless steel foil tape (25 μm thick, 1.2 cm wide) is wrapped under tension onto the cable. The foil wrap stabilizes the cable and provides a slip interface between the cable and the outer sheath.

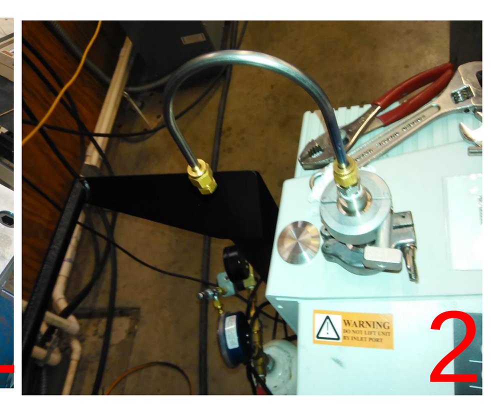
The wrapped cable is then inserted into a straight length of sheath tube. The sheath tube is oversize to accommodate pulling the cable through.

Next, one end of the cable is fused and swaged to initiate the drawing process.

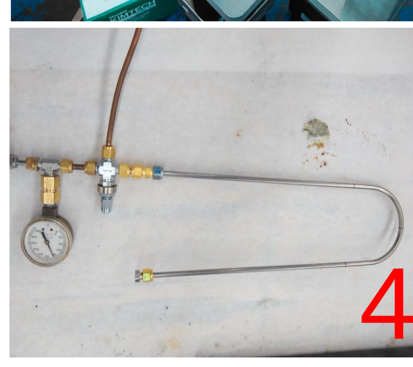
The drawn CIC (above right) is then spooled onto a large spool (above left). The large radius is chosen to prevent ovaling of the CIC.

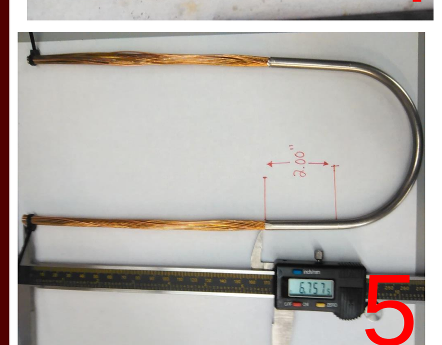
## Testing CIC: Seamless Outer Sheath and Continuous Tube Filling and Forming (CTFF) Outer sheath

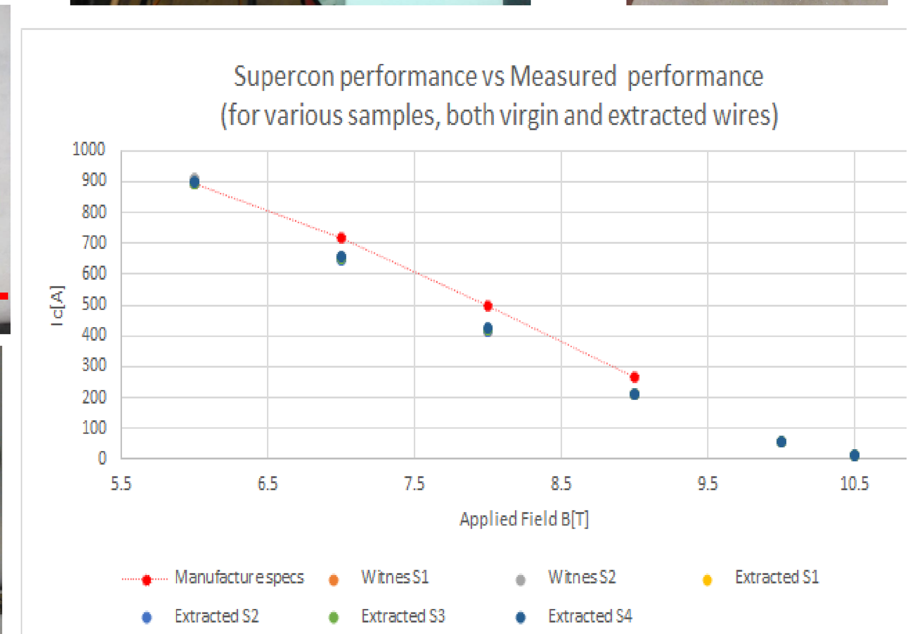






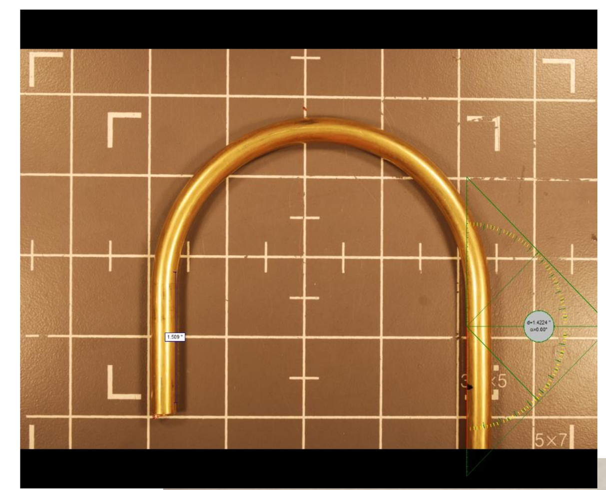




Above is a series of tests conducted on a segment of bent CIC to insure that there are no failures on the weld line of the outer sheath. This specific procedure was used on the CIC for the JLEIC Seamless CIC along with the HyperTech CTFF CIC . The procedure is as follows:

1. Helium leak test sample as-received(2).
2. Bend 180° (+ 27° over-bend), at an angular velocity of 150°/min (1)
3. Helium leak check (2)
4. Cold shock at 77 K(3)
5. Helium leak check(2)
6. High pressurize to 40 bar(4)
7. Helium leak check. (2)

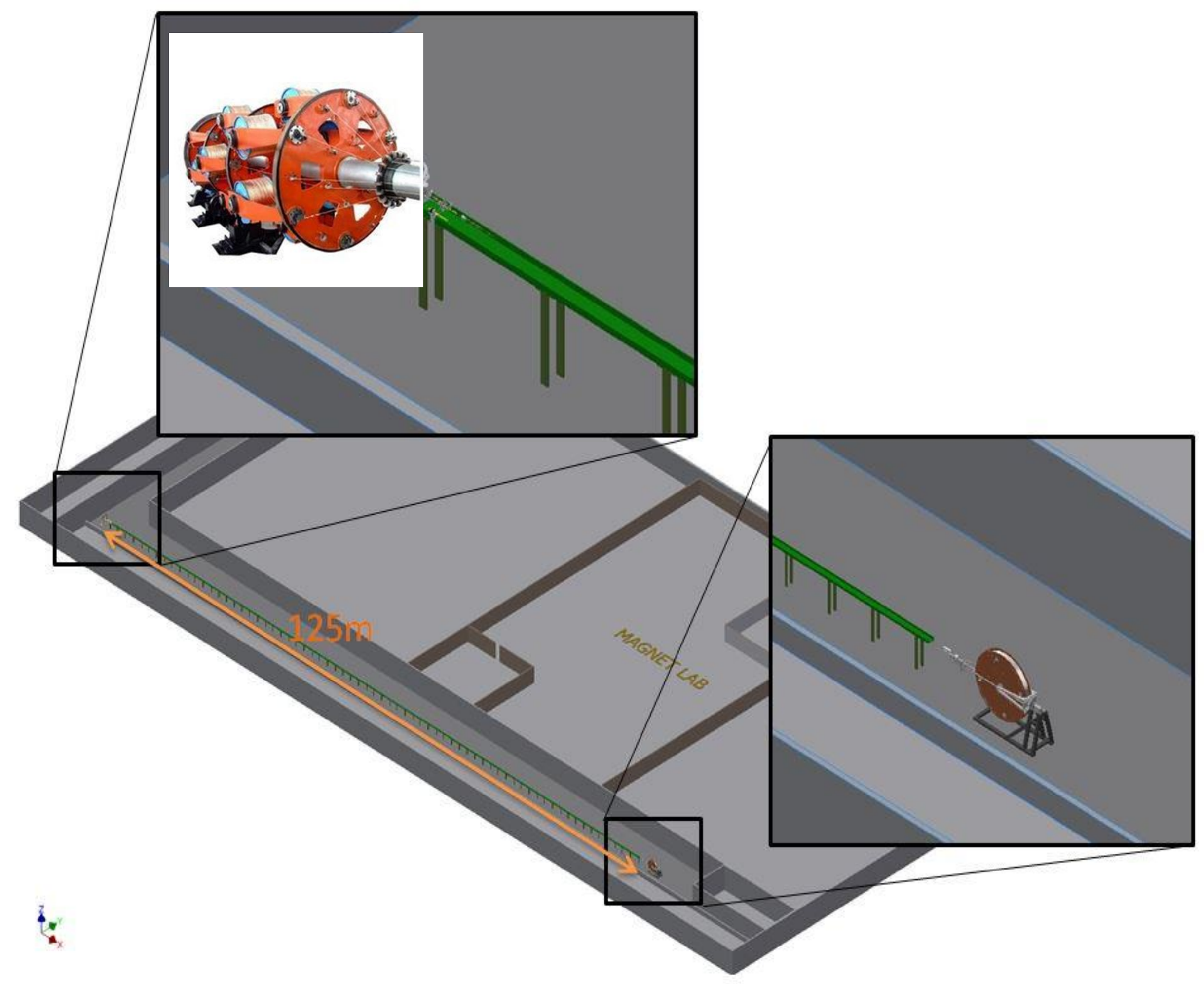
After the tests, several superconducting wires were removed from the core (5) and Ic tested at various fields. The performance of the superconducting wires were compared to a control wire taken directly from the spool. The above graph shows the results.



To the left is a segment of CIC (seamless outer sheath) bent at a 1.833" radius. It was over bent to prevent spring back effects. Below is a superconducting wire extracted from the CIC segment. The wire was etched in a ferric chloride solution and tested for filament breakage. Only 5 out of 7400 were broken.

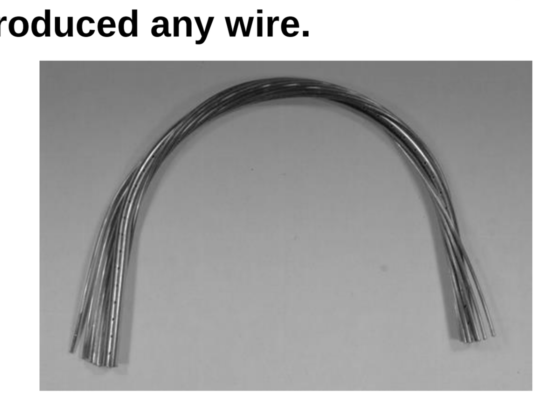
## Developing long-length CIC fabrication

Below is the floor plan for long length production using with a planetary stranding machine and an extension of our drawbench.




The long-length manufacturing strategy strands the wires around the center tube, wraps the core with the SS-foil tape, pulls the wrapped cable into the sheath tube, and draws the sheath tube down onto the core in a single straight process line. The stranding machine provides constant tension and twist pitch of the cabling.

Control of twist pitch is crucial to make it possible to bend the CIC (with CIC diameter ~1 cm). strongly in the ends of a magnet winding (bend radius ~4 cm) without damaging the wires inside.
In the bend region, each wire on the inside of the bend is compressed and each wire on the outside is stretched. If the catenary length of the bend is an integral multiple of the twist pitch, all the wires will have remain exactly the same length – no extra tension will be produced any wire.



## Conclusion

A short sample of CIC (~10 m) has been produced and coiled. We are developing an assembly that integrates all operations into a single long-length in-line process that strands and wraps the cable, pulls it through the sheath tube, and draws the sheath tube onto the cable to complete the CIC.
ARL is preparing to fabricate 125 m lengths for use in the windings for the arc dipoles of JLEIC.
ATC is preparing to launch a product line of CIC conductor up to 500 m piece length, for cable applications requiring NbTi, $Nb_3Sn$, $MgB_2$, or Bi-2212 superconductor.

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