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

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Abstract. A superconducting cable-in-conduit (CIC) is being developed for the windings of superconducting magnets for a proposed electron-ion collider and for other applications. Short-length samples have been successfully developed and tested for the required performance. The equipment and procedures have been developed for fabrication of long-length conductors. A 10 m CIC has been successfully fabricated and evaluated. The process is now being extended to make 125 m cables in a straight-line process.

1. Introduction

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. CIC conductors have been in use for many years for various applications, including fusion magnets, superconducting magnetic energy storage, electric motors, detector magnets and accelerator magnets [1].

The Accelerator Research Lab has developed a CIC conductor for the windings of the 3 T dipoles and accompanying quadrupoles of the Ion Ring in the Jefferson Lab Electron Ion Collider (JLEIC) [2]. The CIC design was chosen to facilitate cost-effective fabrication of a compact block-coil dipole that can provide collider-homogeneity magnetic fields over a large field range in the large aperture required for the Ion Ring.

The CIC conductor reported in this paper for JLEIC dipoles consists of a single-layer of NbTi/Cu wires which are cabled with a twist pitch around a perforated thin-wall stainless steel center tube (the choice of twist pitch is presented later). The cable is then wrapped with an overwrap of thin-foil 316L stainless steel foil tape (25microns thick, 1.25 cm wide), and the cable is pulled through a copper nickel sheath tube. The sheath tube is drawn down to compress the strands against the center tube and immobilize them. The sheath provides stress management at the cable level, so accumulation of Lorentz stress cannot cause degradation of superconducting performance. It also preserves the benefits of interior helium flow, so that the overall magnet is not required to serve as a He vessel. In windings made from this CIC conductor, liquid helium flows within the center tube and through the perforations in the center tube, so that He bathes all wires to enhance stability against microquenches.

Table 1 summarizes the main parameters of the cable and of the JLEIC dipole in which it is used for the windings.
Table 1. Main parameters of the CIC for the JLEIC dipole.

| Operating conditions in dipole winding |       |
|--------------------------------------|-------|
| Operating temperature ($T_0$)        | 5 K   |
| Design dipole field in bore ($B_0$)  | 3.0 T |
| Conductor current @ $B_0$, $T_0$      | 13.7 kA |
| Maximum field at conductor @ $B_0$   | 3.5 T |
| Bore field at short sample           | 3.8 T |

*Specifications of NbTi/Cu wires in CIC*

| Specification                              | Value |
|-------------------------------------------|-------|
| Copper: SC ratio                          | 1.5   |
| Cu RRR                                    | 140   |
| # filaments in wire                       | 7000  |
| Wire diameter                             | 1.2 mm |

*Specifications of CIC conductor*

| Specification                              | Value |
|-------------------------------------------|-------|
| # wires                                   | 15    |
| OD of finished CIC conductor              | 8.128 mm |
| OD of perforated center tube              | 4.76 mm |
| Sheath thickness                          | 0.50 cm |
| Twist pitch of wires in cable             | 7.6 cm |

*316 SS foil tape overwrap on cable*

| Specification                              | Value |
|-------------------------------------------|-------|
| Tape thickness                            | 25 μm |
| Tape width                                | 1.7 cm |
| Overlap wrap? yes/no                      | No    |

*Specifications for forming CIC bends*

| Specification                              | Value |
|-------------------------------------------|-------|
| Bend radius for all 3 T winding ends       | 5 cm  |
| Overbend angle to produce 180° bend        | 30°   |

The CIC conductor has been developed in three phases. In the first phase, a ~2 m long CIC was fabricated using a small “manual-stranding device” (see figure 1.a), which place the superconductors around the perforated inner tube with the desired twist-pitch. In this process, a uniform and synchronized motion of pulling and twisting the device is vital for providing constant twist-pitch. With this method we were able to control the twist pitch within 0.05% of error in twist-pitch length. That work is summarized in the following section.

![Figure 1. Cable-in-Conduit conductor that is being developed for the windings of the JLEIC dipole: a) Manual-stranding device; b) cutaway showing the cable on the center tube with tape overwrap and sheath tube; c) cross-section photo of a fabricated segment of CIC.](image-url)
In the second phase, the equipment and methods were developed for fabricating long-length CIC conductor. A first step was to develop in-line fabrication tooling to make 10 m long CIC samples. In-line fabrication development is complete and is reported in Section 3. From the in-line fabrication development, a complete design has been developed for the 125 m segments of CIC conductor that are required for the windings of the JLEIC dipoles. The complete design is presented in Section 4.

Figure 2. a) wire feed manifold set up on drawbench to cable 10 m CIC segment; b) winding operation in action showing twist pitch of the cable; c) Twist-Pitch uniformity for the 10 m CIC segment.

Figure 3. Methods used to hand-fabricate short lengths of CIC cable; a) hand cabling the CIC; b) drawing the outer sheath down onto the core.

2. Fabrication and testing of short segments of CIC cable
The Cable-in-conduit is an arrangement of a number of superconductors (NbTi, MgB2, Nb3Sn depending the desired field and or critical current) in which a single-layer of wires is cabled around a high strength perforated inner tube at a specific twist pitch as shown in figure 2. If there was no twist pitch, a wire that is located on the outside of a bend in the CIC would traverse a longer catenary path after the bend than before, and a wire that is located on the insider of the bend would transverse a shorter catenary path. Therefor the twist pitch of the cabling is adjusted to be equal to the path length of a 180° bend with the bend radius of 5 cm that is used in all bends of the dipole winding. Each wire then has the same path length on the outside as on the inside, so no residual wire strain. The cable is then wrapped with a thin stainless steel foil that acts as sliding plane as seen in figure 1b). Next, the whole assembly is inserted into a high strength outer sheath which is drawn down to compress the wires against the center tube and immobilize them shown in figure 3b). This sheath provides stress management at the cable level, so accumulation of Lorentz stress cannot cause degradation of superconducting performance.

Sample cables were tested to validate that the NbTi/Cu wires were undamaged by the cabling and drawing process. All of the 7000 filaments of the bent NbTi/Cu wires were inspected under a
microscope and no broken filaments were found. To confirm that there was no current degradation, Ohio State University performed $I_c$ tests on four strands extracted from a bent CIC and two strands that were directly from the new NbTi/Cu wire spool. As it can be seen in figure 4, the $I_c$ test shows that the cabling, drawing and bending procedures used to reproduce typical conditions as would be experienced by the CIC following JLEIC specifications, do no contribute to the current degradation. The data is presented in figure 4.

![Critical Current of NbTi strands from CIC](image)

**Figure 4.** $I_c$ test for NbTi/Cu CIC. Samples 1, 2, 3 and 4 represent the $I_c$ performance of 4 NbTi/Cu extracted strands taken from a CIC. As seen in the graph, there is no visible difference in the measurements. Samples labeled as "Un-strained 1 and 2" represents the $I_c$ performance of "witness strands." Witness strands are strands that did not experience any stress or strain and were taken directly from the superconductor spool.

![Image of bending CIC conductor to form the flared ends of the dipole winding](image)

**Figure 5.** Bending CIC conductor to form the flared ends of the dipole winding: a) motorized tool for forming 180° bend; b) motorized tool for bending the 180 loop to form c) the 90° flare end region of completed dipole winding.

Three highlights from the short-segment studies are noteworthy. First, a procedure for forming bends that preserves the internal registration of the CIC through a 5 cm radius bend, and prevents wire strain from developing in the bend [3].
Second, motorized tooling was developed with which to form the bends required for the flared ends of the JLEIC dipole windings. Figure 5a shows the motorized tool that forms the 180° U-bend with leg spacing appropriate for each layer of the winding. Figure 5b shows the tool that forms the 90° bend of the U-bend to form the flared end and vertical jog for step transitions. Figure 5c shows one flared end region of a complete mockup winding [3].

Third, a complete mockup winding was fabricated, in which the winding was supported on a precision-machined G-11 structural beam that is integral with the JLEIC dipole design. Metrology was performed to measure the precise location of each of the 24 turns of hollow tube that mimicked the conductor in the geometry of the structural beam. The measured position errors were then fed back into the magnetic simulation of the dipole to determine the multipole field errors that would be produced. The measured locations corresponded to a field distribution that was within tolerance for the collider requirements [3].

3. Fabrication of 10 m segments of CIC cable
An important objective of the second-stage development was to develop methods for the cabling and tape-wrapping, insertion of the cable into the sheath tube, and drawing the sheath to final diameter, that are compatible with extension to the full 125 m length required for the windings of the JLEIC dipole. The cabling, wrapping and pull-through-sheath operations were performed on a drawbench shown in figure 6. The 10 m cables were measured with a micrometer along the length of the cable. The segments showed that the cable diameter and twist pitch were sustained with required precision, and the drawing operation went smoothly. The twist pitch was measured with a set of calipers shown in figure 2c.

![Figure 6](image)

**Figure 6.** Procedures for fabrication of long-length CIC conductor: a) wrapping the cable; b) pulling the cable through the sheath tube; c) drawing the sheath tube to final size.

The above succession of steps were undertaken with all components – straightened the wires, the perforated center tube, and the sheath tube. We found that the succession steps benefit greatly from the entire process being done as an inline operation, without spooling the cable at intermediate stages. Spooling at intermediate stages would entail a degree of ovaling of the cable and/or tubes that complicate the subsequent operations.

4. Long length CIC fabrication
4.1. In-line cable fabrication
The overall process developed above is now being extended for the construction of 125 m cable CIC segments. A commercial planetary stranding machine is being acquired for the cabling and wrapping operations.

The bed of the 10 m draw bench is being extended to 125 m length. The tape-wrapping will be performed as a last operation on the stranding machine, and the wrapped cable will be pulled through a
straightened sheath tube that is mounted on the drawbench. In that way all stages of CIC fabrication can be performed as an in-line cabling and drawing operation.

4.2. Continuous tube forming to make CIC conductor

As opposed to pulling the wrapped cables into an outer sheath, it is possible to use Continuous Tube Forming and Filling (CTFF). Hyper Tech has developed and uses a (CTFF) machine for continuous forming of a cable containing up to 37 filaments of MgB\textsubscript{2} superconducting monofilaments within a Monel sheath superconducting wire [4]. They are collaborating with the Texas A&M group to adapt CTFF processing to continuously form the sheath tube as an in-line process.

In CTFF, the tube is then formed from a foil strip by roll-forming the cusp and curving it around the cable as it passes through the former. The seam is laser-welded to seal the tube. The strip width is chosen to provide a loose fit onto the cable so that there is sufficient gap that the cable can be pulled through the sheath tube. Finally the tube diameter is reduced to the final CIC diameter. Sample cable segments have been prepared, and the sheath tube has been checked along its seam to determine whether there are any vacuum leaks that would compromise the helium containment which is one of the attributes of the CIC approach for dipole magnets.

Sample cable segments were bent using the motorized bend tools and cold-shock tested at liquid nitrogen temperature to evaluate the integrity of the CTFF weld seam. Some early samples showed leaks at the seam. After process development of CTFF for this system, additional 2 m segments were fabricated, and were found to be leak-tight. The segments were then bent to a U-bend and then pressure-tested to 40 bar, under vacuum and at room temperature and at 77 K.

All samples passed the leak test. A dissection was performed on the bend regions and superconducting wires were removed. Half of the wires were etched in a ferric chloride solution and tested for broken filaments. The other half was sent for short-sample measurement of superconducting performance. After etching, there were less than 5 out of 7000 filaments broken filaments in the wires. The superconductivity test revealed no current degradation. Hyper Tech is continuing their development of the CTFF for the CIC application.

5. Conclusion

The construction of a ~10 m sample of Cable-In-Conduit (CIC) has been completed. All challenges regarding the short sample fabrication have been overcome. The next step is scaling to a long length manufacturing process. There are two paths capable of scaling up to long length fabrication. In-Lab production that would easily adopt the short sample fabrication method. CTFF is another option that proved to be promising for long length development of CIC based on a set of integrity tests and current test performed on the samples taken from both manufacturing paths. Both processes have been tested and proven to be viable options of long length production.

6. References

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