CIC Cable Technologies for High-Current Windings

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Abstract: Superconducting cable-in-conduit has been used for the high-current windings of dipoles for several accelerators. A novel CIC design is currently being developed for use in the booster and ion ring for the proposed JLEIC. Enabling technologies for long-length cable fabrication, coil-winding and low-resistance splice and leads are summarized.

1. Introduction

The Accelerator Research Lab (ARL) at Texas A&M University is developing a new technology for high-performance superferric magnets that provides a cost-effective basis for fabrication of the arc dipoles for the ion ring of the proposed Jefferson Lab Electron-Ion Collider (JLEIC) facility. A central element of the JLEIC dipoles design is a cable-in-conduit (CIC) conductor, with unique benefits for manufacturing of superconducting magnets for particle accelerators, and for a number of practical applications including windings for the toroidal field coils for tokamak reactors, superconducting magnetic energy storage systems, and power transmission lines, among others.

The JLEIC is a proposed facility in which highly polarized beams of ions and electrons would be collided at energies up to ~100 GeV/u for ions and 20 GeV for electrons [1]. The arc lattice of the ion ring requires 256 4-m dipoles operating at a 3 T field, with a dynamic aperture of ~10 cm x 6 cm [2]. The ARL group has developed a design for a superferric dipole that utilizes a round NbTi cable-in-conduit (CIC) conductor.

The CIC technology developed at ARL allows the superconductors to be formed in complex windings at a relatively small bending radius (25mm), provides direct contact between wires, facilitating current sharing in case a quench event is developed, and it provides mechanical support to conductors while serving as its own cryogenic vessel. Four basic components integrate the CIC conductor: 1) The superconductor (NbTi, MgB₂, Nb₃Sn or Bi2212), 2) the high strength, thin wall, non-reactive, inner tube made of perforated stainless steel, 3) the stainless steel thin foil wrap, that acts as a slip plane for the conductors, and 4) the high strength outer tube, that provides protection and support to the superconductors.

In 2017, the ARL partnered with Accelerator Technology Corp. (ATC) to undertake the development of a fully operational long-length CIC production facility, capable of producing high volumes of CIC conductor at high speeds and in a wide variety of CIC designs with the intent to target several different applications. The capabilities of the CIC production facility include the adjustment
for different parameters on the CIC conductor, as may be required for different applications, i.e., the number of superconductors per cable, the dimension of the superconductor, the desired CIC diameter, variations on the required twist-pitch of the superconductors and the kind of superconductors used. The challenges and results are described in the next session, making special emphasis in the development of the technology that allows the production and processing the CIC conductor into high current coils.

2. CIC long length production facility
In August 2018, the ARL and ATC joint collaboration completed the development of a CIC long-length production facility, capable of mass producing 130m-long sections of NbTi CIC conductor. Three main components were used to produce the CIC conductors: 1) a high-speed planetary stranding machine, responsible for applying the spiral wrap of the superconductors around the perforated inner tube; 2) the taping head unit, responsible for adding the protective layer of thin foil stainless steel tape, and 3) a set of two caterpillars, one responsible for providing active insertion of the cables into the rigid outer tube and the other responsible for drawing the CIC into the required dimensions, see Figure 1.

2.1. CIC conductor long length production
The production process of long sections of CIC conductor is divided into three stages. First, a long spool of perforated stainless steel tube feeds the planetary stranding machine, which contains 15 spools of 1.2 mm OD NbTi wires. Then, the superconductors are fixed across the joint of the ending portion of the inner tube and the initial portion of a galvanized cable, which is used merely to initiate the cabling process by providing a lead end to pull from the caterpillar. The previous assembly is sent through a compactor die, which avoids wire overlapping, ensuring a uniform cable of the right dimensions (Figure 1a). The angular rotation of the spools in the stranding machine is linked by a system of mechanical gears to the linear motion of the rubber band clamp in the caterpillar (Figure 1b). The synchronized motion of both systems is configured to match the desired twist-pitch of the JLEIC CIC conductor, for instance, 73.13mm [3]. The taping head unit is located in between the compactor die and the caterpillar and is responsible for applying a constant wrap of stainless steel tape. For the JLEIC CIC conductor, a no-spaced wrap is applied. Nevertheless, the unit offers the possibility to adjust the spacing if needed, Figure 1c.

Figure 1. Manufacturing process of Cable-in-conduit conductor. Figure 1a), shows the superconductors at the exit of the stranding machine being winding around the perforated stainless steel inner tube, and passing through the compactor die, to produce a uniform and registration-free cable. Figure 1b) shows the exit of the caterpillar pushing out the CIC core, including the stainless steel tape. Figure 1c) shows the taping head unit applying a non-overlap stainless steel foil, preparing the CIC core to be pulled by the caterpillar. The motion of this machines is all synchronized to produce the desire twist-pitch to the superconductor.

The second stage of the procedure involves inserting the product coming from the caterpillar (CIC core) to a pre-straightened long section of high strength outer tube. In this process, the galvanized
cable is used again to ease the insertion of the CIC core to the long-length of the outer tube and avoids friction accumulation. The pulling force is provided by a powered take-up spool unit. Once the CIC core is fully inserted into the outer tube, the CIC is obtained.

The third stage involves the drawing of the CIC. To produce an operational CIC, a two-step drawing process is required. The first drawing eliminates the gap between the outer tube and the CIC core, while the second compacts the wires onto the inner tube, immobilizing them and providing direct contact between neighboring wires. This is a critical property for current-sharing. For the NbTi wires inside the JLEIC CIC conductor, the contact region takes 12% of the surface of the wires.

The latter is a general procedure that allows the CIC production facility at ATC, to span the development of CIC conductors. It covers a wide range of possibilities for development of CIC conductors for diverse applications, which may include the fabrication of multilayer CIC conductors, which could be used to produce D-shape toroidal coils for nuclear fission reactors.

3. Coil forming
Cable-in-conduit conductor possess a number of properties that make it suitable for high current winding: the robustness of the cable; the fact that it constitutes its own cryogenic vessel, bathing the superconductors at all times, and providing thermal stability; the shoulder-to-shoulder contact between strands; and the ability of the rigid structure to allow for complex wind forming using relatively small bend radius. The former property depends on the dimensions of the CIC components, the twist-pitch of the conductor and the kind of superconductor used.

![Figure 2a](image1.jpg)  ![Figure 2b](image2.jpg)

Figure 2. CIC winding for the JLEIC 3T dipoles. Figure 2a) shows three saddle bends at the end of the 3T dipoles for the JLEIC proposed facility, using a 13kA NbTi CIC conductor. Figure 2b) shows one the robotic bender, providing a 90 deg flare bend for the saddle end, shown at the figure 2a).

To form CIC conductor into complex windings, as the ones required by the saddle ends of dipoles and quadrupoles, two components are required, a bending die of proper dimensions that provides full confinement of the CIC conductor, and a bending arm to form the CIC around the die. Provisions for spring back effect must be considered to compensate for the change in radius [3]. For the JLEIC CIC, a set of three robotic benders fully formed the NbTi CIC conductor into the complex bends shown in Figure 2a). The bending speed, the bending radius and the over-bend required to compensate spring-back were studied and described in [3]. The high accuracy and reproducibility of the complex bends achieved by robotic benders (< 1 deg), enhance magnet design and manufacture by allowing complex windings.

4. Splice Joint
The CIC technology involves the development of a low-resistance splice joint system that allows testing, operation and powering the magnets prior and during operation at the ion ring of the JLEIC facility. The ARL group has developed a reliable and easy-to-operate design of a splice joint system,
for the CIC conductor of the JLEIC superferric magnets. The design, consists of a two halves of helium-rated flanges containing two copper matrices, responsible for the positioning and cooling of the superconductors. In this system, a CIC conductor is inserted and secured to one of the flanges. A small portion of the outer tube is removed, leaving the superconducting wires exposed. Then the superconductors are flared out and confined into narrow channels embedded into the front side of a thin wall copper matrix, located at the centre of the flange. The back side of the matrix, is in direct contact with the liquid helium flow, coming from the CIC conductor’s inner channel, providing conduction cooling to the superconductors. Once the conductors are flared and locked in position at the front side of the thin wall copper matrix, a thin film of cryogenic solder is applied to the outermost surface of the conductors. Then the two halves are clamped together, aligning the superconductors one in front of the other, see figure 3a). To detach the joint, a set of high power (8 x 250 W) heat cartridges embedded at the back side of the copper matrix (Figure 3b) provide the required heat to rapidly melt the eutectic solder (474 K in 40 s), allowing for an easy detachment of both halves of the splice joint. This design provides a low resistance < 2x10-9 ohms joint, with a non-interruptive flow of cryogenics and easy to assembly procedure, Figure 3b).

Figure 3. Splice Joint design for JLEIC CIC conductor. Figure 3a), shows the two halves of the splice joint with the NbTi wires flared and locked in place in the copper matrix, depicted in white. For illustration purposes, a PLA 3D printed version of the splice joint is used. Figure 3b), shows the back side of the thin wall copper matrix, and the heating and water cooling system (serpentine) of the heat cartridge, required to increase/decrease the temperature of the eutectic solder to the melting point.

5. Conclusions
The ARL in collaboration with ATC has patented and developed a new Cable-In-Conduit technology suitable for high current applications. Current efforts have recently led the ATC group to complete the CIC production facility capable of producing long-length segments of CIC conductors, as required by the 3 T dipoles for the proposed JLEIC collider, and other applications. The CIC production facility is designed to produce costumed made CIC conductors, comprising NbTi, Nb3Sn, MgB2 and Bi2212 conductors. Its capabilities are not limited to the production of single layer CIC, nor the dimension of each of its components, allowing a wide range of feasible products for diverse applications. The manufacturing procedure and the development of the technology required to produce complex windings was described, along with an easy-to-operate design of a low-resistance splice joint.

References
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