Nb_3Sn CIC for Outsert Windings of Hybrid Dipoles

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***Abstract*— A Nb_3Sn Cable-in-Conduit (CIC) conductor is being developed for use in the outsert winding of a hybrid dipole for a future hadron collider. The CIC provides several significant benefits for use in a hybrid dipole: Lorentz stress is managed at the cable level, flared ends can be formed with small bend radius with no degradation to the wires within, and supercritical helium cooling flows through the perforated center tube to provide enhanced wire stability. The Nb_3Sn outsert is heat-treated as an autonomous assembly, then assembled onto a REBCO insert and preloaded within the dipole yoke structure. The cable and coil technologies of the Nb_3Sn CIC are described, and its incorporation in the 18.5 T hybrid dipole is presented.**

***Index Terms*—cable-in-conduit; hybrid dipole; Nb_3Sn**

I. Introduction

THE cost and performance of a hadron collider are dominated by the magnetic field strength and field homogeneity of the rings of superconducting magnets that channel the colliding beams. That has motivated an effort over the past two decades to develop technology for dipoles with magnetic field B >16 T [1].

Extending dipole field beyond 16 T entails utilizing high-temperature superconductors REBCO or Bi-2212. Those superconductors are extremely expensive, and practical designs must utilize a hybrid design in which a Nb_3Sn outsert winding is used in the regions where B <11 T, and a REBCO or Bi-2212 insert winding is used where B > 11 T.

Hybrid dipoles pose several formidable challenges:

- Lorentz stress is huge, and it accumulates through the thick windings to a level that could demage the superconducting wires: how to manage stress between the outsert and insert?
- The windings must be flared with small bend radius at the ends to accommodate the beam tube: flaring Nb_3Sn Rutherford cable in the hard-bend direction tends to unlock the cable and cause premature quench [2], and REBCO CORC cable [3] is stiff for forming to small-radius bends.
- The Nb_3Sn outsert must be heat-treated at 665 C, but a REBCO insert must *not* be heat-treated: how to fabricate the flared windings separately and then assemble them?
- The Nb_3Sn outsert winding must operate at <5 K, but the REBCO insert winding could operate at >20 K. If we could design the structure between the insert and outsert to provide adequate support but sufficient thermal isolation to accommodate the two temperatures, the cryogenic cooling to remove heat from synchrotron radiation and beam losses would be reduced >tenfold.

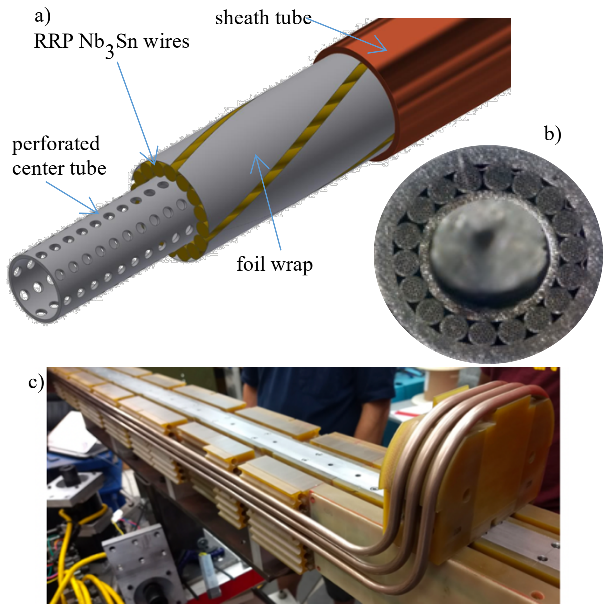

Fig. 1. SuperCIC: a) cutaway showing cable structure; b) cross-section of Nb_3Sn SuperCIC cable; c) flared-end NbTi SuperCIC winding.

Those challenges motivated us to design an 18.5 T hybrid dipole [4] in which the insert is a conformal winding of REBCO tape-stack cables and the outsert utilizes a Nb_3Sn cable-in-conduit (CIC). The insert winding is configured so that the faces of all REBCO tapes are parallel to the lines of force (so that all tapes operate with maximum critical current), and the tapes within the tape-stack cable are maintained under compression so that current-sharing naturally re-arranges the current distribution within each cable as winding current is ramped from injection to collision. The insert design is presented in a companion paper [5].

The CIC cable (dubbed SuperCIC) for the outsert utilizes a design that was furst designed in 2017 by a collaboration of Accelerator Research Lab (ARL) and Accelerator Technology Corporation (ATC). It was conceived for the NbTi windings of a 4 T dipole for the EIC design proposed by Jefferson Lab [6]. In the very different context of a Nb_3Sn outsert winding of a high-field dipole, SuperCIC offers solutions to the above challenges,

This work was supported by DOE SBIR project DDE-SC0021688 and DOE research grant to Texas A&M University: DE-SC0023028. *(Corresponding author: Gareth May.)*

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Fig. 2. CIC manufacturing process at ATC: a) 24-spool stranding machine; b) SS foil over-wrap; c) pulling the long-length cable through the sheath turbe; d) drawing of sheath onto cable.

as will be seen in the following sections. In 2017 ARL and ATC collaborated with Hypertech to develop short-length specimens of Nb_3Sn-based CIC [7].

II. SuperCIC

Superconducting cable-in-conduit was originally proposed by Hoenig [8] and has been used for many years: in supercon-ducting magnetic energy storage (SMES) [9,10,11], in the windings for magnetic confinement fusion [12], and by Miller in outsert windings for hybrid solenoids [13]. For those applications CIC provides a robust basis for high-current cable (typically 20-50 kA) with large bend radius.

Kovolenko *et al*. pioneered the use of CICC for the windings of accelerator dipoles and used them successfully in the Nuclotron dipole [14,15], in which a single layer of NbTi wires onto the outer surface of a tube ('cable-outside-conduit').

A. SuperCIC Fabrication

Fig. 1a shows the internal structure of the SuperCIC cable. A single layer of 24 Nb_3Sn strands is cabled with a twist pitch around a perforated thin-wall center tube. An over-wrap of 316 SS tape is applied with the opposite pitch, to provide a slip surface between the wires and the 90/10 CuNi sheath. The cable is pulled through a CuNi alloy sheath tube as a loose fit, and the sheath tube is drawn down just so that the wires are compressed against the center tube and immobilized. Fig. 1b shows a cross-section of an 18-wire SuperCIC cable made using 0.85 mm dia. RRP Nb_3Sn wire. Fig. 1c shows the flared-end of the innermost layer of a 3-layer block SuperCIC dipole winding for our earlier 4 T NbTi dipole.

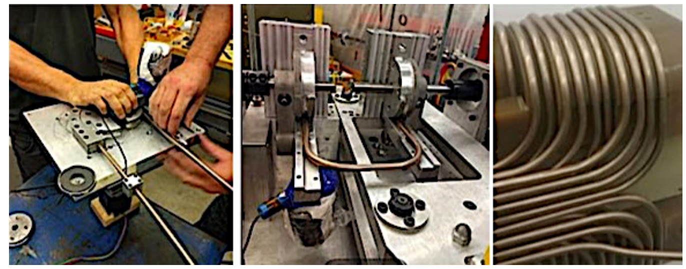

Fig. 3. (a) Creation of the U bend in the cable (b) 90 degree bending of the U (c) Assembly of multiple fabricated NbTi cable flared ends [2]

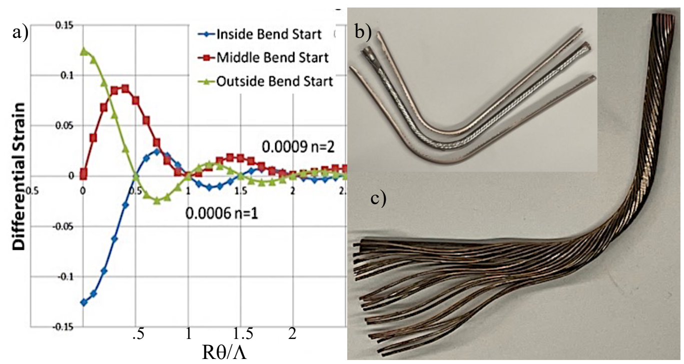

Fig. 4. a) Differential strain among wires that start at the innermost, outermost, and waist locations at the beginning of a bend; b) dissection of cables after bending; c) details showing that registration was retained, no strain among wires.

The cable fabrication procedure was first perfected by hand-forming of the cable on a draw-bench. Once the procedure was perfected, ATC built a long-length fabrication line sequence shown in Fig. 2: a) a 24-head stranding machine is loaded with feed spools of wire, the perforated center tube is fed into the central aperture, and the wires are twist-pitch cabled onto the center tube; b) the cable is spiral-wrapped with 304SS tape to preserve registration; c) the wrapped cable is pulled through a straight long length of sheath tube as a loose fit; and d) the sheath tube is drawn through a die to compress the wires against the center tube.

The perforated center tube provides several benefits in the cable. First, during heat treatment of a Nb_3Sn SuperCIC winding a purge flow of argon gas is sustained to prevent oxidation of the Cu matrix. Second, during cryogenic operation of the dipole supercritical helium (SCHe) is circulated through the tube, and permeates through the perforations to bathe all surfaces of the wires. The enthalpy of the SCHe helps to stabilize against propagation of microquenches. Third, the thin-wall center tube provides a soft-modulus spring so that small deformations of the sheath tube when the winding is operating at maximum Lorentz stress cannot damage the wires inside.

B. Small-radius bends for flared-end windings

A methodology has been perfected with which small-radius bends of 90° and 180° can be formed while retaining the registration of the wires inside and without producing any residual strain on any of the wires.

The twist pitch Λ with which the wires are cabled is chosen to be equal to the arc length of the bends that will be made to form the flared-ends of the winding. For a bend of radius *R*

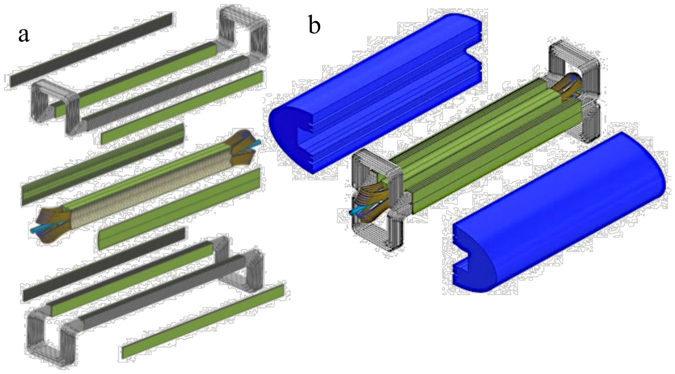

Fig. 5. Blow-up illustration of the winding and assembly of the hybrid dipole. a) The outsert winding is fabricated as two halves while the insert is fabricated; b) The outsert is then assembled with Inconel supports (green) around the insert winding, the flux returns are slid on, and preload is applied.

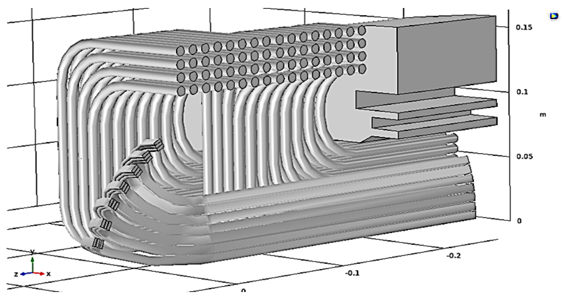

Fig. 6. Cutaway isometric view of the flared-end region of the windings.

through angle θ and a pitch $\Lambda = R\theta/N$, each wire passes around N twists convolutions within the span of the bend. For any integer N, every wire in the cable traverses exactly the same path length within the bend, so no residual strain is produced, Fig 3a shows the residual strain as a function of the twist pitch. Twist pitch optimization resolved a problem of strain degradation that was encountered previously by the INTAS project [16].

Bends are formed using robotic bend tools in which a half-cylinder forming die is rotated around a mating half-torus forming die to form the CIC sheath around the desired-radius bend, while constraining the its outside contour to remain exactly round as it bends to the curvature. In that forming process the die pair deforms the sheath tube (stretching it on the outside of the bend compared with the inside of the bend), but crucially the interior remains locally round throughout the bend. It is necessary to stress-relieve the sheath tube before fabricating the SuperCIC so that its alloy can elastically stretch without cracking during the robotic bend operation.

Three robotic benders are used to form the 3-layer winding shown in Fig. 3c. A planar bender (Fig. 3a) is used to form a pair of 90° bends separated by a distance that is adjusted for each turn to provide the correct separation. A flare bender (Fig. 3b) is used to flare the U-bend by 90°. A compound bender is used to form two 90° bends that are stepped up or down to accommodate the tier-tier step of a barrel wind. The above procedure has been performed successfully to fabricate all turns of a 3-layer, 24-turn winding. The registration and wire integrity in bends has been investigated by carefully removing the sheath tube from a bend (Fig. 4c) examining the registration or wires around the bend, and sectioning wires to look for any evidence of deformation.

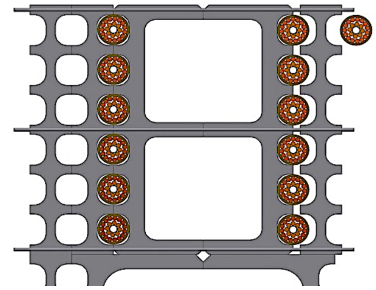

Fig. 7. Multi-channel plates for the structure of the successive layers of the SuperCIC outsert winding.

TABLE 1. MAIN PARAMETERS OF THE 18.5 T HYBRID DIPOLE.

Operating bore field	18.5	T
Series winding current	18.5	kA
Operating temperature	5	K
Bore diameter	30	mm
Stored energy	.577	MJ/m
Inductance	.034	H
Multipoles:	b_2, b_4, b_6, b_8	
18.5 T	-3.5, 5.0, -0.3, 0.05	
1.8 T	-7.9, 2.8, -0.1, 0.03	
Max ave. von Mises stress, deviatoric strain		
REBCO	σ = 200 MPa, ε = .003	
Nb_3Sn	σ = 68 MPa, ε = .003	

All wires remain in registration, and there is no evidence of deformation of any wires.

The prior experiment tests for NbTi and short length Nb_3Sn forms of this CiC showed results of less than 1% current degradation during this manufacturing process [17].

III. 18.5T HYBRID DIPOLE MAGNET

The SuperCIC cable of Fig. 1b is being used for the outsert winding in the development of an 18.5 T hybrid dipole. Fig. 8 shows one quadrant of the dipole, containing a conformal REBCO insert winding and a Nb_3Sn SuperCIC outsert. The insert is a conformal winding of tape-stack cables of REBCO tapes. Its design is the subject of a separate parallel research program [18]. The conformal winding orients all tapes of the insert so that the face of every tape is everywhere closely parallel to the local magnetic field. REBCO has ~3x more current capacity in that orientation, so only 1/3 as many tapes are required in the insert [4]. Using SuperCIC in the outsert makes it possible to manage stress throughout, and to cool all turns in the (thick) winding, and to configure it as an separate winding for the staged assembly required for a hybrid dipole. summarizes the main parameters of the tape-stack REBCO cables for the insert, the SuperCIC cables for the outsert, and an alternative Rutherford cable for an alternative design discussed below.

A. Flared ends; winding of the SuperCIC outsert

The 24-wire SuperCiC has an overall diameter of 9.7 mm. The robotic bend tools can form 90° bends with a bend radius of 6 cm while preserving internal registration of the wires. Fig. 6 shows a configuration of flared ends that can be formed which allows for box ends to be constructed for the hybrid dipole of Fig. 8. The tape-stack REBCO cables can similarly be formed

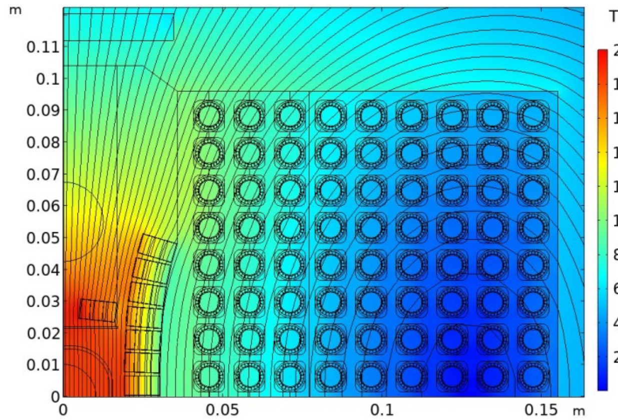

Fig. 8. Quadrant cross-section of 18.5 T hybrid dipole using the Nb_3Sn CIC in the outsert winding with a 30 mm diameter aperture.

with flared ends (Fig. 6) that preserve the favorable orientation of the tapes in the fringing end field distribution.

Each layer of the SuperCIC outsert is barrel-wound onto an Inconel 718 multi-channel extrusion, as shown in Fig. 7. This approach was used successfully with machined G-11 multi-channel plates for the 4 T NbTi CIC dipole (Fig. 1c). For the Nb_3Sn CIC outsert, the Inconel 718 multi-channel plates will be precision-machined so that the multi-shell winding assembly can be heat-treated in final form.

B. Electrical insulation of CIC in the alloy plate structure

Table 2. Structural Properties of the structure materials

Material	Yield strength @ 4K[MPa]	Poisson's Ratio
Ti6Al4V	1700	0.33
Inconel 718	1400	0.27
CTD101	140	0.34

Two forms of electrical insulation are provided to isolate the CIC winding from the side walls of the alloy channel plates. First, the sheathed CIC is coated with a thin ceramic composite [19] that is sufficiently robust to withstand the bend-forming of the flared ends. Second, the SuperCIC is sheathed in S-glass fiber sock. A fine-filament S-2 fiberglass fabric sock was developed for robust insulation of Nb_3Sn cable [20]. The compressed thickness of the fabric is only 55 μm, yet the dielectric strength (300 V turn/turn) is superior to conventional thicker tapes and socks. The sock will be pulled onto each turn of the CIC (see Fig. 11) after its flared ends have been formed so that the sock is not damaged in the bend-forming procedure, and socks for succeeding turns will be overlapped.

C. Assembly of the hybrid dipole; stress management

The insert and outsert windings are designed to be fabricated separately and then assembled as a nested coil and integrated with the flux return core. Fig. 5 illustrates the sequence of steps. First the outsert dipole is fabricated in two halves so that they can be heat treated and then assembled around the insert dipole, then that assembly is compressed by the flux return and loaded. Each of the separate windings is a robust subassembly.

The insert and outsert windings of the 18.5 T hybrid dipole are configured with pier-and-beam stack of multi-channel plates

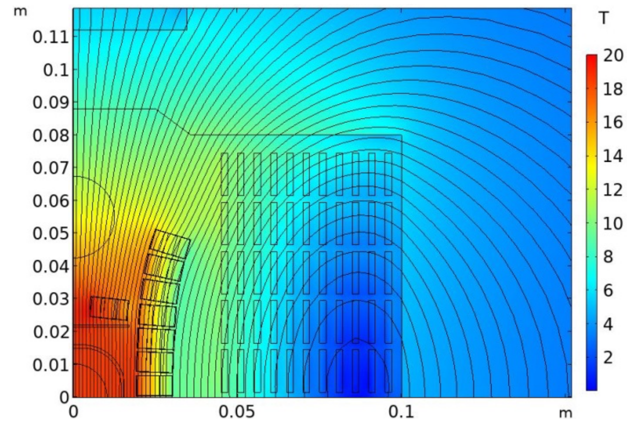

Fig. 9. Quadrant cross-section of 18.5 T hybrid dipole using Nb_3Sn Rutherford cable in the outsert winding; same cable current and bore field as in Fig. 8

TABLE 2. WINDING PARAMETERS IN TWO MODELS OF HYBRID DIPOLE.

	SuperCIC	Rutherford	
Operating current I_0	18.5	18.5	kA
Bore Field @I_{max}	18.5	18.5	T
B_{max} in Cable @I_{max}	11.4	11.4	T
Percentage I_o/I_c	84%	84%	
# of wires in Cable	24	35	
Wire diameter	0.96	0.96	mm
Nb_3Sn RRP filaments	108/127	108/127	
Cu/SC	1.17	1.17	
# of cable turns/bore	144	110	
Wire I_c @ 4.2 K 12 T	920	920	A
Operating temp	5	5	K
Total wires/bore	3456	2750	

that intercepts and bypasses the Lorentz stress produced by the windings so that the stress in the actual windings never exceeds the limits for strain damage to the superconducting elements. The structural plates are precision-machined from Inconel 718, which has a cold yield strength ~1400 MPa [21], and the gaps around each sheathed cable in its channel are filled with CTD 101K epoxy. Note from Fig. 10 that the maximum von Mises stress in the channels is ~500 MPa – 36% of the yield strength of the Inconel.

Bordini *et al*. [22] summarized recent measurements of I_c degradation due to transverse strain $\varepsilon_\perp$ in RRP Nb_3Sn wire, and presented recommendations for use in high-field dipoles. Fig. 13(copied from their paper) shows the degradation as a function of $\varepsilon_\perp$. As seen in Fig. 10, the maximum von Mises stress in the wires of the outsert is 50 MPa – no resulting current degradation of I_c. While REBCO begins to suffer around 300 MPa[23]

IV. RUTHERFORD VS SUPERCIC

It has long been believed that there is a strong premium on configuring the windings of a high-field dipole as close as possible to the bore tube to minimize the total quantity of expensive superconductor. Until the present efforts to push to >16 T that wisdom has been to some degree true. But with the daunting challenges summarized in the introduction, it is interesting to re-examine that belief. Fig. 9 shows a quadrant cross-section of a

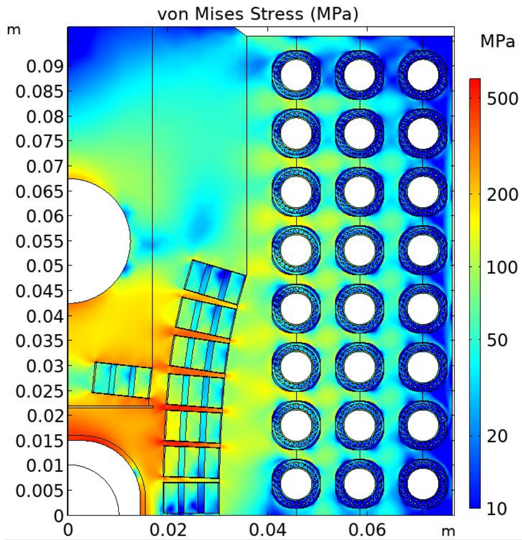

Fig. 10. Distribution of von Mises stress in the hybrid dipole at 18.5 T.

hybrid dipole in which the outsert is configured as a block coil of Nb_3Sn Rutherford cable.

It is directly comparable to CIC-based design of Fig. 8: bore field, same aperture, same conformal REBCO insert, same Nb_3Sn wire. In order to calculating the I_c we used Summers' parameterization because our strain percentage sits around 0.3% [24]. Table I summarizes the parameters of the windings for the two dipoles: the Rutherford-based design requires ~20% less Nb_3Sn than the SuperCIC-based design. While the Rutherford design requires less superconductor, it leaves unresolved isses of stress management, flared ends, and assembling a hybrid.

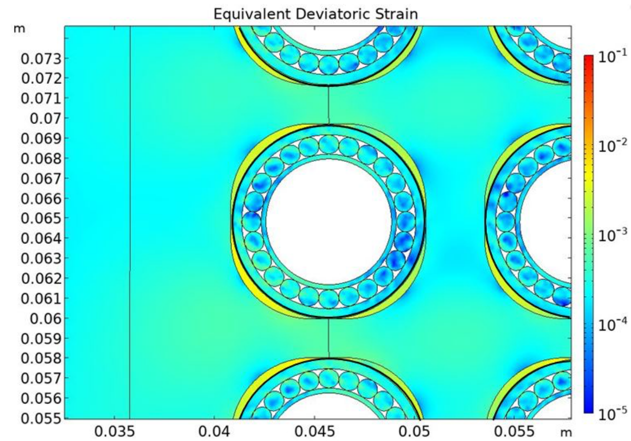

Fig. 11. Simulated deviatoric strain distribution in the CIC winding turn with greatest stress. Insulating S-2 fiberglass sock (black) is pulled over the sheath tube.

V. Plans for testing SuperCIC cable

The Nb_3Sn SuperCIC cable is a new development, and has not yet been tested in long length, in a test winding, and in magnetic field comparable to what will be required for the outsert of the 18.5 T hybrid dipole.

Two modes of testing are planned. First, short lengths of subscale Nb_3Sn SuperCIC have been fabricated and will be tested in the cable test facility at Fermilab [25]. The number of wires will be chosen so the cable I_c ~9 kA in self-field at 4.2K (accessible using the 10 kA power supply and ternary leads of the cryostat). Third, a subscale SuperCIC winding for the outsert of the hybrid dipole will be built, with body length of ~30 cm, assembled in its flux return, and tested in the ATC cryostat as shown in [26].


Fig. 12. Test cryostat, configured to test a short-body model of the 18 T hybrid dipole.

VI. Conclusion

We have designed an 18.5 T hybrid dipole which utilizes a conformal insert winding of REBCO stape-stack cable and a Nb_3Sn Cable-in-Conduit outsert winding. We have built and tested short-length samples of the Nb_3Sn CIC cable. Both windings provide stress management at the cable level, and the CIC outsert limits Nb_3Sn wire strain to <.003. The CIC winding provides cryogen flow throughout. The insert and outsert can be fabricated separately and then assembled in the flux return and preloaded.

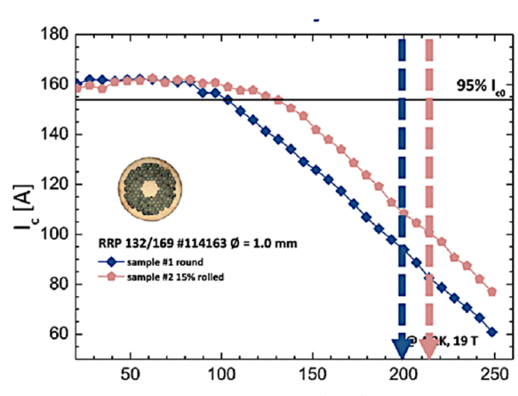

Fig. 13. Degradation of RRP Nb_3Sn wire under transverse stress(Ref. 22).

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