

Nb₃Sn CIC for Outsert Windings of Hybrid Dipoles

G. D. May, J. S. Rogers, Jr., and P. M. McIntyre *Member, IEEE*

Abstract— A Nb₃Sn 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 Nb₃Sn 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 Nb₃Sn CIC are described, and its incorporation in the 18 T hybrid dipole is presented.

Index Terms—cable-in-conduit; hybrid dipole; Nb₃Sn

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 Nb₃Sn 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 damage 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 Nb₃Sn 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.

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.*)

G. D. May is with the Accelerator Research Lab, Texas A&M University, College Station, TX 77843, USA and also with Accelerator Technology Corporation (e-mail: gdmay@tamu.edu).

J. S. Rogers is with the Accelerator Research Lab, Texas A&M University, College Station, TX 77843, USA and also with Accelerator Technology Corporation (e-mail: jsr12e@tamu.edu).

P. M. McIntyre is with the Accelerator Research Lab, Texas A&M University, College Station, TX 77843, USA and also with Accelerator Technology Corporation (e-mail: p-mcintyre@tamu.edu).

Color versions of one or more of the figures in this paper are available online at <http://ieeexplore.ieee.org>.

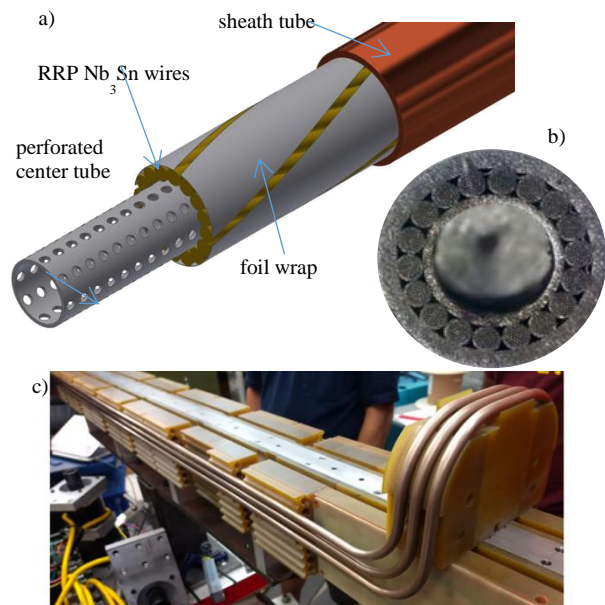


Fig. 1. SuperCIC: a) cutaway showing cable structure; b) cross-section of Nb₃Sn SuperCIC cable; c) flared-end NbTi SuperCIC winding.

- The Nb₃Sn 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 Nb₃Sn 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 > 10 -fold.

Those challenges motivated us to design an 18 T hybrid dipole [4] in which the insert is a conformal winding of REBCO tape-stack cables and the outsert utilizes a Nb₃Sn 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 first 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 Nb₃Sn outsert winding of a high-field dipole, SuperCIC offers solutions to the above

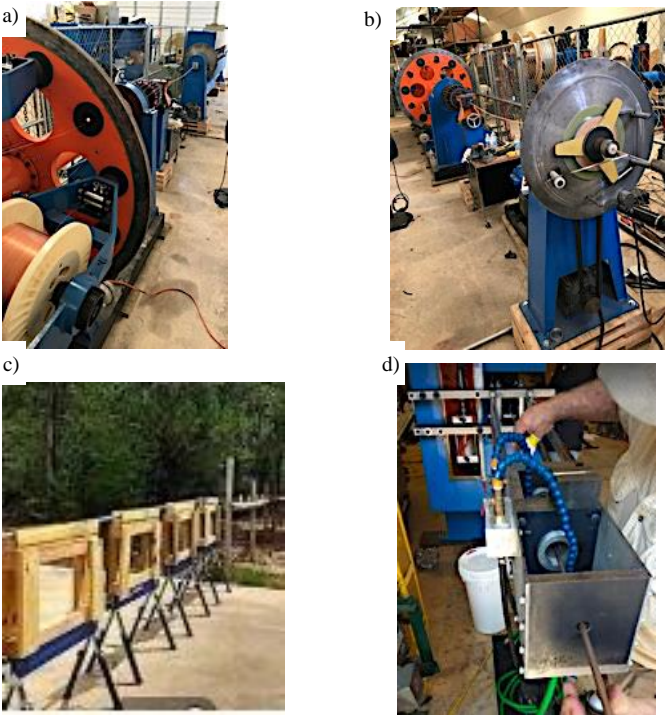


Fig. 2. CIC manufacturing process at ATC: a) 24-spool stranding machine; b) SS foil over-wrap; c) pulling the long-length cable through the sheath tube; d) drawing of sheath onto cable.

challenges, 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 superconducting 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.

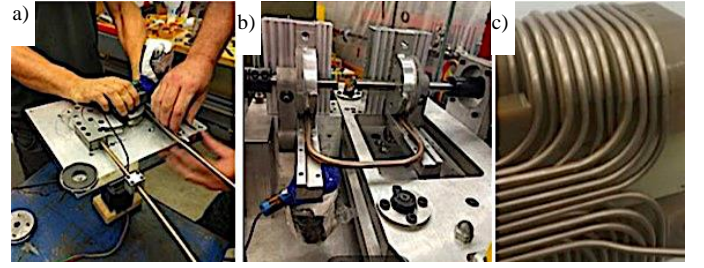


Fig. 3. (a) Creation of the U bend in the cable (b) 90 degree bending of the U (c) Assembly of multiple fabricated NbTi cable flared ends [2]

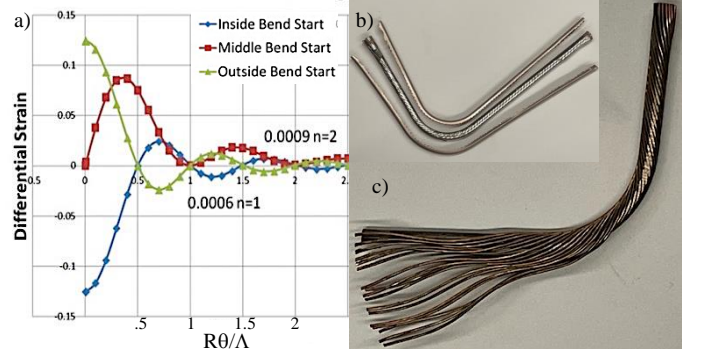


Fig. 4. a) Differential strain among wires that start at the innermost, outermost, and waist locations at the beginning of a bend; b) dissection of cables after bending; c) details showing that registration was retained, no strain among wires.

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

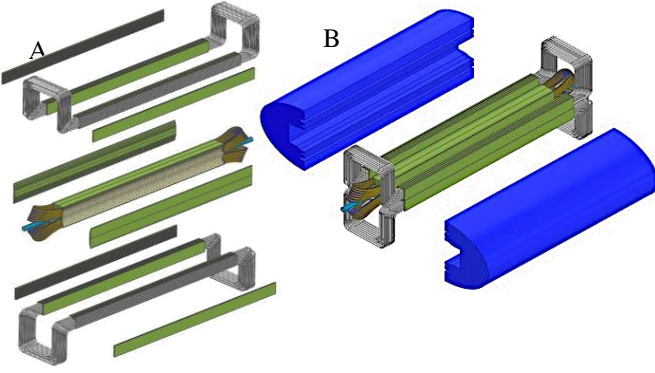


Fig. 5. Blow-up illustration of the winding and assembly of the hybrid dipole. a) The outsert winding is fabricated as two halves while the insert is fabricated; b) The outsert is then assembled with Ti6Al4V supports (green) around the insert winding, the flux returns are slid on, and preload is applied.

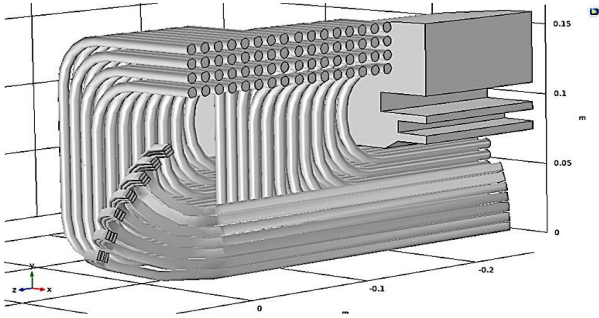


Fig. 6. Cutaway isometric view of the flared-end region of the windings.

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

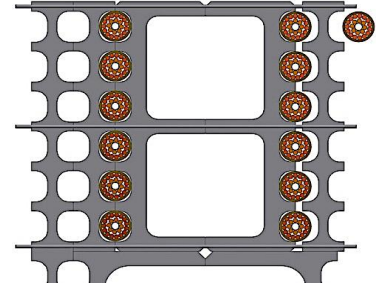


Fig. 7. Ti6Al4V extrusions for the structure of the successive layers of the SuperCIC outsert winding.

wires around the bend, and sectioning wires to look for any evidence of deformation. All wires remain in registration, and there is no evidence of deformation of any wires.

The prior experiment tests for NbTi and short length Nb₃Sn forms of this CiC showed results of less than 1% current degradation during this manufacturing process [17].

III. 18T 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 Nb₃Sn 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 $\sim 3\times$ 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 9.0 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 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 a multi-channel extrusion 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 Nb₃Sn CIC, the multi-channel plates will be fabricated as Ti6Al4V extrusions. Each extrusion is finish-machined to define the pattern of channels that support the cable turns. The Ti extrusion is heat-treated to grow a tough oxide surface layer, which provides

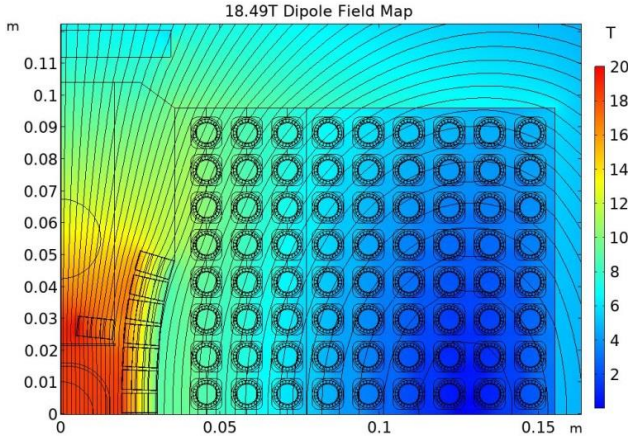


Fig. 8. Quadrant cross-section of 18.5 T hybrid dipole using the Nb₃Sn CIC in the outsert winding with a 30 mm diameter aperture.

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	$\sigma = 200$ MPa, $\varepsilon = .003$	
Nb ₃ Sn	$\sigma = 68$ MPa, $\varepsilon = .003$	

electrical ground-plane insulation. The SuperCIC is sheathed in S-glass fiber sock to provide further insulation. The extrusions stack with precise registration one upon the next, and precisely locate each CIC turn to control field homogeneity.

B. Assembly of the hybrid dipole

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 unto itself.

C. Stress Management

The insert and outsert windings of the 18.5 T hybrid dipole are configured with pier-and-beam structure 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 elements are all made of Ti6Al4V, which has yield strength ~1600 MPa [19], and the gaps around each sheathed cable in its channels is filled with CTD 101K epoxy. Note from Fig. 10 that the maximum von Mises stress in the Ti channels is ~500 MPa – 40% of yield strength.

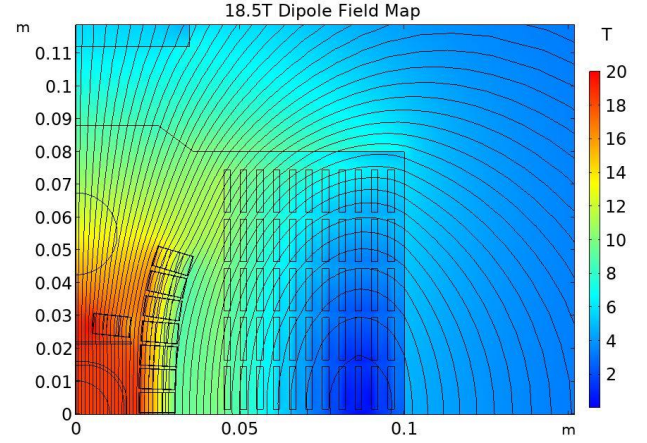


Fig. 9. Quadrant cross-section of 18.5 T hybrid dipole using Nb₃Sn Rutherford cable in the outsert winding; same cable current and bore field as in Fig. 8

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_0/I_c	84%	84%
# of wires in Cable	24	35
Wire diameter	0.96	0.96 mm
Nb ₃ Sn 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

Bordini *et al.* [20] summarized recent measurements of I_c degradation due to transverse strain ε_{\perp} in RRP Nb₃Sn wire, and presented recommendations for use in high-field dipoles. Fig. 11(copied from their paper) shows the degradation as a function of ε_{\perp} . As seen in Fig. 10, the maximum von Mises stress in the wires of the outsert is 68 MPa – no resulting current degradation of I_c . While REBCO begins to suffer around 300 MPa[21]

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 hybrid dipole in which the outsert is configured as a block coil of Nb₃Sn Rutherford cable.

It is directly comparable to CIC-based design of Fig. 8: bore field, same aperture, same conformal REBCO insert, same Nb₃Sn wire. In order to calculating the I_c we used Summers' parameterization because our strain percentage sits around 0.3% [22]. Table I summarizes the parameters of the windings

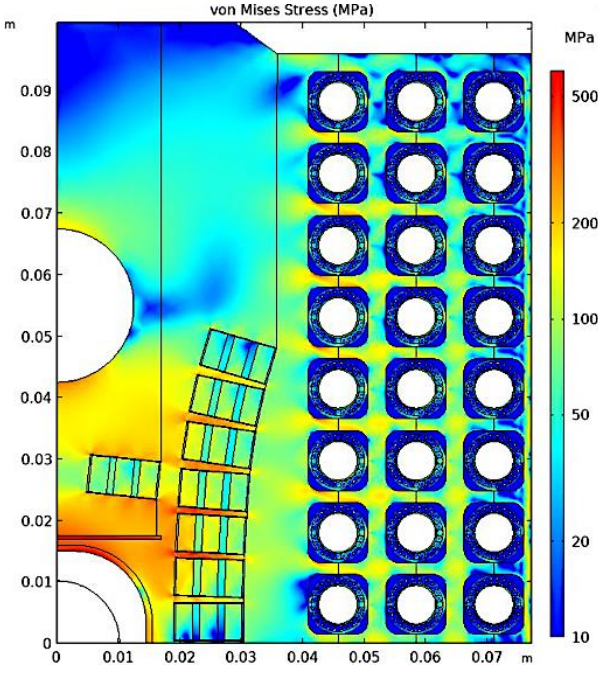


Fig. 10. Distribution of von Mises stress in the hybrid dipole at 18 T.

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 issues of stress management, flared ends, and assembling a hybrid.

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 sub-scale Nb_3Sn SuperCIC have been fabricated and will be tested in the cable test facility at Fermilab [23]. The number of wires will be chosen so the cable $I_c \sim 9$ 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 Fig. 13 [24].

VI. CONCLUSION

We have designed a 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 <0.003 . The CIC winding provides cryogen flow throughout. The insert and outsert can be fabricated separately and then assembled in the flux return and preloaded.

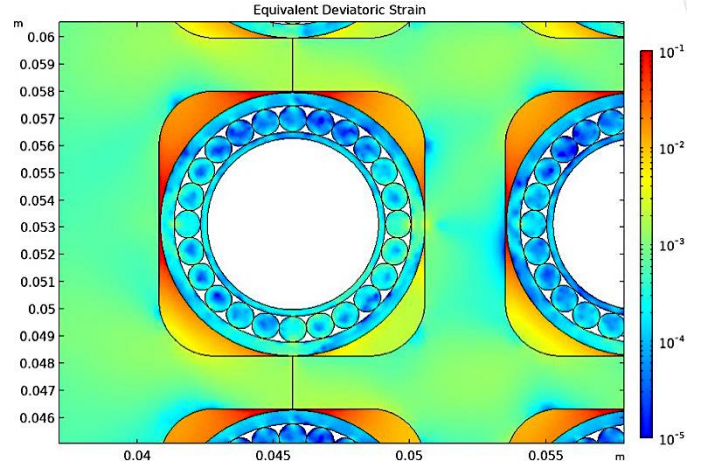


Fig. 12. Simulated deviatoric strain distribution in the CIC winding turn with greatest stress.

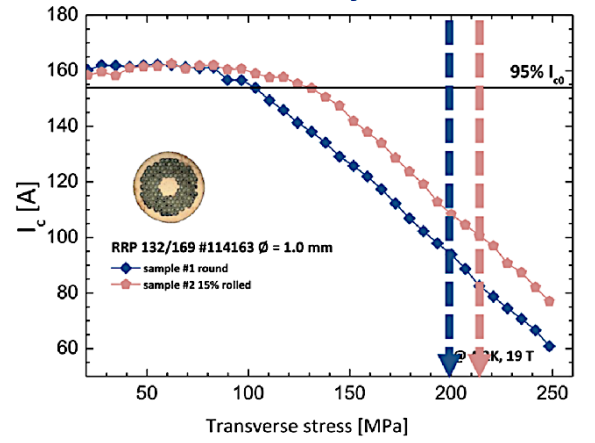


Fig. 11. Degradation of RRP Nb_3Sn wire under transverse strain (from Ref. 20).

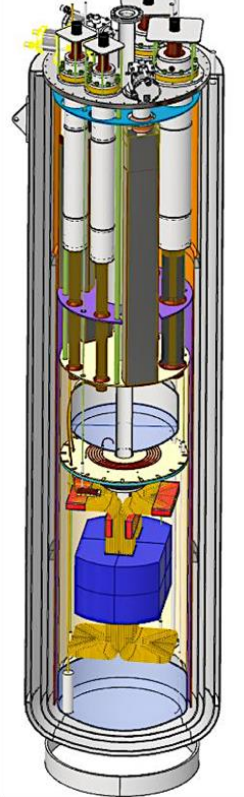


Fig. 13. Test cryostat, configured to test a short-body model of the 18 T hybrid dipole.

REFERENCES

- [1] P. Ferracin, G. Ambrosio, D. Arbelaez, L. Brouwer, Member, IEEE, E. Barzi, L. Cooley, L. Garcia Fajardo, R. Gupta, M. Juchno, V. Kashikhin, V. Marinozzi, I. Novitski, E. Rochepault, J. Stern, A. Zlobin, and N. Zucchi, "[Towards 20 T hybrid accelerator dipole magnets](#)", *IEEE Trans. Appl. Supercond.* Vol.32, No. 6, Sept. 2022, Art. no. 4000906.
- [2] P. Ferracin, B. Bingham, S. Caspi, D. W. Cheng, D. R. Dietderich, H. Felice, A. Godeke, A. R. Hafalia, C. R. Hannaford, J. Joseph, A. F. Lietzke, J. Lizarazo, G. Sabbi, F. Trillaud, and X. Wang, "[Assembly and test of HD2, a 36 mm bore high field Nb₃Sn dipole magnet](#)", *IEEE Trans. Appl. Supercond.* Vol. 19 no. 3, 2009, pp. 1240 -1243.
- [3] V.A. Anvar, K. Llin, K.A. Yagotintsev, B. Monachan, K.B. Ashok, B.A. Kortman, B. Pellen, T.J. Haugan, J.D. Weiss, D.C. van der Laan, R.J. Thomas, M.J. Praksh, M.S.A. Hossain, and A. Nijhuis, "[Bending of CORC cables and wires: finite element parametric study and experimental validation](#)", *Superconduct. Sci. and Tech.* Vol. 31, 2018, Art. no. 315006.
- [4] J. S. Rogers, P. M. McIntyre, T. Elliott, G. D. May, and C. T. Ratcliff, "[Strategies for conformal REBCO windings](#)", *IOP Conf. Ser.: Mater. Sci. Eng.* Vol. 1241, 2021, Art. no. 012029.
- [5] J. S. Rogers, G. D. May, C. D. Coats, and P. M. McIntyre, "Dynamics of current-sharing within a REBCO cable", *proceedings of this conference*.
- [6] P.M. McIntyre, J. Breitschopf, D. Chavez, T. Elliott, R. Garrison, J. Gerity, J.N. Kellams, and A. Sattarov "[Cable-in-Conduit dipoles for the Ion Ring of JLEIC](#)", *IEEE Trans. Appl. Superconduct.* Vol. 29, No. 5, Aug. 2019, Art. no. 4004806.
- [7] P. McIntyre, J. Breitschopf, D. Chavez, J. Gerity, J. Kellams, A. Sattarov and M. Tomsic, "[Block-coil high-field dipoles using superconducting Cable-in-Conduit](#)", *IEEE Trans. Appl. Superconduct.* Vol. 28, No. 3, 1 (2018).
- [8] M. O. Hoenig and D. B. Montgomery, "[Dense supercritical helium cooled superconductors for large high field stabilized magnets](#)", *IEEE Trans. Mag.*, Vol. 11, Issue 2, 1975, pp. 569 - 572.
- [9] J. Zeigler, J. Colvin, R. Huson, R. Rocha, G. Shotzman, P. Michels and S. Peck, "[A test facility for 200 kA SMES/ETM conductors](#)", *IEEE Trans. Appl. Supercond.*, Vol. 27, No. 2, 1991, pp. 2395 - 2398.
- [10] H. Hayashi, Y. Hatabe, T. Nagafuchi, A. Taguchi, K. Terazono, T. Ishii and S. Taniguchi, "[Test results of power system control by experimental SMES](#)", *IEEE Trans. Appl. Superconduct.* Vol. 16, No. 2, 2006, pp. 598-601.
- [11] R. M. Schottler, "[Cooling of small SMES system with forced flow supercritical helium](#)", *Cryogenics* Vol. 34, No. 10, 1994, pp.825-831.
- [12] L. Muzzi, "[Cable-in-conduit conductors: lessons from the recent past for future developments with low and high temperature superconductors](#)", *Superconduct. Sci. and Tech.* 28, 2015, Art. no. 053001.
- [13] J. R. Miller, M. D. Bird, S. Bole, A. Bonito-Oliva, Y. Eyssa, W. J. Kenney, T. A. Painter, H.-J. Schneider-Muntau, L. T. Summers, S. W. van Sciver, S. Welton, R.J. Wood, J.E.C. Williams, S. Bobrov, Y. Iwasa, M. Leupold, V. Stejskal and R. Weggel, "[An overview of the 45-T hybrid magnet system for the new National High Magnetic Field Laboratory](#)", *IEEE Trans. Appl. Superconduct.* Vol. 30, No. 4, 1994, pp. 1563-1571.
- [14] A. D. Kovalenko, A. Kalimov, H. G. Khodzhbagiy, G. Moritz, C. Muhle, "[Optimization of a superferric Nuclotron type dipole for the GSI fast pulsed synchrotron](#)", *IEEE Trans. Appl. Superconduct.* 12, 1, March 2002, pp. 161-165.
- [15] A. M. Baldin, N. N. Agapov, S. A. Averichev, A. M. Donyagin, E. I. D'yachkov, H. G. Khodzhbagiy, A. D. Kovalenko, L. G. Makarov, E. A. Matyushevsky and A. A. Smirnov, "[Superconducting fast cycling magnets of the Nuclotron](#)", *IEEE Trans. Appl. Supercond.* Vol. 5, No. 2, 1995, pp. 875-879.
- [16] V. E. Sytnikov, V. S. Vysotsky, A. V. Rychagov, A. V. Taran, G. Moritz, M. Kauschke, E. Fischer, S. A. Egorov, I. Y. Rodin, V. E. Korsunsky, L. Bottura, and M. N. Wilson, "[Development and test of a miniature novel cable-in-conduit conductor for use in fast ramping accelerators with superconducting magnets](#)", *IEEE Trans. Appl. Supercond.*, Vol. 16, No. 2, 2006, pp. 1176-1179.
- [17] D. Chavez, *Design and development of Cable-in-Conduit superconductor technology for the magnets of the future Electron-Ion Collider*. Ph.D. dissertation (2018). Universidad de Guanajuato
- [18] J. S. Rogers, G. D. May, C. D. Coats, and P. M. McIntyre, "Dynamics of current-sharing within a REBCO cable", *proceedings of this conference*.
- [19] Nagai K., Yuri, T., Ogata T., Umezawa O., Ishikawa K., Nishimura T., Mizoguchi T., & Ito Y. (1991). "[Cryogenic Mechanical Properties of Ti6Al4V Alloys with Three Levels of Oxygen Content](#)". *Isij International – ISIJ INT.* 31.882-889.10.2355/isijinternational.31.882.
- [20] B. Bordini, C. Senatore, M.Dhallé "[Specifications for Conductors and proposed conductor configurations: Milestone M5.3](#)" (2018) CERN report ACC-2018-0015. – section 3.2.2.
- [21] K. Ilin, K. A. Yagotintsev, C. Zhou, P. Gao, J. Kosse, S. J. Otten, W.A.J. Wessel, T. J. Haugan, D.C. van der Laan, and A. Nijhuis, "[Experiments and FE modeling of stress-strain state in ReBCO tape under tensile, torsional and transverse load](#)". (2015) *Supercond. Sci. Technol.* **28** 055006
- [22] L.T. Summers, M.W. Guinan, J.R. Miller, and P.A. Hahn. "[A Model for the prediction of Nb₃Sn Critical Current as a Function of Field, Temperature, Strain, and Radiation Damage](#)"(1991). *IEEE Trans on Magnetics.* Vol 27, No. 2
- [23] E. Barzi, V. V. Kashikhina, V. Lombardoa, D. Turronia, A. Rusya and A. V. Zlobina, "[Commissioning of 14 T/ 16 T Rutherford cable test facility with bifilar sample and superconducting transformer](#)", *AIP Conference Proceedings > Volume 1573, Issue 1*, 2015.
- [24] C. D. Coats, J. S. Rogers Jr., and P. McIntyre, 'Design of a helium-free test cryostat for superconducting wires, cables, and windings', *proceedings of this conference*.