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2-layer Cable-in-Conduit for Hybrid-Coil Magnets

J Breitschopf[1], D Chavez[2], T Elliott[3], J Kellams[4], P McIntyre[5], and A Sattarov[2]

[1] Department of Physics, Colorado State University, Fort Collins, CO 80523 USA

[2] Institute de Physica, Universidad Guanajuato, Leon, GTO 37150 Mexico

[3] Accelerator Technology Corporation, 9701 Valley View Drive, College Station, TX 77845 USA

[4] Lockheed Martin Aeronautics, 1011 Lockheed Way, B601, Palmdale, CA. 93599 USA

[5] corresponding author: Peter McIntyre, Department of Physics, Texas A&M University, College Station, TX 77845 USA p-mcintyre@tamu.edu

Abstract. Recent results are reported in the development of 2-layer cable-in-conduit (SuperCIC) that is designed for use in hybrid-coil magnets. SuperCIC preserves the full performance of the individual wires, and can be formed into flared-end windings for dipoles into layer-wound toroids and solenoids for hybrid windings for tokamaks. The structure of the SuperCIC windings is designed to accommodate winding and heat-treating sub-windings of Bi-2212, Nb3Sn, and NbTi separately and then assembling them and preloading in the magnet.

1. Introduction

Ever-higher magnetic field is desired for proposed hadron colliders, tokamaks, and similar applications. Each of the superconductors that has been rendered into practical wire has an upper limit to the magnetic field that immerses the winding: NbTi is limited to ~8 T, Nb_3Sn is limited to ~15 T, and only the Bi-2212 and REBCO and Bi-2223 can operate at higher fields. At the same time the superconductor cost increases dramatically for each succeeding step in operating field: ~\$1/kA-m for NbTi [1], ~\$5/kA-m for Nb_3Sn, and ~\$100/kA-m for Bi-2212 and Bi-2223, and considerable more for REBCO [2]. There is therefore a strong motivation to develop hybrid magnet technology, in which the winding is segmented into sub-windings of the respective superconductors in which the field at each superconductor conductor is within its field range.

Hybrid windings have long been used successfully for superconducting solenoids, Nb_3Sn/NbTi assemblies for many years [] and recently for NMR spectrometers [3]. The geometry of a solenoid accommodates hybrid windings naturally, since the sub-windings are configured as concentric cylindrical shells, each with its own stress shell to support Lorentz forces.

The cable technology used in all collider dipoles is Rutherford cable [4], shown in Fig. 1a. The high-current windings for the toroids and solenoids of tokamaks and most windings for superconducting magnetic energy storage (SMES) utilize the 'cable-of-ropes' CIC shown in Fig. 1b.

Hybrid windings with both Rutherford cable and CIC pose major challenges for fabrication, assembly, stress management, and magnetization effects on field homogeneity. NbTi and REBCO sub-windings do not require heat treatment, but Nb_3Sn sub-windings require heat treatment in final form to 650 C in inert gas, and Bi-2212 sub-windings require heat treatment in final form to 890 C in a gas mixture of 49 bar N_2 +1 bar O_2. Nb_3Sn and Bi-2212 sub-windings are fragile after heat treatment and so assembly of sub-windings is challenging. Lorentz forces within the winding increase ~B^2 and would cause strain damage in Nb_3Sn or Bi-2212 with B > 15 T unless the Lorenz stresses on inner windings were

intercepted and bypassed past the outer windings. Lastly REBCO tapes have much larger effective filament size than NbTi or Nb$_3$Sn, yet they must be used in the highest field region of the winding which is closest to the high-field region of a collider dipole. Persistent currents develop in the filaments and would generate significant multipole errors for high-field collider dipoles. In light of the above challenges, no hybrid windings have yet been built for either dipole or toroid applications.

In recent years CERN has examined the possibility of doubling the energy of LHC by replacing the 8 T magnet ring by a >16 T ring [5,6,7] – HE-LHC, and the larger vision of a 100 TeV hadron collider – FCC-hh [8]. Superconducting dipole R&D efforts are progressing at a number of laboratories worldwide [9]. All of the designs under development utilize Rutherford cable in winding geometries of cos θ, block-coil, canted cos θ, and common-coil. All designs face a number of daunting challenges: how to manage Lorentz stress within the thick windings; how to configure the ends of each turn to accommodate the beam tube yet provide a compact stress support; how to integrate hybrid windings that would minimize the quantity of the most expensive superconductors.

Also in recent years there has been growing interest in developing fusion tokamaks with stronger toroidal field at the plasma radius and more compact geometry than that of ITER [10]. The interplay of parameters that govern the potential of a tokamak to reach practical breakeven as an energy source has led to designs for a compact spherical tokamak with ~1 m plasma radius and aspect ratio ~2:1. Of particular importance is the overall winding power density J$_{WP}$ (including CIC and structure) [11]. Adopting hybrid windings for a tokamak would require that each sector winding be fabricated as a layer-wound configuration. In the ~40 kA Nb$_3$Sn windings of the ITER toroid there is significant degradation of critical current in the wires of the 'cable-of-ropes' configuration of cable-in-conduit (CIC) [12]. Along the length of any wire in the ITER CIC, there are unsupported regions and regions where adjacent wires are crushed onto one another to make a divot. Both effects significantly reduce critical current in the wires so that J$_{WP}$ is only ~14 A/mm^2. The analysis of Ref. 11 shows that J$_{WP}$ > 70 A/mm^2 will be required for optimum electric power generation and breakeven for power generation.

A collaboration among Texas A&M University (TAMU), Accelerator Technology Corp. (ATC), and HyperTech Research has developed a novel ordered-structure cable-in-conduit (SuperCIC), shown in 5 1c, that specifically address the above challenges [13]. The ordered-structure CIC provides uniform stress support for all wires within the cable, and stress management at the cable level throughout a winding, including the flared ends. It accommodates separate fabrication and heat treatment of sub-windings, and assembly and preload of assembled windings.

The initial development of the CIC was done using one layer of NbTi wire for use in a 3 T large-aperture dipole [14] for the arcs of the proposed electron-ion collider JLEIC [15]. Then a 2-layer NbTi CIC (Figure 1d) was developed for use in a 6 T dipole [16], shown in Figure 4, to double the ion beam energy for JLEIC [16].

This paper reports recent development of 2-layer SuperCIC using Nb$_3$Sn and Bi-2212 wire to provide a basis for hybrid-coil dipoles and tokamaks with bore fields >16 T.
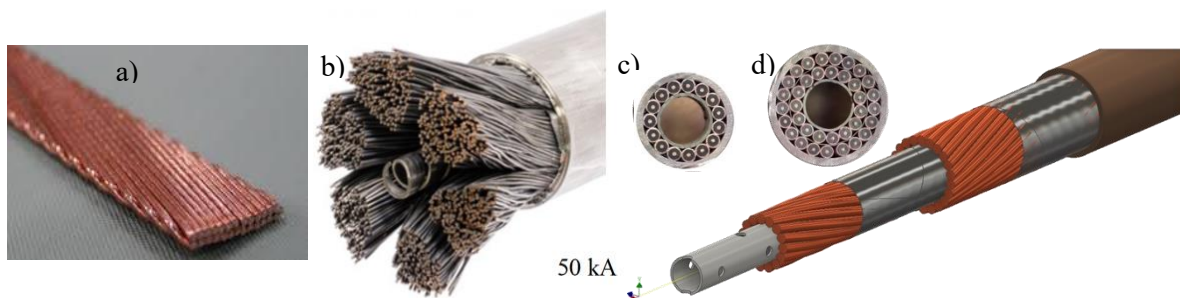

Figure 1. Cables used in superconducting magnets (to same scale): a) Rutherford cable is used in superconducting dipoles; b) 'cable-of-ropes' CIC is used in toroids and solenoids for tokamaks and energy storage; c) single-layer SuperCIC was developed the arc dipoles of JLEIC; d) 2-layer SuperCIC is being developed for use in high-field hybrid-coil dipoles, toroids, and solenoids. The 2-layer SuperCIC and ITER CIC are shown to same scale, with same operating current.
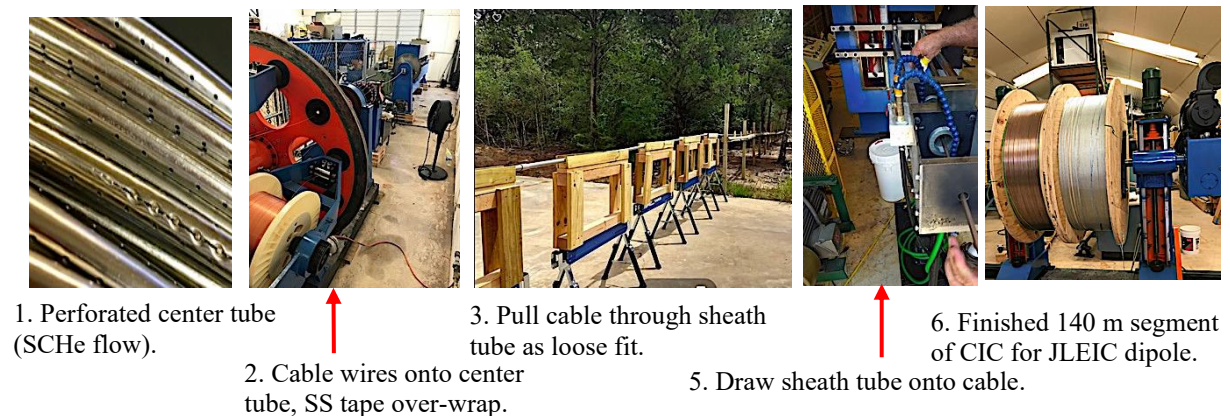
1. Perforated center tube (SCHe flow).

2. Cable wires onto center tube, SS tape over-wrap.

3. Pull cable through sheath tube as loose fit.

5. Draw sheath tube onto cable.

6. Finished 140 m segment of CIC for JLEIC dipole.

Figure 2. Fabrication procedure for SuperCIC.

2. Two-layer NbTi cable-in-conduit

The single-layer NbTi CIC used in the 3 T JLEIC dipole is formed by cabling wires onto a thin-wall perforated stainless steel (316SS) center tube Fig. 2a) with a twist pitch. The cabling is done using a 24-spool stranding machine, shown in Fig. 2b. Next a spiral over-wrap of SS foil tape is applied, and the cable is inserted in a seamless CuNi sheath tube (Fig. 2c), and the sheath tube is drawn onto the cable (Fig. 2d) to compress all wires against the center tube and immobilize them.

Several innovations were important to the success of the 3 T CIC dipole, each has been adapted for the 2-layer NbTi Super CIC for a 6 T JLEIC dipole, and each is being utilized in developing 2-layer Super-CIC containing Nb_3Sn and Bi-2212 for high-field applications:

2.1. Robotic benders to form the flared ends for dipole windings

The ends of each turn in a dipole must be flared up/down to accommodate the beam tube. The flared ends have presented a focal challenge in most high-field dipole developments. A set of robotic benders has been developed that form a constant-radius bend of the SuperCIC while maintaining the sheath tube to be locally round in transverse profile as it is bent into an arc. This is accomplished using conformal die sets and robotic bend tools shown in Fig. 3a,b. The sheath tube is actually inelastically deformed throughout the bend to maintain its round contour, so that the interior geometry remains benign to the registration of the enclosed superconducting wires.
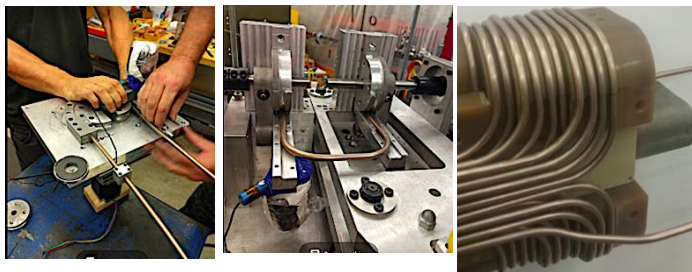

Figure 3. Robotic bending tools used to form a) the 180° bend and b) the 90º saddle bend that comprise the end geometry of each winding turn for a collider dipole; c) a completed 24-turn end region of the 3 T JLEIC dipole.
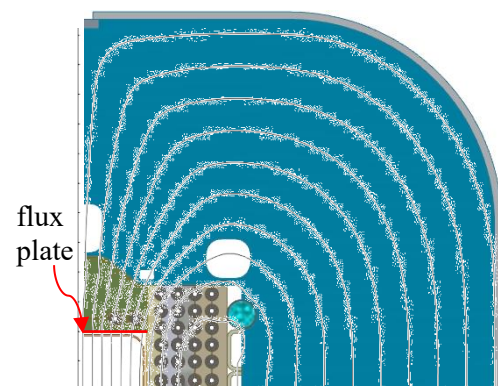

flux plate

Figure 4. Quadrant cross-section of the 6 T CIC dipole: green and gray– G-11 structure elements, blue – steel flux return. Note the steel flux plate.

2.2. Eliminating differential strain in the bends of flared ends
As an end is formed, wires located on the outside of the bend must transit a longer catenary length than those on the inside. The twist pitch of the wires in each layer of cable is chosen to be exactly equal to the mean bend arc length used to form the end windings around a 90º arc. With that choice all wires have exactly the same catenary length around each bend segment, so that no strain is propagated into the straight regions of cable flanking the bend.

With that provision, the wires still must locally shift transversely as each 90º bend is formed as the each wire spirals from inside of the bend to the outside or *vice versa*. To facilitate this transverse shift without residual strain in the wires, it was found necessary to provide a spiral-wound over-wrap of 316 stainless steel (316SS) which provides a slip-surface on the outside of each wire layer. Samples of the cable were formed and bent to a 180º arc with the bend radius required for the dipole winding. Samples were dissected, wires were etched to determine filament breakage, and wires were tested for short-sample current and compared with witness samples. After optimization of the bend tools and of a function-alized multi-layer over-wrap, there was no filament breakage and extracted wires in the bend-formed SuperCIC retained the same short-sample current as witness wires.

In order to achieve the larger cable current required for the 6 T NbTi dipole for JLEIC, it was neces-sary to add a second layer of wires to the SuperCIC cable. This was accomplished using the same stranding machine (Fig. 1b), but significant development was required to achieve the bending properties for the larger and stiffer SuperCIC structure.

A problem arose in tight-radius bending of the 2-layer SuperCIC. The spiral over-wrap was applied on the inner layer, leaving a 1 mm-wide gap between foil turns to provide for liquid helium flow during magnet operation. When segments of the 2-layer SuperCIC were formed into a U-bend and dissected, it was found that the foil of the over-wrap had carved divots into the wires of the inner layer in the region of the bend (Figure 5a). The divots were formed by the edge of each spiral wrap of 316SS foil digging into the wires as the bend was formed. A multi-laminar inter-layer over-wrap was applied between the first and second layers. The inner wires are cabled with a clockwise (CW) pitch, the inner 316SS over-wrap is applied with a counter-clockwise (CCW) pitch and 1 mm gap. Two layers of Cu foil tape are applied with opposite signs of pitch and 1 mm gap: the outer 316SS over-wrap is applied with a CW pitch and 1 mm gap, and the outer wires are cabled with a CCW pitch. Samples of the SuperCIC were formed and bent and then dissected as before. No surface damage was observed on either layer (Figure 5b). Similar procedures were used to validate that wire performance is preserved in the finished 2-layer NbTi CIC.

3. Support structure for CIC winding for a dipole
A support structure was developed to support the inner SuperCIC turns in precise geometry, and to similarly position succeeding SuperCIC layers precisely. It is an epoxy-impregnated assembly of a fiber-reinforced polymer (FRP) support beam with the 10 cm x 6 cm 316SS beam tube, and a set of FRP side plates that support the succeeding layers of the winding as shown in Figure 4.

Figure 5. a) single-layer over-wrap carved divots in the wires of the inner layer; b).a multi-layer over-wrap was applied between inner and outer wire layers, there was no surface damage.
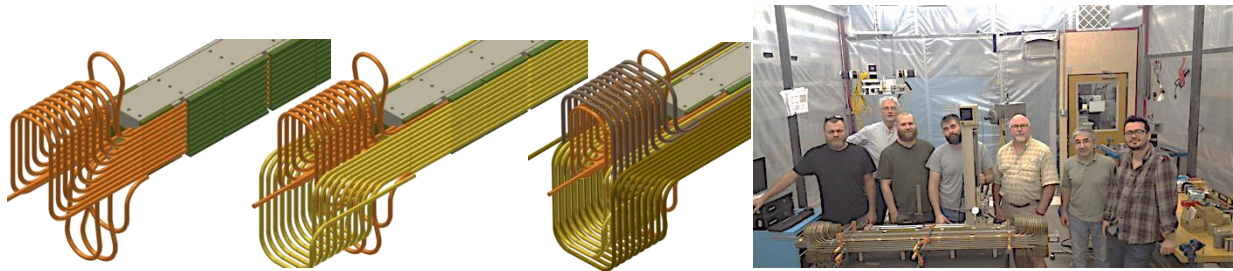
Figure 6. Winding the layers of a CIC block-geometry dipole: a) completed winding of 3 T JLEIC dipole; b) winding strategy for the 6 T CIC winding, showing the stages when successive layers are complete.

The pattern of channels that support and position all SuperCIC turns was precision-machined in the support beam and side plates. The SuperCIC turns for a 1.2 m model dipole were wound, and metrology was performed to measure the r.m.s. precision with which the SuperCIC turns are confined in the positions defined in the magnetic design to produce field homogeneity within the bore tube. The measured r.m.s. position error of individual SuperCIC turns was <.05 mm in the global frame of the dipole, corresponding to random field multipoles a_n, b_n < 1 unit (10^{-4} with reference radius 2/3 of the bore) over the field range from injection to collision energy [14].

Figure 6a summarizes the sequence for barrel-winding the SuperCIC layers of a block-coil dipole. Figure 6b shows a completed winding for the 3-T JLEIC dipole, still mounted on the winding table. The robotic bending tools can be seen suspended above. The total length of the flared-end winding on the 6 T JLEIC dipole is 300 m.

4. Development of 2-layer Nb₃Sn SuperCIC

A collaboration of Texas A&M, Accelerator Technology Corp., and HyperTech Research developed a single-layer Nb_3Sn-based CIC [17]. The development was done using HyperTech's fine-filament tube-process Nb_3Sn wire. In developing the 2-layer NbTi CIC and the Nb_3Sn SuperCIC, a proprietary sensor method was used to detect any filament breakage within strands during the forming of the bends. The method was very useful in optimizing the material choices and pre-heat treatments for the perforated center tube, the foil over-wraps, and the sheath.

Figure 7 shows a 2-layer Nb_3Sn SuperCIC: the cross-section of the tube-process Nb_3Sn wire, the succession of over-wraps, and the completed SuperCIC. U-bend samples have been evaluated by dissection (Figure 8), etching, and short-sample measurement, and there is no filament breakage from the optimized bending process. Testing of sample segments of 2-layer Nb_3Sn in background field is planned.

Figure 7. 2-layer Nb₃Sn SuperCIC: a) HyperTech's tube-process Nb₃Sn wire, b) over-wraps of inner layer 316SS and Cu foil tapes applied; c) outer layers of Cu foil and 316SS tapes applied; d) finished SuperCIC.

5. Development of 2-layer Bi-2212 SuperCIC

Bi-2212/Ag wire is soft and has limited strength. Also the cable must be heat-treated in final shape through a partial melt, during which the metal atoms in the liquid phase are highly mobile in the silver matrix and susceptible to formation of parasitic phases. Also metal atoms from surfaces that contact the wires can diffuse through the silver matrix and form intermetallics within the superconducting cores. Considerable effort was made to develop a combination of under- and over-wrap foils that provide two distinct functions:

- a diffusion barrier foil provides a soft cushion to protect the wires from deformation from the alloy foil layers during bending of flared ends, and prevents metal migration between the wires and the center tube and sheath tube;
- slip-surface foil over-wrap on the outer layer to enable wires to re-arrange configuration as the SuperCIC is bent.

An optimum choice of materials and surface treatments was found that provides those functions, and sample segments of 2-layer Bi-2212 SuperCIC were fabricated and bent with the required 5 cm bend radius. Figure 7a shows the completed SuperCIC. Figure 7b shows an enlargement of the interlayer region showing the under- and over-wrap layers. A specimen of the SuperCIC was carefully dissected to examine all of its components, shown in Fig. 7c. There was slight deformation of the cross-section of the wires, but less than is occasioned in forming of Rutherford cable. There are no divots or other damage to any wires.

The 2-layer Bi-2212/Ag SuperCIC will be heat-treated using overpressure processing, in which 50 atm pressure is maintained during heat treatment (including 1 atm partial pressure of O_2). The center tube and sheath tube have been made from Haynes 230 alloy, which is not damaged by exposure to oxygen for periods of hours. The Haynes 230 sheath tube has sufficient strength at 870 C to serve as a 50 atm pressure barrier. Flow of the high-pressure buffer gas is provided through the center tube, and the perforations in the it and the gaps in the over-wraps enable ready access of oxygen during the periods of partial melt and annealing. This eliminates the need for a high-pressure furnace that puts an entire winding in the 50 atm buffer gas.

6. Cryogenic considerations

Cryogen flow is supported through the center tube. It is anticipated to operate the SuperCIC using supercritical helium (SCHe), so that single-phase flow is assured during operation. Simulations of quench propagation have been made for the high-windings in the dipole and toroid magnets described in the following section. When quench protection heaters are fired at both ends of a 150 m-long

Figure 8. 2-layer Bi-2212 CIC: a) cross-section half-way around a bend; b) detail showing under- and over-wrap foils; separate components from within the 2-layer CIC after dissection.

SuperCIC winding, a maximum temperature of ~100 K is reached and the maximum pressure within the sheath tube is ~60 atm, well within the strength of the Haynes 230 sheath tube.

7. Application of Super CIC for high-field hybrid-coil dipoles

The 2-layer SuperCIC offers an attractive option for the hybrid windings for high-field dipoles [18]. Figure 9 shows a design for a 19 Tesla dipole suitable for use in HE-LHC. It contains sub-windings of Bi-2212, Nb$_3$Sn, and NbTi, each configured as barrel-wound sub-windings with planar vertical boundaries. The divisions are made so that the magnetic field at conductor for each sub-winding is within the limits for that superconductor. The sub-windings are assembled in Russian doll fashion, connected in series, and the size and number of wires in each 2-layer CIC are chosen so that all sub-windings operate at the same fraction of critical current at maximum excitation. Parameters are summarized in Table 2.

Table 1. Main parameters for hybrid-winding 16 T toroid.

R_0	1.2	m
B @R_0	6.7	T
B @coil	17.4	T
A	2.0	
CIC	# strands, wire dia.	
Bi-2212	42 strands, 0.97 mm	
Nb$_3$Sn	42 strands, 0.97 mm	
J_{WP}	140	MA/m^2
I_{op}	28.7	kA
I_{op}/I_c @4.2K	0.7	
# layers	11	
SC(Layers)	Bi-2212 – 5 layers	
	Nb$_3$Sn – 6 layers	

Table 2. Main parameters of a hybrid-winding 16 T collider dipole.

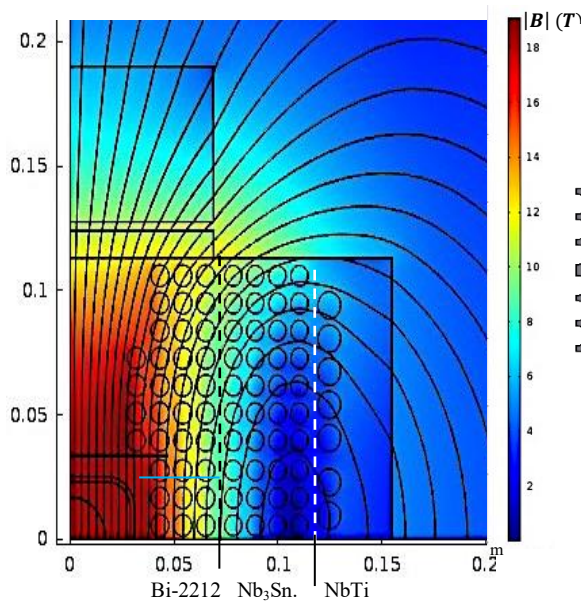| Coil current				28	kA
Operating temp range				4.2-4.6	K
2-layer CIC sub-windings:					
	NbTi:	# layers, turns/bore	1	14	
		# wires, wire dia.	16+22	1.2	mm
		B$_{max}$ in sub-winding		7.3	T
	Nb$_3$Sn:	# layers, turns/bore	4	80	
		# wires, wire dia.	17+23	0.88	mm
		B$_{max}$ in sub-winding		12.4	T
	Bi-2212	# layers, turns/bore	4	68	
		# wires, wire dia.	17+23	0.88	mm
		B$_{max}$ in sub-winding		19.4	T

Figure 9. 19 T hybrid dual dipole. Lines of force and color-code of $|B|$ are shown at full excitation (27 kA).
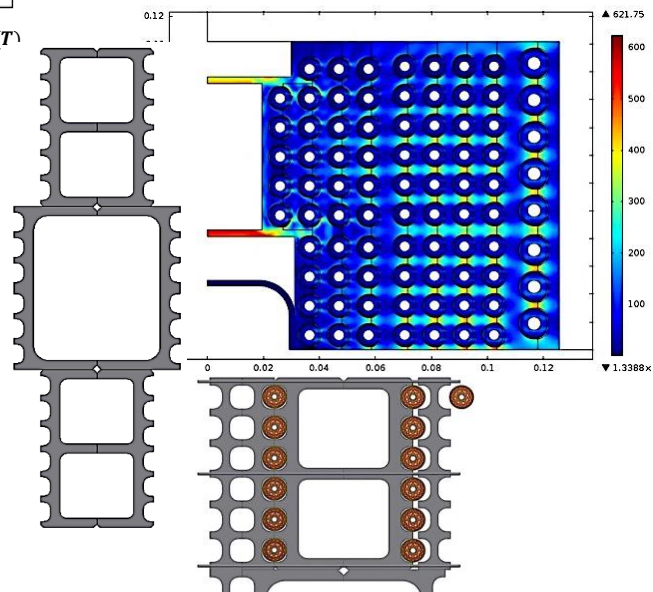

Figure 10. a) Cross-section of the central support structure of the hybrid dipole; b) simulated von Mises stress (MPa) in the windings, c) detail showing first stages of winding the Bi-2212 sub-winding.
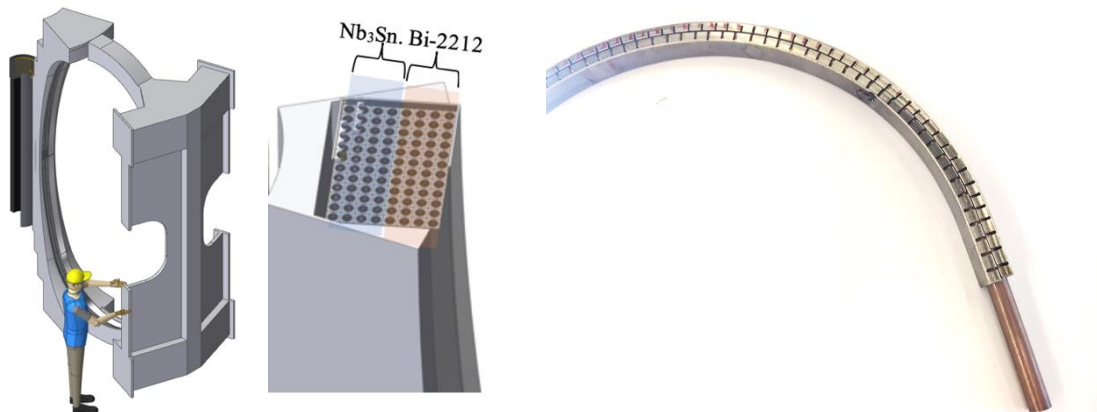
Figure 11. a) 16 T compact tokomak currently under design at PPPL using hybrid 2-layer CIC;
b) detail of one hybrid winding showing the layer-wound sub-windings of Nb_3 Sn and Bi-2212;
c) armor shell for the 2-layer CIC, co-wound with the CIC to form the toroid winding.

The structural elements are made of Ti-6Al-4V alloy, precision-machined to define the positions of all SuperCIC turns, as shown in Fig. 10a. Figure 10b shows a simulation of the von Mises stress distribution within the winding at 18 T bore field. The maximum stress in the sheath tubes is 219 MPa, 38 MPa, and 338 MPa, respectively. The maximum stress in the wires within each turn of SuperCIC appears to be ~half of those values (and so within the limits to avoid strain degradation), but multi-scale modeling of a twisted cable within a conduit with spring-loaded center tube in a winding is extremely difficult and must ultimately be validated in actual model dipoles.

8. Application of SuperCIC for high-field hybrid-coil toroids

Figure 11a shows a conceptual design of an 18 T toroid for a compact spherical tokamak designed by Menard and Brown [11]. It utilizes a layer-wound hybrid winding, containing sub-windings of Bi-2212 (for the inner layers) and Nb_3Sn (for the outer layers), shown in Fig. 11b. The solenoidal winding is made entirely of Nb_3Sn SuperCIC. Each 18 T toroid winding is a layer-wound hybrid in which the outer 4-layer sub-winding (in lowest field) is wound with Nb_3Sn SuperCIC and the inner 4-layer Bi-2212 sub-winding is wound with Bi-2212 CIC. By using the expensive Bi-2212 only in regions where the field in conductor is >14 T, the superconductor cost is minimized and the winding current density is maximized. SuperCIC windings uniquely make it possible to use hybrid-coil toroids, to make separate heat-treats for each sub-winding, and to assemble and preload the windings with precise geometry.
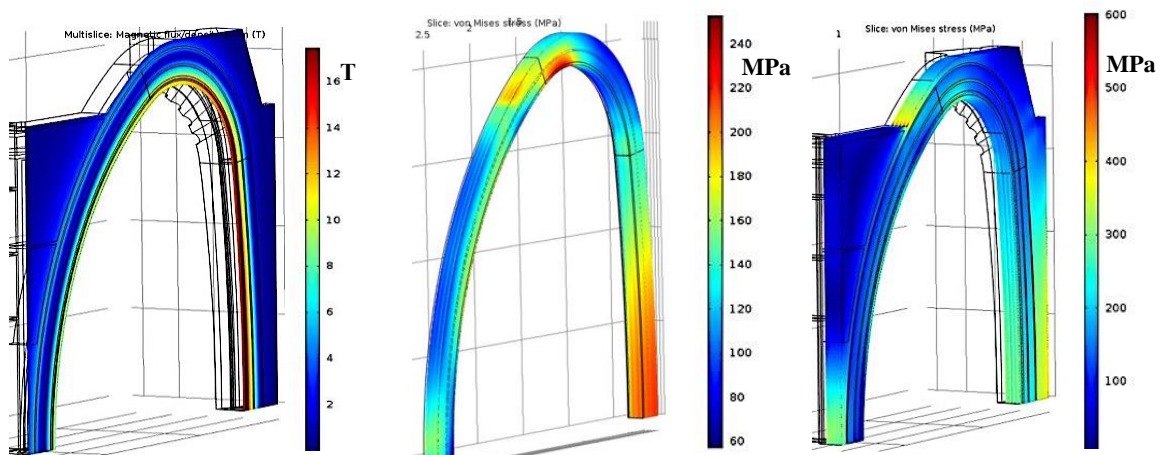

Figure 12. a) Calculated field distribution in a winding module of a 16 T toroid; b) von Mises stress distribution in the co-wound armor of the winding.

The accumulating stress in a large-scale toroid winding must be managed by enclosing the SuperCIC in an armor shell made of high-strength alloy. We have made an innovation for the winding structure, in which the armor shell is configured as two half-shells that enclose the SuperCIC. The three elements - inner half-shell, SuperCIC, and outer half-shell – are co-wound to form the sub-winding of each toroid segment. The armor half-shells are slit as shown in Fig. 11c with a row of kerf-cuts. The half-shells can be bent readily to the required curvature radius without deforming its bulk metal or the SuperCIC. This uses the same principal as a carpenter uses when he saws a row of kerf-cuts part-way through the wooden molding for a stair-case. The hybrid SuperCIC and the kerf-cut co-wound armor are key to achieving $J_{WP} \sim 140$ A/mm^2.

Table 1 summarizes the main parameters of a 16 T toroid for the compact spherical tokamak of Ref. 11 that provides 6.7 T at the plasma radius 1.2 m. Each toroid winding is configured as hybrid sub-windings of Nb$_3$Sn and Bi-2212. shows the calculated stress distribution in the overall structure and in the armor sheaths of the SuperCIC windings. As with the dipole, the maximum stress in the wires is estimated to be <half that in the armor sheath, but accurate simulation requires multi-scale modeling (in progress) and will need to be validated in model windings.

9. Conclusions

A novel approach to superconducting cable-in-conduit is being developed for applications requiring hybrid windings operating at high magnetic field. SuperCIC supports all wires within the CIC so that strain degradation can be prevented even at very high fields. The robust sheath tube provides stress management within each sub-winding. SuperCIC is now available as a product in lengths up to 150 m.

The internal structure permits bending of SuperCIC on a radius ~8x cable radius, which accommodates applications for collider dipoles. A co-wound armor shell can be applied for toroid applications to provide high-strength structure without degradation of the cable during winding. Designs for SuperCIC have been made in prototype for up to 50 kA operating current. SuperCIC hybrid windings appear to offer promising performance in high-field magnets for particle accelerators and for fusion magnetics.

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