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18 T hybrid dipole for an LHC energy doubler

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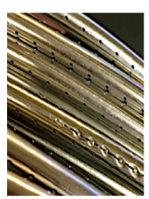
Abstract: We report the design for a hybrid block-coil dual dipole using advanced cable-in-conduit windings. The dipole is designed for use in the arcs of an energy-doubling lattice in the LHC tunnel.
The block-coil design facilitates configuration of hybrid sub-windings of Bi-2212, Nb_3Sn, and NbTi, each operating to the same fraction of critical current. The cryogenics utilizes supercritical helium, operating in the window 4.2-4.6 K. A novel support structure provides robust support and stress management. The three sub-windings can be separately wound and heat-treated and then assembled and preloaded to complete the dipole.

I. Cable-in-Conduit Technology = SuperCIC



1. Perforated center tube (SCHe flow).

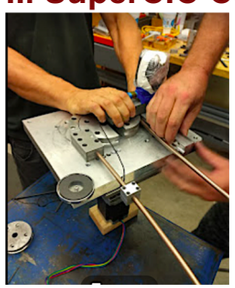
2. Cable wires onto center tube, SS tape over-wrap. Repeat step 2 for layer 2.

3. Pull cable through sheath tube as loose fit.

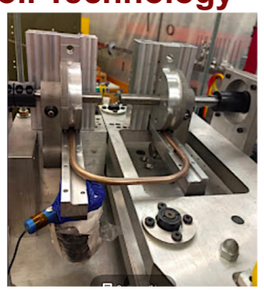
4. Draw sheath tube onto cable to compress wires against center tube.

5. Finished 140 m segment of 13 kA CIC for JLEIC dipole.

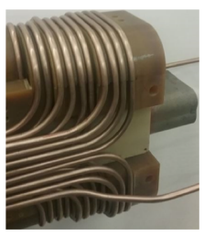
II. SuperCIC Coil Technology



180° U-bend



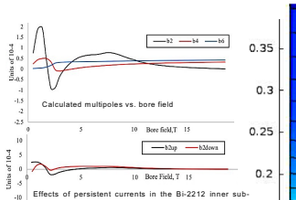
90° flare of U-bend

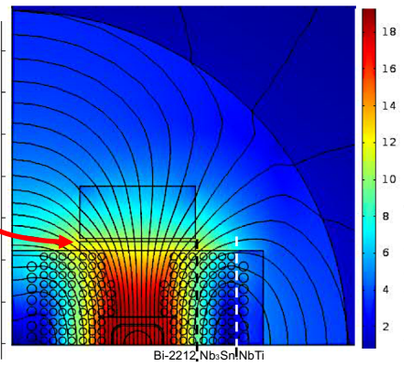


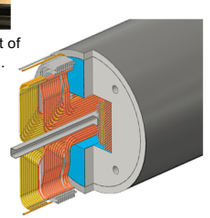
Completed 24-turn CIC winding

ATC manufactures 140 m lengths of SuperCIC – product for sale!

III. 18 T hybrid-coil dual dipole

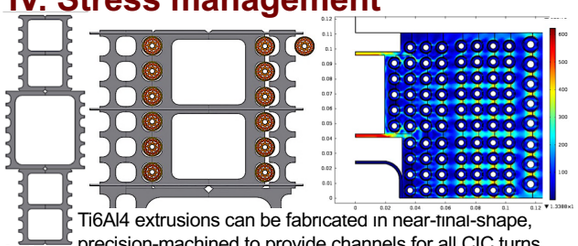






Coil current				28	kA
Operating temp range				4.2-4.6	K
2-layer CIC sub-windings:					
	NbTi:	# layers, turns/bore	1	14	
		# wires, wire dia.	16+22	1.2	mm
		B_{max} in sub-winding		7.3	T
	Nb_3Sn:	# layers, turns/bore	4	80	
		# wires, wire dia.	17+23	0.88	mm
		B_{max} in sub-winding		12.4	T
	Bi-2212	# layers, turns/bore	4	68	
		# wires, wire dia.	17+23	0.88	mm
		B_{max} in sub-winding		19.4	T

IV. Stress management



Ti6Al4 extrusions can be fabricated in near-final-shape, precision-machined to provide channels for all CIC turns.

Stress in wires is everywhere <120 MPa.

V. Developing 2-layer SuperCIC using Nb_3Sn, Bi-2212

NbTi:

It is critically important to interpose a multi-layer spiral wrap over-wrap that provides a slip-surface between inner and outer layers, and also a spiral over-wrap on the outer layer that provides a slip-surface. For 2-layer cable, those issues required a multi-layer over-wrap between wire layers

Nb_3Sn:

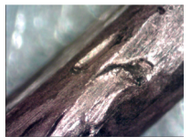
It is critically important to interpose a multi-layer spiral wrap over-wrap that provides a slip-surface between inner and outer layers, and also a spiral over-wrap on the outer layer that provides a slip-surface. For Nb_3Sn it was necessary to adopt different materials for the slip-planes and sheath tube from what worked for NbTi SuperCIC.

Bi-2212:

Bi-2212/Ag wire is soft and has limited strength. Multi-layer over-wrap foils are used to provide two distinct functions: Haynes 214 diffusion barrier foil prevents diffusion between wires and the center tube and sheath tube; slip-surface foil enables wires to re-arrange small-radius ends are formed. The Haynes 233 sheath on the Bi-2212 SuperCIC provides pressure containment during 880 C over-pressure heat treatment – ***no need for high-pressure furnace.***

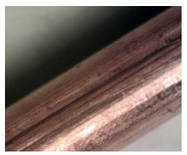
The Bi-2212 and Nb_3Sn sub-windings are fabricated and heat-treated as separate sub-assemblies.
The SuperCIC cables of NbTi, Nb_3Sn, Bi-2212 are powered in series with the same critical current in each sub-winding - ***minimum quantity of CIC turns, expensive superconductor.***

2-layer NbTi CIC



Problem: Damage to wire in U-bend with single-layer over-wrap.

2-layer Nb_3Sn CIC: cross-section half-way around a bend



Solution: No damage using multi-layer functionalized over-wrap.

Total superconductor cross-section, wire cost for one 15 m dual dipole

(present-day commercial quotes for small quantity)

Superconductor	Wire cross-section	Wire cost/m	Wire cost for one dual dipole
NbTi	24 cm^2	$3.60/m	**$119 K**
Nb_3Sn	78 cm^2	$6.56/m	**$1,345 K**
Bi-2212	66 cm^2	$64.77/m	**$11,275 K**

VI. Super-critical He cryogenics

All windings are cooled by flow of SCHe through the 4.2 mm ID center tube in the SuperCIC.
The Nb_3Sn sub-winding has the longest length:

Heat load/bore	1	W/m
SCHe flow	0.3	m/s
Temperature rise	0.3	K
Pressure drop	0.8	bar
PdV work	0.03	W