ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-MOPMP048

LHC DOUBLER: CIC DIPOLE TECHNOLOGY MAY MAKE IT FEASIBLE AND AFFORDABLE*

P.M. McIntyre† and D. Chavez, Texas A&M University, College Station, TX USA
J. Breitschopf, J. Kellams, A. Sattarov, Accelerator Technology Corp., College Station, TX USA

Abstract

There is new physics-driven interest in the concept of an LHC doubler with collision energy of 30 TeV and high luminosity. The cost-driver challenge for its feasibility is the ring of 16 T dual dipoles. Recent developments in cable-in-conduit (CIC) technology offer significant benefit for this purpose. The CIC windings provide robust stress management at the cable level and facilitate forming of the flared ends without degradation. The CIC windings provide a basis for hybrid windings, in which the innermost layers that operate in high field utilize Bi-2212, the center layers utilize Nb_3Sn, and the outer layers utilize NbTi. Cryogen flows through the interior of all cables, so that heat transfer can be optimized throughout the windings.

The design of the 18 T dipole and the 27 kA CIC conductor are presented. Particular challenges for integration in an LHC doubler are discussed.

INTRODUCTION

New developments in the phenomenology of SUSY [1] have led during the past year to a realization that a further increase of collision energy to ~30 TeV would probe substantially the entire parameter space predicted for SUSY. That has motivated CERN to examine the possibility of doubling the energy of LHC by replacing the 8 T magnet ring by a >16 T ring [2-4] – HE-LHC, and the larger vision of a 100 TeV hadron collider – FCC-hh [5]. Superconducting dipole R&D efforts are progressing at a number of laboratories world-wide [6]. 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 extremely expensive superconductors.

A collaboration among Texas A&M University (TAMU), Accelerator Technology Corp. (ATC), and HyperTech Research is developed a novel cable-in-conduit (CIC) that specifically address the above challenges [7]. The CIC windings provide high-strength support for all coil elements, including the flared ends, and bypass Lorentz stress so that it cannot degrade wire performance at high field. The CIC windings naturally accommodate a hybrid block-coil geometry containing sub-windings of Bi-2212, Nb_3Sn, and NbTi that minimizes the amount of expensive high-field superconductor in the sub-windings

* This work was supported by the US Dept. of Energy, grants DE-SC0017205 and DE-SC0015198.
† p-mcintyre@tamu.edu

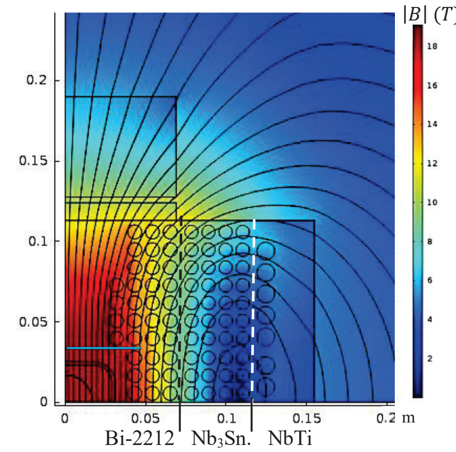

Figure 1: 19 T hybrid dual dipole. Lines of force and color-codes of $|B|$ are shown at full excitation (27 kA).

The block-geometry CIC hybrid winding also facilitates integration of a steel flux plate that suppresses the multipoles from persistent currents at injection field, so that a 30 TeV HE-LHC could accommodate injection at 500 GeV just like as LHC does.

The following sections describe the CIC design and fabrication, the robotic forming of CIC windings, and the magnetic and mechanical design for an 18 T HE-LHC dipole shown in Fig. 1.

CIC FOR HYBRID DIPOLES

The fabrication sequence is illustrated in Fig. 2. The superconducting wires are cabled with a twist pitch around a perforated thin-wall center tube of stainless steel (Fig. 2a). A thin-foil tape overwrap is applied with opposite twist pitch (Fig. 2c). The above sequence is repeated to cable a second layer of superconducting wires for the 2-layer CIC required for the HE-LHC dipole windings. The cable is then pulled through a sheath tube (Fig. 2d), and the sheath tube is drawn down upon the cable (Fig. 2e) to compress the wires against the center tube and immobilize them. Fig. 3a shows a cross-section of a completed 2-layer CIC.

The perforations of the center tube provide fluid connection between the hollow interior of the center tube and the void spaces among the wires. The enthalpy of the liquid helium contacting the wire surfaces provides a valuable stabilization against growth of micro-quenches.

The twist pitch λ of the wires is chosen to be equal to the arc length around a 90° bend on the cable ends with the bend radius R needed for the desired winding geometry: $\lambda = \pi R/2$. With this choice, all wires have the same catenary length around the bend, so no differential strain is produced among the wires.

ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-MOPMP048

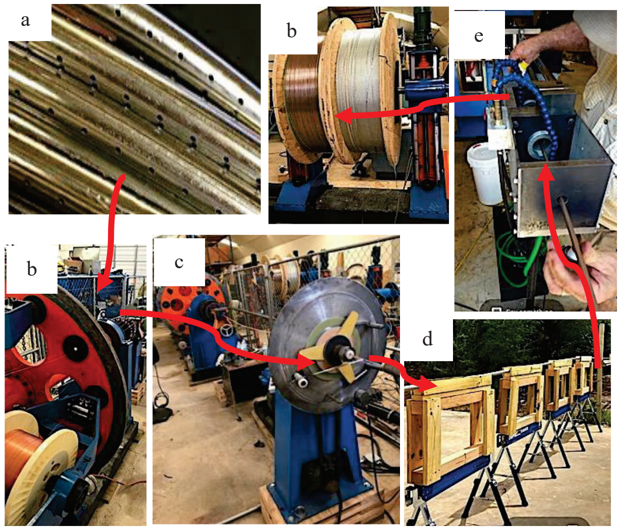

Figure 2: Fabrication of CIC: a) perforated center tube; b) cable superconducting wires onto center tube, c) apply foil over-wrap; d) pull straight 150 m cable through sheath tube with loose fit; repeat b-d for second layer; e) draw sheath tube onto cable.

Motorized bend tools (Fig. 3b) were developed with which saddle bends are formed in two stages: first a pair of 90° bends is formed into a U-bend with the spacing required for a given turn in the dipole winding, then the U-bend is bent 90° to form a flared end for the winding. Extensive experiments have verified that, in a winding with formed ends with R = 5 cm, there is no filament damage within the wires and the critical current of extracted wires is the same as that of witness wire samples [10].

The above procedure was used successfully to fabricate a winding of single-layer NbTi CIC for a short-model of the JLEIC dipole [8]. The winding has three layers of turns, and each turn was successfully formed with saddle-geometry ends. The dipole structure was supported in an assembly of precision-machined beams made of the fiber-reinforced polymer G-11 (Fig. 3d). Registration of the cable elements within the winding was measured using precision metrology. The residual random multipoles that would be produced by registration errors was found to be <0.5 units for all multipoles.

ATC and TAMU collaborated in adapting the cabling machine and draw operations to fabricate 2-layer NbTi CIC (Fig. 3a). ATC has completed a facility that fabricates 1- and 2-layer CIC in 140 m lengths for applications in dipoles, solenoids, and toroids. The robotic bend tools were modified to form saddle-geometry bends in the stiffer 2-layer CIC. ATC is currently developing a 6 T large-aperture dipole for JLEIC that utilizes the 2-layer cable [9]. ARL and ATC are currently collaborating on developing a new set of robotic bend tools that can form the 90° bends for the flared ends shown in Fig. 3c. All of that development is directly applicable to the development of the NbTi, Nb_3Sn, and Bi-2212 2-layer CIC required for the 18 T hybrid dipole.

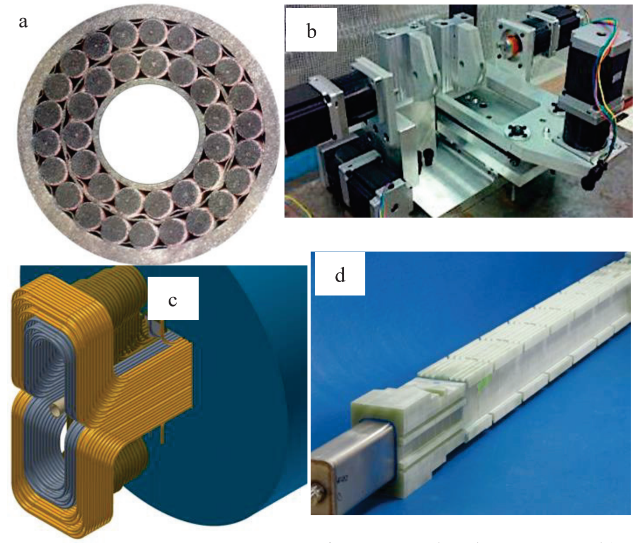

Figure 3: a) Cross-section of 42-strand 2-layer CIC; b) robotic bend fixture used to form the flared ends; end region of the 18 T dipole; b) FRP structural beam for 3 T CIC dipole showing precision channels for inner turns.

NB3SN CIC DEVELOPMENT

TAMU has collaborated with HyperTech to develop single-layer Nb_3Sn-based CIC [7]. The development was done using HyperTech's fine-filament tube-process Nb_3Sn wire. In developing the 2-layer CIC and the Nb_3Sn CIC a proprietary sensor system was used to detect any filament breakage within strands during the forming of the bends. That 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. U-bend samples have been evaluated by dissection, etching, and short-sample measurement, and there is no filament breakage or loss of performance using the optimized bending process.

18 T HYBRID DIPOLE FOR HE-LHC

The hybrid dipole is designed by clustering block-coil windings of Bi-2212, Nb_3Sn, and NbTi in regions of progressively larger distance from the vertical midplane (and correspondingly lower field B_c at the conductor). The separatrix between NbTi and Nb_3Sn is chosen at the contour B_c ~7 T, and the separatrix between Nb_3Sn and Bi-2212 is chosen at the contour B_c ~ 14 T, in each case so that all sub-windings operate with about the same fraction of critical current.

Table 1 summarizes the main parameters of the sub-windings, Fig. 1 shows the field distribution, and Fig. 3c shows the compact end winding configuration. The end winding is contained in a region of 30 cm from the end face of the steel flux return. Note the vertical orientation of the iso-contours of $|B|$ in Fig. 1; this is a unique feature of the block-coil geometry (not at all the case for cos θ, CCT, and common-coil dipoles). It is an essential to optimally partition sub-windings so that they can be separately wound and heat-treated then assembled into the winding.

ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-MOPMP048

Table 1: Main Parameters of 19 T Hybrid Dual Dipole

Bore field @ 5 K s.s.			19	T
Coil current @ 19 T			27	kA
Operating temperature range			4.2 – 5.0	K
Horizontal aperture			6	cm
Stored energy/bore			6	MJ/m
2-layer CIC sub-windings:				
NbTi:	# layers, turns/bore	2	14	
	# wires, wire dia.	16+22	1.2	mm
	B_{max} in sub-winding	6.3		T
Nb_3Sn:	# layers, turns/bore	4	80	
	# wires, wire dia.	17+23	0.83	mm
	B_{max} in sub-winding	11.5		T
Bi-2212	# layers, turns/bore	4	68	
	# wires, wire dia.	17+23	0.88	mm
	B_{max} in sub-winding	19.8		T

Magnetic Design

The magnetic design has been approximately optimized to provide collider-quality field distribution over a field range that extends from 0.5 T (0.5 TeV injection) to 18 T (collision at 15 TeV/beam). Figure 4a shows the calculated multipoles over that range. Multipoles are expressed in dimensionless units (10^{-4}) at a normalization radius of 2 cm.

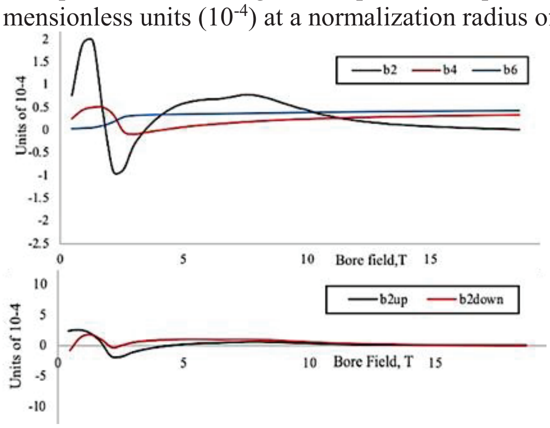

Figure 4: Calculated multipoles vs. field in the 18 T dipole: a) not including, and b) including effects of persistent currents in Bi-2212 inner sub-winding.

Persistent currents (PC) in the wires of the CIC windings produce a pattern of multipoles at low field, and also snap-back when the drive current is switched from discharging to charging. The issue is much worse for inner windings of Nb_3Sn and Bi-2212, which have much larger filament size than NbTi. The CIC dipole contains a novel provision to suppress PC multipoles: horizontal steel flux plates flanking above/below the beam tube (shown in light blue in Fig. 1). This flux plate is un-saturated at injection and imposes a strong dipole boundary condition in the bore tube region. PC multipoles were simulated using magnetization data for multi-filament Bi-2212 wire [10]. The results are plotted in Fig. 4b for the charging and discharging curve. PC multipoles in any other dipole with Bi-2212 or Nb_3Sn windings are at least 20 times larger in any dipole design that does not incorporate flux plates.

Structural Support

All CIC turns are supported within a support assembly consisting of a central beam and a set of plates, each containing precision-machined channels that position and support each turn in its correct position. For the 3 T CIC dipole for JLEIC (shown in Fig. 5d) the structural elements are fabricated from G-11 fiber-reinforced polymer. For Nb_3Sn and Bi-2212 sub-windings a high-temperature material is required.

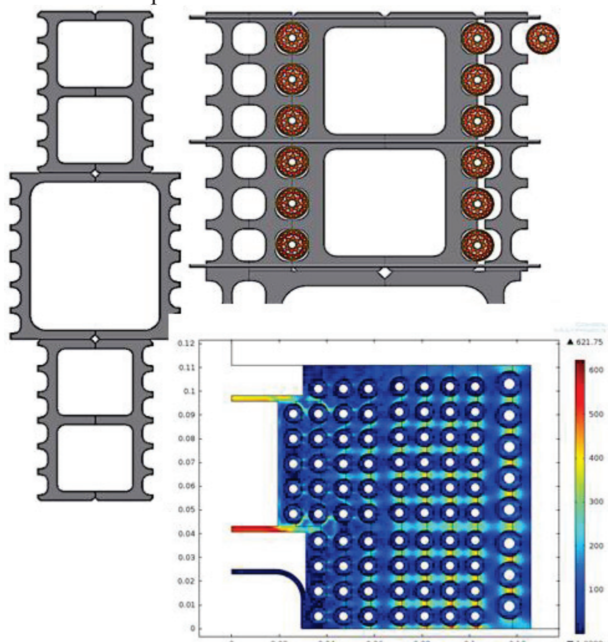

Figure 5: a) Cross-section of the assembly of T16Al4V extrusions that form the central support structure of the hybrid dipole; b) detail showing first stages of winding the Bi-2212 inner sub-winding; c) simulated von Mises stress in the windings and Ti support matrix at 18 T.

We have developed a conceptual design for a titanium-alloy structure that conveys the same benefits for precise geometry and support for the sub-windings of Bi-2212 and Nb_3Sn that must be heat-treated as subassemblies. Plymouth Tube manufactures titanium alloy extrusions for aerospace applications, and they have developed a design for fabrication of a set of extruded shapes for the center structural beam and the channel plates, shown in Fig. 3d. The structure is modeled on the FRP structure that was demonstrated to give robust structure and precise registration for the NbTi windings for JLEIC. Fig.5b shows the simulated von Mises stress in the windings at 18 T. The Ti structure bypasses stress to protect the CIC turns, and it is impervious to the heat treatments for Nb_3Sn and Bi-2212.

CONCLUSIONS

A cable-in-conduit technology has been developed for use in high-field dipoles, and associated coil technology has been developed suitable for an 18 T dipole for HE-LHC. Its properties address all of the major challenges.

ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-MOPMP048

REFERENCES

[1] A. Aboubrahim and P. Nath, "Supersymmetry at a 28 TeV hadron collider: HE-LHC", *Phys. Rev D* 98, 1, 015009 (2018). https://arxiv.org/abs/1804.08642

[2] P. McIntyre et al., "20 T dipoles and Bi-2212: the path to the LHC energy upgrade", Proc. EuCARD Workshop on High-Energy LHC, Malta, Oct. 14-16, 2010. CERN-2011-003. http://arxiv.org/abs/1108.1640

[3] P. McIntyre and A. Sattarov, "On the feasibility of a tripler upgrade for LHC", *Proc. 21st Particle Accelerator Conference*, Knoxville, pp. 611-613 (2006). doi: 10.1109/PAC.2005.1590511

[4] J.L. Abelleira *et al.,* "High-Energy LHC design", *J. Phys.: Conf. Ser.*, vol. 1067, 022009 (2018). doi 10.1088/1742-6596/1067/2/022009

[5] M. Benedikt *et al.,* Future Circular Collider. v3: FCC-hh, CERN-ACC-2018-0058 https://cds.cern.ch/record/2651300

[6] D. Tommassini *et al.,* "Status of the 16 T dipole devel-opment program for a future hadron collider", *IEEE Trans. Appl. Superconduct.*, vol. 28, no. 3, 4001305 (2018). doi 10.1109/TASC.2017.2780045

[7] D. Chavez *et al.,* "Cable-in-conduit using MgB2, Nb3Sn and Bi-2212 for wind-and-react coils", *Proc. Appl. Superconduct. Conf.*, Seattle, Oct. 28-Nov.2, 2018.

[8] P. McIntyre *et al.,* "Cable-in-conduit dipoles for the Ion Ring of JLEIC", *Proc. Appl. Superconduct. Conf.*, Vancou-ver, Sept. 20-27, 2018. https://ieeexplore.ieee.org/iel7/77/6353170/08675432.pdf

[9] P. M. McIntyre *et al.,* "6 T Cable-in-Conduit Dipole to Double the Ion Energy for JLEIC", presented at the IPAC'19, Melbourne, Australia, May 2019, paper MOPMP049, this conference.

[10] C.S. Myers *et al.,* "Reduced magnetization and loss in Ag-Mg-sheathed Bi-2212 wires: systematics with sample twist pitch and length", *IEEE Trans. Adv. Superconduct.,* vol. 25, no.3, 8201604 (2015). doi: 10.1109/TASC.2014.2372614