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6 T CABLE-IN-CONDUIT DIPOLE TO DOUBLE THE ION ENERGY FOR JLEIC*

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

Abstract

The proposed electron-ion collider JLEIC would make high-luminosity collisions of polarized ions and polarized electrons with electron energy up to 12 GeV and ion energy up to 40 GeV/u. Both the luminosity and the collision energy could be increased by doubling the dipole field in the ion ring from 3 T to 6 T, and the enhanced performance would access the full range of parameters for the physics objectives of the project.

A design is presented for a 6 T large-aperture dipole utilizing a novel NbTi cable-in-conduit (CIC) in its windings. Details of the magnet design and development of the 2-layer CIC will be presented.

INTRODUCTION

An Electron-Ion Collider (EIC) has been given priority as the next new construction project for the Nuclear Physics Division of DOE. Two designs are being prepared: eRHIC [1], in which a new electron storage ring would be installed in the RHIC tunnel at BNL; and JLEIC [2], in which a new ion storage ring would be built at JLab and the 12 GeV electron beam would be injected to an electron ring.

An NAS panel [3] recently evaluated both designs for the requirements on collision energy and luminosity for the physics objectives envisaged for the EIC project.

- How does the mass of the nucleon arise?
- How does the spin of the nucleon arise?
- What are emergent properties of dense gluon systems?

The NAS report concluded that neither EIC design currently meets the combination of beam energy and luminosity that would be required to cover the physics objectives: it is unlikely that the eRHIC design can meet the luminosity goal, and the present choice of a 100 GeV ion ring for JLEIC would not meet the collision energy goal.

If the energy of the Ion Ring for JLEIC were doubled, both collision energy and luminosity would be enhanced and JLEIC would access substantially the entire kinematic domain characterized in the NAS report.

The baseline design of the Ion Ring utilizes 3 T superferric dipoles whose windings are made from single-layer cable-in-conduit [4]. Motivated by the potential enhancement of the physics program, we have prepared a design for a 6 T CIC dipole that would make it possible to double the ion energy for JLEIC.

Figure 1 shows a cutaway view of the end region of the 6 T CIC dipole. Its design follows closely that of the 3 T

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†email p-mcintyre@tamu.edu

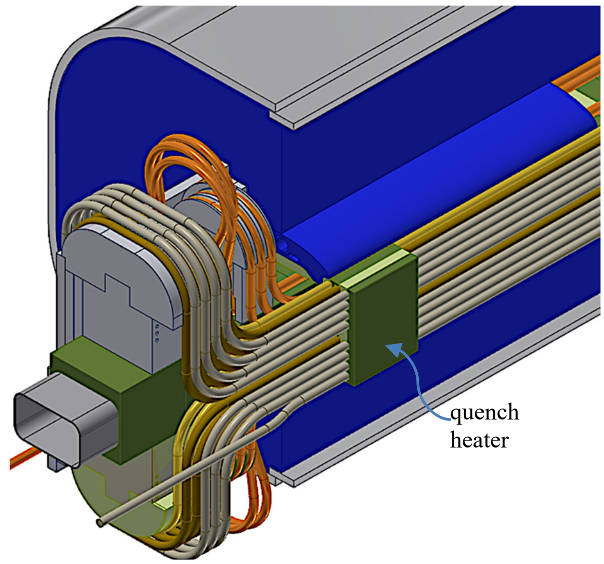

Figure 1: Cutaway of the 6 T CIC dipole design, showing the FRP structure, the 4-layer CIC winding, the beam tube, the steel flux return, and a quench heater.

JLEIC dipole: the CIC windings are arranged in a block geometry, the ends are flared in a compact assembly, and the winding comprises four layers of CIC windings instead of three. The most important difference is that a 2-layer CIC conductor is used, carrying a coil current of 23 kA. In the following sections the development of this cable is presented, the magnetic design of the dipole is presented, and the enhancements that were required for fabricating the cable and forming it into windings are discussed.

2-LAYER CABLE-IN-CONDUIT

The single-layer CIC used in the 3 T JLEIC dipole is formed by cabling NbTi strands onto a thin-wall perforated stainless steel (316SS) center tube with a twist pitch. Next an over-wrap of SS foil tape is applied, and the cable is inserted in a seamless CuNi sheath tube. Finally a CuNi alloy sheath tube is drawn onto the cable to compress all strands against the center tube and immobilize them.

Several innovations were important to the success of the 3 T CIC dipole, and each has been adapted for the 6 T CIC design. First, a set of robotic benders (Fig. 2a) were developed to form a constant-radius bend of the CIC while maintaining the sheath tube to be round as it is bent. This is accomplished using conformal die sets and motorized drives. Thus the sheath tube is actually deformed throughout the bend to maintain its round contour, while the interior geometry remains benign to the enclosed registration of superconducting wires.

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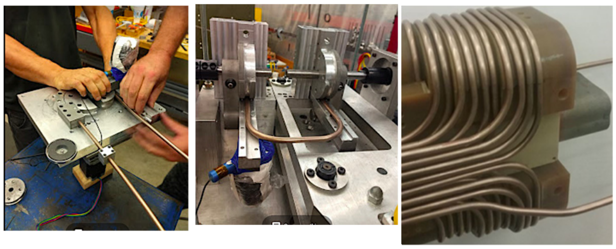

Figure 2: Robotic bending tools used to form a) the 180° bend and b) the 90° saddle bend that comprise the end geometry of each winding turn; c) a completed 24-turn end region of a 3 T CIC dipole.

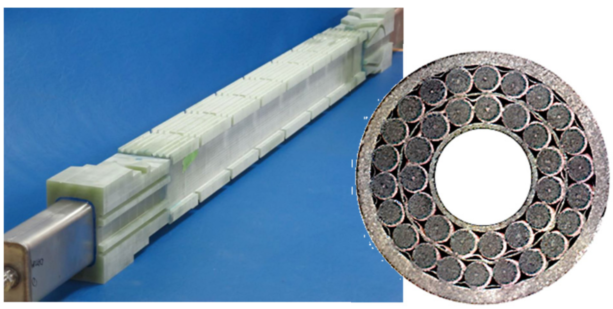

Figure 3: a) FRP support beam, formed by assembling 'window-frame' segments of G-11 FRP onto the 316SS beam tube, vacuum-impregnating the assembly, and precision-machining the half-round channels that position each CIC turn; b) cross-section photo of 2-layer NbTi CIC.

A second innovation was to form the twist pitch of the cable with exactly the mean bend radius used to form the end windings, so that all wires have exactly the same catenary length around a bend.

The larger cable current required for the 6 T dipole requires that a second layer of wires be wound onto the cable. This was accomplished using the same stranding machine (Fig. 4b). Significant development was required to achieve the bending properties for the larger and stiffer CIC structure. A multi-laminar inter-layer was applied between the first and second layers, which provides the re-arrangement of wires during bending so that no accumulated wire strain is produced. The same procedures were used to validate that wire performance is preserved in the finished 2-layer CIC.

FABRICATION OF THE CIC WINDING

A third innovation was to develop a support structure of fiber-reinforced polymer (FRP), consisting of an assembly of an impregnated support beam (Fig. 3a) and a set of side plates that precisely locate and support all turns for the requirements of field homogeneity (Fig. 5).

The entire support assembly was precision-fabricated, the turns for a 1.2 m model dipole were wound, and metrology was performed to measure the r.m.s. precision with which the turns CIC are confined in the of positions defined in the magnetic design to produce field homogeneity within the 10 cm x 6 cm bore tube. The measured r.m.s. position errors were <.05 mm, corresponding to random field multipoles a_n, b_n < 0.5 unit over the field range from injection to collision energy.

Figure 4: CIC manufacturing at ATC: a) 24-spool stranding machine; b) SS foil over-wrap; c) drawing of sheath tube onto cable.

Figure 6 summarizes the sequence for winding the CIC layers of a block-coil dipole. Figure 6a shows the completed winding of the 3-layer winding for the 3-T JLEIC dipole. It is still mounted on the winding table, and the robotic bending tools can be seen suspended above. The four layers for the 6 T dipole are barrel-wound as shown in Fig. 6b.

The total length of the flared-end winding is 30 cm. This compactness is particularly important for its use in the JLEIC arcs, in which each half-cell contains two 4 m long dipoles that are cocked to minimize the sagitta of the beam within the dipole aperture.

MAGNETIC DESIGN

The magnetic design of the 6 T CIC dipole is illustrated in the cross section shown in Fig. 5. The winding is arranged in a block geometry, except for the two turns on the top/bottom surfaces of the beam tube region. Those turns produce a sextupole component that corrects the structure sextupole at low field. Saturation multipoles are controlled by placement of holes and cavities in the steel flux return. The holes are shielded from the bore at low field but control the saturation front as field strength is increased.

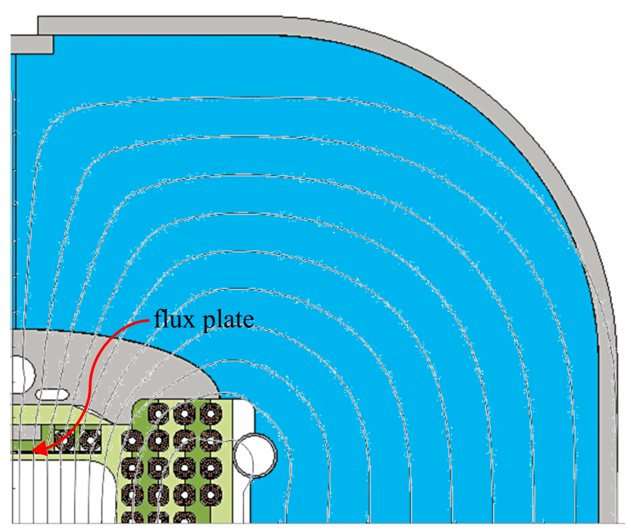

Figure 5: Quadrant cross-section of the 6 T CIC dipole: green – G-11 structure elements, blue and gray – steel flux return. Note the steel flux plate.

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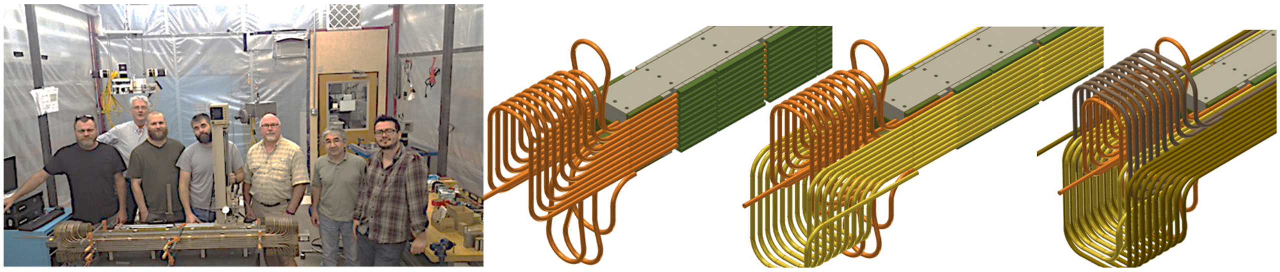

Figure 6: Winding the layers of a CIC block-geometry dipole: a) completed winding of 3 T JLEIC dipole; b) winding strategy for the 6 T CIC winding, showing the stages when successive layers are complete.

A particular feature is the horizontal steel flux plates located above/below the beam tube. At injection field the steel is unsaturated, and the flux plate presents a strong dipole boundary condition. It naturally suppresses multipoles produced by persistent currents (PC) and snap-back from the magnetization that is induced in the superconducting wires within the CIC turns as the winding current is increased and decreased. We have simulated PC magnetization in the CIC windings [4] and determined that the flux plate pair suppresses PC and snap-back by a factor of 5. This benefit is particularly important for the JLEIC doubler because the Ion Ring must inject at 8 GeV (for protons), corresponding to a dipole field of 0.25 T at injection and 6 T at collision.

Table 1: Main Parameters of 6 T Dipole and 2-layer CIC

Dipole			
Operating bore field	B_0	6	T
Coil current	I_0	23	kA
Operating temp	T_0	4.5	K
Max bore field @S.S.	B_{max}	6.45	T
# turns/pole		19	
Stored energy		0.7	MJ/m
Inductance		2.5	mH/m
Cable-in-Conduit	NbTi/Cu		
CIC diameter		11	mm
#strands inner+outer		15+21	
Strand diameter	d_{strand}	1.2	mm
Cu:SC stabilizer		1:1	

COMPARISON WITH COS θ DIPOLE

It is interesting to compare the 6 T CIC dipole with a 6 T 2-shell cos θ dipole using Rutherford cable that was developed for SIS300 by a collaboration of GSI and IHEP [5]. It has the same 10 cm horizontal aperture required for JLEIC, and would be a candidate for a JLEIC doubler. systematic cost estimation methodology developed by Willen [6], which was based upon the construction contract experience from building the 4 T dipoles for RHIC. His analysis concludes that dipole cost is determined mainly by the number of turns and ends in the winding and the quantity of superconductor in the windings. Table 2 summarizes the parameters of the two designs. Comparison suggests that CIC offers significant promise as a method to provide large aperture at high field with minimum cost.

Table 2: Main Parameters of the: cos θ Dipole for SIS300 and the CIC Dipole for JLEIC

	2-shell cos θ	**CIC**	
Operating field	6	6	*T*
Aperture	10 dia.	10 x 6	*cm*
# turns/pole	71	19	
Wire cross-section/pole	13.7	7.8	cm^2

CONCLUSIONS

A 6 T dipole has been designed for the purpose of doubling the energy of JLEIC. It utilizes a novel 2-layer cable-in-conduit conductor and a flux-plate magnetics to provide the twice-larger operating range so that injection can be made at 8 GeV and collision at 200 GeV. Considering the number of turns and the quantity of superconductor as cost drivers according to Willen, the CIC design appears to have significant potential to be a minimum-cost design.

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