SUPERFERRIC Arc DIPOLES FOR THE ION RING AND BOOSTER OF JLEIC*

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Abstract

The Jefferson Laboratory Electron Ion Collider (JLEIC) project requires 3 Tesla superferric dipoles for the half-cells in the arcs of its Ion Ring and Booster. A superferric design using NbTi conductor in a cable-in-conduit package has been developed. A mockup winding has been constructed to develop and evaluate the coil structure, manufacture winding tooling and evaluate winding methods, and measure errors in the position of each cable placement in the dipole body.

INTRODUCTION

The accelerator research lab at Texas A&M University College Station, TX has been tasked to design and build a 1.2m mock dipole magnet for the figure-eight shaped Ion Collider project at Jefferson Lab[1]. The figure-eight design has two 260° arcs coupled by two strait sections. In each arc, there are 32 half-cells which consist of two 4m long dipole magnets per half-cell along with other components. The dipole magnets are required to have a 3 T uniform field, and a beam aperture of 10cm x 6cm[1].

A 15 strand NbTi cable-in-conduit design is used for the superconductor to meet the demands of field strength and stability. Precision milled G-11 forms ensure accurate placement of the cable in order to achieve the desired field quality. To evaluate the bending and winding procedures for the dipole magnet, a mock cable (empty refrigeration tubing) was used to assemble a prototype magnet. Once the mock cable was bent and placed into the form, each cable placement was measured.

CABLE AND FORM DESIGN

Cable-In-Conduit (CIC)

The CIC superconductor design originated from a concept developed by Hoenig M O and Montgomery [2]. The general style of CIC used in this project has been previously developed by the International Accelerator Facility at GSI-Darmstadt[3]. However, the specific design used in JLEIC dipole is made of 15 1.2 mm Cu-NbTi strands shown in Fig. 1. The coolant, helium for the JLEIC dipole, flows within an inner tube and the superconductor is wrapped on the outside of this tube. Then there is a seamlessly welded sheath that is formed on the outside of the superconducting strands. This provides a stable package for all the strands, and can be easily shaped.

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Figure 1: Cross-section of cable in conduit design.

Form Design

The cables are properly located in the body of the magnet by channels in the form in a block-coil configuration. This form consists of a central winding form and three layers of cables on each side, separated by segments of milled G-11 blocks. Each segment is removable so that each layer can be formed and put into place. Figure 2 shows a body cross section of the dipole with different layers and the end regions where the ion beam enters and exits the dipole.

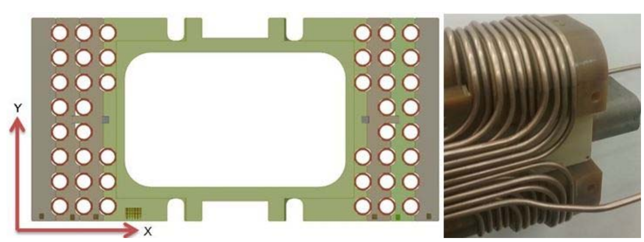

Figure 2: Body cross section of dipole (left) showing separate G-11 layers. End region form showing vertical bends (Right).

The G-11 blocks have their fiber orientation lying normal to the XY plane, with the Z axis as the beam axis. This orientation mitigates effects of thermal expansion of the block pieces. The X and Y expansion coefficients are about the same, 1.4 x10-5 K-1 and 1.2 x10-5 K-1 respectively, and the Z component is 7.0 x10-5 K-1[4].

CONSTRUCTION

Bending

In Fig. 2. (left) the cable in the winding form runs from the left hand side of the magnet to the right continuously. It must also be bent out of the way of the beam aperature. Therefore the cable must be bent 180 degrees then another 90 degrees see Fig. 2. (right) for clarity.

This was accomplished utilizing a 180 degree bender and the compound 90 degree bender and a winding procedure featured in Fig. 6 (one layer only). Each line in Fig. 3. indicates a half turn that consists of a 180 degree bend and a 90 degree bend. The turns were put into the appropriate channels once formed. On the transition end, the cable transitions to a different channel placement in Y while the non-transition end stays at the same level in Y from the left side to the right.

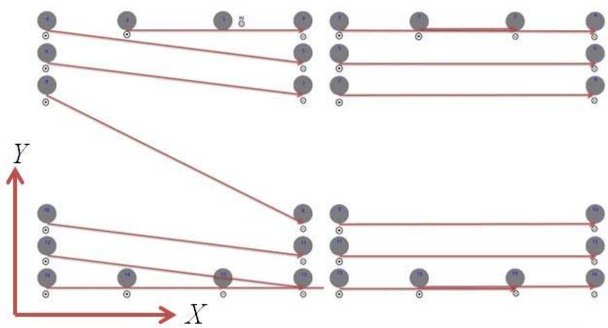

Figure 3: The left picture shows the transition end where the cables are transitioning from one level to another and the right shows the non-transition end. This is just for layer one.

Tooling

Normal pipe and tube benders cannot be utilized for this application since they generally stretch the tube being bent and consequently the superconductor inside the cable. This stretching causes the superconducting filaments within the strands of superconductor to break therefore lowering the critical current (I_c) and making quenches more likely to occur.

Original bend testing was performed on a Teledyne Republic bender now owned by Parker[5]. This style bender forms the cable without damaging the superconductor when bent on a 2" radius[6]. The benders developed for this project were designed to have the same benefits the Parker bender provided.

The benders operate by forming the cable with a die block that remains stationary relative to the cable. This die block is moved by a bending arm that slides/rolls along the back of the block and forms the cable around a forming die. The bending arm is actuated by a NEMA 34 motor and a G-code interface. Three separate benders were designed and built. Figures 4. and 5. show a 180degree bend and a 90 degree bend respectively.

The 180 degree bender bends the cable around two separate forming dies involving two setups. Figure 4 shows the second setup, but the first setup for the most part is the same. The cable is clamped into place and the moving die block is actuated to form the cable. The result after both setups is a 180 degree bend with the proper X width determined by the placement of the forming dies.

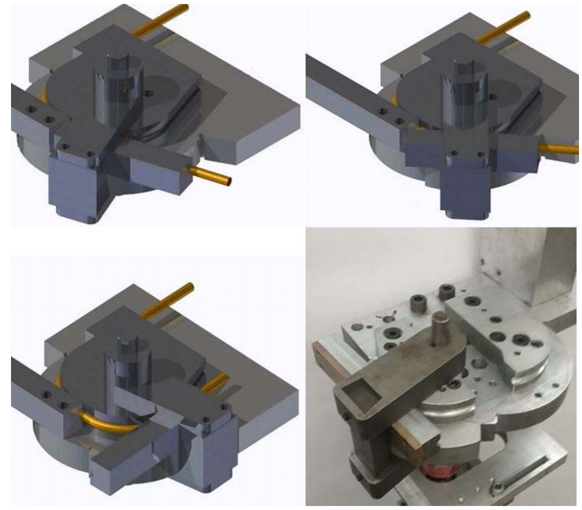

Figure 4: Bender for 180 degree bend.

The 90 degree bender is more complicated than the 180 degree bender because it has compound movement. The cable is bent the same way with forming dies, moving die blocks and the same bending radius. However to transition from one level to another, one forming die must be able to move in Y.

While the cable is being bent up to the 90 degrees, the left side of the bender is being actuated to match the angle of the bend. Equation (1) shows the path of the left side of the bender

$$A = R\sin(\theta)$$
$$B = R\cos(\theta) \quad (1)$$

where A is the "forward/backward" movement, B is the "up/down" movement, θ is the angle that the cable is bent and R is the transition height from one level to another in in Y of the cable.

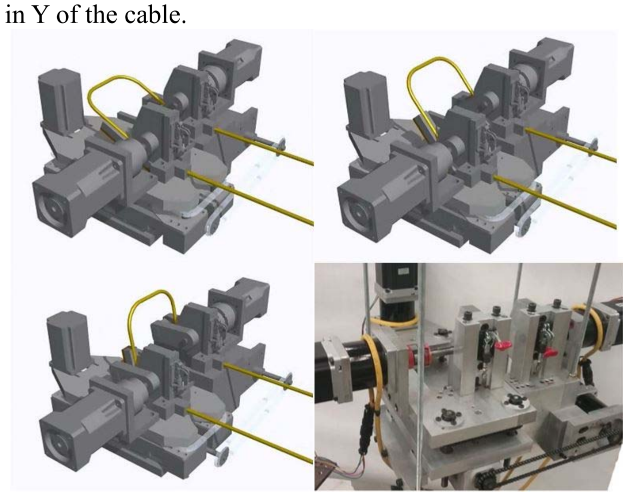

Figure 5: Bender for 90 degree bend.

A specialty bender was also developed to bend the four cables that are closer to the center of the magnet. Since these cables are less than 4" apart in X, the bender must create what looks like a "dog bone" on one end to maintain the 2" minimum bend radius required to avoid damage to the superconductor. This bender forms the cable in the same way, but with three setups to accomplish the desired shape as seen in Fig. 6.

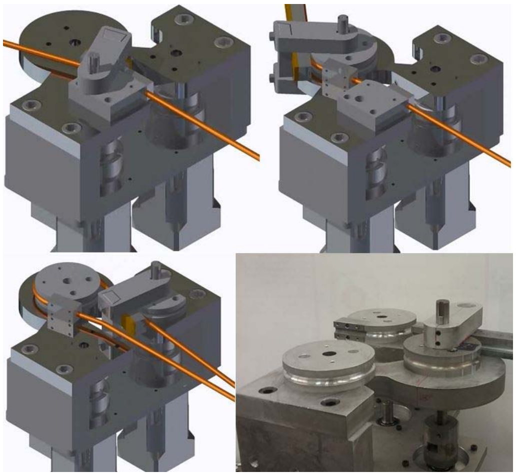

Figure 6: Bender to create the "dog bone" bend.

QUALITY CHECK OF FIELD

Setup

After each layer of cables was completed a quality check(QC) was performed. No direct field measurement was possible since empty tubing was used for the mock winding. However, the multipoles can be estimated from the error in the cable placement using the magnetic design model.

A 3-axis indicator was used to find the placement of the cables in X and Y at 10 points along the body of the magnet (5 each side). An example of this sample point is shown in Fig. 7. with locations along the magnet example measurement.

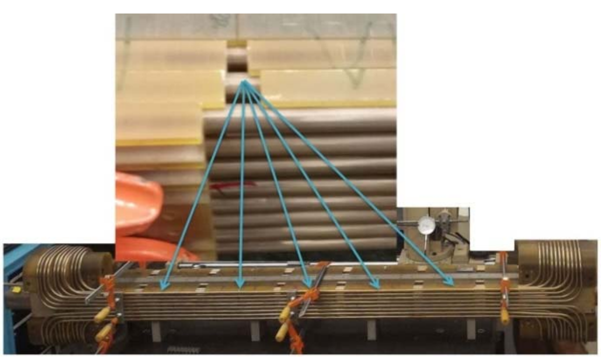

Figure 7: Locations along body of magnet to find cable placement and an example measurement.

To measure the cables in Y, the aforementioned 3axis indicator was set to zero at the top of the magnet and then it was touched off the top of each cable. This measurement along with the cable and G-11 dimensions gives the center location of the cable. The same procedure was performed for the X measurement with the indicator set to zero on the left or right side of the magnet.

Results

A matrix of multipole deviations from design errors per 0.001" of cable misplacement was generated using COMSOL from the multipole expansion equations shown in Eq. (2)

$$B_r(r,\theta) = \sum_{n=1}^{\infty}\left(\frac{r}{R_{ref}}\right)^{n-1}\left(B_n\sin(n\theta) + A_n\cos(n\theta)\right)$$
$$B_\theta(r,\theta) = \sum_{n=1}^{\infty}\left(\frac{r}{R_{ref}}\right)^{n-1}\left(B_n\cos(n\theta) + A_n\sin(n\theta)\right) \quad (2)$$

where B_n is the $2n$-pole normal multiple, A_n is the $2n$-pole skew multiple and R_{ref} is a reference radius (2cm for this calculation)[7].

The error matrix was used in conjunction with the placement error of the cables to get the resulting multipoles. Design multipole errors are all less than one Unit and the numbers presented in Table 1. are the deviations from those values. The table is expressed in Units which comes from the coefficients of the multipole expansion being divided by a reference B-field and then multiplied by 10^4[7].

The skew quadrupole is over the allowable 1 Unit, and this error arose from the cables being misplaced in the second and third layer. However, the errors overall are low and within 1.0 Unit.

Table 1: Multipole Errors

Multipole	Error in Units
Dipole	.000015
Quadrupole	0.00045
Sextipole	0.096
Octipole	0.00084
Skew Quadrupole	-1.1
Skew Sextipole	-0.26
Skew Octipole	-0.078

IMPROVEMENTS

There were two contributors to the large skew quadrupole error. The overall size of the cable is 0.322" +/- 0.002" and the channel is 0.328" +/- 0.002" in X and Y. this mismatch gives the center of the cable a placement error of +/-0.010". This mismatch occurred because the cable was oval-shaped and had to be redrawn to a smaller size. For a production dipole the cable will be 0.326", and this error will be reduced.

In addition to the undersize cable error, the separate layers of G-11 were registered by the previous layer of cables. This produced a propagation of error in the outer layers which led to undesirable multipole errors. To remedy this, an extra slot is milled into the G-11 blocks. This updated version, shown in Fig. 2, registers the G-11 blocks to the central winding form instead of the cables. Along with the extra groove the G-11 pieces were modified so that each cable is fully supported by the G-11 blocks.

CONCLUSION

Effective tooling has been fabricated that will be able to form the cable into the necessary shape that will fit into the winding form. With the exception of the skew quadrupole, the errors were within design requirements, and this can be further reduced with proper size cable and modified G-11 pieces. Therefore the CIC design is now ready for construction of a cold-mass 3T model dipole.

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