SUPERCONDUCTING DOUBLE-HELIX ACCELERATOR MAGNETS*

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Abstract

We describe an important contribution to accelerator magnet technology based on the concept of modulating the helical turns of solenoid coils to produce pure multipole fields of any order. Calculations show that these configurations inherently produce virtually error free fields of the desired multipole order in a large fraction of the aperture in the two dimensional cross section without the presence of iron. The characteristics of one such configuration, the double-helix dipole (DHD), are described. It is also explained how the novel geometry of the double-helix coils simplifies the manufacturing, eliminates complex coil parts, and thus significantly reduces the cost of the magnets in comparison to the conventional cosine theta (racetrack design) coils. This has been demonstrated by the design and construction of a prototype dipole that produces a 4T field in an 80 mm aperture (without iron).

FOREWORD

The double helix coil configuration represents a significant advance in accelerator magnet technology over the conventional cosine theta type (racetrack design) coils. The performance of virtually any type of accelerator magnet is improved while the cost of manufacture is substantially reduced with this magnet configuration.

The double-helix dipole and higher multipole magnets have been previously described [1,2,3]. They achieve pure multipole fields by the sinusoidal modulation of the axial position of the turns of a solenoid wound coil. For example, in the case of the dipole, the axial position of the conductor path is described as shown in Figure 1 and Figure 2 shows a 2-layer double helix dipole magnet (DHD).

Each turn of the coil can be well approximated as an ellipse tilted at an angle α with respect to the axis of the coil. This produces a transverse field component superimposed on a solenoid field component. When pairs of such windings with opposite tilt angles are assembled concentrically, the solenoid field components cancel and the dipole components add to produce a pure dipole field.

Higher order multipole fields can be obtained by modulating the axial position z of the winding according to the relation $z = h + A_n \sin(n\theta)$, where h is the helical advance and A_n is the amplitude of the modulation. Using a modulation frequency of $n = 2$, the result is a magnet with a pure quadrupole field. Similarly, $n = 3$ produces a sextupole, $n = 4$ produces an octupole, and so forth.

Combined function magnets are also possible by modulating the conductor path at 2 frequencies. For example, $z = h + A_0 (\sin\theta + 0.01 \sin 3\theta)$ will produce a dipole with a small amount of sextupole.

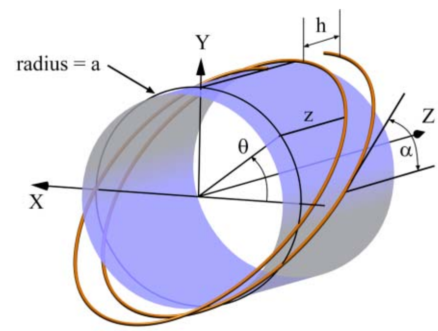

Figure 1: For the case of the dipole, the z coordinate of the conductor path is given by $z = h + A_0 \sin\theta$ with $A_0 = a / \tan\alpha$, where a is the radius of the coil aperture, α is the tilt angle of the winding with respect to the horizontal axis, and h is the helical advance per turn.

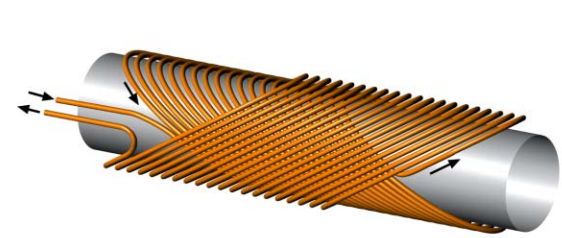

Figure 2: Double helix dipole (DHD) concept uses pairs of layers with opposite tilt and current direction. Aperture may be circular or elliptical. High field values can be obtained by using multiple pairs of layers with the transition between layers as shown.

The high magnetic fields required for future accelerators can only be achieved with Nb_3Sn, or other A15 or HTS type superconductors, which are brittle and sensitive to mechanical strain. The traditional cosine-theta racetrack dipole and quadrupole configurations make it difficult and expensive to employ such conductors. The double helix design, however, facilitates the use of pre-reacted, brittle conductors for such applications.

In this paper we describe some of the characteristics of double-helix magnets for accelerator applications and show how a double-helix dipole model magnet (DHD002) was designed and constructed.

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CHARACTERISTICS OF DOUBLE-HELIX DIPOLE MAGNETS

Field Strength and Multipole Content

The dipole field (without iron or end effects) contributed by current I in each layer of a DHD is given by $B_y = I\ (\mu_0/2d)\ \cos\alpha$ where d is the effective width of the conductor. Theoretically there are no higher order multipoles created in the ideal double-helix configuration. Actual coil geometry with helicity and finite sized conductors produces a very low level of harmonic content in a large portion of the coil aperture. Table 1 shows the multipole fields computed at the center of the model magnet DHD002.

Table 1: DHD002 multipole fields in gauss at 9238 A, computed with AMPERES at the magnet longitudinal center and R_{ref} = 25 mm (~2/3 of coil aperture).

Multipole order	Skew	Normal	Multipole Units
0	0.0055	-40320.0000	10000
1	0.0019	-0.4100	0.101687
2	-0.0003	-0.1940	0.048115
3	-0.0006	-0.2240	0.055556
4	0.0005	-0.2580	0.063988
5	0.0007	-0.0580	0.014385
6	0.0001	0.0960	-0.02381
7	0.0002	-0.0440	0.010913
8	0.0000	-0.1320	0.032738
9	-0.0001	0.0240	-0.00595

End Fields

Three-dimensional magnetic analysis was performed using AMPERES. The graph in Figure 3 shows the normal multipoles present in the ends (final ~200 mm) of the 1500 mm long DHD002. The graph for skew multipoles is similar. Although end field harmonics are present, the integral of those harmonics tends to vanish.

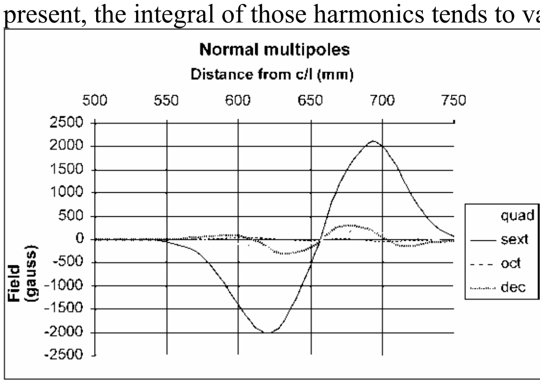


Figure 3: Normal Multipoles in the End Region

Comparison with Conventional Accelerator Magnet Technology

Although the conventional Rutherford style cosine theta racetrack coils can produce a given magnetic field with perhaps the least mass of superconductor, the unique coil geometry of the double-helix configuration enables a relatively simple and inexpensive method of making accelerator magnets. While the conventional method of coil fabrication uses flat insulated cable, wrapped with adhesive and molded under heat and pressure, in comparison the manufacture of DH coils is remarkably simple. Furthermore the conventional coils require many precise and expensive parts, while DH coils use only five types of components:

- Stainless steel support / bore tube
- Round multi-strand conductor
- Cylindrical composite tubes for placement of the conductor turns
- Cryogenic grade epoxy for impregnating the assembled coils
- Aluminum alloy cylinders that are thermally shrunk on the completed coil assembly to provide structural reinforcement.

Another significant difference of the DHD design is the elimination of the requirement for applying azimuthal pre-stress to the coils. Therefore, very high field magnets can be made using the DHD configuration and adequately reinforced by using thermally-shrunk aluminum cylinders on a completed impregnated coil assembly.

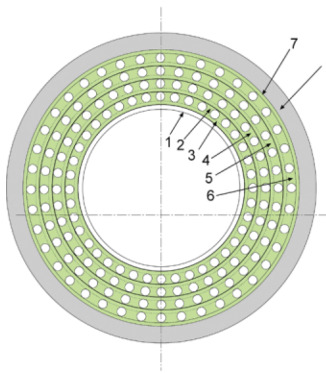
Also, the double helix design facilitates the use of pre-reacted brittle superconducting materials. The mechanical strain induced in the strands of the cable can be kept to less than 0.4% in the manufacture of DHD coils. This is accomplished by using small strand conductor (typically 10 –12 mil diameter) in the pre-reacted cable and controlling the change in radius of curvature of the conductor from the reacted state to the placement on the coil form. This is enabled by the relatively large minimum bend radius in the DHD geometry and the identical geometry of each turn in the coil.

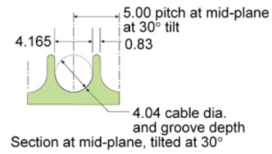
THE DHD MODEL MAGNET DHD002

Parameters

A DHD model magnet was designed and constructed under a DOE Phase I SBIR grant. An objective was to demonstrate the simplicity of the design, ease of manufacture, and performance of this technology. The completed magnet assembly was delivered to Brookhaven National Laboratory in early April and will be tested in June or July.

This model has an 80 mm coil aperture and a length of 1.5 m. It has 4 coil layers, which were wound with a round cable composed of 19 strands of NbTi material of the type that was used for the SSC inner coils. The bare cable diameter was 4.04 mm and the effective width including insulation between the turns was 5 mm. The magnet cross section is shown in Figure 4.





Item #	Description	Material
1	RHIC bore tube	SS
2	DHD layer 1	Composite tube
3	Groove depth in layer (typ.)	
4	DHD layer 2	Composite tube
5	DHD layer 3	Composite tube
6	DHD layer 4	Composite tube
7	Outer insulator-spacer	Composite tube
8	Reinforcing cylinder	6061-T6

Figure 4: Cross section of DHD002. Helical turns of cable are represented by a series of circles; however, the circles do not represent actual conductor cross section/position.

The calculated performance of DHD002 with α=30° and operating current = 9238 A is central field = 4.02 T, peak field = 4.19 T. At an operating temperature of 4.35 K, the quench current is 11,311 A giving a current margin of 22.4%. Current densities in the SC and copper at operating conditions are J(NbTi,operating) = 2181 A/mm^2 and J(Cu,operating) = 1678 A/mm^2. The current density in the copper is rather high for this application, but the use of 1.3:1 SSC inner strand was dictated by its availability. The magnet inductance is 3.66 mH.

Magnet Fabrication Procedure

Composite tubes of appropriate diameter for each of the coil layers were obtained and grooves having the tilted helical geometry (and also the lead and layer transition path) were machined in them using a computer-controlled milling machine. The base cylinder was bonded on the RHIC bore tube that was supplied by BNL and bare conductor was placed in the grooves using a simple fixture with adjustable tension.

The additional composite tubes were added sequentially and the conductor placed in the pre-machined grooves without splices between the layers. The type of continuous layer transition shown in Figure 2 was used between layers.

The completed coil assembly was covered with a thin composite tube barrier and vacuum impregnated with cryogenic grade epoxy. A sample section of coil used to evaluate the vacuum impregnation procedure is shown in Figure 5.

The assembly was completed by sliding pre-heated segments of aluminum alloy cylinders over the completed coil assembly to provide radial pre-compression to the coil for reinforcement. Note that the double helix construction technology uses a modular approach that easily enables the construction of very long magnets.

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Figure 5: A few turns of epoxy impregnated coil, with a Lexan cover, show typical turn geometry. Insulation is provided by the web of the coil support grooves and the epoxy impregnation.

SUMMARY

The principle of obtaining pure multipole fields by modulating the axial position of the turns in helically wound (solenoid) coils can be applied to accelerator magnets to yield a simple design that is easy to manufacture and significantly less costly than conventional coil designs. We have shown how this technology can produce a high field quality, low cost design that can be fabricated using standard machine tools and simple fixtures rather than expensive dedicated tooling. The method of using bare, round multi-strand cable placed in pre-machined grooves in composite cylinders produces a precisely-wound, splice-free coil assembly. When impregnated with epoxy and reinforced with thermally-shrunk aluminum cylinders, the result is a self-supporting coil assembly that is adequately reinforced for very high Lorentz force without the requirement of applying high azimuthal pre-stress to the coils.

ACKNOWLEDGMENT

The authors would like to acknowledge the contribution and help of Brookhaven National Laboratory that supplied the surplus RHIC bore tube for DHD002 and has agreed to perform cryogenic testing and multipole measurements. This work is scheduled to be undertaken in June -July 2003.

REFERENCES

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[2] R. B. Meinke, C. L. Goodzeit, and M. J. Ball, "Modulated Double-Helix Quadrupole Magnets", Paper 4LC08, ASC2002, Houston, TX, August 2002; to be published, *IEEE Transactions on Superconductivity,* June 2003.

[3] AML has Patents Pending on the use of the double helix configuration for accelerator magnets and other applications.