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MultiPhysics Simulation of Direct Double Helix Magnets for Charged Particle Applications

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Abstract: Charged particle beam manipulation requires magnetic dipoles for steering and quadrupoles for focusing. Conventional magnets are currently used leading to very large and heavy systems. Miniaturization of the optic magnets would enable the development of more affordable systems and potentially portable devices. The Advanced Magnet Lab, Inc. has developed a revolutionary magnet topology and packaging allowing for a significant increase of performance in field generation and field homogeneity. Indeed, direct double helix (DDH) magnets inherited the outstanding features of double helix windings [1], while at the same time exhibit a lower resistance and improved heat transfer. DDH magnets are obtained by creating conducting paths in-situ directly from a conducting cylinder, the conductor thus created presents a variable cross-section leading to a lower overall resistance. The paper presents electro-thermal simulations of DDH magnets and explains through numerical analysis how the unmatched performance is obtained.

Keywords: .

1. Introduction

Double Helix (DH) magnet technology allows for the generation of magnetic multipoles with unmatched field homogeneity. Intrinsically, because the conductor distribution forms an almost perfectly sinusoidal current distribution, field homogeneity better than 10^{-4} can be achieved. Double Helix technology is therefore ~~very~~ well suited for charged particle applications but also to rotating machines, in which the lack of harmonics is a valuable advantage in terms of vibrations and torque ripple. DH magnets can achieve ~~such~~ high field homogeneity thanks to a manufacturing process that stabilizes the conductors in precisely machines grooves. As a result, the conductors are ~~then~~ very stable and large Lorentz forces, present in superconducting magnets can be handled very effectively. Since the magnets are built as a splice-free multilayer system, combined function magnets can be developed within a single winding such as a superimposition of several multipole orders and/or twisting or bending. This unique capability is performed without affecting the field homogeneity. Figure 1 shows different configurations of DH windings. On the left hand side, a 6-pole coil is shown; the center part shows a 6-pole flared coil and the right hand a twisted rotor winding.

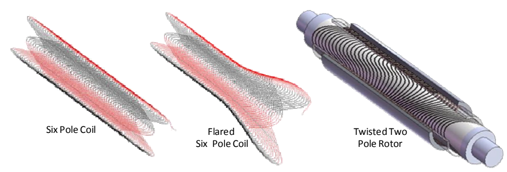

Figure 1. Various Double Helix configurations

The double-helix coil configuration uses concentric pairs of oppositely-tilted helical windings to generate transverse magnetic fields. Figure 2 shows a 2-layer magnet generating a transverse dipole field.

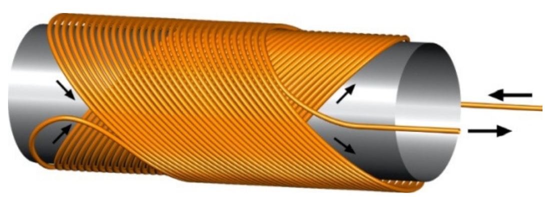

Figure 2. Example of a 2-layer winding used to form a DH dipole magnet

The DH solenoid-like windings are imbedded in concentric cylinders of high-strength material. Together with an overbanding of high-modulus, high-strength fibers, forces can be contained easily. The minimum bend radius of the conductors in the DH coil configuration is significantly larger than in racetrack-shaped coils used in conventional magnets. This facilitates the use of strain sensitive (brittle) materials such as high temperature superconductors while keeping substantially smaller dimensions.

In DH dipole magnets, each layer generates a tilted dipole field with respect to the axis as shown in figure 3. Each layer generates a field with transverse and axial components; by combining several layers together, a purely transverse field or a purely axial field can be obtained. Switching from transverse field to axial field can be done by changing the current flow direction in the oppositely tilted layers.

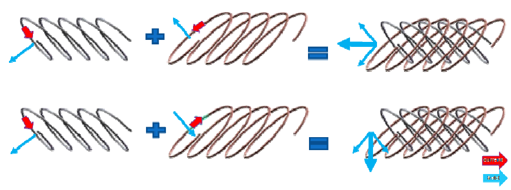

Figure 3. Principle of field direction switching.

The DH geometry is not limited to dipole fields, but can be used in coils with all the advantages of DH windings with any multi-pole order [2,3]. To generate a dipole field in the DH geometry the axial position of a solenoid winding is modulated with $A\ sin(\theta)$, where θ is the azimuth angle around the cylinder and $A=a/tan(\alpha)$ controls the tilt of the winding as shown in Figure 5. Using an axial modulation with $A\ sin\ (2\theta)$ generates a pure error-free quadrupole field as in figure 4, and a modulation $A\ sin\ (n\theta)$ generates a n^{th}-order multi-pole field with all the advantages of DH windings over the corresponding saddle coils.

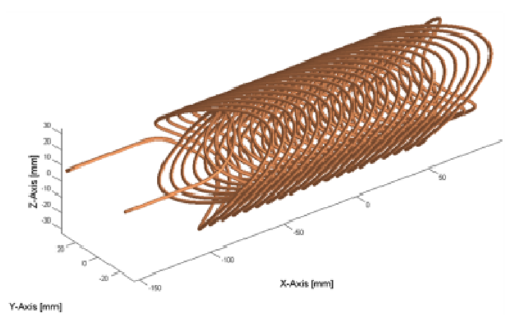

Figure 4. Quadrupole DH magnet

The current follows a path governed by the following equation:

$$X(\theta) = \frac{h}{2\pi}\theta + \frac{a}{\tan(\alpha)}\sin(n\theta + \varphi)$$
$$Y(\theta) = a\cos(\theta) \qquad (1)$$
$$Z(\theta) = a\sin(\theta)$$

The different parameters of equation (1) are defined in figure 5.

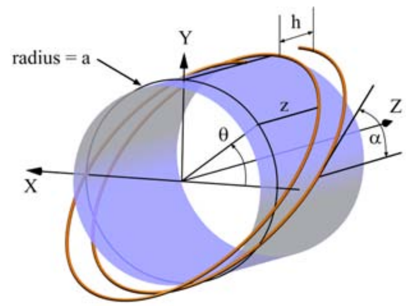

Figure 5. Geometric properties of DH winding

3. Direct Double Helix Magnets

Direct Double Helix (DDH) magnets are manufactured the same way as DH magnets, but instead of laying conductors in grooves, the grooves are machined out of conductive cylinders and form the conductive paths. An example of DDH magnet is shown in figure 6. DDH magnets offer significant advantages over wire based windings:

- the conductor cross section area is increased by going to a square cross section
- the cross section area of the conducting path is variable leading to a global reduction of resistance
- the conductor can be exposed leading to improved heat transfer
- the wider sections act as heat sinks thus improving thermal management
- The multi-layer configuration provides very good mechanical stability

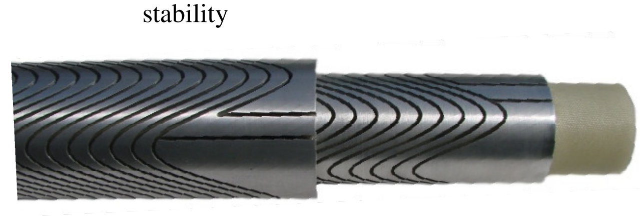

Figure 5. Two concentric cylinders of a DDH coil in a sextupole configuration

The conductor used is no longer restricted to the availability of material in the form of wire. Depending on the application, different materials can be used as support structure of the conductive material, including ceramics that can operate at much higher temperature than conventional conductors.

Since the wider section of the conductor does not contribute significantly to the transverse field generation, the outstanding field homogeneity of DH windings is conserved in DDH magnets. Because of the lower resistance and very good heat transfer, very large current densities can be flowing in the narrow section with conventional water cooling. Stable operation with peak current densities in excess of 150 A/mm^2 have been achieved thus enabling more compact steering and focusing magnets for charged particle beam optics.

4. Example of Application

Small dipoles for horizontal and vertical beam steering are presented in Figure 6. The two DDH coil pairs shown fit into each other. The inner coil diameter is 20 mm, the outer diameter is 40mm. A special manufacturing technique allows for the two layers forming a DDH coil to be built with only one support structure between them as shown in figure 6. The complete magnet assembly with the water containment vessel is shown in figure 7. Table I and Table II report the coils performance. The coils produce the needed fields of about 950 Gauss for horizontal steering and 250 Gauss for vertical steering, respectively.

Figure 6. Two sets of DDH coils for horizontal and vertical beam steering.

Table I and Table II also show the operational currents, the power consumption, the calculated peak current density in the conductor, the inlet water temperature (35C and 10C), and the measured peak temperature at the conductor.

Figure 7. Exploded view of magnet assembly for the DDH coils of Figure 6. The SS housing with inlet and outlet water cooling tubes are shown.

Table 1: Operational parameters of vertical steering dipole

I_{nom} (A)	P (W)	Jc Peak (A/mm^2)	T_{Inlet} (C)	T_{Peak} (C)	Field (Gauss)
5.5	73	39	35	39.6	83
7.0	120	49	35	42.7	105
8.5	181	60	35	46.3	128
10	251	70	35	51	150
11	309	78	35	55	165
13	369	92	10	44	195

Table 2: Operational parameters of horizontal steering dipole

I_{nom} (A)	P (W)	Jc Peak (A/mm^2)	T_{Inlet} (C)	T_{Peak} (C)	Field (Gauss)
20	174	38	35	41.1	308
25.0	268	48	35	44.4	385
30	387	58	35	47.8	463
35	515	67	35	52.2	540
40	692	77	35	57.5	617
45	792	86	35	57	694
55	578	106	10	62.5	848
60.0	714	115	10	77.8	925

As can be seen from the data, the coils operate reliable at peak current densities of more than 100 A/mm^2. While the maximum measured temperature at the conductor is 77.8 C, the water temperature rise at the outlet of the magnet is less than 10 C. Even higher currents and fields have been achieved during testing of the magnet system showing that operation above 150 A/mm^2 is possible.

4. Creating the Geometry

Understanding the limitations of DDH magnets is paramount to the deployment of the technology. The next section shows how COMSOL MultiPhysics was used to visualize the current distribution in the magnet and to simulate the heat transfer in steady state operation.

4.1 2D Geometry

The geometry of interest is governed by equation (1) and cannot be built precisely through the graphical interface of COMSOL. A script has been developed to create the geometry of an unrolled turn of a DDH magnet. The functions used are *geomspline* and *geomcoerce* allowing the creation of curves from point coordinates and solid objects from curves. Part of the script is shown below. The parameter *a* is the aperture of the magnet, *t* represents the angular position, *alpha* the tilt angle, *h* the turn advance and *p* the number of pole pairs. The variable *tool* accounts for the diameter of the tool used to machine the grooves.

```
for i=1:n
t=(i-1)*2*pi/n;
x(i)=t*a;
y(i)=h*t/2/pi+a/tan(alpha)*sin(p*t)+tool/2;
end
l1=geomspline(p1);
for i=n+1:2*n
t=(i-1)*2*pi/n;
x1(i-n)=(i-n-1)*2*pi/n*a;
y1(i-n)= h*t/2/pi+a/tan(alpha)*sin(p*t)-tool/2;
end
l2=geomspline(p2);
l3=line1([x(1) x1(1)], [y(1) y1(1)]);
l4=line1([x(n) x1(n)], [y(n) y1(n)]);
DDH=geomcoerce('solid',{l1,l2,l3,l4});
```

The geometry created can be imported in COMSOL as shown in figure 8.

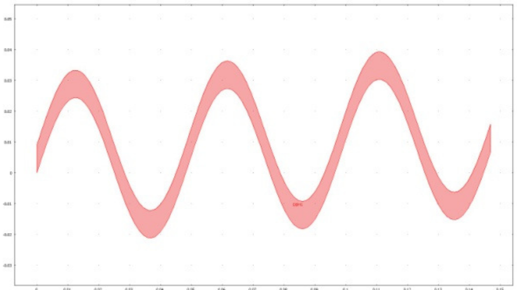

Figure 8. 2D geometry of an unrolled turn of a 6-pole DDH

4.2 3D Geometry

Creating the geometry in 3D also requires developing some script or importing from a dedicated CAD program. Using script, the geometry can be created through the use of the function *simplesweep3*. The first step is to create vectors of coordinates describing the groove geometry and extruding a rectangular object along the path. An example of script is shown below.

```
c=rect2(A,B,'Base','center');
for i=1:n
t=(i-1)*Nb_turns*2*pi*pi/n;
x(i)=a*cos(t);
y(i)=a*sin(t);
z(i)=h*t/2/pi+a/tan(alpha)*sin(p*t);
end
p=[x;y;z];
helix=simplesweep3(c,p)
```

The result is equivalent to a DH winding that can be subtracted from a hollowed cylinder as shown in figure 9.

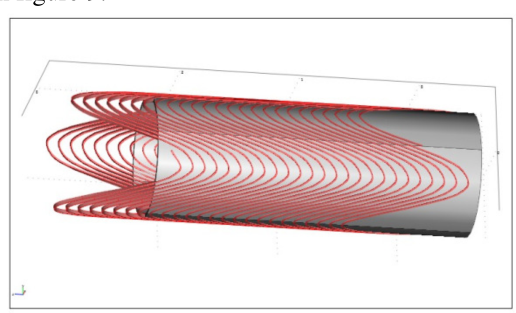

Figure 9. 3D geometry of a layer of a 6-pole DDH before subtraction

Because of the high number of points, required to represent accurately the geometry, and because of the nature of the simulations, only 1 turn was included in the simulations.

4.3 Mesh

The mesh used for the simulations is shown in figure 10. It consists of about 5500 elements leading to a system with about 12,500 degrees of freedom.

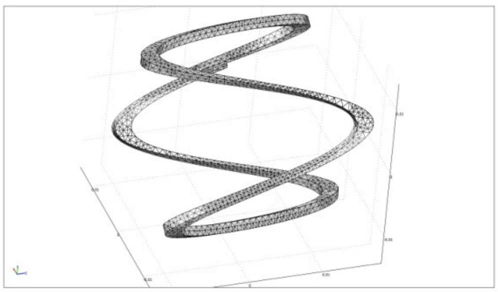

Figure 10. Mesh of 1 turn of DDH magnet

5. Problem Settings

The simulation requires coupling of the Conductive Media DC and General Heat Transfer modules. An inward current density is applied on one end of the conducting path, the other end is set to ground, and the other boundaries are set to electrical insulation.

The heat transfer problem includes heat transfer through the top surface of the conductor mimicking active water cooling.

The two physics modules are coupled through the resistive heating parameter and the electrical resistivity depending on temperature.

6. Simulation results

6.1 Current Distribution

The current distribution was simulated both in 2D and 3D as shown in figures 11 and 12. As expected, the current distribution is not uniform and a strongly reduced current density is present in the wider section of the conductor. The current distribution explains the reduced resistance measured across the DDH magnets.

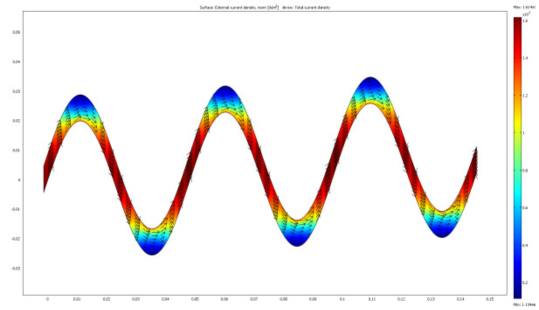

Figure 11. Current density distribution in 1 unrolled turn of DDH magnet

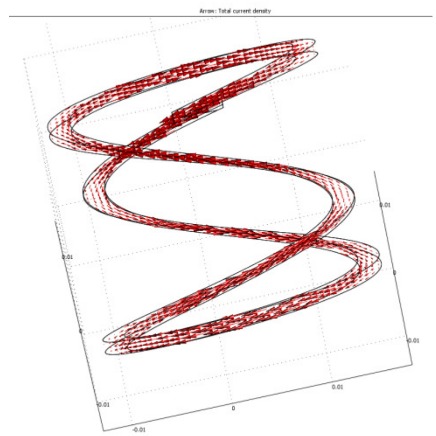

Figure 12. Current density distribution in one turn of DDH magnet

The influence of multipole order, on the conductor bends and on the variation of conductor cross section can be determined. Figure 13 shows the current distribution in one turn of DDH magnets for different multipole orders. As the number of poles increases, the current density modulation increases up to a bending radius value. Figure 14 shows the reduction in resistance relative to an equivalent magnet wound with round wire as a function of multipole order. The value given in Figure 14 for pole number equal to zero, reflects the gain due to the square instead of round cross section. The additional gain resulting from the variation in conductor width depends on multipole order and levels off for sextupoles, i.e., number of poles equal to 3. This is a very interesting result showing that DDH magnets is a superior magnet packaging, generating more field for a given heat load or capable of operating at lower power for a given field.

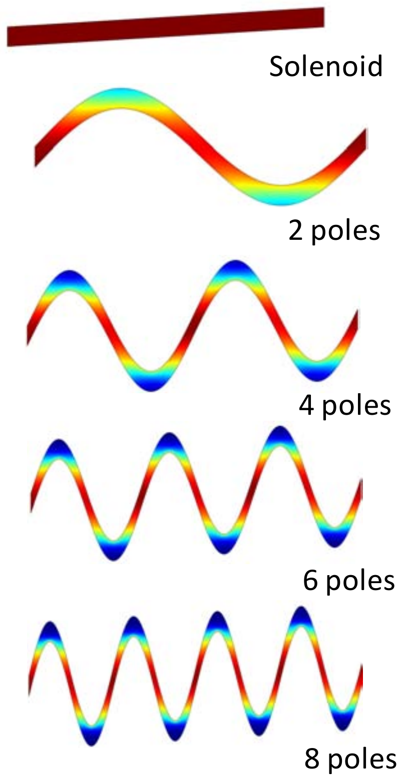

Figure 13. Current density distribution in 1 turn of DDH magnet for different pole numbers

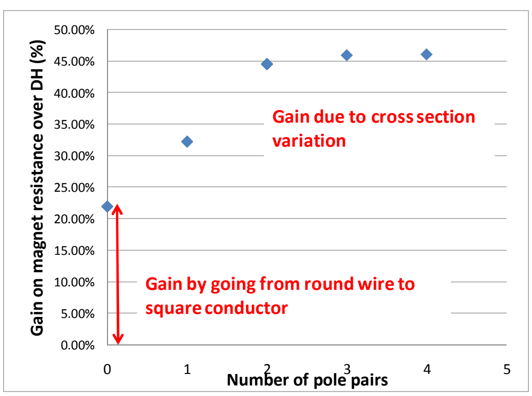

Figure 14. Resistance reduction of DDH magnets relative to round wire wound magnets

6.3 Temperature Distribution

The lower resistance of DDH magnets leads to an important reduction of the heat load. Additionally, the fact that the conductors are directly exposed to a cooling fluid, allows for a very effective heat removal. Figure 15 shows the resistive heating distribution in the DDH magnet, obviously, the heat load is the highest where the current density is large.

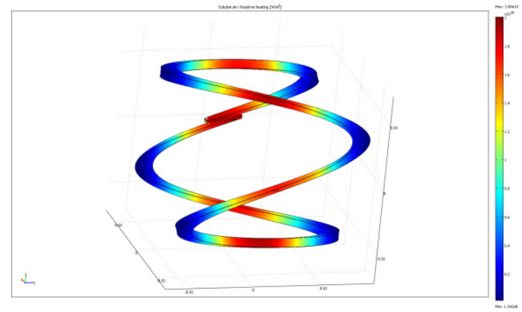

Figure 15. Resistive heating distribution in 1 turn of DDH magnet

The temperature distribution in steady state operation is shown in figure 16. The conductor presents a temperature gradient because the heat is extracted from the top surface. The wider sections are kept at lower temperature and act as heat sinks allowing to even more heat to be removed from the wider sections of the conductor.

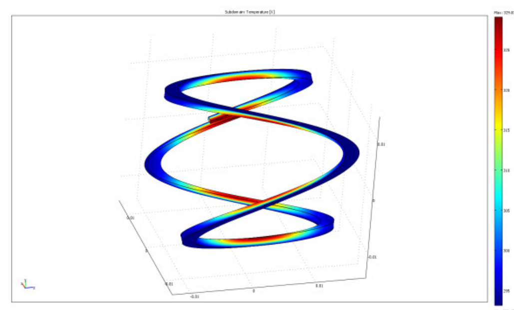

Figure 16. Temperature distribution in 1 turn of DDH magnet with active cooling on the top side

Figure 17 shows the heat flux during steady state operation, the arrows show that most of the heat transfer is done at the narrow part of the conductor, however, the surface color representing the axial component of the heat flux shows that some heat is conducted from the narrow sections to the wide sections. Figure 18 displays a closer view of the axial heat transfer showing that the wider section actually act as local heat sinks.

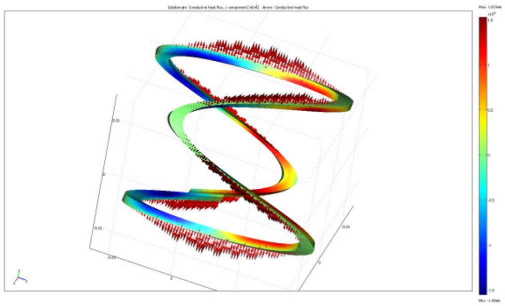

Figure 17. Heat flux distribution in 1 turn of DDH magnet

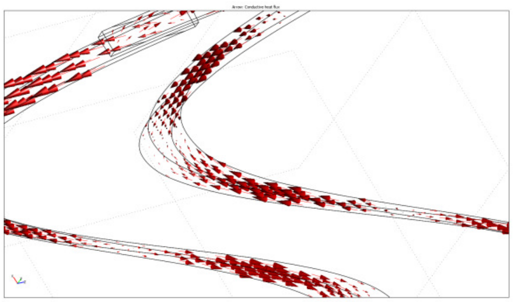

Figure 18. Heat flux distribution in 1 turn of DDH magnet

7. Conclusions

Because of their unique electrical and thermal performance, Direct Double Helix magnets have the potential of significantly improving charged particle beam optics by making them lighter, smaller and more affordable. DDH magnets have a large number of application such high speed generators and specialized magnets. Through the use of COMSOL MultiPhysics the physics of DDH magnets has been better understood and will lead to further improvements and even better magnets in the future.

8. References

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