DIRECT DOUBLE-HELIX MAGNET TECHNOLOGY

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Abstract

Magnets for beam steering, focusing and optical corrections often have demanding requirements on field strength, field uniformity, mechanical robustness and high radiation strength. The achievable field strength in normal conducting magnets is limited by resistive heating of the conductor. A break-through magnet technology, called "Direct Double-Helix™" allows operation at current densities in excess of 100 A/mm^2 with conventional water cooling. The conductive path generating the magnetic field is machined out of conductive cylinders, which are arranged as concentric structures. Geometrical constraints of conventional conductors, based on wire manufacturing, are eliminated. The coolant, typically water or air, is in direct contact with the conductor and yields very high cooling efficiency. Based on Double-Helix™ technology the conductor path is optimized for high field uniformity for accelerator magnets with arbitrary multipole order or combined function magnets. Advanced machining technologies, enable unprecedented magnet miniaturization. These magnets can operate at temperatures of several hundred degrees Celsius and can sustain high radiation levels.

INTRODUCTION

Currents described by Eq. 1 produce simultaneously axial and transverse magnetic fields.

$$X(\theta) = \frac{h}{2\pi}\,\theta + \sum_n A_n \sin(n\theta + \varphi_n) \qquad (1)$$
$$Y(\theta) = R\cos(\theta)$$
$$Z(\theta) = R\sin(\theta)$$

Superimposing two such currents with appropriate direction allows cancelation of either the axial or the transverse magnetic field. Pure transverse magnetic fields of arbitrary multipole order can be produced. Coils based on this technology have high field uniformity without the use of field forming spacers as required in other winding configurations. Conductors surround the coil aperture giving intrinsic mechanical stability to the coils. The resulting winding configurations are called Double-Helix™ coils [1]; examples of a dipole and quadrupole are shown in Figure 1.

Direct Double-Helix Technology

Double-helix coils (DH) can be produced by machining the current path out of conductive cylinders, which are then arranged as concentric structures (see Figure 2). This patented technique, called "Direct Double-Helix" (DDH) technology offers significant advantages over conventional coil winding, which uses wire, cable or tape conductors.

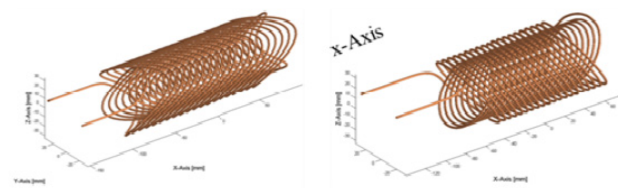

Figure 1: Left: 2-layer quadrupole winding. Right: 2-layer dipole winding. Both windings produce transverse magnetic fields.

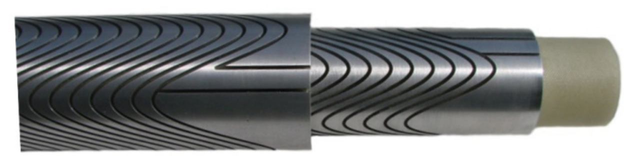

Figure 2 : Two concentric cylinders of a DDH coil in a sextupole configuration

Machining the current path out of a cylinder with a given wall thickness produces a conductor with rectangular cross section that changes with azimuth angle around the coil axis as shown in Figure 3.

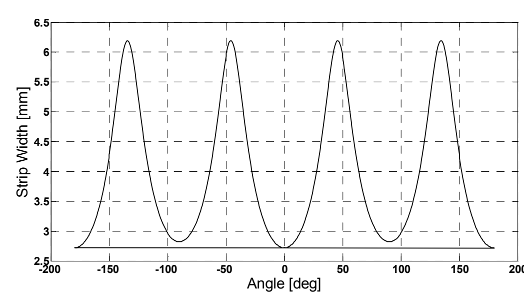

Figure 3: Variation in conductor width as a function of azimuth angle for a single turn of a DDH coil.

The resulting resistance of the machined conductor is significantly smaller than a round wire that would fit in the thickness given by the cylinder. Already a square has about 25% more area than its inscribed circle. But more important is the effect that the machined conductor is significantly wider in sections that are perpendicular to the coil axis and do not contribute to the generation of a transverse field. The machined conductor also eliminates any constraints from the wire or cable manufacturing process, and arbitrary bending radii of the conductor are possible. As for the DH coil configurations DDH coils have high intrinsic mechanical robustness, since the conductor completely surrounds the coil aperture as in solenoidal windings.

Material Choice

Depending on the application a large choice of materials is possible for the conductors and the support structures needed for DDH coils. For normal conducting coils copper or aluminium are natural choices as conductors. If the coil has to operate at very high temperatures, in the range of several hundred degrees Celsius, carbon or tungsten can be used. Advanced composite conductors like carbon nanotubes in a Cu matrix, which are currently under development [2] will lead to coils with unprecedented performance. These conductors can have a resistivity that is 10 times lower than Cu, and enable performances that are normally only possible with superconductors. The support structures needed for some DDH coils can be made from ceramic materials, which allow high operational temperatures and yield very high radiation hardness.

Field Uniformity

Based on double-helix technology, which produces almost pure multipole fields away from the coil ends, DDH coils show excellent field uniformity. Furthermore, computer controlled machining of the conductor path with possible variation of conductor cross section allows for unique field optimization potential. No field forming spacers are required, and high field uniformity can be achieved without cost penalty.

Possible field configurations include, dipoles for beam steering, quadrupoles for beam focusing, higher-order multipole magnets for beam optics corrections, combined function magnets (typical dipole with superimposed quadrupole), twisted dipoles for polarized beams, twisted quadrupoles for multi-directional focusing. If needed, bent magnets can be produced or those with flared ends.

Conductor Cooling

As seen in Figure 3, the conductor cross section varies along each turn of the helical winding and is largest, where it does not contribute to the transverse magnetic fields that form dipoles, quadrupoles and higher-order multipole fields. As a result the resistive losses are automatically small when a conductor segment does not contribute to the required magnetic field. Figure 4 shows the temperature distribution along one conductor turn, indicating the reduced temperature in the wider part of the conductor.

The space between the concentric cylinders forming the DDH coils are used as cooling channels with large cross section. In contrast to conventional Cu coils made with hollow conductor, very little pressure is needed to force the coolant through a DDH coil, and very small temperature gradients exist along the path of the coolant. Additionally, the machined groove between adjacent turns can be used as a cooling channel and the conductor can be cooled from 3 sides. Cooling efficiency can be further improved by using heat conducting support structures.

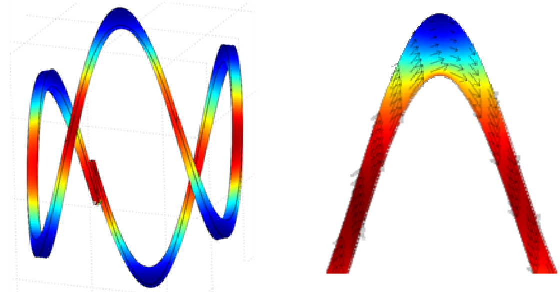

Figure 4: Left: Temperature profile along a single turn of a DDH coil, showing reduced temperatures, where the conductor width is largest. Right: Current density distribution near a conductor bend.

Dimensional Scaling

The DDH Technology is applicable to a wide range of coil dimensions. Laser or electron beam machining enables unprecedented coil miniaturization and coils with dimensions of a few mm are feasible. Figure 5 (Left) shows small dipole coils with apertures of about 1 mm. DDH coils also lend themselves for large dimensions, and machining the conductor avoids the cross section distortions that result from bending prefabricated conductors. The required cylinders for large coil aperture are formed and seam welded.

Figure 5: Left; Miniature DDH coil for medical applications. Right: Larger quadrupole coil with an aperture of 100 mm.

Achievable Current Densities

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 (see Figure 6). The complete magnet assembly with the water containment vessel is shown in Figure 7. As shown in Table I and Table II, 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 that fit into each other forming one unit for horizontal and vertical beam steering.

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

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, and even higher currents and fields are possible.

CONCLUSIONS

A novel magnet technology has been developed in which the field generating current path is machined out of conductive cylinders. This technique offers complete control over the conductor cross section along its path and the usual constraints caused by wire manufacturing are eliminated. The unprecedented cooling efficiency in these coils enables current densities in water cooled copper conductor in excess of 100 A/mm^2. Such current densities have been achieved in long term tests with DC operation.

Based on double-helix coil configurations arbitrary multipole orders of magnets and combined function magnets with high field uniformity are possible.

A computer controlled manufacturing process on conventional CNC machines, and the lack of magnet-specific tooling makes these magnets highly cost-effective. With advanced manufacturing techniques, using lasers or electron beams, unprecedented miniaturization of coils is feasible. DDH coils also allow operation at temperatures of several hundred degrees Celsius and high ionizing radiation.

REFERENCES

[1] R. B. Meinke et al., "Superconducting Double-Helix Accelerator Magnets", IEEE Proceedings of PAC 03, 2003, Vol.3, pages 1996-1998.
C. Goodzeit et al., IEEE Proceedings of PAC 07, Vol.1, pages 561-563.

[2] D. Elcock, "Potential Impacts of Nanotechnology on Energy Transmission Applications and Needs", Argonne Technical Report, No. ANL/EVS/TM/08-3, 2008, DOE-Information Bridge.