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ALTERNATE METHODS FOR FIELD CORRECTIONS IN HELICAL SOLENOIDS*

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Abstract

Helical cooling channels have been proposed for highly efficient 6D muon cooling. Helical solenoids produce solenoidal, helical dipole, and helical gradient field components. Previous studies explored the geometric tunability limits on these main field components. In this paper we present two alternative correction schemes, tilting the solenoids and the addition of helical lines, to reduce the required strength of the anti-solenoid and add an additional tuning knob.

INTRODUCTION

Helical cooling channels (HCC) based on a magnet system with a pressurized gas absorber in the aperture have been proposed as a highly efficient way to achieve 6D muon beam cooling [1-2]. The cooling channel was divided into four sections to provide the total phase space reduction of muon beams on the level of 10^5-10^6, and to reduce the equilibrium emittance each consequent section has a smaller aperture and stronger magnetic fields.

The strength of the solenoid (*Bs*), helical dipole (*Bt*), and helical gradient (*G*) fields are strongly dependent on the coil and helix geometry [3-6]. The ratio *Bt*/*G* is fixed by the geometry but the absolute value can be adjusted independently from *Bs* by the means of an external anti-solenoid. However, this can be quite challenging due to the required magnetic field strength of this solenoid [4]. An additional knob capable of adjusting the ratio *Bt*/*G* independently of the coil geometry is highly desirable.

TILTED COILS

The coils for the helical cooling channel produce a dipole and gradient which rotates with the period of the helix. Two tilting schemes, shown in figure1, and their effect on the two transverse field components, were studied. In the "pitch" tilting arrangement, the coils were rotated about an axis at each coil which was tangent to the helix. The "yaw" tilting is about the axis of the angle to the rotated coil position, or an axis that is perpendicular to the pitch tilting.

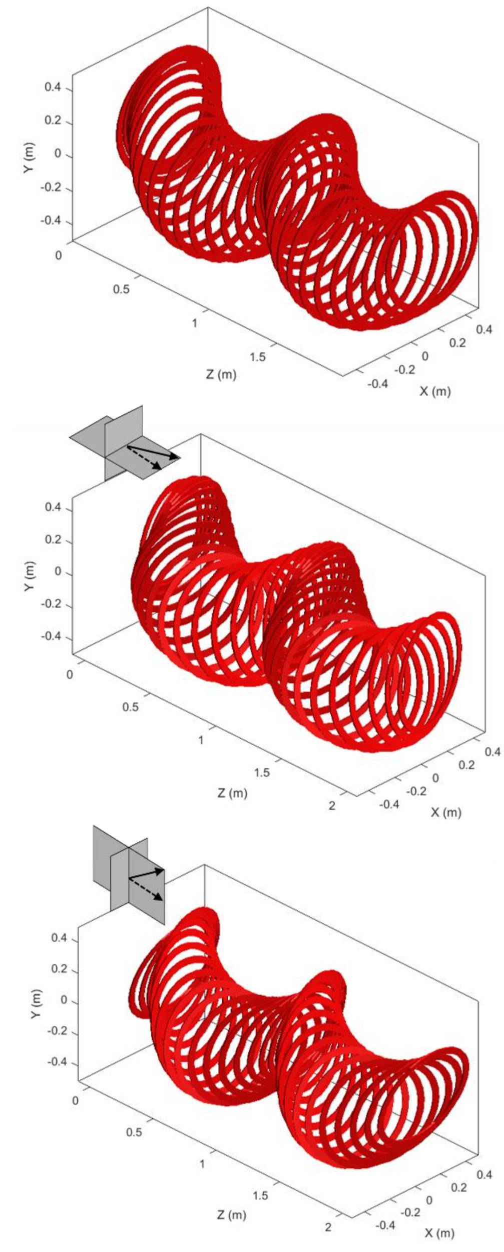

Figure 1: Helical coil arrangement of the non-tilted coil (top), Yaw tilt (middle), and Pitch tilt (bottom). The spacing between the coils and tilt were exaggerated for clarity.

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The coils were spaced apart to accommodate each coil tilting about a slightly rotated axis and this spacing was kept constant for both tilting schemes and in the non-tilted case for comparison. The coil spacing was kept to less than half the coil width to limit the dipole and gradient ripple [5], limiting the tilt angle to +/- 5 degrees before the coils interfere. The tilt simulations were performed using SolCalc [7] with *Bs* normalized to 1. For both tilting directions, the period (λ) was set to 1 m and *Bt* and *G* were studied as a function of aperture radius (*IR*) and coil thickness (*DR*).

The pitch tilt produced the largest effect on both the dipole and gradient components. The top two plots in Figure 2 show *Bt* with the dipole field from the non-tilted case subtracted out. The results of the pitch tilt on the *G*, also with the non-tilted gradient subtracted, are shown in the bottom two plots. Figure 3 shows the same information for the yaw tilt case. The yaw tilt results were about an order of magnitude smaller than the pitch tilt for both *Bt* and *G*.

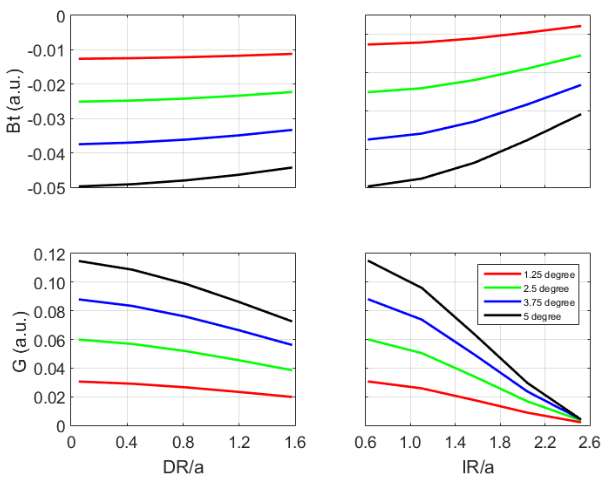


Figure 2: *Bt* (top) and *G* (bottom) as function of *DR*/*a* (left) and *IR*/*a* (right) for the pitch tilt case

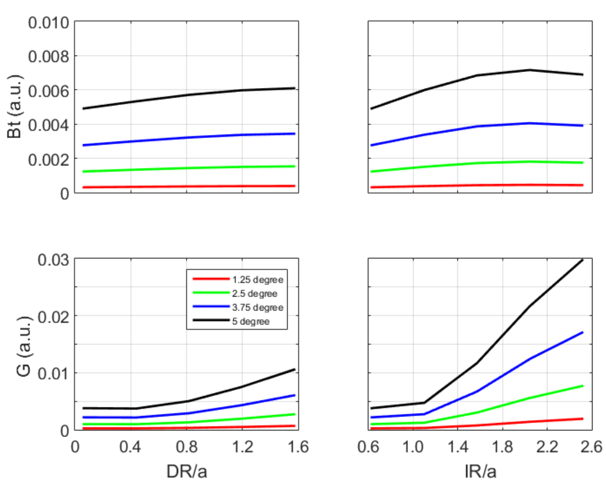


Figure 3: *Bt* (top) and *G* (bottom) as function of *DR*/*a* (left) and *IR*/*a* (right) for the yaw tilt case

HELICAL WIRES

Another option investigated for controlling the dipole and gradient field components was the addition of helical wires on the inner bore of the helical coils. Wires were placed at four positions: 0, 90, 180, and 270 degrees around the center of the coil (see figure 4).

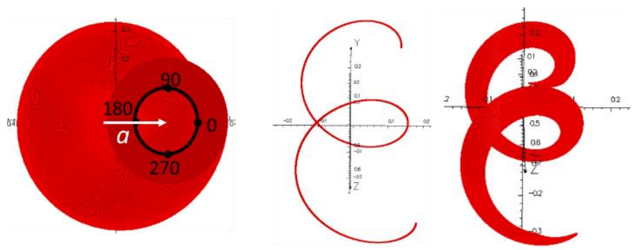


Figure 4: End view of the helical cooling channel showing the four positions for the added helical lines (left). An example of a single helical line and twenty lines (right).

The number of wires added to each position was varied from 1 to 20, which corresponds to an azimuthal coverage of about 2.8 to 56 degrees on the inner radius of the coil. The total current was held constant for all wire arrangements. Figure 5 shows the dipole field produced at the center of the helical solenoid from a single wire placed at each of the four locations, where in this setup, the desired dipole field is in the y direction. The only locations which add to the dipole field and gradient in the correct direction are the 0 and 180 degree positions.

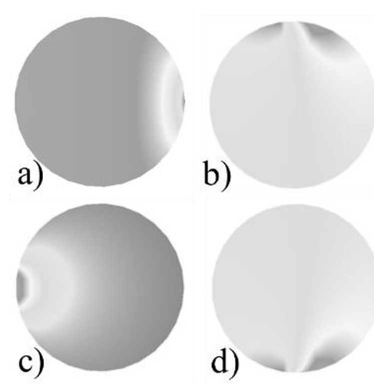
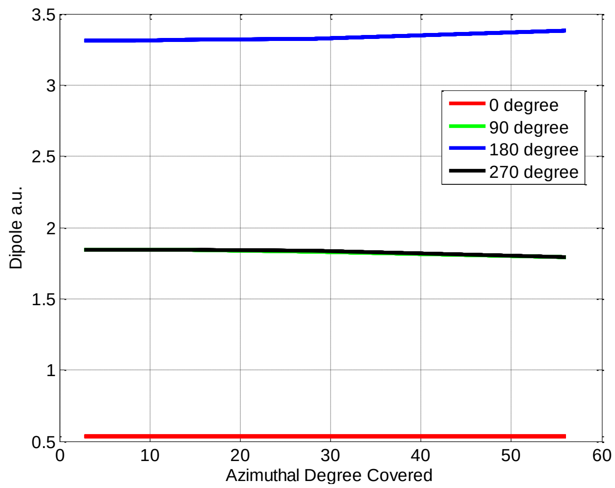


Figure 5: Dipole field from a single helical wire placed at a) 0 degrees, b) 90 degrees, c) 180 degrees, and d) 270 degrees.

As with the tilted studies, the solenoidal field component produced by the wires was normalized to 1. Varying the number of wires centered about each location had very little effect compared to concentrating the current in a single wire as is shown from the relatively flat lines in figure 6. The large difference in the 0 degree and 180 degree placement in both the dipole and gradient is a result of helical line following a tighter helix at the 180 degree position.



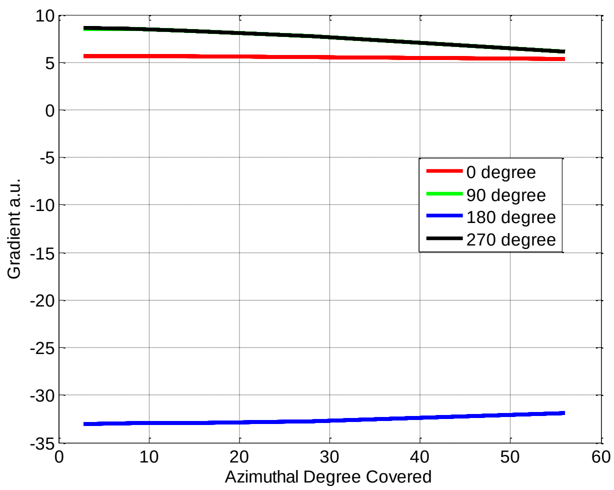


Figure 6: Dipole (top) and Gradient (bottom) produced by the addition of helical lines on the inner bore.

CONCLUSION

Two alternative schemes were considered to reduce the required strength of the anti-solenoid and to add an extra adjustment knob; tilting the coils and adding additional helical wires. The most promising of these methods was the pitch tilted coils. The coil can be tilted in the positive pitch direction to produce an increase in the gradient and a decrease in the dipole. The coils can also be tilted in the negative pitch direction to produce and increase in both dipole and gradient. The same is true in the yaw direction, with less effect. The helical wires could be used to adjust the dipole to gradient ratio, but this would come with the cost of requiring an even larger anti-solenoidal field. One major drawback in both of these methods, is the complication introduced to the winding. Also, once the geometry is tilted, they would no longer be adjustable.

REFERENCES

[1] Y. Derbenev and R. Johnson, “Six-Dimensional Muon Cooling Using a Homogeneous Absorber”, Phys. Rev. ST AB, 8, 041002, 2005.

[2] K. Yonehara et al, “Studies of a Gas-Filled Helical Muon Beam Cooling Channel”, Proc. of EPAC2006, Edinburgh, Scotland, 2006.

[3] A. Zlobin et al., “Design Studies of Magnet Systems for Muon Helical Cooling Channels”, Proceedings of EPAC08, Genoa, 2008

[4] M. Lopes et al., “Studies of the High-Field Section for a Muon Helical Cooling Channel”, Proc. of PAC2009, Vancouver, BC, Canada, 2009.

[5] M. Lopes et al., “Studies of High-field Sections of a Muon Helical Cooling Channel with Coil Separation”, Proc. of PAC2011, New York, NY, USA, 2011.

[6] M. Lopes et al., “Magnetic Design Constraints of Helical Solenoids”, Proceedings of IPAC14, Dresden, Germany, 2014.

[7] M. L. Lopes, “SolCalc: A Suite for the Calculation and the Display of Magnetic Fields Generated by Solenoid Systems”, Proc. of IPAC2014, Dresden, Germany, 2014.