STUDIES OF HIGH-FIELD SECTIONS OF A MUON HELICAL COOLING CHANNEL WITH COIL SEPARATION*

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Abstract

The Helical Cooling Channel (HCC) was proposed for 6D cooling of muon beams required for muon collider and some other applications [1]. HCC uses a continuous absorber inside superconducting magnets which produce solenoidal field superimposed with transverse helical dipole and helical gradient fields. HCC is usually divided into several sections each with progressively stronger fields, smaller aperture and shorter helix period to achieve the optimal muon cooling rate. This paper presents the design issues of the high field section of HCC with coil separation. The effect of coil spacing on the longitudinal and transverse field components is presented. The paper also describes methods for field corrections and their practical limits.

INTRODUCTION

The high-field section of the helical cooling channel (HCC) based on a helical solenoid (HS) was studied in [2]. That work summarizes the limits of the tunability of a HS in the case of a continuous distribution of coils along the longitudinal axis. There are several proposals [3] on incorporating the RF cavity (or its coaxial feed) into the magnet system and they usually involve coil separation along the longitudinal axis. The coil separation can be done in three different ways. Figure 1 shows these geometries and the geometry without coil separation.

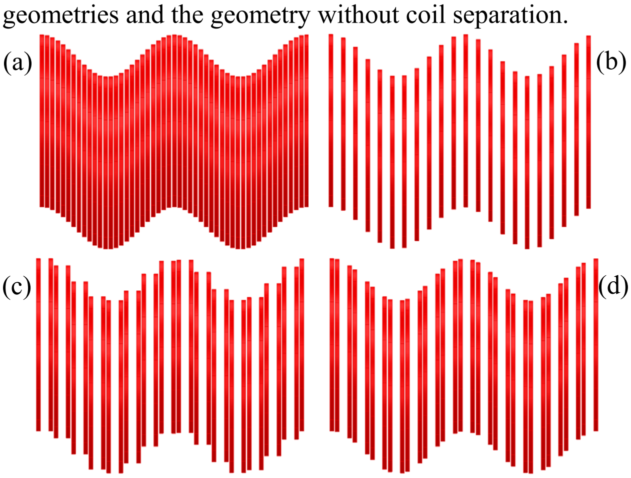

Figure 1: Helical solenoid (a) without separation, (b) spacing type 0, (c) spacing type 1, (d) spacing type 2.

The coil separation type 0 is very challenging from the winding point of view since the connections of leads between each single "pancake" is very difficult. The type 1 is the same one proposed in [3]. It consists of a basic unit composed of coil-spacer-coil. Each unit is then placed along the helix. Type 2 has as basic unit double "pancake" (in helix) and the spacer (also in a helix). This type imposes a limitation in the aperture available - for example, for placement of the RF cavity - since the apertures of two consecutive units have an offset.

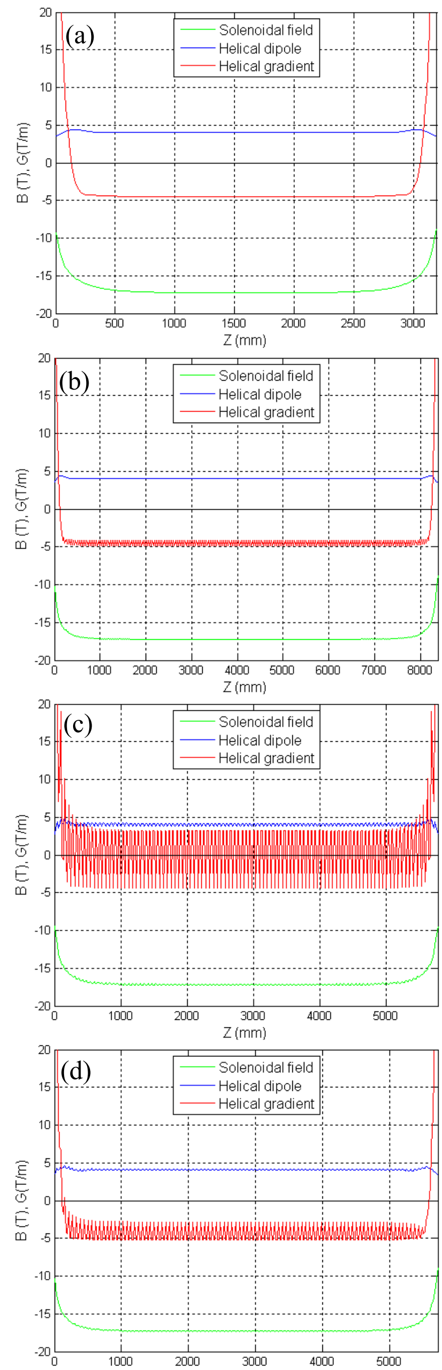

Figure 2: Magnetic field performance (a) continuous, (b) type 0, (c) type 1, (d) type 2.

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Figure 2 shows the magnetic field components (B_z, B_t, and G) along the length of a HS for each one of the coil separation types described. As can be seen, the performance in terms of the solenoidal field component (B_z) and helical dipole (B_t) are very similar. The helical gradient (G), however, is the one that will be affected the most.

TUNABILITY

In this work, we have assumed the type 1 geometry. This geometry is the one being considered as the baseline design [3] and it presents the highest ripples. The helical gradient ripples can be tuned by modifying the geometry. This is done by changing the coil longitudinal thickness or changing the coil helix period. It was also assumed that the target values are the ones for the last section described in [4]. The geometry is the one described in [2]. Table 1 summarizes the parameters and geometry of the high-field section of the HS.

Table 1: Parameters for the High-Field Section of the HS

Parameter	Unit	Value
Section length	m	40
Helix period	m	0.40
Orbit radius	m	0.064
Solenoidal field, B_z	T	-17.3
Helical dipole, B_t	T	4.06
Helical gradient, G	T/m	-4.5
Coil radial thickness	mm	210
Coil longitudinal thickness (HTS YBCO tape width)	mm	12
Inner diameter	mm	100

Coil Longitudinal Thickness

For the data presented in Figure 2, it was assumed that the coils have 12 mm longitudinal thickness. The mean value can be tuned by changing this parameter. Figure 3 shows the helical gradient mean value as well as the magnitude of the ripple as function of the coils longitudinal thickness. In the same picture, it was considered two spacer lengths 15 and 30 mm.

Thinner coils tend to tune the gradient to the target value and, at the same time, the ripple is dramatically reduced. Wider coils also reduce the ripple (although not as fast as thinner coils) and also tune the gradient to the target.

The practical limits for the tuning are given by the helical dipole and the operation margin. Figure 4 shows the helical dipole as function of the coil width and figure 5 shows the operation margin as function of the coil width for different spacer lengths. For the operation margin it was considered the short sample limit (SSL) for a 2G high-temperature superconductor (HTS) YBCO tape from Super Power [5].

Wider coils impact the ripple of the helical dipole, even though the magnitude of the ripples is relatively lower compared with the magnitude of the field. On the other hand, thinner coils will impact the performance of the magnet due to the reduction of the operational margin. Wider coils will also have its operation margin reduced.

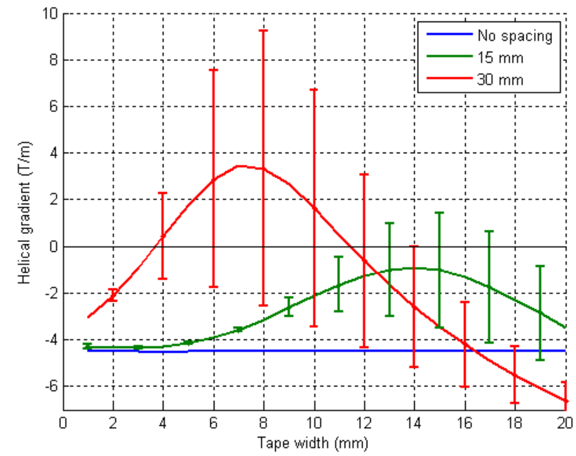

Figure 3: Average G as function of the coil longitudinal thickness. The error bars represent ripple amplitude.

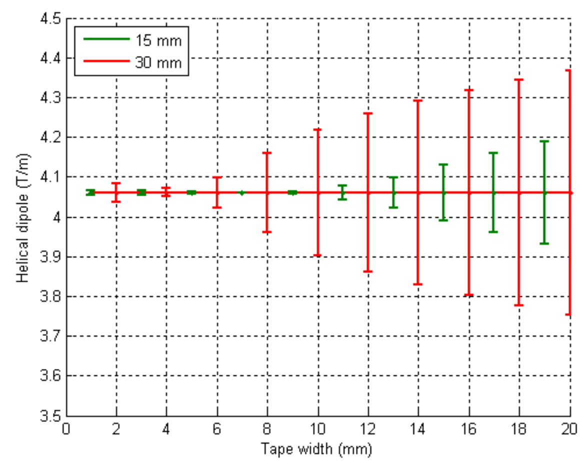

Figure 4: Average B_t as function of the coil longitudinal thickness The error bars represent ripple amplitude.

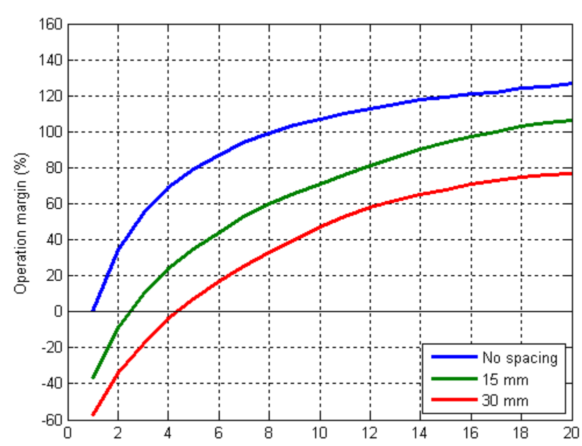

Figure 5: Operation margin as function of the coil longitudinal thickness.

Coil Helix Period

The gradient can also be tuned by changing the helix period. Changes in the helix period also change the radius of the helix [1]:

$$k = \frac{2\pi}{\lambda}, \boldsymbol{\kappa} = k.a \qquad (1)$$

where k is the wave number, λ is the helix period, a is the radius of the helix, and $\boldsymbol{\kappa}$ is the helical reference pitch. When $\boldsymbol{\kappa} = 1$, it gives the best cooling results [5].

The results of the helical gradient as function of the helix period can be seen in Figure 6. It can be seen that longer periods results in the reduction of the ripple and the helical gradient approaches to the target value.

Figure 7 shows the average gradient as function of the coil longitudinal thickness and helix period for a 30 mm spacer. Figure 8 shows the magnitude of the ripple in G as function of the coil longitudinal thickness and helix period for a 30 mm spacer.

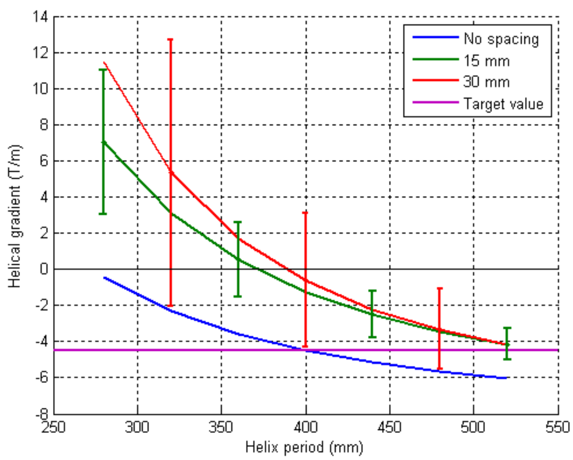

Figure 6: Average G as function of the helix period. The error bars represent ripple amplitude. It was assumed that the longitudinal thickness of the coils is 12 mm.

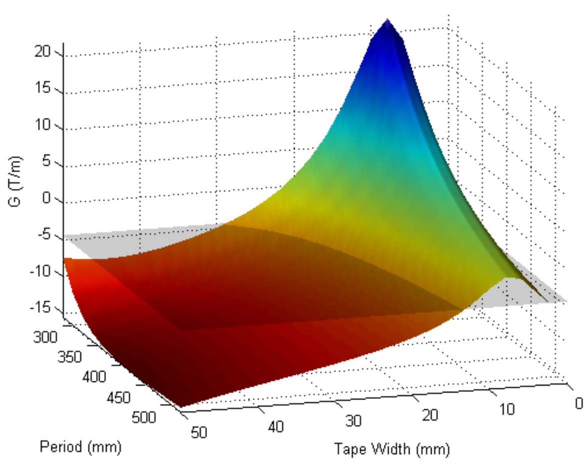

Figure 7: Average G as function of the helix period and the coil longitudinal thickness. The gray plane represents the target value. It was assumed that the longitudinal spacer is 30 mm.

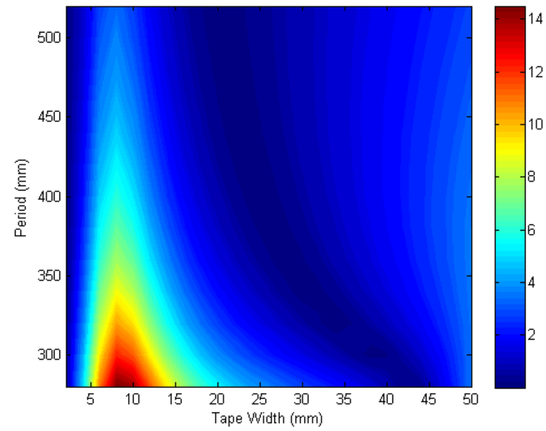

Figure 8: Magnitude of the ripple in G as function of the helix period and the coil longitudinal thickness.

CONCLUSIONS

The magnetic performance of the helical solenoid with coil separation was studied. The separation could be done in three different ways and the ripples in the gradient could be very different. The geometry should be carefully described and studied during the beam cooling simulations. The design that is currently being considered [3] is attractive from the design and fabrication viewpoint. However, it presents ripples in all three components, in particular in the helical gradient which could be quite large. Moreover, the average gradient could be off, which could affect the cooling performance.

This work summarized methods to tune the gradient regarding the average value and the ripple. The coil longitudinal thickness and the helix period can be used to tune G. Thinner coils tend to reduce the ripples and also bring G to its target value. However, this technique reduces dramatically the operational margin. Wider coils can also reduce the ripple (not as much as thinner coils) and also tune the gradient to its target value. Longer helix periods reduce ripple and correct the gradient to the target value.

REFERENCES

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

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

[3] S. Kahn et al., "Incorporating RF into a Muon Helical Cooling Channel", Proc. of IPAC2010, Kyoto, Japan, 2010.

[4] K. Yonehara et al, "Studies of a Gas-Filled Helical Muon Cooling Channel", Proc. of EPAC2006, Edinburgh, Scotland (2006).

[5] V. Lombardo et al, "Critical current of YBCO Tapes and Bi-2212 Wires at Different Operating Temperatures and Magnetic Fields", IEEE Trans. Applied Superconductivity (2011).