INCORPORATING RF INTO A MUON HELICAL COOLING CHANNEL*

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Abstract

A helical cooling channel (HCC) consisting of a pressurized gas absorber imbedded in a magnetic channel that provides solenoidal, helical dipole and helical quadrupole fields has shown considerable promise in providing six-dimensional cooling for muon beams. The energy lost by muons traversing the gas absorber needs to be replaced by inserting RF cavities into the HCC lattice. Replacing the substantial muon energy losses using RF cavities with reasonable gradients will require a significant fraction of the channel length to be devoted to RF. However to provide the maximum phase space cooling and minimum muon losses, the HCC should have a short period and length. In this paper we examine an approach where each HCC cell has an RF cavity imbedded in the aperture where the magnetic coils are split to allow for half of the cell length to be available for the RF coupler and other services.

INTRODUCTION

A muon beam cooling technique, using a continuous gaseous hydrogen absorber inside a helical solenoid channel is one of the cooling approaches being considered for a muon collider. This approach has shown promise in both analytical [1] and simulation [2] studies. A muon collider requires a reduction of muon beam phase space by a factor of 10^6. The implementation of this helical solenoid channel for muon cooling requires the development of high field solenoid magnets with relatively large apertures to be able to contain RF cavities [3] to replace the energy lost by muons traversing the absorber. The HCC channel that is being considered is filled with 180 atm (room temperature equivalent) pressurized H_2 gas along with 60 µm Be RF windows act as an absorber for the cooling process. A 200 MeV/c muon traversing the channel will lose energy with dE/dx=8.8 MeV/m along its path. With the beam synchronized to RF cavities at 140° phase, required peak electric gradient is 28 MV/m to replace the lost energy. This is a substantial amount of RF and it does not allow much free space in the lattice without RF. The pressurized gas provides a further benefit in suppressing breakdown in the cavities.

HELICAL SOLENOID DESIGN

The helical solenoid magnet system is comprised of short solenoid coils arranged along a helical path. The HCC is composed of eight sections with progressively shorter periods, higher frequencies and higher fields to continue the cooling as the emittance becomes smaller. The parameters describing the HCC sections [4] are given in Table 1. The field description of the HCC sections is shown in Table 2. $B_{Z,,}$ B_φ and dB_φ/dr are the solenoid field, helical dipole and helical field gradient, respectively calculated at the reference orbit. The ratio B_φ/B_Z is determined by the muon reference momentum and the HCC period. The field derivative at the reference orbit is determined by the value of the dispersion necessary to provide equal cooling decrements in each of the three dimensions.

Table 1: The parameters describing the HCC segments are shown.

Segment	*Start Z*	*Frequency*	$\kappa=P_\perp/P_{\|}$	*Period* λ
	m	MHz		m
1	0	325	1	1
2	40	325	1	1
3	49	325	1	0.9
4	129	325	1	0.8
5	219	650	1	0.5
6	243	650	1	0.4
7	273	650	1	0.3
8	303	1300	1	0.3

Table 2: The field parameters of the HCC segments.

Segment	B_Z	B_φ	dB_φ/dr
	T	T	T/m
1	-4.2	1.3	-0.5
2	-4.2	1.3	-0.5
3	-4.8	1.4	-0.6
4	-5.2	1.7	-0.8
5	-8.5	2.6	-2.0
6	-9.8	3.2	-3.1
7	-14.1	4.3	-5.6
8	-14.1	4.3	-5.6

Cavity Constraints

Incorporating RF cavities into the HCC lattice imposes constraints on the design of the magnetic channel. NbTi and Nb_3Sn conductors are proposed for coils in the lower field segments and they would most effectively operate at 4.3°K to achieve the necessary current density. The pressurized H_2 must operate above its boiling point at 20.4°K to remain gaseous. Also the RF cavities need to be cooled to remove the Joule heating generated in the cavity walls. This could be performed at 77° K using liquid N_2 which would require a thermal barrier between the cavity and the rest of the system. However, it may be possible to use force-flow pressurized H_2 gas as a refrigerant to cool the cavities.

The inner radius of the coils must be larger than the outer radius of the RF cavity. The outer radius of a

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pillbox RF cavity is related to its frequency by the expression $R = \frac{2.405v}{2\pi f}$, where v is the velocity of light in the absorber and f is the cavity resonant frequency. If the cavity is filled with hydrogen gas the radius is reduced by 3% because of the slower velocity of light in the dielectric gas. For a 325 MHz cavity the radius is 34.5 cm. The cavity radius can be reduced by as much as 50% by using ceramic dielectric material in the outer part of the cavity [5]. Table 3 shows parameters describing the geometry of the coils used to implement HCC segments 2 and 6. The coils of segment 2 could be wound using NbTi conductor. The segment 6 coils could be wound with Nb_3Sn or HTS conductor. The HTS conductor could be operated at a higher temperature than 4.2ºK.

Table 3: Parameters describing the geometry of specified HCC segments.

Seg	*a*	R_{coil}	R_{in}	R_{out}	L_{cell}	N_{cell}	J_{Eff}
	cm	*cm*	*cm*	*cm*	*cm*		A/mm^2
2	16	28	35	40	10	20	256
6	6.3	15.8	18	28	2.5	16	332.9

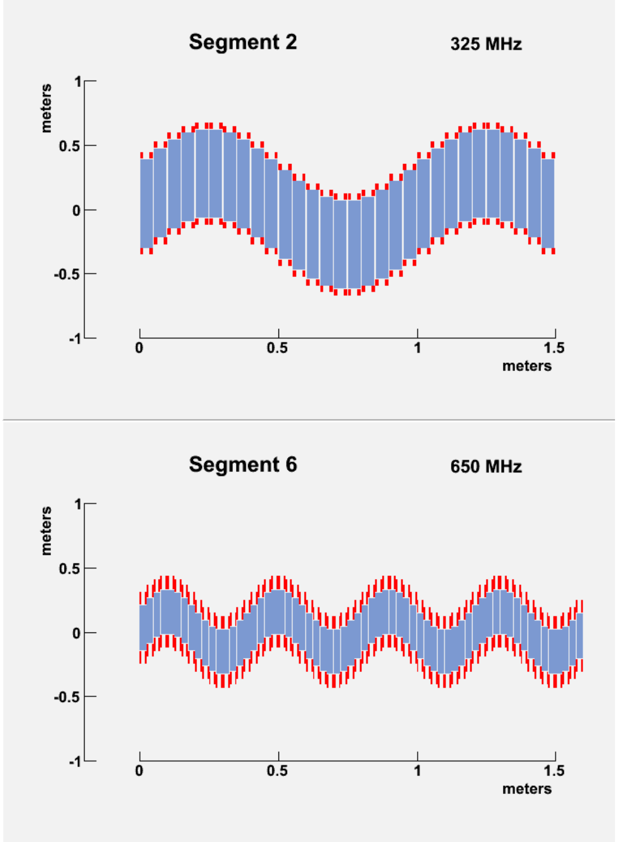

Figure 1: Sketches of layouts for HCC sections 2 and 6. Cavities are shown in blue and coils are shown in red.

Figure 1 shows sketches of HCC segments 2 and 6. There is one cavity and two coils per cell with each coil occupying 25% of the cell length. This allows 50% of the cell length available for RF services.

Cavity Design

It is assumed that each cavity will have its own coax feed which will fit into the open 50% of cell length available. Each cavity will have its own RF source that is phase matched to its neighbours. Two magnetic coils are attached to the outside of the cavities with some clearance for thermal isolation. Figure 2 shows a design concept for the cavity module with the coils affixed to the outside. Figure 3 shows inner details of the cavity including the magnetic coupling and a grid to form an open window. Also shown is a ceramic filled dielectric in the outer part of the cavity which reduces the outer diameter of the cavity. The use of the ceramic dielectric is being investigated, but its use is not certain at this moment. The use of a grid for the cavity window may be an optimum choice for use with the pressurized gas since it eliminates a pressure differences across the window. Figure 4 shows cavities incorporated into the helical solenoid coils.

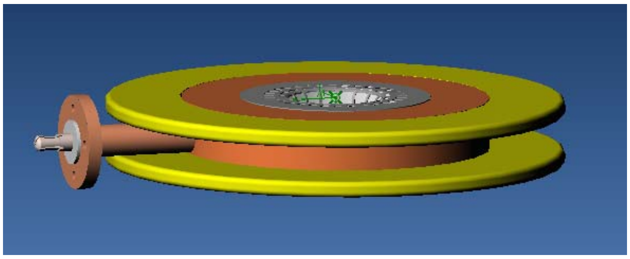

Figure 2: Design concept for RF cavity module.

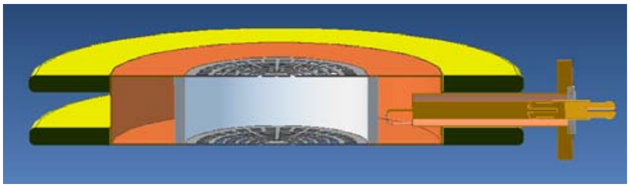

Figure 3: Cavity detail showing the interior of the cavity.

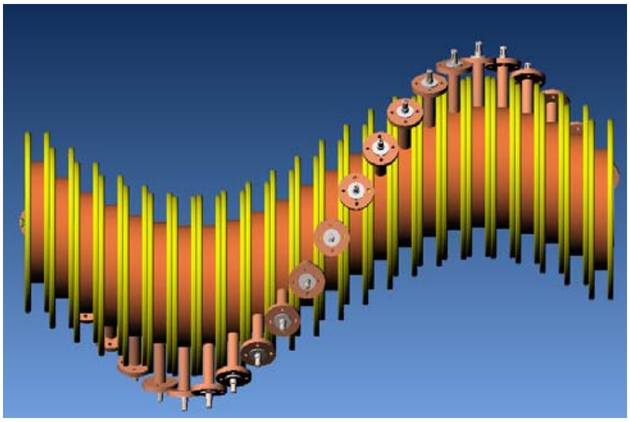

Figure 4: Sketch of helical solenoid coils with RF cavities included.

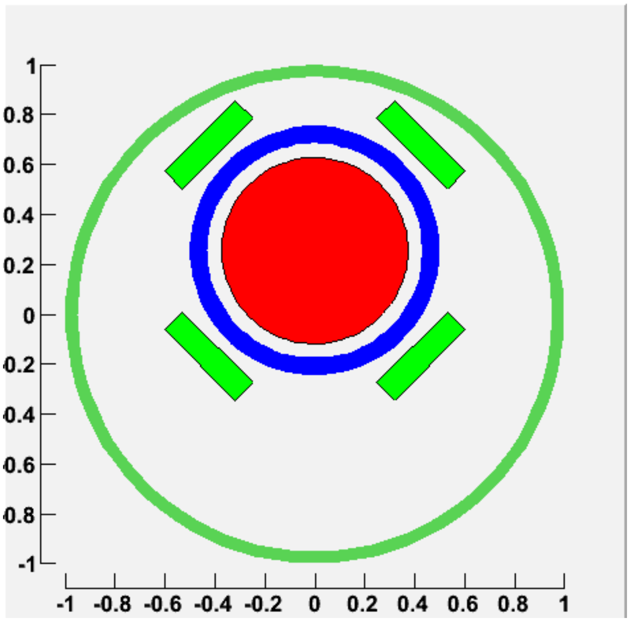

Figure 5: Cross-section of HCC magnet system showing the primary helical coil (blue), the global solenoid coil (green), quadrupole correction coils (yellow-green) and cavity (red).

CORRECTION COILS

The field values listed in Table 2 can not be achieved from the helical solenoid coils alone. As the helical solenoid coil radius is increased to accommodate the RF cavity the helical dipole component is decreased and the solenoid component is increased. In order to compensate for these effects, an additional solenoid coil outside the helical solenoid coils is added to adjust the ratio B_φ/B_Z. Figure 6 shows outer solenoid (in light green) which bucks the Bz from the HCC primary coil (shown in blue) to achieve the ratio. Also increasing the primary coil radius adjusts the quadrupole component dB_φ/dr. The dB_φ/dr should be set to provide the proper dispersion to the channel. Supplementary quadrupole coil as shown in figure 5 outside the primary HCC coils are added to provide this desired quadrupole. The primary HCC coils and the quadrupole coils rotate with the helical period while the global solenoid coils remain stationary.

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