

# MAGNET SYSTEM FOR HELICAL MUON COOLING CHANNELS\*

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## Abstract

A helical cooling channel consisting of a pressurized gas absorber imbedded in a magnetic channel that provides superimposed solenoid helical dipole and helical quadrupole fields has shown considerable promise in providing six-dimensional cooling of muon beams. The analysis of this muon cooling technique with both analytic and simulation studies has shown significant reduction of muon phase space. A particular channel that has been simulated is divided into four segments each with progressively stronger fields and smaller apertures to reduce the equilibrium emittance so that more cooling can occur. The fields in the helical channel are sufficiently large that the conductor for segments 1 and 2 can be Nb<sub>3</sub>Sn and the conductor for segments 3 and 4 may need to be high temperature superconductor. This paper will describe the magnetic specifications for the channel and two conceptual designs on how to implement the magnetic channel.

## INTRODUCTION

A muon beam cooling technique, using a continuous gaseous hydrogen absorber inside a magnetic channel consisting of helical dipole and solenoid fields has shown promise based on both analytical and simulation studies. The central orbit of the muon beam in this channel is a helix, which is produced by opposing forces from the solenoid and helical dipole fields acting on the muons. The implementation of this method of muon beam cooling requires the development of high-field superconducting magnets with relatively large apertures. These magnets are innovations in themselves.

The significance of this muon cooling technique is to create bright muons with small emittance for use in particle accelerators and storage rings. Of particular interest is the development of a muon collider which requires the reduction of muon phase space by a factor of 10<sup>6</sup>. Simulations have shown that the helical cooling channel (HCC) can provide a phase space reduction of 50000 [1]. The continuous gaseous energy absorber in the magnetic channel with dispersion can be used to cool the momentum spread of a muon beam by exploiting the fact that the higher momentum particles have longer path length and therefore larger energy loss. The muons lose energy as the beam is cooled. The longitudinal momentum is replaced by RF cavities resulting in a cooler beam. This approach to emittance exchange and six-dimensional cooling has been described analytically [2]. Simulation results showing the transverse, longitudinal and 6D emittances of a muon beam as a function of position along the cooling channel is shown in figure 1.

The cooling channel is divided into four segments, each with smaller and stronger magnets. As the emittance of the beam is reduced it approaches the equilibrium emittance where no more cooling can occur. By increasing the magnetic field, the equilibrium emittance is reduced allowing further cooling to take place.

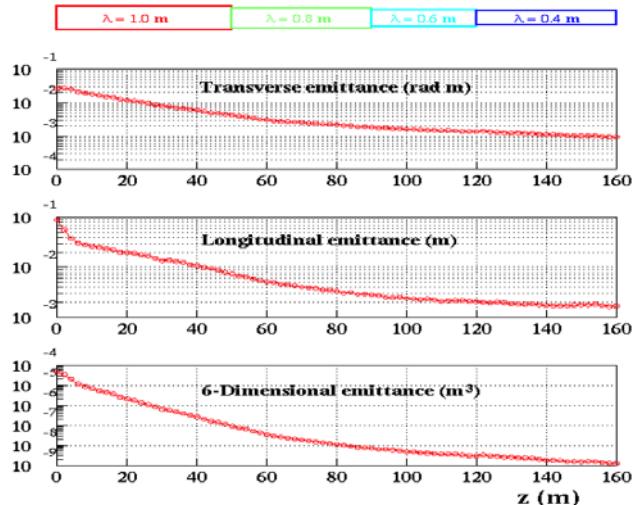


Figure 1: Emittance evolution of a muon beam in four sequential HCC segments. A cooling factor of 50000 has been achieved in a total channel length of 160 m.

## MAGNETIC COOLING CHANNEL

Table 1 summarizes the design parameters that describe the four sections of the cooling channel that is shown in Fig 1. Also shown in the table are the corresponding parameters for the MANX muon experiment, which intends to demonstrate cooling with a helical magnetic channel [3]. In the table we assume that the inner coils of the magnet start at a radius 2a, which is twice the reference orbit radius. The field from a helical dipole can be calculated analytically [2] giving:

$$b_\phi = 2b_d I_1(k\rho) \cos \psi / k\rho$$

$$b_\rho = 2b_d I_1'(k\rho) \sin \psi$$

$$b_z = -k\rho b_\phi$$

Where  $\psi = \phi - kz$  is the azimuth in the local rotated frame. Similarly the helical quadrupole field is described by

$$b_\phi = b_q I_2(2k\rho) \cos 2(\psi - \psi_2) / k^2 \rho$$

$$b_\rho = \frac{b_q}{k} I_2'(2k\rho) \sin 2(\psi - \psi_2)$$

$$b_z = -k\rho b_\phi$$

Series HCCs							
Parameter			Segment				
	1 <sup>st</sup>	2 <sup>nd</sup>	3 <sup>rd</sup>	4 <sup>th</sup>			
<b>L</b>	Length	m	50	40	30	40	4
<b><math>\lambda</math></b>	Helix period	m	1.0	0.8	0.6	0.4	2
<b>a</b>	Ref. orbit radius	m	0.16	0.13	0.095	0.064	0.255
<b><math>\kappa</math></b>	Helix pitch		1.0	1.0	1.0	1.0	0.8
<b><math>B_s</math></b>	Solenoid field	T	-6.95	-8.68	-11.6	-17.4	-4.39
<b><math>b_d</math></b>	Helix dipole	T	1.81	2.27	3.02	4.53	0.946
<b><math>b_q</math></b>	Helix quad	T/m	-0.35	-0.44	-0.59	-0.88	0.603
<b><math>b_s</math></b>	Helix sextupole	T/m <sup>2</sup>	0.031	0.039	0.051	0.077	0

It may be desirable to increase the radius to reduce losses of muons interacting with the coils, however increasing the radius increases the field on the coils significantly because  $I(k\rho) \sim e^{k\rho}$ .

We have investigated two schemes to implement the HCC magnet system. The first scheme that was examined was to wind helical dipole (and helical quadrupole) coils outside of a solenoid magnet as shown in Figure 2. The major drawback to this approach is that the radius of the coils must be large enough to include the helical beam (with an estimated radius of  $4a$ ) and the RF cavities. Since the helical fields grow exponentially at large radius, the fields necessary at the coil radius to produce the desired fields at the beam orbit would be unrealistically large.

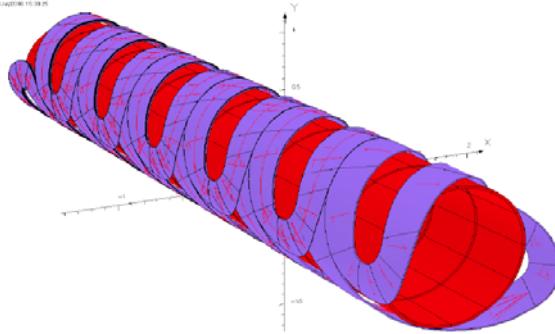


Figure 2: A scheme for winding helical dipole (and higher order) coils around solenoid coils.

The second approach would be to construct the HCC magnetic channel out of current rings. Figure 3 shows a drawing of the HCC built out of current rings. The geometric placement of the current rings is such that the desired solenoid, helical dipole and helical quadrupole fields are generated. There are several important advantages of this idea: 1) the ring aperture is only  $2a$ ,

half the value of the previous scheme, 2) The maximum field at the coils is significantly reduced, and 3) the extent of the fringing fields at the entrance to the channel is shorter making the matching problem into the channel easier.

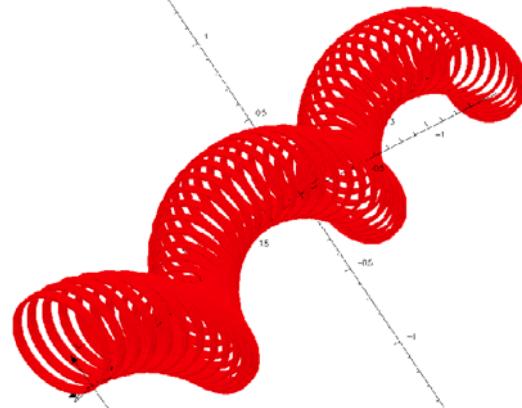


Figure 3: The arrangement of coils to form a helical solenoid channel. The configuration produces both the desired solenoid and helical dipole fields.

In order to have the flexibility to set  $\lambda$ ,  $\kappa$ ,  $B_s$ , and  $b_d$  independently, it will be necessary to have the current rings inside a global solenoid field. This global solenoid field is expected to be of more modest magnitude than that of the current rings. Figure 4 shows a comparison of the analytic field shown in red with that obtained from adding the contributions from all the current rings in the channel plus the global solenoid field shown in blue. The discrepancy at the beginning and end of the channel reflect that a short finite length channel was used. The current ring configuration represents the analytic field reasonably well. The current rings in this figure are closely spaced and there are 16 rings per helix period.

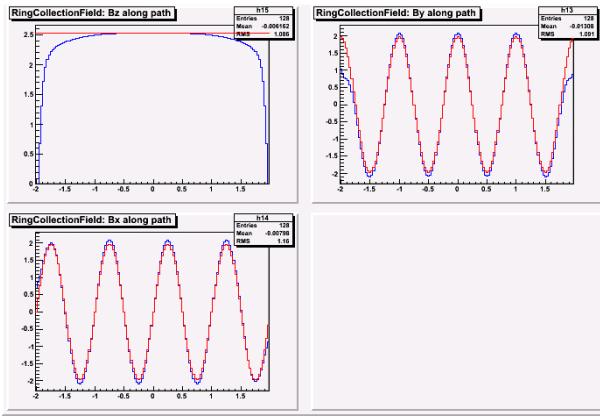


Figure 4:  $B_z$ ,  $B_y$ , and  $B_x$  are shown for the analytic field (red) and for the field constructed from current rings (blue). There are 16 closely spaced current rings per helix period.

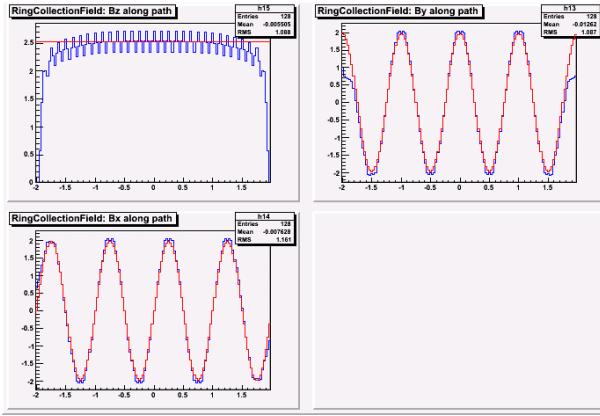


Figure 5:  $B_z$ ,  $B_y$ , and  $B_x$  are shown for the analytic field (red) and for the field constructed from current rings (blue). There are 8 rings per helix period with 60% of the space in the channel open.

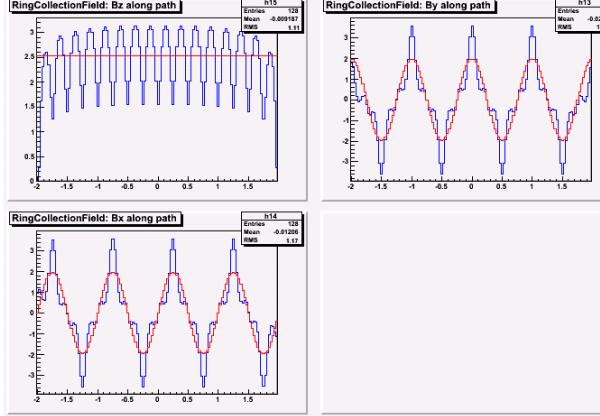


Figure 6:  $B_z$ ,  $B_y$ , and  $B_x$  are shown for the analytic field (red) and for the field constructed from current rings (blue). There are 4 rings per helix period with 60% of the space in the channel open.

## INCLUDING RF

A significant amount of RF acceleration will be needed to replace the energy loss of the muon beam. Two approaches are being investigated. If we can reduce the

radial size of an RF cavity, it can be placed inside the current rings. Taking advantage of the permittivity of  $H_2$  and using 400 MHz in the first segment of the HCC, it should be possible to fit the RF cavity inside the rings. The high frequency of the RF requires some longitudinal pre-cooling of the beam to fit into the RF bucket. Also there are design issues as to how to couple the RF power into the cavities. These issues are currently being studied. The other approach is to make space in the HCC lattice by using fewer current rings with spacing in between. In Figure 5, there is a 6.25 cm gap between adjacent 5 cm rings. This would allow approximately 50 % of the HCC free for RF cavities to be used for re-acceleration. In this figure there are 8 rings per helix period but the current in each ring is double of that in Figure 4. The field still matches the analytic field reasonably well except for some noise in the  $B_z$  distribution at a harmonic of the helix period. An attempt to use only 4 rings per helix period to allow more contiguous space for RF cavities is shown in Figure 6. This field distribution deviates from the nominal analytic form. In this scenario the RF cavities could be placed between the adjacent rings. The cavities could extent beyond the radius of the rings, which would allow easy access for the RF coupling. Furthermore, the lower frequency 200 MHz RF, which is better matched to the lattice could be used. This scheme does lengthen the cooling channel by about a factor of two over the continuous RF scheme, which means that there will be greater loss of muons through decays. We are in the process of simulating the cooling performance with both of these cases.

## CONCLUSIONS

The use of a pressurized gas filled helical magnetic channel appears to be a promising way to cool muon beams. We have shown a conceptual design of how to implement the magnetic lattice using current rings. We have also described how to incorporate RF cavities into the magnetic lattice to replace the energy lost in the  $H_2$  absorber.

## ACKNOWLEDGMENTS

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