# 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 lattice. Replacing the substantial muon energy losses using RF cavities with reasonable gradients will require a significant fraction of the channel length be devoted to RF. However, to provide the maximum phase space cooling and minimal muon losses, the helical channel should have a short period and length. In this paper we shall examine three approaches to include RF cavities into the HCC lattice: (1) Use higher frequency cavities that can be placed inside the magnetic channel, (2) Interleave cavities between magnetic coil rings, and (3) Place banks of RF cavities between segments of HCC channels. Each of these approaches has positive and negative features that need to be evaluated in selecting the proper concept for including RF into the HCC system.

## INTRODUCTION

A muon beam cooling technique, using a continuous gaseous hydrogen absorber inside a helical solenoid channel has shown promise based on both analytical and simulation studies. The goal of this muon cooling technique is to create bright muon beams 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 beam phase space by a factor of $10^6$ Simulations have shown that the HCC can provide a significant phase space reduction [1]. The implementation of this helical solenoid channel for muon cooling requires the development of high-field superconductor magnets with relatively large apertures [2]. The HCC must also accommodate RF cavities to replace the energy lost by the muons traversing the absorber. The HCC proposed is filled with 400 atm (room temperature equivalent) pressurized $H_2$ gas as the absorber. A 250 MeV/c muon traversing the channel will lose energy with dE/dx=14.3 MeV/m along its path. With the HCC proposed in [2] and the beam synchronized to RF cavities at 140º phase, the required peak gradient would be 31.4 MV/m to replace the lost energy. Since the pressurized gas suppresses the cavity breakdown, this gradient should be achievable for frequencies greater or equal to 200 MHz. At higher frequencies the achievable gradient can be higher. This is a substantial amount of RF and it does not allow much free space in the lattice without RF.

The parameters that describe the HCC are shown in table 1. There are three segments to the channel with successive segments having higher fields and smaller dimensions. As the beam nears the equilibrium emittance in its segment, it is necessary to change the parameters so that the cooling continues. Most of the work performed so far has concentrated on the first segment. The segment 1 parameters would be appropriate for the MANX muon cooling experiment that is being proposed [4]. The ratio $B_D/B_S$ is determined by the muon reference momentum and the HCC period. The field derivative at the reference orbit is selected to provide equal cooling decrements in the three directions [5].

Table 1: The parameters describing the three HCC segments is shown.

| Parameter | Period | $B_S$ | $B_D$ | $dB_D/dr$ | f | $R_{IN}$ |
|---|---|---|---|---|---|---|
| Unit | m | T | T | T/m | MHz | cm |
| $1^{st}$ HCC | 1.6 | -4.3 | 1.0 | -0.2 | 400 | 25.5 |
| $2^{nd}$ HCC | 1.0 | -6.8 | 1.5 | -0.3 | 800 | 16 |
| $3^{rd}$ HCC | 0.5 | -13.6 | 3.1 | -0.6 | 1600 | 8 |

The HCC magnetic channel will be implemented with short solenoid coils arranged along the helical reference path. This approach for the magnetic channel minimizes the magnetic field at the coils. Thus far, we have considered four schemes for incorporating RF cavities into the HCC. Each of these schemes has advantages and disadvantages. These schemes are being examined for cooling effectiveness, space requirements and ease of engineering. These schemes include:

[1] RF cavities placed inside the coil rings as shown in the figure.
[2] RF cavities interleaved between coil rings.
[3] Sequences of HCC cooling sections free of RF followed by blocks of RF cavities.
[4] A scheme of using open cavities in a traveling wave configuration.

## PHYSICAL CONSTRAINTS

Incorporating RF cavities into HCC lattice imposes constraints on the design of the magnetic channel. The NbTi, $Nb_3Sn$ and HTS conductors used for the magnetic coils would most effectively operate at 4.3ºK to achieve the necessary current density. The pressurized $H_2$ gas absorber must operate above the 33ºK critical temperature to insure that it remains gaseous. Also the RF cavities need to be cooled which could be at 77ºK if $N_2$ is used. It may be possible to the force-flow pressurized $H_2$ gas for

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cooling for certain configurations. There must be an insulating vacuum to maintain these temperature differences. Also the coils will be subjected to Lorentz forces that must be supported structurally and there must be structural support for the RF cavity walls to maintain the high cavity Q. Since the channel is filled with pressurized gas, the walls of the containment vessel must be thick enough to contain it. The containment wall thickness is dependent on the gas pressure at cryogenic temperatures and on the strength of the wall material. In addition room must be allowed to feed the RF into the cavity. Table 2 shows the radial spacing that was used to separate the coils from the RF cavities. We expect that the clearance between the cavities and the coils should be from 5-8 cm. This clearance has been used the analysis performed so far.

Table 2: Radial spacing needed to separate the RF cavities from the coils

| | Radial Space |
|---|---|
| Coil Support | 2 cm |
| Insulating Vacuum | 1-2.5 cm |
| High Pressure Containment | 3.1 cm |

## RF SCHEMES

### *Scheme 1: Placing Cavities Inside Coils*

This scheme makes effective use of the lattice space by placing RF cavities along the entire helical trajectory. A schematic of this arrangement is shown in figure 1 for the parameters in segment 1. The frequency of the cavity is restricted by the radial space. The nominal coil design radius for segment 1 is 25.5 cm, however in order to accommodate a 400 MHz cavity with radial clearance 35 cm was used. It is not possible to use 200 MHz cavities in this scheme, which would be desirable for cooling for the first segment of the HCC. When the coil radius is increased from the nominal radius the ratio of the field components $B_D/B_S$ and the quadrupole, $dB_D/dr$, will change enough to alter the HCC characteristics. We will describe how to use correction coils restore the field to nominal values.

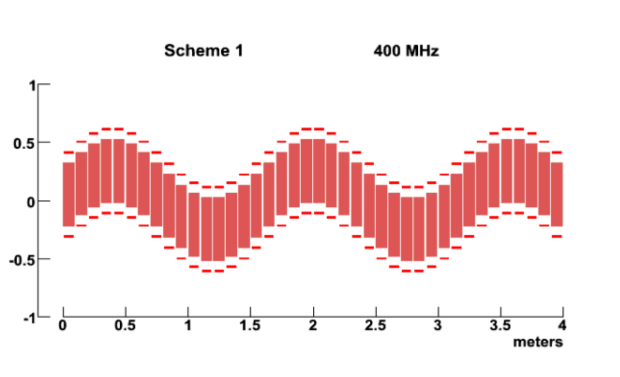


Figure 1: Layout of scheme 1 where the RF cavities are placed inside the helical solenoid coils. Dimensions are in meters.

### *Scheme 2: Interleave Cavities Between Coils*

This scheme places RF cavities between adjacent helical solenoid coils. Figure 2 shows sketches of the layout for 200 MHz and 400 MHz cavities. RF cavities would occupy half of the path length of the channel. Assuming the same RF gradient, the pressure of the $H_2$ gas would be reduced and the length of the channel would need to be increased. The smaller dE/dx of the absorber will mean a larger equilibrium emittance. Modifications to the magnetic lattice will need to be made to accommodate this scheme. There will be half the number of coils, each with twice the current to allow space for the RF cavities. It has been shown [3] that eight coils per helical period leaving 50% of the path open produces a similar field on the reference path to that of 16 coils per period place with no free space. There appears to be a higher order harmonic present, but does not significantly affect the field. A simulation using G4beamline [4] of a 50 m long vacuum filled helical channel with the parameters of HCC segment 1 in table 1 that shows that the eight-coil per period arrangement produces similar performance to the 16 coil period closely packed channel. Figure 3 shows the transmission and transverse emittance along this channel. The curves marked *h* corresponds to the channel with 16 closely spaced coils per period. The curves marked *f* and *g* correspond to eight coils per period with NbTi and $Nb_3Sn$ conductor. The eight coil case, which allow 50% of the space free for RF cavities plus additional space for clearance between the coils and the cavities, show that the transmission and transverse emittance are similar to the closely packed 16 coil per

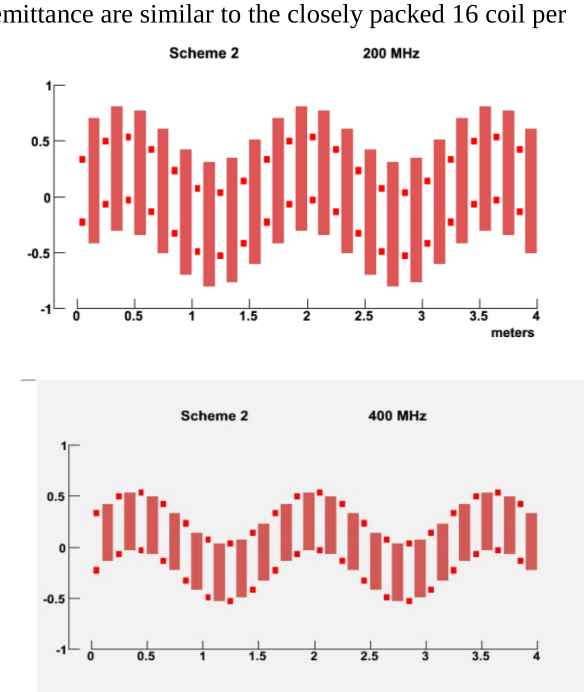


Figure 2: Layout for scheme 2 with RF cavities interleaved between solenoid coils. the upper (lower) figure shows the layout with 200 MHz (400MHz) cavities.

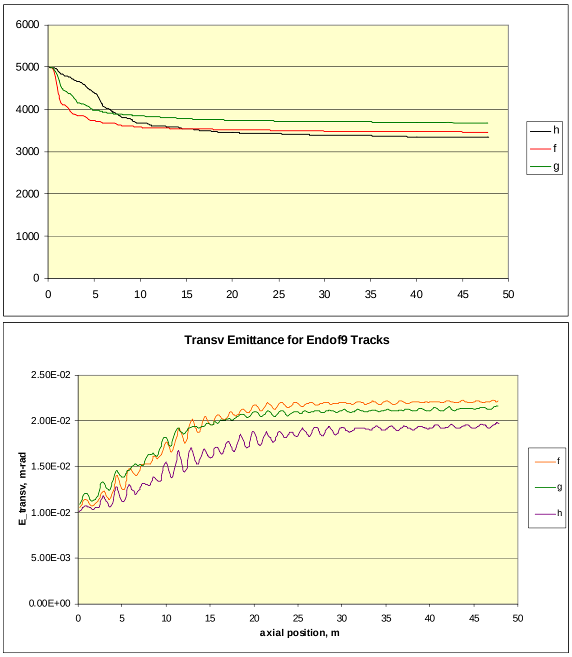


Figure 3: The upper (lower) plot shows the transmission (transverse emittance) of muons traversing a channel.

period configuration. The advantage to this scheme is that the cavities are easily accessible for wave-guides, however there are engineering difficulties with integrating the pressurized gas containment with the cavities.

### *Other Approaches*

Other approaches have also been investigated. A third scheme where the magnetic and RF parts of the channel are in separated blocks is favored from an RF engineering point of view, however has not been shown to be as effective for muon cooling. In addition there would have to be space allotted in the lattice for beam-matching sections from the HCC magnetic lattice to the RF cavities and back. There would be a significant energy loss along the HCC part of the lattice, which would have to be accommodated by varying the current in the coils along the channel. Furthermore a solenoid magnet will have to surround the cavities to hold the beam together.

We have also looked at whether the cavity windows can be removed, since they generate a significant heat load. In that case because the cavities are close enough to each other that the RF becomes a traveling wave and the phase velocity, which is 0.953c, must match the muon velocity. Unfortunately the muon momentum (325 MeV/c) is higher than desired.

## AN ATTRACTIVE IMPLEMENTATION

An implementation of scheme 1 that allows room for a 300 MHz cavity and an 8 cm clearance between the cavity and coils is shown in figure 4. The lower frequency is beneficial in that it improves the cooling performance. The figure shows two additional coils to accommodate the increased primary helical coil radius. As the coil radius is increased the helical dipole component is decreased and the solenoid component is increased. In order to compensate for these effects, an additional solenoid coil (correction coil 2) is added adjust the ratio $b_d/B_S$. Also, increasing the radius decreases the negative quadrupole component $db_d/dr$. A second correction coil (correction coil 1) is added to control the quadrupole. The primary coil, correction coil 1 and the cavity rotate along the longitudinal direction with the helical period, while correction coil 2 remains stationary. The inclusion of correction coils as described would be necessary with the other schemes in order to obtain the field quality.

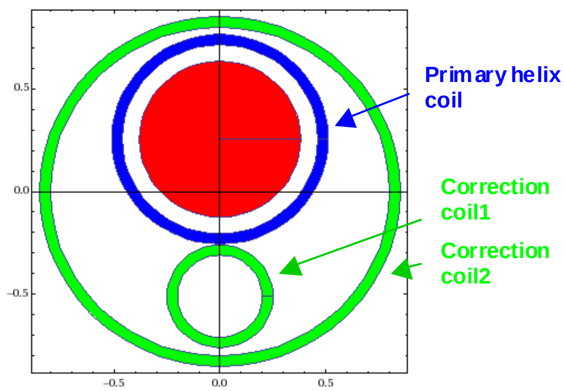


Figure 4: Schematic of scheme 1 design with radius increased to contain 300 MHz cavities. Correction coils are added to adjust field values and harmonics to their design values.

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