INTEGRATING THE MANX 6-D MUON COOLING EXPERIMENT WITH THE MICE SPECTROMETERS*

S.A. Kahn#, R.J. Abrams, C. Ankenbrandt, M.A.C. Cummings, R.P. Johnson, T. Roberts, Muons Inc., Batavia, IL, U.S.A.
K. Yonehara, Fermilab, Batavia, IL, U.S.A.

Abstract

The MANX experiment is to demonstrate the reduction of 6D muon phase space emittance using a continuous liquid absorber to provide ionization cooling in a helical solenoid magnetic channel. The experiment involves the construction of a short two-period long helical cooling channel (HCC) to reduce the muon invariant emittance by a factor of two. The HCC would replace the current cooling section of the MICE experiment now being setup at the Rutherford Appleton Laboratory. The MANX experiment would use the existing MICE spectrometers and muon beam line. This paper shall consider the various approaches to integrate MANX into the RAL hall using the MICE spectrometers. This study shall discuss the matching schemes used to minimize losses and prevent emittance growth between the MICE spectrometers and the MANX HCC. Also the placement of additional detection planes in the matching region and the HCC to improve the resolution will be examined.

INTRODUCTION

The MANX experiment is being proposed to test the theory of using a Helical Cooling Channel (HCC) to reduce the 6D phase space of a muon beam. The HCC cooling scheme uses a continuous absorber to provide ionization cooling in a helical solenoid channel [1]. The HCC will have an application in providing the six orders of magnitude in 6D muon phase space reduction that will be necessary for a muon collider. The HCC combines a solenoid field with helical dipole and helical quadrupole fields to provide a large acceptance channel. The most efficient approach to create the magnetic lattice for the HCC is to construct it from short solenoid coils arranged along the helical path as shown in figure 1. This has been shown to produce the desired field without an undesirably large magnetic field at the superconducting coils [2, 3]. The HCC proposed for a muon collider would use 400 atm. (room temperature equivalent) pressurized H_2 gas as the absorber. A muon traversing the channel would lose energy with dE/dx=14.3 MeV/m along the path. RF cavities would be inserted into the channel to replace the energy lost in the absorber. The RF requirements are substantial and would not allow much free space in the lattice without RF cavities. In the MANX demonstration experiment liquid helium is chosen as the absorber and there will be no RF cavities to replace the lost energy. These choices are made to both control costs and reduce the timeline to mount the experiment.*

The experiment has been proposed to be performed at the Rutherford-Appleton laboratory in the MICE hall at ISIS. The experiment would make use of the MICE muon beam with the magnets configured for a muon momentum of 350 MeV/c in the upstream MICE spectrometer. The muon beam line is shown in figure 1a. The upstream part of this beam line consists of two bending dipoles with a focusing solenoid magnet for a decay channel in between. Table 1 summarizes the beam parameters after the second bend and after the beam diffuser just before entering the upstream spectrometer. The pion contamination in the muon beam after the second bend is estimated to be 0.65%. MANX will use the upstream and downstream tracking spectrometers from MICE. The existing Cherenkov detector should be able to tag the residual pions in threshold mode. The downstream EM calorimeter or similar device will be used to tag decay electrons and give a muon momentum measurement to a certain precision. The MICE H_2 absorbers and RF cavities will not be used. They will be replaced with a short HCC channel and matching sections.

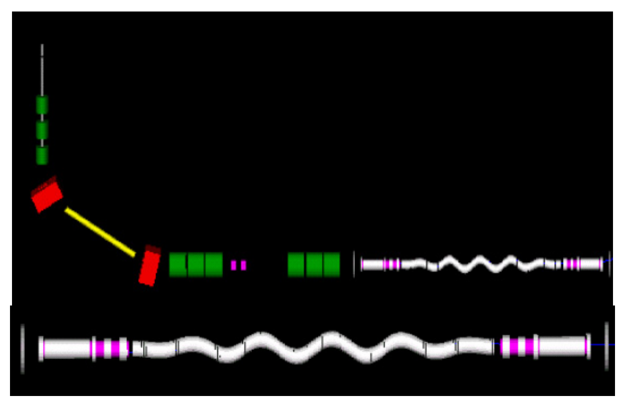

Figure 1: MANX baseline matching design. (a) MANX layout including beam line. (b) Enlarged MANX HCC with baseline matching sections.

Table 1: Parameters Describing the MICE Beam Adjusted for 350 MeV/c Muons

Parameter	*After 2nd Bend*	*After Diffuser*
P, MeV/c	375	341
σ_P, MeV/c	44	36
σ_X, mm	102	55
σ_Y, mm	56	41
σ_{Px}, mm	11	32
σ_{Py}, mm	7	30
σ_T, ns	0.29	0.47

* Work supported by U.S. DOE contract DE-AC02-07CH11359
#kahn@muoninc.com

HCC AND MATCHING SECTIONS

The experiment will incorporate a 4 m long HCC filled with liquid helium. The field is provided by a helical arrangement of solenoid coils which will provide B_Z=4.5 T and B_ϕ=1 T at the beginning of the channel. The field profile will fall off along the channel to match the energy loss from the absorber so that the beam maintains the helical geometry. Table 2 displays the parameters used to describe channel. The cooling performance is shown in figure 2, which gives the 6D emittance expected in the HCC. This is described in refs [4, 5].

Table 2: Parameters Describing the MANX HCC

Parameter	*Value*
Helical Period	2 meters
Pitch Tangent: $\kappa = P_\perp/P_\parallel$	0.8
Channel Length	4 meters
Reference Radius	0.255 meters
Initial Solenoid Field	4.5 T
Initial Helical Dipole Field	1 T
Initial Mean Muon Momentum	350 MeV/c
Solenoid Coil Inner Radius	0.25 meters

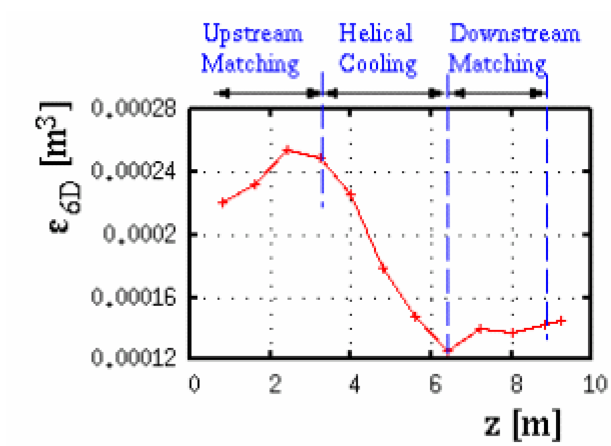

Figure 2: The 6D emittance is shown in the HCC and upstream and downstream matching regions. (This figure uses slightly different parameters than in Table 2).

The beam must be inserted into the channel at the reference radius and with the angular incline of the pitch. We have looked at a scheme where upstream and downstream of the HCC cryostat solenoid coils are place so as to gradually guide the beam from the orbit in the MICE spectrometers to reference orbit in the HCC. This matching transition uses 1.5 helical periods with fields approaching more than 6 T. Figure 1b shows the HCC with the 1.5 period long gradual matching sections. An attempt to shorten the transition distance requires a significant increase of the field which becomes impractical. The HCC plus matching section is 10.4 meters long which is 4 meters longer than the planned MICE cooling section. There exists enough space in the MICE hall to move the downstream spectrometer to accommodate the MANX cooling channel. Simulations show that, for a beam described by parameters in Table 2, 70% of the non-decaying muons in the upstream spectrometer will traverse the HCC cooling channel. The downside to this scheme is that the cost of the magnetic structure for the matching section will exceed that of the HCC cooling channel itself.

An alternate approach to the previously described matching scheme is to position the HCC off axis to the MICE spectrometers as shown in figure 3. In this scheme the HCC is positioned at 45º with respect to the MICE spectrometers so that muon beam from the spectrometer will enter properly oriented into the HCC. If no further beam matching is performed only 39% of the non-decaying muons will survive to the end of the HCC channel. Figure 4 shows that increasing the current in the MICE matching coils can improve this transmission somewhat. The figure gives the fraction of muons seen in the upstream spectrometer that survive to the end of the HCC as a function of the MICE matching coil current (shown as a scale factor times the nominal current). As the nominal MICE matching currents are near their current limits, some modification of these coils would be necessary for this improvement.

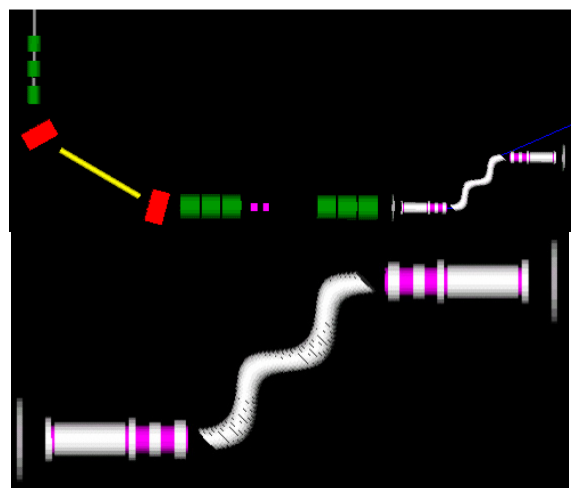

Figure 3: The HCC channel (lower) is shown positioned between the two MICE spectrometers. Also shown (upper) is the off axis HCC channel positioned with the entire MICE beam line.

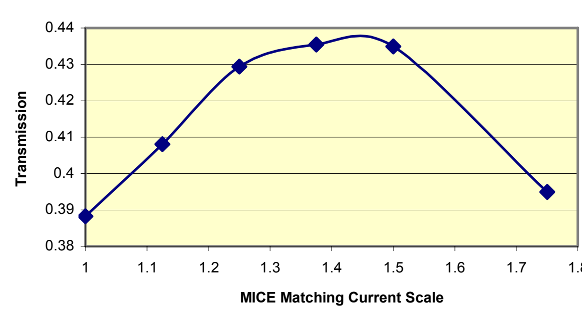

Figure 4: Muon transmission in the HCC channel as a function of the MICE matching coil current. The current is shown as a scale factor to be applied to the nominal MICE matching coil current.

Additional improvement can be achieved by also increasing the current in the first several HCC coils. Figure 5 shows the transmission as a function of a current scale factor applied to the first two HCC short solenoid coils. The several curves are for different scale factors applied also to the MICE matching coils. This off axis configuration can achieve a transmission of 55%. There is a concern that there will be large transverse magnetic forces between the HCC coils and the MICE spectrometer magnets with the off axis configuration that would have to be accommodated.

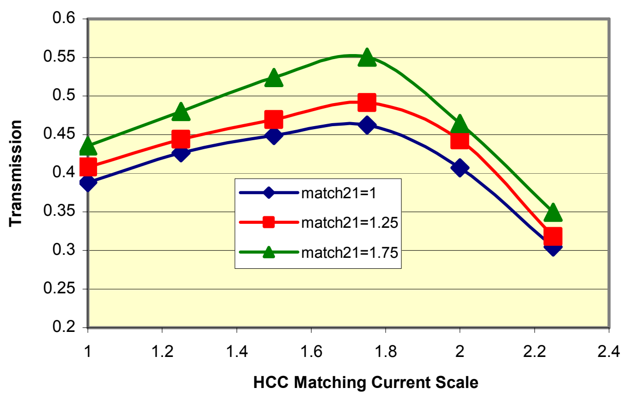

Figure 5: Muon transmission in the HCC channel as a function of the current in the first two HCC short solenoids. The current is shown as a scale factor to be applied to the nominal current in those solenoids. The different curves shown correspond to different currents in the MICE matching coils.

DETECTOR RESOLUTION

The MANX experiment will use the MICE spectrometer scintillating fiber (SciFi) planes which have an effective wire spacing of 1.65 mm when seven fibers are ganged together for the electronic readout. Timing measurements in MICE are provided by time-of-flight detectors with a resolution of 50 ps. The MANX experiment will add an additional two SciFi planes in each of the matching sections and four planes inside the HCC itself. The detector arrangement is described elsewhere [6, 7]. In a simulation study where a muon track first passes through the detector planes creating simulated detector hits. In a second pass the parameters describing the track are fit to these hits to reconstruct the track. This procedure provides the errors to the track parameters. Table 3 shows the errors that were found using the MICE planes alone and the MICE planes in conjunction with additional planes in the matching region. These errors are from measurement alone. They do not include errors related to the uncertainties of the field which are currently being studied. The errors quoted for the MICE SciFi tracker alone are valid for the center of that detector. When the variables are extrapolated to HCC the errors in those variables grow significantly. This is the justification for putting additional detection planes in the matching region. The errors shown for the Mice SciFi plus matching planes are calculated for the beam variables as seen in the matching region just before the entrance to the HCC cryostat. Using these track measurement errors one can obtain the expected error in the determination of the emittance. Table 4 shows the relative measurement errors of transverse and 6D emittance for these cases. In order to calculate the 6D emittance we have assumed that the incoming beam has a 0.8 ns time structure that would be representative of 200 MHz RF of an upstream phase rotation or pre-cooling section. These errors are more than adequate for the anticipated physics of the MANX program.

Table 3: Measurement Errors Expected from SciFi Detection Planes in MANX

Case	σ_X	σ_{Px}	σ_{Pz}
	mm	MeV/c	MeV/c
Upstream Mice SiFi Alone	0.74	1.3	1.0
Downstr. Mice SiFi Alone	0.95	0.94	0.4
Mice plus Matching Planes	2.4	3.0	1.7

Table 4: Relative Measurement Errors for Transverse and 6D Emittance

Case	$\Delta\varepsilon_{TR}/\varepsilon_{TR}$	$\Delta\varepsilon_{6D}/\varepsilon_{6D}$
Upstream Mice SiFi Alone	0.10%	1.44%
Downstream Mice SiFi Alone	0.32%	0.77%
Mice plus Matching Planes	0.28%	1.58%

REFERENCES

[1] Y. Derbenev and R.P. Johnson, "6-D Muon Beam Cooling …", PhysRev STAB **8**, 041002 (2005).
[2] V.V. Kashikhin et al., "Design Studies of Magnet Systems for Muon Helical Cooling Channels".
[3] S.A. Kahn et al., "Magnet System for Helical Muon Cooling Channel", Proceedings of PAC07, Albuquerque, NM, USA, p 443.
[4] K. Yonehara et al, "Status of the MANX Muon Cooling Experiment", Proceedings of EPAC08, Genoa, Italy.
[5] K. Yonehara et al., "The MANX Cooling Demonstration Experiment", Proceedings of PAC07, Albuquerque, NM, USA.
[6] K. Yonehara et al., "MANX, A 6-D Muon Beam Cooling Experiment for RAL", submitted to PAC09, Vancouver, BC.
[7] R. Abrams, et al., "Advances in Multi-Pixel Photon Counter Technology", submitted to PAC09.