MANX, A 6-D MUON BEAM COOLING EXPERIMENT FOR RAL*

K. Yonehara†, V. Kashikhin, M. Lamm, A. Zlobin, Fermilab, Batavia IL, USA
R. Abrams, C. Ankenbrandt, M.A.C. Cummings, R.P. Johnson, S. Kahn,
Muons, Inc., Batavia, IL, USA
J. Maloney, Northern Illinois University, DeKalb, IL, USA

Abstract

MANX is a six-dimensional muon ionization cooling demonstration experiment based on the concept of a helical cooling channel in which a beam of muons loses energy in a continuous helium or hydrogen absorber while passing through a special superconducting magnet called a helical solenoid. The goals of the experiment include tests of the theory of the helical cooling channel and the helical solenoid implementation of it, verification of the simulation programs, and a demonstration of effective six-dimensional cooling of a muon beam. We report the status of the experiment and in particular, the proposal to have MANX follow MICE at the Rutherford-Appleton Laboratory (RAL) as an extension of the MICE experimental program. We describe the economies of such an approach which allow the MICE beam line and much of the MICE apparatus and expertise to be reused.

INTRODUCTION

The P5 committee reported prospective future projects for HEP activity in May, 2008. According to their road map, a muon collider will be an appropriate long term project if progress is made on the necessary breakthrough technologies. There are two immediate challenges for muon colliders. First, muons should be accelerated within their short lifetime. Second, quick six-dimensional (6D) phase space cooling of the beam is required to achieve effective muon acceleration. Therefore, a compact muon accelerating and cooling system is required. Because high-gradient high-power RF is preferable for quick acceleration, using SRF is a desirable solution. To this end, the beam phase space needs to be cooled down to the acceptance of the SRF system.

Recently, a novel 6D phase space cooling channel based on ionization cooling called a helical cooling channel (HCC) was proposed [1]. It consists of helical dipole, helical quadrupole, and solenoid magnetic components that confine the beam in a helical path filled with dense hydrogen gas. To compensate for ionization energy loss, a continuous RF acceleration field is needed. In order to simultaneously provide low-Z absorber and high-gradient RF, a high pressure hydrogen gas filled RF (HPRF) cavity was designed. It has been successfully tested and investigated for cooling applications [2]. By integrating the HPRF into the HCC, the HCC can be the most compact muon cooling channel.

*Work supported by USDOE STTR Grant DE-FG02-06ER86282 and by FRA under DOE Contract DE-AC02-07CH11359
#yonehara@fnal.gov

The HCC has been studied in simulation and shows exceptional cooling performance [3]. We proposed the demonstration experiment to verify the helical cooling theory and to test a special helical solenoid (HS) magnet technology [3] that can provide the required HCC field components. The project is named MANX (Muon collider And Neutrino factory demonstration eXperiment). MANX has been designed as an extension of MICE (Muon Ionization Cooling Experiment) at RAL. The concept of this demonstration experiment will be discussed in this paper.

LAYOUT OF MANX CHANNEL AT RAL

The MICE experiment is now being installed in a beam line at ISIS, an 800 MeV proton synchrotron. As shown in Figure 1, the proton beam hits a titanium target to generate pions that are then focused, momentum-selected, and transported to a decay solenoid to decay into muons. The muons are momentum-selected and transported into the MICE hall. Figure 1 shows the hoped-for configuration that will follow the successful completion of MICE, where the magnets and RF of that experiment are replaced by the MANX cooling channel (HCC) [4]. In the figure, the HS of MANX is shown placed between the MICE solenoid spectrometers, which will be reused.

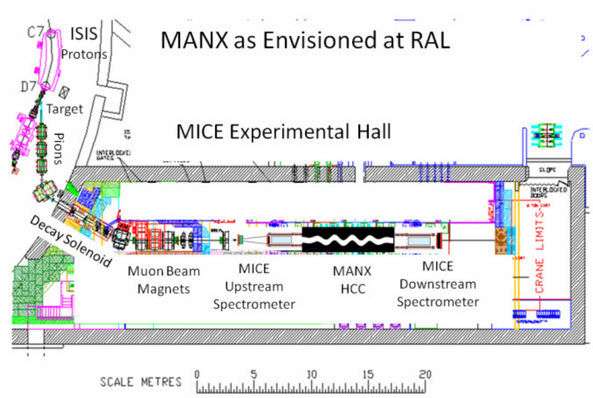

Figure 1: Layout of MANX in the MICE beam line at RAL. In addition to the MICE spectrometers there are MICE beam counters and particle identification detectors that will be reused for MANX.

Figure 2 shows the MANX HCC in more detail, including proposed tracking detectors inside the HCC [5]. The HCC is comprised of a central liquid-helium-filled helical solenoid (HS) and 2 matching sections to provide smooth transitions between the HS and the MICE spectrometers. Five sets of detectors are shown, three within the HS and two sets between the HS and the matching sections.

To avoid complications and to reduce costs, there is no RF in the MANX channel and helium is used instead of hydrogen. Hence, the magnetic field in the cooling section is reduced to correspond to the reduction of the reference momentum as the beam loses energy by ionizing the liquid helium. The detailed field parameters for MANX have been reported previously [6].

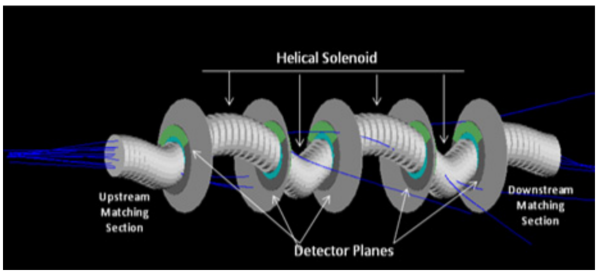

Figure 2: The helical cooling channel, with helical solenoid, matching sections and internal tracker units shown.

The key feature of 6D phase space cooling is emittance exchange. This process takes place by manipulating the path length of a particle as a function of its momentum in an ionization cooling absorber. Hence, magnetic dispersion is required. With the proper dispersion, particles with higher momentum traverse longer path lengths in a cooling absorber while lower momentum particles have shorter path lengths. This process causes the beam to become more monoenergetic at the expense of having larger transverse size generated by the dispersion. Consequently, transverse phase space is swapped with longitudinal phase space via this coupling between transverse and longitudinal momenta. A period of the coupling oscillation in the HCC is typically 1.5λ, where λ is one helical period. Hence, the length of cooling section in MANX is chosen 2λ to observe the coupling oscillation. In case of using liquid helium as a cooling absorber, the expected cooling factor per one plane is equally 1.3, yielding a 6D cooling factor of 2.0 in a 2 m MANX channel [4].

The MANX spectrometer yields six measurements {x, y, x' (or p_x), y' (or p_y), E (from p_x, p_y, *and* p_z), t (or s)} for each particle, where s is the path length of particle. These quantities are used to compute the 6-D emittance. Data will be taken with and without absorber. Without absorber, there is no interference between variables due to the stochastic aspects of Coulomb scattering. Hence, the clear correlation between path length (s) and particle momentum (p) will be observable. This will be direct evidence of the coupling oscillation in the dispersive magnet field, which will characterize the emittance exchange process. The path length measurement, however, will have ambiguity in the reconstruction of particle tracking. To address this, time of flight measured in the helical magnet will be used to resolve the ambiguity between path length and momentum. Fast timing resolution from devices that are available today is sufficient to meet the requirements.

Figure 3 shows the correlation between path length (s) and channel length (z) for various momenta from 200 to 300 MeV/c. Figure 4 shows the transit times versus momentum for a 3.2 m channel. The time of flight plot indicates that 1 MeV/c momentum differences can be measured with a pair of TOF counters 3.2 m apart with 50 ps timing resolution located upstream and downstream of the helical cooling channel. Time of flight counters are presently being developed with a resolution goal of better than 10 ps using micro-channel plates [7], which is applicable if better than 1 MeV/c resolution is required.

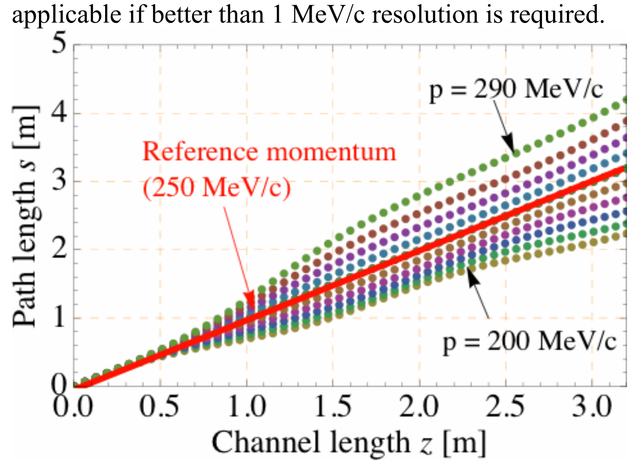

Figure 3: Dependence of path length for momenta in the range (250 MeV/c ± 20 %) as a function of HCC length z. The blue points are for the highest momentum.

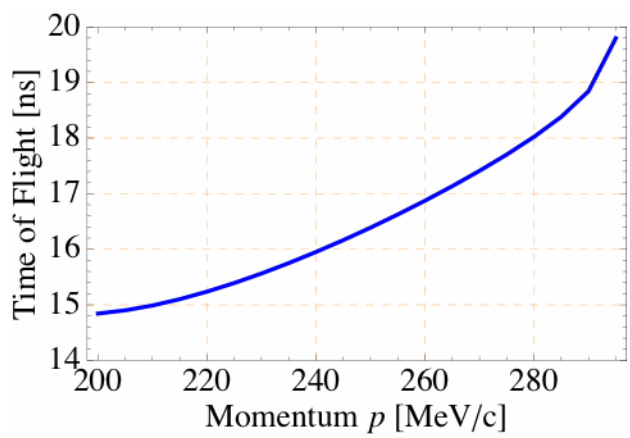

Figure 4: Time-of-flight versus momentum for a 3.2 m long HCC. This shows that the time difference per 10 MeV/c is approximately 500 psec.

The detector system must be well calibrated without absorber. The calibration will allow particle track reconstruction with sufficient precision to study stochastic processes by adding the time of flight information.

RESOLUTION ANALYSIS IN COLLECTIVE MODE

Single particle events can be aggregated to approximate collections of particles. In a 3.2 m HCC filled with LHe absorber 300 MeV/c muons are degraded to less than 170 MeV/c. Figures 5 and 6 show the RMS deviations of the transverse phase space parameters, r and p_r, in the HCC as a function of distance along the HCC length. The RMS of the spatial distribution is almost constant in the HCC. Hence, 50 mm position resolution must be sufficient for the position resolution of the detector in the HCC magnet. On the other hand, the transverse momentum is changing as a function of the HCC length. The RMS of momentum drops by 10 MeV/c. Hence, the required transverse momentum resolution of the detector is less than 10 MeV/c. The study of momentum resolution is ongoing and it requires development of reconstruction methods.

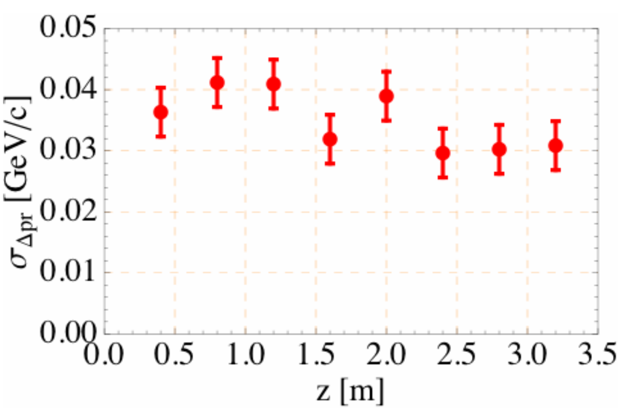

Figure 5: RMS of radial beam distribution in the HCC.

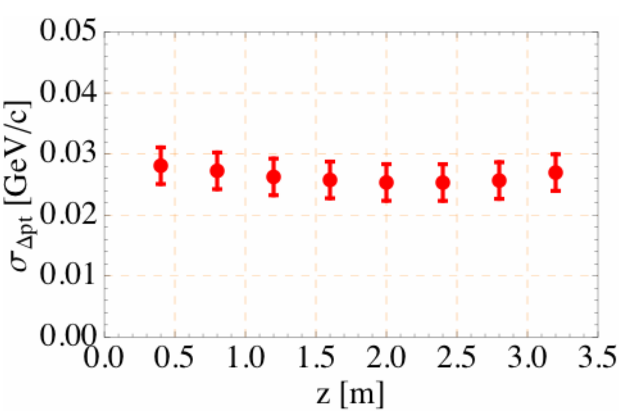

Figure 6: RMS of transverse momentum distribution in the HCC.

Figures 7 and 8 show the time and total momentum phase space parameters. The RMS of the time spread seems to be constant. This means that we do not need a fast timing detector in the HCC. The RMS of total momentum is changing as a function of the HCC length. The required resolution of the total momentum is 1 MeV/c. This measurement seems to be the most challenging in the HCC detector system.

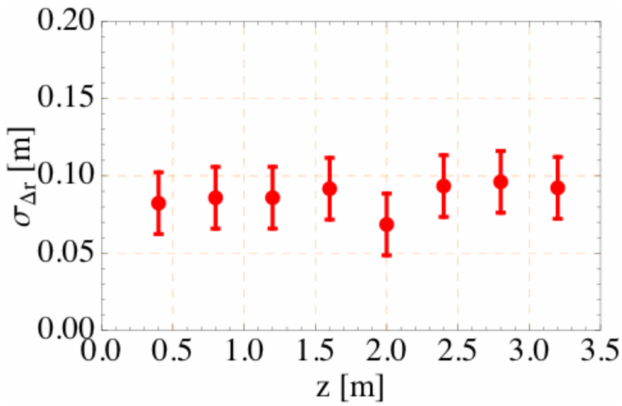

Figure 7: RMS of time spread in the HCC.

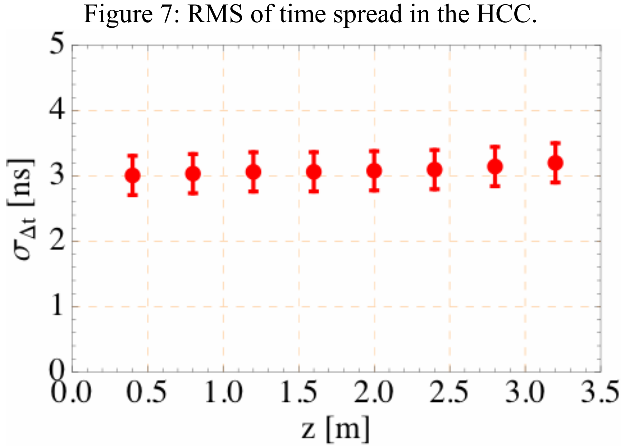

Figure 8: RMS of total momentum distribution in the HCC.

CONCLUSION

The MANX experiment is proposed to demonstrate 6-D muon ionization cooling in a helical cooling channel. The concept of the MANX experiment is discussed. Two measurement modes are shown. By observing the momentum dependent time of flight without absorber in the HCC, the essential features of the HCC will be determined. In addition, the required resolution for the 6-D parameters is discussed. The most challenging measurement is the total momentum. This resolution will be determined by reconstruction in the particle tracking system.

REFERENCES

[1] Y. Derbenev and R.P. Johnson, PRSTAB 8 (2005)
[2] K. Yonehara et al, PAC09 paper TU5PFP020
[3] Yonehara et al, PAC'05
[4] S. Kahn et al, PAC09 paper WE6PFP095
[5] R. Abrams, et al, PAC09 paper TH5RFP078K.
[6] K. Yonehara et al, EPAC'08
[7] V. Ivanov et al, PAC09 paper THRFP079