STATUS OF THE COMPLETE MUON COOLING CHANNEL DESIGN AND SIMULATIONS*

C. Yoshikawa#, MuPlus, Inc., Newport News, VA 23606, U.S.A.
C. Ankenbrandt, R. P. Johnson, S. Kahn,, F. Marhauser, Muons, Inc., Batavia, IL 60510, U.S.A.
Y. Derbenev, V. Morozov, A. Sy, JLab, Newport News, VA 23606, U.S.A.
Y. Alexahin, D. Neuffer, K. Yonehara, Fermilab, Batavia, IL 60510, U.S.A.

Abstract

Muon colliders could provide the most sensitive measurement of the Higgs mass and return the US back to the Energy Frontier. Central to the capabilities of such muon colliders are the cooling channels that provide the extraordinary reduction in emittance required for the precise Higgs mass measurement and increased luminosity for enhanced discovery potential of an Energy Frontier Machine. We present the status of the design and simulation of a complete muon cooling channel that is based on the Helical Cooling Channel (HCC), which operates via continuous emittance exchange to enable the most efficient design.

INTRODUCTION

One of the most challenging components in a muon collider is the 6D cooling channel that must cool muons by six orders of magnitude in phase space before they decay (τ=2.2γ µs). The Muon Accelerator Program (MAP) is a national effort headed at Fermilab that is charged with assessing the feasibility of a muon collider and a muon ring based neutrino factory. MAP established an Initial Baseline Selection (IBS) process, which involves a first pass end-to-end evaluation of candidate cooling channels. The layout of a muon collider is shown in Figure 1 and the scope of the end-to-end evaluation is highlighted. It begins after the Initial Cooling and Charge Separation, since an earlier study successfully demonstrated charge separation of the higher emittance Front End (FE) beam, which also consists of bunches interleaved with opposite charges [1]. The scope terminates just prior to Final Cooling, which is an emittance exchange to lower ε_T at expense of raising ε_L to increase luminosity for an Energy Frontier Machine; Final Cooling would not be used in a Higgs Factory in order to preserve the lowest ε_L for optimal measurement of the Higgs mass width. The evaluation of the HCC is presented here, as well as highlights of advances since the submission to the IBS.

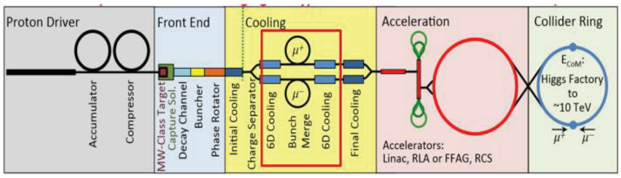

Figure 1: Layout of a Muon Collider. The scope of the end-to-end simulation is demarcated by the red box.

BASICS OF HELICAL COOLING CHANNEL THEORY

In a HCC [2], a solenoid field is augmented by a transverse helical dipole field that provides constant dispersion along the channel for emittance exchange for longitudinal cooling and a helical quadrupole field to provide beam stability. The solenoid magnet creates an inward radial force due to the transverse momentum of the particle, while the helical dipole magnet creates an outward radial force due to the longitudinal momentum of the particle:

$$F_{h-dipole} \approx p_z \times b; b \equiv b_{\phi}; \quad F_{solenoid} \approx -p_{\perp} \times B; B \equiv B_z, \qquad (1)$$

where B is the field of the solenoid, the axis of which defines the z axis and b=b$_\varphi$ is the field of the transverse helical dipole. The equilibrium orbit satisfies:

$$p(a) = \frac{\sqrt{1+\kappa^2}}{k}\left[B - \frac{1+\kappa^2}{\kappa} b_{\varphi}\right] \qquad (2)$$

where

- p is reference momentum; a is reference radius
- $k = 2\pi/\lambda$; λ is the helix period
- $\kappa = p_{transverse}/p_z = 2\pi a/\lambda =$ helix pitch

The conditions for transverse stability about the equilibrium orbit are:

$$0 < G \equiv \left[\left(\frac{B\sqrt{1+\kappa^2}}{pk} - 1\right) + \left(\frac{\left(1+\kappa^2\right)^{3/2}}{pk^2}\left\langle \left.\frac{\partial b_{\varphi}}{\partial \rho}\right|_a \right\rangle\right)\right]\hat{D}^{-1} < R^2 \equiv \frac{1}{4}\left(1 + \frac{\left(\frac{B\sqrt{1+\kappa^2}}{pk} - 1\right)^2}{1+\kappa^2}\right)^2 \qquad (3)$$

where the dispersion factor $\hat{D}$ is:

$$\hat{D}^{-1} = \frac{a}{p}\frac{dp}{da} = \frac{\kappa^2 + (1-\kappa^2)[(B\sqrt{1+\kappa^2}/pk) - 1]}{1+\kappa^2} - \frac{(1+\kappa^2)^{3/2}}{pk^2}\left.\frac{\partial b_{\phi}}{\partial \rho}\right|_a \qquad (4)$$

and $\left.\dfrac{\partial b_{\phi}}{\partial \rho}\right|_a$ is the gradient of the dipole field.

The motion of particles around the equilibrium orbit is shown schematically in Figure 2.

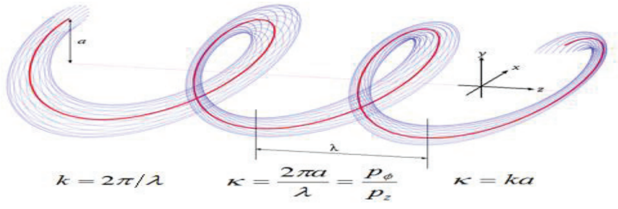

Figure 2: Schematic view of beam motion in a HCC using G4beamline [3]. The reference trajectory is shown in red.

---

*Work supported in part by DOE STTR grant DE-SC 0007634

#cary.yoshikawa@MuPlusInc.com

ISBN: 978-3-95450-132-8 doi:10.18429/JACoW-IPAC2014-TUPME016

COMPONENTS DESIGNED & EVALUATED

The components designed and evaluated begin after an assumed Charge Separator that follows the Initial Cooling Channel [4], which simultaneously cools muons of both charge signs. In this study, we assume the Charge Separator splits the charges with 100% efficiency and no emittance growth, allowing us to design our components with respect to the output of the Initial Cooling Channel. The components are given in Table 1. All HCC segments operate with H_2 gas density of 160atm at 293K, 20 RF cavities per helix period λ, 60 μm thick shared Be cavity walls, and maximum E field of 20 MV/m. The remaining components operated in vacuum.

Table 1: Components Designed & Simulated

MB and SB indicate multi-bunch and single bunch beam of muons, respectively.

Component	Length(m)
1.Matching Section into the HCC	30
2.MB HCC Segment 1 λ=1m f=325MHz	32
3.MB HCC Segment 2 λ=0.8m f=325MHz	70.4
4.MB HCC Segment 3 λ=0.5m f=650MHz	120
5.Bunch Merge (scaled from [7])	105
6.SB HCC Segment 4 λ=0.8m f=325MHz	188
7.SB HCC Segment 5 λ=0.5m f=650MHz	120
8.SB HCC Segment 6 λ=0.5m f=975MHz	77.2
9.Matching Section out of HCC	10

The matching section evaluated in the IBS is displayed in Figure 3. A bent solenoid is used to create dispersion that along with dispersion created in the gap, matched the dispersion of the HCC. The RF-free bent solenoid is preceded by RF gymnastics consisting of:

- A 3m long section with RF and 2T that serves as a buffer between the Front End (FE) 2T and matching section 5.8T.
- A 1m long ramp up of coil currents from 2 to 5.8 T with RF.
- A 2m long RF-free drift in 5.8T.
- A 3m long section with RF to induce an over-compensating tilt in longitudinal phase space that results in an upright ellipse at the end of the RF-free bent solenoid and start of the HCC.

where RF is identical to that in the FE, which consists of 325 MHz cavities of length 25 cm, operating with maximum electric field 20 MV/m and all magnetic fields created by coils with currents to generate the appropriate solenoidal field. The RF in the HCC portion is the same as described above for HCC segments; H_2 gas is present and L_{RF}=λ/20. The transmission for matching into the HCC is ~60% as shown in Figure 4, while a subsequent design increases the matching efficiency to 80% [5].

Muons exiting the matching section, which includes 18m of HCC, are propagated through a series of HCC segments identified in Table 1. Figure 5 shows a 2.5 m long section of HCC segment 1. In this non-optimal evaluation, particles traversing one segment are directly inserted into the next downstream HCC segment without any matching other than aligning references. It is worth noting that matching sections can be designed to transport particles without loss and emittance growth, as was demonstrated between HCC segments that have changes in both λ (0.5m to 0.8m) and frequency (325 MHz to 650 MHz) [6]. Since this end-to-end exercise was to identify show stoppers and not to design an optimal cooling channel, such matching sections are not implemented.

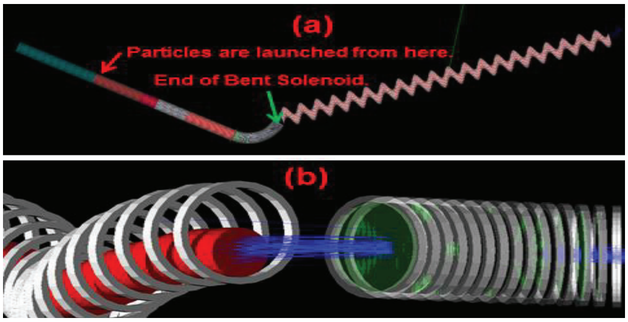

Figure 3: Matching section between Initial Cooler and HCC. Top view (a) shows location of particle launch from Initial Cooler exit with the red arrow and end of the bent solenoid with the green arrow. The gap between end of bent solenoid and start of HCC is shown in (b) with direction of view indicated by the green arrow in (a).

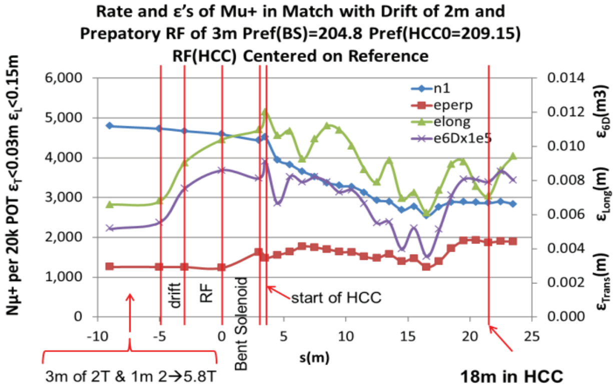

Figure 4: Transmission rate and emittances of muons in the matching section. An improved matching section provides 80% transmission [5].

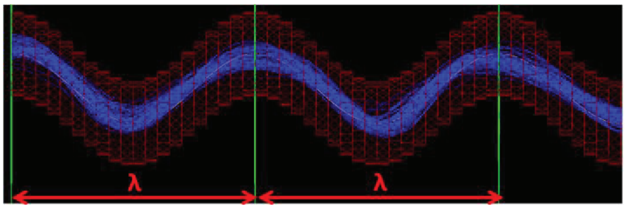

Figure 5: Display of muons in a 2.5 helical period (λ) long portion of a typical HCC segment. The particular segment shown is Segment 1.

Muons at the end of HCC Segment 3 are cold (ε_T=0.792 mm & ε_L=1.18 mm), but are spread over many bunches. Merging multiple bunches into one increases the collider luminosity and such coalescing in a HCC was successfully demonstrated in a channel using RF with 200

MHz [7]. That study designed for 9 bunches and achieved 90% efficiency for merging 13 bunches using a RF fill factor as low as 25%. To scale the result for 200 MHz to 325 MHz, we note that the performance is driven by the energy range where the slip is linear. Hence, performance of 13 bunches at 200 MHz is expected to be similar for 21 (21≈13x325/200) bunches at 325 MHz. The concepts behind the Helical Bunch Merge are illustrated in Figure 6. Recent work to merge with 325 MHz RF studied the acceleration to 200 MeV (KE) and λ match from 0.5 to 0.8 m; losses and emittance growth were observed and are under investigation.

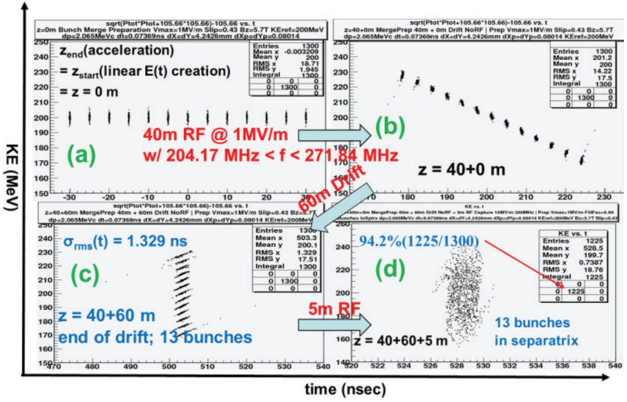

Figure 6: Bunch Merge Concept. Muon bunches that have been accelerated to 200 MeV (KE) in (a) are subjected to 40m of RF with variable frequencies to create the linear energy-time correlation in (b). After 60m of drift in the HCC, the 13 bunches are aligned in time in (c), where RF (10 MV/m) is introduced resulting in the single bunch of muons at 5m in (d).

The single bunch muon beam is cooled by sequential traversals through HCC Segments 4 to 6. At the end of segment 6, the helical beam must be matched into a straight solenoid of strength 3T for matching into the downstream final cooling and acceleration to collision energies. The layout and B-field profiles for such a matching out section are shown in Figure 7.

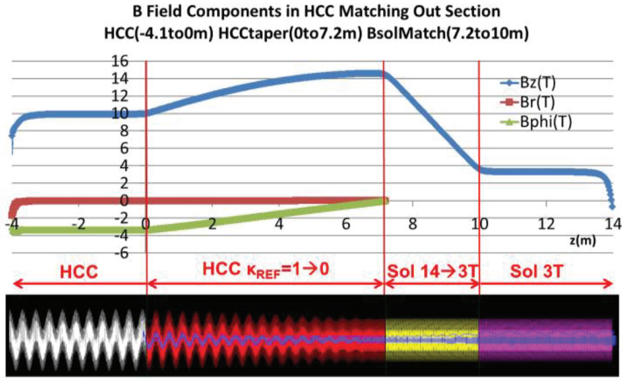

Figure 7: Matching out section from the HCC to a straight solenoid. B-field components are shown at top and a display of the layout is below. The aspect ratio of the display has the transverse dimension enlarged.

RESULTS & FUTURE

The results of this study are collected in Table 2. The largest particle loss occurs during the match into the HCC. As mentioned above, an updated matching design achieves 80% transmission [5] and further improvement is imminent. Future optimizations will design an emittance evolution path to minimize the length of the HCC (to minimize decay losses and costs of infrastructure and operations) and achieve the coldest muon beam possible to allow for the most precise measurement of m_H in a Higgs Factory and increased luminosity for enhanced discovery potential at the Energy Frontier Muon Collider.

Table 2: Summary of Results

Reported values are at the end of each component.

Component	ε_T (mm)	ε_L (mm)	ε_{6D} (mm^3)	Trans
0.Initial Cooler	2.95	6.58	52.2	0.70
1.Match in HCC	4.37	7.09	79.1	0.60
2.MB HCC Seg 1	3.44	6.82	49.3	0.94
3.MB HCC Seg 2	1.62	2.41	4.35	0.90
4.MB HCC Seg 3	0.792	1.18	0.55	0.81
5.Bunch Merge	16.6	24.8	242.6	0.90
6.SB HCC Seg 4	1.62	2.41	4.35	0.80
7.SB HCC Seg 5	0.792	1.18	0.55	0.81
8.SB HCC Seg 6	0.613	0.89	0.25	0.85
9.Match out HCC	0.523	1.54	0.42	0.95
Total/Final	0.523	1.54	0.42	0.14

REFERENCES

[1] C. Yoshikawa, C. Ankenbrandt, R. P. Johnson, Y. S. Derbenev, V. Morozov, D. Neuffer, K. Yonehara “A Charge Separation Study to Enable the Design of a Complete Muon Cooling Channel”, NA-PAC13, THPHO19

[2] Y. Derbenev and R. Johnson, Phys. Rev. ST – Accelerators and Beams 8 (2005) 041002, http://www.muonsinc.com/reports/PRSTAB-HCCtheory.pdf

[3] G4beamline, T. Roberts, http://www.muonsinc.com

[4] Y. Alexahin, “H2 Gas-Filled Helical FOFO Snake for Initial 6D Ionization Cooling of Muons,“ MAP-doc-4377-v1

[5] C. Yoshikawa, C. Ankenbrandt, R. P. Johnson, Y. S. Derbenev, V. Morozov, D. Neuffer, A. Sy, K. Yonehara “Design and Simulation of a Matching System into the Helical Cooling Channel,” IPAC14, TUPME017

[6] C. Yoshikawa, C. Ankenbrandt, R. P. Johnson, Y. S. Derbenev, V. Morozov, D. Neuffer, K. Yonehara “Complete Muon Cooling Channel Design and Simulations,” IPAC13, TUPFI060

[7] C. Yoshikawa, C. Ankenbrandt, D. Neuffer, “Bunch Coalescing in a Helical Channel,” IPAC12, TUPPD013