DESIGN AND SIMULATION OF A MATCHING SYSTEM INTO THE HELICAL COOLING CHANNEL*

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 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. The Helical Cooling Channel (HCC) is able to achieve such emittance reduction and matching sections within the HCC have been successfully designed in the past with lossless transmission and no emittance growth. However, matching into the HCC from a straight solenoid poses a challenge, since a large emittance beam must cross transition. We elucidate on the challenge and present evaluations of two solutions, along with concepts to integrate the operations of a Charge Separator and match into the HCC.

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=2.2μs). The Helical Cooling Channel (HCC) [1,2] is able to achieve such emittance reduction via continuous emittance exchange that enables the most efficient design of a 6D cooling channel. The HCC operates above transition, while the preceding Front End (FE) and Initial Cooling channels operate below it. Hence, transition must be crossed in matching into the HCC. Our first attempt to match into the HCC took beam out of the Front End (FE) and adiabatically crossed transition during the match into the HCC, while subsequent designs took advantage of a colder beam that went through Initial Cooling [3] and crossed transition instantaneously. In all cases, it is assumed that a Charge Separator had split the beam into two separate beams of single charge sign with 100% efficiency and no emittance growth, since an earlier study successfully demonstrated charge separation on the higher emittance FE beam [4].

ADIABATIC MATCH

The first attempt to match out of the HCC followed an adiabatic approach suggested by an earlier study [5] and operated on the hotter FE beam. We first note that a beam having large momenta spread will suffer more distortion and potentially more losses as it crosses transition compared to a beam with a lower momenta spread due to asymmetric slip below and above transition, where an idealized design would have kinematics above transition cancel the accumulated slippage below it. A linear approximation that describes the possible cancelation is given by:

$$\Delta\sigma_z = \int m_z^{-1}\frac{\Delta\gamma}{\gamma}dz = \frac{\Delta\gamma}{\gamma\beta^3}\int\left(\frac{\kappa^2}{q+\kappa^2(1-q)}-\frac{1}{\gamma^2}\right)\sqrt{1+\kappa^2}\,dz \quad (1)$$

where

- κ = helix pitch = $p_{transverse}/p_z = 2\pi a/\lambda$
- p is the reference momentum; a is reference radius
- a is reference radius; λ is helix period
- $k_c = B\sqrt{1+\kappa^2}\,/\,p$; B is the solenoid field
- $q = (k_c/k)-1$; $k = 2\pi/\lambda$

The layout and performance of a design utilizing the above concept are shown in Figure 1. The appropriate B in the HCC for muons exiting the FE is 5.9 T. The coils that generate the helical field components are used upstream in the matching section, where the helical pitch, κ, is linearly ramped down to zero (solenoid) at z=4m. The current is changed from that in the HCC to that of a straight solenoid supporting 2T from z=4m to z=3m.

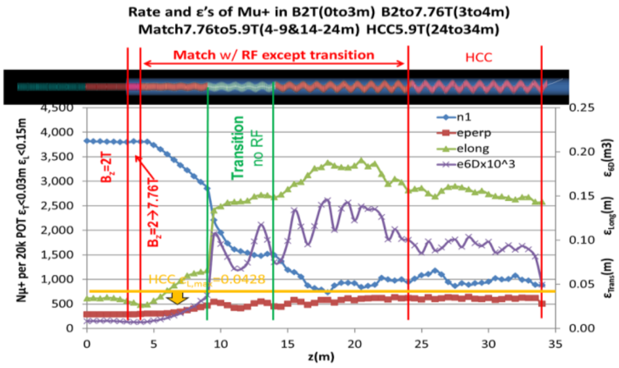

Figure 1: Layout and performance of an adiabatic match of muons exiting the Front End channel into the HCC.

The performance degrades upon entry into the matching section, where particles losses begin and ε_L grows. Entry into the transition region where RF is absent shows an immediate increase in ε_L and a correspondingly increase in particles loss. We recognize the inherent difficulty in designing a lattice that accommodates a beam with a large momentum spread to cross transition efficiently. Hence, going forward, we will leverage the capabilities of the Initial Cooler to design the match into the HCC with the

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#cary.yoshikawa@MuPlusInc.com

colder beam. Another concept we will investigate is to cross transition instantaneously.

NON-ADIABATIC MATCH USING A BENT SOLENOID

The first non-adiabatic matching design that crosses transition instantaneously used a bent solenoid to create dispersion that along with dispersion created in the gap, matched the dispersion of the HCC. This is the matching-in design for the HCC that was evaluated for the Initial Baseline Design (IBS) for the Muon Accelerator Program (MAP) [2]. The design is shown in Figure 2. The RF-free bent solenoid was preceded with RF gymnastics consisting of:

- A 3m long section with RF and 2T that serves as a buffer or fringe fields 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 Front End (FE), which consists of 325 MHz cavities of length 25 cm, operating with maximum electric field 20 MV/m and all magnetic fields are created by coils with currents to generate the appropriate solenoidal field. The HCC being matched into operates with H_2 gas density of 160atm at 293K, 20 RF cavities per helix period λ=1m, 60 µm thick shared Be cavity walls, and maximum E field of 20 MV/m. The transmission for matching into the HCC from the output of the Initial Cooler with p_{ref} = 204.8 MeV/c is ~60% as shown in Figure 3.

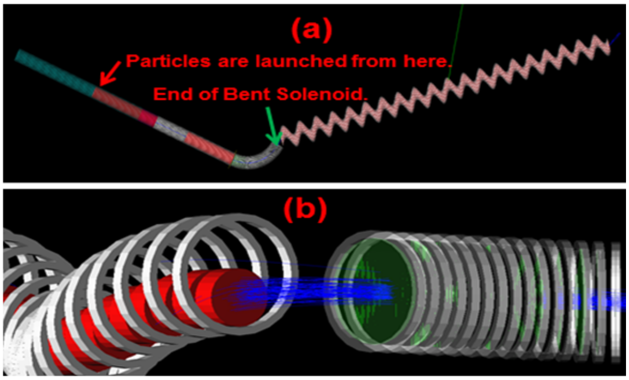

Figure 2: Matching section between Initial Cooler and HCC. Top view in (a) shows location of particle launch from Initial Cooler exit with the red arrow and end of the bent solenoid with the green arrow. The gap between end of bent solenoid and start of HCC is shown in (b) with direction of view indicated by the green arrow in (a).

NON-ADIABATIC MATCH DIRECTLY FROM A STRAIGHT SOLENOID INTO THE HCC

The non-adiabatic matching method using a bent solenoid to match dispersion grows the transverse size of the beam. A practical HCC design may be limited by the aperture size. So, we consider matching in directly out of a straight solenoid into the HCC. Fringe fields between the end of the straight solenoid and start of the HCC will bend particles in ways that cannot be calculated analytically. Hence, this design will be driven by simulations. We will design after the bulk of the muon distributions that emerge after the Initial Cooler. This is as opposed to designing after the reference where that has the added complication of the reference accurately describing the bulk and taking into account non-linearities away from the reference. To measure the matching efficiency, we selected only those particles that are in the acceptance of the HCC.

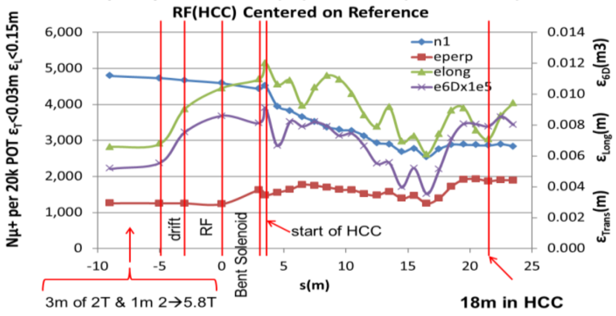

Figure 3: Transmission and emittances of muons in the non-adiabatic matching in section that uses a bent solenoid to match dispersion.

The optimization procedure removed RF and H_2 gas with the assumption that there is relatively little cooling achieved over the short matching distance and that the purpose of the RF is to compensate for energy loss from the gas. RF and H_2 gas are added when analysing the final transmission for the optimal configuration. Figure 4 shows the top view of the apparatus undergoing optimization with respect to rotation about the y-axis followed by rotation about the x'-axis and displacements in x and y.

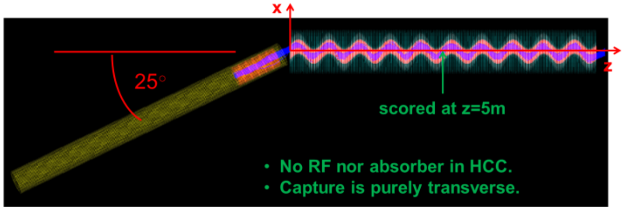

Figure 4: Top view of configuration under optimization with RF and H_2 gas removed.

Table 1 shows the optimal configuration and preliminary (no RF/H_2 gas) transmission for particle input distributions from the Front End, a cooled Front End distribution that maintained p_{ref} of 242 MeV/c, and one traversing the Initial Cooler that lowered p_{ref} to 204.8 MeV/c. The evaluations used an aperture of 238 mm that was driven by geometry for RF that would fit inside helical coils for matching out of the Front End. The helical coil configuration for p = 204.8 MeV/c allows the aperture to increase by ~30 mm.

Table 1: Optimized configurations without RF nor H_2 gas for various initial particle distributions. The optimal configuration going forward is indicated in the red box.

Particle Input	Front End (FE)	~FE Mom. w/ Init Cooling	Init. Cooling to low mom.
P_{ref} (MeV/c)	242	242	204.8
θ_Y (°)	30	30	25
Θ_X (°)	5	5	10
Δx (mm)	40	40	50
Δy (mm)	30	30	45
N(1k init)	668	990	996

Results of incorporating RF and H2 gas into the optimal configuration for particles traversing the Initial Cooler are shown in Figure 5, where the transmission has increased to 80% from 60% that used the bent solenoid on the same input.

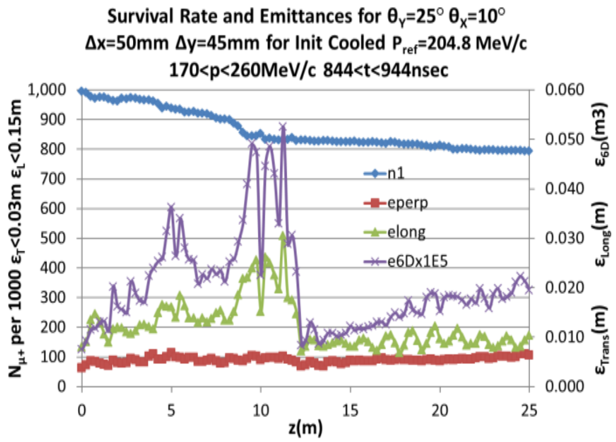

Figure 5: Transmission and emittances after incorporating RF and H_2 gas into the optimal configuration for particles traversing the Initial Cooler.

NON-ADIABATIC REFERENCE BASED MATCH (FUTURE)

There is potential improvement as one observes oscillations in the helical pitch κ and radius for the reference particle in the "optimal" configuration evaluated with RF and H_2 gas as shown in Figure 6. A straight-forward method to derive a configuration that results in a reference that does not oscillate in κ and radius is to initiate a muon from the middle of the HCC directed backwards up toward the straight solenoid.

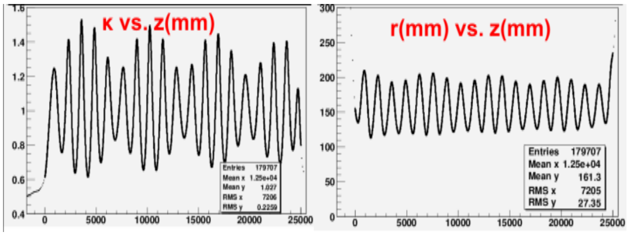

Figure 6: Oscillation in helical pitch κ in left and radius on right for the reference in the "optimal" configuration.

INTEGRATION OF CHARGE SEPARATION & MATCH INTO THE HCC

There are two concepts to separate charges and simulteneously match into the HCC:

- The Easy Way
- The Hard Way

The Easy Way consists of a single bent solenoid that has the p_{ref} lowered (170 MeV/c) to increase the dispersion that is created in the bent solenoid as the charges are separated. The pros are:

1. Shorter channel meaning simpler, less cost, shorter distance for beam to spread
2. Both charge separated channels are the same length (longer channel to avoid overlapping coils in reverse bend is eliminated).

The con is lower momentum means more time spread per unit distance.

The Hard Way incorporates a full forward bend, a straight for one charge sign to avoid overlapping coils, and partial reverse bends to achieve the desired dispersion. The pro is more flexibility in momentum choice. The cons are:

1. Longer channel meaning more complexity, higher cost, longer distance for beam to spread.
2. One charge sign channel is longer to avoid overlapping coils in reverse bend.

RESULTS & FUTURE

Adiabatic and non-adiabatic matching schemes were presented with a non-adiabatic method achieving 80% transmission into the HCC. Further improvements are expected based on fine tuning of the reference and concepts for integrating the charge separation and match capabilities of bent solenoids were provided.

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