QUASI-ISOCHRONOUS MUON COLLECTION CHANNELS

Final Report for Project starting 07/20/2008, ending 08/14/2012

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PREPARED FOR THE UNITED STATES

DEPARTMENT OF ENERGY

Work Performed Under grant DE-SC0002739

ABSTRACT

Intense muon beams have many potential commercial and scientific applications, ranging from low-energy investigations of the basic properties of matter using spin resonance to large energy-frontier muon colliders. However, muons originate from a tertiary process that produces a diffuse swarm. To make useful beams, the swarm must be rapidly captured and cooled before the muons decay. In this STTR project a promising new concept for the collection and cooling of muon beams to increase their intensity and reduce their emittances was investigated, namely, the use of a nearly isochronous helical cooling channel (HCC) to facilitate capture of the muons into RF bunches. The muon beam can then be cooled quickly and coalesced efficiently to optimize the luminosity of a muon collider, or could provide compressed muon beams for other applications. Optimal ways to integrate such a subsystem into the rest of a muon collection and cooling system, for collider and other applications, were developed by analysis and simulation. The application of quasi-isochronous helical cooling channels (QIHCC) for RF capture of muon beams was developed. Innovative design concepts for a channel incorporating straight solenoids, a matching section, and an HCC, including RF and absorber, were developed, and its subsystems were simulated. Additionally, a procedure that uses an HCC to combine bunches for a muon collider was invented and simulated. Difficult design aspects such as matching sections between subsystems and intensity-dependent effects were addressed. The bunch recombination procedure was developed into a complete design with 3-D simulations. Bright muon beams are needed for many commercial and scientific reasons. Potential commercial applications include low-dose radiography, muon catalyzed fusion, and the use of muon beams to screen cargo containers for homeland security. Scientific uses include low energy beams for rare process searches, muon spin resonance applications, muon beams for neutrino factories, and muon colliders as Higgs factories or energy-frontier discovery machines.

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Motivation

The ability to produce bright and intense muon beams would be a tremendous enabling technology leading to many scientific uses and potential commercial applications. Muon beams have potential commercial use in areas such as cargo container screening for homeland security, low-dose radiography, and for muon catalyzed fusion. In material science, probing the structure of substances via muon spin resonance would become quicker and more precise. In elementary particle physics, bright low-energy muon beams would allow precise searches for and detection of small effects pointing to physics beyond the Standard Model. Examples of possible small effects include charged lepton flavor violation (such as the conversion of a muon to an electron in the field of a nucleus as well as muon decays to an electron plus a photon), the anomalous g- factor of the muon, and a non-zero muon electric dipole moment. Rapid acceleration of bright muon beams would make possible neutrino factories based on muon storage rings. Higgs factories could take advantage of the fact that the Higgs boson couples much more strongly to muons than to electrons. Ultimately, muon colliders could lead the U.S. high-energy physics community back to the energy frontier. In short, mastering this technology would create a variety of opportunities in basic and applied science.

Background

The motivation for a muon collider stems from the limitations of other collider types. Hadron collider energies are limited by their size and the constraints on the magnetic bending fields. Lepton colliders have an advantage compared to hadron colliders because leptons are pointlike particles, making the full beam energies available for fundamental processes. Extending e^+e^- colliders to the multi-TeV scale is problematic because synchrotron radiation makes it impractical to accelerate them in circular machines and beamstrahlung impairs the knowledge of the energy of the initial state, a traditional strong point of lepton colliders. Since $m_\mu/m_e = 207$, muons have negligible synchrotron radiation and can thus be accelerated, stored and collided in rings. Furthermore, it is possible that muon colliders may achieve luminosities comparable to those of e^+e^- colliders at the same energy. Additional advantages of muon colliders include their physical size or footprint: they are much smaller than a linear e^+e^- collider of the same energy. Since the muons pass several times through each RF cavity, the cost of RF systems for a given energy can be much less. Additionally, they require much less precise alignment than electron linear colliders, as the final transverse beam sizes are orders of magnitude larger than an equivalent e^+e^- machine, and antiparticles circulating in opposite directions in the same magnetic ring have the same closed orbit. This makes a high energy muon collider a very attractive prospect for an energy frontier program. A muon collider would provide a facility to follow up on the discoveries at the LHC as well as being a discovery machine in its own right. To realize these advantages, the challenges of creating, cooling, and accelerating the muons must be met. A successful cooling scheme is a crucial step toward a collider.

Making the muons is not the most difficult problem: they can be produced copiously by targeting an intense proton beam and letting the resulting pions decay into muons. The problem, rather, lies in collecting and cooling the muons efficiently, swiftly, and affordably.

Efficient collection is difficult because the parent pions are produced in all directions with a broad range of momenta. Even using a small production target does not help that much because the pions travel considerable distances before they decay: 7.8 meters on average for a pion whose momentum is numerically equal to its rest mass. That means that the effective source size of the tertiary swarm of muons (for it cannot really be called a beam yet) is also large.

For convenience and consistency with previous work we will refer to the swarm as the beam from now on. Muon beams with the intensity required by a muon collider can only be produced into a large phase space (the beam has large emittances in all three degrees of freedom, where emittance is the average spread of particle coordinates in position-and-momentum phase space). Currently existing/affordable acceleration technologies require small input beam emittances. The disparity between the initial muon beam size and the acceptance of current acceleration schemes could conceivably be overcome by developing new, large aperture acceleration technologies, but beam cooling techniques to reduce the beam emittances are a much more promising approach. In principle we know how to cool the muon beam. Given the 2.2 microsecond lifetime in the rest frame of the muon, ionization cooling is the only feasible cooling candidate. Ionization cooling involves the muons traversing an energy absorbing medium along with accelerating devices within a strongly focusing magnet system. In order to satisfy the beam requirements of a muon collider, the beam volume needs to be reduced by about six orders of magnitude in the 6D phase space that the beam occupies.

Before efficient cooling can take place, the particles must be captured into the stable areas in longitudinal phase space (buckets) generated by the RF cavities. This allows the re-acceleration of the muons in the z-direction (as described in the context of ionization cooling). The cavities may be interspersed between locations of energy degrading low-Z material, or they may contain the energy-loss material itself. The salient point is that in order to produce a bright beam for a muon collider we need a system to capture the particles in the RF buckets. The capture system must maximize the number of captured particles and must be designed in a way as to be compatible with the acceptance of the overall cooling system.

The proposed RF capture system can best be introduced by analogy with longitudinal dynamics processes that take place in proton synchrotrons such as the Fermilab Booster, an accelerator with which the authors of this report are quite familiar. The first process of interest takes place shortly after injection. Several turns of H^- beam from the linac are injected into the Booster via charge-stripping injection, resulting in a coasting proton beam with a finite momentum spread. If there is a small non-zero ring voltage during injection, some of the beam will fall into pre-existing buckets, and some will land above, below, or between the buckets in longitudinal phase space. Most of the beam can be captured by rapidly raising the amplitude of the RF voltage, resulting in migration of the uncaptured beam across the bucket boundaries into the buckets. (This process is sometimes, albeit misleadingly, called adiabatic capture.)

Analogously, in a muon capture front end, it would be useful to be able to make the bucket area grow as the particles move downstream, keeping in mind that the amount of RF voltage in the channel will already be made as large as possible. The capture process would be even more efficient if there were a way to make the particles spiral toward the buckets and a way to make high-momentum particles above the buckets lose energy. It will turn out that all of these features will be present in the proposed muon capture system. The distribution of muons will have six-dimensional emittances that are about a million times larger than the proton emittances in the booster. Designing a capture and cooling scheme for such an emittance regime is incredibly challenging. Additionally, coping with intensity-dependent effects on the longitudinal motion, such as beam loading and potential well distortion will be challenging. The work described here includes the study of intensity-dependent effects. The emphasis will be on longitudinal intensity-dependent effects because the effects on the transverse motion are not likely to be serious in the front end because the beam is so large transversely.

Other phenomena of interest for this discussion occur in synchrotrons operating around the transition energy. To appreciate this proposal, it is necessary to understand transition, so some background is provided here for the convenience of the reader. The revolution time of a particle in a circular accelerator is given by the ratio of the path length (the orbit length of a single turn) and its velocity. In a synchrotron, the path length differences are proportional to fractional momentum differences. The proportionality constant, usually called the momentum compaction, depends on the focusing properties of the ring. The difference in the revolution times for two particles having different momenta depends on the relative magnitudes of their path lengths and velocities. In many strong-focusing synchrotrons of moderate energy, there is an energy at which the changes in revolution time due to path length and the changes due to velocity cancel each other to first order. That energy is called the transition energy. The corresponding ratio of the energy and the rest mass energy of the particles is called the transition gamma of the ring. There is a simple relationship between the transition gamma and the momentum compaction. A ring at transition is often referred to as being isochronous because, to first order in the momentum offset, all the circulating particles take the same time to go around the ring. The most important aspect of transition for the present discussion is that, as the beam energy in a synchrotron approaches the transition energy, the bucket area grows rapidly. This rapid bucket area growth arises from the presence of a singularity at the transition energy in the formula for bucket area. Also, above transition, particles with a positive momentum offset take longer to go around the ring.

As may already be apparent, processes analogous to those above will be extremely useful for RF capture if they can be implemented in a muon transport channel. Traditionally, in straight single-pass systems such as linacs, the concept of transition energy does not normally arise. For straight trajectories, the path length does not depend on momentum. Fortunately, the RF capture system being designed/optimized here, the HCC [5], is not a straight single pass system in the sense that a linac is. In fact, an HCC exhibits some of the dynamical properties normally discussed in the context of rings, such as transition. Some of the challenges of designing the RF capture system can be overcome by exploiting the ring-like dynamical properties.

As the name suggests, an HCC sends the beam on a spiral path, and there is a positive correlation between the spiral path lengths and the momenta of the muons. An HCC filled with low-Z material can be made to cool the beam simultaneously in all three spatial degrees of freedom, i.e. in 6-dimensional phase space. Ionization cooling shrinks the transverse emittances in the usual way. Longitudinal cooling occurs because higher-momentum particles encounter more degrader material than the lower-momentum particles do; strictly speaking, it results in emittance exchange from the longitudinal to one or both transverse degrees of freedom. Achieving 6-D cooling was the original motivation for the invention of the HCC. The design of the HCC and the exploitation of the associated dynamical processes are important steps toward a full muon cooling system.

Since an HCC has adjustable momentum compaction, the transition gamma can be varied by changing the HCC parameters. As alluded to earlier, varying the transition gamma can be used to facilitate RF capture. One of the exciting new ideas that arose from the Phase I work was the use of a straight solenoid filled with high-pressure hydrogen gas, RF cavities, and beryllium plates to pre-condition the beam upstream of the HCC. The straight solenoidal channel filled with as much RF voltage as possible will establish a certain bucket area which some of the muons will populate. The resulting beam can be matched into an HCC with the same amount of RF. Once in the HCC, the bucket area can be made to grow to enhance particle capture. The HCC bucket growth is achieved by reducing the HCC transition gamma toward the beam gamma. Longitudinal cooling in an HCC also aids in capturing particles into the buckets. This is because the high-momentum particles lose more energy than low-momentum particles. The longitudinal cooling will also cause particles undergoing synchrotron motion to spiral into the buckets in longitudinal phase space. Muon capture based on synchrotron motion causing particles to spiral into the RF buckets only happens if the muon energy is sufficiently high. If the capture energy is too low, the heating caused by the momentum dependence of dE/dx overwhelms the cooling effect. In that case low-energy particles lose energy from ionization loss faster than the RF can put it back.

Finally, the isochronous condition conveys additional advantages. Even before particles are captured into buckets, isochronicity limits the longitudinal spread of the beam. (Note that this approach is opposite to that of Neutrino Factory Study 2A, in which the distribution was deliberately allowed to lengthen.) The short length of the resulting distribution of bunches facilitates the later process of coalescing them into a single bunch to maximize the luminosity of a muon collider. Also, as the transition gamma is lowered, particles with momenta above the buckets and with gamma above transition will migrate backwards in phase space toward the buckets that have already been occupied by the lower-momentum particles. (In real space, the lower-momentum particles will be moving downstream faster than the higher-momentum ones and will catch up with them because the latter now have longer path lengths.) Since the high-momentum particles will also be losing energy to the degrader material, there will be a second chance to capture them.

The following paragraphs provide some mathematical background about the concepts introduced above as they apply to HCCs. Some preliminary simulation results are also shown and discussed.

An HCC [1] causes charged particles to move along helical trajectories according to the relationship:

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

where

- B is the solenoidal magnetic field
- b_ϕ is the dipole component
- $\kappa = p_\perp/pz$ is the tangent of the pitch angle
- $k=2\pi/\lambda$ is the helix wavelength
- p is the design particle momentum
- a is the reference particle radius.

The novel concept we are proposing centers around designing an apparatus that uses an HCC with the beam gamma near the transition gamma (γ_T). This allows the system to be operated in a mode that is close to satisfying the isochronous condition. This nearly isochronous operation will enhance the capture rate into RF buckets. An expression for the slip factor for an HCC, η_H, is derived in [1]:

$$\eta_H = \frac{\sqrt{1+\kappa^2}}{\gamma\beta^3}\left(\frac{\kappa^2}{1+\kappa^2}\hat{D} - \frac{1}{\gamma^2}\right) \tag{2}$$

where γ becomes γ_T when $\eta_H = 0$ and the dispersion factor D is related to apparatus quantities and design momentum via:

$$\hat{D}^{-1} = \frac{a}{p}\frac{dp}{da} = \frac{\kappa^2 + (1-\kappa^2)[(B\sqrt{1+\kappa^2}/pk) - 1]}{1+\kappa^2} - \frac{(1+\kappa^2)^{3/2}}{pk^2}\frac{\partial b_\phi}{\partial \rho} \tag{3}$$

with $\partial b_\phi/\partial\rho$ being the quadrupole component of the field in the channel.

The RF bucket area that the QIHCC aims to enlarge when operating near transition is approximated by:

$$A_{bucket} \cong \frac{16}{w_{rf}}\sqrt{\frac{eV'_{\max}\lambda_{rf}\, m_\mu c^2}{2\pi|\eta_H|}}\left[\frac{1-\sin(\phi_s)}{1+\sin(\phi_s)}\right] \tag{4}$$

where the term in brackets is an approximation to the moving-bucket factor and

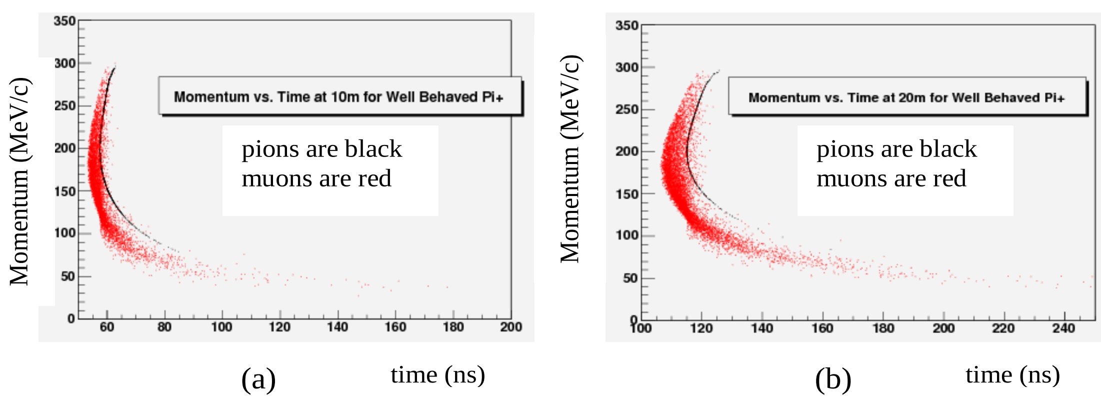
- w_{rf} is the RF frequency in radians/second

- V'_{max} is the maximum E-field voltage gradient
- λ_{rf} is the RF wavelength
- m_{μ} is the mass of the muon
- φ_s is the synchronous particle RF phase

In principle, equations (1) to (4) provide the analytic basis to design a QIHCC.

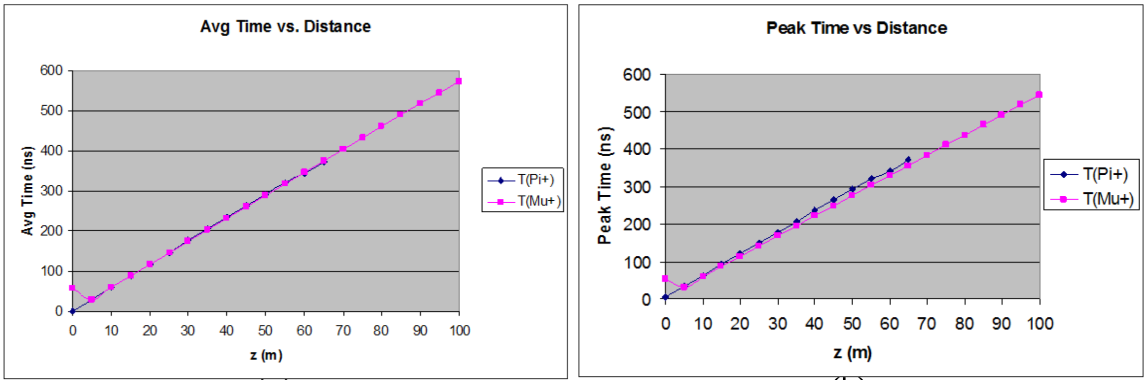
An important kinematic property of the decay of relativistic pions is that the resulting muons have similar velocities to their parent pions, since the muon has about 76% of the mass of the pion and retains on average about 79% of the momentum of the pion. Hence, an RF capture system designed for pions at a particular velocity also captures most of the decay muons as well. That means that the capture process can begin even before all the pions have decayed. However, absorber should not be introduced until most of the useful pions have decayed. Figure 1 shows the momentum vs. time dependence for pions and muons at 10 m and 20 m longitudinal propagation distance downstream in an HCC without RF, where the initial beam consisted of pions with momenta characterized by a Gaussian distribution of 200+/-50 MeV/c.

The time distributions at any particular z are asymmetric. The average and peak values for each time distribution at 5 m increments along z are shown in Figure 2. Both average and peak time values along z are nearly identical for pions and muons, reinforcing the concept that an apparatus designed with timing to capture muons will also capture parent pions, enhancing the overall muon collection rate.



(a) (b)

Figure 1: Momentum versus Time dependence for Pions and Decay Product Muons. Pions are injected at z=0 and t=0 with Gaussian Momenta of 200+/-50 MeV/c. (a) At 10 meters downstream. (b) At 20 meters downstream.



(a) (b)

Figure 2: Time versus Longitudinal Propagation Distance for Pions and Muons. Pions are injected at z=0 with p=200+/-50 MeV/c. Time distribution at any z location is asymmetric. (a) Average time vs. longitudinal distance. (b) Most likely arrival time vs. longitudinal distance.

HCC Design and Engineering

The support for detailed engineering design of helical cooling channels is outside the scope of this project. However, significant progress has also been achieved in that area during the course of this project as a result of parallel efforts, many of which are reported at IPAC10, IPAC11 and IPAC12.

Technical Approach

Accelerator design, which involves extensive simulation activities guided by an understanding of analytical accelerator physics principles, is the crux of this project. The success of that activity is highly dependent on the relevant experience of the designers. G4Beamline, a product created and supported by Muons, Inc. is the primary simulation tool. Our involvement in collaborations with many other experts engaged in similar activities is an important reason why our past efforts have been successful.

Technical Objectives

A major goal of the project reported on here was to design a front end for an intense muon beam facility, starting from the end of the tapered solenoid and delivering intense muon beams into HCCs that are optimized for cooling. The probability of capturing high-momentum pions and muons will be increased by the introduction of material and RF in the second straight solenoid. Maximizing the useful muon yield is critical to providing the desired performance of a future muon facility. The pions and muons are captured into large RF buckets in a system that is operating near transition. Finally the particles will be matched into an HCC that is optimized for cooling.

Various parameters characterizing the design concept were optimized. For example, the longitudinal starting position of the second straight solenoid and the profile of the low Z material therein were optimized in the course of the Phase II work. This novel system, whose invention is an important outgrowth of the Phase I project, performs several important functions in the design. It should be noted that some of the secondary particles, mostly protons and high-energy pions, will interact in the second straight solenoid, enhancing the number of useful muons. This effect was included in the simulation as part of the Phase II work.

A guiding principle for RF capture is to maintain growth of the RF bucket area. In order to facilitate bucket area growth we manipulated:

1. Synchronous phase φ_s
2. HCC slip factor η_H via reference γ (or β) and $(\partial b_\phi/\partial r)(z)$
3. Voltage gradient V'_{max}

The first two items are coupled; however, there is some additional freedom associated with the second item coming from the possible manipulation of the field gradient. The third item, the voltage gradient, provides an independent degree of freedom that would however come at the price of running sub-optimally prior to using the maximum achievable voltage gradient.

Another important invention resulting from the Phase I project was the Bunch Recombination system. Further development of this design concept was another result of the Phase II Project.

Integration of the concepts developed in this project into the overall design of intense muon beam facilities was another important outcome of the Phase II project.

Reports of Studies Supported by This Grant

The progress of the studies related to the QIHCC was documented in seven contributions to the International Particle Accelerator Conferences in 2010, 2011, and 2012. These reprints are attached below as appendices. In the next sections, each contribution is summarized, leaving the reader free to find details in the appendices.

MUON CAPTURE IN THE FRONT END OF THE IDS NEUTRINO FACTORY

Appendix I contains the IPAC10 report that was supported by this grant to establish a baseline muon capture beam line for the International Design Study for a Neutrino Factory. In the front end, a proton bunch on a target creates secondary pions that drift into a capture transport channel, decaying into muons. A sequence of rf cavities forms the resulting muon beams into strings of bunches of differing energies, aligns the bunches to (nearly) equal central energies, and initiates ionization cooling. For the International Design Study (IDS), a baseline design had to be developed and optimized for an engineering and cost study. The design is affected by limitations on accelerating gradients within magnetic fields. The effects of gradient limitations are explored, and mitigation strategies are presented. This baseline design and its simulations served as a means to educate us on work that had been done as well as a benchmark to gauge our success with the QIHCC.

QUASI-ISOCHRONOUS MUON COLLECTION CHANNELS

Appendix II is the IPAC10 contribution describing a preliminary design of a system upstream of the HCC to enhance the number of muons in its acceptance. An innovation has been introduced to use the high energy pions to create useful muons by incorporating material at strategic locations. We added RF with H2 gas into the matching section and performed an initial study that involves crossing transition.

HELICAL CHANNELS WITH VARIABLE SLIP FACTOR FOR NF AND MC

Appendix III is an IPAC11 contribution describing design concepts for a system to capture, cool, and coalesce a muon beam. In particular, variants of a helical channel are used, taking advantage of the ability to vary the slip factor and other parameters of such a channel. The cooling application has been described before while this paper reports recent studies of a system that includes two novel concepts to accomplish capture and coalescing via a slip controlled helical channel. The flexibility of the helical channel to capture, cool, and coalesce bunches of muons has been illustrated via this preliminary design of a front end for a NF/MC that promises to be simpler and more cost-effective than the baseline design. As the design is preliminary, it is premature to compare its performance with the baseline. Regarding capture, further studies including longitudinal cooling will enhance its effectiveness. For bunch coalescing, the 1D simulations provide promising results, which is the source of excitement for anticipated results from 3D simulations that are soon to come.

MUON CAPTURE FOR THE FRONT END OF A $\mu^+\mu^-$ COLLIDER

Appendix IV is an IPAC11 contribution on the design of the muon capture front end for a $\mu^+\mu^-$ Collider. We presented approaches to extending the Neutrino factory front end design to the more demanding requirements of a μ^+-μ^- collider. In the front end, a proton bunch on a target creates secondary pions that drift into a capture transport channel, decaying into muons. A sequence of rf cavities forms the resulting muon beams into strings of bunches of differing energies, aligns the bunches to (nearly) equal central energies, and initiates ionization cooling. The muons are then cooled and accelerated to high energy into a storage ring for high-energy high luminosity collisions. Our initial design is based on the somewhat similar front end of the International Design Study (IDS) neutrino factory.

INTENSE MUON BEAMS FOR EXPERIMENTS AT PROJECT X

Appendix V is a contribution to IPAC11 that describes a coherent approach for providing muon beams to several experiments for the intensity-frontier program at Project X. Concepts developed for the front end of a muon collider/neutrino factory facility, such as phase rotation and ionization cooling, are applied, but with significant differences. High-intensity experiments typically require high-duty-factor beams pulsed at a time interval commensurate with the muon lifetime. It is challenging to provide large RF voltages at high duty factor, especially in the presence of intense radiation and strong magnetic fields, which may preclude the use of superconducting RF cavities. As an alternative, cavities made of materials such as ultra-pure Al and Be, which become very good --but not super--conductors at cryogenic temperatures, can be used. There are promising new preliminary concepts for using the beam from the Project-X CW linac directly to provide high-duty-factor muon beams with a variety of useful characteristics. Further development is needed for design, simulation, and optimization of the whole channel, as well as RD&D on hyperconductive RF cavities—the enabling technology.

USE OF HELICAL TRANSPORT CHANNELS FOR BUNCH RECOMBINATION

Cooling scenarios for a high-luminosity Muon Collider require bunch recombination for optimal luminosity. In the IPAC12 contribution reproduced in Appendix VI we describe a new method for bunch recombination. We combine the high-chronicity of a helical transport channel (HTC) with the high-frequency bunching and phase-energy rotation concept (time reversed) to obtain a compact bunch recombination system adapted to a muon collider scenario. We first present an idealized 1-D system with multiple chronicity transports. We then implement the concept in a single-chronicity channel, obtaining bunch recombination of 13 200MHz-spaced bunches to a single collider-ready bunch within a compact transport with modest rf requirements. That example is demonstrated within G4BL 3-D simulations. Variations and adaptations for different recombination requirements are discussed.

BUNCH COALESCING IN A HELICAL CHANNEL

Appendix VII is an IPAC12 contribution that considers a high-luminosity Muon Collider that requires bunch recombination for optimal luminosity. As in Appendix VI, we take advantage of the large slip factor attainable in a helical transport channel (HTC) to coalesce bunches of muons into a single one over a shorter distance than can be achieved over a straight channel. Extending the work in Appendix VI, a bunch coalescing subsystem in a helical channel has been designed that makes minimal modifications to the magnetic fields of an existing HCC design that cool muons. The ~105 m long coalescing subsystem that is designed to merge 9 bunches is able to achieve efficiencies of 99.7%, 98.4%, and 94.2% for 9, 11, and 13 bunches, respectively. Simplified designs incorporating fill factors for RF cavities of ~25% and ~50% obtained efficiencies of 96%, 94-95%, and 90-91% for 9, 11, and 13 bunches, respectively. The efficiencies do not include decay losses, which would be ~8% for muons with kinetic energy of 200 MeV. As shown in the table, a linear coalescing system that was envisioned before the HCC concept was applied would be longer, more expensive and lose over 3 times as many muons by decay.

Conclusions

The Helical Cooling Channel concept has been extended by analytic and numerical simulations to facilitate the merging of several RF bunches into one bunch. The potential luminosity of a muon collider will be enhanced by this technique relative to others previously considered by being more efficient in that transverse and longitudinal acceptances are large such that fewer particles are lost by escaping the channel and in that the channel is shorter so that fewer muons are lost by decays.

Publications Supported by this grant

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[2] C. Yoshikawa, C. Ankenbrandt, D. Neuffer QUASI-ISOCHRONOUS MUON COLLECTION CHANNELS, WEPE073, IPAC10.
[3] C. Yoshikawa, C. Ankenbrandt, D. Neuffer, K. Yonehara, HELICAL CHANNELS WITH VARIABLE SLIP FACTOR FOR NEUTRINO FACTORIES AND MUON COLLIDERS, MOP047, IPAC11.
[4] D. Neuffer, C. Yoshikawa, MUON CAPTURE FOR THE FRONT END OF A μ+-μ- COLLIDER, MOP030, IPAC11.
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[6] D. Neuffer, K. Yonehara, C. Ankenbrandt, C. Yoshikawa, USE OF HELICAL TRANSPOR CHANNELS FOR BUNCH RECOMBINATION, MOPPC034, IPAC12.
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MUON CAPTURE IN THE FRONT END OF THE IDS NEUTRINO FACTORY *

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Abstract

We discuss the design of the muon capture front end of the neutrino factory International Design Study. In the front end, a proton bunch on a target creates secondary pions that drift into a capture transport channel, decaying into muons. A sequence of rf cavities forms the resulting muon beams into strings of bunches of differing energies, aligns the bunches to (nearly) equal central energies, and initiates ionization cooling. For the International Design Study (IDS), a baseline design must be developed and optimized for an engineering and cost study. The design is affected by limitations on accelerating gradients within magnetic fields. The effects of gradient limitations are explored, and mitigation strategies are presented.

INTRODUCTION

The goal of the IDS Neutrino Factory is to deliver a reference design report by 2012 in which the physics requirements are specified and the accelerator and detector systems are defined, with an estimate of the required costs[1]. It consists of:

- a proton source with a baseline intensity goal of 4MW beam power (50Hz, ~10GeV protons, ~2ns bunches. (~5×10^{13}p/ pulse),
- a target, capture and cooling section that produces π's that decay into μ's and captures them into a small number of bunches.
- an accelerator that takes the μ's to 25 (or 50) GeV and inserts them into storage rings. μ decay in the straight sections provides high-energy ν beams for:
- ~100 kton ν-detectors at 4000-7500km baselines with sufficient resolution to identify ν-interactions.

The goal is > 10^{21} ν's /beamline/ year in order to obtain precise measurements of ν-oscillation parameters.

The present paper discusses the muon capture and cooling system. In this system we follow ref. [2], and set 201.25MHz as the baseline bunch frequency. The π's (and resulting μ's) are initially produced with broad energy spreads, much larger than the acceptance of any accelerator, and much larger in phase space than a 200MHz rf bucket. In this "front end" system, we capture this large phase space of μ's into a string of ~200MHz bunches, rotate the bunches to equal energies, and cooled them for acceleration to full energy. The method captures both μ^+'s and μ^-'s simultaneously and can be adapted to feed a μ^+-μ^- collider.

*Research supported by US DOE under contract DE-AC02-07CH11359 and SBIR grant DE-SC-0002739.

IDS BASELINE FRONT END

The baseline front end is shown in Figure 1. ~10GeV protons are targeted onto a Hg jet target that is encapsulated in a 20 T solenoid. π's created from the target are captured as they traverse the 15m long solenoid, that has a field profile that starts at 20T and 7.5cm radius at the target and tapers off to ~1.5T and 30cm radius at the end. This section captures π's and μ's with transverse momenta p_t < eBr/2 = 0.225GeV/c, with an adiabatic damping of the transverse momentum.

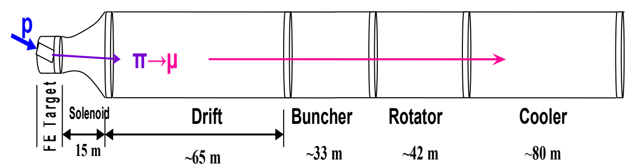

Figure 1: Overview of the front end, consisting of a target solenoid (20 T), a tapered capture solenoid (20 T to 1.5T, 15m long), Drift section (65m), rf Buncher (33 m), an energy-phase Rotator (42m), and a Cooler (~80m).

The taper is followed by a Drift section, where π's decay to μ's, and the bunch lengthens, developing a high-energy "head" and a low-energy "tail". In the Buncher, rf voltages are applied to the beam to form it into a string of bunches of different energies. (fig. 2) This is obtained by requiring that the rf wavelength of the cavity is set to an integer fraction of the cτ between reference particles:

$$\lambda_{rf}(L) = \frac{L}{N}\left(\frac{1}{\beta_N} - \frac{1}{\beta_0}\right)$$

In the baseline, muons with p_0 = 232 MeV/c, and p_N = 154 MeV/c with N=10 are used as reference particles. The reference particles (and all intermediate bunch centers) remain at 0-phase throughout the buncher. The rf frequency decreases from 320 to 232 MHz along the 33m Buncher while the rf gradient in cavities increases from 0 to 9 MV/m. In the Rotator, the lower energy reference particle is moved to an accelerating phase as the wavelength separation is also lengthened. (10 → ~10.05) At the end of the Rotator the reference particles are at the same momentum (~232MeV/c) and the rf frequency is matched to 201.25 MHz.. μ's with initial momenta from ~80 to 500 MeV/c have been formed into a train of 201.25 MHz bunches with average momenta of ~232 MeV/c and $\delta p_{rms}/p \approx 10\%$. The bunch train is ~60m long with ~40 bunches.

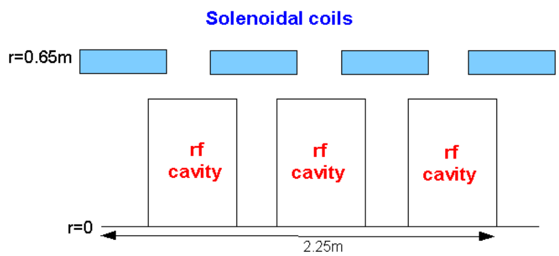

Figure 2: Baseline Layout of RF + magnets in Buncher and Rotator. The rf is in 0.5m cavities with 0.25 drifts, with a 1.75T focusing solenoid field throughout.

The μ's are matched into a cooling section (fig. 3) which consists of rf cavities, LiH absorbers for cooling and alternating solenoids (AS) for focusing. (B oscillates from 2.7 to -2.7T with a 1.5 m period.). The cooling doubles the number of accepted μ's while reducing the rms transverse emittances by a factor of 3. After ~75m of cooling, we find that the system accepts ~0.1μ^+/ 10 GeV proton within reference acceptances of $\varepsilon_{L,N}$ <0.2m, $\varepsilon_{t,N}$ <.3cm, which are the acceptances of the downstream acceleration and storage rings. As a bonus, the method simultaneously produces bunch trains of both signs (μ^+ and μ^-) at equal intensities.

The baseline presented here is a variation of the front end presented in ref. [1] and is ~25% shorter with somewhat smaller magnetic fields and rf gradients. The changes are designed to reduce cost and the risks of large rf gradient requirements.

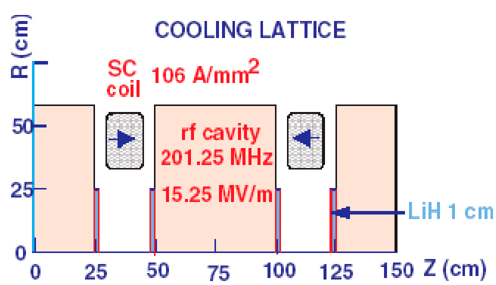

Figure 3: Baseline cooling channel cell layout, with LiH absorbers, rf cavities and focusing coils.

IMPLEMENTATION FOR THE IDS

For the IDS, the method must be evaluated for practicality and cost. The initial concept had a continuous variation of frequency from cell to cell; an implementation with ~13 separate frequencies in the buncher and ~15 in the rotator is used for a practical implementation. These rf cavities will be grouped into units with matched power supplies, and the configurations will be evaluated.

In a first approximation, the rf cavities are copper pillbox shapes (at 200 MHz, a=0.57m, Q=58000) and are similar to the 200 MHz rf cavities (rounded Cu cylinders with Be windows) built for MICE.[3] From the MICE rf specifications, scaled by the pillbox cavity model, we can estimate the rf requirements of the IDS, and these are summarized in Table 1.

Table 1: Baseline rf requirements

Region	Number of rf cavities	rf frequencies	rf gradients, peak power
Buncher	37	320 to 231.6 MHz, 13 frequencies	0-7.5 MV/m, 0.5 to 3.5MW per frequency
Rotator	56	230 to 202.3 MHz, 15 freq.	12 MV/m, ~2.5MW/cavity
Cooler (75m)	100	201.25 MHz	15MV/m, ~4MW / cavity

The front end will also require significant magnet costs, initially determined from combining the 20 to 1.5 T solenoid r=7.5cm to r=30cm) with a ~150m long 1.5 T solenoid and 75m of AS coils (100 coils) for the cooling. This component count, with civil construction, will be used to set an initial cost baseline for the IDS.

Performance estimates and optimizations are being obtained using ICOOL,[4] G4Beamline,[5] and G4MICE[6] particle tracking simulations and the results are consistent. Fig. 4 shows results of a simulation of μ-capture from π's produced by 10000 8-GeVp on target. ~0.09μ/p are within the IDS acceptance. Fig. 5 displays the longitudinal phase space through the system.

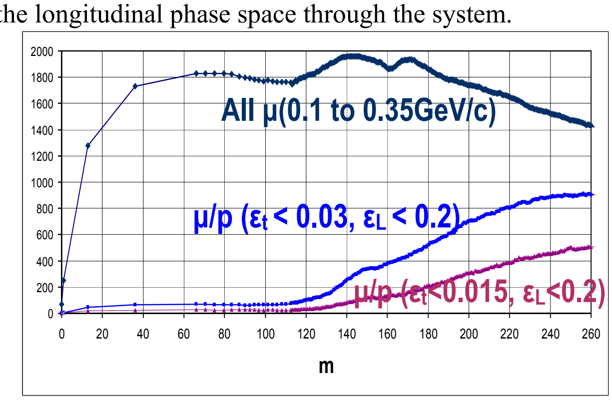

Figure 4: Captured μ's in the system. μ's are captured in a ~60m long train of λ=1.5m bunches. At z= 160m ~0.04 μ/p are captured in the acceptance. At end of cooling~ 0.09 μ/p have been cooled to within the acceptance. $\varepsilon_{t,\,rms}$ is cooled from ~0.017 to 0.006m (ICOOL result.).

RF GRADIENT LIMITATIONS

The μ capture concept requires using relatively high gradient rf fields interleaved with relatively strong solenoidal magnetic fields. In the Buncher, rf gradients of ~7MV/m at ~200MHz within 1.5T solenoids are needed. The Rotator uses 12MV/m gradients within 1.5T, and the Cooler uses ~15MV/m within AS fields. Recent experiments appear to show that maximum rf gradients are reduced in magnetic fields. Operation of 200 MHz rf within a solenoid will be tested soon.[7] If limitations are found, we have several mitigation strategies that can be used to maintain a practical design. These are described in more detail a separate paper. They include changing the rf cavities by using Be or using open-cell cavities, or using magnetically-insulated rf cavities, or using magnetic shielding. Gas-filled rf cavities can also be used, since experiments have shown that H_2 gas suppresses breakdown in magnetic fields. [8, 9, 10]

Lower gradient operation

If limitations exist but are not too stringent, lower gradient operation may provide adequate mitigation. In the present baseline, the buncher rf fields (<~7MV/m) are expected to be relatively safe. In the Rotator, rf at 12MV/m could be reduced to 8MV/m without degradation by increasing the rf occupancy from 2/3 to 1. We have also studied the effects of reduced gradients in simulation, and found that the buncher/rotator acceptance is not greatly reduced by reducing the gradients by as much as a factor of 2.

Reduction of gradients in the Cooler is more difficult, since the rf must compensate for ionization energy loss as well as bunch the beam. (It is possible that the AS field does not limit gradients as much as a constant solenoid.) A 12 MV/m cooler had ~25% less acceptance than the baseline 15MV/m, and much lower gradients could eliminate the gain from cooling.

Simulations also show that acceptance is improved if greater gradients are available, particularly in cooling. Increased gradients are likely to be available as experience in operation is developed.

VARIATIONS & FUTURE STUDIES

We have presented a baseline design that sets the scale of the IDS front end system. rf R&D may require changes in that baseline, but should not change the scale of the system. Variations that improve performance and/or reduce cost will be considered and developed.

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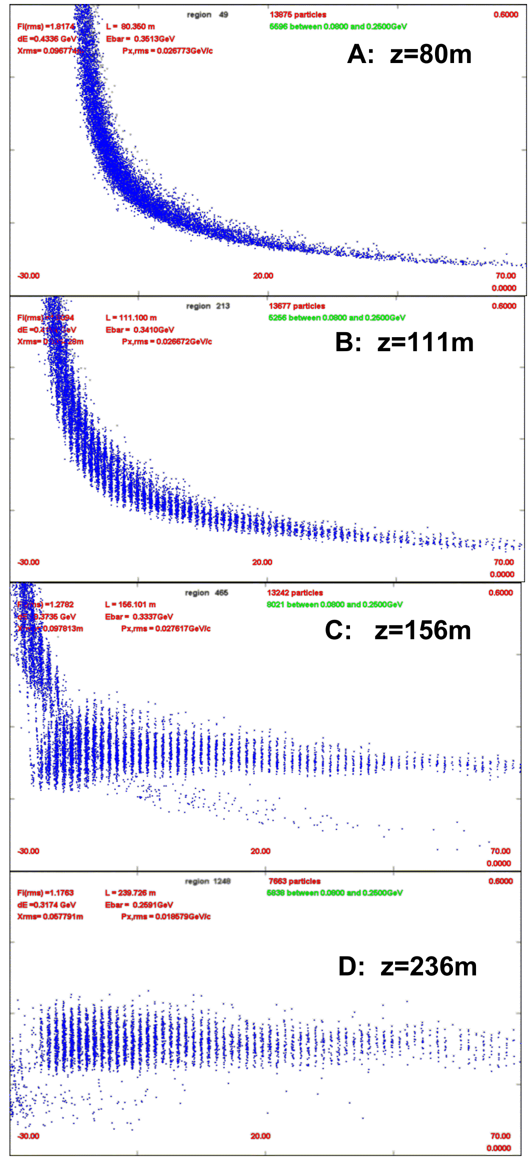

Figure 5: ICOOL simulation results of the buncher and phase rotation. A:μ's as produced at the end of the solenoidal capture + drift.(z=80m) B: μ's at z=11m after the buncher. C: μ's at z=156m, the end of the rotator. The beam has been formed into a string of ~200MHz bunches at ~equal energies. D: At z= 236m after ~80m of cooling. μ's captured within rf buckets are cooled. In each plot the vertical axis is momentum (0 to 0.6 GeV/c) and the horizontal axis is longitudinal position (-30 to 70m).

QUASI-ISOCHRONOUS MUON COLLECTION CHANNELS*

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Abstract

Intense muon beams have many potential applications, including neutrino factories and muon colliders. However, muons are produced as tertiary beams, resulting in diffuse phase space distributions. To make useful beams, the muons must be rapidly cooled before they decay. An idea conceived recently for the collection and cooling of muon beams, namely, the use of a Quasi-Isochronous Helical Channel (QIHC) to facilitate capture of muons into RF buckets, has been developed further. The resulting distribution could be cooled quickly and coalesced into a single bunch to optimize the luminosity of a muon collider. After a brief elaboration of the QIHC concept, recent developments are described.

INTRODUCTION

A Quasi-Isochronous Helical Channel (QIHC) is being investigated as an alternative to a significant portion of the baseline front end for a neutrino factory or muon collider. The study 2A [1] front end consists of a target solenoid (20 T), a tapered capture solenoid (20 T to 2T, 12 m long), a drift section (99 m), an RF buncher (50 m), an energy-phase rotator (54 m), and a cooling region (80 m). The QIHC might be developed to replace all but the last cooling stage, and this cooling section may be replaced by a Helical Cooling Channel (HCC) [2,3]. The QIHC offers a more natural match into the potentially more efficient HCC.

The QIHC concept takes advantage of the larger RF buckets for particles traveling in nearly isochronous orbits. Critical components of a QIHC system, as presently conceived, include the following: (1) a helical magnetic field that creates helical particle trajectories near a reference orbit of a selected muon momentum, (2) RF cavities that capture particles in stable buckets, and (3) an absorber that reduces the energy of particles that would otherwise be too energetic to be captured. In this paper, we present the analytic theory behind the concept along with simulation results. However, current simulations are based on an existing HCC configuration [3] and hence do not fully exercise all possible parameters; further simulations are to be performed in the near future.

NEARLY ISOCHRONOUS CONDITION

The QIHC aims to take advantage of a larger RF bucket area when operating near transition:

$$A_{bucket} \cong \frac{16}{w_{rf}} \sqrt{\frac{eV'_{\max}\lambda_{RF} m_\mu c^2}{2\pi|\eta_H|}} \left[\frac{1-\sin(\varphi_s)}{1+\sin(\phi_s)}\right] \qquad (1)$$

where

- the term in brackets is an approximation for the moving-bucket factor
- w_{rf} is the RF frequency in radians/second
- V'_{max} is the maximum E-field voltage gradient
- λ_{rf} is the RF wavelength
- m_μ is the mass of the muon
- φ_s is the synchronous particle RF phase, and

η_H is the slip factor, derived in [2] for an HCC as:

$$\eta_H = \frac{\sqrt{1+\kappa^2}}{\gamma\beta^3}\left(\frac{\kappa^2}{1+\kappa^2}\hat{D} - \frac{1}{\gamma^2}\right) \qquad (2)$$

where γ becomes γ_T when η_H=0 and the dispersion factor $\hat{D}$ relates to apparatus quantities and design momentum via:

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

in which

- p is reference momentum; a is reference radius
- $\kappa = p_{transverse}/p_z$ = helix pitch
- B is the solenoid B_z
- $k = 2\pi/\lambda$; λ is helix period
- $\frac{\partial b_\phi}{\partial\rho}$ being the quadrupole component

DESIGN & SIMULATION

Since the HCC is charge specific [2], this paper focuses on capture of μ^-. Our original intention was to manipulate the parameters that control transition in a HCC after matching into it from a solenoid. However, preliminary studies showed that transition occurs in the match itself for an existing HCC configuration optimized for cooling. Instead of redesigning the match, we decided to start our simulation effort based on an established HCC design and its matching portion [3]. All simulations utilized G4beamline [4].

The cooling HCC has B_z on the reference of 4.2 T and the acceptance is approximately 150 MeV/c < p < 300 MeV/c. Hence, we modified the portion upstream of the HCC as follows:

1. The tapered solenoid is modified from Bz with 20 T → ~2 T to 20 T → 4.2 T. This shortens the tapered solenoid from about 10 m to 4.5 m.
2. In order to maximize the number of muons that fall into the HCC acceptance, we implement two sequential straight sections:
   a. 20 m of RF in vacuum at 5 MV/m to capture μ's and π's and allow lower momenta π's to decay into μ's.
   b. 20 m of RF in material (Be & 100 atm H_2 gas) at 35 MV/m to enlarge RF bucket size and cause otherwise useless higher energy π's to interact

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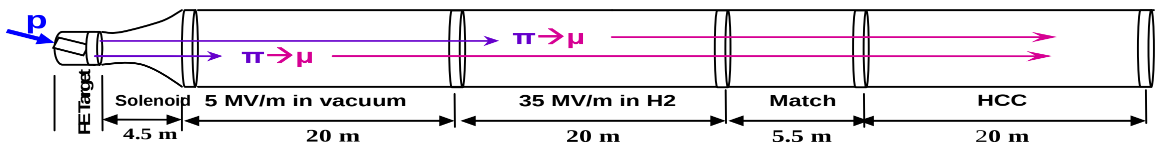

Figure 1: Layout showing modified tapered solenoid ending with Bz=4.2T, 20 m of RF with 5 MV/m in vacuum, 20 m of RF with 35 MV/m in H2 gas and Be windows with varying thicknesses, the matching section, and the HCC.

Table 1: Layout Parameters

z(m)	Subsystem	Purpose	Physical Dimensions	Fields
0.0 to 4.5	Capture/Tapered Solenoid	Enhance pion/muon capture	L = 4.5 m R = 7.5 cm → 35 cm	Bsol = 20 T → 4.2 T
4.5 to 24.5	First straight RF Buncher in vacuum	1. Initial capture of π's & μ's into RF buckets. 2. Allow lower momenta π's to decay into μ's.	L = 20 m R = 35 cm	Bsol = 4.2 T 160 RF Cavities: V'_{max} = 5 MV/m, f= 162.5 MHz φ_s=186°: P(μ−)=150→162 MeV/c
24.5 to 44.5	Second straight RF Buncher in 100 atm H2 w/ variably thick Be windows.	1. H2 gas allows higher RF gradient. 2. Be causes higher momenta π's to interact, enhancing useful μ's. 3. Transverse cooling.	L = 20 m R = 35 cm	Bsol = 4.2 T 160 RF Cavities: V'_{max} = 35 MV/m, f= 162.5 MHz φ_s=208→194°, P(μ−)=162→237 MeV/c
44.5 to 50.0	Match into HCC	1. To match between straight solenoid into HCC. 2. Enhance μ capture due to transition occurring in match.	L = 5.5 m (5.5 λ's) R = 35 cm	Bsol = 6.3 T →4.2 T 44 RF Cavities: V'_{max} = 35 MV/m, f= 162.5 MHz φ_s varied to maintain P(μ−)=237 MeV/c
50.0 to 70.0	HCC	To cool muons in 5D phase space.	L = 20 m (20 λ's) R = 35 cm	Bsol = 4.2 T 160 RF Cavities: V'_{max} = 35 MV/m, f= 162.5 MHz φ_s=-12.6° to maintain P(μ−)=237 MeV/c

with material, producing lower energy π's that decay into μ's in the useful momenta range.

After the modified portion upstream of the HCC, we began to use the established match and HCC. The match has added to it RF, H_2 gas, and Be windows. The HCC itself also incorporates RF and material, but this is an innovation for the matching section. Figure 1 and Table 1 show and describe the layout, respectively.

Figure 2 shows that muons from a MERIT-like targetry [5] exiting the tapered solenoid peak at around 150 MeV/c in momenta, near the bottom of the HCC acceptance. So, the first 20 m straight is timed to capture 150 MeV/c muons and phased to accelerate them to 162 MeV/c at the end of this first straight, with results shown in Figure 3.

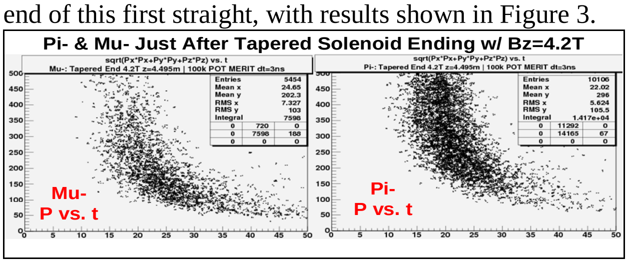

Figure 2: Momentum (MeV/c; vert.) vs. arrival time (nsec; horiz.) for μ^-'s and π^-'s exiting tapered solenoid.

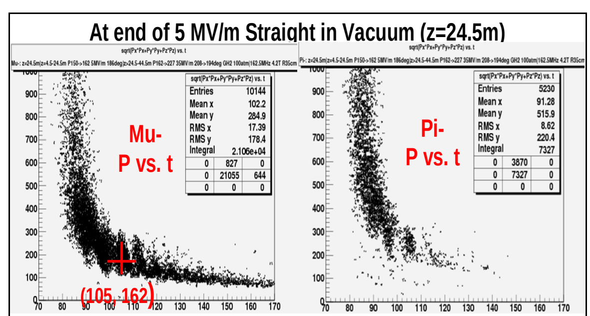

Figure 3: Momentum (MeV/c) vs. arrival time (nsec) for μ^-'s and π^-'s after the first straight solenoid in vacuum.

The second straight section introduces a variable amount of Be, totaling half an interaction length for pions, to cause the otherwise useless higher energy pions to interact and create lower energy pions that decay into muons of the right energy for the HCC acceptance. Figure 4 shows the momenta and longitudinal position at creation of muons and pions; pion creation is readily seen at the start of the second straight. The longitudinal dynamics of μ's and π's at the end of the second straight section are displayed in Figure 5.

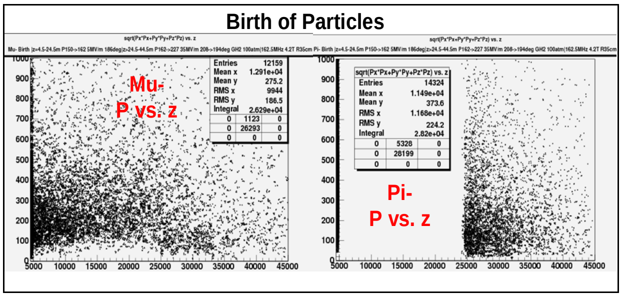

Figure 4: Momentum (MeV/c) vs. z (mm) for μ^-'s and π^-'s at the particle's creation.

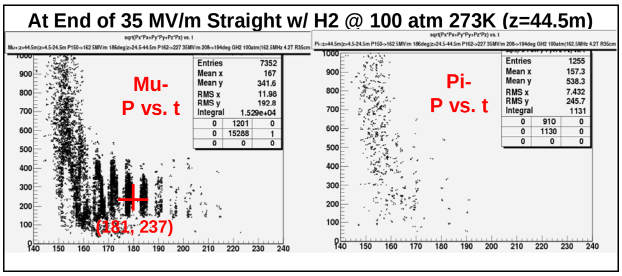

Figure 5: Momentum (MeV/c) vs. z (mm) for μ^-'s and π^-'s at exit of the second straight and entrance of the matching section.

In this first study, the design philosophy for the match was to keep the RF bucket as large as possible throughout, which translated into keeping a constant momentum of 237 MeV/c. Since the pitch (κ=P_{trans}/P_z) of the path grows from 0 to 1, the path length likewise grows per unit of z, necessitating a growth in φ_s as the μ- plows through more material, causing the RF bucket size to shrink due to the factor in square brackets in equation 1. We also extracted γ_T from the match via the fastest time of flight between transverse planes, which guided us to know when to jump the phase to maintain stability. Figure 6 shows the accelerating phase, φ_s, the derived bucket area, and other relevant parameters. Figure 7 contains the final distribution of μ's and π's at the end of the match.

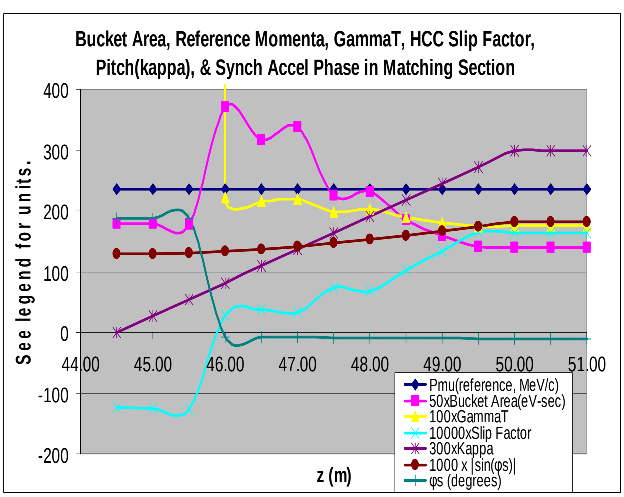

Figure 6: Design parameters in matching section. Accelerating phase φ_s is designed to maintain constant momentum of 237 MeV/c.

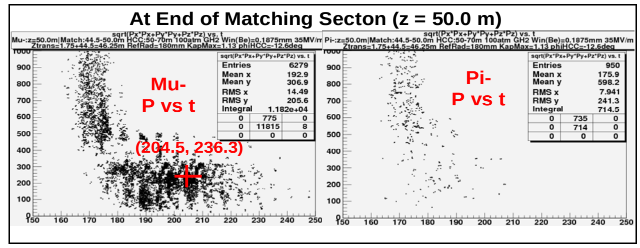

Figure 7: Momentum (MeV/c) vs. z (mm) for μ^-'s and π^-'s at exit of the matching section.

SUMMARY & FUTURE

We have made a preliminary design of a system upstream of the HCC to enhance the number of muons in its acceptance. An innovation has been introduced to use the high energy pions to create useful muons by incorporating material at strategic locations. We have added RF with H_2 gas into the match and performed an initial study that involves crossing transition.

The established matching portion upon which we based our study was designed without RF or material. We believe that capture into RF buckets in the match can be greatly increased by designing it with RF and material from the start. In particular, the size of the RF bucket in equation (1) is driven by φ_s, η, and V'_{max}. We have seen that to maintain a fixed momentum, the increase in pitch κ forces φ_s to increase, which decreases the RF bucket size, although it is possible to manipulate p(z) to achieve a monotonic growth of bucket area. The slip factor, η_H, provides a degree of freedom to control bucket area growth. Via equations (1) to (3), a given profile of p(z) will define $(\partial b_\phi/\partial r)(z)$ that is necessary to obtain the desired $A_{bucket}(z)$. If for some unforeseen reason the desired $(\partial b_\phi/\partial r)(z)$ cannot be obtained by current containing coils, the last degree of freedom exercisable is $V'_{max}(z)$. Hence, we plan to design a matching section that fundamentally integrates RF and material to achieve very large RF buckets for capture and transport into the HCC, which has been demonstrated to be a very efficient cooling scheme for a neutrino factory or muon collider.

Once the match and HCC are designed, the profile of material in the second straight section will be optimized, including other particles created at the target that will increase the rate of muons captured and transported.

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HELICAL CHANNELS WITH VARIABLE SLIP FACTOR FOR NEUTRINO FACTORIES AND MUON COLLIDERS*

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Abstract

In order to realize a muon collider or a neutrino factory based on a muon storage ring, the muons must be captured and cooled efficiently. For a muon collider, the resulting train of bunches should be coalesced into a single bunch. Design concepts for a system to capture, cool, and coalesce a muon beam are described here. In particular, variants of a helical channel are used, taking advantage of the ability to vary the slip factor and other parameters of such a channel. The cooling application has been described before [1,2]; this paper reports recent studies of a system that includes two novel concepts to accomplish capture and coalescing [3] via a slip-controlled helical channel.

INTRODUCTION

The helical cooling channel (HCC) [1] was invented to achieve efficient ionization cooling in all three degrees of freedom, i.e. in 6-D phase space. However, there is considerable flexibility in the design of helical channels, so other applications are also possible. In particular, the magnetic parameters, RF parameters, and contents of the volume (e.g. vacuum or gas, slab absorbers or wedge absorbers) can be varied, allowing the design of helical channels for other purposes: to capture muons upstream of the cooling section, to allow extreme cooling (EPIC [4]), and to coalesce multiple bunches into a single bunch downstream of the cooling section. This paper focuses on the upstream capture subsystem, called a quasi-isochronous helical channel (QIHC), and the downstream bunch merger subsystem, called the bunch-coalescing helical channel (BCHC [3]).

Providing multiple functions in the same type of magnetic channel greatly simplifies the transitions between subsystems, since the parameters of the channel can be varied adiabatically to accomplish the matching. The resultant front end that provides multiple functions in a single helical channel is likely to be simpler and less expensive than the baseline muon collider front end [5] and its associated bunch merger [6,7]. Besides the QIHC and BCHC, other structures in the channel provide the initial capture of muons into RF bunches as well as cooling in the HCC and EPIC before the bunch merging. These other subsystems are included as necessary parts of the whole system, but this paper focuses on the QIHC and BCHC.

CONCEPTS UNDERLYING THE QIHC

The QIHC captures a train of muon bunches in RF buckets by varying the channel parameters in order to cause the RF bucket area to increase monotonically as the beam propagates downstream. The bucket area is given by:

$$A_{bucket} \cong \frac{16}{w_{rf}} \sqrt{\frac{eV'_{\max} \lambda_{RF} m_\mu c^2}{2\pi |\eta_H|}} \left[\frac{1-\sin(\varphi_s)}{1+\sin(\phi_s)} \right] \quad (1)$$

where

- the term in brackets is an approximation for the moving-bucket factor
- w_{rf} is the RF frequency in radians/second
- V'_{max} is the maximum E-field voltage gradient
- λ_{rf} is the RF wavelength
- m_μ is the mass of the muon
- φ_s is the synchronous particle RF phase, and

η_H is the slip factor, derived in [1] for an HCC as:

$$\eta_H = \frac{\sqrt{1+\kappa^2}}{\gamma\beta^3} \left(\frac{\kappa^2}{1+\kappa^2} \hat{D} - \frac{1}{\gamma^2} \right) \quad (2)$$

where $1/\gamma_T^2 = \left(\kappa^2/(1+\kappa^2)\right)\hat{D}$ and the dispersion factor $\hat{D}$ relates to apparatus quantities and design momentum via:

$$\hat{D}^{-1} = \frac{a}{p}\frac{dp}{da} = \frac{\kappa^2 + (1-\kappa^2)[(B\sqrt{1+\kappa^2}/pk) - 1]}{1+\kappa^2} - \frac{(1+\kappa^2)^{3/2}}{pk^2}\frac{\partial b_\phi}{\partial \rho} \quad (3)$$

in which

- p is reference momentum; a is reference radius
- $\kappa = p_{transverse}/p_z$ = helix pitch
- B is the solenoid B_z
- $k = 2\pi/\lambda$; λ is helix period, and
- $\frac{\partial b_\phi}{\partial \rho}$ is the quadrupole component.

Thus, the RF bucket area in the QIHC can be adjusted by varying the gradient of the dipole field ($\partial b_\phi / \partial \rho$), the reference momentum (p), the accelerating phase (φ_s), the transition energy γ_t, and the maximum gradient (V'_{max}).

DESIGN & SIMULATION LAYOUT

The QIHC and BCHC are integral parts of a proposed front end shown in Figure 1 that exploits the flexibility of the helical channel. The simulations described here involved 100k 8 GeV protons on a Hg target in a MERIT-like configuration [8] followed by a tapered capture solenoid with a $B_z(z)$ profile similar to that of the baseline design [5], but modified to end at 4 T instead of 2 T. Subsequent to the tapered solenoid is a first straight RF buncher in vacuum for 20 m to capture lower energy pions/muons in the useful range, followed by a second straight RF buncher in high-pressure hydrogen gas to allow higher electric field gradients together with variable amounts of Be foils. This material provides transverse precooling of the muons and also allows the otherwise useless higher energy pions and protons to interact, thereby possibly creating additional useful muons. Following the second straight is the QIHC, which not only serves to enhance capture via enlarged RF buckets, but also provides the matching from a straight

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solenoid channel into the HCC, which has a pitch angle of 45°. The HCC provides 6-D cooling of multiple muon bunches and is followed by EPIC for even further cooling. The BCHC takes the train of cooled muon bunches and coalesces them into a single bunch. If space charge precludes bunch merging at this low energy, the bunches will be accelerated before coalescing.

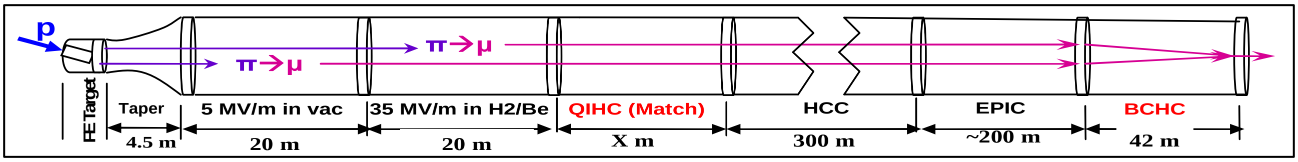

Figure 1: Layout showing a tapered solenoid for initial π/μ capture, 20 m of buncher with 5 MV/m in vacuum, 20 m of buncher with 35 MV/m in H_2 gas plus π degrader via Be windows, the QIHC which also provides matching of trajectories from straight solenoid into the HCC, the HCC that cools multiple muon bunches, the EPIC for extreme cooling, and the BCHC to merge the cooled bunches into a single muon bunch.. Acceleration may be needed before entering the BCHC if space charge precludes bunch merging at low energies.

QIHC DESIGN & SIMULATION

Figure 2 shows the longitudinal dynamics for μ^{-}'s at the end of a previous QIHC design [9]. That design phased the RF cavities to keep a constant momentum for the reference particle as it traversed a matching section based on gradually increasing coil displacements [2].

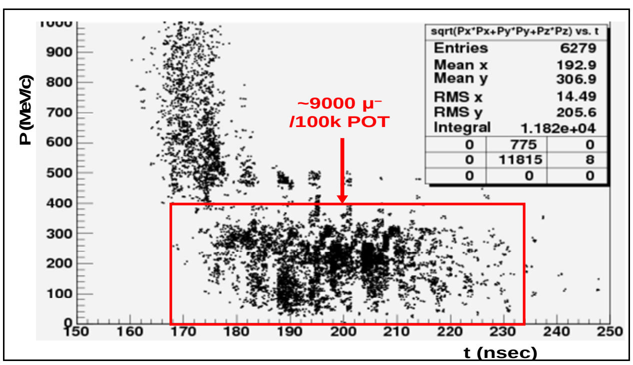

Figure 2: Longitudinal dynamics of μ-'s at end of a previously designed QIHC.

The current iteration of the QIHC design was motivated by the fact that the output emittance of the muon beams exiting the second straight solenoid (ε_T=11 mm-rad, $\varepsilon_{\|}$= 378 mm-rad) did not match the acceptance of the HCC (ε_T = 20 mm-rad, ε_L = 40 mm-rad). Hence, the new QIHC must also provide longitudinal cooling. In the new system, the parameters of the first 51m of the front end are adjusted to provide a monotonically increasing bucket area to optimize capture. Those parameters include γ_t, the accelerating phase φ_s, and the reference momentum, as illustrated in Figure 3.

Figure 4 shows a relatively high yield of pions and muons (~0.1 per proton on target for 150 MeV/c ≤ p ≤ 450 MeV/c) exiting the second straight and heading for the QIHC. Since the QIHC will be receiving muons from a straight channel, it must start below transition, so a desirable transition momentum corresponds to ~450 MeV/c. Reception of longitudinally hot muons from a straight channel also suggests that the QIHC operate at a small pitch, κ, to provide longitudinal cooling.

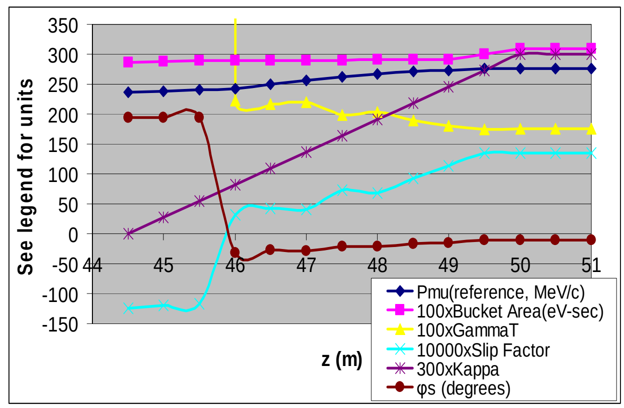

Figure 3: Parameters for monotonically increasing bucket area in the first part of a QIHC matching section.

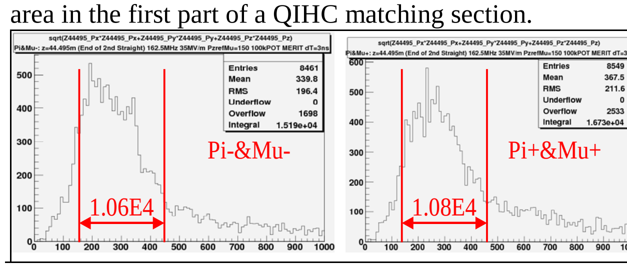

Figure 4: Momenta (MeV/c) of π's and μ's at the end of the second straight that enters the QIHC from 100k POT.

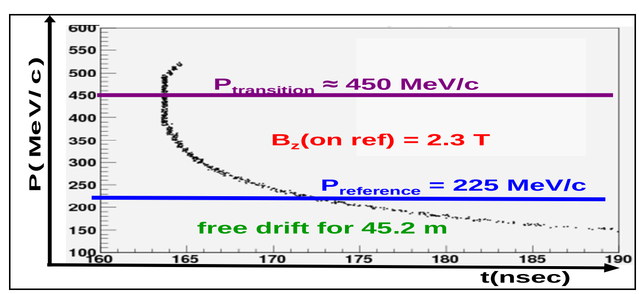

Figure 5: Longitudinal dynamics of a QIHC with κ=0.25.

A design for the magnetic fields of a QIHC that achieves the above criteria can be realized; its longitudinal dynamics are shown in Figure 5. To enhance longitudinal cooling, maximal use of a cylindrically symmetric Be wedge (1.48 mm thick on reference every 10 cm) along with 60 atm of H_2 gas at 293K (at the knee of the Paschen breakdown curve [10]) provided the largest ε_L acceptance compared to other cases with less use of wedges. For example, it provides a 19% enhancement of the ε_L acceptance compared to a case that has no wedges but the same total energy loss provided by only the gaseous H_2(200atm) as shown in Table 1. However, the equilibrium ε_L at ~30 m is lowest for the case without any wedge. So, a configuration to consider is to incorporate the maximal amount of Be wedges for the first ~20m of the κ=0.25 QIHC for largest longitudinal acceptance, followed by a region with no wedges to achieve the smallest equilibrium ε_L.

Table 1: Effect of varying amounts of Be wedge on ε_L. Maximal use of wedge has 60 atm of H_2. Equal use of wedge (E_{loss}(wedge)=E_{loss}(H_2)) has 100 atm of H_2. No use of wedge has 200 atm of H_2. All cases have same total energy loss in materials (E_{loss}(wedge)+E_{loss}(H_2)).

	H2:200 atm	H2:100 atm	H2: 60 atm
ε_L(m-rad) at z=0m	0.13300	0.14810	**0.15820**
ε_L(m-rad) at z=30m	**0.09619**	0.09843	0.09901

CONCEPTS UNDERLYING THE BCHC

The BCHC has a large slip factor to facilitate coalescing. The RF gymnastics that occur in the BCHC consist of three steps, as follows:

1. A frequency incommensurate with the bunch spacing is applied to the muon bunch train for two purposes:
   a. To apply a phase rotation within individual bunches to reduce the energy spread and increase the time spread of each bunch.
   b. To apply energy offsets between bunch centers that put early arriving bunches at higher energies and late arrivals at lower energies. Multiple frequencies may be used if needed to linearize the rotations.
2. A drift (with no RF) of the bunches in a helical channel to align the bunches in time. The slip factor is positive, so higher energy bunches take a longer time travelling downstream than lower energy bunches. The drift distance needed to align the bunches, which can be shortened by a large slip factor, is given by:

$$\delta(c\tau) = \eta_H \frac{\delta E}{m_\mu c^2} z \qquad (4)$$

3. When the bunches are time aligned, they encounter RF voltage to capture them into a single bunch.

BCHC DESIGN & SIMULATION

To illustrate the concepts underlying the BCHC, a design to merge 11 bunches with 5 nsec spacing (200 MHz) into a single bunch over a longitudinal distance of ~42m was simulated. A purely longitudinal simulation provides promising results as shown in Figure 6. An RF frequency of 204.08 MHz is applied to the 11 bunches that are initially separated with 5 nsec (200 MHz) spacing in order to induce phase rotation within each bunch as well as cause energy offsets between bunch centers as shown from Figure 6(a) to Figure 6(b). At the end of a 32.5 m-long drift in a region with η=0.43, the bunches are aligned. RF is then applied to capture ~95% of the muons in a single bunch. This successful longitudinal simulation motivates a full 3-D one using G4beamline [11].

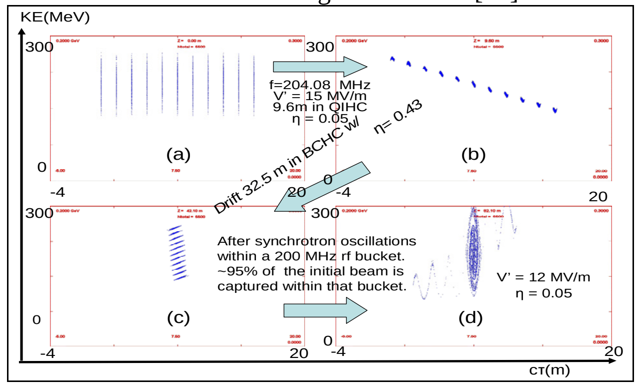

Figure 6: A longitudinal simulation of the BCHC. The 11 initial bunches with 5 nsec (200 MHz) bunch spacing are shown in (a). The energy displaced bunch centers and phase rotated muons within bunches after application of off-resonant frequency are shown in (b). At end of a 32.5 m long drift, the bunches are aligned in (c). RF is applied to capture ~95% of the muons in a single bunch in (d).

SUMMARY & FUTURE PLANS

The flexibility of the helical channel to capture, cool, and coalesce bunches of muons has been illustrated via this preliminary design of a front end for a NF/MC that promises to be simpler and more cost-effective than the baseline design. As the design is preliminary, it is too early to compare its performance with the baseline. Regarding capture, further studies including longitudinal cooling will enhance its effectiveness. For bunch coalescing, the 1D simulations provide promising results, which is the source of excitement for anticipated results from 3D simulations that are soon to come.

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MUON CAPTURE FOR THE FRONT END OF A μ^+-μ^- COLLIDER*

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Abstract

We discuss the design of the muon capture front end for a μ^+-μ^- Collider. In the front end, a proton bunch on a target creates secondary pions that drift into a capture transport channel, decaying into muons. A sequence of rf cavities forms the resulting muon beams into strings of bunches of differing energies, aligns the bunches to (nearly) equal central energies, and initiates ionization cooling. The muons are then cooled and accelerated to high energy into a storage ring for high-energy high luminosity collisions. Our initial design is based on the somewhat similar front end of the International Design Study (IDS) neutrino factory.

INTRODUCTION

The goal of a μ^+-μ^- collider is to provide high-energy high-luminosity collisions of μ bunches. It consists of:

- a proton source with a baseline intensity goal of 4 MW beam power (15Hz, ~10GeV protons, ~2ns bunches. (~3×10^{14}p/ pulse),
- a target, capture and initial cooling section that produces π's that decay into μ's and captures them into a small number of bunches.
- a cooling section that reduces the beam emittances to collider intensities by ionization cooling.
- an accelerator that takes the μ's to high energy and inserts them into a storage ring for collisions within a high-sensitivity detector.

The present paper discusses the muon capture and initial cooling system.

The front end is based on the similar front end of a neutrino factory, as presented in the IDS design study,[1] but reoptimized toward the somewhat different requirements of a collider system. In this paper we first present and discuss the IDS design and then discuss extensions toward a μ^+-μ^- collider front end. We then present a collider version and discuss future R&D directions and efforts. In this system we follow ref. [1], and set 201.25 MHz as the baseline bunch frequency. The π's (and resulting μ's) are initially produced with broad energy spreads, much larger in phase space than a 200 MHz rf bucket. In this "front end" system, we capture these μ's into strings of ~200 MHz bunches, rotate the bunches to equal energies, and cool them for acceleration to full energy. The method captures both μ^+'s and μ^-'s simultaneously and can be adapted to feed a μ^+-μ^- collider. The major difference is that for a collider we will need to recombine the trains of μ^+'s and μ^-'s to single (or a few) bunches for maximal luminosity.

ν-FACTORY FRONT END

The IDS front end is shown in Figure 1. ~10 GeV protons are targeted onto a Hg jet target that is encapsulated in a 20 T solenoid. π's created from the target are captured as they traverse the ~15m long solenoid that has a field profile that starts at 20T and 7.5cm radius at the target and tapers off to ~1.5T and 30cm radius at the end.

The taper is followed by a Drift section, where π's decay to μ's, and the bunch lengthens, developing an energy/time correlation. The following Buncher and Rotator sections contain rf cavities within focusing ~1.5T solenoids (Figure 2). In the Buncher, rf voltages are applied to the beam to form it into a string of bunches of different energies. This is obtained by requiring that the rf wavelength of the cavities be set to an integer fraction of the cτ between reference particles:

$$\lambda_{rf}(L) = \frac{L}{N}\left(\frac{1}{\beta_N} - \frac{1}{\beta_0}\right)$$

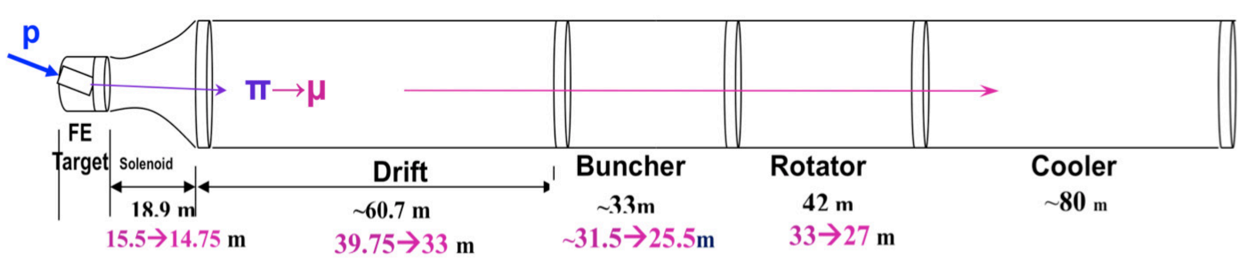

Figure 1: Overview of the IDS neutrino factory front end, consisting of a target solenoid (20 T), a tapered capture solenoid (20 T to 1.5T, 19m long), Drift section (~60m), rf Buncher (33 m), an energy-phase Rotator (42m), and a Cooler (~80m). In developing the N=10 and N=8 variants more suited to a μ^+-μ^- Collider, we reduce the section lengths (as indicated in magenta in the figure) while increasing rf and focusing fields.

*Research supported by US DOE under contract DE-AC02-07CH11359 and SBIR grant DE-SC-0002739.

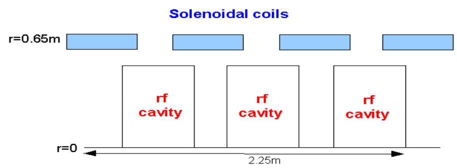

Figure 2: Radial projection of a Buncher and Rotator section, with rf cavities and solenoidal focusing.

In the IDS baseline, muons with p_0 = 232 MeV/c, and p_N = 154 MeV/c at N=10 are used as reference particles. The rf frequency decreases from 320 to 232 MHz along the 33m Buncher while the rf gradient in cavities increases from 0 to 9 MV/m. In the Rotator, the lower energy reference particle is moved to an accelerating phase as the wavelength separation is also lengthened. (10 → ~10.05) and the rf gradient increases to 12 MV/m. At the end of the Rotator the μ's have been formed into a train of 201.25 MHz bunches with average momenta of ~232MeV/c and $\delta p_{rms}/p \approx 10\%$. The bunch train is ~80m long with ~50 bunches.

The μ's are matched into a cooling section (Figure 3) which consists of rf cavities, LiH absorbers for cooling and alternating solenoids (AS) for focusing. (B_z oscillates from 2.7 to -2.7T with a 1.5 m period.). The cooling doubles the number of accepted μ's while reducing the rms transverse emittances by a factor of 3. After ~75m of cooling, we find that the system accepts ~0.1μ^+/ 10 GeV proton within reference acceptances of $\varepsilon_{L,N}$ <0.15m, $\varepsilon_{t,N}$ <.3cm, which are the acceptances of the downstream acceleration and storage rings. As a bonus, the method simultaneously produces bunch trains of both signs (μ^+ and μ^-) at equal intensities. As a result, the IDS neutrino factory is designed to use both signs in its acceleration and decay ring. The capture of both signs implies that it should be possible to extend the neutrino factory front end to initiate a collider, where simultaneous μ^+ and μ^- bunches are required.

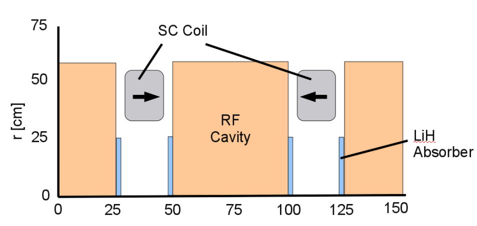

Figure 3: Radial projection of the baseline cooling channel cell layout, with LiH absorbers, cylindrical rf cavities, and focusing coils.

The μ capture concept requires using relatively high gradient rf fields interleaved with relatively strong solenoidal magnetic fields. Presently, we are uncertain what gradients are possible within magnetic fields, and alternate configurations using "bucked-field" or magnetic insulation or gas-filled rf cavities may be needed. In the present scenario, we assume that the solution is found and that gradients can be extended from the NF solution to higher levels in the second-generation μ^+-μ^- Collider front end.

This method obtains IDS bunch trains of ~80m length or ~56 200MHz bunches, but with ~67% of the μ's within the first ~20 bunches. A collider would need to recombine these bunches and that task would be eased if the bunch train were shortened.

REOPTIMIZATION FOR A μ^+-μ^- COLLIDER

The neutrino factory requires bunch trains that maximize the total number of μ's; the number of bunches is unimportant. However, for maximum luminosity the collider requires μ^+ and μ^- to be recombined into a small number of bunches and to be cooled to small longitudinal and transverse emittances. To facilitate recombination the initial capture should be in a shorter bunch train. This can be obtained by capturing at higher momentum within a shorter system.

An evolutionary variant of the IDS baseline with this purpose was developed. In that variant, reference particle 0 was moved to 280 MeV/c, and the Drift, Buncher and Rotator lengths were reduced to ~55m, 31.5 and 36m, respectively, with rf gradients increased to 15, 16 and 18 MV/m, respectively. The focusing fields were increased to 2T. The bunch spacing between the 280MeV/c and 154 MeV/c reference is 10 rf wavelengths (N=10) These incremental changes compress the ~80 m bunch train to ~54 m, so that a similar number of muons are obtained within ~16 bunches.

We also considered further iterations in which rf gradients are increased to 15, 18, and 20 MV/m and also in which the spacing between the reference particles was reduced to 8 wavelengths, (N=8) while the transport lengths were further reduced to ~49, 25 and 27m.

Performance estimates and optimizations are obtained using ICOOL[4] and G4beamline[5]; see Figure 5. The N=10 and N=8 examples obtain higher energy bunch trains, with somewhat more muons in the initial bunches of the trains. These bunches have a greater momentum width which will require cooling. The IDS bunches had a central momentum of ~250MeV/c with a full width of ~±60MeV/c, while the newer ones have P_μ =~300 ±~90MeV/c.

Overall muon capture is significantly better in this shorter system, partially from the use of higher gradients. The larger central momentum with the larger momentum spread acceptance captures muons over a broader initial production momentum range. The newer system accepts muons produced from π's with momentum from ~100 MeV/c to ~600 MeV/c, while the IDS accepted from ~100 to 400MeV/c. The larger acceptance matches the production momentum spread more closely.

Table 1 presents some simulations results on muon capture obtained with ICOOL simulations from initial π distributions generated from 8GeV protons on a Hg-jet target (using MARS[6]). The simulations show relatively more μ^- than μ^+ captured in each case; probably from higher initial production (simulated) in the acceptance. Limiting acceptance to the best 20, 16, and 13 bunches for the three cases captures 2/3 of the total produced muons, although there are extended trains of low-density bunches. In these initial scenarios we have retained the transverse cooling system developed for the neutrino factory, but with thicker absorbers and higher rf gradients. The cooling system reduces transverse emittances from ~0.02 to ~0.007 m. For a collider we need to transition to cooling systems that include longitudinal cooling, which require dispersive transport with wedge-type absorbers. In future simulations we need to add an initial longitudinal cooling section and explore matching optimizations.

As in the neutrino factory, we chose 201.25 MHz as our baseline frequency. A lower-frequency baseline would make it easier to obtain a smaller number of initial bunches. A higher-frequency case may enable higher gradients, but it would become difficult to fit the large initial beam from the target into smaller higher-frequency rf cavities.

The Front End begins with 4MW of protons on target and ends with ~50kW of muons. A large number of secondaries are produced, and are transported down the channel, with losses throughout it. Much of that beam power is deposited on the walls of the beam transport, and beam losses are ~100W/m in much of the channel, these losses may overheat components and inhibit hands-on maintenance. This effect must be studied and procedures to limit and manage the losses must be developed.

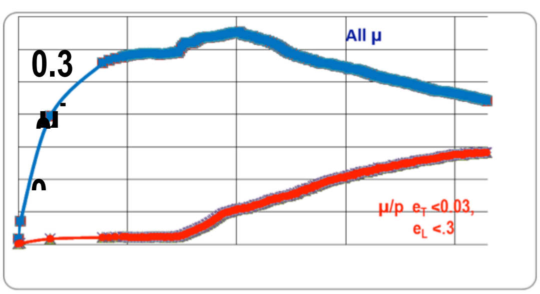

Figure 4: Total μ^- and μ^- within the acceptance criteria along the N=8 Front End. Transverse cooling after z=100m increases μ's within the acceptance.

VARIATIONS & FUTURE STUDIES

We have presented approaches to extending the Neutrino factory front end design to the more demanding requirements of a μ^+-μ^- collider. Variations that improve performance and/or reduce cost will be considered and developed. We will also consider variants that are dramatically different from this evolutionary approach.

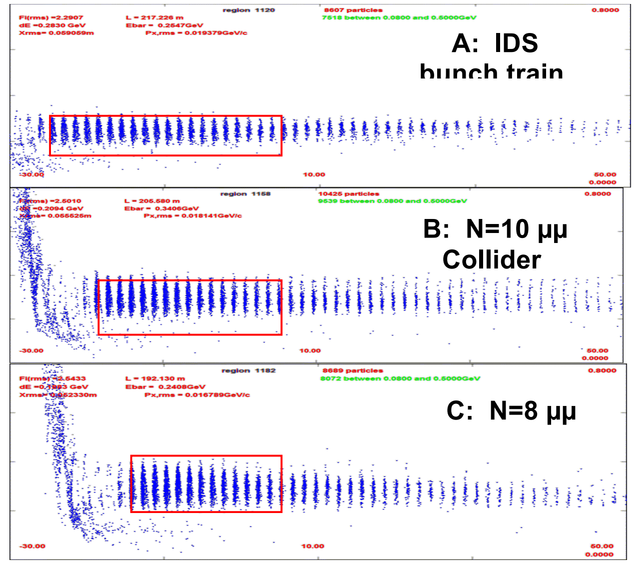

Figure 5: Longitudinal projections of the μ^- bunch trains developed in Front End simulations. A: IDS neutrino factory front end at z=217m. B: N=10 μ+-μ^- Collider front end at z=207m. C: N=8 example at z=192 m. In each plot the vertical axis is momentum (0 to 0.8 GeV/c) and the horizontal axis is longitudinal position (cτ) (-30 to 50m). Bunches to be recombined are outlined in red.

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Table 1: Comparison of Muon Source Front End Systems

Front end Scenario	Drift, Buncher, Rotator Length	RF Voltages (Buncher, Rotator, Cooler)	Full length w/ 75m cooling	μ^+/p (ε_t<0.03, ε_L<0.3m)	μ^-/p (ε_t<0.03, ε_L<0.3m)	Core bunches, N_B, all μ^-/p
IDS/NF	80.6, 33, 42m	0→9, 12, 15	230m	0.086	0.116	20/0.107
N=10	55.3, 31.5, 33	0→12, 15, 18	205	0.106	0.143	16/0.141
N=8	47.8, 25.5, 27 m	0→15, 18, 20	180	0.102	0.136	13/0.123

INTENSE MUON BEAMS FOR EXPERIMENTS AT PROJECT X*

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Abstract

A coherent approach for providing muon beams to several experiments for the intensity-frontier program at Project X is described. Concepts developed for the front end of a muon collider/neutrino factory facility, such as phase rotation and ionization cooling, are applied, but with significant differences. High-intensity experiments typically require high-duty-factor beams pulsed at a time interval commensurate with the muon lifetime. It is challenging to provide large RF voltages at high duty factor, especially in the presence of intense radiation and strong magnetic fields, which may preclude the use of superconducting RF cavities. As an alternative, cavities made of materials such as ultra-pure Al and Be, which become very good --but not super-- conductors at cryogenic temperatures, can be used.

INTRODUCTION

As part of its proposed Project X [1], Fermi National Accelerator Laboratory aspires to develop a world-class program of intensity-frontier experiments that perform very precise measurements and study extremely rare processes that may provide evidence for new physics beyond the Standard Model of particle physics. A 3-GeV superconducting linac that accelerates 1 mA of H^- beam in continuous-wave (CW) mode is proposed as the driver for that program. The plan is to split the beam so that three experimental areas, for kaon, muon, and nuclear experiments, can operate simultaneously.

Many experiments that study rare processes involve the detection of more than one particle in the final state. In these cases accidental coincidences between unrelated events, each of which supplies a particle that mimics one of the final-state particles of interest, are often the dominant background. To reduce the rate of such background events, high duty factors, i.e. beams that are "on" for a large fraction of the time, are essential. That in fact is the primary motivation for the decision to operate the 3-GeV Project-X linac in CW mode. Even when only one final-state particle is detectable, as in a muon-to-electron conversion experiment, a high duty factor may be useful to reduce singles rates in the detector, albeit at the expense of greater sensitivity to cosmic ray backgrounds.

For the muon experimental area, a number of experiments are under consideration [2], including searches for charged lepton flavor violation in processes such as muon to electron conversion in the field of a nucleus as well as in the decays $\mu \rightarrow e\,\gamma$ and $\mu \rightarrow 3e$. For several of the muon experiments that have been discussed, the signature of the rare process involves more than one detected particle in the final state. Thus those experiments require muon beams that have both high intensity and high duty factor.

Muon beams originate predominantly from the decay of pions produced when protons impinge on a target; as such, they are rather diffuse at first. Ionization cooling is necessary in order to concentrate high muon fluxes into usable phase-space volumes. Ionization cooling has undergone considerable conceptual development in connection with design efforts for muon colliders and neutrino factories [3]. Those facilities, however, will operate at low duty factor. In order to apply ionization cooling to the generation of low-energy beams having high duty factor, RF cavities are needed that can operate continuously in a harsh environment of intense radiation and strong magnetic fields.

Development of muon beam designs using this technology will allow the efficient and flexible operation of a diverse program of world-class experiments at the intensity frontier.

TECHNICAL APPROACH

The experiments that are being contemplated for the muon program in the Project-X era impose diverse requirements on the muon beam in terms of major parameters such as beam intensity, muon polarization, tolerable beam contamination, energy, emittances, time structure and duty factor. The Project-X CW linac is explicitly designed to provide high duty factor beams with flexible time structures to the intensity-frontier experiments. It is reasonable to take advantage of that capability by using the produced pions and their muon decay products directly, i.e. without intermediate processing that washes out the time structure delivered to the pion production target. A beam design that provides flexibility in the other major parameters would allow a diverse program of experiments to be implemented without major reconfigurations between experiments.

Besides preserving the time structures that can be delivered from the linac, the other major idea embodied in this proposal is to take advantage of the important conceptual advances in muon collection and ionization cooling that have occurred in conjunction with design efforts for the (common) front end of muon colliders and neutrino factories based on muon storage rings. However, there are differences that must be taken into account between muon collider front ends and ones meant to deliver low-energy muon beams. Table 1 compares the major parameters.

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The need for high duty factor for the low-energy muon beam requires RF cavities that can operate continuously; that is the main complicating factor. The other differences make things easier and less expensive. So, for example, 1 MW on target is easier to handle than 4 MW and may allow the use of a solid target as opposed to the mercury jet target chosen for muon colliders. Also, the very short proton bunches delivered from the linac suggest that it may be possible to maintain the bunching throughout the pion/muon collection and ionization cooling system, thereby preserving the timing distribution delivered from the linac.

Table 1: Major parameters of beams for muon colliders and low-energy muon beams.

Comparison	Mu collider	P-X Mu beam
Protons		
Beam energy	8 GeV	3 GeV
Beam power	4 MW	1 MW
Bunches/second	15	10^6
Duty factor	low	high
rms bunch length	3 nsec	20 psec
Muons		
muon/proton ratio	0.1	~0.001
required cooling	extreme	moderate

Note that RF capture into a single bunch precludes the necessity of the long drift that is needed in the muon collider case to allow a correlation to develop between the time of arrival at a downstream location and the momentum of the muons. (That correlation is used to facilitate capture of the muons into a train of about a dozen bunches separated by 5 nsec apiece for a muon collider.) Further preliminary concepts include the intention to capture forward-going pions from a thick target around the peak of their momentum distribution at ~300 MeV/c. The resulting decay muons cluster around 200 MeV/c, a momentum at which ionization cooling works well.

The μ/p ratio, i.e. the ratio of useful muons to protons incident on the production target, is an important figure of merit for low-energy beam designs. The value of 0.001 specified in Table 1 would enable a world-class program of experiments at the intensity frontier. Note that it is two orders of magnitude below the value resulting from simulations of the muon collider front end. As a result, much less elaborate measures are necessary to generate a useful low-energy beam.

Many muon experiments require the muons to stop in a thin stopping target. Thus the beam must be decelerated. Since the stopping target often must be as thin as possible, the momentum spread must first be reduced by ionization cooling. RF cavities would be used rather than an absorber for deceleration to avoid the longitudinal heating that happens in an absorber. (The spreading of a momentum distribution in an absorber follows from the fact that in the momentum range of interest, low-energy muons lose more energy than high-energy ones in traversing a given slab of material, amplifying any initial momentum spread.) Of course random variations in the amount of energy loss, known as straggling, add an additional heating term.

In transverse ionization cooling, passage of a beam through matter reduces the magnitude of the momentum vectors of the particles. The longitudinal momentum component is then restored by acceleration in RF cavities. Longitudinal cooling (which is really emittance exchange from longitudinal to transverse degrees of freedom) results when high-momentum particles are caused to traverse more material than the low-momentum ones. This process can also reduce the contamination of unwanted particles in a muon beam because the energy gain from the RF cavities is set to match the energy loss by ionization only for the muons. Of course transmission through a long beam path also purifies the beam because most contaminants, in particular pions, have a much shorter lifetime than the muons.

Some experiments require polarized muons. A polarized muon beam can be generated by a double momentum selection, first on the parent pions, then on the muons, because the forward-going and backward-going muons (in the pion rest frame) have opposite polarization. A channel that confines the pions and then the muons in RF buckets can deliver a muon beam of variable polarization merely by adjusting the phasing of the cavities to capture different ratios of pion to muon momenta. The acceptance of such a system is likely to be much larger than a system that does the two momentum selections by magnetic bending and momentum slits.

The expected advantages resulting from these very preliminary design concepts include a good muon/proton ratio, small momentum spread allowing use of very thin stopping targets, time distributions for the muons that reflect the flexible proton distributions at the pion production target, variable polarization, and very little beam contamination. Obviously, simulations are necessary to verify these expectations. Concomitant design work supported by simulations may result in significant changes from the initial design concepts described here.

SIMULATION RESULTS

We have performed a few preliminary simulations to illustrate our capabilities in this regard. G4Beamline, a program developed by Muons, Inc. that provides a user-friendly interface to Geant4 for designs of beams that pass through matter, was used for this purpose.

Fig. 1 illustrates the setup. A 3 GeV/c proton beam impinges from the left on a gold target about 1.6 interaction lengths thick. The target is located on the axis of a 10 T uniform solenoid, represented in yellow. The next element is another solenoid whose field tapers from 10 T to 4 T over 2 meters as its radius expands from 7.5 cm to 12 cm. The following element, represented in red, is a series of 325-MHz RF cavities embedded in a 4 T solenoid, operating at a gradient of 10 MV/meter.

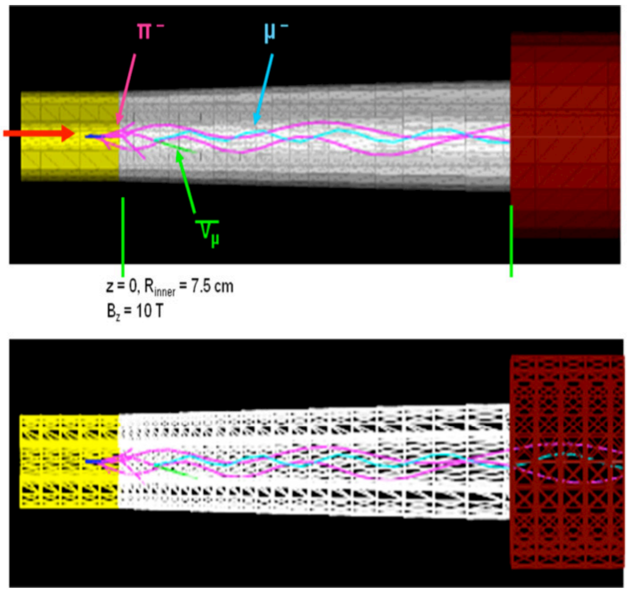
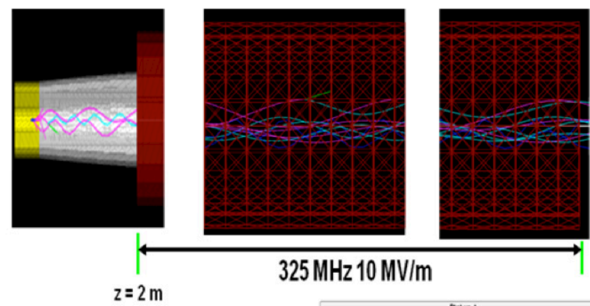


Figure 1: G4Beamline illustration of the upstream end of a channel starting at the target solenoid.

Fig. 2 shows preliminary results of this simple example simulation. The top pictures show the tracks continuing downstream through the RF cavities. A few more pion decays are visible. The picture on the lower right is a scatter plot of the momenta, in MeV/c, of pions and muons versus their time of arrival, in nsec, at a location 17 meters downstream from the target. The RF cavities were phased to capture the bunch of pions and muons shown in the red oval. The tables on the lower left show the results. For example, 785 particles (muons and pions) are contained in the oval bunch 17 m downstream from the target per 100,000 protons incident on the production target. The muon to proton ratio at 32 meters is 622/100000, or 0.0062. Many of the 84 pions that have not yet decayed will also produce useful muons. These ratios are to be compared to the desired ratio of at least 0.001 at the end of the beam after cooling and deceleration.

The lower table in Fig. 2 compares the transverse and longitudinal emittances of the simulated distribution of muons in the oval bunch to the acceptances of an HCC that might be used for longitudinal cooling. The transverse emittances can be contained in the HCC, but the longitudinal emittances are about a factor of two too large. That motivates a change in the capture frequency from 325 to 650 MHz in a future simulation. A smaller bucket may still produce an acceptable ratio of muons to protons.

This kind of channel needs CW RF cavities to manipulate the beam. The initial design strategy is to use superconducting RF cavities wherever that is feasible. However, the channel components, particularly at the upstream end, will be immersed in an intense radiation field. Furthermore, focusing by strong magnetic fields is necessary to confine the large transverse emittances of the beam. Superconducting RF cavities will not operate in strong magnetic fields, and intense radiation may cause them to quench. Wherever possible, shielding (against radiation and magnetic fields) will be implemented. However, it seems inevitable that it will be necessary to use normally-conducting cavities in parts of the channel. Operating such cavities at room temperature with high gradients would cause excessive heat loss and consume too much RF power. The solution proposed here is to use materials that become very good conductors at low temperature for the walls of the cavities. Two materials are prime candidates for this application: beryllium and aluminum. Studies of limitations due to magnetostrictive effects and anomalous skin depth, especially at higher frequencies, are essential first steps.



	# particles in bunch per 100k POT at z = 17 m	# particles in bunch per 100k POT at z = 32 m
μ^-	531	622
π^-	254	84
μ^- & π^-	785	706

	ε_{trans} (mm-rad) of μ^-'s	ε_{long} (mm-rad) of μ^-'s
z = 17 to 32 m	11	60 to 90
HCC	20	40

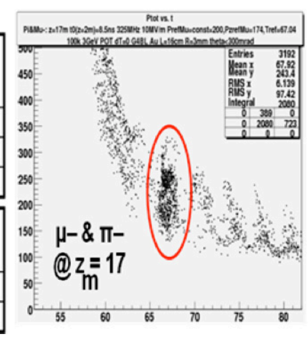


Figure 2: Results of the G4Beamline simulation of the upstream end of a channel.

CONCLUSIONS AND FUTURE PLANS

There are promising new preliminary concepts for using the beam from the Project-X CW linac directly to provide high-duty-factor muon beams with a variety of useful characteristics. Further development is needed for design, simulation, and optimization of the whole channel, as well as RD&D on hyperconductive RF cavities—the enabling technology.

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[3] c.f. http://map.fnal.gov/

USE OF HELICAL TRANSPORT CHANNELS FOR BUNCH RECOMBINATION*

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Abstract

Cooling scenarios for a high-luminosity Muon Collider require bunch recombination for optimal luminosity. In this paper we describe a new method for bunch recombination. We combine the high-chronicity of a helical transport channel (HTC) with the high-frequency bunching and phase-energy rotation concept (time-reversed) to obtain a compact bunch recombination system adapted to a muon collider scenario. We first present an idealized 1-D system with multiple chronicity transports. We then implement the concept in a single-chronicity channel, obtaining bunch recombination of 13 200MHz-spaced bunches to a single collider-ready bunch within a compact transport with modest rf requirements. That example is demonstrated within G4BL 3-D simulations. Variations and adaptations for different recombination requirements are discussed.

INTRODUCTION

For a μ^+-μ^- collider, muons from a high intensity production system must be cooled into short, intense bunches for maximal luminosity [1, 2]. The muons are produced within a very large phase space that must be compressed and cooled to obtain high-luminosity parameters. Ref. [3] presents a scenario for this capture and cooling process. Longitudinally, the muons are initially captured into a string of rf bunches, and kept within those bunches until cooled, both longitudinally and transversely. At that point is desirable to recombine the bunches, recapturing into a single bunch with large longitudinal acceptance. That single bunch would then receive further cooling toward collider densities.

Figure 1 shows the progression of transverse and longitudinal emittances through the muon cooling system [3]. The muons are produced with initial emittances of ~0.02m transverse and ~0.4m longitudinally (~0.03/bunch) and are captured in ~12 bunches (200MHz). The bunches are cooled to ~0.0015m transverse and ~0.001m/bunch longitudinally, where they are then merged into a single bunch (step 5 of Fig. 2). The merged bunch is further cooled and emittance exchanged to collider emittances. The merger into a single bunch was imagined to require a very long rf and transport section, with losses of ~50% from μ decay alone. In this report we note that the large chronicity that is possible in a helical transport channel enables performing this bunch combination in a much more compact system that should be much more efficient. An HTC transport segment is shown in Fig. 2.

*Work supported by US DOE under contract DE-AC02-07CH11359 and DOE SBIR grant DE-SC00002739.

HTC BEAM DYNAMICS

In Ref. [4], Derbenev and Johnson proposed the use of helical transport channels (HTC) for cooling of muon beams to small emittances.

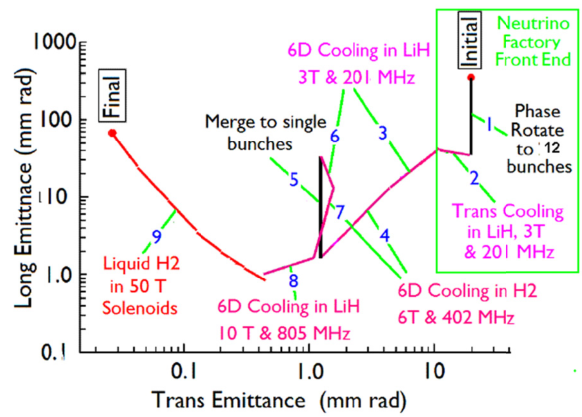

Figure 1: Cooling scenario overview.

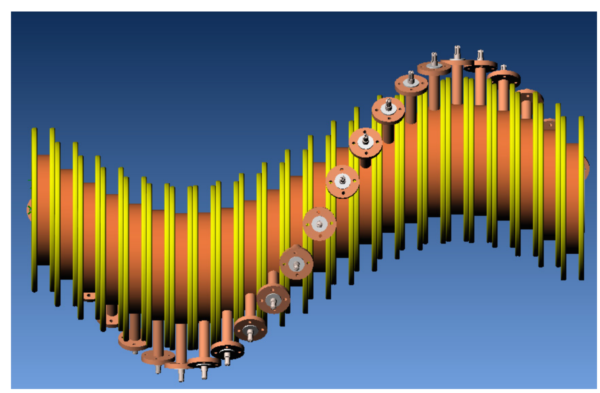

Figure 2: A cell of an HTC as designed for muon cooling.

The core feature of the HTC is the helical magnetic field, which consists of a constant solenoid plus a periodic component: $\vec{B} = B_o\,\vec{e}_z + \vec{b}(\rho,\psi)$, where $\psi = \varphi - kz$ with $k = 2\pi/\lambda$. λ is the helical period and (ρ, φ, z) are cylindrical coordinates for the HTC. In the helical fields there will be periodic orbits with radius a depending on the momentum p. The relationship between p and a is:

$$p(a) = \frac{\sqrt{1+(ka)^2}}{k}\left[B_0 - \frac{1+(ka)^2}{ka}\,b(a)\right].$$

A critical function is the dispersion factor:

$$\hat{D} = \frac{p}{a}\frac{da}{dp}$$

which can be calculated from inverting the above expression, obtaining:

$$\hat{D}^{-1} = \frac{a}{p}\frac{dp}{da} = \frac{\kappa^2}{1+\kappa^2} + \frac{(1-\kappa^2)(1+\kappa^2)^{1/2}}{pk^2 a} b - \frac{(1+\kappa^2)^{3/2}}{pk^2}\frac{\partial b}{\partial a}$$

where κ=*ka*. The time slip factor that appears in the longitudinal motion equations (Δ(ct) /Δ(z)) is $\sqrt{1+\kappa^2}/\beta$. and its dependence on energy is:

$$\frac{\partial \frac{\sqrt{1+\kappa^2}}{\beta}}{\partial E} = \frac{\eta_{HTC}}{mc^2} = \frac{\sqrt{1+\kappa^2}}{mc^2\gamma\beta^3}\left(\frac{\kappa^2}{1+\kappa^2}\hat{D} - \frac{1}{\gamma^2}\right)$$

The factor $\eta_T = \frac{\kappa^2}{1+\kappa^2}\hat{D}$ is analogous to the $1/(\gamma_T)^2$ factor that appears in synchrotron motion.

In Fig. 3 we display time of flight τ as a function of momentum for various HTC transport channels. At ~200MeV/c the beam is nearly isochrnous, enabling quasiisochronous transport [5, 6]. But at p ≈ 300MeV/c (kinetic energy ~ 200 MeV) there is a strongly anisochronic dependence, which is also very linear in δE. (η_{HTC} ≈ 0.4). Those characteristics are very important in developing bunch combination over a large momentum spread with minimal phase-space dilution and distortion.

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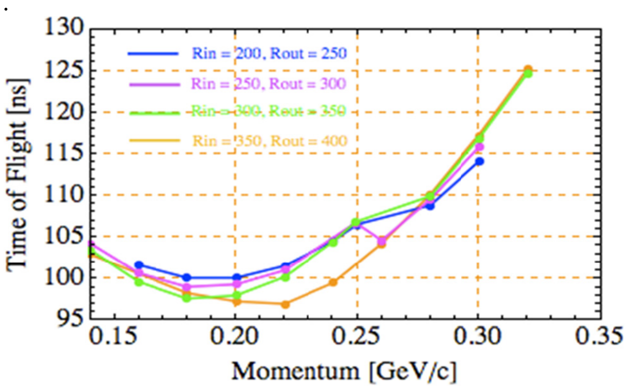

Figure 3: Time of flight as a function of muon momentum for various HTC transport channels.

BUNCH RECOMBINER-INITIAL EXAMPLE

In an initial example, we start with beam at the end of the baseline cooling channel. The bunches have relatively small longitudinal emittances (0.002m with σ_z=0.6cm, σ_E = 33MeV) The bunches have a mean kinetic energy of ~200MeV, and are spaced at ~200MHz.

In the initial section of the BR, rf voltages place the bunches at different energies, with the head bunches at a higher energy than the trailing bunches, while the individual bunch momentum spreads are reduced. An rf system with a frequency near 200 MHz. The difference between that frequency and the baseline is used to place the centers of the bunches at different phases such that head bunches are accelerated and tail bunches are decelerated. Setting the BR parameters such that internal synchrotron oscillation compresses the beam (~1/4 synchrotron oscillation) enables a solution where the high frequency rf naturally bunches the beam into the longer-bunch smaller-δE format needed for the BR drift. For the BR buncher we choose an rf wavelength of (λ_{RF}=1.5-0.03) meters, obtaining an rf frequency of ~204.08 MHz. The rf system is 9.6m long, with V_{rf} = 15MV/m gradient and a transport chronicity of η_{HTC}=0.05. At these parameters, we find the bunches formed into a string of compact bunches with linear energy spacing. (σ_z=~10cm, σ_E = ~2.5MeV, with ~10 MeV spacing.). (See Fig. 3)The HTC transport would then be modified to obtain high η_{HTC} ,(~0.43) (i. e., λ=1.6m, *κ* = 1, and HTC fields of *B* = 4.2T b_d= 0.75, and b_q=-0.45) Drift over ~40m within a large-η_{HTC} transport superimposes the bunchlet areas, at which a modest 200 MHz system forms the beam into a single bunch. (see Fig. 4)

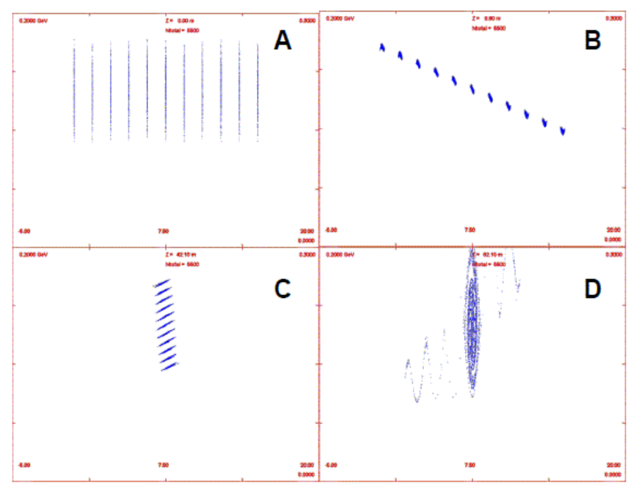

Figure 4: Overview of bunch recombiner with initial quasi-isochronous bunch formation.

3-D HTC BUNCH RECOMBINER

After establishing the principle of bunch combination in 1-D motion, we present a first example within a complete 3-D G4Beamline simulation [7]. To eliminate matching complications and simplify design, this initial 3-D study will use an existing HTC design, with a constant slip factor of η_{HTC}= 0.43 throughout the BR, matched to an upstream HCC cooling channel.

Values of the helical channel parameters are: λ = 1m, a_{ref} = 16 cm, κ = p_T/p_z = $2\pi a_{ref}/\lambda$ = 1 = (tangent of the pitch angle of the reference trajectory), B_0 = 5.7 T, $B_z(a)$ = 5.0 T, $b_\varphi(r)|_{\text{on reference}}$ = 0.72 T and $\delta b_\varphi/\delta\rho$(ref)= -1.2 T/m.

We start the BR with a train of 13 bunches at the central energy of 200MeV/c, and emittances as would be cooled in an HCC. Bunching and energy rotation at large η_{HTC} requires an adiabatic solution, with a weak rf gradient (~1MV/m). and rf frequencies that vary along the channel. The frequency set is by the time difference between the center reference bunch that is not being accelerated and the fourth bunch ahead of it that is being accelerated with a phase of 30º; hence, there are $4^1/_{12}$ rf wavelengths between these four bunches. (The 4^{th} bunch behind is then decelerated at phase = -30º.) From an initial 200 MHz spacing, this places the initial rf frequency at 204.17MHz.

As the train progresses down the channel, the bunch spacing decreases, and the rf frequency increases to maintain the bunch phases. The buncher is continued for 40m, which is an empirical optimum for energy rotation with minmal bunch distortion. The range of rf frequencies used is 204.17 to 271.84 MHz. Figure 5 shows the effect of this transport on a train of 13 bunches, where the extreme ± 6 bunches are at ±45º, displaying development of the longitudinal beam distributions.

After the buncher the beam continues to drift in the HTC until the bunches overlap, after ~60m. The distance L_z needed to align the bunches is determined by the ΔE/Δt slope of the bunch string and the slip factor of the channel. In particular,

$$L_z = \frac{1}{\eta_{HTC}} m_\mu c^2 \frac{c}{\left|\Delta E/_{\Delta t}\right|} = 60m$$

where ΔE/Δt is -1.23 MeV/nsec, obtained from the beam distribution at the end of the buncher. Figure 6a displays simulation of the resulting bunch recombination. The beam is then suitable for capture within a single bunch. To approximate beam capture, we place the beam within a 200 MHz rf system with V'=10 MV/m. After ~5m, the individual bunch structure is diluted and a single captured bunch appears in simulation, as displayed in Fig. 6b.

~94% of simulated particles in the 13 bunch system are captured, with most of the losses and mismatch from the leading/trailing bunches. The simulations presented here are 3-D simulations within the G4Beamline simulation code. The simulations included 3-D evaluations of the magnetic fields with a pillbox model for the accelerating cavities.

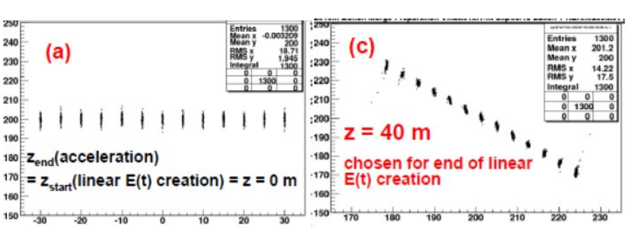

Figure 5: Creation of linear energy-time correlation from bunches at 200 MeV kinetic energy. The string of bunches injected into the HTC at 200 MeV is shown in (a); bunches after 40m are shown in (c) .

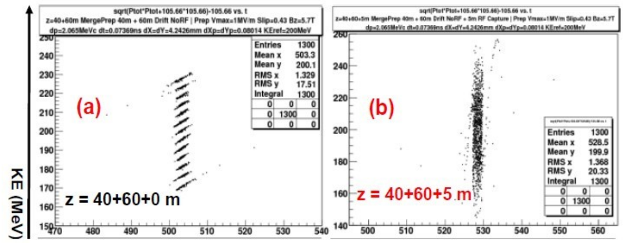

Figure 6: RF capture into a single bunch from 13 initial bunches. Bunches at the end of the drift section and start of the RF capture are shown in (a). Results of RF capture into a single bunch are shown in (b).

DISCUSSION

The simulation demonstrates an example of bunch recombination using a HTC. It is certainly not an optimum example. An HTC with η_{HTC} changing between buncher drift and rf section (as in the 1-D model) would be more compact, and a 3-D example should be developed.

We would also like to study an HTC with a larger acceptance to test the limits of the concept. A longer period HCC with weaker fields is likely to have a larger momentum aperture, with somewhat weaker focusing. A larger momentum aperture would increase the range of bunch compression.

The longitudinal bunch combiner can also be used with a transverse combiner for a more symmetric solution. This option is being explored by Palmer et al. [8].

The concept must also be integrated into a complete cooling scenario, with the pre- and post- merge cooling reoptimized following the 3-D beam dynamics. An optimum scenario is likely to have less transverse cooling before the merge and more transverse cooling after.

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ISBN 978-3-95450-115-1

BUNCH COALESCING IN A HELICAL CHANNEL*

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Abstract

A high-luminosity Muon Collider requires bunch recombination for optimal luminosity. In this paper, we take advantage of the large slip factor attainable in a helical transport channel (HTC) to coalesce bunches of muons into a single one over a shorter distance than can be achieved over a straight channel.

INTRODUCTION

A muon collider provides a possible path for the U.S. to return to the high energy leadership. One configuration of a muon collider [1] is shown in Figure 1. The start of the muon collider is at pion production from protons on a high-Z target. The pions are captured in a tapered solenoidal field (not shown at the target) and are allowed to simultaneously decay into muons and drift to develop an energy-time correlation that is used in a phase rotation to create a string of mono-energetic bunches. The bunch string is cooled transversely in the Linear Cooler, followed by further 6D cooling in the Helical Cooler. The cooled string of bunches are then merged into a single bunch, which is the subject of this paper, and re-cooled in 6D to produce a single bunch of muons that is ready for the final stage of cooling, followed by a series of accelerations to their final collision energy. The study reported here exploits the larger slip factor attainable in a helical channel to merge the muon bunches over a shorter distance than is possible over a straight channel.

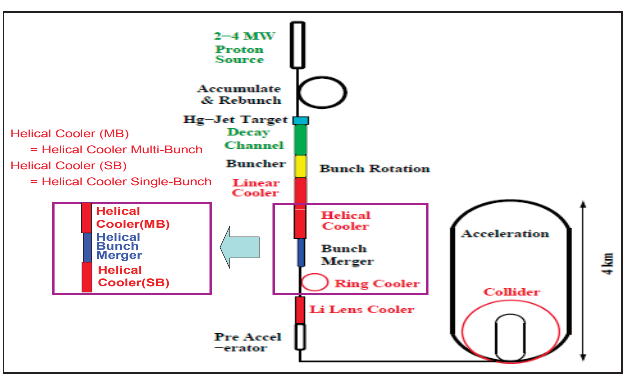

Figure 1: Muon Collider layout. To the right of the arrow is a configuration of a muon collider [1]. This study coalesces muon bunches in a helical channel, as shown to the left of the arrow.

ADVANTAGES OF BUNCH COALESCING IN A HELICAL CHANNEL

As stated above, muon bunches can be coalesced over a shorter distance in a helical channel than can be achieved in a straight channel, resulting in reduced decay losses and likely lower cost of infrastructure and operation. The shorter coalescing distance is afforded by the larger absolute value for the slip factor attainable in a helical channel rather than relying solely on kinematics of the particles in a straight one. Table 1 quantifies the difference for muons with a variety of kinetic energies where there is an initial energy-distance (E-D) relation of dE/d(ct) = 4.09 MeV/m. The distance needed to align bunches with a linear E-D relation in a straight channel is:

$$L_{z,straight} = \left(\beta^3 \gamma m_\mu\right) / \left(\eta / \left(dE/d(ct)\right)\big|_{bunches}\right) \quad (1)$$

where β and γ are the usual Lorentz kinematic parameters and η is the slip factor defined in a straight channel as:

$$\eta = -\frac{1}{\gamma^2} \quad (2)$$

The distance over which bunches can be coalesced in a helical channel is[2]:

$$L_{z,HC} = \frac{1}{\eta_{HC}} \frac{m_\mu}{\left(dE/d(ct)\right)\big|_{bunches}} \quad (3)$$

where the slip factor for a Helical Channel η_{HC} is derived in [3] and the value used is driven by that in a design of the upstream Helical Cooling Channel, HCC, [4,5]:

$$\eta_{HC} = \frac{\sqrt{1+\kappa^2}}{\gamma\beta^3}\left[\frac{\hat{D}\kappa^2}{1+\kappa^2} - \frac{1}{\gamma^2}\right] \cong 0.43 \quad (4)$$

$$\hat{D}^{-1} = \frac{\kappa^2 + (1-\kappa^2)}{1+\kappa^2}\left[\frac{B\sqrt{1+\kappa^2}}{pk} - 1\right] - \frac{\left(1+\kappa^2\right)^{3/2}}{pk^2}\frac{\partial b}{\partial a} \cong 0.59 \quad (5)$$

with values for other helical channel parameters[6]:

- λ = longitudinal spatial period = 1 m
- r_{ref} = reference radius = 16 cm
- $\kappa = p_T/p_z = 2\pi r_{ref}/\lambda = 1$ = tangent of the pitch angle of the reference trajectory
- $B_z|_{z\text{-axis}} = 5.7$ T, $B_z|_{\text{on reference}} = 5.0$ T
- $b_\varphi(r)|_{\text{on reference}} = 0.72$ T
- $\delta b_\varphi/\delta\rho(\text{ref}) = -1.2$ T/m.

Table 1: Coalescing distances and muon decay losses in straight and helical channels for muon bunches with initial energy-distance relation of dE/d(ct) = 4.09 MeV/m. Reference particle kinetic energy is 200 MeV.

KE (MeV)	P (MeV/c)	$L_{z,straight}$ (m)	$L_{z,HC}$ (m)	ΔN/N straight (%)	ΔN/N HC (%)
120	199	174	60	13	6.6
200	287	517	60	25	4.6
250	340	858	60	33	3.9

HELICAL CHANNEL BUNCH COALESCING SUBSYSTEM

The Helical Channel Bunch Coalescing (HCBC) subsystem consists of five subcomponents, each performing a specific operation:

1. Acceleration to desired initial energy

*Work supported in part by DOE SBIR grant DE-SC00002739
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- Accelerates bunches out of HCC to higher energies where bunch coalescing works better.

2. Creation of linear energy-time correlation
   - Creates an energy-time correlation amongst the bunches, so they can be aligned at end of the drift.
3. Drift to align bunches in time
   - The bunches drift and are aligned and the end.
4. Capture into a single RF bucket
   - RF is turned on where the bunches are aligned.
5. Deceleration and longitudinal cooling
   - Decelerate bunch to match the downstream HCC.
   - Longitudinal cooling may also be needed.

Acceleration to Desired Initial Energy

Bunch coalescing works best at higher energies due to the more linear relationship between the relativistic parameter β and energy, but must also consider the acceptance of the channel. These points are best illustrated via simulations, as shown in Figure 2, where this is illuminated in two ways. In Figure 2(a), muons of differing energies start their drift in the Helical Channel and 60 m downstream they have the energy-time (E-T) relation shown in Figure 2(b), where a linear E-T relation has developed at the higher energies. Conversely, if a linear E-T relation exists at the start as in Figure 2(c), free drifts over 60 m result in the E-T relation in Figure 2(d), where the higher energy muons with kinetic energies between ~170 to ~270 MeV have now been aligned in time and longitudinal location. Note that muons exiting the upstream HCC will be in a consecutive series of RF buckets having kinetic energy of 120 MeV (p = 200 MeV/c). So, the first subcomponent will adiabatically accelerate those cooled bunches from 120 to 200 MeV, while maintaining the cooled normalized emittances of $\varepsilon_{T,N}$ = 0.34 mm-rad and $\varepsilon_{L,N}$ = 1.1 mm [4].

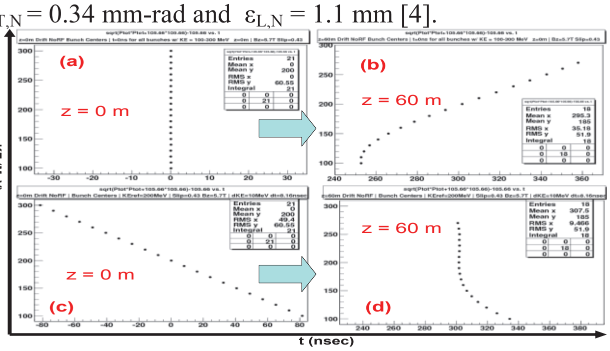

Figure 2: Simulations illustrating kinematics that motivate use of higher energies to coalesce bunches. See text for explanation.

Creation of Linear Energy-Time Correlation

After the cooled muon bunch string from the HCC has been accelerated to 200 MeV, the bunch string must now be manipulated to have a linear E-T relation, as in Figure 2(c). Our method is designed to coalesce 9 bunches and uses a modest RF gradient is used (V'_{max} = 1 MV/m) with frequencies varying along the channel, where the frequency at any particular location is determined by the time difference between the center reference bunch that is not accelerated and the fourth bunch ahead of it that is accelerated with a phase of 30º; hence, there are $4^1/_{12}$ number of wavelengths between these four bunches. The resultant range of frequencies is 204.17 to 271.84 MHz and application of this RF system to 13 bunches (recall designed for 9) is shown in Figure 3, where the end of this section is chosen at 40m, since ΔE within each bunch is minimized. The resulting slope between the bunches is dE/dt = -1.229 MeV/nsec (or dE/d(ct) = 4.09 MeV/m).

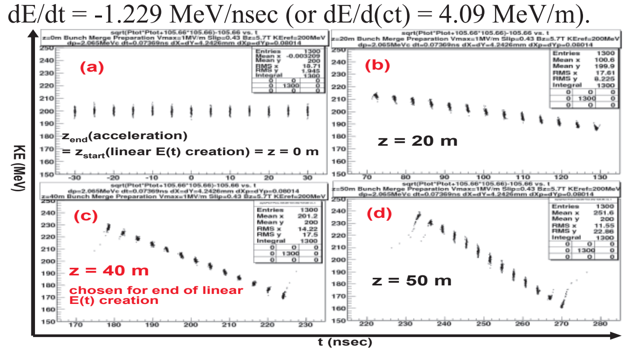

Figure 3: Creation of linear energy-time relation. The bunch string at end of the initial acceleration to 200 MeV is shown in (a) and linear energy-time relation at 20m, 40m, and 50m are shown in (b), (c), and (d), respectively.

Drift to Align Bunches in Time

The distance over which the bunches are aligned is determined in the linear approximation by the dE/dt slope of the bunch string and the slip factor of the channel. In particular,

$$L_z = \frac{1}{\eta_{HC}} m_\mu c^2 \frac{c}{\left|\frac{dE}{dt}\right|} = 60m \qquad (6)$$

where

- L_z is the length over which bunches are aligned
- η_{HC} = 0.43 is the slip factor in equation (4)
- dE/dt=-1.229 MeV/nsec from Figure 3(c)

Simulations shown in Figure 4 confirm the calculated bunch coalescing distance of 60 m.

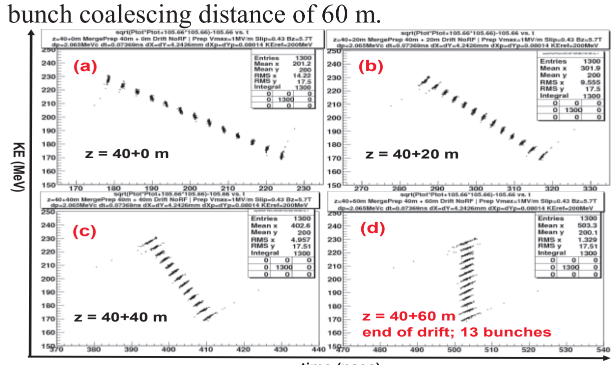

Figure 4: Drift of bunches to time align. Bunches enter the drift region in (a) and drift 20m, 40m, and 60m in (b), (c), and (d), respectively, aligning at 60 m as calculated.

Capture into a Single RF Bucket

As the multiple bunches are time aligned, RF is applied to hold them together in a single bunch. We used 200 MHz with a voltage gradient of 10 MV/m in vacuum; the longitudinal dynamics 5 m into the RF capture are shown

ISBN 978-3-95450-115-1

in Figure 5. The rate of capture of the original 9, 11, and 13 bunches are 99.7%, 98.4%, and 94.2%. Muon decays are ignored, which would be ~8% for the 105m (horizontally) long channel, which ignores the section that provides the initial equal acceleration to all bunches.

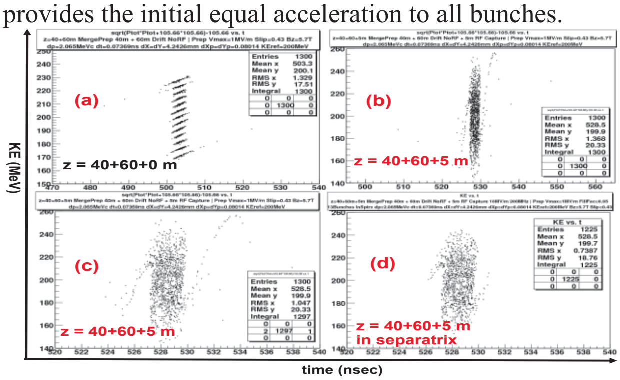

Figure 5: RF capture into a single bunch. Bunches at end of drift section in (a) and captured into a single bunch in (b). Zoomed in views are shown in (c) and (d), where only muons in the separatrix are shown in (d).

Deceleration and Longitudinal Cooling

A single bunch HCC has not yet been designed, but if one is to use the multi-bunch HCC's acceptance for guidance, longitudinal cooling may be necessary at expense of growing transverse emittance [6]. A design that addresses this is to implement radial wedges and phase the RF to zero crossing at the single bunch center, which realizes the following benefits:

- Deceleration is accomplished by material, not RF, so the bucket size remains large.
- Emittance exchange shrinks ε_L at expense of growing ε_T, where growth of ε_T is tolerable.

The amount of deceleration and longitudinal cooling needed will be determined from the future design of the second HCC.

SIMPLIFICATION OF THE HELICAL BUNCH COALESCING SUBSYSTEM

The most complicated section in the bunch coalescing subsystem is the portion that creates the linear energy-time correlation via a large number of RF cavities, each having its own frequency and short length of 10 cm. We investigated the effect of engineering simplifications that use longer RF cavities (25 cm long), less fill factors (~50% and ~25%), and larger gradients (2.2 MV/m and 4.4 MV/m) as described in Table 2. Simulations are carried to the end at the RF capture, with efficiency being calculated by muons inside the separatrix, as shown in Figure 5(d) with results in Figure 6. The configurations with the reduced fill factor (~50% and ~25%) performed equally well and were consistently ~4% less efficient compared to the original configuration that consists of 400 cavities, thus adding confidence in the robustness of the technique to coalesce bunches in a HTC.

Table 2: RF fill factor (FF) characteristics of original and simplified versions

	Configuration		
	Original	~50% FF	~25% FF
RF Field FF (%)	95%	49%	24.5%
Cavity Length (cm)	10	25	25
Number of Cavities	400	80	40
V'max (MV/m)	1.0	2.2	4.4

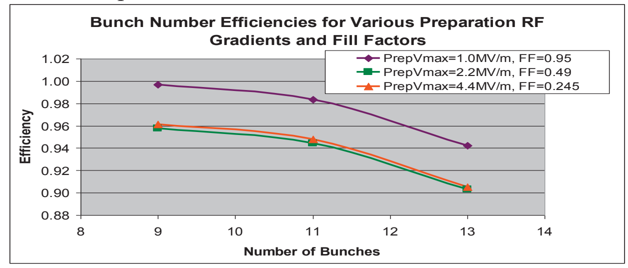

Figure 6: Efficiency of bunch coalescing for different configurations to create the linear energy-time relation for different number of bunches, as calculated by muons in the bunch separatrix.

SUMMARY AND FUTURE

A bunch coalescing subsystem in a helical channel has been designed that makes minimal modifications to the magnetic fields of an existing HCC design that cool muons. The ~105m long coalescing subsystem that is designed to merge 9 bunches is able to achieve efficiencies of 99.7%, 98.4%, and 94.2% for 9, 11, and 13 bunches, respectively. Simplified designs incorporating fill factors for RF cavities of ~25% and ~50% obtained efficiencies of 96%, 94-95%, and 90-91% for 9, 11, and 13 bunches, respectively. The efficiencies do not include decay losses, which would be ~8% for muons with kinetic energy of 200 MeV. Radial wedges in the helical channel may be needed to reduce the longitudinal emittance and reduce the operating energy to that of the second HCC, which is yet to be designed.

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