QUASI-ISOCHRONOUS MUON CAPTURE[*]

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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, some recent developments are described.

INTRODUCTION

A Quasi-Isochronous Helical Channel (QIHC) is being investigated as a possible alternative to a significant portion of the baseline front end for a neutrino factory or muon collider, the front end described in the report of Neutrino Factory Study 2A [1]. The idea was introduced in a paper submitted to EPAC08 [2]; after a brief reprise, subsequent conceptual developments are described herein.

The crux of the idea is to use a pion/muon collection system based on a Helical Cooling Channel (HCC) [3] to facilitate capture of a muon beam into RF buckets. One crucial feature of an HCC for this purpose is that its transition energy can be varied by changing its parameters. Another important property is its ability to cool in all six phase space dimensions, thereby rendering the capture process more efficient.

A major goal of this approach is to shorten both the system and the resulting bunch train compared to that of Neutrino Factory Study 2A. A shorter system is likely to be less expensive, may have higher transmission efficiency, and certainly would have smaller decay losses. Starting with a shorter bunch train could make the subsequent coalescing of the train into a single bunch for a collider easier and more efficient. [4].

SYSTEM OVERVIEW

For purposes of orientation, a description of how the proposed collection and capture channel might fit into the front end of a muon complex is provided here.

1) The complete system would begin with the usual pion production target in a strong tapered solenoidal magnetic field.

2) That would be followed by some combination of bent solenoid and/or dipole magnets to effect a separation of the positive and negative beams.

3) That would be followed by matching the beams into a double-barrelled HCC of the type shown in Figure 1, adapted from [5]. These HCCs with imbedded RF cavities would comprise the RF capture subsystems that are the subject of this paper.

4) Once the beams are captured, ionization cooling would continue in the HCCs or in other types of cooling subsystem.

5) Subsequent beam processing, whether acceleration, coalescing, and/or other beam manipulations, would depend on the intended use of the muons.

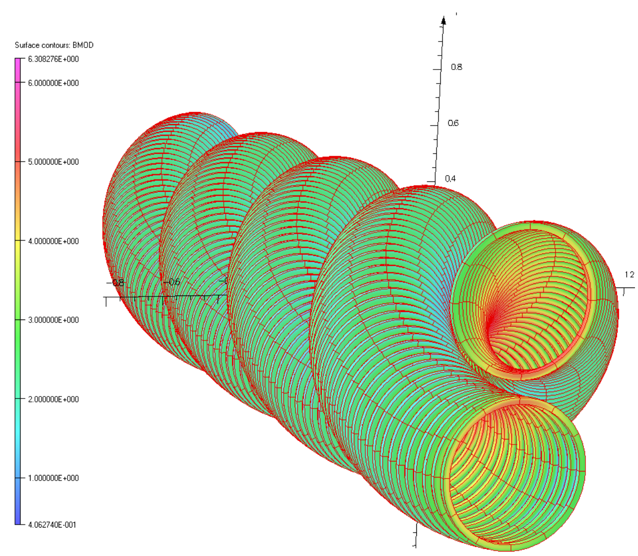

Figure 1: Double Helical Solenoid geometry and flux density. The colors indicate the field strength

THE SYNCHROTRON ANALOGY

For those familiar with beam dynamics in circular accelerators, the proposed muon capture system can best be introduced by analogy with longitudinal dynamics processes that take place in proton synchrotrons such as the Fermilab Booster.

Phenomena that occur in a synchrotron around the transition energy are relevant to this discussion. The most important aspect of transition for present purposes is that, as the beam energy in a synchrotron approaches the transition energy, either from above or below, the bucket area grows rapidly because, in the formula for the bucket

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area, there is a singularity at the transition energy. Note also that above transition, particles with positive momentum offset take longer to go around the ring.

The RF capture process that takes place shortly after injection from a linac into a synchrotron such as the Booster is also relevant. Several turns of H^- beam from the linac are injected into the Booster via charge-stripping injection, resulting in a coasting beam with a finite momentum spread. If there is a non-zero ring voltage during injection, some of the beam will fall into pre-existing buckets; the rest 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.)

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. In particular, it would be useful to be able to make the bucket area grow as the particles move downstream in a muon capture front end, keeping in mind that the amount of RF voltage in the channel is already likely to be 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. An HCC can provide these features.

One of the challenges for any muon capture concept is to design a system that will succeed with a muon distribution whose six-dimensional emittance is about a million times larger than that of the proton beam in the Booster. Another challenge is to cope with intensity-dependent effects, such as beam loading and potential well distortion, on the longitudinal motion. (Intensity-dependent effects on the transverse motion are not likely to be serious in the front end because the beam is so large transversely.)

COLLECTION, CAPTURE, & COOLING

In straight single-pass systems such as a linac, the concept of transition energy does not normally arise because for straight trajectories, the path length does not depend on momentum. In other words, the transition energy is infinite. An HCC provides finite transition energy; furthermore, it allows the transition energy to be varied in a single-pass system.

As the name suggests, an HCC sends the beam on a helical path and creates 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 the higher-momentum particles pass through more degrader material than lower-momentum ones do. (Achieving 6-D cooling was the original motivation for the invention.)

The fact that HCCs indeed have a finite transition energy is illustrated in Figure 2, adapted from reference [2]. Plot (a) shows the normal time broadening due to the momentum width for muons propagating 14 meters down a straight channel versus the narrower time spread in (b) for muons traversing 10 meters down the QIHC. Muons with p = 250 MeV/c and p = 150 MeV/c are spread by about 7 nsecs in the straight drift, while muons of the same momentum band in the QIHC are spread by ~1.5 nsecs.

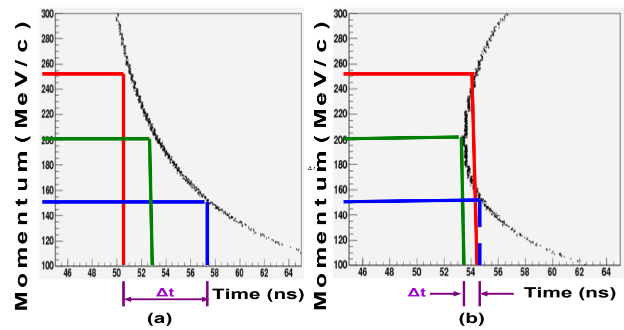

Figure 2: Momentum (MeV/c) vs. time (ns) of μ^+s generated with gaussian momentum spread of 200 ± 50 MeV/c. (a) Muons at 14 meters in straight drift channel. (b) Muons at 10 meters in a QIHC operating at the transition energy for muons with p=200 MeV/c.†

An important kinematic aspect is that muons produced from pion decays necessarily have similar velocities as their parent pions. Hence, designing an RF capture system for pions at a particular velocity also can capture the decay muons as well. That means the capture process can begin even before the pions have decayed. Figure 3, also adapted from reference [2], shows the momentum/time dependence for pions and muons at downstream longitudinal propagation distances of 10m and 20m, where the initial beam consisted of only pions with a Gaussian momentum spread of 200+/-50 MeV/c.

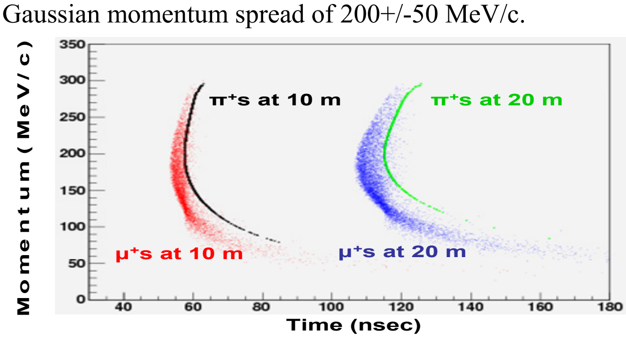

Figure 3: Momentum versus time for pions and decay product muons at 10 and 20 meters in a QIHC. Pions are injected at z=0 and t=0 with a Gaussian momentum spread 200+/-50 MeV/c along the reference direction.

† Because of the helix pitch angle, the actual particle trajectory is longer than z by the secant of the angle (factor of 1.414 here).

The correlation between path length differences and momentum differences in an HCC determines its transition energy, which can be varied by changing the HCC parameters. That property can be used to facilitate RF capture. Starting with a straight channel that has infinite transition energy, the transition energy of an HCC can be gradually reduced toward the beam energy as the beam traverses the channel. At the start, a straight solenoidal channel filled with as much RF voltage as possible will establish a certain bucket area into which some of the muons will land. If the beam is then matched into an HCC with the same amount of RF, in which the transition gamma is gradually reduced toward the beam gamma, the bucket area will grow, capturing more of the beam into the buckets. Particles near the expanding separatrices will jump across them as the particles move downstream.

The longitudinal cooling in an HCC also aids and abets capture into buckets because high-momentum particles lose more energy than low-momentum particles. That causes particles undergoing synchrotron motion to spiral into the buckets in longitudinal phase space. (This condition 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.)

Meanwhile, muons above the synchronous energy will lose energy in the absorber, thereby migrating toward the buckets. Also, as the transition energy is lowered, high-momentum particles with momenta above the buckets and with energy above the transition energy 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 in the buckets and near transition 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.

Finally, the isochronous condition conveys additional advantages. Even before particles are captured into buckets, isochronicity prevents the distribution of muons from spreading out very much longitudinally. (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.

The QIHC might be developed to replace all but the last cooling stage of Neutrino Factory Study 2A, and that last stage may be replaced by a Helical Cooling Channel (HCC). The QIHC offers a more natural match into the potentially more efficient HCC.

NEXT STEPS

The system described above includes many parameters that can be varied along its length. Three of the main ones are the synchronous energy of the particles in the buckets, the transition energy of the channel, and the density of absorber along the beam path. The next steps in the design effort must include simulations to optimize the way these parameters vary along the beam path. Of course, analytical work will be necessary to guide the simulation efforts, and past experience will be invaluable.

CONCLUSIONS AND FUTURE PLANS

A concept called a Quasi-Isochronous Helical Channel, which may lead to an alternative design for the front end of a neutrino factory and/or a muon collider, has been developed. Detailed simulations of the system are needed to examine its feasibility and to optimize its performance.

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