LOW EMITTANCE MUON COLLIDERS*

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Abstract

Advances in ionization cooling, phase space manipulations, and technologies to achieve high brightness muon beams are stimulating designs of high-luminosity energy-frontier muon colliders. Simulations of Helical Cooling Channels (HCC) show impressive emittance reductions, new ideas on reverse emittance exchange and muon bunch coalescing are being developed, and high-field superconductors show great promise to improve the effectiveness of ionization cooling. Experiments to study RF cavities pressurized with hydrogen gas in strong magnetic fields have had encouraging results. A 6-dimensional HCC demonstration experiment is being designed and a 1.5 TeV muon collider is being studied at Fermilab. Two new synergies are that very cool muon beams can be accelerated in ILC RF structures and that this capability can be used both for muon colliders and for neutrino factories. These advances are discussed in the context of muon colliders with small transverse emittances and with fewer muons to ease requirements on site boundary radiation, detector backgrounds, and muon production. Compared to studies done 10 years ago where larger bunch intensities were assumed, there now are more possibilities for acceleration, low beta insertions, and detector designs.

INTRODUCTION

The enthusiasm that existed 10 years ago for a muon collider was dampened by the failure to come up with a credible scheme to achieve fast longitudinal cooling. Consequently, the idea that a neutrino factory based on a muon storage ring would be an easier first step toward a muon collider, has meant that efforts for the last 10 years have been focused on neutrino factory designs [1,2]. But the large number of muons required for a factory has led to large emittance accumulation and storage schemes rather than the small 6D emittances needed for a collider.

Recently, many advantages of small 6D emittance for a collider have become apparent [3], where, for example, the cost of muon acceleration can be reduced by using the high frequency RF structures being developed for the International Linear Collider (ILC). We believe that the muon collider has now become an upgrade path for the ILC or its natural evolution if LHC results imply that the ILC energy is too low or if its cost is too great.

Effective 6D cooling and the recirculating of muons in the same RF structures that are used for the proton driver may enable a powerful new way to feed a storage ring for a neutrino factory [4]. This would put neutrino factory and muon collider development on a common path.

*Supported by DOE SBIR/STTR grants DE-FG02-03ER83722, 04ER86191, 04ER84016, 05ER86252, 05ER86253 and 06ER86282.
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IONIZATION COOLING TECHNIQUES

Emittance Exchange with Continuous Absorber

The simple idea that emittance exchange can occur in a practical homogeneous absorber without shaped edges followed from the observation that RF cavities pressurized with a low Z gas are possible [5,6]. Figure 1 is a schematic description of the new approach.

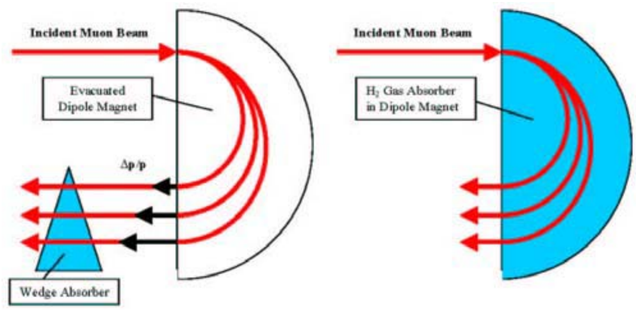

Figure 1: LEFT: Older Wedge Absorber Technique RIGHT: Proposed Homogeneous Absorber Technique where dispersion causes higher energy particles to have longer path length and thus more ionization energy loss.

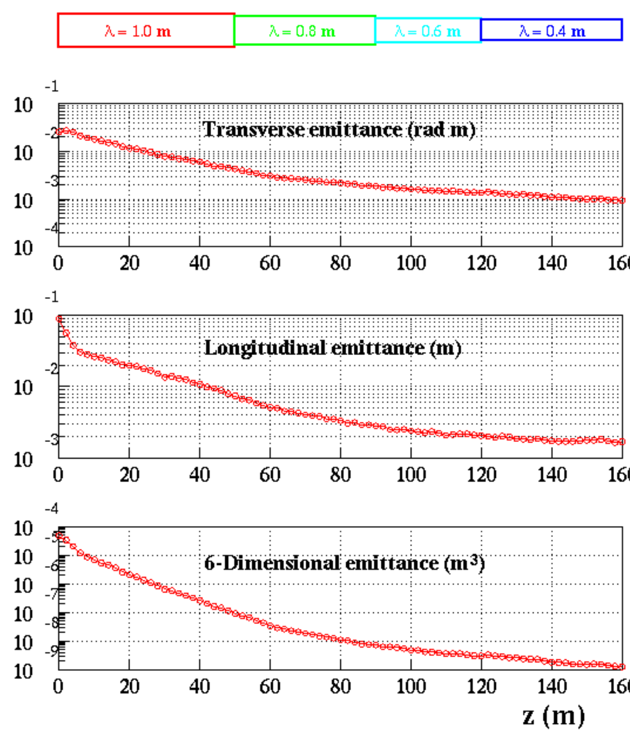

Figure 2: Simulation results of a series of 4 pressurized HCC segments which are matched to the beam by having smaller cavities and stronger fields as the beam cools.

Gas-filled HCC

The HCC is an attractive example of a cooling channel based on this idea of energy loss dependence on path length in a continuous absorber. The HCC uses a series of high-gradient RF cavities filled with dense hydrogen gas, where the cavities are in a magnetic channel composed of a solenoidal field with superimposed helical transverse dipole and quadrupole fields [7,8]. In this scheme, energy loss, RF energy regeneration, emittance exchange, and transverse cooling happen simultaneously.

By moving to the rotating frame of the helical fields, a time and z-independent Hamiltonian can be formed to derive the beam stability and cooling behavior [9]. The analytic relationships derived from this analysis were used to guide simulations using a code developed based on the GEANT4 [10] program called G4Beamline [11].

Figure 2 shows the simulation results for a series of 4 250 MeV/c HCC segments, where the magnetic fields are increased as the beam cools. In this example the final field would be 17 T with a hydrogen gas pressure of 400 atmospheres. The 6D emittance is reduced a factor of 50,000, with equal cooling in the three planes. Muon scattering measurements imply that an additional factor of 3 to 4 will be gained when the model is updated.

Momentum-dependent HCC

While the HCC described above operates at constant energy, another set of applications follows from HCC designs where the strengths of the fields are allowed to change with the muon momentum. The first example was a 6D precooler, where the beam is slowed in a liquid hydrogen absorber at the end of the pion decay channel. Figure 3 shows a G4BL simulation of this use of a HCC, with 6D emittance reduction by a factor of 6. Another example is a stopping muon beam based on a HCC [12].

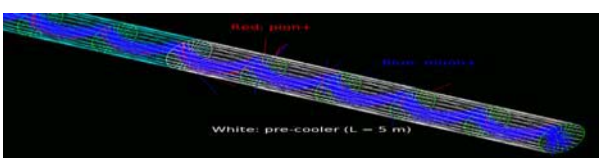

Figure 3: A G4BL simulation of a HCC used as a precooler for a muon beam slowing in liquid hydrogen.

6D Cooling Demonstration Experiment

An even more striking use of the HCC with variable field strengths is as a 6D muon cooling demonstration experiment. An experiment is being designed to slow a 300 MeV/c muon beam to about 150 MeV/c in a HCC filled with liquid helium [13]. Figure 4 shows the emittance reduction for this case which is being designed at Fermilab to be run in the next few years.

Parametric Resonance Ionization Cooling

Parametric-resonance Ionization Cooling (PIC) [14], requires a half integer resonance to be induced in a ring or beam line such that the normal elliptical motion of particles in $x - x'$ phase space becomes hyperbolic, with particles moving to smaller x and larger x' as they pass down the beam line. (This is almost identical to the technique used for half integer extraction from a synchrotron where the hyperbolic trajectories go to small x' and larger x to pass the wires of an extraction septum.) Thin absorbers placed at the focal points of the channel then cool the angular divergence of the beam by the usual ionization cooling mechanism where each absorber is followed by RF cavities. Thus in PIC the phase space area is reduced in x due to the dynamics of the parametric resonance and x' is reduced or constrained by ionization cooling. The basic theory of PIC is being developed to include aberrations and higher order effects. Simulations using linear channels of alternating dipoles, quadrupoles, solenoids, or HCC's are now underway [15].

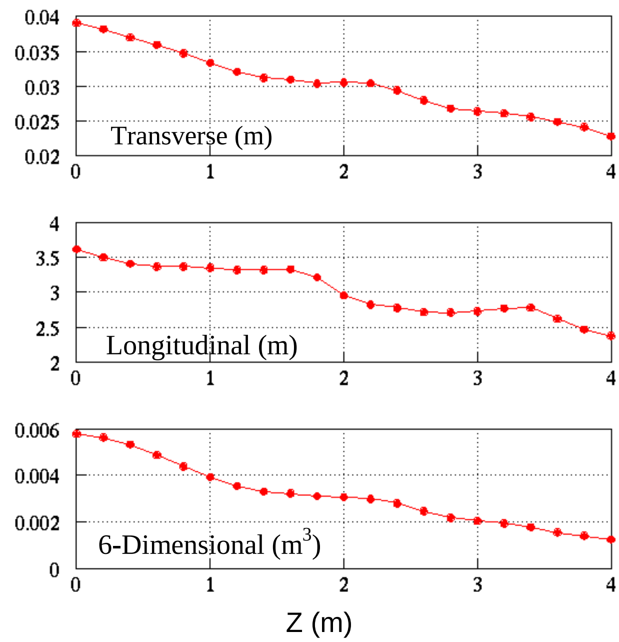

Figure 4: Transverse (top), longitudinal (middle), and 6D (bottom) invariant emittances plotted for a liquid helium filled HCC with variable fields, where the muon momentum decreases from 300 to 150 MeV/c.

PHASE SPACE REPARTITIONS

Reverse Emittance Exchange Using Absorbers

A muon beam that is well cooled at one or two hundred MeV/c will have its unnormalized longitudinal emittance reduced by a factor of a thousand or more at 100 or more GeV/c collider energy. At the interaction point in the collider the bunch length would then be much shorter than the IR focal length. In reverse emittance exchange, we propose to repartition the emittances to lengthen each bunch and narrow the transverse emittances using beryllium wedge energy absorbers.

Preliminary calculations show that two stages of reverse emittance exchange, one at low energy and one at a higher energy before energy straggling becomes significant, can reduce each transverse emittance by an order of magnitude.

Muon Bunch Coalescing

One of the newest ideas is to cool less intense bunches at low energy and to recombine them into intense bunches at higher energy where wake fields, beam loading, and space charge tune shifts are less problematic [16].

NEW COOLING TECHNOLOGY

Pressurized RF Cavities

A gaseous energy absorber enables an entirely new technology to generate high accelerating gradients for muons by using the high-pressure region of the Paschen curve [5]. This idea of filling RF cavities with gas is new for particle accelerators and is only possible for muons because they do not scatter as do strongly interacting protons or shower as do less-massive electrons. Measurements by Muons, Inc. and IIT at Fermilab have demonstrated that hydrogen gas suppresses RF breakdown very well, about a factor six better than helium at the same temperature and pressure. Consequently, much more gradient is possible in a hydrogen-filled RF cavity than is needed to overcome the ionization energy loss, provided one can supply the required RF power. Hydrogen is also twice as good as helium in ionization cooling effectiveness, viscosity, and heat capacity. Present research efforts include tests of materials in pressurized RF Cavities in magnetic fields [17] as shown in Figure 5, where an external field causes no apparent reduction in maximum achievable gradient. Crucial beam tests of the concept are scheduled for the end of this year.

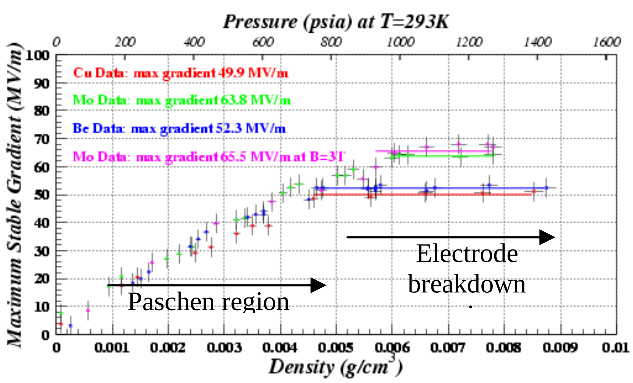

Figure 5: Measurements of the maximum stable RF gradient as a function of hydrogen gas pressure at 805 MHz with no magnetic field for three different electrode materials: Cu (red), Mo (green), and Be (blue). The cavity was also operated at the same gradients in a 3T field with Mo electrodes (magenta).

High-pressure RF cavities near the pion production target can be used to simultaneously capture, bunch rotate, and cool the muon beam as it emerges from the decaying pions [18]. We have started an R & D effort to develop RF cavities that will operate in the extreme conditions near a production target and an effort to simulate the simultaneous capture, phase rotation, and cooling of muons as they are created from pion decay.

High Temperature Superconductor

Magnets made with high-temperature superconducting (HTS) coils operating at low temperatures have the potential to produce extremely high fields for use in accelerators and beam lines. The specific application of interest that we are proposing is to use a very high field (greater than 30 Tesla) solenoid to provide a very small beta region for the final stages of cooling for a muon collider. With the commercial availability of HTS conductor based on BSCCO technology with high current carrying capacity at 4.2 K, very high field solenoid magnets should be possible. We are evaluating the technical issues associated with building this magnet [19]. In particular we are addressing how to mitigate the high Lorentz stresses associated with this high field magnet.

SUMMARY

Several new ideas for high brightness muon beams have rejuvenated the idea of an energy-frontier muon collider in the nearer future. High-pressure RF experiments are underway, with encouraging results. A 6D HCC demonstration experiment is being designed and plans for 1.5 TeV and 3 TeV muon colliders are being studied at Fermilab. Two new synergies have been identified in that very cool muon beams can be accelerated in ILC RF structures and that this capability can be used both for muon colliders and for neutrino factories.

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