# ADVANCES IN BEAM COOLING FOR MUON COLLIDERS *

R. P. Johnson#, Muons Inc., Batavia, IL 60510, U.S.A.
Y. S. Derbenev, Jefferson Lab, Newport News, VA 23606, U.S.A.

*Abstract*

A six-dimensional (6D) ionization cooling channel based on helical magnets surrounding RF cavities filled with dense hydrogen gas is the basis for the latest plans for muon colliders. This helical cooling channel (HCC) has solenoidal, helical dipole, and helical quadrupole magnetic fields, where emittance exchange is achieved by using a continuous homogeneous absorber. Momentum-dependent path length differences in the dense hydrogen energy absorber provide the required correlation between momentum and ionization loss to accomplish longitudinal cooling. Recent studies of an 800 MHz RF cavity pressurized with hydrogen, as would be used in this application, show that the maximum gradient is not limited by a large external magnetic field, unlike vacuum cavities. Two new cooling ideas, Parametric-resonance Ionization Cooling and Reverse Emittance Exchange, will be employed to further reduce transverse emittances to a few mm-mr, which allows high luminosity with fewer muons than previously imagined. We describe these new ideas as well as a new precooling idea based on a HCC with *z* dependent fields that is being developed for an exceptional 6D cooling demonstration experiment. The status of the designs, simulations, and tests of the cooling components for a high luminosity, low emittance muon collider will be reviewed.

## INTRODUCTION

New developments have revived the hopes generated by the pioneering work of Skrinsky and Parkhomchuk [1]. 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 [2,3]. 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 [4], 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 the LHC finds that the ILC energy is too low or 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 [5]. This would put neutrino factory and muon collider development on a common path.

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# rol@muonsinc.com

## 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 [6]. Figure 1 is a schematic description of the new approach.

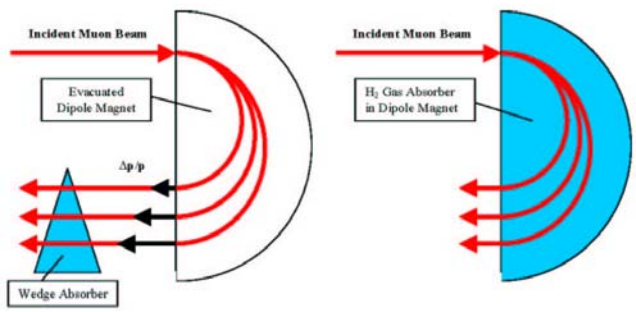


Figure 1: LEFT: Older Wedge Absorber Technique RIGHT: Proposed Homogeneous Absorber Technique where dispersion causes higher energy particles to have longer path length and thus more ionization energy loss.

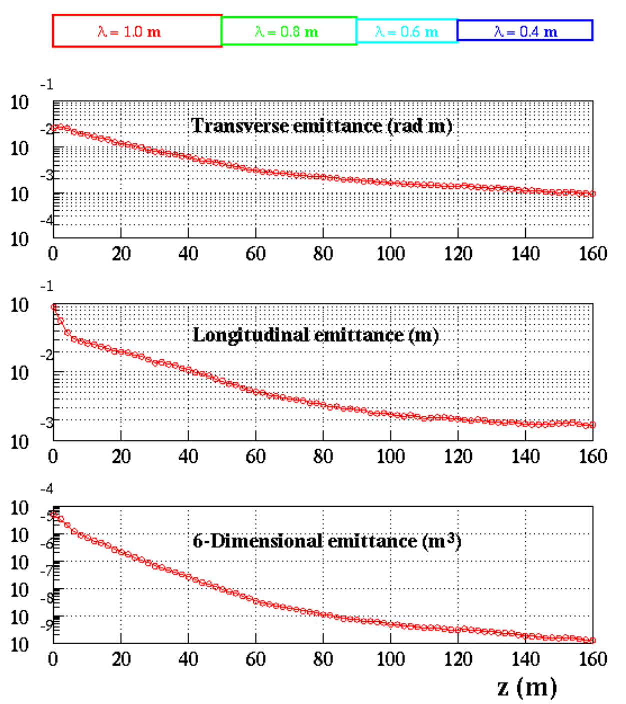


Figure 2: Simulation results of a series of 4 pressurized HCC segments which are matched to the beam by having smaller cavities and stronger fields as the beam cools.

### *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. 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 [7]. The analytic relationships derived from this analysis were used to guide simulations using a code developed based on the GEANT4 [8] program called G4Beamline [9].

Figure 2 shows the simulation results for a series of 4 HCC segments, where the RF cavity frequency and the magnetic fields are increased as the beam cools. In this 250 MeV/c example the final field would be 17 T and the RF frequency 1.6 GHz 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. Recent 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.

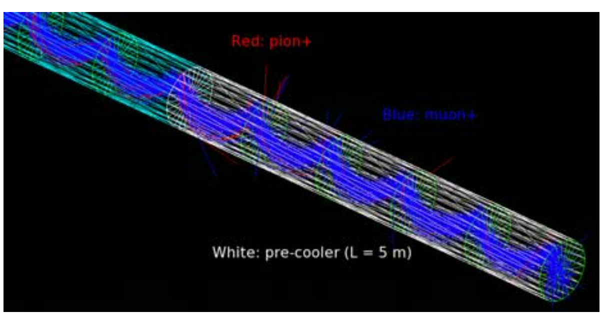


Figure 3: A G4BL simulation of a HCC used as a precooler for a muon beam slowing in liquid hydrogen.

### *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 [10]. 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) [11], 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 [12].

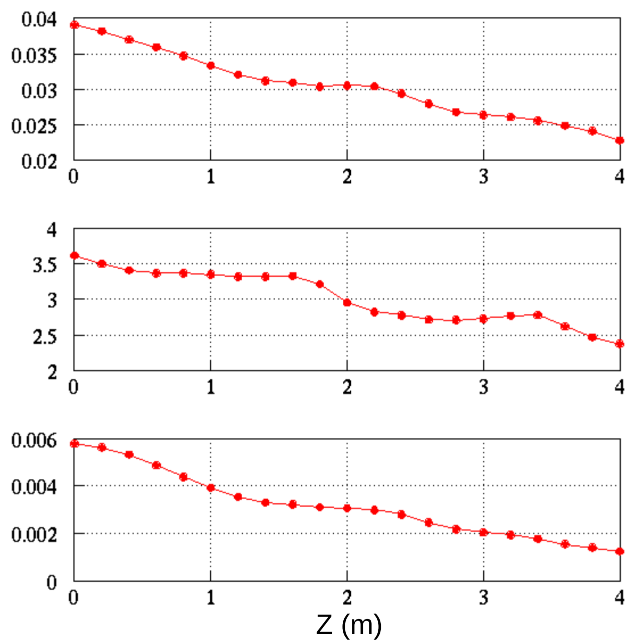


Figure 4: 6D invariant emittance plotted for a liquid helium filled HCC with variable fields, where the muon momentum decreases from about 300 to 150 MeV/c.

## 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 [13].

## 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 [14]. 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 [15] as shown in Figure 5, where an external field causes no apparent reduction in maximum achievable gradient.

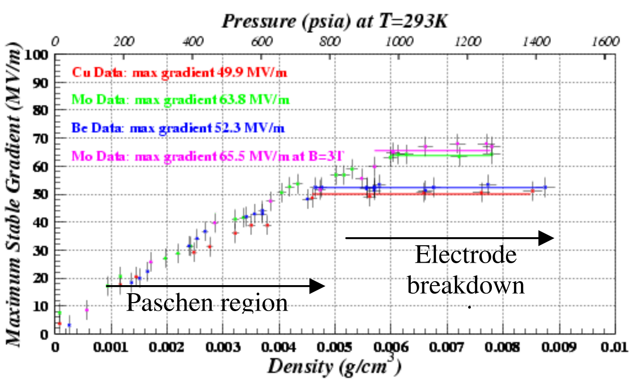


Figure 5: Measurements of the maximum stable RF gradient as a function of hydrogen gas pressure at 805 MHz with no magnetic field for three different electrode materials: Cu (red), Mo (green), and Be (blue). The cavity was also operated at the same gradients in a 3T field with Mo electrodes (magenta).

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 [16]. 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 (of the order of 50 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. In particular we are addressing how to mitigate the high Lorentz stresses associated with this high field magnet.

## SUMMARY

**S**everal 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 a 1.5 TeV muon collider 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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