Technical Challenges of Muon Colliders*

Rolland P. Johnson, *Muons, Inc. Batavia, IL, USA* and
Yaroslav Derbenev, *Jefferson National Accelerator Facility, Newport News VA, USA*

1. Introduction

Muon colliders need small muon flux to reduce proton driver and targetry demands, detector backgrounds, and site boundary radiation levels. Extreme beam cooling is therefore required to produce high luminosity at the beam-beam tune shift limit. The same beam cooling will allow the use of high-frequency RF for affordable acceleration to very high energy in recirculating Linacs and also make low beta insertions at the collider interaction points more effective. This last point follows from the fact that low beta insertions require a high beta at some limiting aperture that is less limiting for lower emittance beams.

Thus, the overriding technical challenge for muon colliders is to reduce muon beam emittances to those generally found in conventional electron and hadron colliders. This is a particularly formidable problem considering the 2.2 µs muon lifetime. Antiproton beams used in $p\bar{p}$ colliders must have their six-dimensional (6D) emittances reduced by some 8 orders of magnitude, but that process, based on stochastic and electron cooling, takes a day. For a similar muon beam emittance reduction in just a few microseconds, a series of clever tricks now under development may provide the solution.

2. Collider Parameters

For a 2.5 TeV/c on 2.5 TeV/c collider of 1 km radius that is limited by a beam-beam tune shift of $\Delta\nu = 0.06$, the peak luminosity is;

$$L_{peak} = \frac{N_1 n \Delta\nu}{\beta^* r_\mu} f_0 \gamma = 10^{35} / cm^2 - s$$

where we have used $n = 10$ bunches, $N_1 = 10^{11} \mu^-$ per bunch, and $\beta^* = 0.5\,cm$. For this set of conditions, $f_0 = 50 kHz$, $\gamma \approx 2.5 \times 10^4$, and $\tau_\mu \approx 50\,ms \Rightarrow 2500\, turns/\tau_\mu$. If the collider is filled at 20 Hz, this requires a 26 GeV proton driver of 300 kW power if it generates $0.3 \mu^\pm / p$ and the average luminosity is 0.43 of the peak value.

Figure 1 shows a conceptual picture of such a collider that would take advantage of excellent muon cooling to accelerate the beams in sections of the 1.3 GHz International Linear Collider accelerating sections using recirculation arcs to reduce costs. The magnetic arcs shown could occupy one tunnel, where the short pulse trains would make splitting and recombining the beams straight forward.

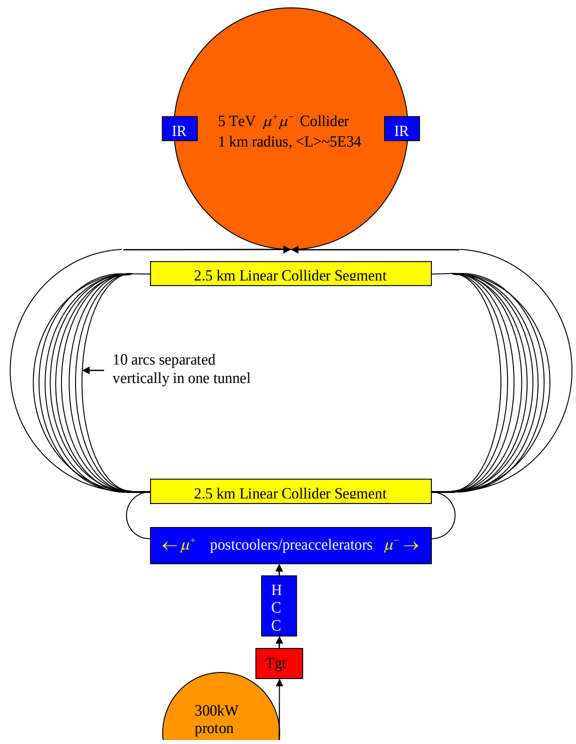


Figure 1. Conceptual diagram of a 5 TeV COM muon collider.

To get to that tune shift with such bunches requires normalized transverse emittances of 2 μm in each plane. To get to that value from an initial emittance of 34,000 μm requires the following steps that will be described below. First an intial precooler reduces the emittance to 20,000, then a helical cooling channel (HCC) will reduce the 6D emittance by a factor of a million or each transverse emittance to 200 μm, then parametric-resonance ionization cooling (PIC) to 25 μm, then reverse emittance exchange (REMEX) to 2 μm.

3. Ionization Cooling

Ionization cooling is a method for reducing the angular divergence of a beam by passing it through an energy absorber where it loses all three components of momentum, but only the longitudinal momentum is replaced with RF cavities.

In a beam line or ring, the position and angle of each particle in transverse phase space is usually exchanged often, so that two absorbers placed 90 degrees apart in betatron phase advance would reduce both the position and angular spread of a beam. Note that this technique is most effective when the natural angular spread of the beam is large; for this reason absorbers for ionization cooling are usually placed where the focusing is strongest, namely at a low beta point in a lattice. The cooling of the angular divergence will continue until it comes into equilibrium with the heating caused by multiple Coulomb scattering. Thus, low Z energy absorber is best to get the smallest equilibrium emittance.

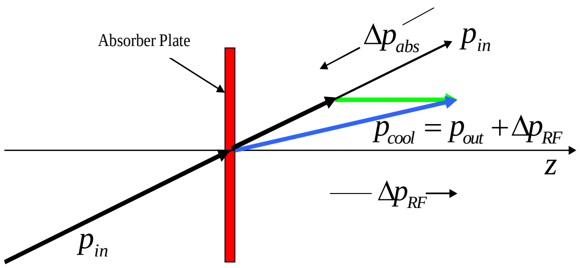
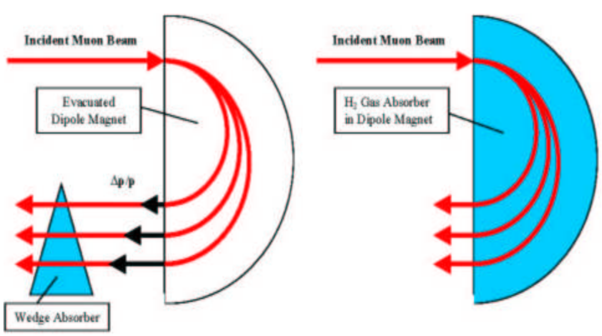


Figure 1. Diagram of ionization cooling, where the angular spread of a beam is reduced.

An interesting idea to combine the energy loss and reacceleration is being developed in studies to operate RF cavities filled with gaseous hydrogen [1]. This project takes advantage of the fact that muons do not interact through the strong force and have reduced scattering compared to protons and muons have more mass than electrons and so do not create electromagnetic showers. The gas operates high density and also suppresses RF breakdown and dark currents.

4. Emittance Exchange in Continuous Absorber



Figures 2 (LEFT) **and 3** (RIGHT) Comparison of the usual method of emittance exchange based on a wedge absorber (Left) with the method using a continuous energy absorber as is possible with pressurized RF cavities (Right).

In fact, the high-pressure RF cavity project generated the idea that a continuous gaseous absorber could be used to exchange transverse and longitudinal emittances so that ionization cooling could be used to reduce the momentum spread of a muon beam. The conceptual pictures of the older and newer methods are shown in figures 2 and 3.

5. Helical Cooling Channels

A remarkable magnetic channel based on helical magnets, which were developed for proton spin control in synchrotrons, has been developed for muon cooling applications [2]. This HCC combines solenoidal, helical dipole, helical quadrupole, and helical sextupole magnets to maintain orbit stability for a large beam while providing the required dispersion to achieve the emittance exchange discussed in the previous section. Recent simulation studies have shown 6D emittance reduction factors of over 50,000 for a series of four HCC segments [3] with magnet and RF technology of the future. Studies of materials and techniques of magnets [4] and RF [5] for HCC development are just starting at Fermilab.

6. Further Emittance Reductions

Parametric-resonance Ionization Cooling (PIC) is being studied to reduce emittances to levels below those achievable with helical channels using present-day state of the art magnets. In PIC, a ½-integer resonance is induced in a muon cooling channel to cause the elliptical motion of the beam in betatron phase space to become hyperbolic. Muons then stream to smaller x and larger x' as shown in figure 4. By focusing the beam on thin absorbers, ionization cooling is used to shrink the spread in x'. A factor of ten or more reduction of transverse emittance may be possible by using this technique. Detuning effects such as chromatic and spherical aberrations are serious complications to this technique and are being studied carefully [6].

In the example of a muon collider discussed above, the momentum increases from the cooling situation at 250 Mev/c to 2.5 TeV/c in the collider, a factor of 10,000. The momentum spread $\Delta p / p$ similarly diminishes by the same factor leaving a bunch length that is much smaller than the low beta focal length of the collider. In REMEX, the bunch length is lengthened until it matches the low beta focal length while the transverse beam dimensions are reduced using wedge absorbers in a reversal of the emittance exchange shown in figure 2.

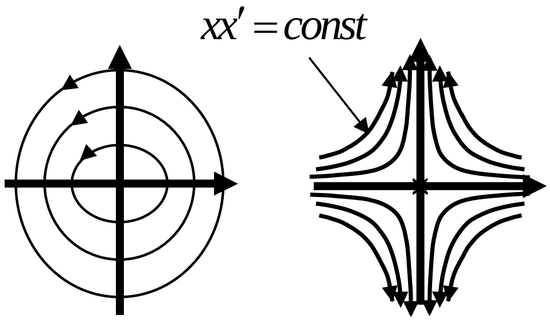


Figure 4. Comparison of particle motion at periodic locations along the beam trajectory in transverse phase space for: LEFT ordinary oscillations and RIGHT hyperbolic motion induced by perturbations at a harmonic of the betatron frequency. The horizontal and vertical axes are x and x'.

7. Neutrino Factory as an Intermediate Step

Recent work on neutrino factories has focused on the use of large acceptance FFAG synchrotrons to accelerate muon beams to high energy for storage in a ring with long straight sections. It is even argued by some that muon cooling in such a scenario is not cost effective.

In order to put a neutrino factory on the path to a muon collider, it is proposed that a cost effective neutrino factory based on extreme muon cooling could be built as an add-on to a superconducting proton driver [7]. In this case the incremental cost to upgrade a superconducting proton driver Linac to feed a neutrino factory storage ring may be considerably less than the $2B that has been the estimates of previous neutrino factory studies. The possibility of CW operation of such a Linac would imply a much larger neutrino flux with fewer problems with targetry.

8. 6D Cooling Demonstration Experiment

A convincing demonstration of 6D cooling and the HCC concept in particular is an essential prerequisite for the neutrino factory and muon colliders that have been discussed here. Recent work has shown that a 4.5 m long, 70 cm wide HCC filled with LHe could show over a factor of four in 6D emittance reduction using magnets with less than 5.5 T maximum field [8]. Such an experiment may be compatible with the spectrometers that are part of the MICE experiment to be done at Rutherford-Appleton Laboratory in England [9].

9. Summary

New ideas on muon cooling have the potential to rejuvenate the idea of an energy frontier muon collider to be built in the nearer future. The work being done on the International Linear Collider accelerating structures could be immediately applicable to muon acceleration if the beam can be cooled as described above. The recirculation possible with a muon beam may lead to collision energies 10 or more times higher than the ILC with less cost.

The incremental cost of a neutrino factory based on a muon storage ring fed by recirculating muons in a linear superconducting proton driver may be a fraction of the amount now envisioned for a dedicated neutrino factory with its own proton driver and independent acceleration scheme. Further, if the Linac were to operate in a CW mode such that a higher repetition rate were possible, considerably more neutrinos could be produced than with the schemes that have been investigated so far.

The next step towards these goals of an affordable neutrino factory and a compelling muon collider is to demonstrate that an effective 6D cooling channel can be built that has the properties predicted by analytic and simulation calculations.

References

* Supported by DOE SBIR/STTR grants DE-FG02-02ER86145, 03ER83722, 04ER84015, 04ER86191, and 04ER84016

[1] R. P. Johnson et al. LINAC2004, http://www.muonsinc.com/TU203.pdf
[2] Y. Derbenev and R. P. Johnson, *Phys.Rev.STAB* **8**, 041002, (2005)
[3] R. P. Johnson et al., COOL05
[4] L. Del Frate et al., PAC05
[5] M. Alsharo'a et al., PAC05
[6] Y. Derbenev, COOL05
[7] M. Popovic and R. P. Johnson, this workshop
[8] K. Yonehara et al., COOL05
[9] D. M. Kaplan, COOL05