# COMPARISON OF 6D RING COOLER SCHEMES AND DIPOLE COOLER FOR μ+ μ- COLLIDER DEVELOPMENT

David Cline, Al Garren and Yasuo Fukui, Center for Advanced Accelerators, Dept. of Physics & Astronomy, UCLA
Harold Kirk, BNL

*Abstract*

We discuss the various schemes to use ring coolers for 6D cooling for $\mu^+\mu^-$ colliders. The earliest successful cooler used dipoles and quadrupoles and a high dispersion low beta region. This was also proposed in the form of solenoids. Recently there have been many new ideas. The simplest is to use a simple dipole ring with high-pressure gas absorber or Li hydride. We show the results of simulations and compare with the results for other cooler schemes.

## THE MUON COLLIDER

The development of a $\mu^+\mu^-$ collider could be very important to study and LHC discoveries such as (a) SUSY Higgs particles (200 – 600 GeV) in the S channel and (b) new hish mass particles such as Squarks (TeV) [1]. The $\mu^+\mu^-$collider is the only possible circular high energy Lepton collider that can be sited on FNAL or CERN sites. It could be installed into the Tevatron Tunnel.

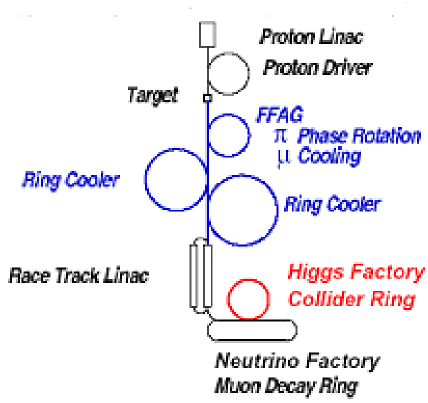


Figure 1: A schematic diagram of a ν factory and a μ+μ- collider.

The Muon Collider is a relatively old idea that was revived at a meeting in Napa Valley, Dec. 1992. [1] During 1990s there were 5 dedicated workshops [2] to the development of the Muon Collider and the formation of a Muon Collaboration. These studies focused on the transverse cooling of the muons and spent little time discussing the 6D (6 dimensional) cooling. Around 1998, it was realized that a muon storage ring could produce a powerful Neutrino Factory [2] with the discovery of the neutrino oscillation by SuperK. The interest in a Neutrino Factory grew rapidly. By the time of the 2001 Snowmass APS Meeting, it was clear that the Muon Collider required new thinking about 6D cooling. At that meeting there were two proposals for Ring Coolers to provide 6D cooling [3]. This was the start of a major new effort on 6D cooling of muons.

## 6D COOLING WITH RING COOLERS

The basic concept of 6D cooling in a Ring is simple, - a wedge of liquid Hydrogen is placed in a region of high dispersion and muons of different momentum lose more or less dE/dx depending on the position.

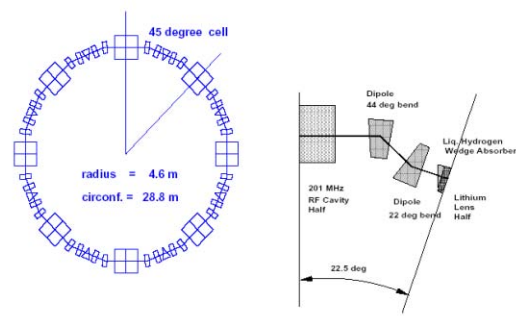


Figure 2: A top view of a muon cooling ring and a schematic diagram of a half of 45 degree bending cell.

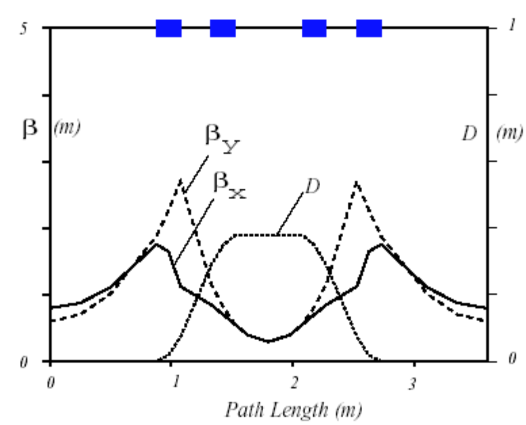


Figure 3: βx, βy and η as a function of z in a 45 degree bending cell.

The quadrupole ring cooler is easiest to understand. Using an insert regional low beta and high dispersion region is created [3]. The low beta keeps multiple scattering low where the dispersion and the wedge absorber give energy loss proportional to the muon beam energy – thus "cooling" the muons. All Ring Coolers work in this method to some extent. In the case of the High Pressure Gas Ring Cooler the absorber is distributed over the ring. An example of an early ring cooler was presented at Snowmass 2001 [3].

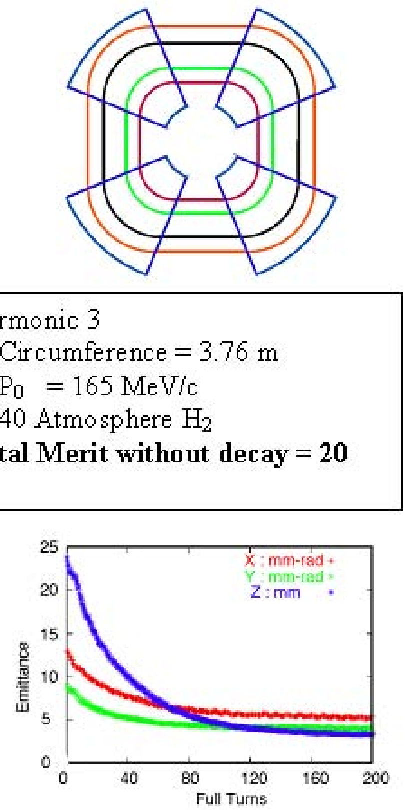


Figure 4: 4-dipole ring: schematic diagram, parameters and performance for harmonic number 3.

## HIGH PRESSURE RING COOLERS

The MICE experiment will produce a compelling test of transverse muon cooling. However this experiment is not optimized to cool the energy of the muon beam. So a dedicated Ring Cooler could be imagined to demonstrate the full 6D cooling. An SBIR study of such a ring was granted . Just Stage was approved but failed to obtain full funding. However this studies showed that such a High Pressure Gas Dipole Ring could be constructed to test the concept of 6D cooling [5].

A design scenario to demonstrate 6D muon cooling has been made using the concepts discussed above. In order to make this demonstration economically feasible, the cooling goals were reduced to correspond to a merit factor of at least 10, where

$$\textit{Total Merit} = \textit{Transmission} \times (e_x\, e_y\, e_z)_{\text{initial}} / (e_x\, e_y\, e_z)_{\text{final}}$$

Figure 4 shows evolution of the normalized transverse emittances, $\varepsilon_{\eta x},\varepsilon_{\eta y}$, and the normalized longitudinal emittance, $\varepsilon_{\eta x}$, and a merit factor as a function of the path length along the central trajectory [6]. Here, x is the horizontal coordinate and its positive direction goes outside of the muon cooling ring, y is the vertical coordinate, and the z goes along the central trajectory with beam. With the minimum β at 30 cm at the wedge absorbers and the Lithium lenses, expected normalized vertical equilibrium emittance $\varepsilon_{\eta x},\varepsilon_{\eta y}$ is 1.9 mm-rad and we obtained 2.3 mm-rad in the ICOOL simulation which is close enough to the expected number. This ring showed clear 6D cooling in the simulation; see Fig. 6.

## A POSSIBLE LI LENS FOR A FINAL COOLING RING

While ring coolers may give adequate longitudinal cooling for a muon collider, extra transverse cooling is needed as well. This requires a low β cooler. We have studied Li lens instance ( β* ~1 cm) for this purpose [7].

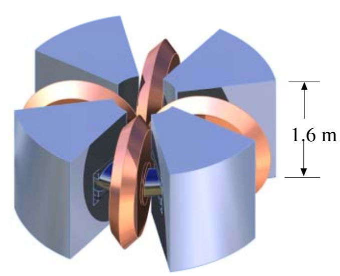


Figure 5: Ring cooler with dipole.

Table 1: Parameters that describe the muon cooling ring.

| Parameter | Value |
|---|---|
| Dipole Field | 1.8 T |
| Number of Cells | 4 |
| Reference Momentum | 172.12 MeV/c |
| Ring Circumference | 3.81 m |
| X Aperture | ±20 cm |
| Y Aperture | ±10 cm |
| $P_z$ Acceptance | ±10 MeV/c |
| Minimum $\beta_X$ | 38 cm |
| Maximum $\beta_X$ | 92 cm |
| Minimum $\beta_Y$ | 54 cm |
| Maximum $\beta_Y$ | 66 cm |
| Hydrogen Gas Pressure | 40 Atm @ 300º K |
| RF Gradient | 10 MV/m |
| RF Frequency | 201.25 MHz |
| Total RF Length | 1.2 m |
| Total Orbit Turns | 100 |

We designed muon cooling rings with a Lithium lens, which is made of 2 matching higher β Lithium lenses sandwiching the central lower βProgress in Designing a Muon Cooling Ring with Lithium Lenses Lithium lens. β

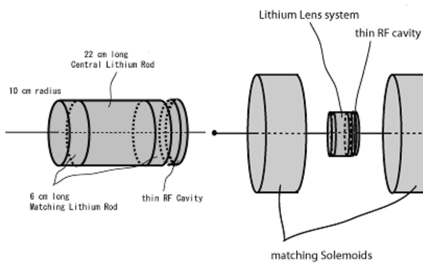


Figure 6: A schematic diagram of a Lithium lens (left) and straight section (right).

at the inner 22 cm long Lithium lens is 1.0 cm . The matching Lithium rod with the length of 6.3 cm each,which sandwich the central Lithium lens, has an equilibrium β at 4.0 cm, which swings the β function from the β at 16 cm at the outer end to the β at 1 cm at the inner end of the matching Lithium rod [7].

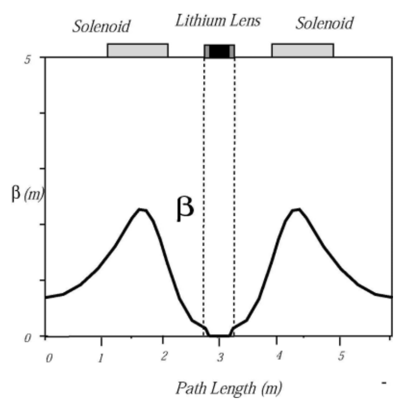


Figure 7: β as a function of s in the Lithium lens and matching cells with solenoids

The solenoids have 6 Tesla $B_z$ field where the $B_z$ direction of solenoids is opposite to each other, and each solenoid is 1.3 m long. Figure 6 shows a schematic diagram of a Lithium lens and straight section, which is made of 2 matching solenoids and a set of Lithium lenses. Figure 7 shows the β as a function of z in the Lithium lens and matching cells with solenoids.

In order to study the muon beam dynamics through a Lithium lens and matching solenoid lattices which sandwich the Lithium lens, we performed tracking simulation with ICOOL tracking code. Original model was designed by using the SYNCH which generates the input date for the tracking code ICOOL.

Figure 8 shows the development of the normalized transverse emittance as a function of z through 33 sets of 5.9 m long straight channel. In this simulation, the loss of muon $p_z$ due to the dE/dx energy loss through the Lithium lens is recovered through a thin RF cavity by adding average $p_z$ kick.

We have also studied curved Li lens cooling rings that are discussed in other PAC 07 papers. The use of a ring cooler for a muon collider is given in [8].

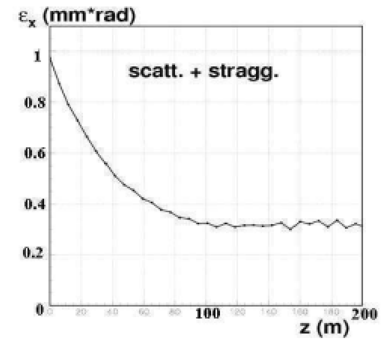


Figure 8: Normalized transverse emittance as a function of z through 33 sets of straight sections.

## REFERENCES


[1] Proceedings from the First Workshop on Muon Colliders (Napa, California, 1992), Nucl. Inst. Methods, Vol. A350, pp. 24-56, 1994., P. Chen and K. MacDonald, Summary of the Physics Opportunities Working Group, AIP Conference Proceedings 279, Advanced Accelerator Concepts, 853 (1993); Proceedings of the Mini-Workshop on mu+mu− Colliders: Particle Physics and Design, Napa CA, Nucl. Inst. and Meth., A350 (1994); ed. D. Cline; Physics Potential and Development of mu+mu− Colliders, 2nd Workshop, Sausalito, CA, ed. D. Cline, AIP Press, Woodbury, New York (1995); Proceedings of the 9th Advanced ICFA Beam Dynamics Workshop, ed. J. Gallardo, AIP Press (1996); Proceedings Symposium on Physics Potential and Development of mu+mu− Colliders, San Francisco, CA, December 1995, Supplement to Nucl.Phys. B, ed. D. Cline and D. Sanders.

[2] M.Alsharo, et. al., "Recent Progress in neutrino factory and muon collider research within the muon collaboration", Phys. Rev. ST Accel. Beams 6, 081001 (2003).

[3] H.Kirk, D.Cline, Y.Fukui, A.Garren, "Progress towards a Muon Ring Cooler", Snowmass M1 workshop Proceedings, July 2001.

[4] Y. Fukui, D. Cline, A. Garren, H. Kirk, "Muon Cooling Rings for the neutrino factory and mu+mu-collider", ICAP2002 proceedings.

[5] H. Kirk, S. Kahn, F. Mills, D. Cline, A. Garren, "A Compact 6D Muon Cooling Ring", PAC05 proceedings.

[6] Al Garren, private communication.

[7] Y.Fukui, D.Cline, A.Garren, H.Kirk, "Progress in Designing a Muon Cooling Ring with Lithium Lenses", PAC03 Proceedings.

[8] D. Cline, "Development of muon ring coolers, neutrino factories and supersymmetric Higgs factory", J. Phys. G: Nucl. Part. Phys. 29 No 8 (August 2003).




 1-4244-0917-9/07/$25.00 ©2007 IEEE