RACETRACK MUON RING COOLER USING DIPOLES AND SOLENOIDS FOR A MUON COLLIDER

X. Ding[#], D. Cline, UCLA, Los Angeles, CA 90095, USA
A. A. Garren, Particle Beam lasers, Inc., Northridge, CA 91324, USA
H. G. Kirk, J. S. Berg, Brookhaven National Laboratory, PO BOX 5000, Upton, NY 11973-5000

Abstract

A racetrack muon ring cooler for a muon collider is considered. The achromatic cooler uses both dipoles and solenoids. We describe the ring lattice and show the results of beam dynamic simulation that demonstrates a large aperture for acceptance. We also examine the 6D cooling of the muon beam in the cooler and discuss the prospects for the future.

INTRODUCTION

The future facility of muon collider based on intense beams of muons offers the promise of extraordinary physics capabilities [1]. As shown in Figure 1, there are two significant technical challenges to face when one considers the development of an intense muon beam. The first is the production and collection of the muons and the second is the reduction of the phase space (cooling) of the muon beam in order to facilitate the ultimate application of the muon beam for physics research. In order to optimally cool the muon beam it is desired to collapse its extent in 6D (6 dimensional) phase space, i.e. in each of the three space and three momentum dimensions [2]. A principle technique for muon beam cooling is ionization cooling, in which the magnitudes of 3-dimensional momentum vectors of the muon particles are reduced via energy loss in an ionizing media followed by the subsequent restoration of only the longitudinal momentum component with RF power.

Whereas 4D transverse cooling can be achieved in a linear channel, it is necessary for the beam to have dispersion so that longitudinal cooling can also be realized. This is because dispersion gives the beam a correlation between energy and transverse displacement. The placement of absorbing wedges in the beam creates a corresponding correlation between particle energy and energy loss, and this allows longitudinal cooling. Thus it is natural to consider rings, in which dispersion arises naturally from the bending in the dipole magnets.

The earliest successful 6D cooling of ring coolers for $\mu+\mu-$ colliders used dipoles and quadrupoles and a high dispersion low beta region [3]. In this paper, we investigate the possibility of a racetrack muon ring cooler which uses both dipoles and solenoids. We describe the achromatic ring lattice and show the results of beam dynamic simulation that demonstrates a large aperture for acceptance. We also examine the 6D cooling of the muon beam with liquid hydrogen absorbers in the cooler and discuss the prospects for the future.

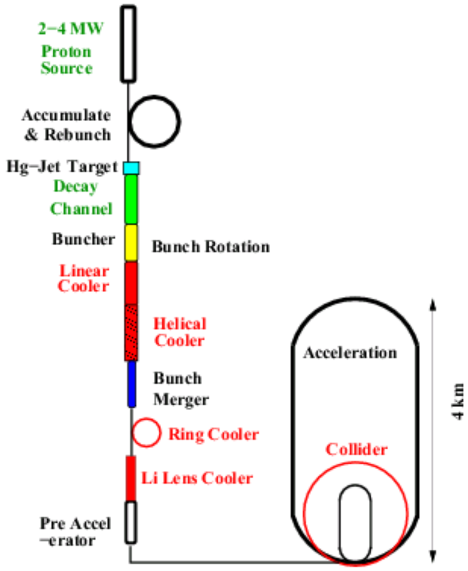

Figure 1: A schematic diagram of a $\mu+\mu-$ collider.

THE CONCEPT OF ACHROMATIC SOLENOID-DIPOLE RING COOLER

In recent years, we have developed a lattice concept for muon cooling called the achromatic ring cooler. We show a schematic of the ring cooler with an injection system in Figure 2, using a superconducting flux pipe [4]. The magnet system of such a ring uses solenoids and dipoles. The ring is composed of two or more modules (or superperiods), each consisting of an arc and a straight section. The arc provides dispersion in spaces for the energy-loss wedge absorbers needed for 6D cooling. The straight sections are dispersion-free and provide spaces for injection and extraction and RF cavities. The arc module is tuned to have a betatron phase advance of 360 degrees, so that the betas are the same and the dispersion is zero at both ends, and therefore through the straight section; the beam size is reduced there due to the 0-dispersion property.

This achromatic ring lattice design can be converted to one for a single-pass snake-like device by alternating the polarity of the dipole fields from one arc to the next. This is possible due to the dispersion-free straight sections. Hence, one can envision a scheme in which a series of rings connected by snakes are tailored to fit the decreasing emittance of the beam as it is cooled.

The magnet systems of these lattices are composed of solenoids and dipoles. The solenoids focus the beam equally in both transverse dimensions. The straight

---

[#] xding@bnl.gov

sections have solenoids only, while the arcs have magnets of both types. In order to preserve equal focusing in the arcs, the dipoles have 0-gradients and edge angles chosen that also give equal focusing (this could also be achieved using gradient magnets). The lattice design process is simplified since there is only one beta function and the dispersion to adjust. Another advantage of this design is that the rings and snakes are planar.

In recent designs, the arcs and straight sections are each composed of 4 cells with one solenoid in each; those in the arcs have 2 dipoles as well.

THE RACETRACK SOLENOID-DIPOLE RING COOLER

The original racetrack lattice shown in Figure 2 has a small dynamic aperture. In Figure 3, we show a modified racetrack lattice which has been tuned at reference energy from 1.60 to 1.75. In Figure 4, we show the beta function and dispersion of the modified lattice. In Table 1 we provide the lattice parameters for this design. In Figure 5, we see the aperture of the modified lattice is much larger than the original lattice.

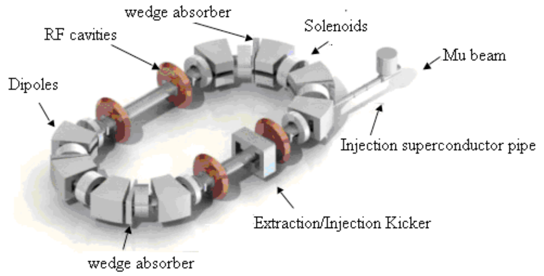

Figure 2: Schematic drawing of an achromatic ring 6D ring cooler with superconducting flux pipe injection system.

Table 1: Parameters of the Racetrack Ring Cooler

Parameter	Value
Momentum	145 MeV/c
Superperiods	2
Number of dipoles	16
Number of straight section solenoids	8
Number of arc solenoids	8
Arc length	6 m
Straight section length	5.85 m
Dipole length and field	0.15 m, 1.26624 T
Dipole bend and edge angles	22.5 deg, 5.625 deg
Arc solenoid length and field	0.15 m, 1.814 T
Straight section solenoid length and field	0.275 m, 1.814 T
Superperiod length and xytunes	11.85 m, 1.748
Circumference	23.7 m

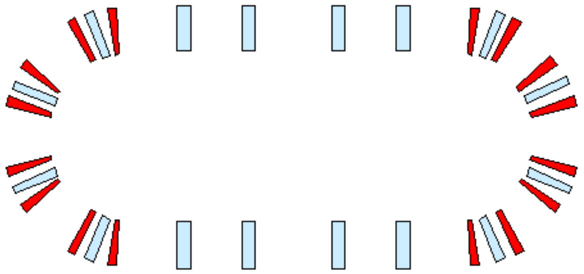

Figure 3: Modified lattice of the racetrack ring cooler using Dipoles and Solenoids.

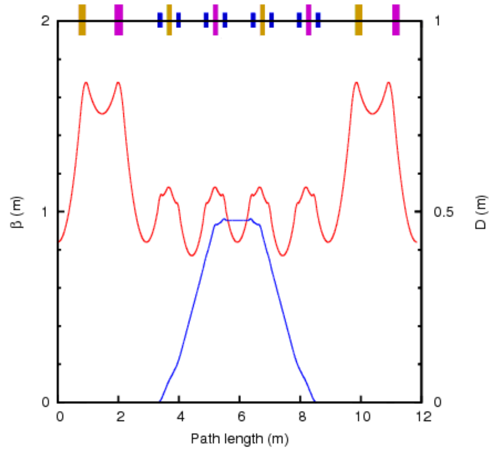

Figure 4: Beta function and dispersion in one superperiod of the modified racetrack ring cooler at momentum of 145 MeV/c.

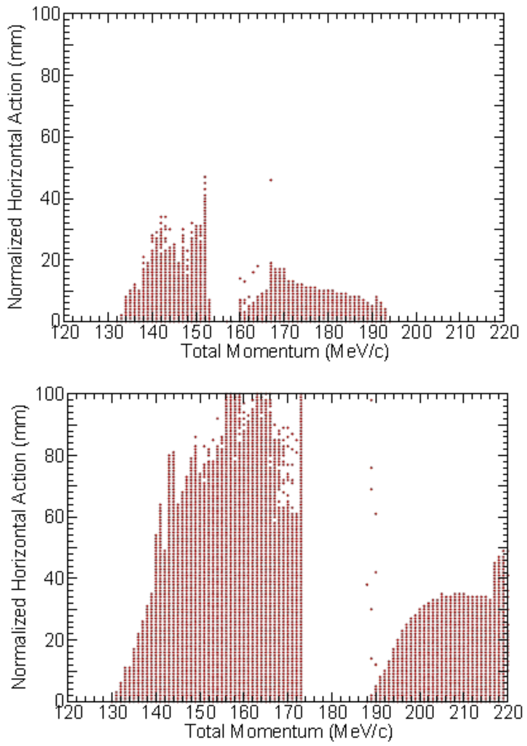

Figure 5: Dynamic aperture of the original (top) and modified (down) racetrack lattice.

SIMULATION OF 6D COOLINING WITH THE RACETRACK RING

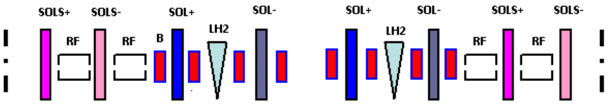

Figure 6: Schematic drawing of the ring half in the racetrack and achromatic ring cooler.

We use ICOOL [5] to perform tracking simulation. In Figure 6, we show the ring half for the racetrack solenoid-dipole ring cooler. The ring has two 180-degree arcs and eight dipoles separated by solenoids in each arc. The working momentum of the muons was chosen to be 145 MeV/c. In order to cool the beam, the liquid hydrogen (LH_2) wedge coolers will be inserted into a region with low β and high dispersion, as shown in Figure 4 and 6. Each LH_2 wedge absorber has a length of 15.8 cm, an energy loss rate of 0.3 MeV/cm, and a wedge angle of 10 degrees. Four 201.25 MHz accelerating cavities (RF) are placed in the superperiod. Its accelerating gradient is 15 MV/m and RF phase is 30 deg. The RF cavities will restore the energy of the muon beam that is lost in the LH_2 absorbers. In Fig. 7 we show the evolution of the beam parameters in the cooling process during 15 turns of the four-sided ring cooler when we turn off the decay and multiple scattering during the simulation. We see there is few cooling in the horizontal and longitudinal direction. It's even worse when we turn on the straggling and scattering in the absorber.

In general, our modified racetrack lattice has significantly improved the dynamic aperture. However, this ring had to operate at a relatively low momentum (145 MeV/c), a level required to maintain synchrotron oscillations. This low momentum caused the sum of the damping rates to be rather small, resulting in almost no horizontal and longitudinal cooling. In addition, the lattice had a small passband in momentum, leading to a small energy acceptance and preventing the use of a large RF voltage to obtain a high cooling rate.

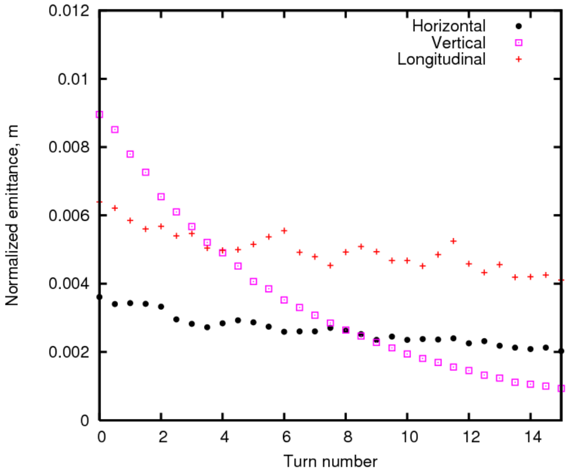

Figure 7: Beam emittance at the cooling without multiple scattering in the simulation.

In Ref. [6], a four-sided lattice has evolved from this modified racetrack lattice. The four-sided lattice has a big dynamic aperture, a high minimum time of flight, big passband and high working momentum. In addition, the study of 6D cooling with the four-sided ring demonstrates that a robust 6D cooling of the muon beam phase space can be achieved.

CONCLUSIONS

We have described the racetrack achromatic ring cooler using both solenoids and dipoles in detail. The beam dynamic simulation shows that the modified ring cooler has a large aperture. However, this ring has a high beam loss with multiple scattering and few 6D cooling. Based on the racetrack module, we have successfully designed a four-sided ring cooler that has strong 6D cooling [6].

ACKNOWLEDGMENTS

This work was supported by the U.S. Department of Energy in part under award numbers DE-FG02-92ER40695 (UCLA), DE-AC02-98CH10886 (BNL) and DE-FG02-07ER84855 (Particle Beam Lasers, Inc.)"

REFERENCES

[1] R&D Proposal for the National Muon Accelerator Program, FERMILAB-TM-2459-APC,2010, http://mctf.fnal.gov/mapproposal.pdf/view.

[2] M.Alsharo'a, 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; Y. Fukui, D. Cline, A. Garren, "Muon Cooling Rings for the neutrino factory and mu+mu- collider", ICAP2002 proceedings.

[4] F. Martin, S.J. St. Lorant, W.T. Toner, "A four-meter long superconducting magnetic flux exclusion tube for particle physics experiments", Nuclear Instruments and Methods, Volume 103, Issue3, 1972, p. 503.

[5] R. C. Ferrow, "ICOOL: A Simulation Code for Ionization Cooling of Muon Beams" in proceedings of PAC99, New York, New York, edited by C. A. Luccio, W. Mackay, (1999) p. 3020.

[6] X. Ding et al., "Robust 6D Muon Cooling in Four-sided Ring Cooler using Solenoids and Dipoles for a Muon Collider", these proceedings, MOP055, 2011.