ROBUST 6D MUON COOLING IN FOUR-SIDED RING COOLER USING SOLENOIDS AND DIPOLES FOR A MUON COLLIDER

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Abstract

We present a four-sided ring cooler that employs both dipoles and solenoids to provide robust 6D muon cooling of large emittance beams in order to design and build a muon collider. Our studies show strong 6D cooling adequate for components of a muon collider front end.

INTRODUCTION

We face two significant technical challenges when considering the development of an intense muon beam. The first is the production and collection of muons. 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 [1]. In order to optimally cool the muon beam we desire 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 through the use of ionization, where 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.

The earliest successful 6D cooling of ring coolers for μ+μ- colliders used dipoles and quadrupoles, plus a high dispersion low beta region [3]. In this paper we examine the possibility of replacing quadrupole-focusing with solenoids. We describe the lattice and the beam dynamics of this dipole-solenoid ring. In addition we show the result of 6D cooling simulation with liquid hydrogen absorbers.

BRIEF HISTORY OF THE MUON COLLIDER

The development of a μ+μ- collider could be very advantageous in studying LHC discoveries such as (a) SUSY Higgs particles (200 – 600 GeV) in the S channel and (b) new high mass particles such as Squarks (TeV) [1]. The μ+μ-collider is the only possible circular high energy Lepton collider that can be situated at FNAL or CERN sites.

The muon collider is a relatively old idea that was revived at a meeting in Napa Valley, December 1992. [1] During 1990s there were five dedicated workshops [1] involving the development of the muon collider and the formation of a muon collaboration. These studies focused on transverse cooling of the muons and spent little time discussing 6D-cooling theories.

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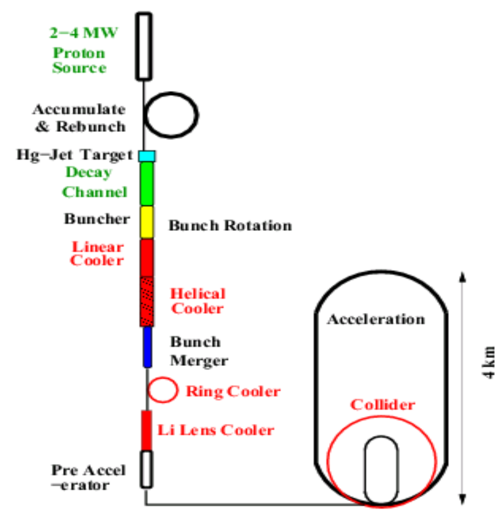

Figure 1: Achromatic diagram of a $\mu^+\mu^-$ collider.

THE ACHROMATIC SOLENOID-DIPOLE RING COOLER

Our initial studies of ring coolers [4] found some difficulties with their design. The rings require sufficient space for injection and extraction hardware. They need to have small beta functions while simultaneously having a large dynamic aperture.

Such a cooler system could be used to cool large to small emittances using a series of ring coolers. The final cooler would concentrate more on transverse cooling to achieve the emittance required for a muon collider. We show a schematic of the ring cooler with an injection system in Figure 2, using a superconducting flux pipe [5].

THE EVOLUTION OF THE SOLENOID-DIPOLE RING COOLER DESIGN

The lattice design has evolved from the original concept shown in Figure 2 to a lattice design that is much more effective for cooling. The original design suffered from several problems. It had a relatively low dynamic aperture. This resulted in significant beam loss due to multiple scattering at the absorbers, even when starting with a zero emittance beam, as well as a relatively small ratio of an injectable emittance to the final equilibrium emittance. The 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. Finally 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.

We changed the lattice from a racetrack design to a four-sided one, which further reduced the dispersion (see Figure 4), thereby increasing the momentum of the minimum in the time of flight, as shown in Figure 5. This then allowed us to raise the central momentum of the lattice to 220 MeV/c, where the sum of damping partition numbers is better than at 145 MeV/c. The dynamic aperture of the four-sided ring is shown in Figure 6 and it is much larger than the racetrack ring in Figure 2 [6]

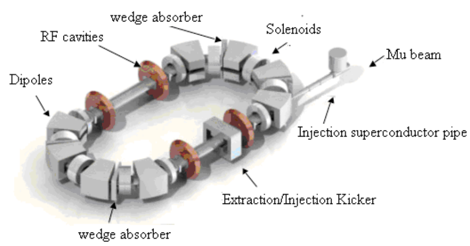

Figure 2: Schematic drawing of an achromatic ring 6D ring cooler with superconducting flux pipe injection system.

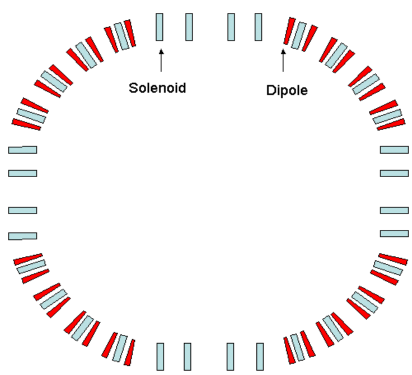

Figure 3: Schematic drawing of the four-sided ring cooler using dipoles and solenoids.

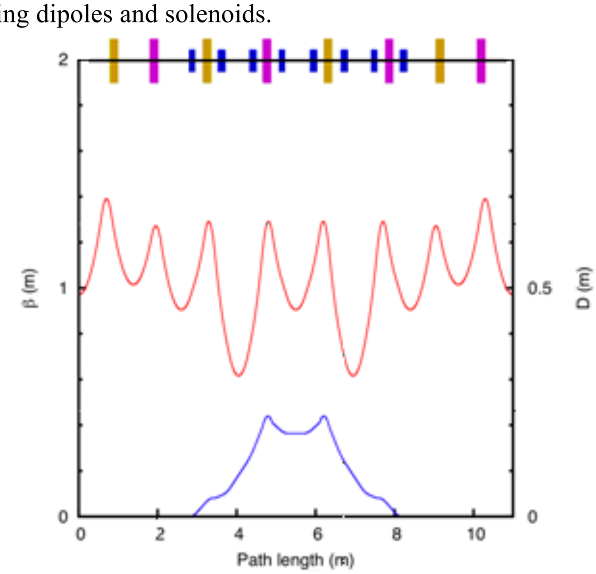

Figure 4: Beta function and dispersion in one superperiod of the four-sided ring cooler at momentum of 145 MeV/c.

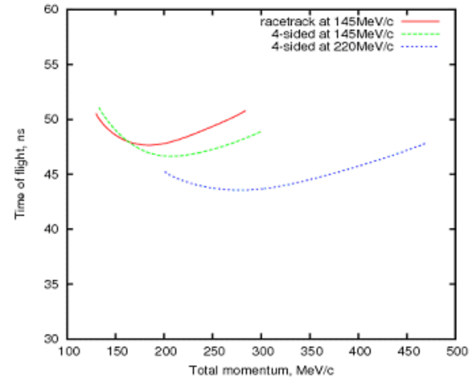

Figure 5: Time of flight for one superperiod of a modified racetrack and four-sided achromatic lattice.

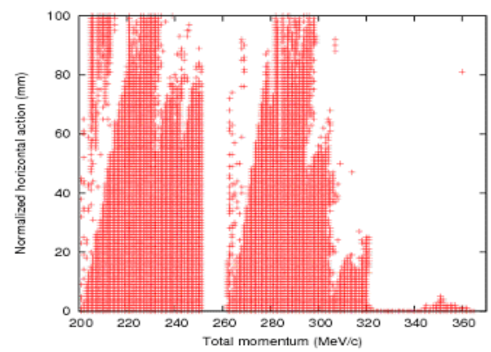

Figure 6: Dynamic aperture of the four-sided lattice.

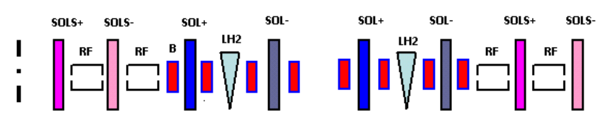

Figure 7: Schematic drawing of the ring quadrant in the four-sided and achromatic ring cooler.

THE CONCEPT OF A FOUR-SIDED SOLENOID-DIPOLE RING COOLER

In Figure 7, we show the ring quadrant for the four-sided solenoid-dipole ring cooler. It has four 90-degree arcs and eight dipoles separated by solenoids in each arc. The arcs are nearly achromatic both horizontally and vertically. The result is that the dispersion is zero in the straight sections between the arcs. In order to reduce the horizontal and vertical coupling, we see the fields of successive solenoids alternate in direction.

STUDY OF 6D COOLINING WITH THE RING

We use ICOOL [7] to perform tracking simulation. Our working momentum of the muons was chosen to be 220 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. We have achieved this as shown in Figure 4 and 6. Each LH_2 wedge absorber has a length of 19.5 cm, an energy loss rate of 0.303 MeV/cm, and a wedge angle of 23 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. Our compact four-sided ring has a positive dispersion, which means that higher-momentum particles have longer paths around the ring, and thus lose more energy per turn than low energy particles do. Consequently cooling takes place in the longitudinal as well as the transverse dimensions. In Fig. 8 we show the evolution of the beam parameters in the cooling process during 15 turns of the four-sided ring cooler. The initial and final beam parameters for 6D cooling are given in Table 1. If we time the entire horizontal, vertical, and longitudinal invariant emittance together, the initial quantity decreases by a factor 23.2 during 15 revolutions. So we see that the circulating muon beam has been cooled in each of the three space and three momentum dimensions

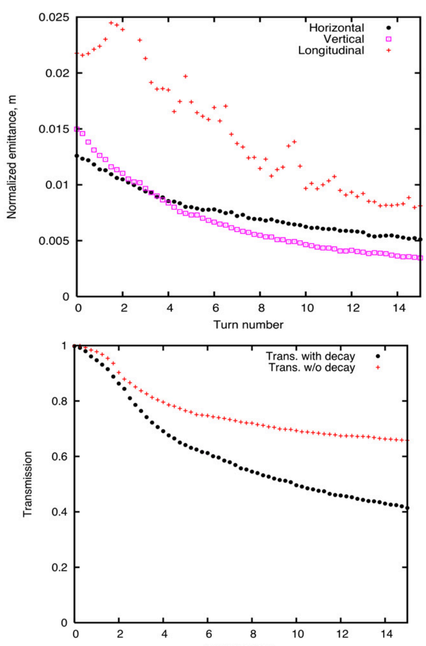

Figure 8: Beam emittance (top) and transmission (down) at the cooling.

CONCLUSIONS

For the first time we have described the achromatic ring cooler using both solenoids and dipoles in detail. The beam dynamic simulation shows that the four-sided ring cooler has a large aperture for acceptance. In addition, the study of 6D cooling for the four-sided ring at the working momentum of 220 MeV/c shows that 6D cooling of the muon beam phase space can be achieved.

ACKNOWLEDGMENTS

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Table 1: Beam Parameters vs. Number of Turns

Number of turns	0	15	Reduction
Normalized horizontial emittance (mm)	12.59	5.338	5.338
Normalized vertical emittance (mm)	14.98	3.911	3.911
Normalized longitudinal emittance (mm)	21.77	8.489	2.56
Transmission (%)	100		65.8

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