6D “Garren” Snake Cooler and Ring Cooler for $\mu^{\pm}$ Cooling of a Muon Collider

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Abstract

Six dimensional cooling of large emittance μ^+ and μ^- beams is required in order to obtain the desired luminosity for a muon collider. In our previous study, we demonstrated that a 6D “Garren” ring cooler using both dipoles and solenoids in four 90° achromatic arcs can give substantial cooling in all 6 phase space dimensions. In this paper, we describe the injection/extraction requirements of this four-sided ring. We also present the performance of an achromat-based 6D “Garren” snake cooler. The achromatic design permits the design to easily switch between a closed ring and a snaking geometry on injection or extraction from the ring.

Keywords: Muon Collider 6D cooling Snake Cooler Ring Cooler Injection

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1. Introduction

Six dimensional cooling of large emittance μ^+ and μ^- beams is required in order to obtain the luminosity desired for an energy-frontier muon collider [1] or a muon-based Higgs factory [2, 3]. A muon collider was first considered practical when it was realized that a collected muon beam could be cooled by a process utilizing energy losses during the passage of the muons through an appropriate material [4–6]. In this technique, referred to as ionization cooling, muons alternately pass through a material absorber and are then re-accelerated. If there is sufficient focusing at the absorber, then the transverse phase space volume is reduced: i.e., the muons are cooled in the transverse dimension. A consequence of the transverse cooling is an increase of the longitudinal phase space caused by the unfavorable slope of energy loss as a function of energy for momenta below the ionization minimum, and by energy straggling in the material [7]. In order to realize longitudinal cooling via the energy loss process, it is necessary for the beam to have dispersion. This is because dispersion gives the beam a correlation between energy and transverse displacement. The placement of absorbing wedges in the beam then creates a favorable correlation between particle energy and energy loss, and this allows longitudinal cooling. Over the past decade various approaches have been studied in the design and simulation of 6D cooling lattices [7-13] based on emittance exchange. In particular, a RFOFO ring [7] and a RFOFO helix, also known as the Guggenheim channel [12], that use tilted solenoids to generate dispersion, have been shown to provide at least 2 orders of magnitude reduction of the normalized 6D phase-space volume with a transmission above 50%. A Guggenheim channel avoids serious problems with injection and extraction of large emittance beams but since the beam passes through each RF cavity only once, it is large and expensive. Furthermore, it can only cool one sign of muons. The RFOFO cooling ring significantly reduces the cost and scale of the cooling system by allowing multiple passes through the RF cavities and the cooling of both muon signs, but suffers from a significant loss of performance when injection is added to the compact ring, which has little space in its basic lattice cell. In a previous publication [14], we have described a four-sided achromatic cooling ring, which is called 6D “Garren” ring cooler in this paper. The

ring has four achromatic arcs containing dipoles and solenoids plus long straight sections between the arcs (see Fig. 1). We demonstrated that this ring cooler can give substantial cooling in all six phase space dimensions.

Figure 1. Schematic drawing of a 6D “Garren” ring cooler.

The biggest challenge in both our dipole/solenoid ring cooler and the RFOFO cooling ring are the injection and extraction systems. They require large aperture kickers due to the large emittance of the muon beam, and there is very little space available in the lattice for these kickers. We can make some initial estimates of the kicker requirements starting from estimates of the beam and lattice parameters. Assume the average momentum of the beam is 200 MeV/c, its normalized transverse emittance is 0.012 m rad, and the beta function at the kicker is 1 m. The kicker should bend the beam by an angle of at least four times the rms divergence of the beam, and should have a half aperture of at least three times the rms beam size. This leads to a bend of at least 300 mrad, requiring an integrated kicker field of at least 0.22 T m, and an aperture of at least 45 cm. These parameters make it clear that a compact ionization cooling ring will not be possible without the development of powerful, large aperture kicker magnets. Grant applications have been sought through the small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR) programs from U.S. Department of Energy in FY 2014 [16] to further this kicker development.

In this paper, we first describe the injection/extraction requirements of our four-sided ring. Sec. 2 estimates the parameters for the injection system into the 6D “Garren” ring cooler. Sec. 3 presents some

our simulations of the injection/extraction system. In Sec. 4, we next discuss a snake cooler, which is an open cooling channel using a lattice cell identical to our ring cooler, but bending in alternate directions for each cell, thereby avoiding injection and extraction altogether. We conclude with a summary in Sec. 5.

2. Estimate of the parameters for the injection into 6D “Garren” ring cooler

As shown in Fig. 2, we calculate the offset of the injected beam and the kick angle needed 90 degrees away in betatron phase to make the beam follow the central orbit. The design in [14] has a beam with an average momentum of 220 MeV/c, a normalized emittance of 1.2 cm, and a beta function at the injection point of 1.2 m. In Table 1 we list the estimated the kicker parameters required to inject this beam while maintaining a 3 sigma acceptance.

Figure 2: Schematic diagram for estimation of the kicker system.

Table 1: The parameters of the kicker system for a 3 sigma acceptance.

Name	Unit	Value
Brho	Tm	0.73
Emit	mm	6.0
Maximum beam amplitude	m	0.25
Injected beam centroid offset	m	0.51
Integrated kicker field	Tm	0.31
Length	m	0.8
Kick angle	rad	0.42
Flux	Wb	0.61

Current	kA	52
Voltage	kV	400

3. SIMULATION OF INJECTION THROUGH THE FLUX PIPE

Our simulation for a 6D “Garren” ring cooler shows that the injected beam has to go through one or more solenoids before it can be merged into the circulating orbit. We must insert a device to create a field-free path for the beam inside of those solenoids [14]. In the 1970s, SLAC built a superconducting flux exclusion pipe that created field-free path through a transverse magnetic field of 1.5 T [17]. In our injection system, we use such a superconducting flux exclusion pipe along with two or more induction kickers [18] to merge the beam into the ring.

First, we study the behavior of a single muon in the long straight section of our four-sided ring for extraction [14]. The end fields of the solenoids had a significant effect on the incoming or outgoing beam, so we increased the solenoid lengths from 0.25 m to 0.5 m to reduce this effect. As shown in Fig. 3, a single kicker (K1) is not sufficient to separate the injected beam from the circulating beam in the ring. Therefore we add a second kicker (K2) to obtain necessary separation, at which point we can insert a superconducting flux pipe. This tube will shield the magnetic field from Sol2 and create a field-free path through the Sol2 magnetic field.

Figure 3: Layout of the injection system (K1, K2 and flux exclusion tube are required for injection) (top) and single particle simulation (bottom). Injection is from right to left in the diagram, though particles are tracked in reverse.

Figure 4: Simulation showing the full beam for injection/extraction at the end of K2 (x-y plot).

Figure 5: r - z plot of the portion of the beam with sufficient separation between the injected and circulating beams, containing 85% of the particles.

Figure 6: Portion of the beam with sufficient separation between the injected and circulating beams, containing 85% of the particles, in coordinate space at the end of K2.

Second, we simulate the extraction of a beam distribution. This beam comes from our previous 6D cooling study, and has a normalized horizontal emittance of 1.26 cm and vertical emittance of 1.48 cm. Our simulation (see Fig.4) shows that with the entire beam, we can't obtain sufficient separation between the extracted beam and circulating orbit at the point where the flux exclusion pipe begins (just the front of Sol2, at $z = 2.1166$ m). We found that particles with high horizontal momentum were the most

problematic. By limiting the maximum of horizontal momentum to 0.03 GeV/c, find that we can achieve sufficient separation between the extracted and circulating beams, permitting the insertion of the flux exclusion pipe, while keeping 85% of the particles in the distribution (see Figs. 5 and 6). In addition, we found the field of the first kicker (K1) can be neither too high nor too low. If too low, the deflection is not enough for separation in the following straight section. If too high, the solenoids will over-focus the beam, causing the beam to be headed toward, and not away from, the beam axis in the following straight section. Our best values of the K1 and K2 fields were around 0.26 T and 0.55T, respectively. The required aperture of kicker magnet K2 is as high as 60 cm. Furthermore, we found a solenoid will rotate the median plane and give the beam a tilt, so the r-z plot in Fig. 5 doesn't reflect the real beam separation between the injected/extracted beam and closed orbit at $z = 2.1166$ m; an x-y plot must be used to check if the beam is separated in space (see Fig. 6, which demonstrates that we have sufficient separation with fields of 0.26 T in K1 and 0.55 T in K2).

4. Beam Dynamics in the 6D “Garren” Ring Cooler and Snake Cooler

By alternating the polarity of the dipole fields from one arc to the next, we can convert the lattice of a “Garren” ring cooler to one for a single-pass snake-like device. We call this snake-like shape lattice (see Fig. 7) a 6D “Garren” snake cooler. In this paper, we will compute the 6D cooling performance of the snake cooler, and compare it to that of the corresponding ring cooler.

Figure 7. Schematic drawing of a 6D “Garren” snake cooler.

Figure 8. Beta function and dispersion of a ring quadrant of the 6D “Garren” ring cooler or one-fourth of one period of the 6D “Garren” snake cooler.

As shown in Fig. 8, the basic cell structure of the 6D “Garren” ring cooler or snake cooler consists of an arc and a straight section. Because the arc is achromatic at a particular reference energy, it allows the cell to be used in a closed ring or in an open single-pass configuration, and even to switch between the two. We envision a series of rings connected by snakes for cooling from large to small emittances.

We perform tracking simulations using ICOOL [18]. Liquid hydrogen (LH_2) wedge absorbers are inserted into a region with low β and high dispersion for cooling the beam. Each LH_2 wedge absorber has a length of 19.5 cm along the 220 MeV/c closed orbit. The energy loss in liquid hydrogen is 0.303 MeV/cm and the total angle of each wedge is 23° . Four 201.25 MHz accelerating cavities (RF) are placed in the superperiod. Each cavity has a maximal axial accelerating gradient of 15 MV/m and the RF phase is set at 30° . The RF cavities restore the energy of the muon beam that is lost in the LH_2 absorbers. Evolution of the beam parameters in the cooling process during 30 turns of the ring cooler [14] and 30 periods of the snake cooler are shown in Figs. 9 and 10. The initial and final beam parameters for the 6D cooling are given in Table 2. Compared to 15 turns in the ring cooler, 15 periods of the 6D snake cooler

have more emittance reduction in the horizontal, less emittance reduction in the longitudinal plane, and lower muons survival.

Figure 9. Beam emittance as a function of turn/period number for a 6D “Garren” ring/snake cooler.

Figure 10. Beam transmission as a function of turn/period for a 6D “Garren” ring/snake cooler.

Figure 11 shows the merit factor vs. the number of turns or periods for both the “Garren” ring cooler and snake cooler. As defined in [7], this factor is the ratio of the initial product of the horizontal, vertical, and longitudinal emittances to the final value of that product, multiplied by the fraction of the muons that survive. We can see the “Garren” snake cooler is comparable with the “Garren” ring cooler in 6D cooling performance for the first 15 turns/periods.

Figure 11. Merit factor [8] with muon decay for the 6D “Garren” ring cooler and snake cooler.

Table 2 Beam parameters vs. number of turns (or periods) in 6D “Garren” ring cooler and snake cooler

	Ring cooler		Snake cooler	
Number of turns	0	15	0	15
Normalized horizontal emittance (cm)	1.26	0.51	1.19	0.38
Normalized vertical emittance (cm)	1.48	0.36	1.57	0.34
Normalized longitudinal emittance (cm)	2.32	0.81	2.04	0.91
Transmission (%) w/o decay	100	65.9	100	58.6
Transmission (%) with decay	100	41.3	100	36.3

5. Conclusions

We have proposed an injection/extraction scheme using two kickers and a superconducting flux exclusion tube for our 6D “Garren” ring cooler. Sufficient separation can be created between the circulating and injected/extracted beams at the entrance to the flux exclusion pipe, but only if 15% of the flux is lost. To achieve the required separation, the kickers must have fields of 0.26 and 0.55 T, and the latter kicker requires an aperture of approximately 60 cm. The large aperture and high strength kickers required here are technically challenging and grant applications for the research and development of large aperture kickers for muon cooling rings have been sought through the SBIR/STTR programs of U.S. Department of Energy [16]. To avoid the serious problems with injection and extraction of large emittance beams, which require technically advanced kickers, we can use a snake instead of a ring cooler. Our preliminary study of beam dynamics of an achromatic 6D “Garren” snake cooler using solenoids and dipoles as lattice elements demonstrate that the cooling performance in 6 phase dimensions is similar to that of our 6D “Garren” ring cooler.

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