A TAPERED SIX-DIMENSIONAL COOLING LATTICE FOR A MUON COLLIDER *

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Abstract

Designs for Neutrino Factories and Muon Colliders use ionization cooling to reduce the emittance of the muon beam prior to acceleration. Here the performance of a tapered dispersive ring shaped channel that simultaneously reduces all six phase space dimensions is numerically examined. It is shown that by progressively modifying key lattice parameters such as the ring radius, rf frequency and coil strength a muon beam with a micron-scale transverse rms emittance can be delivered, thus, making this channel suitable for a Muon Collider. Detailed tracking studies using this tapered approach are presented.

INTRODUCTION

Muon colliders allow the high energy study of point-like collisions of leptons without some of the difficulties associated with high energy electrons, such as the synchrotron radiation that requires their acceleration to be essentially linear and, for this reason, long and costly [1]. A key technical challenge in the development of a Muon Collider is that the phase space of the beam that comes from pion decay greatly exceeds the acceptance of downstream accelerators system. Therefore, a cooling channel is required. Given the short life time of a muon particle , ionization cooling is the only practical method that can be realized [2].

In a straight line, ionization cooling reduces only the transverse emittance of the beam because the total momentum including the transverse is reduced when the beam passes through material but when the momentum is restored in an rf cavity the transverse momentum is left unchanged and thus reduced from its value before the absorber. Although this scheme is suitable for a Neutrino Factory [3], a Muon Collider or a Higgs factory demands reduction in the longitudinal emittance as well [1].

Over the past decade several progresses have been made in the design and simulation of 6D cooling rings [4] based on emittance exchange. This is generally accomplished by using a wedge shaped absorber in a region with no dispersion. Particles with higher energies will pass through more material than particles with lower energy as a result of dispersion, eventually leading to reduction of both longitudinal and transverse emittance. Such rings have been shown [5] to provide an impressive to two order magnitude reduction of the normalized 6D phase-space volume with a transmission well above 50%. While most studies have been focused on the pre-merging regime of a Muon Coolider where modest transverse cooling to 1.5 mm is required, little detailed simulation has been done for the post-merging regime where a final 0.24 mm rms normalized emittance is required [6].

In this paper we design and simulate a post merging cooling scheme for a Muon Collider. We show that by applying a novel taper scheme in which parameters of the structure change from turn to turn based on the emittance reduction rate and transmission, we can further cool both longitudinal and perpendicular emittance by an order of magnitude with reasonable transmission.

DESIGN PARAMETERS

The main issue with a Guggenheim channel of a fixed radius, cell length, and frequency is its gradual loss of cooling efficiency. Therefore, to keep the cooling process going we propose a tapered channel in which various parameters change in order to avoid reaching the equilibrium. In this scheme parameters such as cell length and radius of curvature progressively change from turn to turn based on the emittance reduction rate and transmission. Earlier studies have shown [7] that such a concept improves performance. In addition, with this approach the same emittance can be obtained in much shorter scale.

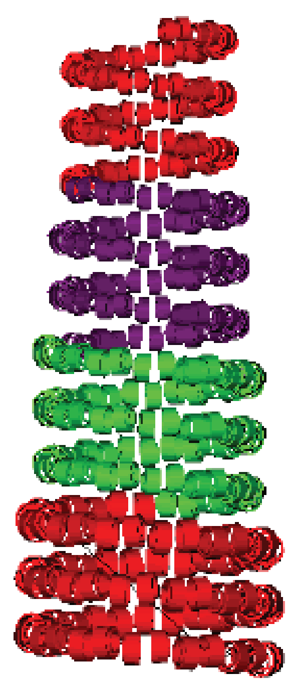

Figure 1: Conceptual design of the first 12 stages of the proposed tapered cooling channel. Different colours label regions of different frequency.

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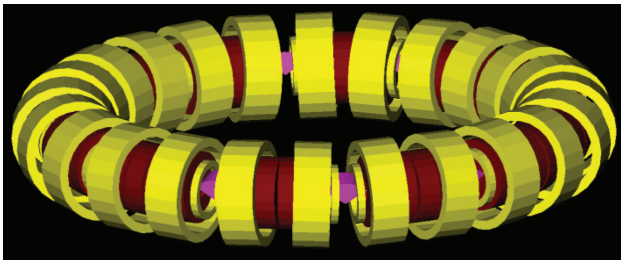

Figure 2: Close view of one of the rings assumed in our computational model. Note that each cell has 4 coils and two of them are raped around the cavities.

The first 12 stages of our proposed cooling system are shown in Fig.1. Each stage consists of a ring with 12 identical cells like the one shown in Fig.2. The coils (yellow) are not evenly spaced; those on either side of the absorber are closer in order to increase the focusing at the wedge absorber (magenta). In order to produce dispersion, they are tilted by 2-3^0. The absorber is wedge shaped so that higher momentum particles go through the thicker part. Each lattice cell contains the same number of rf cavities (dark red) which, depending on the stage, can be 4, 5, or 6.

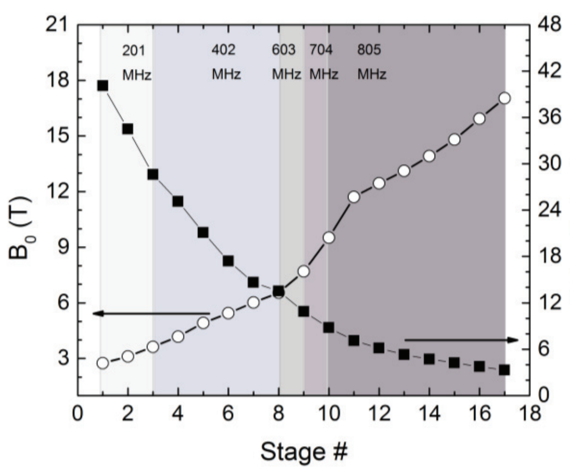

Figure 3: Design value of beta function (right); maximum on-axis field for the solenoid (left). Corresponding rf cavity frequencies are also shown.

The radius of the ring progressively decreases since the cell length becomes smaller and smaller. This configuration has shown to increase dispersion and to reduce the beta function [3]. In the initial stage, when the transverse emittance is large, the focusing must be relatively weak to avoid excessive angular distributions. But the weak focusing implies that the equilibrium emittance is also relatively large so that the transverse cooling weakens as the limit is approached. To avoid this, this stage is terminated and we couple into the next stage that has stronger focusing. This sequence of stages with ever stronger focusing is termed tapering. The beta function and the axial peak field at different stages is shown in Fig. 3. The beta function varies from 40.1 cm to 3.3 cm while the on-axis magnetic field increases from 2.7 T to 17.0 T. The RF frequency increased from 201 MHz to 805 MHz. Ideally, the cooling channel should be tapered with a continuously varying frequency. However, for practical implementation we keep the number of different frequencies as small as possible. As we will illustrate in the next section, 17 stages are enough to achieve the desired emittance for a Muon Collider. Detailed lattice parameters are listed in Table 1.

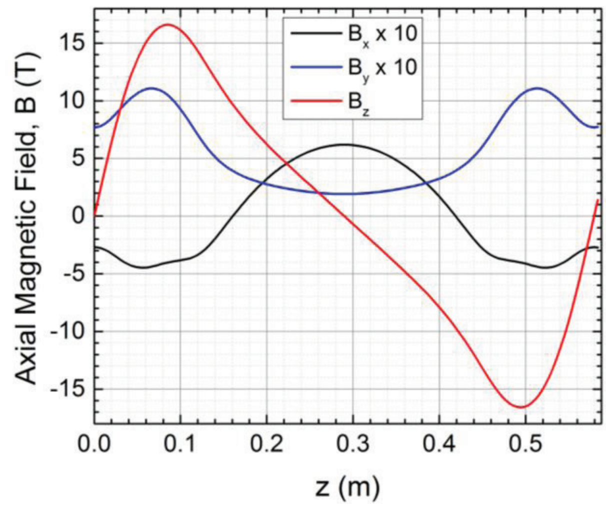

Figure 4: Axial magnetic field for stage 17.

Figure 4 displays the horizontal, vertical and longitudinal axial fields for the last cooling stage (Stage 17). This is the stage with the strongest magnetic field requirement. The longitudinal magnetic field has an approximately sinusoidal dependence on position with a peak magnitude 17 T on axis and 18.4 T in the coil. The solenoids are tilted by 2.81^0 to generate a vertical 1.6 T dipole field on axis. The lattice transmits particles in the momentum band from 173 to 242 MeV/c.

SIMULATION DETAILS

Simulations of the channel performance where done using the ICOOL code [8] with 100,000 particles. We generated 3D cylindrical field maps for each of the stages by superimposing the fields from all solenoids in the cell and its neighbour cells. Closed orbits were found for each of the stages by tracking a reference particle using the field maps. The rf cavities were modelled using cylindrical pillboxes running in the TM010 mode. Since we accelerate muons, the cavities are enclosed with metallic end windows in order to produce the maximum electric field on axis for a given amount of rf power (maximum shunt impedance). The metal for this study was Beryllium. The wedge material was liquid hydrogen and placed in dispersive regions in order to decrease the momentum spread in the beam. The absorbers are enclosed in AlBeMet windows ranging from 500 μm (Stage 1) to 10 μm (Stage 17). The windows are planar and located axially on both sides of the wedge. In reality the window shape will conform to the absorber and the effect on the beam of scattering in the window should be lessened.

Table 1: Lattice Parameters of our Proposed Tapered Cooling Channel

Stage	Cell length [m]	RF Freq. [MHz]	RF Grad. [MV/m]	RF #	RF Length [cm]	Coil Disp. [cm]	Coil Tilt [deg.]	Wedge angle [deg.]
1	2.75	201	15.48	5	37.6	12.5	3.25	110
2	2.36	201	15.48	4	40.0	10.3	2.59	110
3	2.02	201	15.48	4	34.3	10.3	2.03	110
4	1.73	402	15.48	6	19.6	5.3	3.90	99
5	1.49	402	15.48	5	20.1	6.4	2.62	104
6	1.38	402	15.48	5	18.64	6.4	2.62	111.3
7	1.27	402	16.50	6	14.36	6.4	1.91	118
8	1.15	402	16.50	5	15.65	6.4	1.93	120
9	0.995	603	19.50	5	13.49	4.1	2.46	120
10	0.806	704	23.0	5	9.67	2.6	2.46	110
11	0.688	805	23.6	4	8.59	1.9	2.79	120
12	0.688	805	23.6	4	8.59	1.5	2.95	120
13	0.688	805	23.6	4	8.59	1.4	3.28	120
14	0.628	805	23.6	4	8.59	1.2	2.87	120
15	0.608	805	23.6	4	8.59	1.1	2.89	120
16	0.588	805	23.6	4	8.59	1.0	2.97	120
17	0.588	805	24.1	4	8.59	0.9	2.81	120

The transverse, longitudinal emittance and transmission including muon decays as a function of distance along stages 1 to 17 are shown in Fig. 5. The simulation produced a transverse emittance of 0.28 mm and a longitudinal emittance equal to 2 mm, which is closed to the desired values for a Muon Collider. The quoted values are normalized rms.

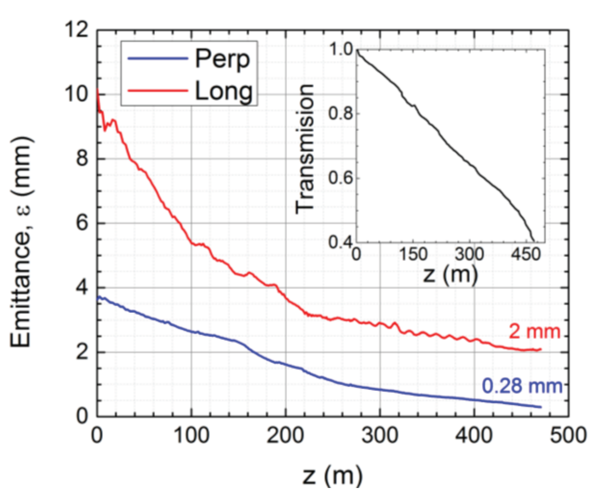

Figure 5: Longitudinal (red), transverse (blue) emittances and transmission as a function of distance along the channel. The final values of the emittances are also shown.

SUMMARY

Cooling large emittance muon beams is an essential step for a Muon Collider. Using a ring offers likely economic advantages in reusing expensive magnets, rf cavities, and absorbers. A ring also provides a natural mechanism for obtaining longitudinal cooling through emittance exchange. As this study demonstrated, by performing tapering the desired emittances for a muon collider can be obtained with a transmission above 40%. The next step would be to improve the matching between individual stages, which will aid in boosting the performance. Thanks to P. Snopok, S. Berg for useful discussions.

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