A COMPACT 6D MUON COOLING RING

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Abstract

We discuss a conceptual design for a compact muon cooling system based on a weak-focusing ring loaded with high-pressure hydrogen gas. We demonstrate that such a ring will be capable of cooling a circulating muon beam in each of the three spatial dimensions so that 6D cooling of the muon beam phase space can be achieved.

INTRODUCTION

Intense proton sources are being planned as part of a worldwide demand for the development of new intense secondary particle beams. As part of this effort, much research and development has been devoted to creating concepts for the production of intense muon beams[1],[2]. In the case of muons, it may not be sufficient to merely develop an intense source. A method to efficiently capture and reduce the phase space of the beam is required. This is particularly true for such advanced concepts as muon colliders[3] or, to some lesser degree, a neutrino factory based on directing neutrino beams which are generated as decay products of muons circulating in a storage ring[4]. We report here on recent work which could provide a useful technique toward reducing the 6D phase space of a captured muon beam. Our approach utilizes compact rings consisting of weakly focusing dipole magnets along with the inclusion of high-pressure hydrogen gas which serves as the energy-loss absorber and rf cavities which restore the energy of the muon beam.

The ring consists of a number of identical sector-shaped, zero-gradient magnets. Transverse focusing is provided by the magnet edges. The resistance of the gas on the particles and acceleration by the rf cavities provide ionization cooling[5]. The ring has positive dispersion, which means that higher momentum particles have longer paths around the ring (Fig. 1), and thus lose more energy per turn, than the low energy particles do. Consequently, cooling takes place in the longitudinal as well as the transverse dimensions.

Studies of rf cavities operating while filled with high-pressure gases, including hydrogen, are on going and encouraging [6]. We chose hydrogen as the loaded gas in order to minimize disruption of the emittance of the circulating muon beam due to multiple scattering and energy straggling.

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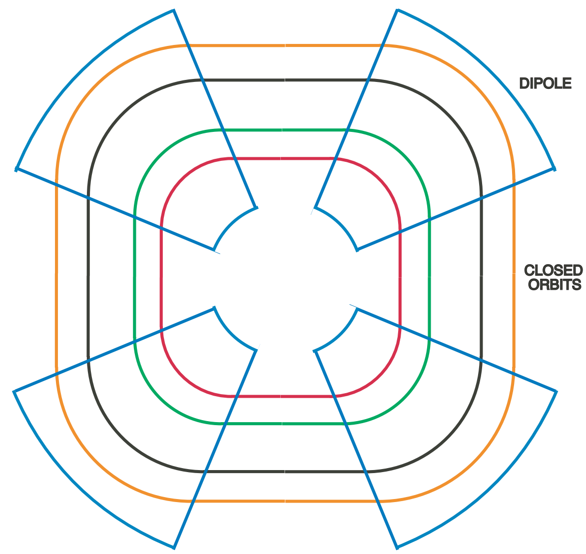

Figure 1: Closed orbits for various beam momenta. Note that positive dispersion results in greater path lengths for higher energy particles.

BEAM DYNAMICS SIMULATIONS

In general, our approach has been to obtain linear lattice solutions using the code SYNCH [7] and then transferring the lattice parameters to the code ICOOL [8] where the effects of energy loss in absorbers and the subsequent energy recovery in rf cavities can be modeled. Details of our approach to simulations have been previous published [9],[10].

In order to insure cooling in the transverse dimensions, we must place the energy reducing absorbing gas in regions of low beta. Since we intend to fill the entire ring with absorbing gas, this requires us to develop lattices with low beta functions throughout the cell. In our designs, the beam beta functions are always less that 1m.

We have simulated several lattices in search of an optimal layout, which could yield substantial cooling in all three spatial dimensions. We define as a figure the merit the quantity

$$Merit = Transmission \times \frac{\epsilon_{x_i}}{\epsilon_{x_f}} \frac{\epsilon_{y_i}}{\epsilon_{y_f}} \frac{\epsilon_{y_i}}{\epsilon_{y_f}} \qquad (1)$$

We find that excellent performances, as measured by this merit factor, can be achieved[11]. Merit factors as high as

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400 have been simulated. These solutions require aggressive parameters such as high field dipoles (5T), high operating pressures (100 bar), and high rf accelerating gradients (45 MV/m).

In order to build a low cost cooling ring while still achieving a measurable reduction in the 6D emittance, we confine ourselves to a peak dipole bending field of 1.8T, a peak RF gradient of ≤15MV/m and a peak gas pressure of 10 atmospheres (at 77 deg K). With these restricted parameters we have still been able to achieve a merit factor of 20 for the hard-edge lattice solutions. In Fig. 2, we show the results of the emittance reduction in each of the three dimensions of the 4-dipole ring.

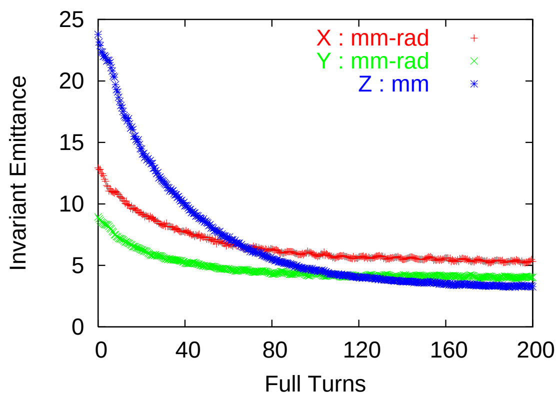

Figure 2: Invariant emittances for each dimension as a function of full turns in the ring.

SOFT-EDGE SOLUTIONS

We have further explored lattice solutions with soft-edge Maxwellian magnetic fields. Magnet design and field computations are computed using the finite element code TOSCA[12].

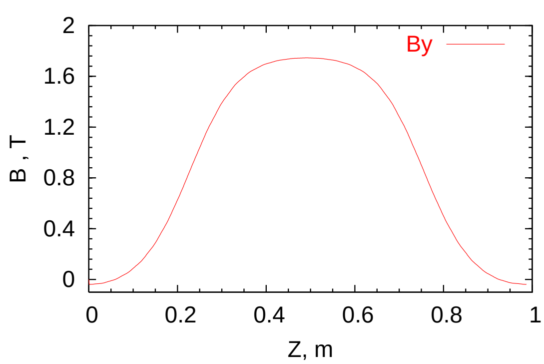

Figure 3: The B_y component of the calculated dipole field.

A single magnet is modeled and the presence of the other magnets is taken into account with the boundary conditions. TOSCA provides the ability to track particles within the program. By launching muons at various start positions on a symmetry plane, a closed orbit can be found. Using a mid-plane field map from TOSCA, the field and its harmonics can be calculated along the closed orbit path. We show in Fig. 3, the longitudinal profile of the dipole field as seen along the closed orbit path of a circulating reference particle with a momentum of 172 MeV/c. Details for this procedure can be found in Ref.[13].

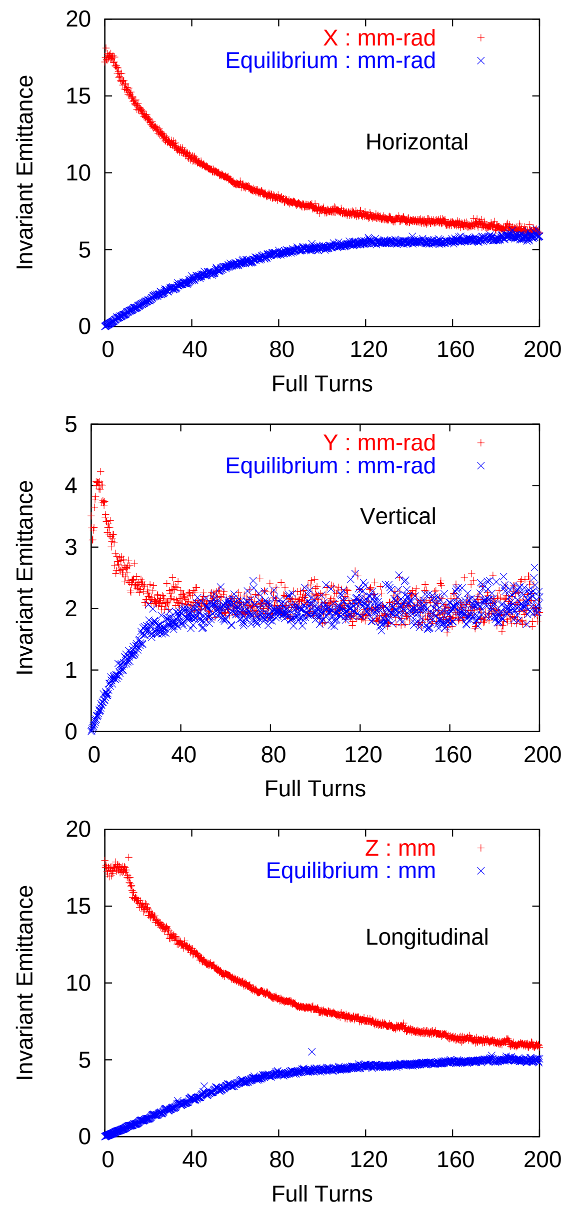

Figure 4: Evolution of invariant emittances for warm and cold muon beams.

The ICOOL simulation program can accept the field as a Fourier decomposition of each of these field harmonics along the closed orbit path. The field can be reconstructed by an expansion in variables of the local coordinate system defined by the closed orbit path.

The input beam admittance for each case is determined by first launching a broad spectrum of particles. This broad spectrum beam is allowed to circulate without the influences of multiple Coulomb scattering and energy straggling. Those particles which survive multiple turns are then re-injected with their initial start values and stochastic processes are switched on.

Fig. 4 shows the evolution of the invariant emittances for each dimension for the case of case of operating with a gas pressure of 10 atmospheres at 77^0 K (40 atmospheres at room temperature) and a peak axial rf voltage of 10MV/m. The rf frequency is 201.25 MHz. We follow with interest the development elsewhere of 201.25 MHz pillbox rf cavities[14] for the acceleration of muon beams.

INJECTION/EJECTION

For purposes of demonstration, we intend to inject muons into the ring as single particles rather than as a bunch. Our strategy will be to exploit the dE/dx energy losses of the loaded high-pressure hydrogen gas which will cause the radius of the circulating particles to be reduced. We will introduce additional absorbers at a high radius which will cause the radius of each particle orbit to be sufficiently reduced so that the supplemental absorbers will not be traversed on subsequent orbits. We note that ejection is not necessary for a proof-of-principle machine but will none-the-less be easier than the the injection problem due to the fact that the 6D phase space of the beam will be greatly reduced.

CONCLUSION

We have shown that a proof-of-principle cooling ring for muon beams can be realized with modest operational parameters. We show in Fig. 5 a schematic layout of our proposed ring.

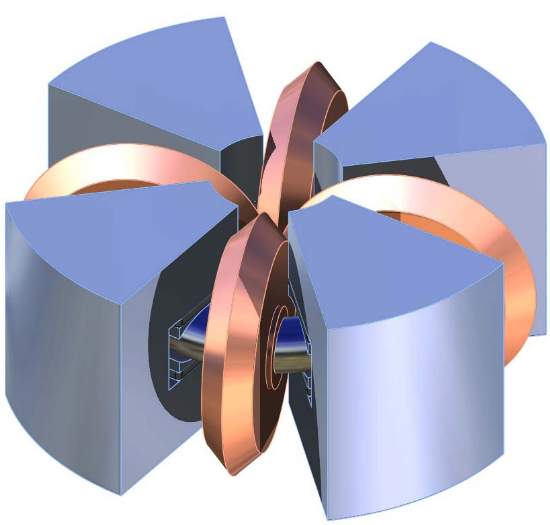

Figure 5: Layout of the cooling ring. The diameter of the cylindrical 201.25 MHz rf cavities is 1.3m

ACKNOWLEDGMENTS

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