RECENT PROGRESS IN SIX-DIMENSIONAL IONIZATION COOLING TECHNIQUES FOR MUON-BASED MACHINES[*]

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Abstract

Ionization cooling is an essential component of a neutrino factory or a muon collider. Ionization cooling in the transverse dimensions is reasonably straightforward, and has been incorporated in published neutrino factory studies. Achieving cooling in the longitudinal dimensions is more difficult, but has the potential to greatly improve the performance of neutrino factories, and is essential to muon colliders. Much progress has recently been made in describing ring cooling lattices which achieve cooling in all three phase space planes, and in the design of the required, but difficult, injection systems. Ring cooling lattices also have the potential of significantly reduced cost compared to single-pass cooling systems with comparable performance. We will present some recent lattice designs, describing their theory, features, and performance, including injection and extraction systems.

1 INTRODUCTION

Because of the way muons are produced, they inherently begin life in a beam with a very large phase space volume. Cooling is therefore needed to transport the beam through a reasonable accelerator lattice. For a muon collider, small transverse emittances are needed to achieve high luminosity. In addition, a small longitudinal emittance is needed both to keep the bunch length small and minimize the hourglass effect, and to keep the beam's energy spread small to achieve good energy resolution (especially important for a Higgs factory). For a neutrino factory, the cost of the acceleration systems and the storage ring increase rapidly with increasing acceptance, so cooling is needed to maximize the number of particles which are within the acceptance of those systems. Longitudinal cooling is not as critical for a neutrino factory, but could potentially improve performance since cooling performance of a straight cooling channel is in many cases limited by the fact that particles fall out of the RF bucket [1]. Furthermore, there is an uncertainty in the neutrino flux at the detector due to the finite energy spread and transverse emittance in the beam (and the inability to precisely measure those quantities) [2], and for certain experiments, this uncertainty could be the dominant one. Reducing transverse emittances and the energy spread in the beam will reduce these uncertainties.

Transverse cooling is achieved by passing a muon beam through an absorber and then accelerating the beam, restoring the average energy lost. The absorber reduces the total momentum parallel to its direction of travel, while the acceleration increases the momentum in the longitudinal direction only, thus reducing the transverse momentum [3]. In the longitudinal plane, there is a potential cooling effect from the energy dependence of the energy loss in the material [3], but in most practical cooling channels that energy dependence has the wrong sign and gives a slight amount of heating (in any case, the longitudinal cooling effect is small). To achieve cooling in all dimensions, not just the transverse, requires some way to make the effective transverse cooling affect the third (longitudinal) degree of freedom.

The earliest solution proposed to this problem is known as "emittance exchange." One cools transversely in a relatively long cooling channel, then inserts a wedge absorber in a region with dispersion, reducing the longitudinal emittance while increasing the transverse emittance [3]. This scheme has problems working in practice. It has been suggested that this was due to large correlations being introduced into the distribution, problems with time-of-flight control in the long emittance exchange section, and matching problems [4, 5].

Recently a great deal of progress has been made by considering systems where the emittance exchange happens much more frequently: essentially in every lattice cell. Two types of systems have been proposed: one involves separating the functions of cooling and emittance exchange in the lattice, another involves adding a bending field to a standard straight cooling channel. The latter technique has dispersion in the RF cavities, which of course introduces longitudinal-transverse coupling. But there is necessarily a longitudinal-transverse coupling in these systems: all three matched phase ellipses of a lattice cell must have a component in the transverse momentum direction at the absorbers to achieve cooling [6]. We describe the characteristics of these these systems here, referring the reader to the references for more details.

2 COOLING RINGS

The systems described here are all rings. They could, with a small amount of modification, be built as spirals instead, but the advantage of a ring is its relatively low cost. However, there is a disadvantage: the difficulty of injection and extraction. Ideas for this will be addressed at the end of this paper. These rings are characterized by a so-called

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[*] Work Supported by Department of Energy Contracts DE–AC02–98CH10886, DE–AC02–76CH03000, W–31–109–ENG–38.

"merit factor" which is the ring's transmission including decay multiplied by the ratio of the initial 6-D emittance to the final 6-D emittance. This gives the increase in the 6-D phase space density at the core of the distribution. One must also look at the distribution of that cooling between longitudinal and transverse planes, as well as the final emittances which are achieved.

2.1 Separated Function Rings [7, 8]

These rings are solenoid focused and separate the functions of cooling and emittance exchange. A dispersion-free straight contains accelerating cavities and an absorber, which generate transverse cooling. These straights are interleaved with a solenoid focused two-bend achromat with a wedge absorber at its center.

One of these rings, with a circumference of 37 m and using 200 MHz RF, designed for a 225 MeV/c beam, achieves a merit factor of 38, including a factor of 2.4 decrease in longitudinal emittance [8]. The transverse normalized emittances are reduced to 2.1 mm, and the final longitudinal normalized emittance is 6.3 mm. It appears that the merit factor improves somewhat if a large beam is injected into the system.

On removing the cavities and absorbers from one straight section to make room for injection and extraction hardware, however, the performance of the system decreased dramatically: the merit factor was only 3.9. This is because the removal of such a large fraction of the RF allows the bunch length to increase too much, preventing the bunch from being captured completely in the subsequent RF cavities.

Another application of this technique is to use low-frequency RF (15 MHz) in a 67 m circumference ring to capture a 190 MeV/c bunch with a very large longitudinal emittance and reduce that longitudinal emittance to the point where it can be captured in a higher frequency RF system [7]. Instead of being tuned to achieve a balance between transverse and longitudinal cooling, this system is designed to do most of its cooling longitudinally. The system has a merit factor of 19, reducing the longitudinal emittance by a factor of 16, and modestly reducing the transverse emittances as well.

The performance of the 200 MHz ring has been independently verified by at least two different simulations, but both of those simulations are using somewhat idealized fields (some end effects have not been included). More realistic field profiles must be considered, and work is progressing on that [9].

2.2 RFOFO-Based Ring Cooler [10]

Another approach is to begin with one of the relatively compact straight cooling channels, add some bending, and replace parallel-faced absorbers with wedge-shaped ones. The form of this that has been most completely studied is based on a so-called RFOFO cooling lattice [10]. A single 2.75 m cell contains an RF cavity and a wedge absorber. Focusing is provided by solenoids which generate longitudinal fields that vanish in the middle of the absorber and the middle of the RF cavity, and changes signs on opposite sides of the zeros. A bending field is created by tilting the solenoids about a horizontal axis perpendicular to the solenoid axis. Smaller bending fields give a better transverse acceptance, so a 0.125 T average bend field was chosen. For a 200 MeV/c beam, this gives a ring with a 33 m circumference.

Simulating this system resulted in a merit factor of 99 with a longitudinal emittance reduction of a factor of 5.9. The final normalized emittances are about 1.7 mm in the transverse dimensions and 6.6 mm in the longitudinal dimension. The fields used in these simulations are believed to be realistic, at least to a modest order in the transverse displacements. Removing one RF cavity and the absorbers that surround it reduces the merit factor to 55. This reduction is less substantial than for Balbekov's ring most likely because of the more compact lattice cells and the smaller fraction of the ring's circumference that has been removed. One could hope to improve this even further with matching, especially in the longitudinal direction.

2.3 Quadrupole Ring Cooler [11]

Another approach to a cooling ring is to use quadrupoles instead of solenoids. The appeal of a quadrupole lattice is the much larger body of expertise in lattice design, the expectation that such a lattice may be simpler to construct, greater ease of injection and extraction, and the possibility of using superconducting RF in such a ring. The challenge of such a system is that since quadrupoles focus in only one plane, a longer cell and/or larger apertures may be required to achieve a sufficiently low beta function at the absorber.

A quadrupole ring cooler lattice has been constructed (an earlier version of this lattice was described in [11]). The lattice is designed for a 500 MeV/c beam, is 165 m in circumference, and uses 200 MHz RF. This lattice combines both the cooling and emittance exchange functions into a single wedge that is in a location which is both a minimum for both beta functions and a maximum of the dispersion. Dispersion is removed at the RF cavities. This lattice is only able to achieve a merit factor of around 6.4, cooling in the longitudinal direction by a factor of 4.2, with an equilibrium normalized emittances of 3.8 mm (horizontal), 1.6 mm (vertical), and 8 mm (longitudinal).

The reason for the relatively poor performance of this lattice is its limited acceptance: it can't start with a very large beam. This is related to the relatively large values that the beta function rises to. To remedy this, one could think about making the lattice cell more compact and foregoing dispersion suppression in the RF.

3 COMMON ISSUES

There are several issues common to all ring designs which must be addressed.

3.1 Injection and Extraction

The modest length of these systems gives significant potential for cost savings. The primary difficulty is that one must be able to inject and extract from these rings. The short length of the ring, the short length for the kicker, and the large aperture impose challenging requirements on such a kicker. The stored energy in the kicker is substantial, almost three orders of magnitude above the CERN $\bar{p}$ kicker. Techniques borrowed from induction linac design must be used to make such a kicker. The power supply current and voltage requirements are made more modest by subdividing the induction loops around the aperture as well as along the length of the kicker. But even with this, one example requires 12 drivers with 192 kA and 182 kV each, with a pulse energy of 870 kJ. Such a pulse can potentially be generated using a multi-stage resonant magamp driver.

The above parameters take advantage of the fact that the kicker uses ferrite to concentrate the flux. However, the solenoid fields around the kicker will likely saturate the ferrite, and furthermore, the ferrite may limit the rise time of the kicker. To remedy this, one could instead remove the ferrites and place current loops in a $\cos\theta$ configuration. This would likely more than double the current and pulse energy requirements for the pulse generators.

Another potential method for injection and extraction is to rapidly re-phase some of the RF cavities in the system, so that the energy in the ring is substantially lower (or higher) than the energy at which the beam is injected and extracted [12]. The phase shift required would be substantial, requiring a very low Q for the cavities if done conventionally. Considering the substantial power requirements for the kicker, this is not necessarily unreasonable. This would also require a spreader/recombiner similar to what occurs in a multiple-arc recirculating accelerator.

3.2 Windows

Most of the above designs were done with absorbers consisting entirely of liquid hydrogen (although Balbekov's designs use LiH wedges). However, containment (generally two levels for safety) of liquid hydrogen requires windows of a higher-Z material, resulting in increased multiple scattering. Furthermore, high cavity gradients are often achieved by having beryllium windows within the cavities, giving an additional source of multiple scattering. Finally, safety concerns with using hydrogen often lead one to want to choose another material for the absorbers, such as helium of LiH.

This increased multiple scattering significantly decreases the performance of these cooling rings. For example, for the RFOFO cooling ring, adding one set of thin windows (0.125 mm) reduces the merit factor to 61, and adding thicker windows (0.5 mm) can reduce it to 31. Switching to LiH for the absorbers reduces the merit factor to 19. It may be possible to modify the lattice design under these circumstances to improve these results, but it is unclear to what degree that is possible.

4 THEORETICAL DEVELOPMENTS

Linear theories for 6-D cooling have been developed for quadrupole lattices [13] and solenoid lattices with weak focusing bends that generate dispersion while preserving symmetric focusing [14], both under the assumption that there is no dispersion in the RF cavities. These theories include damping and stochastic effects and can predict both damping rates and equilibrium emittances. While nonlinearities and losses can give significant departures from these predictions, near the equilibrium emittance one expects the linear approximations to be good. These theories should therefore provide useful design tools for cooling lattices.

A useful measure of cooling channel performance is how many particles are lost for a given reduction in emittance. To quantify this, we define

$$Q = \frac{(d\epsilon_6/ds)N}{(dN/ds)\epsilon_6}, \tag{1}$$

where N is the number of particles and ϵ_6 is the product of the three emittances. If Q is constant, then $\epsilon_6/\epsilon_{60} = (N/N_0)^Q$. For rough collider parameters requiring a reduction in emittance by 10^6 and losing only half the particles, this requires $Q \approx 20$. These ring cooling lattices barely achieve this value, and only for a short period (Q drops quickly as one approaches the equilibrium emittance).

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