RECIRCULATING RING FOR AN IONISATION COOLING CHANNEL

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Abstract

In a muon acceleration facility such as a Neutrino Factory or Muon Collider, the muons created from pion decay occupy a large volume of phase space. For a good capture efficiency this phase space should be reduced and this is typically achieved using ionisation cooling channels. These are quite expensive but the cost can be reduced by recirculating muons through the cooling hardware. Recirculating a high emittance beam typical of a Neutrino Factory is very challenging if it is to be achieved without significant losses. I describe a tilted solenoid ring cooler design that not only permits recirculation, but may also enable longitudinal cooling.

COOLING FOR MUON ACCELERATION

In a Neutrino Factory or Muon Collider, pions are created from protons striking a target. The pions then decay to muons. This process is quite inefficient, and results in a muon beam that has a very large emittance. Many schemes have been proposed to improve the capture efficiency of the muon beam and reduce its emittance, either by some manipulation using RF or by beam cooling [1].

Muon cooling schemes use the momentum loss of muons as they travel through some material to reduce beam emittance [2]. Muons lose transverse and longitudinal momentum in material, but RF cavities only replace longitudinal momentum, resulting in a beam with lower emittance. Typically this is performed at energies where ionisation is the dominant energy loss process, and the process is called ionisation cooling. Multiple Coulomb scattering tends to spoil the effect as particles pick up a random divergence that on average tends to heat the beam.

Muon cooling schemes can be divided between those that reduce only transverse emittance and those that reduce both transverse and longitudinal emittance. As described above, ionisation cooling reduces only transverse emittance. In fact, small changes to longitudinal emittance may also be observed; the difference in energy loss between high energy and low energy particles may induce some longitudinal heating or cooling, while stochastic processes in the energy loss may induce longitudinal heating.

Additional emittance reduction may be provided in longitudinal phase space by introducing emittance exchange. Here, dispersion is introduced into the beam so that muons with higher energy travel at larger radii than those at lower energy. Then using wedge-shaped material as the cooling medium induces a shear in energy-position phase space corresponding to transfer of emittance between longitudinal and transverse. In principle, cooling is only in transverse phase space, but by using this emittance exchange technique both longitudinal and transverse emittance is reduced.

In this note, I present a cooling channel in a ring geometry, with transverse focussing and bending provided by tilted solenoids. Tilted solenoids provide high acceptance and tight focussing needed for a cooling channel, while the tilt induces a dipole field that can be used to provide bending. This enables longitudinal cooling and also enables the recirculation of the beam through the cooling equipment reducing the cost of any future facility.

Such an idea has been proposed before and demonstrated to give a very good cooling performance [3], but due to the very compact lattice it was found that it would not be possible to inject or extract the beam. In addition, it is thought that the presence of strong magnetic fields near to the surface of RF cavities may induce breakdown, reducing the maximum operating voltage of the cavity and hence the overall cooling performance [4].

Here I propose a tilted solenoid ring with a less compact geometry. This results in an acceptance that is still relatively high, but avoids some of the problems mentioned previously.

TILTED SOLENOID LATTICE

The geometry of the solenoid lattice, based on a straight cooling channel described previously [5], is shown in Figure 1. In each cell three superconducting coils provide transverse focussing and the central coil is tilted to provide the necessary dipole field. Liquid Hydrogen absorbers at the ends of the cooling cell provide cooling while two sets of four RF cavities provide acceleration. Each cell is 10 m long and the entire ring consists of 24 cells. Adjacent cells have opposite polarity and opposite tilt so that the dipole field is the same but the solenoid field is reversed. This prevents build up of angular momentum in the lattice and enhances the cooling performance.

Closed Orbit

The closed orbit for the lattice relative to a circular orbit is shown in Figure 2. The solenoid field couples x and y resulting in a closed orbit that rotates around the circular axis. The lattice is designed for a central momentum of 273 MeV/c. At lower momenta the cooling effect is greater as the fractional change in momentum is larger per unit length of absorber, whereas at higher momenta losses due to decay are lower, the geometric emittance of the beam is smaller and longitudinal emittance growth is smaller due to the gradient of the Bethe Bloch curve. 273 MeV/c has been cho-

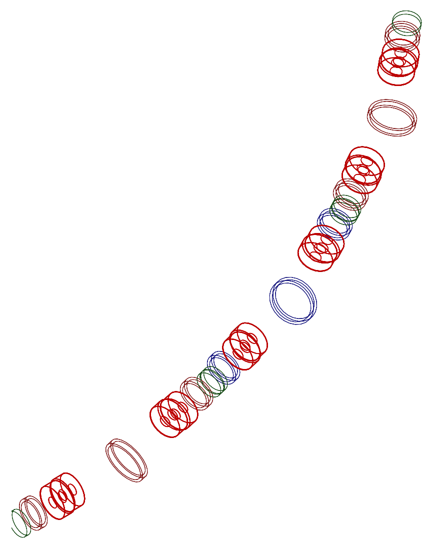

Figure 1: Visualisation of a section of the cooling ring. RF cavities are red, coils of opposite polarities are blue and burgundy, while absorbers are green.

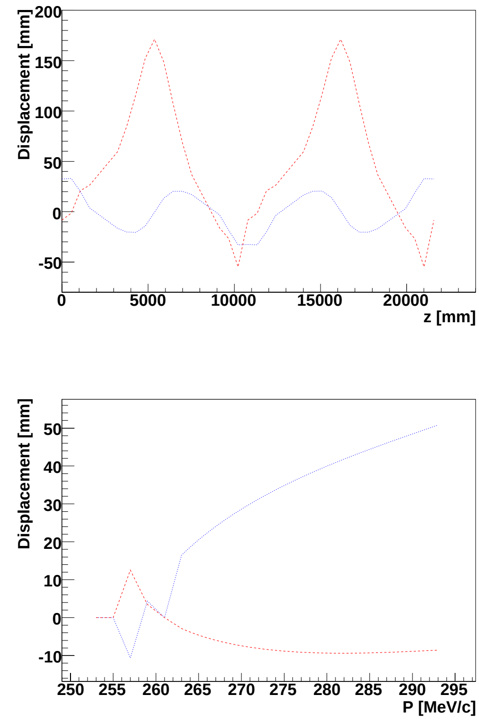

Figure 2: The closed orbit of a cooling cell (top) as a function of path length at 273 MeV/c and (bottom) as a function of reference momentum at the cell ends for (blue, dotted) horizontal displacement and (red, dashed) vertical displacement.

sen as a compromise between the two extremes.

Some optimisation has been performed to improve the momentum acceptance of the lattice. It can be seen in Figure 2 that a closed orbit exists for momenta larger than about 260 MeV/c and lower than about 295 MeV/c. This 35 MeV/c momentum range is a little below the length of the RF bucket, and it may be desirable to perform further optimisations to increase this range.

It should be noted that there is some considerable non-linear effect in the dispersion over such a large energy range. It is hoped that the cooling of the channel offsets any heating due to these factors. In addition, there is non-zero dispersion in the RF cavities, which is expected to couple longitudinal and transverse motions making optical analysis quite challenging.

Optical Function

The on-momentum optical transverse β function is shown in Figure 3. Here cylindrical symmetry has been assumed as in a straight solenoidal lattice. Note, however, that the presence of a dipole field does introduce some significant asymmetry in this focussing.

The lattice has been designed for strong focussing in the absorbers in order to reduce any effect from multiple scattering. The β function has a value of 450 mm in the centre of the absorbers giving a minimum emittance of roughly 2-3 mm for the channel. In addition, shoulders in the β function at the limiting aperture of the RF cavities result in an increased acceptance.

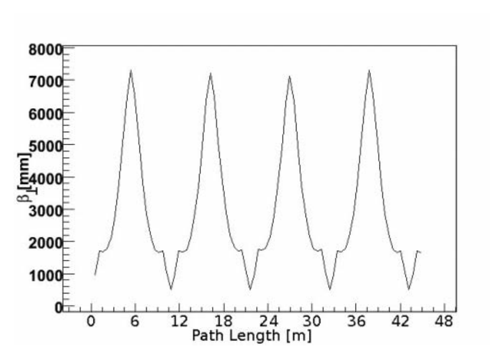

Figure 3: The transverse optical function.

COOLING PERFORMANCE

In this section the cooling performance of the ring is studied. For now only a monochromatic beam is propagated, RF cavities are run in electrostatic mode and cylindrical absorbers are used.

Simulation

The lattice was simulated in the G4MICE simulation code [6]. This provides routines to track particles to arbitrary precision through a wide variety of field maps by integrating the equations of motion. In this case solenoidal fields were simulated using a field map generated from a series of current sheets accurate to about 10^{-3} T. For this study RF cavities were simulated as electrostatic parallel plates, although more detailed models may be used in later studies.

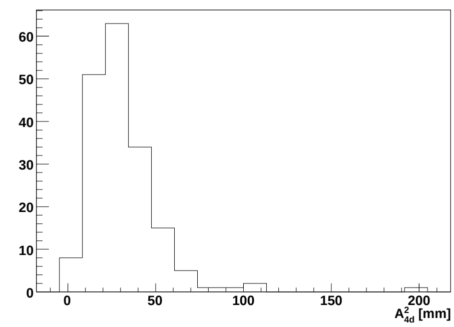

Figure 4: The acceptance of the ring as a function of transverse amplitude.

Absorbers were modelled as cylindrical blocks of Liquid Hydrogen. G4MICE uses the GEANT4 library [7] to provide a detailed model of processes of particles travelling through different materials, including an accurate simulation of multiple Coulomb scattering and ionisation energy loss processes.

Cooling Performance

Ideally, a cooling ring would have a large acceptance, so that relatively high emittance particles are accepted into the ring, and cool quickly to a low emittance. Any cooling effect has to compete with decay losses due to the muon lifetime, which is 2.2 μs in the centre of mass frame.

The acceptance of the ring is shown in Figure 4. Here the initial amplitude of muons that survive a full circumference of the ring is shown. This indicates an acceptance of about 60 mm. The transmission and emittance reduction after a single turn through the ring is shown in Figure 5 for a beam with an initial RMS normalised emittance of 20 mm. It can be seen that the emittance is significantly reduced, although the transmission is relatively low. A lower emittance beam would suffer smaller transmission losses.

CONCLUSIONS

A design for a tilted solenoid cooling ring has been presented. This ring presents several advantages over previous designs as the lattice is much less compact, so that injection and extraction will hopefully be possible and the RF cavities sit in much reduced fields lessening any interference between the fields and the cavity operation. The optics of the ring have been demonstrated and the ring has been shown to cool successfully in transverse phase space. It is hoped that subsequent work will demonstrate full six dimensional cooling.

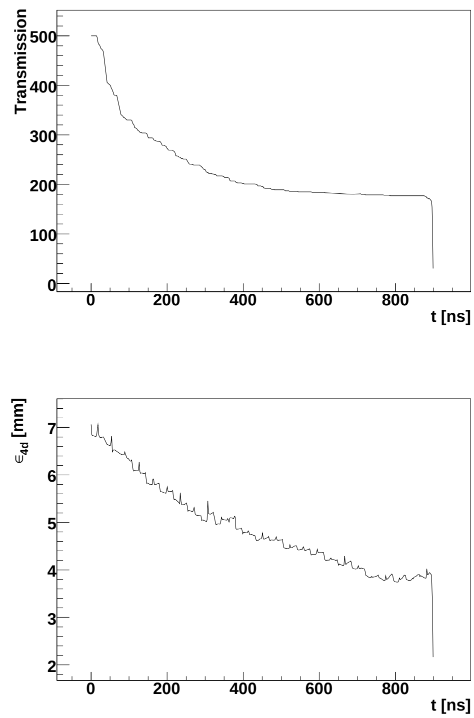

Figure 5: The transmission and normalised emittance of a sample beam as a function of time of flight. A full circumference takes about 850 ns.

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