ALTERNATIVE MUON COOLING OPTIONS BASED ON PARTICLE-MATTER-INTERACTION FOR A NEUTRINO FACTORY*

D. Stratakis#, Brookhaven National Laboratory, Upton, NY 11973, USA
C. T. Rogers, ASTeC, Rutherford Appleton Laboratory, OX110QX, UK
A. Alekou, CERN, Geneva, Switzerland
J. Pasternak, Imperial College London, UK/RAL STFC, UK

Abstract

An ionization cooling channel is a tightly spaced lattice containing absorbers for reducing the momentum of the muon beam, rf cavities for restoring the momentum and strong solenoids for focusing the beam. Such a lattice is an essential feature of most designs for Neutrino Factories and Muon Colliders. Here, we explore three different approaches for designing ionization cooling channels based on periodic solenoidal focusing. Key parameters such as the engineering constraints arising from the length and separation between the solenoidal coils are systematically examined. In addition, we propose novel approaches for reducing the peak magnetic field inside the rf cavities, for example, by using bucked coils for focusing. Our lattice designs are numerically examined against two independent codes: The ICOOL and G4BL code. The performance of our proposed cooling channels is examined by implementing those to the front-end of a Neutrino Factory.

INTRODUCTION

Neutrino factories produce intense beams of neutrinos from the decays of muons in a high energy storage ring with long straight section pointing at a distant detector [1]. The muons originate from pions produced in the interaction of proton beam with a high power target. The 4MW proton beam is delivered in a train of 1-3 bunches produced at 50 Hz. There are two main requirements on the front-end system, which is located between the target and the acceleration systems: First, the front-end system has to collect the pions and form a beam from their daughter muons as efficiently as possible. Second, the front end has to manipulate the transverse and longitudinal phase-space of the beam so that it matches the acceptance criteria of the downstream accelerators. In order to accomplish this, the muon particles are passed through material absorbers reducing both transverse and longitudinal momentum. They are then reaccelerated in RF cavities replacing momentum in only the longitudinal direction resulting in a reduction of transverse emittance. Multiple Coulomb scattering and energy straggling tend to create noise counteracting the emittance reduction. A low-Z material (Lithium Hydride) is chosen for the absorber to minimize these effects. In order to maintain a high acceptance, solenoids are tightly packed around RF cavities and absorbers. Following the muon front end, particles are passed into an acceleration system, accelerated to 12.6 GeV and placed in a storage ring where the majority decays radioactively to form neutrinos. In the baseline, at least 10^{21} muon decays in the production straight are required per year.

In this paper we will review alternative cooling options for the Neutrino Factory Front-End.

MUON CAPTURE SYSTEM

8 GeV protons are targeted onto a Hg jet target that is encapsulated in a 20 T solenoid. The pions that are generated from the target are captured as they transverse the 15 m long drift section where the solenoid field tapers adiabatically from 20 T to 1.5 T while the beam pipe radius increases from 0.075 m to 0.3 m. Ideally, the remaining protons and other background particles are removed from the beam by means of a bent-solenoid chicane and proton absorber and subsequently a time-energy relationship is allowed to develop. For the purpose of this study the chicane is not included in the simulation.

Table 1: Front-End Baseline Parameters

Region	Buncher	Rotator	Cooler
Length [m]	33.0	42.0	~100
Number of cavities	33	56	130
Frequencies [MHz]	319.6 to 233.6	230.2 to 202.3	201.25
Number of frequencies	13	15	1
Peak Grad. [MV/m]	3.42 to 9.01	13	16

The beam passes through a series of RF cavities, the frequency of each selected to be synchronous with particles in the beam and the voltage of each one higher than the previous to adiabatically form micro-bunches. To determine the right parameters we consider reference particles at 233 MeV/c and 154 MeV/c with the intent to capture muons from an initial kinetic energy rage of 50 to 400 MeV. The rf cavity frequency, and phase are set to place these reference particles at the center of the bunches while the rf voltage increases along the channel. Main parameters of the buncher system are listed in Table 1.

Each cell is 75 cm while the rf cavity has length within the 40 to 50 cm range. A constant 1.5 T in the buncher and rotator is applied to focus the beam through the aperture. The rf voltage is progressively increased from cell to cell up to a value of 9 MV/m.

*Work supported by DE-AC02-98CH10886
#diktys@bnl.gov

Once the voltage has reached its nominal peak value the beam enters the rotator region. In that region, the cavity frequency is chosen so that fast muons at the head of the bunch experience a decelerating phase and slow muons at the tail of the bunch experience an accelerating phase. The phase is chosen so that the head bunch and tail bunch has the same energy when the bunch frequency is 201.25 MHz. All cavities are 50 cm long and operate at a gradient equal to 13 MV/m. The average momentum of the rotator is 230 MeV/c and it increases the "accepted" muons by a factor of 4. Subsequently the beam enters an ionization cooling channel.

IONIZATION COOLING SCHEMES

As we pointed out in the introduction, because of the way muons are produced, they inherently begin life in a beam with a very large phase-space volume. Ionization cooling therefore is necessary to transport the beam through a reasonable accelerator lattice. In ionization cooling the fractional change in emittance is proportional to the fractional change in momentum arising from energy loss. Multiple scattering in the absorber material is a competing process that acts to increase the transverse emittance. The balance between those two processes determines whether the net cooling takes place. We consider three different approaches that are described below.

Conventional Flip Focusing Channel (CFF)

In this scheme, the muons upon exiting the rotator are matched into a ~100 m long cooling channel consisting of rf cavities, absorbers for cooling, and altering ±2.8 T solenoids for focusing. Figure 1(a) depicts the configuration of this cooling scheme. This cooling section is similar of the cooling scenario used for the ISS study [2] where each cell was 0.75 m long with two (LiH) absorbers, each 1.15 cm thick, and a 0.5 m long 201.25 MHz rf pillbox cavity operating at a gradient equal to 16 MV/m. For practical implementation, the cell length is now increased to 0.86 m and an empty cell is added after five or seven cavities (Fig. 2). This will give appropriate space between cavities and coils as we as will allow easier removal of parts of the lattice.

For cooling, LiH is chosen as it is low Z material, and hence includes less multiple scattering per unit energy loss. A 100 μm thick layer of Be is placed on the side facing the cavity while a 25 μm thick layer of Be is placed on the absorber side.

Radial Bucked-Coil System (RBC)

In the baseline configuration, the rf cavities are closed-cell pillbox cavities that operate at relatively high gradients within a few Tesla focusing fields. For example, in the buncher and rotator sections, 200 to 320 MHz cavities need to operate in a constant 1.5 T field with gradients up to 13 MV/m. Two experiments at the MuCool Test at Fermi National Laboratory (one with a single pillbox 805 MHz Cu-cavity and one with a single 201 MHz Cu-cavity) provided some evidence that, operating cavities in magnetic fields may cause a decline in the achievable gradient.

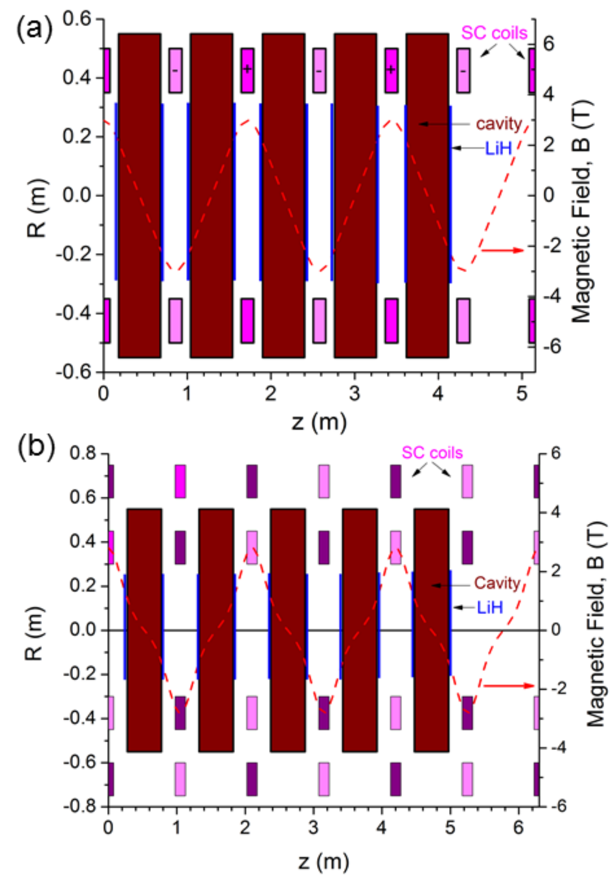

Figure 1: Two different cooling schemes for a Neutrino Factory: (a) A conventional flip focusing channel; (b) A radial bucked coil lattice.

Table 2: Cooler Parameters

Region	Period [m]	Inner [A/mm^2]	Outer [A/mm^2]
CFF	0.86	-	106
RBC1	1.05	120	-90.24
RBC2	1.05	97.2	-77.14
RBC3	1.05	87.48	-66.72
RBC4	0.90	132	-99.26
SHLD	3.0	-	19.33

According to a recent theory [3, 4], this drop in gradient likely occurs after the electrons from a field-emission site are focused by the magnetic field, and damage a surface with high electric fields. Breakdown could be suppressed if the strengths of the magnetic fields generated by the coils will be reduced. A non-flip lattice with longitudinal bucked coils was studied in the IDS-NF in 2008 however; its transmission was only 50%. Then, a lattice with radial bucked coils and a flipped magnetic field configuration was proposed. Cooling simulations with G4MICE showed a much higher transmission making this channel a very promising solution [5]. Figure 1(b) shows a simple example of this principle applied to a single rf cavity with just four coils, two on either side of the cavity. Compared to conventional pillbox cavities, the calculations indicate that such schemes reduce the on axis magnetic field by at least a factor of two. This is clearly depicted in Fig. 1(b) where the doted red line indicates the axial magnetic field.

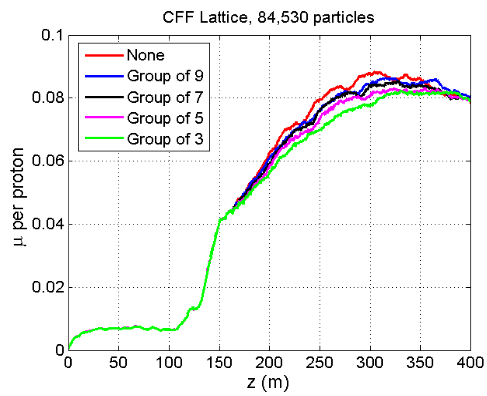

Figure 2: Performance of the lattice shown in Fig. 1(a) as a function of the number of cavities before the "empty" cell.

Shielded Lattice (SHLD)

Another way to achieve improved acceptance is to increase the beam energy [6]. The RF capture scheme outlined above can capture muons at higher energy by working with a small accelerating phase in the phase rotation section. Operation at higher energy can enable use of a lattice with a reasonable acceptance even with a rather long cell length. Lengthening the lattice cell will allow the design of a cooling channel wherein the rf cavities no longer sit in intense magnetic fields.

Figure 3 shows a schematic of our channel. Each cell is 3m long and it includes equally spaced superconducting magnets, normal conducting rf cavities and LiH absorbers. Two key disadvantages of this lattice compared to the other two is that it achieves a lower beta function and the momentum acceptance range is narrower.

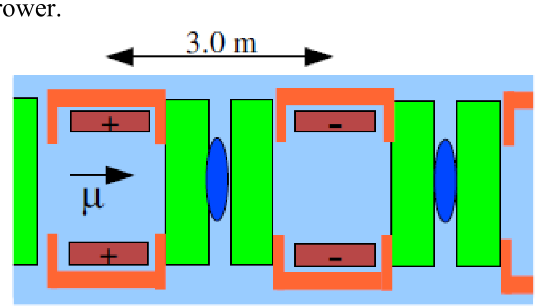

Figure 3: Shielded coil system. The lattice period is 3 m and each cell has two cavities (green) and one LiH absorber (blue).

PARTICLE TRACKING

The majority of the modelling of the aforementioned lattices is performed using the version 3.30 of the ICOOL code [7] and the 2.14 version of the G4Beamline code [8]. ICOOL is a tracking code specifically designed to study ionization cooling. It enables calculation of the actual rf field and solenoidal field maps together. It also includes realistic models of physics processes that are undergone from passing in a material, namely ionization energy loss and multiple Coulomb scattering. We used 84,530 particles for our simulation.

The results for the CFF lattice in Fig. 2 indicate that the optimum performance is achieved when the empty cell is placed after 7 rf cavities with only 3.5% loss in performance. However, the magnetic field on the cavity iris is 2.8 T. Reducing the magnetic field to a quarter of Tesla is possible with the SHLD lattice, however, the numerical study presented in Fig. 4, predicts a muon production at least 25% less. A modest loss of performance is achieved with the bucked coil scheme while the magnetic field on the iris is just below a Tesla (RBC-1) which can be considered a safe limit and thus making this lattice a viable option.

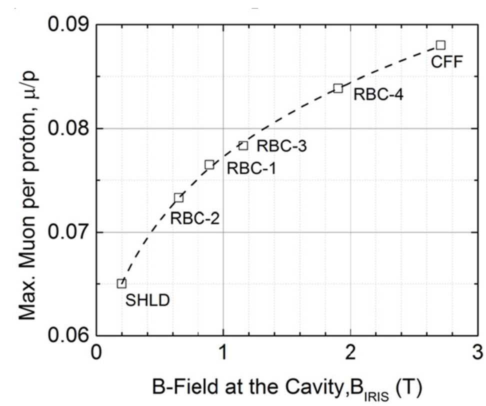

Figure 4: Lattice performance versus the magnetic field on the cavity iris. Higher field on the iris implies also better performance.

ACKNOWLEDGMENT

The authors are grateful to D. Neuffer, P. Snopok, R. Ryne, H. Sayed and S. Berg for useful discussions.

REFERENCES

[1] S. Geer, Phys. Rev. D 57, 6989 (1998).
[2] M. Apollonio et al., Journal of Instrumentation 4, P07001 (2009).
[3] D. Stratakis et al., Nucl. Instr. and Meth. A 620, p. 147 (2010).
[4] D. Stratakis, et al. Phys. Rev. ST Accel. Beams 14, 011001 (2011).
[5] A. Alekou and J. Pasternak, JINST 7, PO8017.
[6] C. T. Rogers, Nufact09, AIP Conf. Proc. 1222, p 298 (2010).
[7] R. C. Fernow, Proc. PAC 1999, p. 3020.
[8] g4beamline.muonsinc.com