FRICTIONAL COOLING FOR A SLOW MUON SOURCE

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Abstract

Slow muon beams are useful for a wide range of physics experiments. The frictional cooling method holds promise for delivering slow muon beams with narrow energy spreads. With this technology, we consider the production of a cold muon beam from a surface muon source, such as that at the Paul Scherrer Institute. A cooling scheme based on frictional cooling is outlined. Simulation results show that the efficiency of slow muon production can be raised to 1%, which is significantly higher than current schemes.

INTRODUCTION

Intense slow muon sources, whose kinetic energies are in keV range, are important for many experiments in particle physics and material research [1]. A muon collider [2] and neutrino factory [3] also require high-quality muon beams.

Muon beams are tertiary beams, produced in the decay of pion beams that are produced by proton beams hitting targets. They initially have large phase space volume that must be reduced. This process, called "cooling," is important for all the experimental endeavors described above. Frictional cooling is one promising method to reduce the phase space volume.

In this paper, we explain the frictional cooling concept and outline a scheme for the production of a slow muon beam from a surface muon source, such as the one available at the Paul Scherrer Institute (PSI), Switzerland [4]. We then compare the efficiency of our cooling scheme to the current slow muon production setup at PSI [5].

FRICTIONAL COOLING

Frictional cooling is the bringing of charged particles to an equilibrium energy by the balancing of energy loss to a material with energy gain from an electric field [6]. Figure 1 shows the stopping power, $\frac{1}{\rho}\frac{\mathrm{d}T}{\mathrm{d}s}$, as a function of kinetic energy T for μ^+ , where ρ is the density of the medium and $\frac{\mathrm{d}T}{\mathrm{d}s}$ is the energy loss per unit path length. The stopping power has been calculated using velocity-scaled proton data [7]. Applying an electric field to restore kinetic energy in the longitudinal direction brings the particles to the equilibrium energy (T_{eq}). Particles with kinetic energies less than T_{eq} accelerate because they gain more energy from the electric field than they lose to the material. Particles with kinetic energies greater than T_{eq} but less than T'_{eq} (see Fig. 1) decelerate because they lose more energy than they gain. Thus all particles with kinetic energy less than T'_{eq} approach T_{eq} and the energy spread decreases.

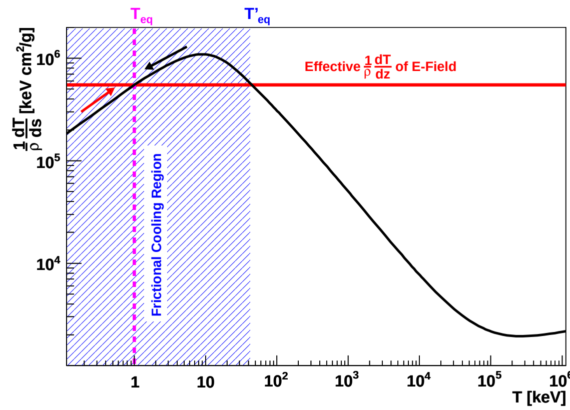

Figure 1: Stopping power for μ^+ in helium as a function of kinetic energy T. T_{eq} is the equilibrium energy. The red line represents the accelerating power of an external electric field. The shadowed band is the frictional cooling region.

COOLING SCHEME

We consider producing a slow muon beam using frictional cooling from a surface muon source such as the μE4 beam at PSI.

Slow Muon Production at PSI

The μE4 beam line delivers the world's highest flux surface μ^+ beam [4]. It is a continuous beam. PSI currently produces a slow muon beam by focusing the μE4 beam onto a thin foil moderator (about $100\ \mu\mathrm{m}$ thick) covered with a very thin layer (less than $1\ \mu\mathrm{m}$) of a condensed van der Waals gas such as argon, neon, or nitrogen cryosolids. Very slow μ^+ exit from the downstream side of the moderator. The energy distribution of these muons has a maximum near $15\ \mathrm{eV}$ and a tail extending to higher energies. An electric field then reaccelerates the muons yielding a beam with mean energy tunable between $0.5\ \mathrm{keV}$ to $30\ \mathrm{keV}$ with a spread of $400\ \mathrm{eV}$. This moderation technique has an efficiency of 10^{-5} to 10^{-4} to convert a surface muon to a slow muon [5].

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Frictional Cooling Scheme

We searched for a way to more efficiently produce a slow muon beam using frictional cooling. Because frictional cooling only works at low energies, we must lower the kinetic energies of the muons to below 50 keV. To achieve this, we inject the muons into a cooling cell, which is a helium gas cell with an electric field in the direction opposite to that of the beam (Fig. 2). The gas and the electric field slow the muons down. The slowing down is primarily due to the electric field. When they turn back, a large fraction of the muons have very low kinetic energies and are brought to T_{eq}. This scheme produces a beam at the equilibrium energy with a very small energy spread, regardless of the initial beam energy spread.

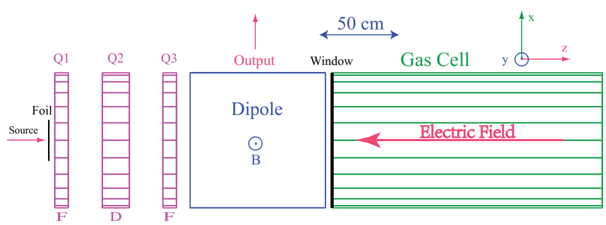

Figure 2: The block diagram of the frictional cooling scheme.

To reduce the required electric potential in the cooling cell, the beam first passes through a foil for an initial energy loss. For a fixed electric field, lowering the mean energy decreases the distance that the muons traveled in the cooling cell, thereby reducing the loss from decay.

The cooling cell is ineffective for muons with large transverse momentum, because when they turn around they have kinetic energies above T'_{eq} (see Fig. 1). The electric field reaccelerates them to approximately their initial energies. Therefore we use quadrupoles to reduce the angular divergence of the beam. The quadrupoles are designed to maximize the number of muons with low transverse momenta.

Between the quadrupoles and the cooling cell is a weak dipole. It has minimal effect on the high-energy input beam, letting it pass straight through. After the dipole, the beam enters the cooling cell.

A window is needed to separate the cooling cell from the input beam line. The window must be thin to allow the cooled muons get out efficiently. After the muons turn around and exit the cooling cell, they enter the dipole again. The magnetic field in the y direction turns the cooled muons in the x direction. We evaluate the momenta and positions of the muons as they exit the dipole.

SIMULATION

Simulation Tools

We have developed a program called CoolSim [8] based on Geant4 [9], in which geometries can be implemented easily by a macro-command interface. For simulating the frictional cooling process, we use the Geant4 low-energy processes [10] to determine energy loss and spatial displacement.

We have added new low-energy physics processes to the Geant4 framework: hydrogen formation for protons, muonium formation for μ^+, and charge exchange interactions for both protons and μ^+.

We also take the decay process for μ^+ into account. The energy losses calculated by the program were verified against the NIST tables.

We simulated the scheme shown in Fig. 2 in the CoolSim program using uniform electric and magnetic fields without fringe fields. The quadrupoles are simulated as a slightly modified FODO cell, which is a symmetric $\frac{1}{2}FODO\frac{1}{2}F$ cell. The parameters of the cooling cell were chosen to keep the equilibrium energy and the efficiency high. All components have the same aperture. The simulation parameters are given in Table 1.

Table 1: Parameters of the Elements in the Cooling Scheme

Aperture	100 cm
Foil:	
Thickness	100 μm
Material	tungsten
Quadrupoles:	
Gradient	1 T/m
Magnet Length	20 cm
Drift space	40 cm
Dipole:	
Strength	0.003 T
Length	100 cm
Cooling cell:	
Length	200 cm
Electric field strength	1.8 MV/m
Gas material	helium
Gas density	0.01 mg/cm^3
Window:	
Thickness	20 nm
Material	carbon

Input Beam

Table 2: Summary of μE4 Beam Properties at PSI

Beam energy	3.7 MeV
x/x' (FWHM)	6.5 cm/150 mrad
y/y' (FWHM)	2.6 cm/300 mrad
Δp/p (FWHM)	9.5%
μ^+ rate	228×10^6 /mA s

We use the Geant4 General Particle Source to reproduce the surface muon beam using the parameters of PSI's μE4 beam (Table 2) and assuming gaussian distributions with no correlations. 100,000 muons were simulated.

Output

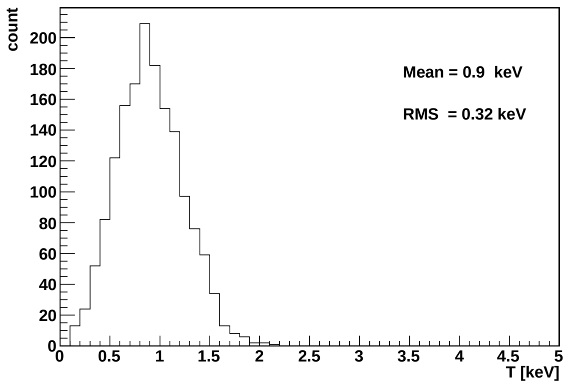

Figure 3: The energy distribution of the output μ^+.

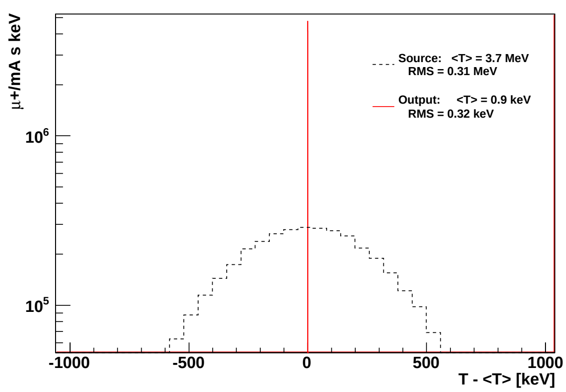

Figure 4: The energy distribution of the output beam compared to the input beam. The distributions are centered on their means.

At the output, the cooled beam has a mean kinetic energy of $0.9\ \mathrm{keV}$ and an RMS of $0.32\ \mathrm{keV}$ (Fig. 3). Figure 4 shows a comparison of the energy relative to the mean energy for muons at the source and muons exiting the scheme. The peak muon rate is $4.8 \times 10^6\ /(\mathrm{mA\,s\,keV})$ while the peak source rate is $2.9 \times 10^5\ /(\mathrm{mA\,s\,keV})$. The energy spread of the beam is greatly reduced. The spatial distribution of muons exiting the dipole is shown in Fig. 5. The RMS sizes of the beam are $20\ \mathrm{cm}$ in x and $24\ \mathrm{cm}$ in y. 1.7% of the source muons exit the dipole; they would then be collected and reaccelerated.

CONCLUSION

Frictional cooling holds promise for producing low energy muon beams with small energy spreads. Our simulation shows that a frictional cooling scheme can cool a surface muon beam to a mean energy of $0.9\ \mathrm{keV}$ with an energy spread of $320\ \mathrm{eV}$. The efficiency for slow muon production is greater than 1%, which is 2 to 3

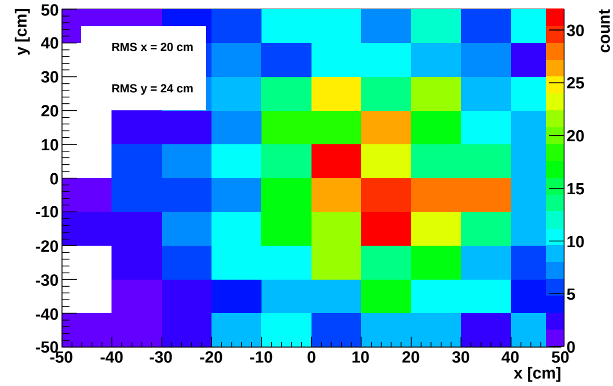

Figure 5: The transverse distribution of cooled muons exiting the dipole.

orders of magnitude higher than the efficiency achieved with the moderation technique. If the frictional cooling scheme is experimentally successful, a surface muon rate of $228 \times 10^6\ /(\mathrm{mA\,s})$ would result in a slow muon rate of $2.3 \times 10^6\ /(\mathrm{mA\,s})$.

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