FRICTIONAL COOLING DEMONSTRATION AT MPP

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Abstract

Frictional Cooling holds promise for delivering beams with a very narrow energy spread. At the Max Planck Institute for Physics (MPP), a demonstration experiment based on this scheme will soon take data. In this paper, the experimental setup and the Monte-Carlo simulation results based on Geant4 are described. The use of frictional cooling as an efficient scheme for producing a low energy muon beam is also simulated yielding a beam with mean energy of 3 keV and an RMS of ~300 eV with an efficiency significantly improved from the current scheme.

FRICTIONAL COOLING

The idea of Frictional Cooling is to bring charged particles into a kinetic energy range where the faster particles lose more energy per distance traveled than slower ones [1]. This is done by passing the beam through a gas. Fig. 1 shows the stopping power for μ^+ in Helium as a function of kinetic energy. For kinetic energies below 10 keV, the stopping power increases with increasing energy. Applying an electric field to restore kinetic energy in the longitudinal direction will bring the particles to an equilibrium energy: particles with kinetic energies less than the equilibrium energy are accelerated because they gain more energy from the electric field than they lose to the gas. Particles with kinetic energies greater than the equilibrium energy are decelerated because they lose more energy than they gain. Thus the phase space is reduced. Additionally, since energy is restored only in the longitudinal direction, the beam divergence is reduced, cooling the beam in the transverse direction.

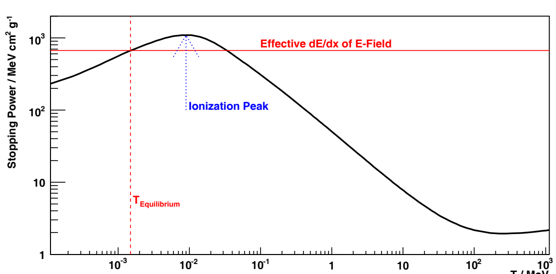

Figure 1: Stopping power of μ^+ in Helium (scaled from the NIST data [2] for protons).

In this energy regime, energy is lost through excitations, elastic scattering on nuclei and charge exchange interactions. Multiple scattering places a lower limit on the emittance achievable by the two cooling effects described above. The cooled beam has an energy spread of ~ 300 eV, which can be preserved during reacceleration, yielding high energy beams with small relative momentum spreads.

EXPERIMENTAL DEMONSTRATION AT MPP

The Frictional Cooling Demonstration (FCD) experiment at MPP is undertaking verification of the principal behind frictional cooling using protons, which are stable and more easily produced than muons.

Experiment Setup

We have constructed a basic cooling cell consisting of a Helium gas cell and a 10 cm long accelerating grid (Fig. 2). The aim of the experiment is to verify that protons starting from rest are accelerated up to an equilibrium energy. The proton source produces protons at rest at one end of accelerating grid. A Silicon Drift Detector (SDD) at the other end of the grid measures the energy of the protons.

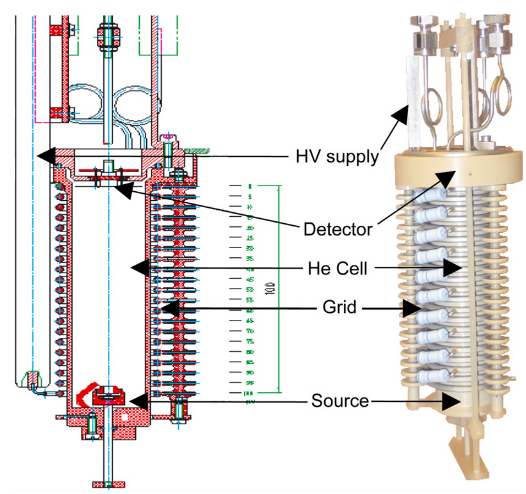

Figure 2: FCD experimental setup.

The Helium gas cell is a PEEK cylinder with two feedthroughs for flowing gas in and out. The flow rate is controled by an electronic valve to maintain a constant gas pressure in the cell. Both the detector and the source are inside the cell, so no windows are required.

The gas cell is mounted inside the accelerating grid. The grid consists of 21 metal rings connected in series by 64 MΩ resistors.The detector-side ring is grounded, and

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the source-side ring is connected to a high-voltage supply capable of providing up to 100 kV. Calculation of the electric field created by the accelerating grid shows that it is very uniform. The results of this calculation were implemented in the whole experiment simulation.

The proton source is contained inside the gas cell. It consists of an alpha source covered by a mylar foil. The alpha particles break the bonds between the Hydrogen and Carbon nuclei of the Mylar molecule, leaving the Hydrogen nuclei free to be accelerated out of the foil by the electric field. The thickness of the foil was chosen carefully according to the results of simulation of the source to maximize the proton production rate.

The SDD was built by the Max Planck Institute Semiconductor Laboratory. The detector can achieve an energy resolution of 500 eV at 5.9 keV at room temperature and better than 150 eV when the detector is cooled to −25 °C.

First Results

To verify the production of protons and characterize the detector's response to protons, we record the spectra of protons with no gas in the cell and with various strengths of the electric field.

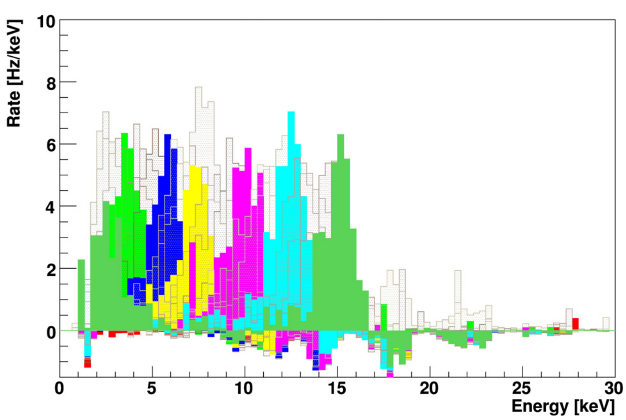

Figure 3: Energy spectra (with background x-rays subtracted) for strengths of the electric field from 10 kV/m to 300 kV/m in 10 kV/m steps (lines) with an evacuated gas cell. The six highlighted spectra are spaced 50 kV/m apart.

Figure 3 shows the energy spectra taken for strengths of the field from 10 kV/m to 300 kV/m, in 10 kV/m steps. The proton source was placed 80 mm from the detector, resulting in energies of 5.6 keV to 24 keV in 800 eV steps, however only a fraction of the energy of a proton is measured by the SDD. Figure 4 shows the mean energies of the spectra plotted as a function of the incoming energies of the protons. The incoming energy is taken from numerical calculation of the electric field. This data is used to characterize the dead layers of the detector and the detector's response to protons.

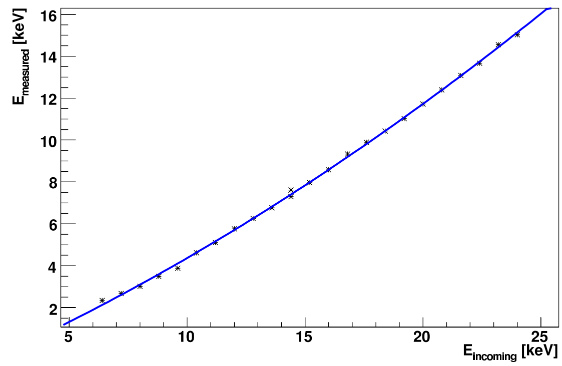

Figure 4: The mean energies of the proton spectra as a function of the incoming energy of the protons.

Status

The gas cell has been commissioned using gas together with high-voltage. The regions of stable operation for high-voltage and gas pressure have been determined. As a next step, proton spectra in various pressures of gas and various strengths of electric field will be taken. The resulting spectra will be compared to Monte-Carlo simulation.

MONTE-CARLO SIMULATION

We have developed a program called CoolSim [3] based on Geant4 [4], in which geometries can be implemented easily by a macro-command interface. We have added new low-energy physics processes to the Geant4 frame work such as Hydrogen formation for protons, Muonium formation for μ^+ and charge exchange interactions for both protons and μ^+.

For simulating frictional cooling, the G4hLowEnergyIonisation and G4MultipleScattering processes are instan-

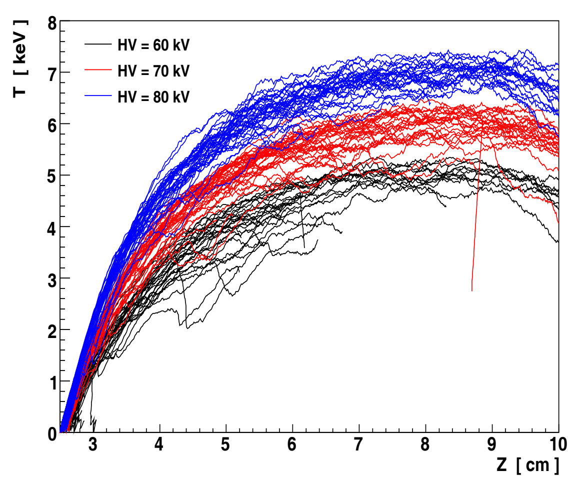

Figure 5: Kinetic energy versus depth in the gas cell for a few representative protons.

tiated in the physics list to determine energy loss and the spatial displacement.

Figure 5 shows the kinetic energies of protons as a function of the depth in the cooling cell for three different High-Voltages [5]. The kinks in the plot are due to sudden large losses of energy from large angle scattering off of gas nuclei.

The corresponding energy distributions at the detector are shown in Fig. 6 [5]. Multiple scattering causes the tail to lower energies in the distributions. The cross section for large angle scattering increases with decreasing particle energy. The mean kinetic energy increases with electric field strength. Therefore the low energy tail in the energy distributions diminishes and the survival rate increases with increasing electric field strength.

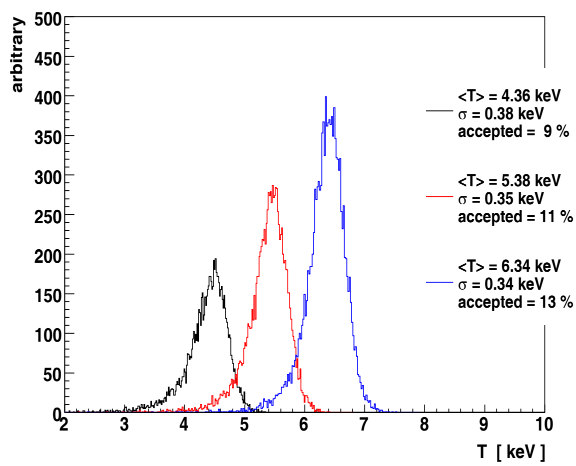

Figure 6: The energy distributions at the detector for three different strengths of the electric field: 600 kV/m (black), 700 kV/m (red), and 800 kV/m (blue)

Figure 7 is a summary of the simulation results under different conditions [5]. By varying the gas density and electric field strength in the experiment, we can vary the equilibrium energy protons attain. The experimental results will be used to test the simulation results.

FRICTIONAL COOLING FOR A LOW-ENERGY MUON BEAM

As an example use of frictional cooling, we consider producing a cold muon beam from a surface muon source. For the simulation, we take the input parameters to be those of the muon beam at the Paul Scherrer Institute (PSI), Switzerland, up to the point where the slow muons are produced [6]. We then compare the efficiency of our scheme to the current scheme at PSI.

The μ^+ Beam at PSI

The new μE4 beam line at PSI delivers the world's highest surface-μ^+ flux of 228×10^8 /mAs with a momentum of

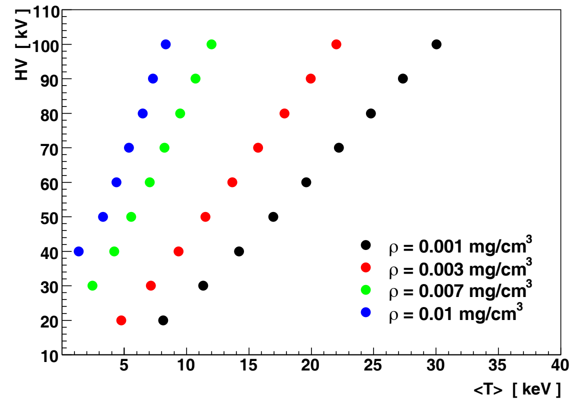

Figure 7: Simulation results: equilibrium energies for different high-voltages (E = HV/10 cm) and gas densities.

28 MeV/c and $\Delta p/p$ (FWHM) of 5.0–9.5%. It has a spatial divergence of x/x' (FWHM) of 6.5 cm/150 mrad and y/y' (FWHM) of 2.6 cm/300 mrad [6].

Cooling Scheme Based on Frictional Cooling

Figure 8 shows the layout of the proposed cooling scheme. Muons pass through a foil for an initial energy loss. The thickness of the foil is optimized to be 110 μm to increase the number of muons that can be cooled by the gas cell with the lowest possible electric potential. A 10 cm

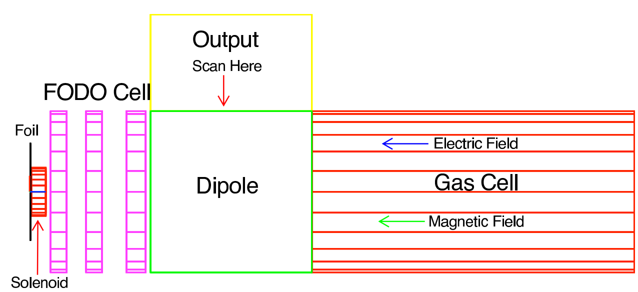

Figure 8: Outline of the scheme based on Frictional Cooling.

long solenoidal magnetic field with strength 1 T collects the muons after the foil. They then pass through a FODO cell to reduce the beam divergence.

After the quadrupoles, a weak dipole of 0.005 T will let the high-energy input beam get through unaffected.

The beam then enters a 2 meter long gas cell filled with Helium at a density of 0.01 mg/cm^3. An electric field of 1.8 MV/m in the opposite direction against the incoming beam is present. A Van de Graff generator may be needed to provide an electric potential of 3.6 MV. Discharge in the Helium gas caused by field configuration may be a serious issue and has to be investigated. The muons will spiral in the gas in a 1 T solenoidal magnetic field. They are slowed down by the gas and the electric field, and turned back by the electric field with an equilibrium energy around several keV.

The cooled muons exit the gas cell and are turned into the output channel by the dipole. We scan the beam on the edge of the dipole as the output.

Figure 9 shows the longitudinal and transverse momentum distributions of the beam before entering the cooling scheme and after the FODO cell (but before entering the gas cell). It also shows the momentum distribution before entering the gas cell for the subset of the beam which can ultimately be cooled. Muons with transverse momenta

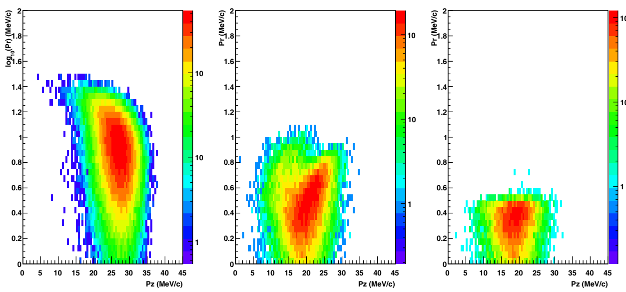

Figure 9: Transverse and longitudinal momentum of source (left), after the quadrupoles (middle) and those can be cooled (right).

greater than 3 MeV/c cannot be cooled because they are not in the coolable region of the stopping power curve (Fig. 1) when they turn around and begin to exit out of the gas cell; they will be accelerated to higher energies by the electric field. The FODO cell has been optimized to increase the number of muons with low transverse momentum.

Simulation Results

This scheme was simulated in the CoolSim program. Ideal fields without fringe fields were used. Figure 10 shows the input and output energy spectra. The energy spread is compressed from 734 keV to 0.263 keV with an efficiency of 5%. With different gas densities and electric field strength, we can attain different equilibrium energies from 1 keV to 8 keV.

The efficiency of this scheme based on frictional cooling is 2 to 3 orders of magnitude higher than that of the existing moderation method, which uses thin cryosolid layers to convert a surface-muon to a low energy μ^+ with an efficiency of 10^{-5} to 10^{-4} [7]. Simulation of a simplified scheme, which requires voltages of only 500 kV (attainable by a common high-voltage supply) and is without the FODO cell, still yields an efficiency of 0.5%.

CONCLUSION

The CoolSim simulations show that frictional cooling holds promise as a scheme for both high-energy accelerator beams, for use in a muon collider [8] or neutrino factory [9], and low-energy muon experiments [10]. In particular, frictional cooling could significantly improve the efficiency for producing slow muons. The FCD experiment is nearing the final data taking stage and hopes to verify the principle behind frictional cooling very soon.

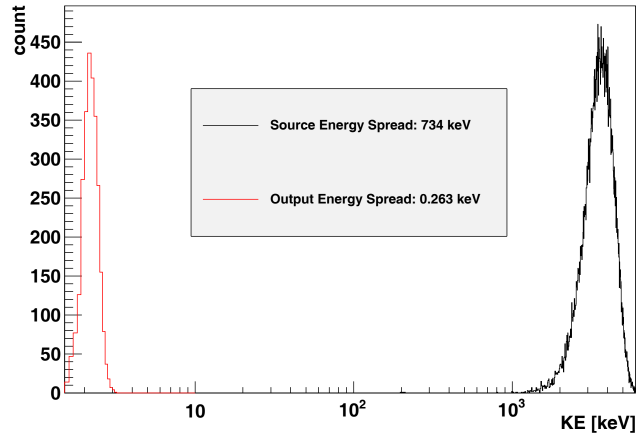

Figure 10: Output energy spectrum compared to the PSI's surface muon beam spectrum. The beam is cooled to 2.7 keV with a narrow spread of 0.263 keV.

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