FRICTIONAL COOLING DEMONSTRATION EXPERIMENT

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Abstract

Simulations of frictional cooling for a muon collider front end scheme show that it is a viable technique for quickly producing colliding beams. The Frictional Cooling Demonstration experiment at the Max Planck Institute for Physics, Munich, aims to demonstrate the working principle of frictional cooling on protons using a ten-cm-long cooling cell. The experiment is nearing the final data taking stages. The status of the experiment is presented along with recent data. Simulation of the experiment setup is also presented.

FRICTIONAL COOLING

Frictional cooling reduces the emittance of a beam of charged particles by restoring the energy loss of the beam's particles to a medium with an electric field. Restoring lost energy in only one direction reduces the tranverse emittancen. The balancing of the energy loss and gain reduces the momentum spread by bringing particles to an equilibrium energy T_{eq} given by

$$q{\cdot}E = \rho{\cdot}S(T_{\mathrm{eq}}) = \left.\frac{\mathrm{d}T}{\mathrm{d}x}\right|_{T=T_{\mathrm{eq}}}, \quad (1)$$

where q is the particle's charge, E is the electric field strength, and $S(T) = (1/\rho)\,\mathrm{d}T/\mathrm{d}x$ is the stopping power of the medium, the density-normalized energy loss gradient. For T_{eq} to be a stable equilibrium energy, the stopping power must increase with increasing kinetic energy, as it does for protons at energies below approximately $80\ \mathrm{keV}$.

Simulations of a muon collider scheme [1] and low-energy muon beam production [2] based on frictional cooling with a gaseous medium have yielded promising results. The Frictional Cooling Demonstration (FCD) experiment at the Max Planck Institute for Physics is working to verify the principal behind frictional cooling by observing the acceleration of protons from rest up to the equilibrium energy in a cooling cell.

EXPERIMENT

The FCD experiment consists of the simplified frictional cooling cell shown in figure 1: a gas cell mounted inside a ten-cm-long accelerating grid consisting of 21 metal rings spaced $5\ \mathrm{mm}$ apart and connected in a resistor chain. The first ring is connected to a one-hundred-kV power supply (HV), and the last ring is grounded. The accelerating grid provides a very uniform electric field aligned with the central axis of the gas cell (the z direction) with strengths up to $1\ \mathrm{MV/m}$. The gas cell and accelerating grid can be placed inside a superconducting solenoid magnet capable of providing magnetic field strengths up to $5\ \mathrm{T}$. The magnetic field is aligned along the z direction, parallel to the electric field, and is merely for collimation to increase acceptance at the detector.

A proton source is mounted inside the gas cell on the high-voltage end of the accelerating grid. It consists of an α emitter, ^{241}Am, covered by a Mylar foil. The α particles break the bonds between the hydrogen and carbon atoms in the Mylar monomer, leaving the ionized hydrogen nuclei free to be accelerated out of the foil by the electric field in the cell.

A silicon drift detector (SDD) designed and built by the Max Plank Institute Semiconductor Lab is mounted inside the gas cell on the grounded end of the accelerating grid. Because the SDD and proton source are mounted inside the gas cell, no entrance or exit window is required, greatly improving detection efficiency.

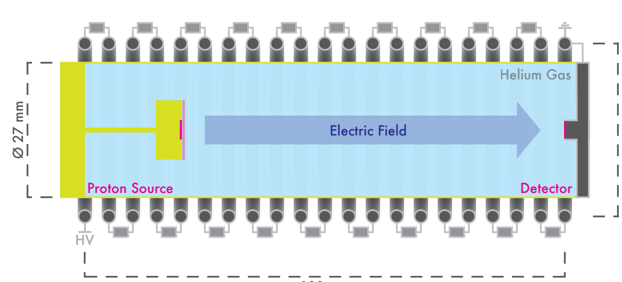

Figure 1: Scale diagram of the FCD experiment's cooling cell.

SIMULATION

A simulation of the FCD cell was undertaken in CoolSim [3], a low-energy particle simulation package based on Geant4 [4] and developed by the FCD experiment. The important physics processes for the simulation are low-energy ionization, low-energy scattering, and charge exchange interactions [5]. The latter is a physics process written for CoolSim and is not a standard part of Geant4; it is discussed in detail below.

Figure 2 shows the kinetic energy of protons as a function of depth (z) in the FCD cell filled with helium gas at a pressure of $40\ \mathrm{mbar}$ and with an electric field strength of $0.4\ \mathrm{MV/m}$. The protons leave the source, placed $20\ \mathrm{mm}$ in from the 1st ring ($z = 0\ \mathrm{mm}$), at rest and accelerate up to the equilibrium energy. The highlighted trajectory has sudden changes in the kinetic energy that are due to large-

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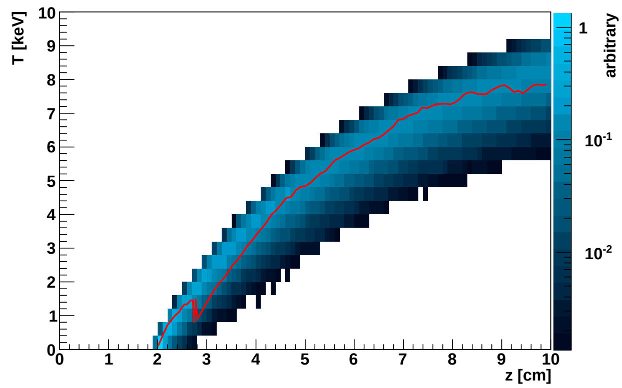

Figure 2: Kinetic energy distribution of protons (shaded) and the kinetic energy of a single proton (line) as a function of z in the FCD cooling cell filled with helium gas at $40\ \mathrm{mbar}$ and an electric field strength of $0.4\ \mathrm{MV/m}$.

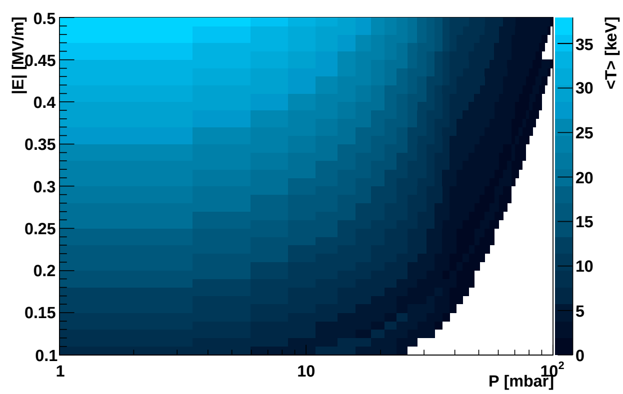

Figure 3: Mean energy of protons at the SDD as a function of helium gas pressure and electric field strength.

angle scattering. The proton scatters in a direction opposed to the electric field, slows down, reverses direction, and is reaccelerated up towards the equilibrium energy.

Using CoolSim, we calculate the mean energy of the protons at the detector plane ($z = 100\ \mathrm{mm}$) as a function of pressure of the helium gas and strength of the electric field (figure 3). For a fixed electric field strength, raising the gas pressure (raising the density) increases the energy loss to the helium, decreasing the mean energy at the detector. For a fixed gas pressure, raising the electric field strength increases the restorative energy gain, increasing the mean energy. Both behaviors are as expected from (1).

Effective Charge

One of the main energy loss mechanisms at low energies for both protons and positive muons is the exchange of charge with the retarding medium through electron capture and loss [5]. The charged particle spends a significant portion of its trajectory as a neutral particle. The mean free path for the capture and subsequent loss of an electron is short compared to the other processes important to tracking low-energy protons and μ^+. Rather than simulating the discrete charge exchange interactions, CoolSim assigns each particle an effective charge representing the instantaneous fraction of time spent in the charged state. This effective charge is calculated from the cross sections for charge exchange,

$$q_{\mathrm{eff}} = \frac{\sum q_j \sigma_{ij}}{\sum \sigma_{ij}},$$

where σ_{ij} is the cross section for the charge exchange process from charge state q_i to charge state q_j. For the simplest case where only single-electron capture and loss are taken into account,

$$q_{\mathrm{eff}} = \frac{\sigma_{\mathrm{loss}}}{\sigma_{\mathrm{capture}} + \sigma_{\mathrm{loss}}}.$$

Figure 4 shows the cross sections for electron capture and loss for protons in helium, and the subsequent effective charge as a function of kinetic energy. The effective charge drops down to as low as $0.4\,e$ in the energy range of the frictional cooling equilibrium energy. To achieve the same T_{eq}, after substituting q_{eff} into (1), stronger electric fields are required.

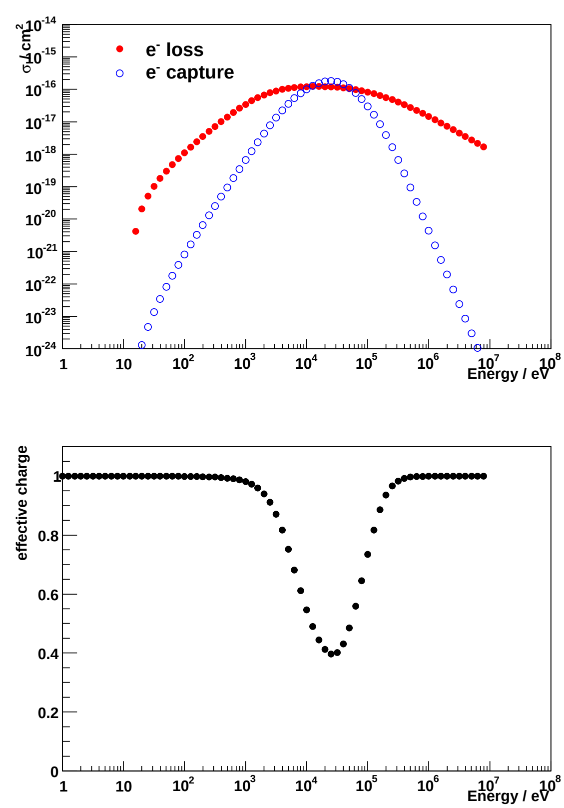

Figure 4: Electron loss and capture cross sections (top) and effective charge (bottom) for protons in helium.

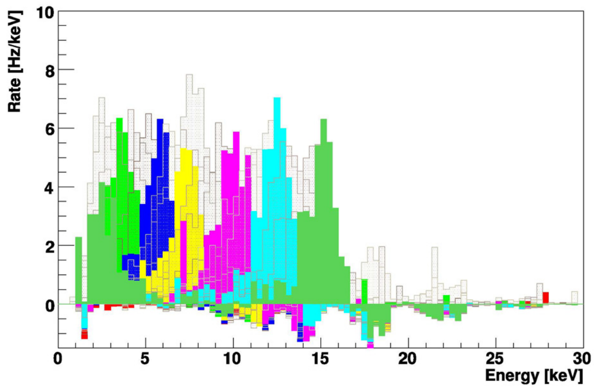

Figure 5: Energy spectra (with background x-rays subtracted) of protons for electric field strengths from $10\ \mathrm{kV/m}$ to $300\ \mathrm{kV/m}$ in $10\ \mathrm{kV/m}$ steps (lines) with an evacuated gas cell. The six highlighted spectra are for strengths of the electric field spaced $50\ \mathrm{kV/m}$ apart.

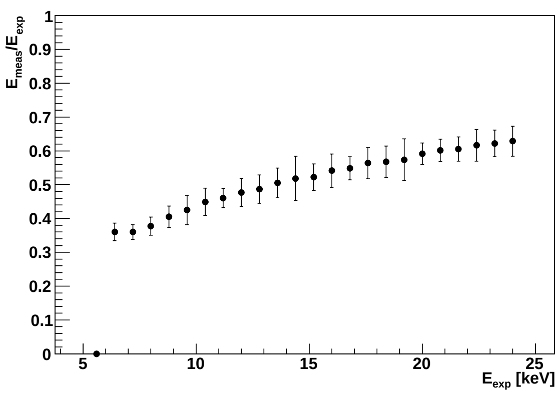

Figure 6: Fraction of proton energy measured by the SDD as a function of the expected entrance energy.

The effective charge is important for tracking low-energy charged particles in media with magnetic or electric fields present and where transitions from medium to vacuum occur. At the moment, this physics process is missing from Geant4. We have implemented an effective charge process for low-energy protons and μ^+ in CoolSim for several common gasses. The effective charge is calculated using available measurements (from [6]) of the charge exchange cross sections for protons. These cross sections are velocity scaled for μ^+. When a proton or μ^+ travels from material to vacuum, a discrete charge state is chosen with probability based on the effective charge at the moment of transition.

EXPERIMENT STATUS

We have commissioned all the pieces of the FCD experiment. The accelerating grid can provide fields with strengths up to $0.6\ \mathrm{MV/m}$ in the cooling cell filled with gas at pressures from less than 10^{-3} mbar to 1.25 bar without electric breakdown. With the gas cell evacuated, the grid has successfully produced fields with strengths up to $0.9\ \mathrm{MV/m}$.

Proton spectra have been measured with the gas cell evacuated (figure 5), allowing for characterization of the SDD's response to protons: The protons deposit energy along their trajectory through the detector. The initial layers of the SDD seen by the protons have inefficiencies for collecting the charges created by the energy deposition, leading to a lower measured energy than expected (figure 6) as calculated from a successive overrelaxation calculation of the field created by the accelerating grid.

Currently some issues with operating the SDD in helium gas are being investigated and preparations are being made for measuring proton energy spectra for various pressures of the helium gas and strengths of the electric field. These measurements will be compared to the CoolSim simulation results.

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