# Frictional Cooling Scheme for Muon Collider: Demonstration Experiment Summary

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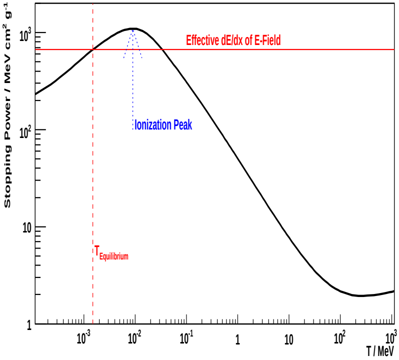
# Frictional Cooling Concept

A particle is brought to an equilibrium energy by application of a constant electric field in a retarding medium where energy loss increases with increasing kinetic energy.

Stopping power for $\mu^+$ in Helium:



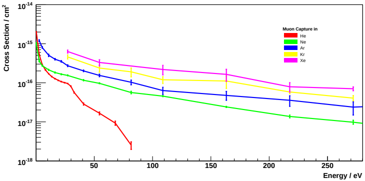

High $\frac{1}{\rho}$ $\mathrm{d}E/\mathrm{d}s$ around around equilibrium energy necessitates medium be gas.

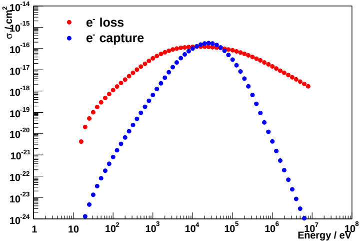
# Cooling Medium

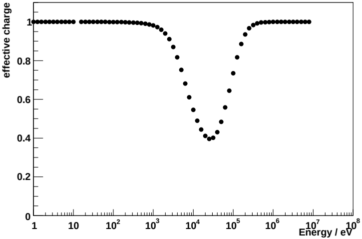
$\mu^+$
charge exchange cross sections for Helium make it the ideal gas

- to reduce loss of muons to formation of Muonium
- to reduce changes to equilibrium energy due to effective charge of muon in medium

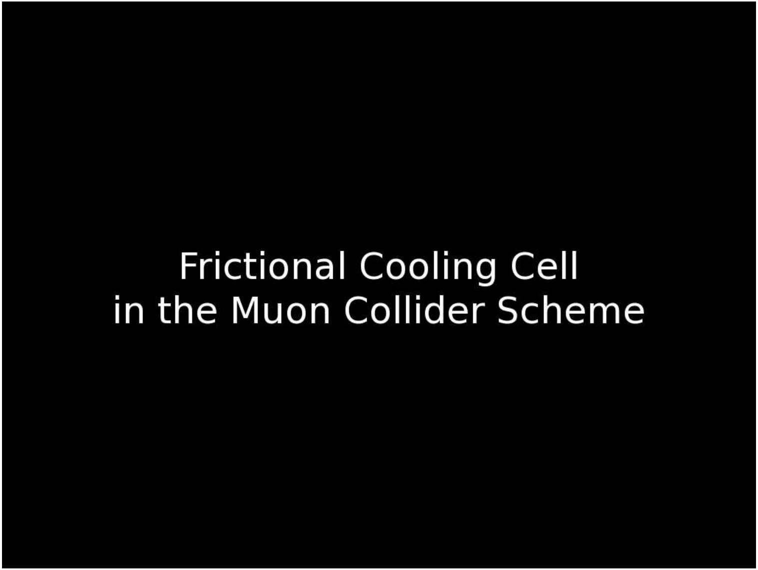
$\mu^-$
capture cross sections for Helium and Hydrogen make them the ideal choice.



# Frictional Cooling Cell



# First Simulations

This frictional cooling scheme was simulated with input from a front end scheme as described in Ankenbrandt, 1999 (arXiv: physics/9901022): a muon beam exiting the pion drift region with emittance

$$\epsilon_{6,N} = 2 \times 10^{-4} (\pi \mathrm{m})^3$$

The goal was to acheive a luminosity as prescribed in Ankenbrandt,

$$L = 7 \times 10^{34} \mathrm{cm}^{-2} \mathrm{s}^{-1},$$

which is acheived with an emittance

$$\epsilon_{6,N} = 2 \times 10^{-10} (\pi \mathrm{m})^3$$

The simulation (arXiv: physics/0410017) yielded an emittance

$$\epsilon_{6,N} \approx 3 \times 10^{-11} (\pi \mathrm{m})^3,$$

and the desired luminosity. (The yield was 0.002 $\mu^+$/p.)

# First Experiment

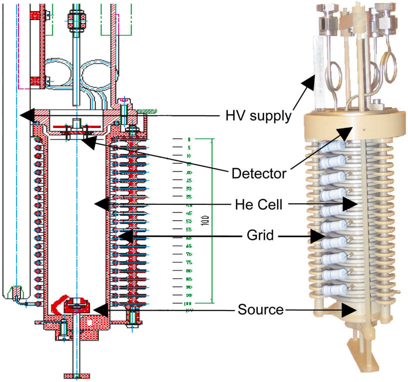
Motivated by the promising results from the first simulations, an experimental verification of frictional cooling using a proton beam was undertaken at Nevis Laboratories, Columbia University. (arXiv: physics/0311059)

Unfortunately, too-thick exit-windows on the cooling cell prevented cooled protons from exiting the experiment, and frictional cooling was not observed.

# FCD Cell

Motivated by the promising results from the first simulations, the FCD experiment at the MPP aims to verify the principle behind frictional cooling.

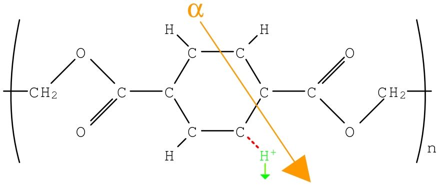
Accelerating-grid and gas-cell construction:



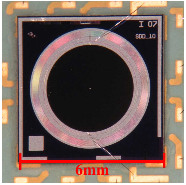

Detector mounted in gas-cell flange:

# Proton Source Mechanism

Protons created by stripping $e^-$ from H atoms in Mylar

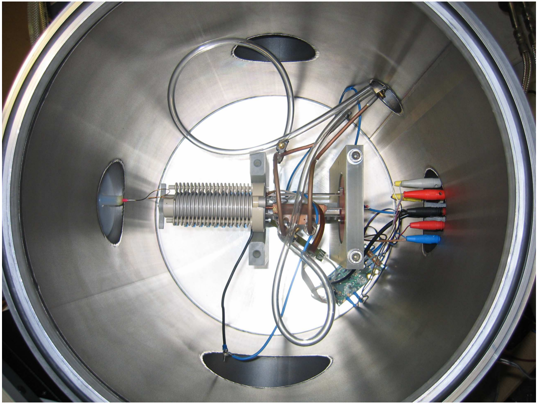



Silicon Drift Detector (from MPI-HLL)



# Experimental Setup

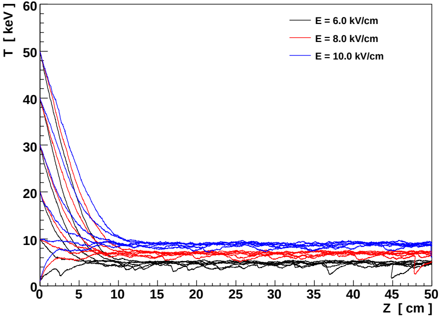
The grid has been operated up to 90 kV, and run stably at 60 kV with the gas-cell filled with Helium at pressures up to 1.25 Atm.

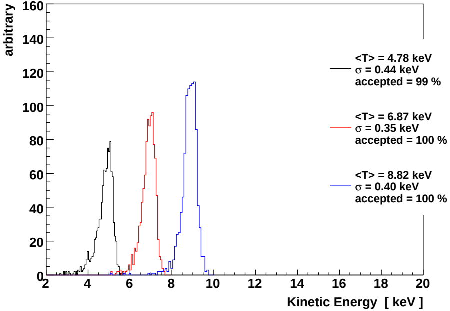


# Ideal Cooling Cell Simulation

Simulation of an ideal cooling cell (uniform fields) was undertaken to investigate various aspects of the frictional cooling principle, specifically:

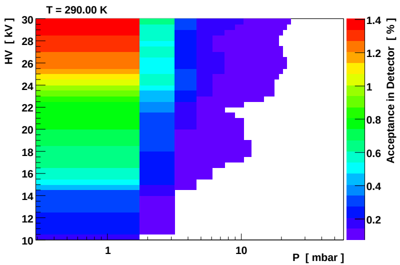
- effects of nuclear scattering and multiple scattering
- the rate of $\mu^-$ capture and muonium formation
- the role of effective charge
- the effects of impurities in the Helium gas

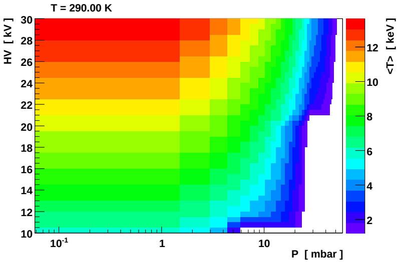


# FCD Cell Simulation

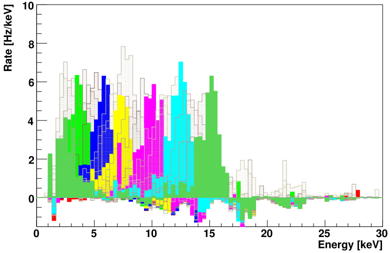
Using realistic shapes of the fields, these simulations predict acceptance rates and mean proton energy as a function of both the electric field (here represented as a high voltage placed on the first ring of the accelerating grid) and Helium gas pressure.

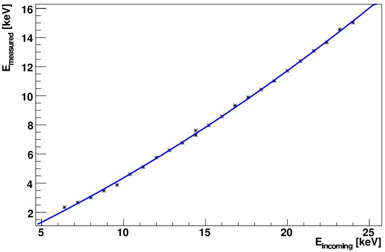


# Most Recent Spectra

Proton spectra have recently been taken for energies between 5.6 keV and 24 keV in 800 eV steps. This allows us to characterize the detector's response to protons very accurately.



# Status

The experiment construction has been successfully commissioned:

- the accelerating grid runs reliably, without breakdown between rings, at voltages above 65 kV (0.65 MV/m).
- the gas cell can hold steady pressures of Helium gas from $2 \times 10^{-3}$ mbar to 1250 mbar,
- the proton source is constructed and operating ($R \approx 20$ kHz)
- detector response well understood

Current Issues:

- breakdown inside the gas
- increases of detector leakage current

Once these are resolved, we will measure proton energy spectra for various strengths of the electric field and densities of the gas. These spectra will be compared to those that have been caclculated from the Monte Carlo simulations.

# CoolSim

We are developing a simulation package based on Geant4 called CoolSim, optimized for tracking particles of particles in (gaseous) matter.

CoolSim features

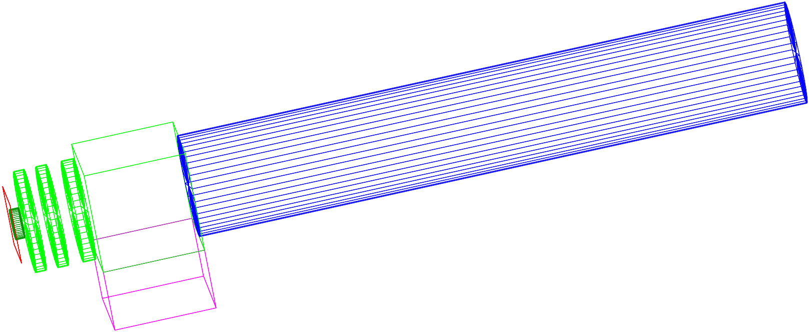
- a human-readable macro-command interface
- capability to implement geometries quickly and modularly
- direct ROOT-tree output
- New physics processes:
  - Charge Exchange / Effective Charge (current):
    - calculation of particle's effective charge as function of material and energy
    - discrete charge changes when transitioning from medium to vacuum
    - planned expansion to low-density discrete charge changes and nongasseous materials
  - $\mu^-$ capture (planned)

# Low-Energy $\mu^+$ Source

A CoolSim application example: a frictional cooling scheme for a low-energy surface muon beam.

The input parameters for the simulation were taken from the Paul Scherrer Institute's muon beam: 4 MeV beam with large momentum spread and angular spread.

The cooling scheme consists of a thin ($\approx 100\mu\mathrm{m}$) Tungsten foil, shown in red; followed by a solenoidal magnetic field (1 T), a FODO cell (0.8 T/m), and a weak dipole (5 mT), all shown in green; then a Helium gas cell ($0.011\mathrm{mg/cm^3}$) with an axial electric field ($0.8\mathrm{MV/m}$) aligned towards the dipole, shown in blue.



# Low-Energy $\mu^+$ Source

```
/CoolSim/AddBox Foil
/CoolSim/Foil/SetX 600 600 0.1 mm
/CoolSim/Foil/SetTranslation 0 0 0.5 cm
/CoolSim/Foil/AddMaterial
/CoolSim/Foil/AddMaterial G4\_W  1.
/CoolSim/Foil/SetDensity 19.3 g/cm3

/CoolSim/AddQuadrupole Q1
/CoolSim/Q1/SetDiameter 100 cm
/CoolSim/Q1/SetLength 10 cm
/CoolSim/Q1/SetTranslation 0 0 18 cm
/CoolSim/Q1/SetMagnitude 3 T/m

/CoolSim/AddBox D1
/CoolSim/D1/SetXYZ 100 100 100 cm
/CoolSim/D1/SetTranslation 0 0 125 cm
/CoolSim/D1/AddEMField
/CoolSim/D1/B/y/SetEquation [0]
/CoolSim/D1/B/y/SetParameter 0 0.005 tesla

/CoolSim/AddCell GasCell
/CoolSim/GasCell/SetLength 600 cm
/CoolSim/GasCell/SetDiameter 100 cm
/CoolSim/GasCell/SetTranslation 0 0 475 cm
/CoolSim/GasCell/AddMaterial G4\_He  1.0
/CoolSim/GasCell/SetDensity 0.011 mg/cm3
/CoolSim/GasCell/E/z/SetEquation [0]
/CoolSim/GasCell/E/z/SetParameter 0 -0.8 megavolt/m
/CoolSim/GasCell/B/z/SetEquation [0]
/CoolSim/GasCell/B/z/SetParameter 0 1 tesla

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/CoolSim/AddOutputFile DataFile /mnt/scratch/DataFile.root RECREATE
/CoolSim/DataFile/AddTree DataTree

/CoolSim/DataFile/DataTree/EN/On
/CoolSim/DataFile/DataTree/SN/On
/CoolSim/DataFile/DataTree/R/On
/CoolSim/DataFile/DataTree/Z/On
/CoolSim/DataFile/DataTree/PR/On
/CoolSim/DataFile/DataTree/PZ/On
/CoolSim/DataFile/DataTree/KE/On
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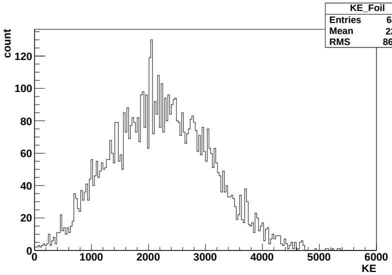
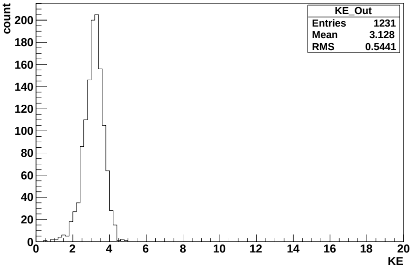
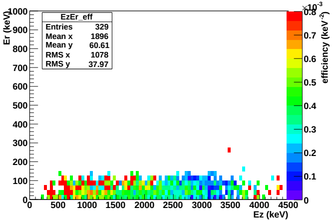
# Low-Energy $\mu^+$ Source

10k muons after the foil:




after the cooling cell + dipole



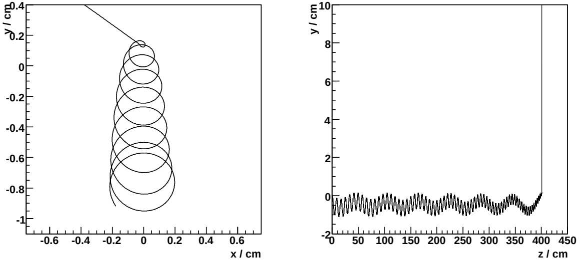
# Future

- Take FCD data for frictional cooling verification
- Implement new physics processes in CoolSim simulation
- Investigate using frictional cooling to increase efficiency of low-energy muon beams
- Expand CoolSim simulation to full muon collider front-end

The Muon Group at the Max-Planck-Institute für Physik:

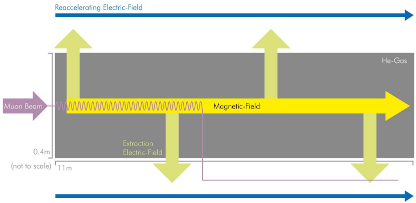
Allen Caldwell, Daniel Greenwald, Bao Yu, Brodie McKenzie, Andrada Ianus; and Daniel Kollar, Raphael Galea, Christian Blume.

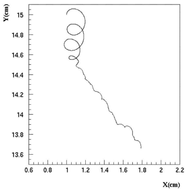
# Slowing down of fast muons

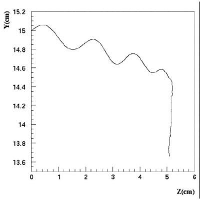


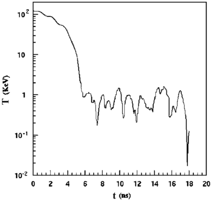
# Frictional Cooling Cell

Muons are guided through gas cell by magnetic field (B⊥E), losing energy until they are below the ionization peak of the $\mathrm{d}E/\mathrm{d}s$ curve.



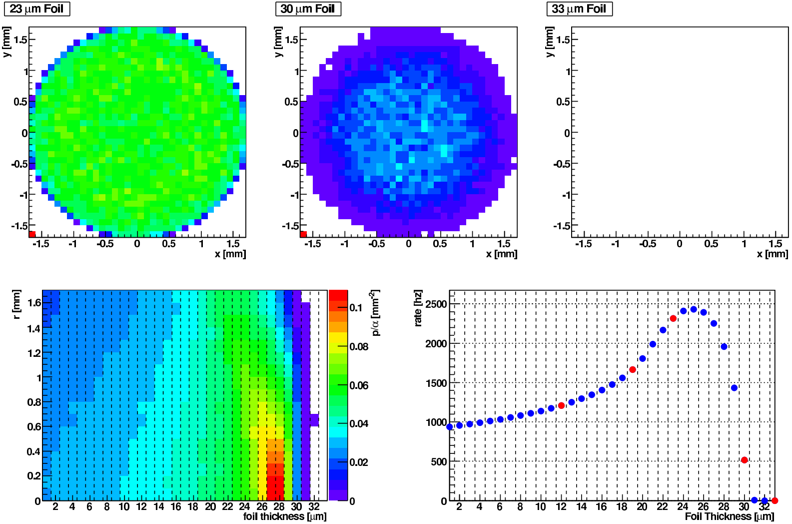



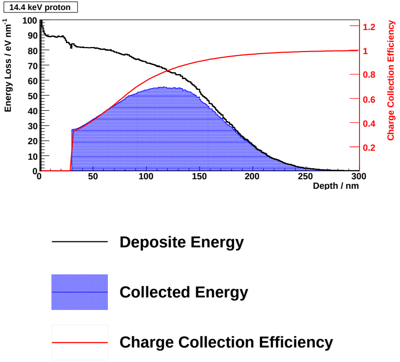
# Proton Source Simulation

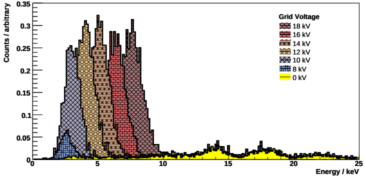
MC (Geant4) simulation of proton source used to predict spacial distribution of protons.

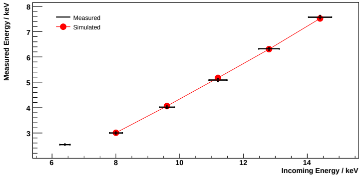


We observe protons with energies between 5 keV and 30 keV. At these energies they deposite all their energy in the first several hundred nanometers of the detector. The detector's dead layers greatly effect how much energy is measured.

The expected proton energies are used to discover the dead-layer characteristics of the SDD.



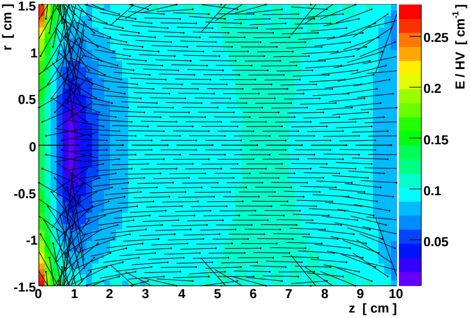



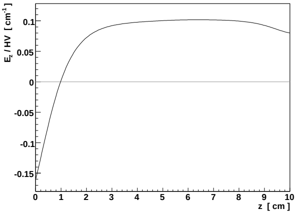



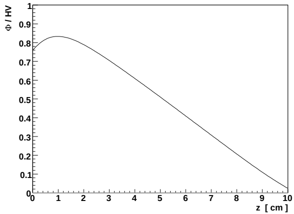
# FCD Cell Simulation

A simulation of the gas cell used in the Fricional Cooling Demonstration experiment is used to predict the energies we will measure when running the experiment.

The electric field calculated from the actual accelerating grid construction is used in the simulations of the FCD cell.



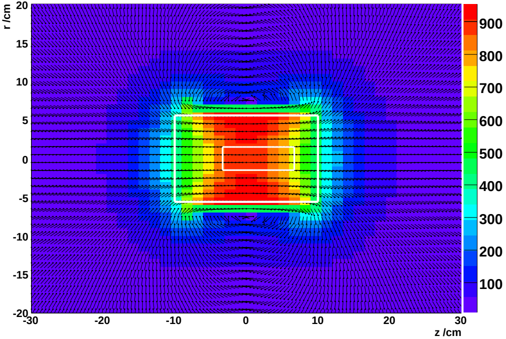



A superconducting magnet is used to provide a collimating magnetic field, along the central axis of the cooling cell. The field strength has been modeled for use in simulations.

Magnet Core

Magnetic Field



These simulations have shown the strong effect of the collimating magnetic field.