Frictional Cooling

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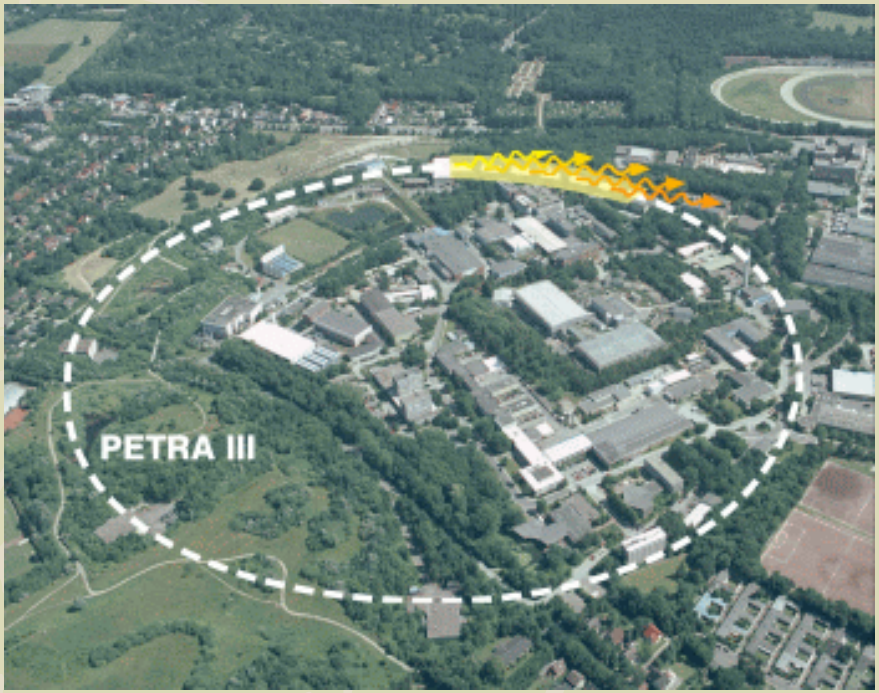
Motivation: Muon Collider

→ compared to electrons:

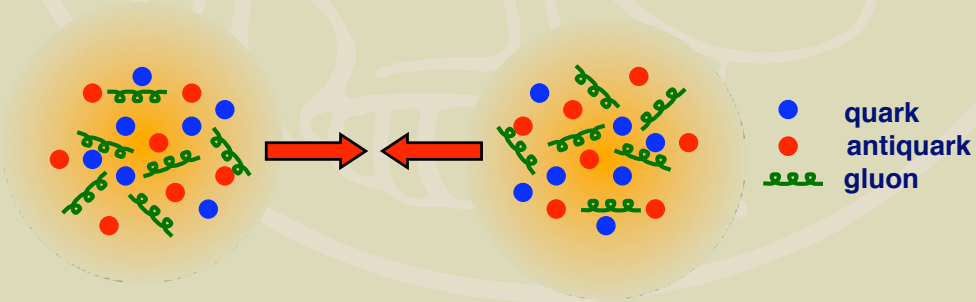
no synchrotron radiation problem

$$P \propto (E/m)^4$$

⇒ **very high energy circular accelerator can be built**

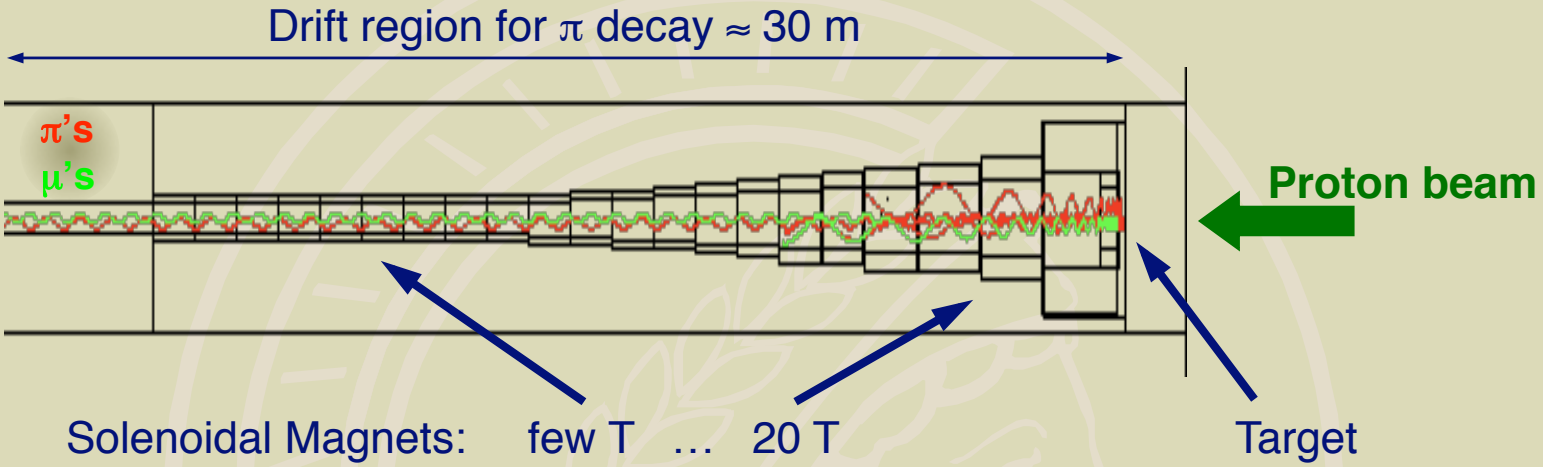


→ compared to protons:



- colliding **point particles** rather than complex objects

μ beam production



beam description using 6D emittance

(6D phase space of the beam)

$$\varepsilon_{6D,N} = \frac{\sigma_x \sigma_y \sigma_z \sigma_{p_x} \sigma_{p_y} \sigma_{p_z}}{(\pi mc)^3}$$

after drift estimate

rms: x,y,z 0.05, 0.05, 10 m

p_x,p_y,p_z 50, 50, 100 MeV

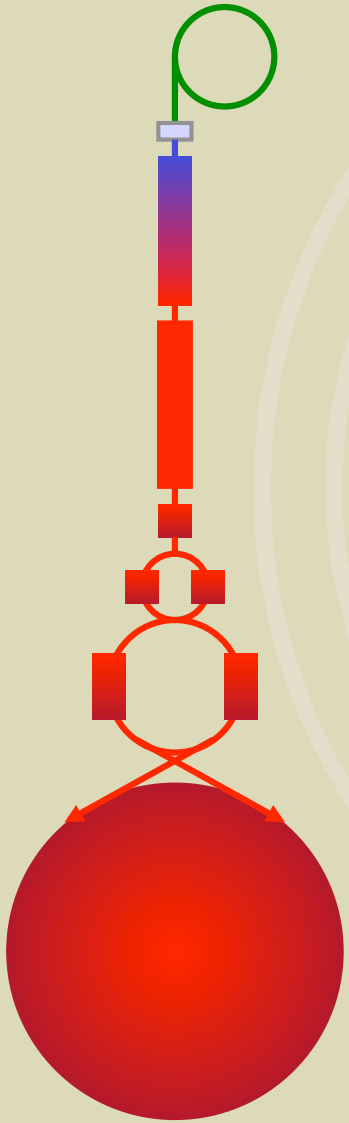
$\varepsilon_{6D,N} \approx 1.7\times10^{-4}$ $(\pi m)^3$

required

$\varepsilon_{6D,N} \approx 1.7\times10^{-10}$ $(\pi m)^3$

COOLING

Typical muon collider scheme



Proton accelerator – 2-16 GeV, few MW (10^{22} p/year)

π production target

π decay channel

μ cooling channel

→ standard techniques too slow

→ new techniques are being developed

- energy loses in interactions with matter
- reaccelerating
- magnetic focusing

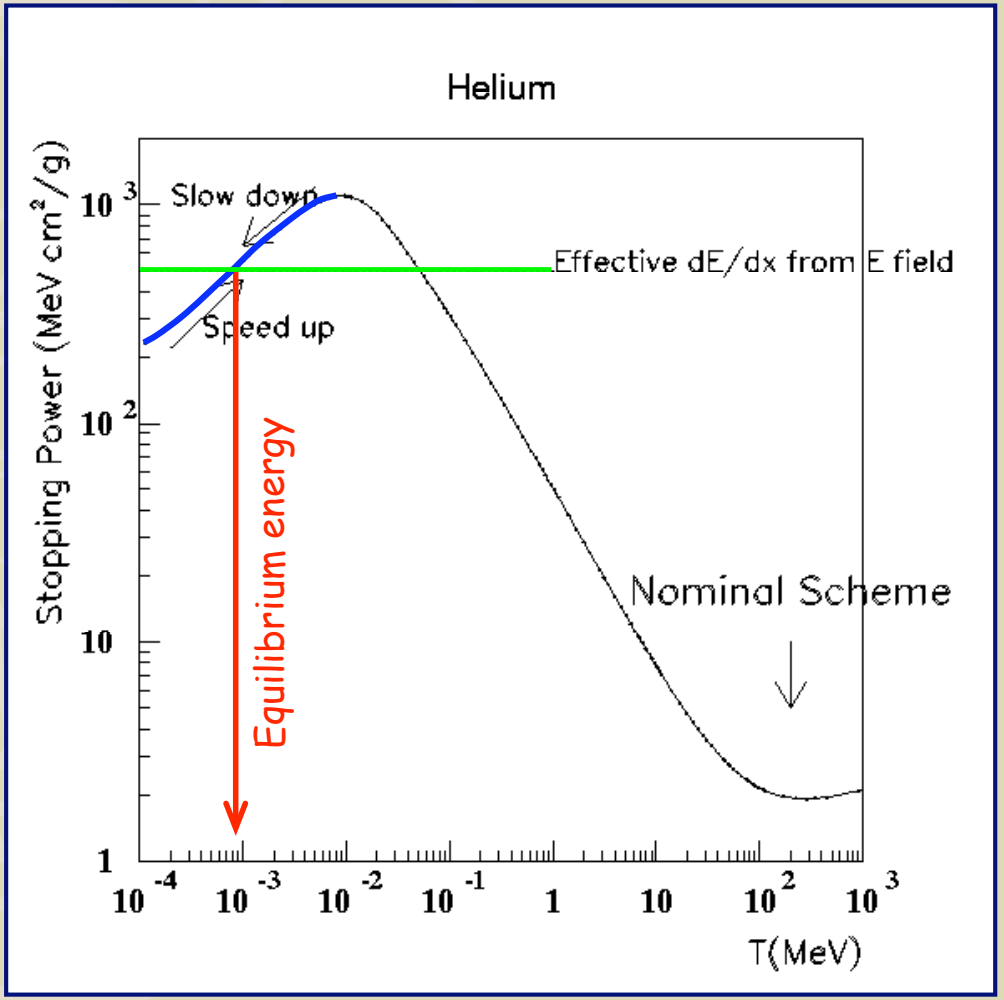
μ accelerators

Muon collider

Frictional cooling

Idea

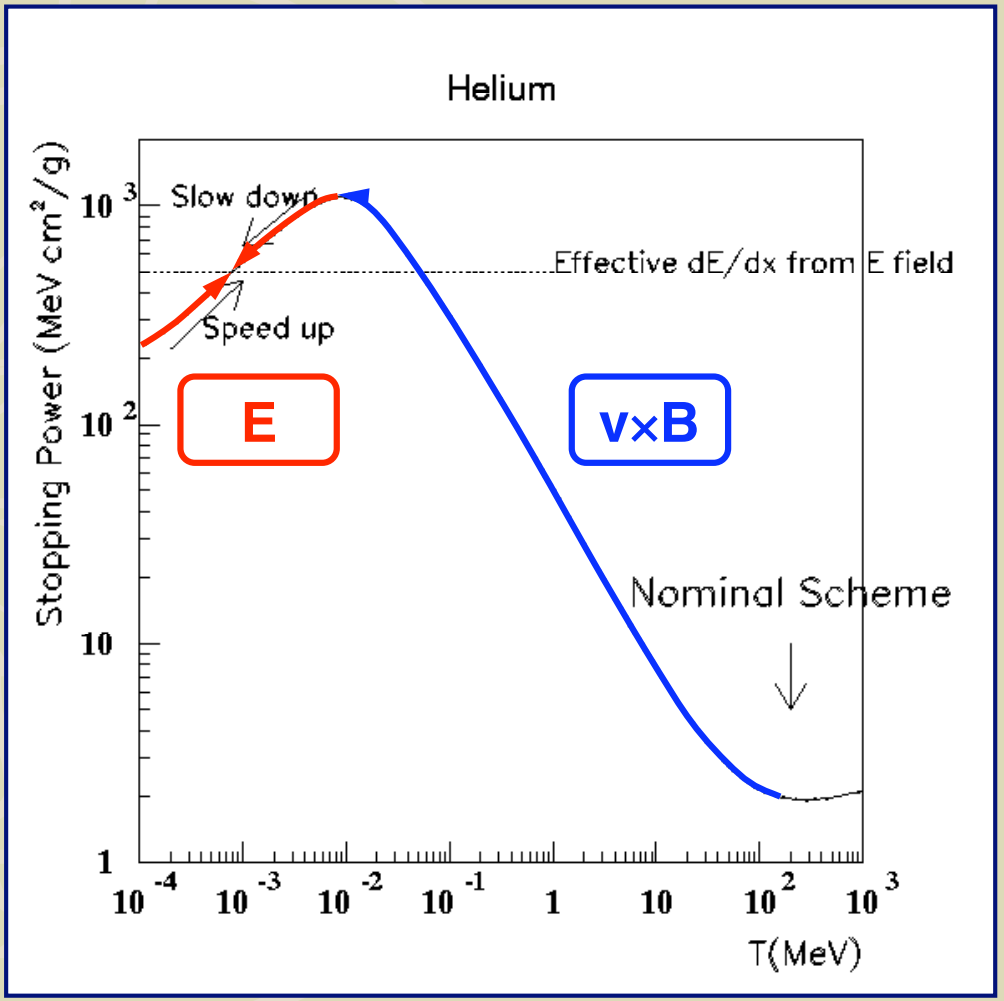
- bring muons to kinetic energy ***T*** where ***dE/dx*** increases with energy
- apply constant accelerating ***E*** field to muons resulting in **equilibrium energy**
- big issue – how to maintain efficiency
- similar idea first studied by Kottmann et al. at PSI



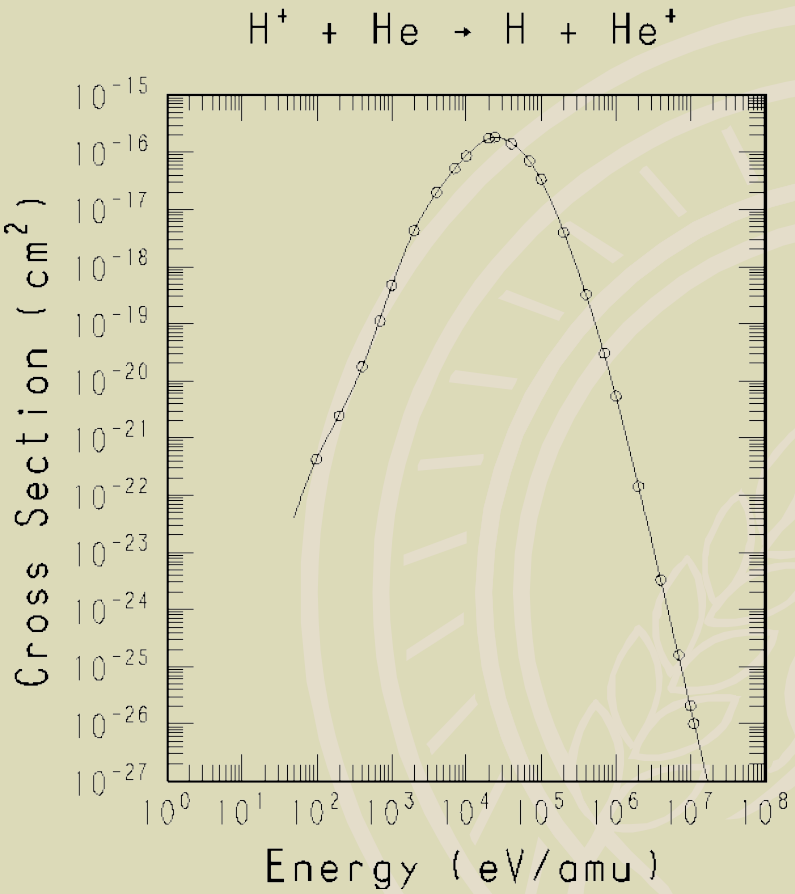
Frictional cooling

Problems/Comments

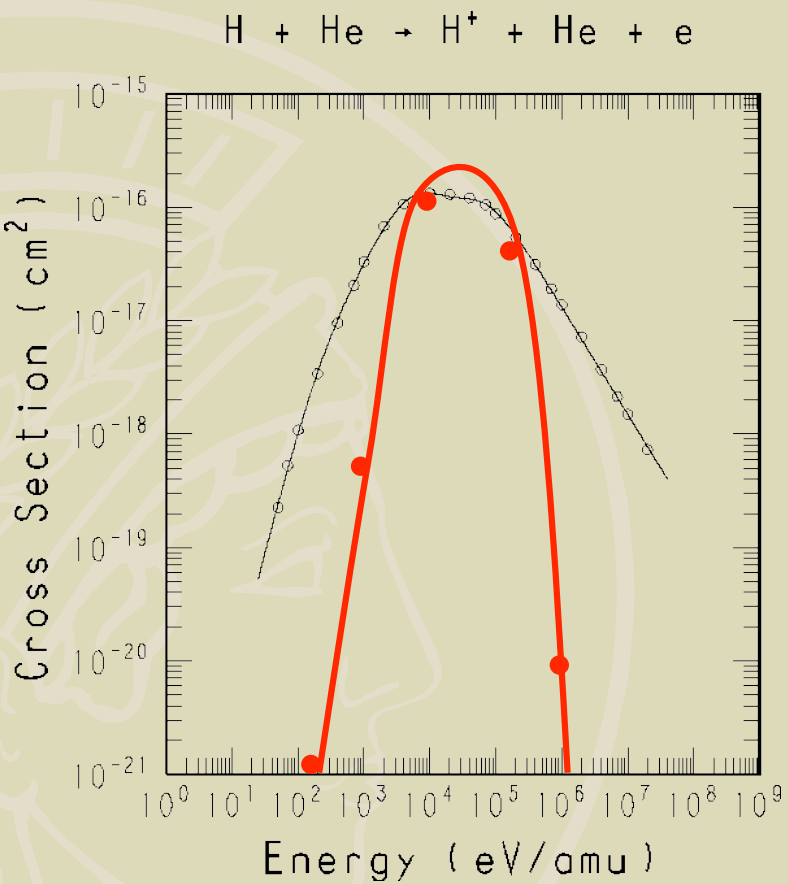
- large ***dT/dx*** at low ***T***
  → low average density of stopping medium ⇒ **gas**
- apply **E⊥B** to get below the *dE/dx* peak $\vec{\mathbf{F}} = q(\vec{\mathbf{E}} + \vec{\mathbf{v}} \times \vec{\mathbf{B}}) - \frac{dT}{dx}\vec{\mathbf{v}}_0$
- **slow μ's** don't go far before decaying $d = 10\,\mathrm{cm} \times \sqrt{T}$ with T in eV
  → sideward extraction (**E⊥B**)
- μ^+ problem – **muonium formation** dominates over e-stripping except for **He**
- μ^- problem – **muon capture** at low energies; σ not known
  ⇒ keep ***T*** as high as possible



Neutralization



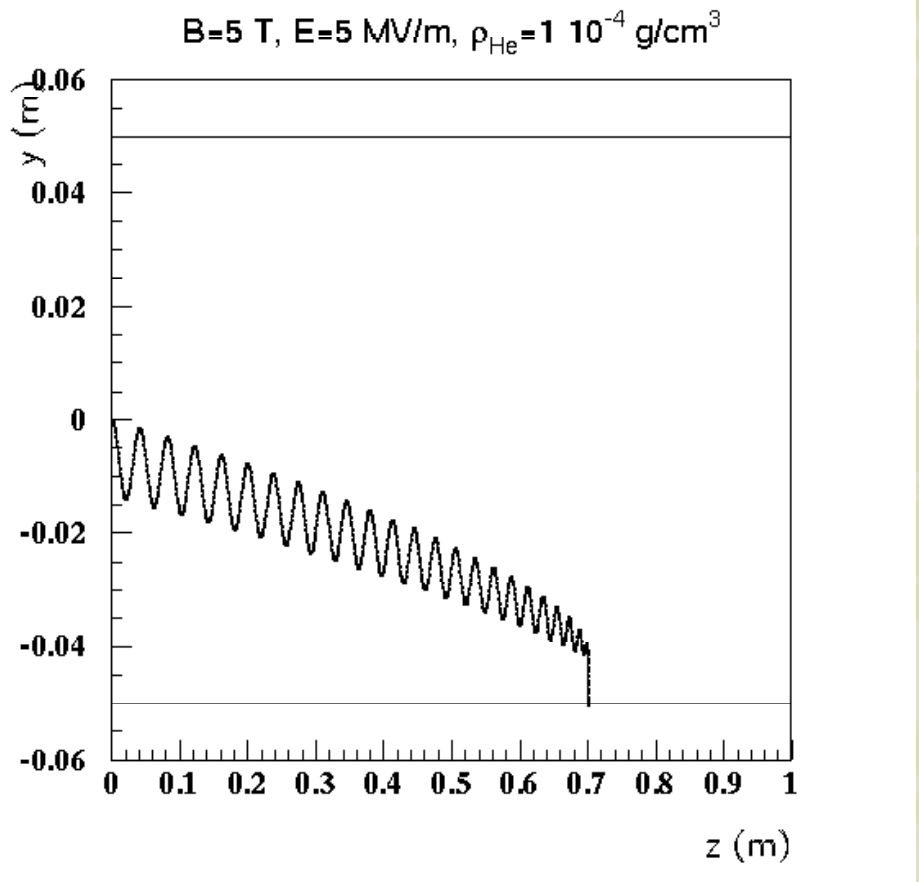
Stripping

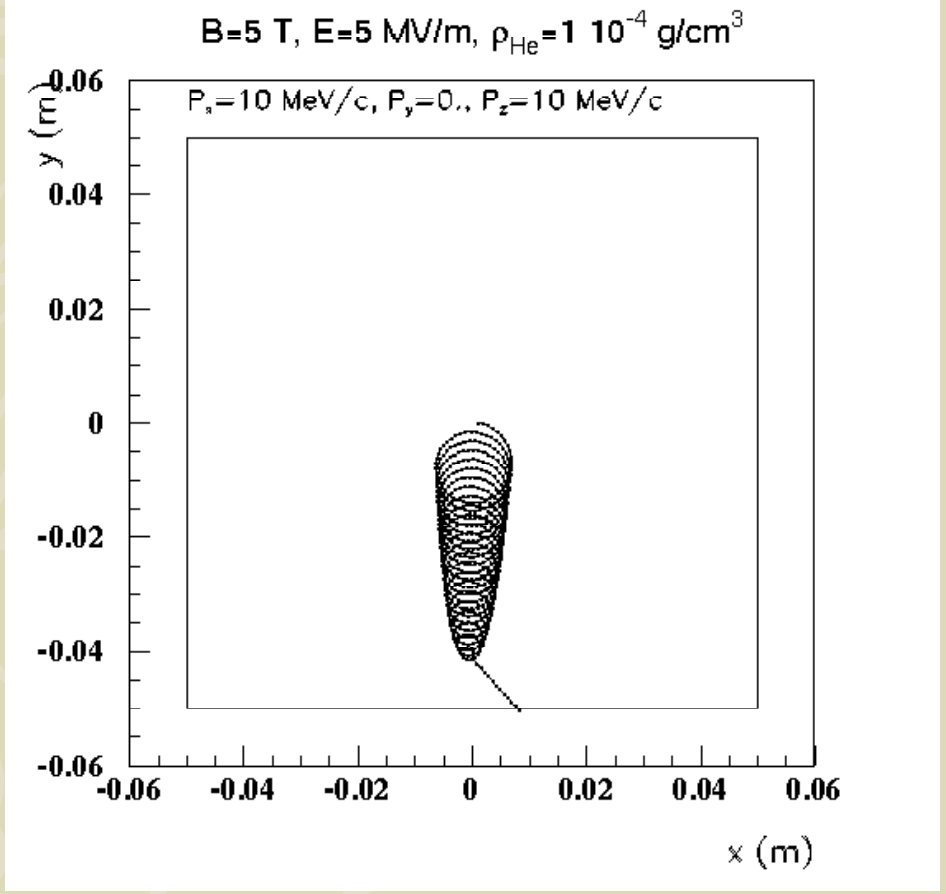


From Y. Nakai, T. Shirai, T. Tabata and R. Ito, *At. Data Nucl. Data Tables* **37**, 69 (1987)

For μ, energy lower by M_μ/M_P

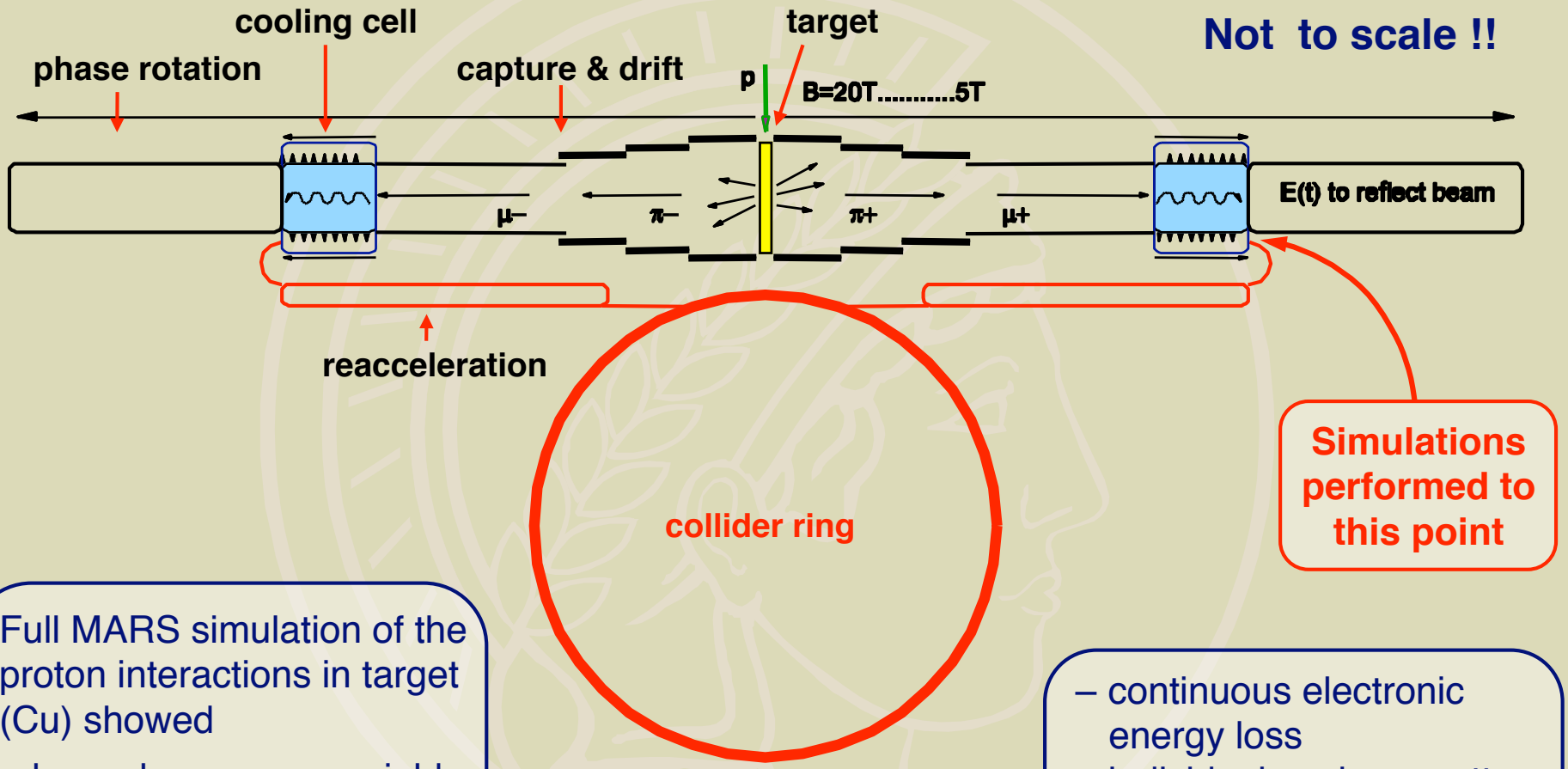
Frictional Cooling: particle trajectory





** Using continuous energy loss

Muon collider scheme based on frictional cooling



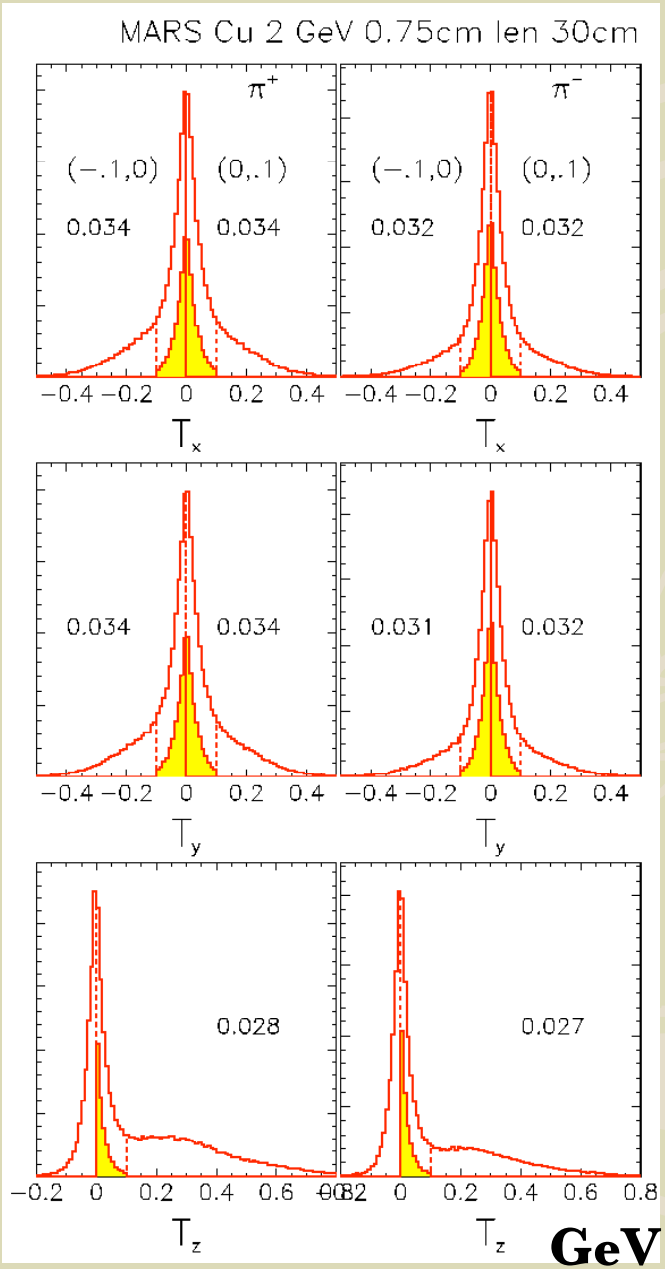
Full MARS simulation of the proton interactions in target (Cu) showed

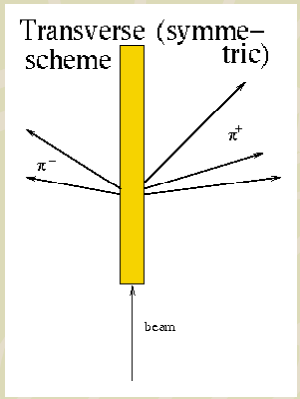
– larger low energy π yield in transverse directions
– nearly **equal π^+ and π^- yields** with $T < 100$ MeV

– **He** gas used for μ^+
– **H** gas for μ^-
– transverse ***E*** field **5 MV/m**

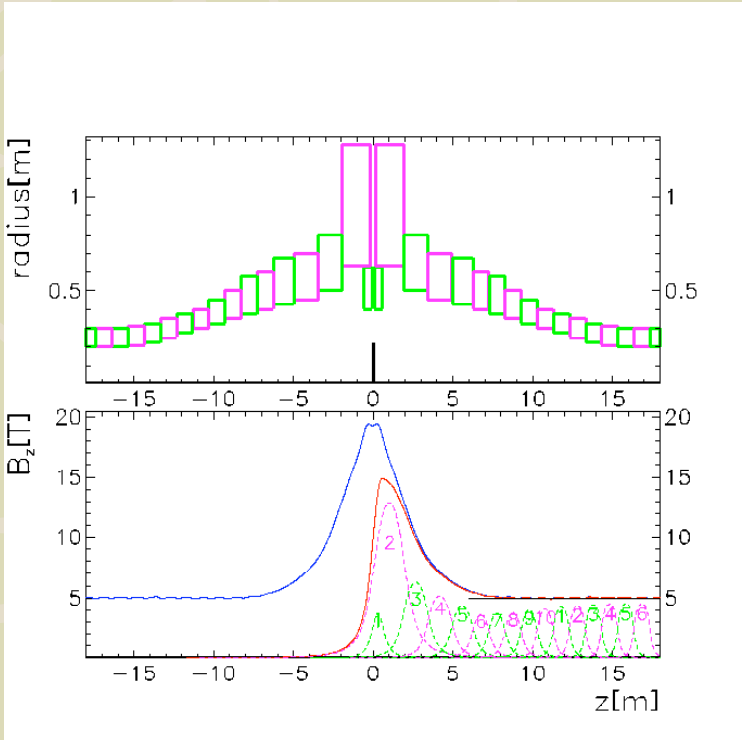
– continuous electronic energy loss
– individual nuclear scatters simulated
→ they result in large angles

Target System

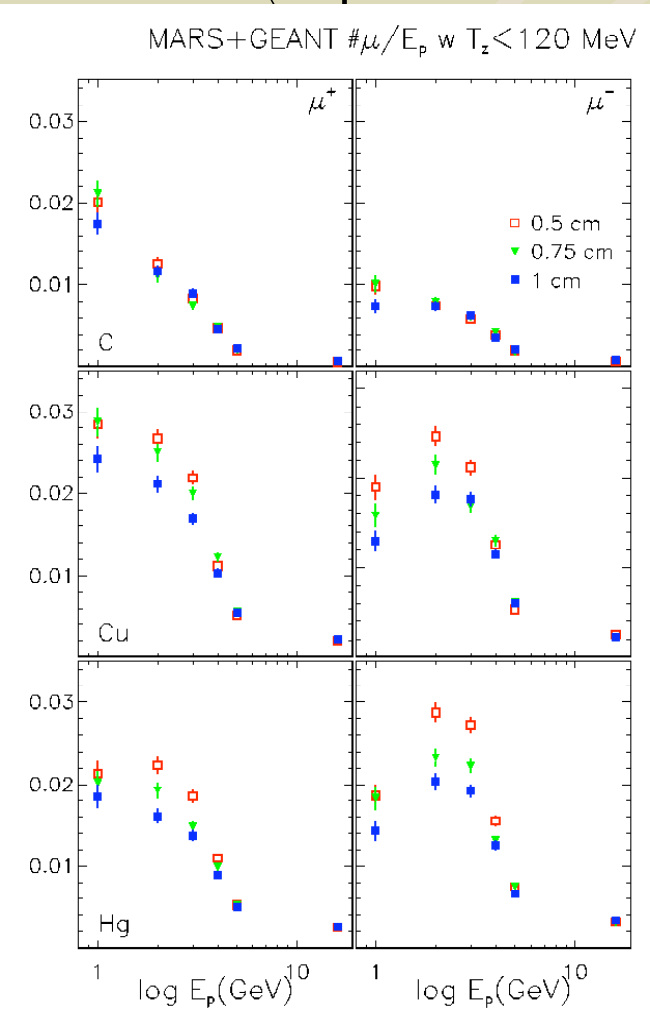


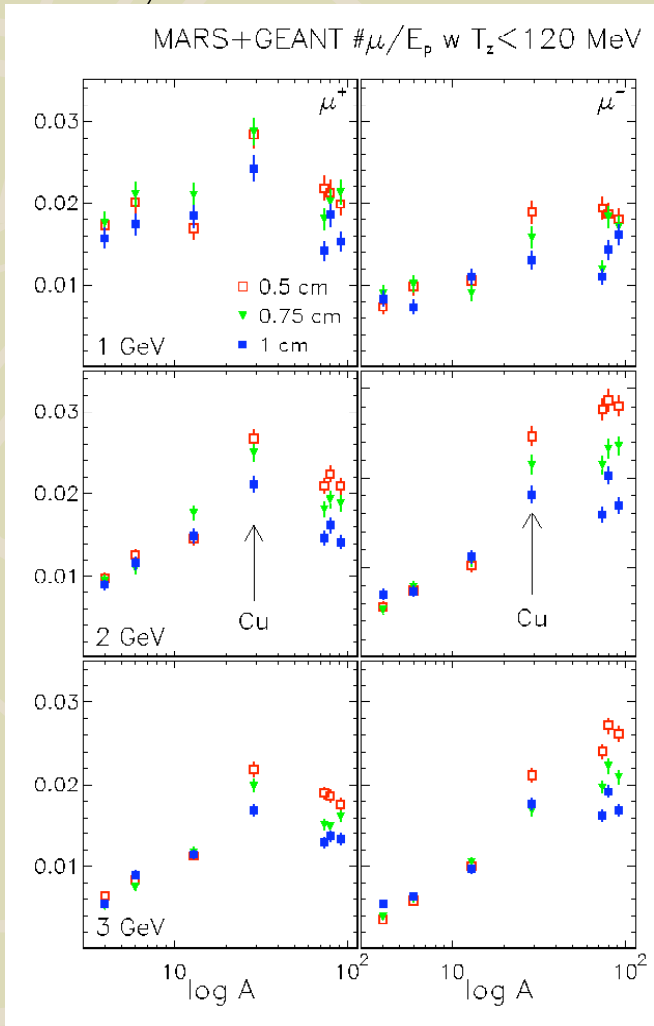


- cool μ^+ & μ^- at the same time
- calculated new symmetric magnet with gap for target



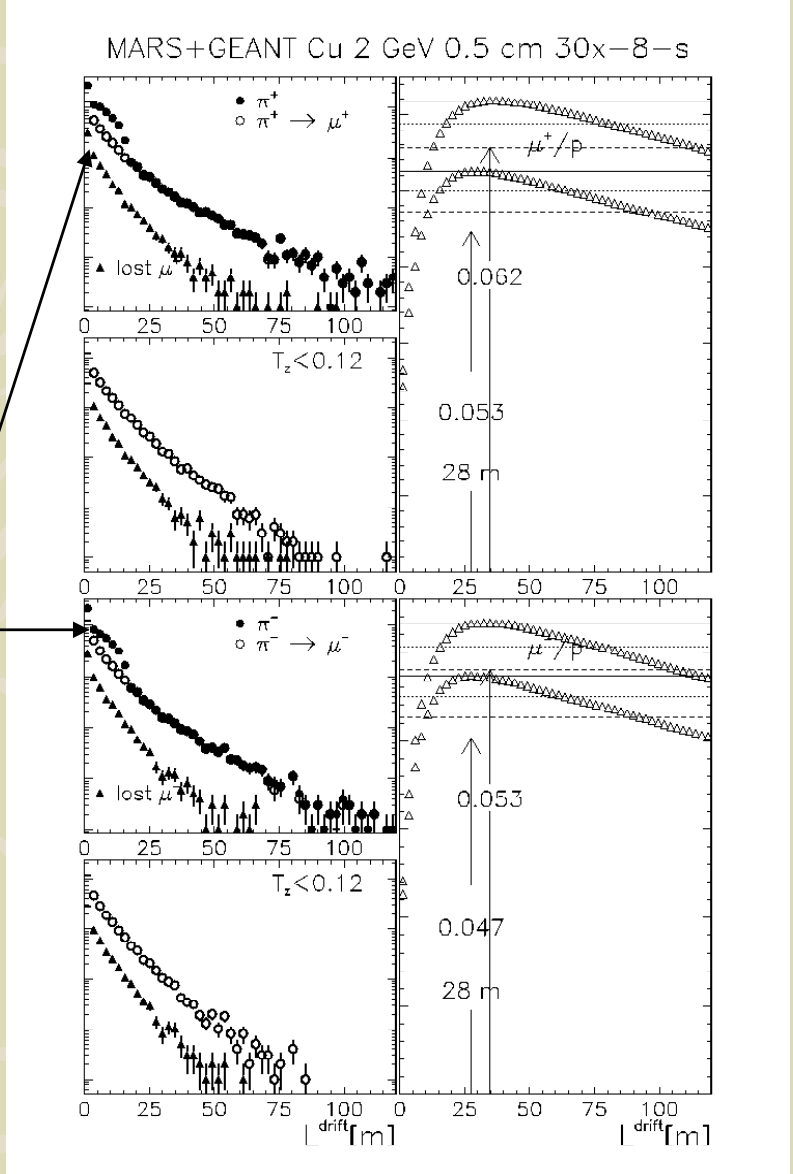
Full MARS target simulation, optimized for low energy muon yield: 2 GeV protons on Cu with proton beam transverse to solenoids (capture low energy pion cloud).



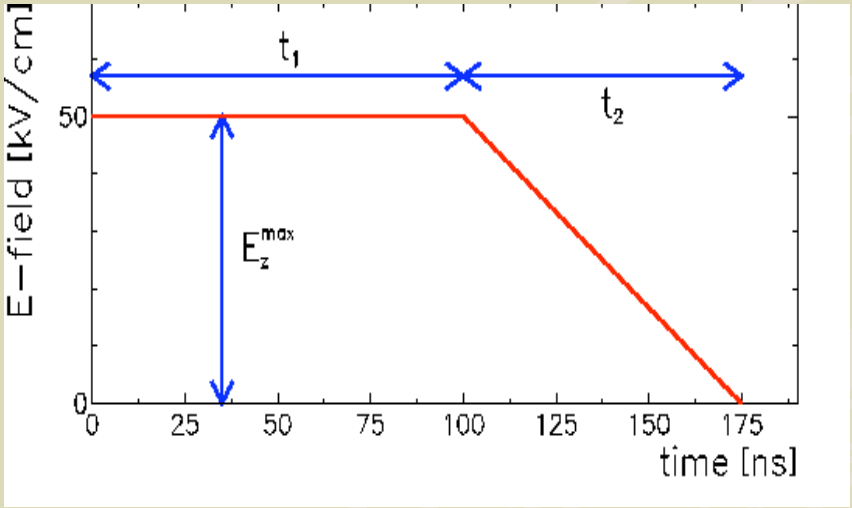


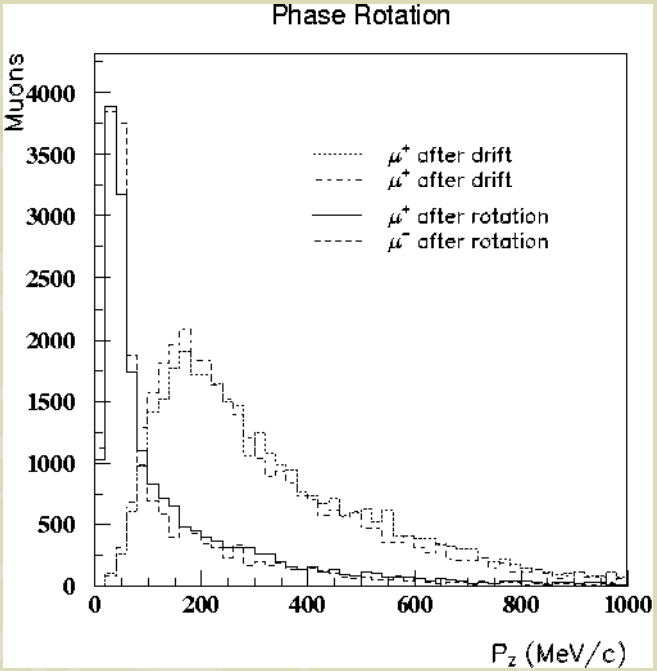
Target & Drift Optimize yield

- Optimize drift length for μ yield
- Some π's lost in Magnet aperture

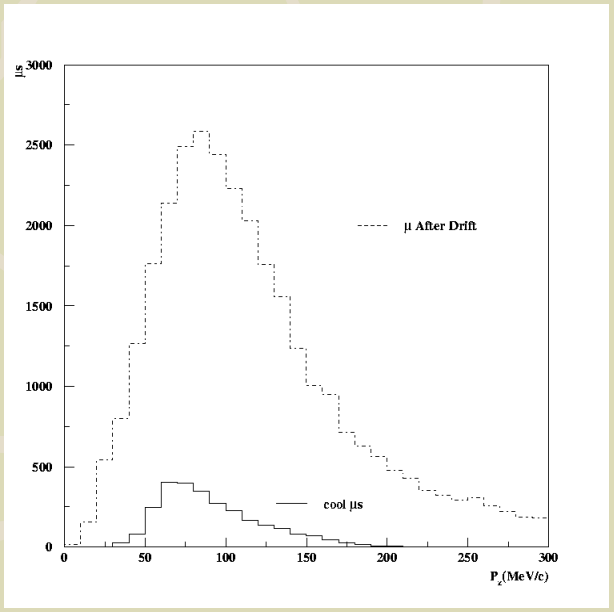


Phase Rotation





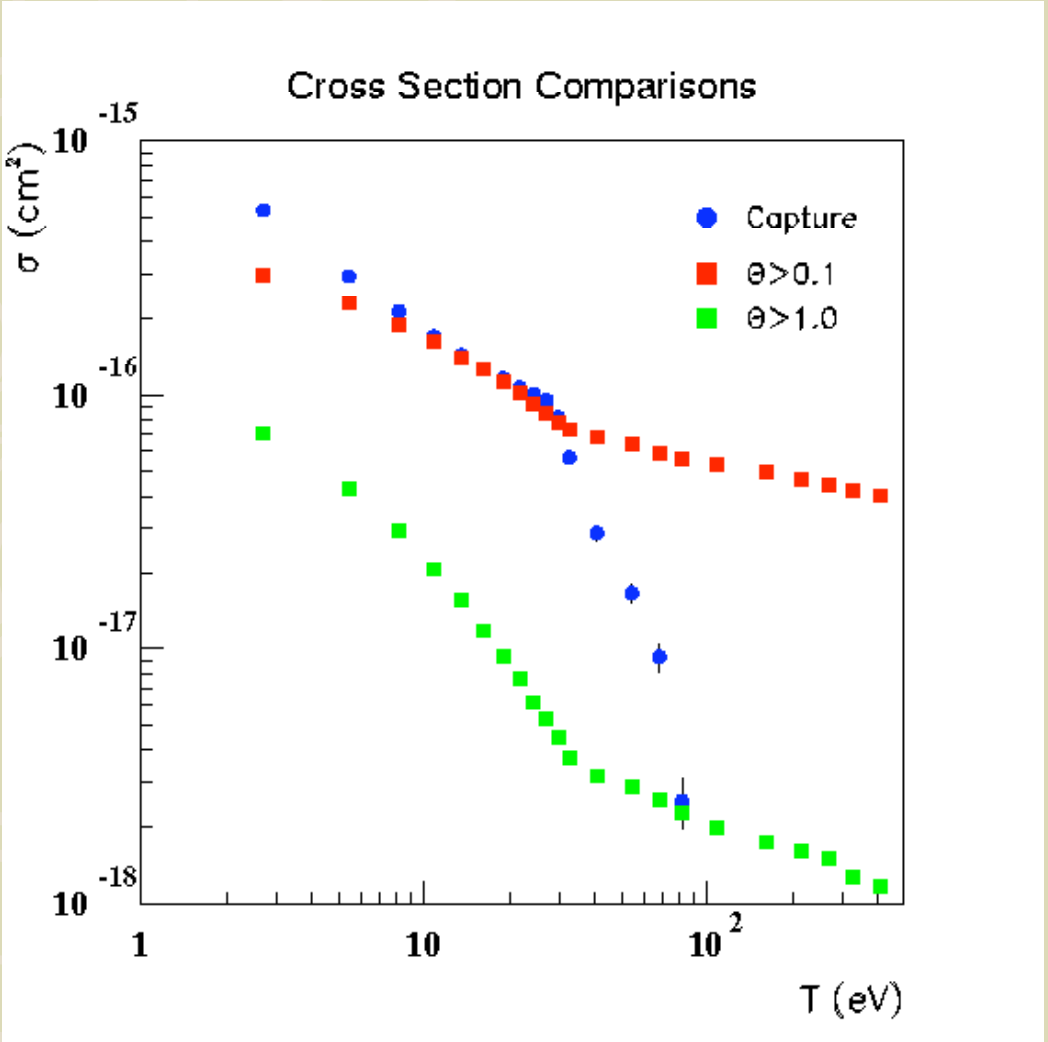
- First attempt simple form
- Vary t_1,t_2 & E_{max} for maximum low energy yield



Cooling cell simulation

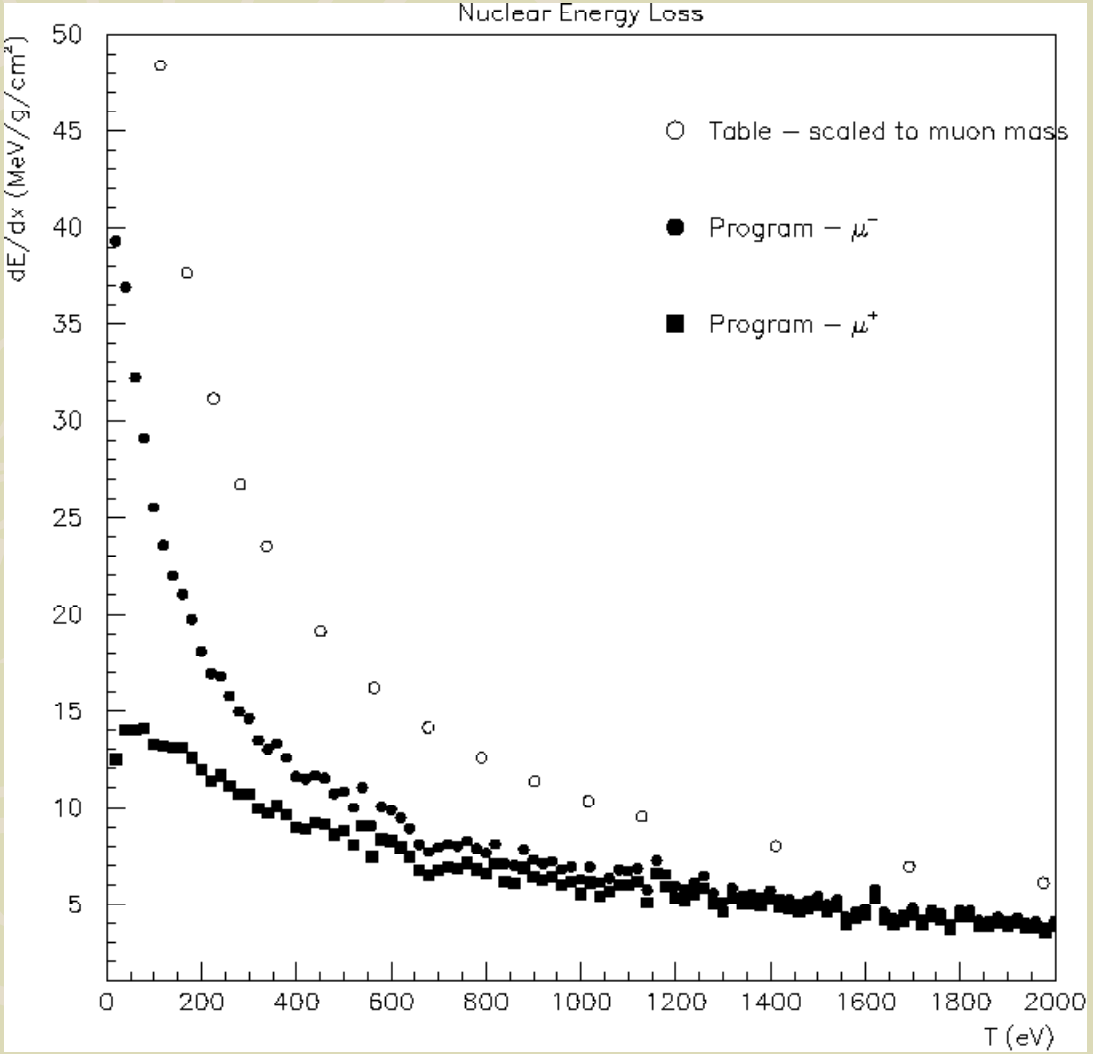
He gas is used for μ^+, H_2 for μ^-.

- Individual nuclear scatters are simulated – crucial in determining final phase space, survival probability.
- Incorporate scattering cross sections into the cooling program
- Include μ^- capture cross section using calculations of Cohen (Phys. Rev. A. Vol 62 022512-1)
- Electronic energy loss treated as continuous

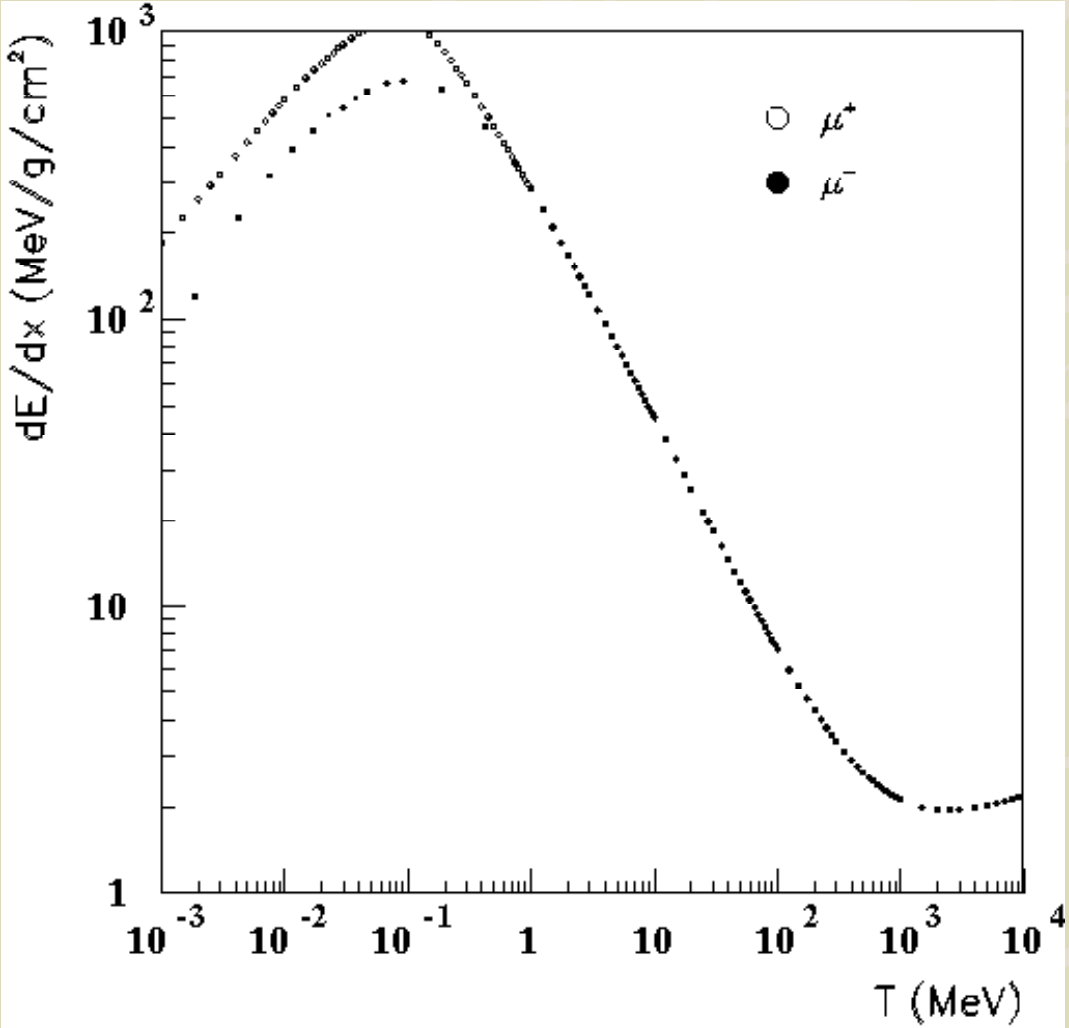


Scattering Cross Sections

- Scan impact parameter and calculate $\theta(b)$, $d\sigma/d\theta$ from which one can get $\lambda_{\text{mean free path}}$
- Use screened Coulomb Potential (Everhart et. al. Phys. Rev. 99 (1955) 1287)
- Simulate all scatters $\theta > 0.05$ rad
- Simulation accurately reproduces ICRU tables for protons

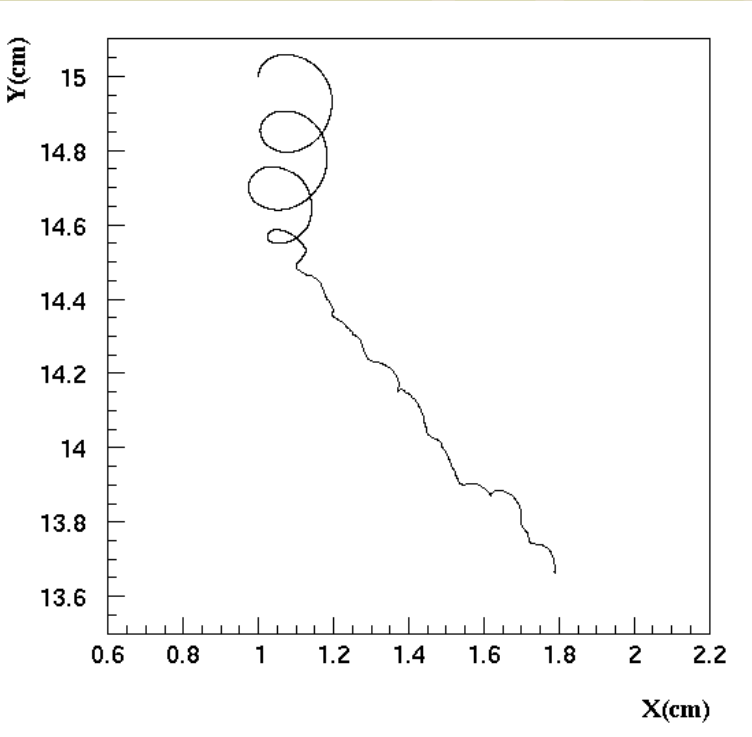


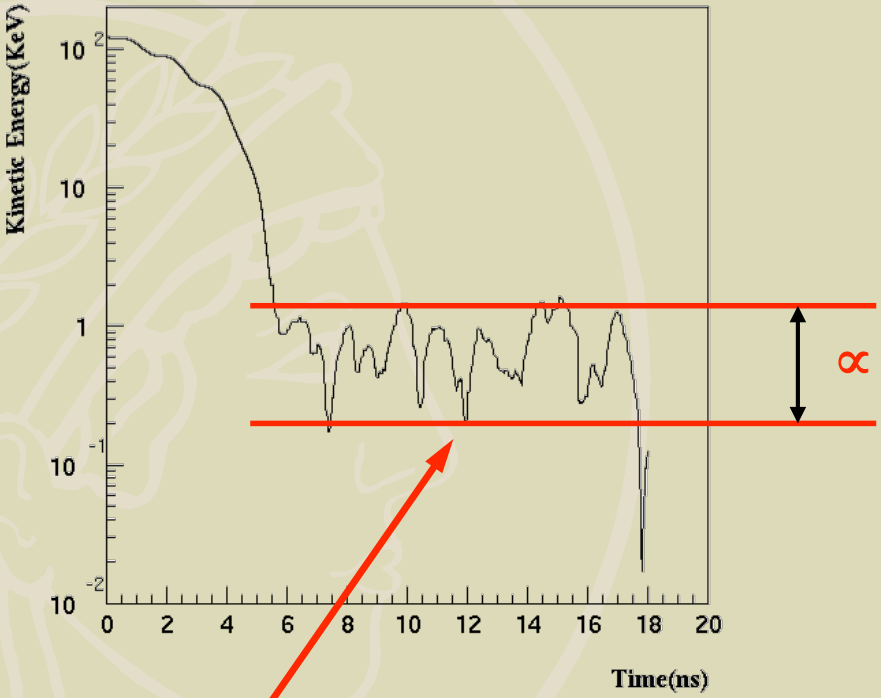
Barkas Effect



- Difference in μ^+ & μ^- energy loss rates at dE/dx peak
- Due to charge exchange for μ^+
- parameterized data from Agnello et. al. (Phys. Rev. Lett. 74 (1995) 371)
- Only used for the electronic part of dE/dx

Simulation of the cooling cell





Oscillations around equilibrium define the emittance

Resulting emittance and yield

Muon beam coming out of 11 m long cooling cell and after initial reacceleration:

rms:	x,y,z	0.015, 0.036, 30 m
	p_x,p_y,p_z	0.18, 0.18, 4.0 MeV

$\varepsilon_{6D,N} = 5.7\times10^{-11}\ (\pi m)^3$

Results for μ^+, still working on μ^-

→ better than required $\mathbf{1.7\times10^{-10}\ (\pi m)^3}$

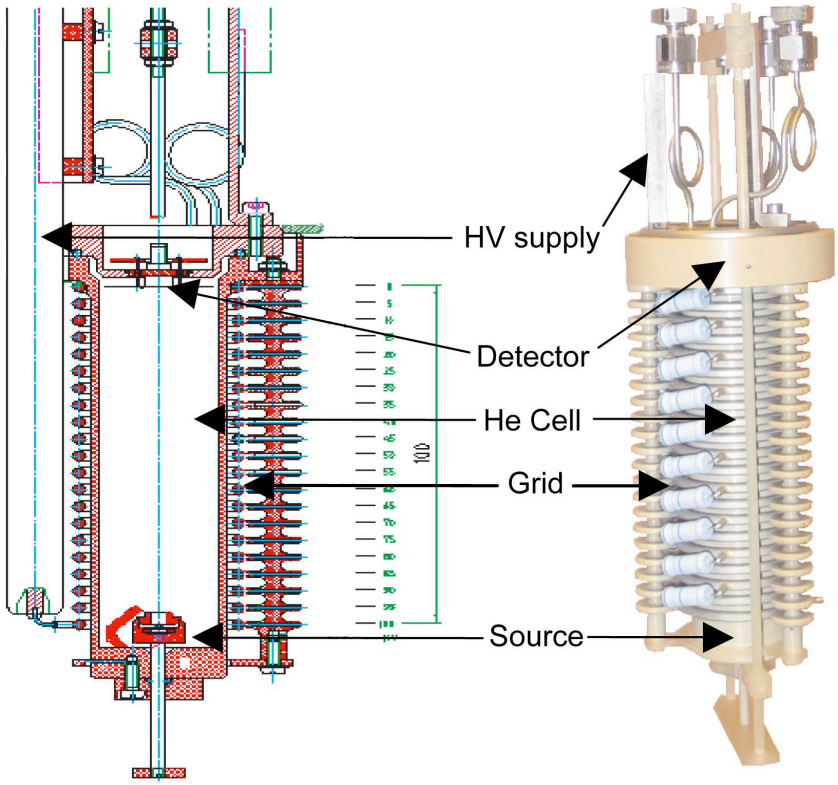
Yield ≈ **0.002 μ per 2 GeV proton** after cooling cell

→ need **improvement by factor of 5** or more

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.

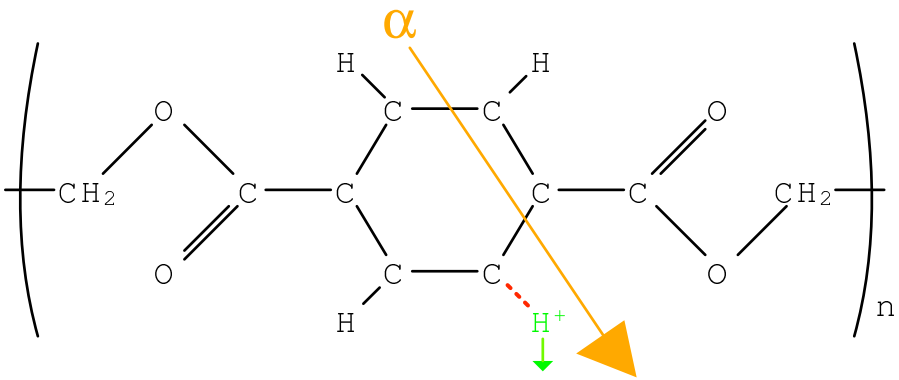
Accelerating-grid and gas-cell construction:



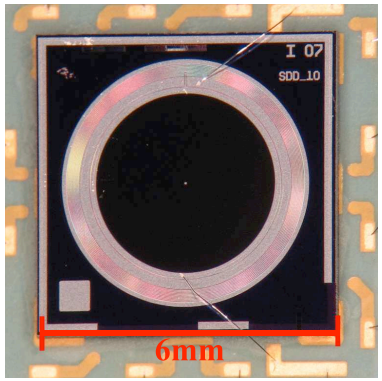
Detector mounted in gas-cell flange:

Proton Source Mechanism

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

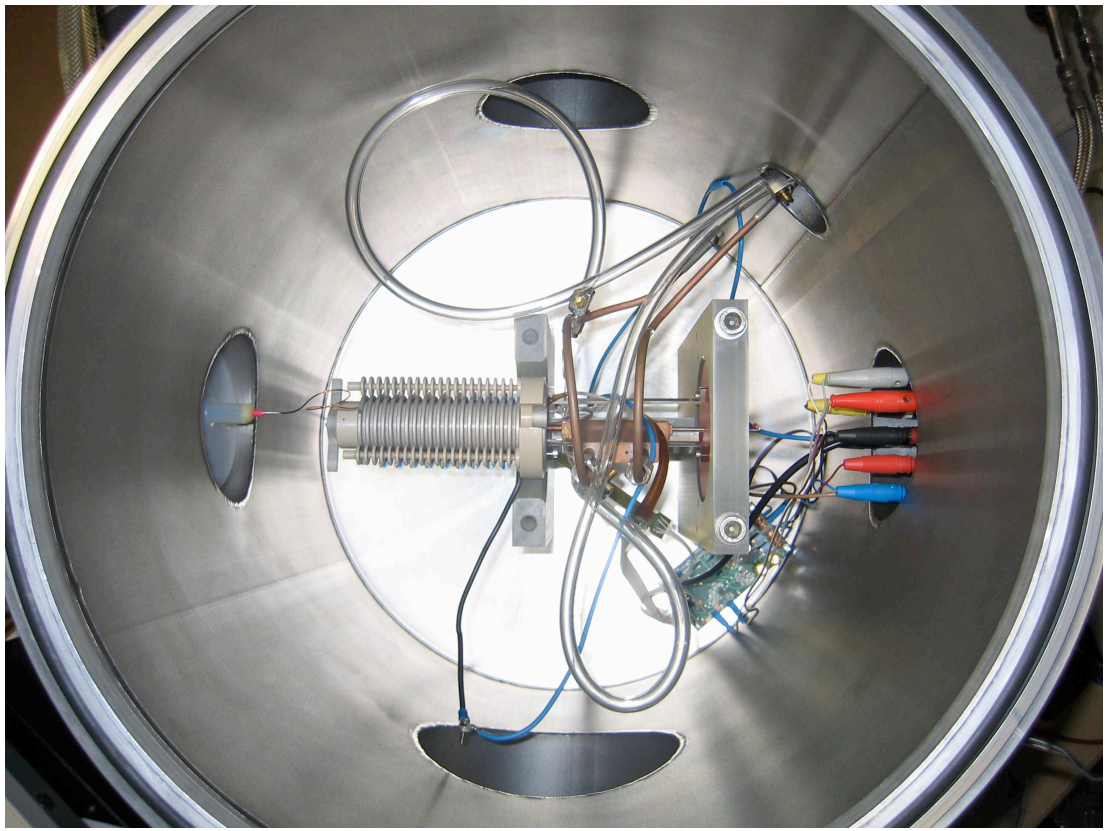


Silicon Drift Detector (from MPI-HLL)



Experimental Setup

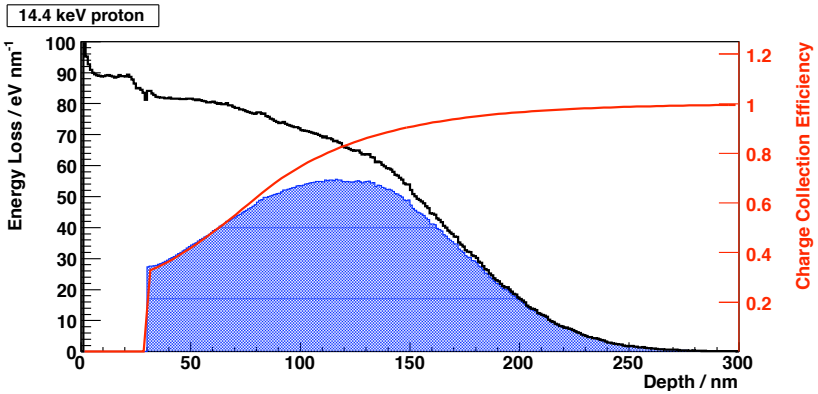
The grid has been operated up to 90 kV (0.9 MV/m), and run stably at 60 kV (0.6 MV/m) with the gas-cell filled with Helium at pressures up to 1.25 Atm.

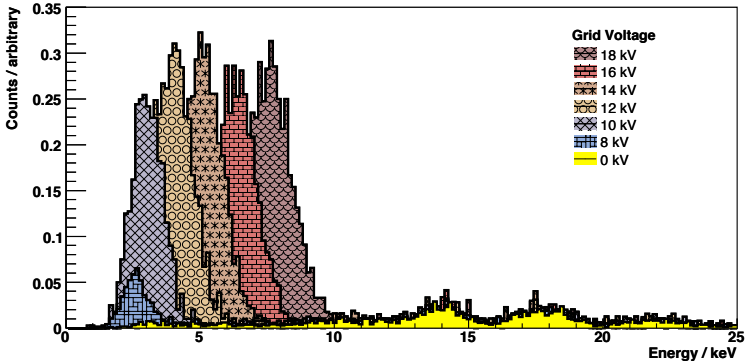


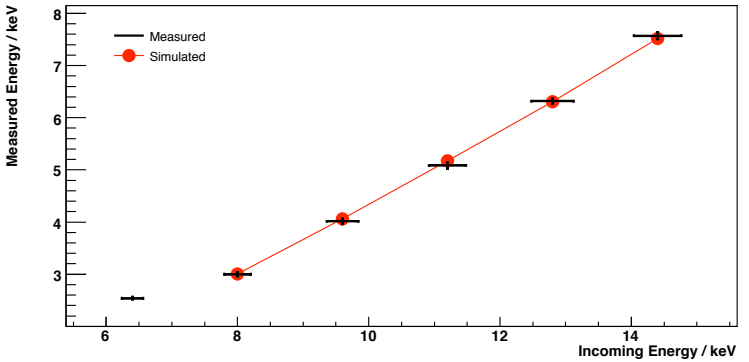
Detector Characteristics

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.







Future plans

run the experiment – demonstrate the frictional cooling

Develop scheme for producing slow muon beam using surface muon source (paper in preparation)