Muon Cooling and the Muon Collider

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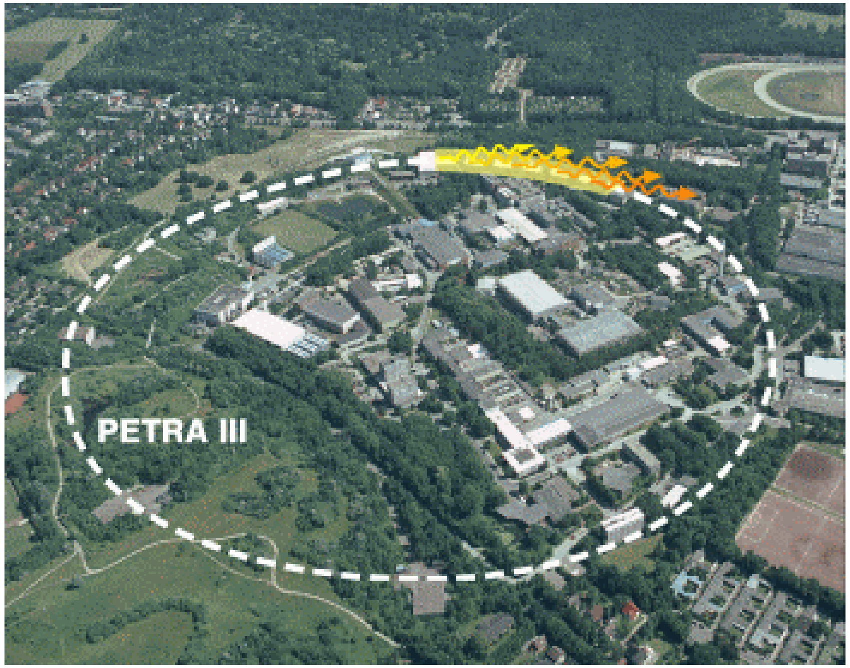
- Motivation
- Difficulties
- Focus on Cooling (frictional cooling)

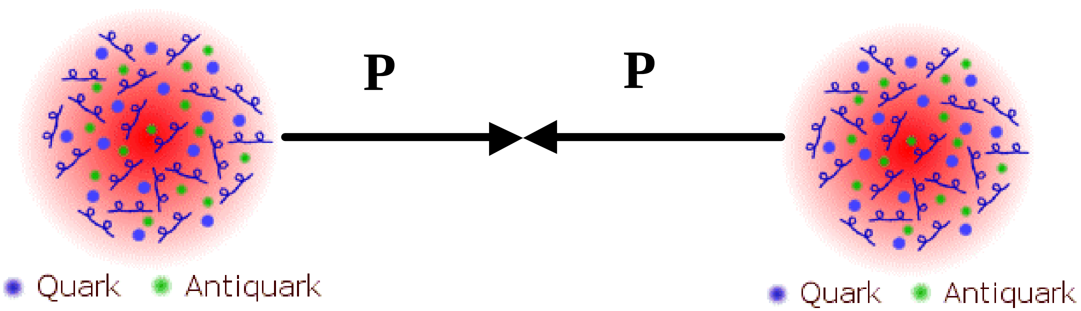
Why a Muon Collider ?

No synchrotron radiation problem (cf electron)

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

Can build a high energy circular accelerator.





Collide point particles rather than complex objects

Some Difficulties

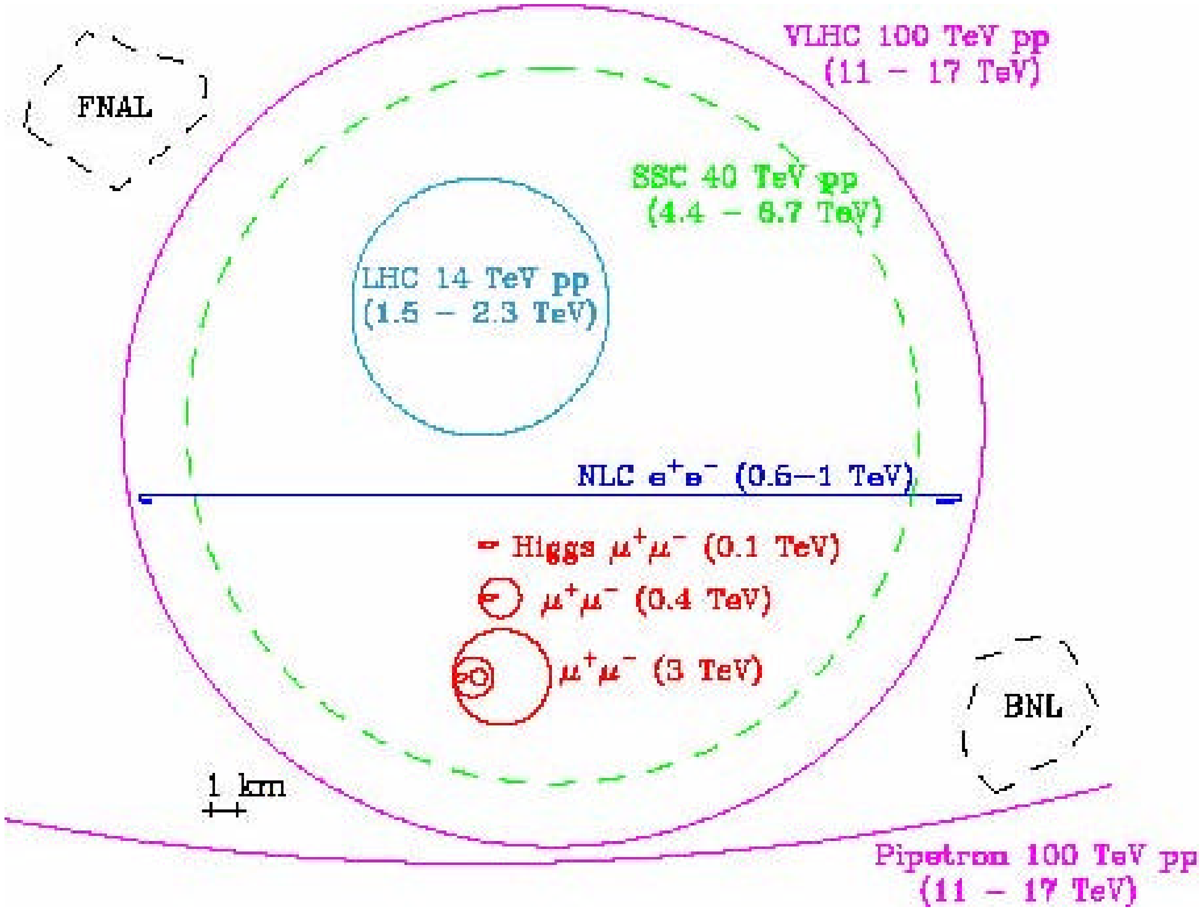
• Muons decay, so are not readily available – need multi MW source. Large starting cost.

• Muons decay, so time available for cooling, bunching, acceleration is very limited. Need to develop new techniques, technologies.

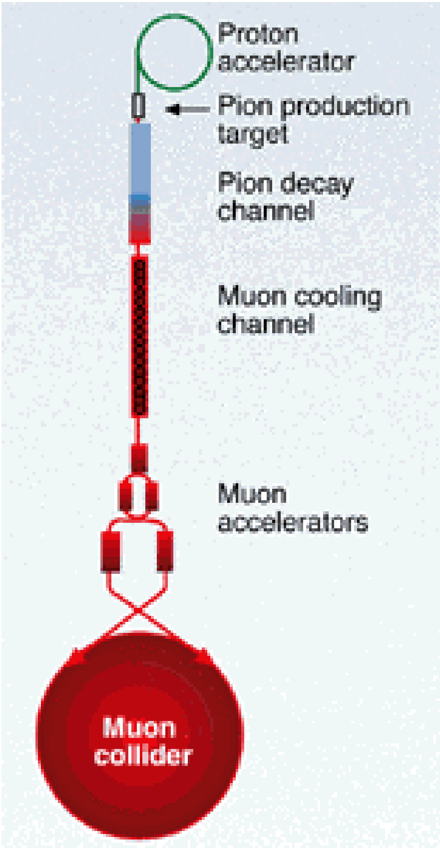
• Large experimental backgrounds from muon decays (for a collider). Not the usual clean electron collider environment.

• High energy colliders with high muon flux will face critical limitation from neutrino induced radiation.

Dimensions of Some Colliders discussed



Physics at a Muon Collider



Muon Collider Complex:

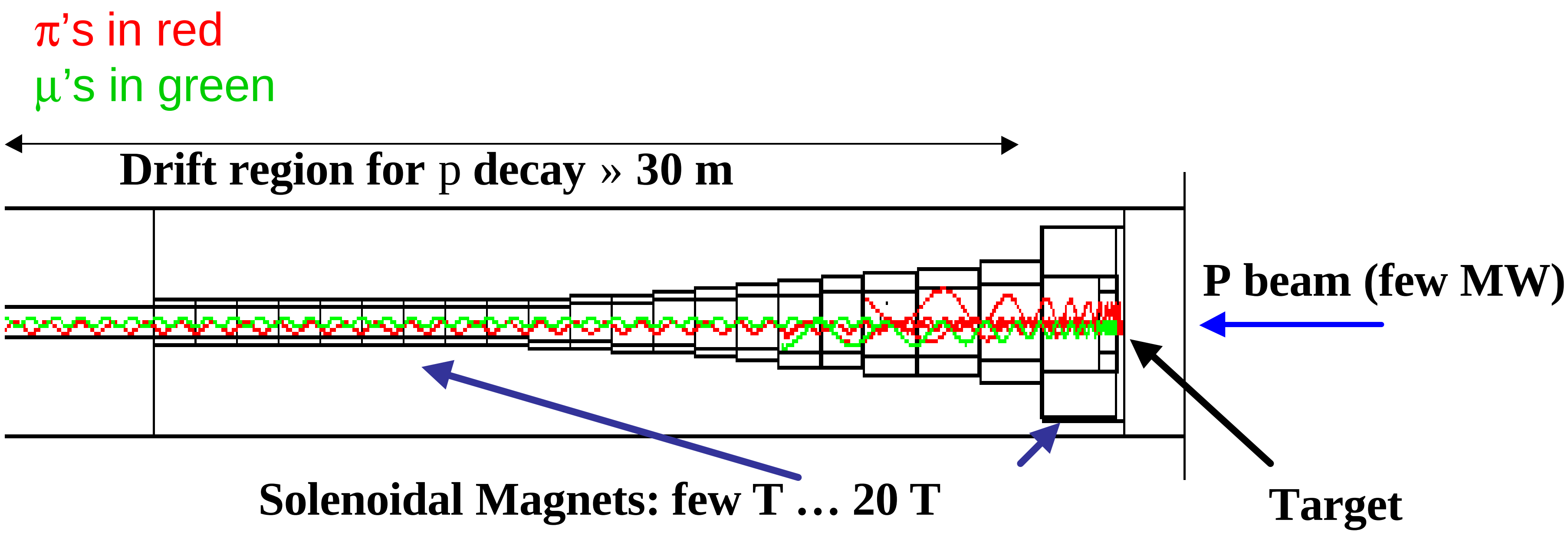
- Proton Driver 2-16GeV; 1-4MW leading to 10^{22}p/year
- π production target & Strong Field Capture
- COOLING resultant μ beam
- μ acceleration
- Storage & collisions

- Stopped μ physics
- ν physics   From target, stored μ
- Higgs Factory $\sigma_{\mu\mu\rightarrow H} = 40000\ \sigma_{ee\rightarrow H}$
- Higher Energy Frontier

HIGH ENERGY MUON COLLIDER PARAMETERS

Baseline parameters for high energy muon colliders. From "Status of Muon Collider Research and Development and Future Plans," Muon Collider Collaboration, C. M. Ankenbrandt *et al.*, *Phys. Rev. ST Accel. Beams* **2**, 081001 (1999).

COM energy (TeV)	0.4	3.0
p energy (GeV)	16	16
p's/bunch	2.5×10^{13}	2.5×10^{13}
Bunches/fill	4	4
Rep. rate (Hz)	15	15
p power (MW)	4	4
μ/ bunch	2×10^{12}	2×10^{12}
μ power (MW)	4	28
Wall power (MW)	120	204
Collider circum. (m)	1000	6000
Ave bending field (T)	4.7	5.2
rms $\delta p/p$ (%)	0.14	0.16
6D $\varepsilon_{6,N}$ $(\pi m)^3$	1.7×10^{-10}	1.7×10^{-10}
rms ε_n (π mm mrad)	50	50
β^* (cm)	2.6	0.3
σ_z (cm)	2.6	0.3
σ_r spot (μm)	2.6	3.2
σ_θ IP (mrad)	1.0	1.1
Tune shift	0.044	0.044
n_{turns} (effective)	700	785
Luminosity (cm^{-2} s^{-1})	10^{33}	7×10^{34}



Simplified emittance estimate:

At end of drift, rms x,y,z approx 0.05,0.05,10 m

P_x, P_y, P_z approx 50,50,100 MeV/c

Normalized 6D emittance is product divided by $(m_\mu c)^3$

$$\varepsilon^{drift}_{6D,N} \approx 1.7\ 10^{-4}\ (\pi m)^3$$

Emittance needed for Muon Collider

$$\varepsilon^{collider}_{6D,N} \approx 1.7\ 10^{-10} (\pi m)^3$$

This reduction of 6 orders of magnitude must be done with reasonable efficiency !

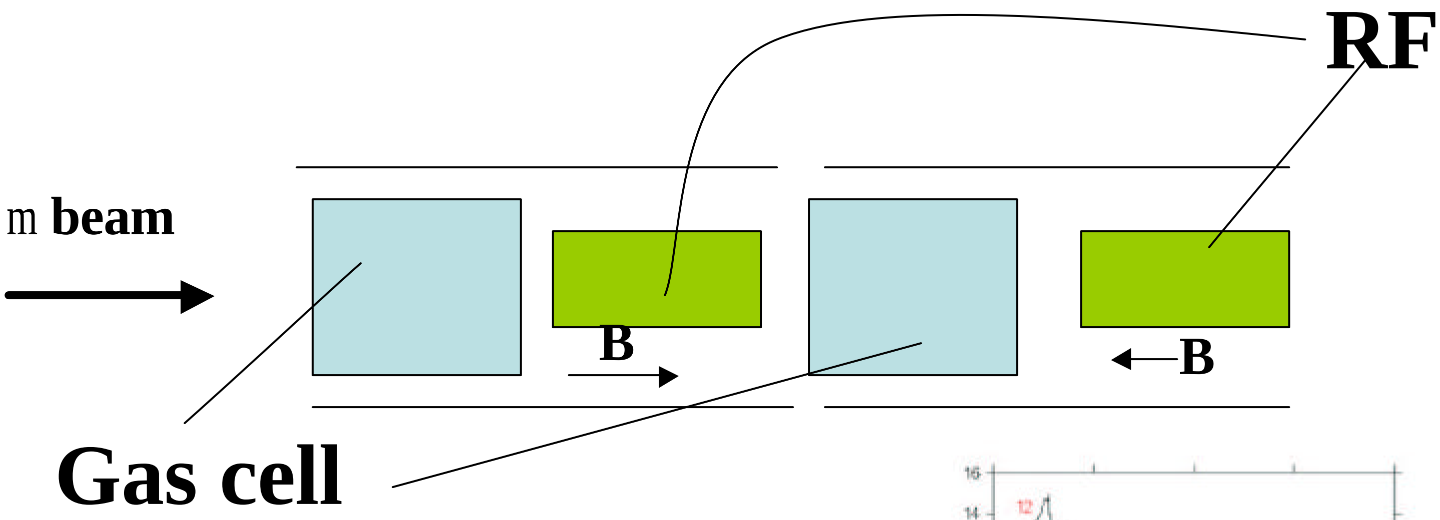
Muon Cooling

Muon Cooling is the signature challenge of a Muon Collider

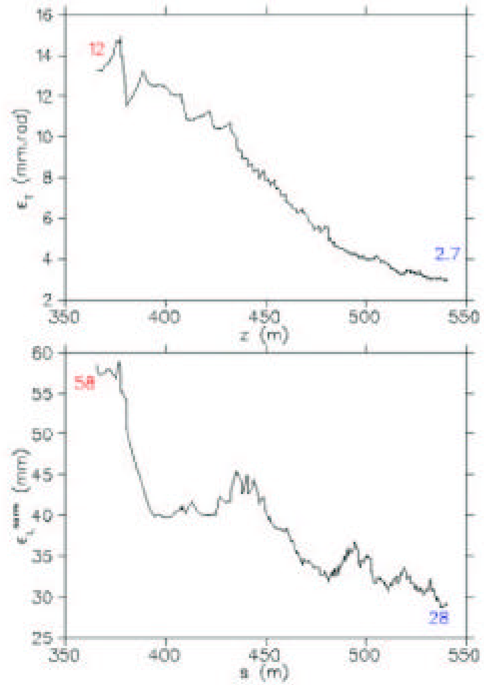
Cooler beams would allow fewer muons for a given luminosity, thereby

- Reducing the experimental background
- Reducing the radiation from muon decays
- Reducing the radiation from neutrino interactions
- Allowing for smaller apertures in machine elements, and so driving the cost down

Cooling Ideas

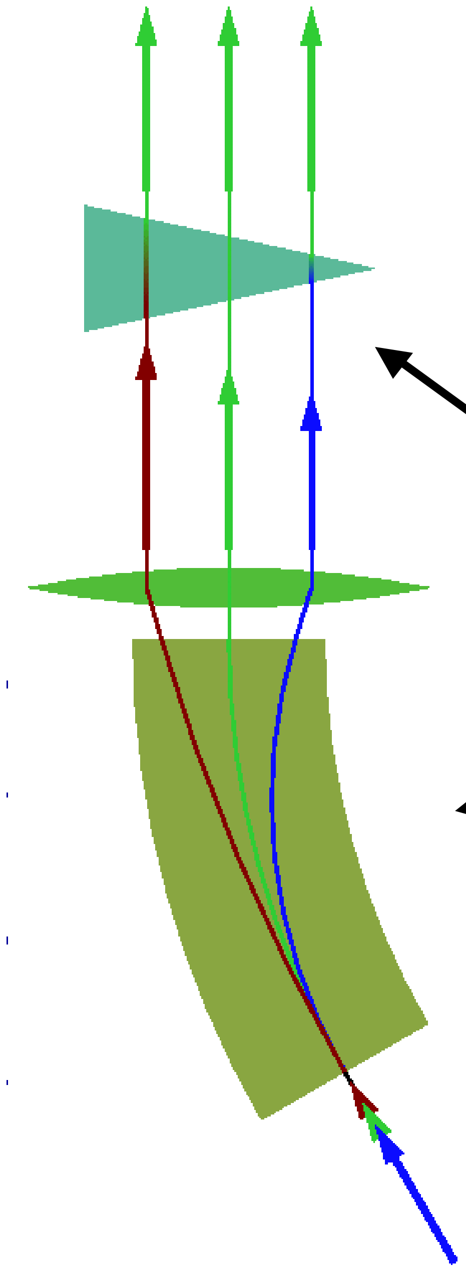


Ionization cooling (Skrinsky, Neuffer, Palmer, …): muons are maintained at ca. 200 MeV. Transverse cooling of order x20 seems feasible (see ν-factory feasibility studies 1-2). Longitudinal cooling not solved.



Longitudinal Cooling via Emittance Exchange

Transform longitudinal phase space into transverse (know how to cool transverse)

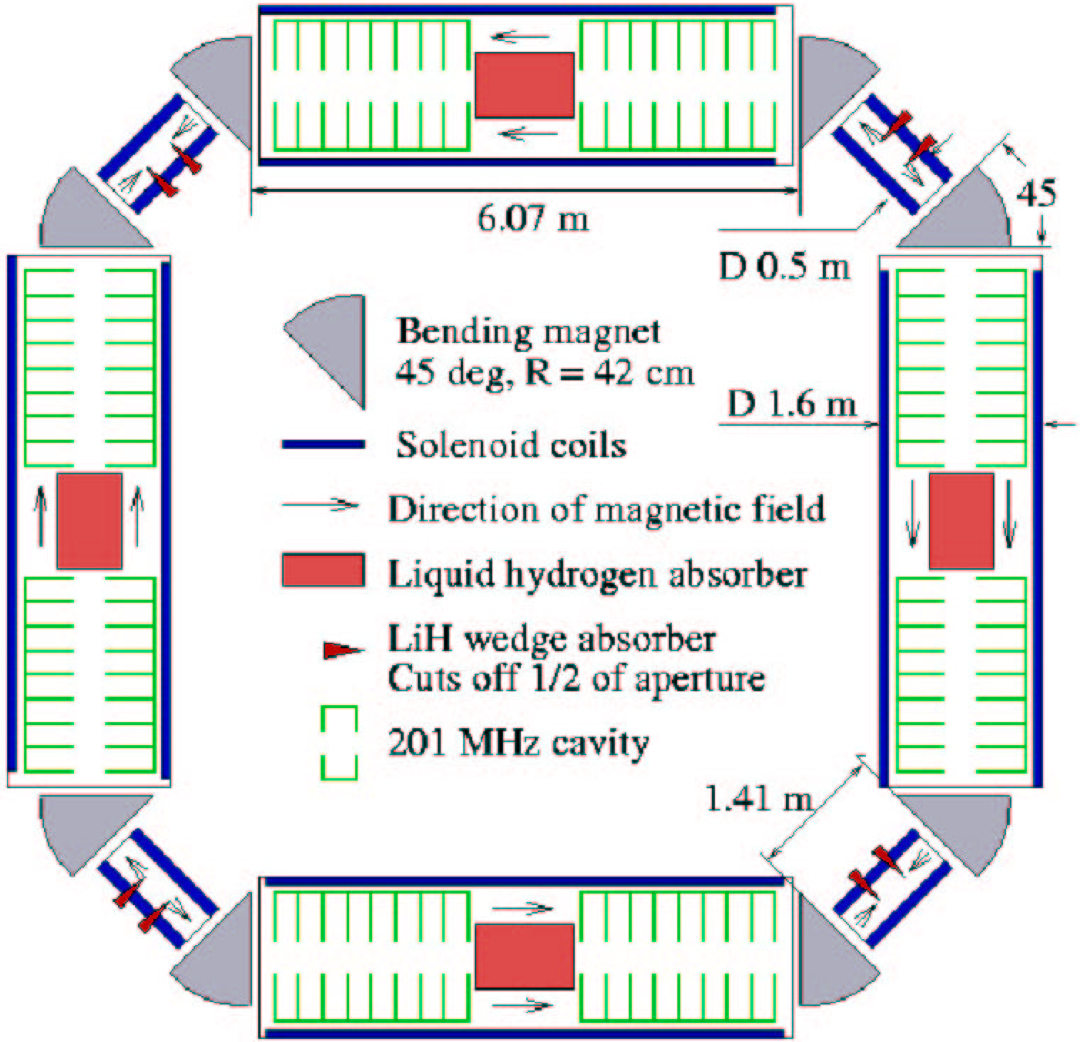


Wedge shaped absorber

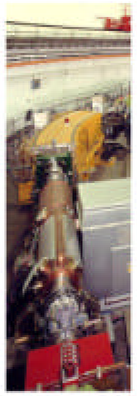
Bent solenoid produces dispersion

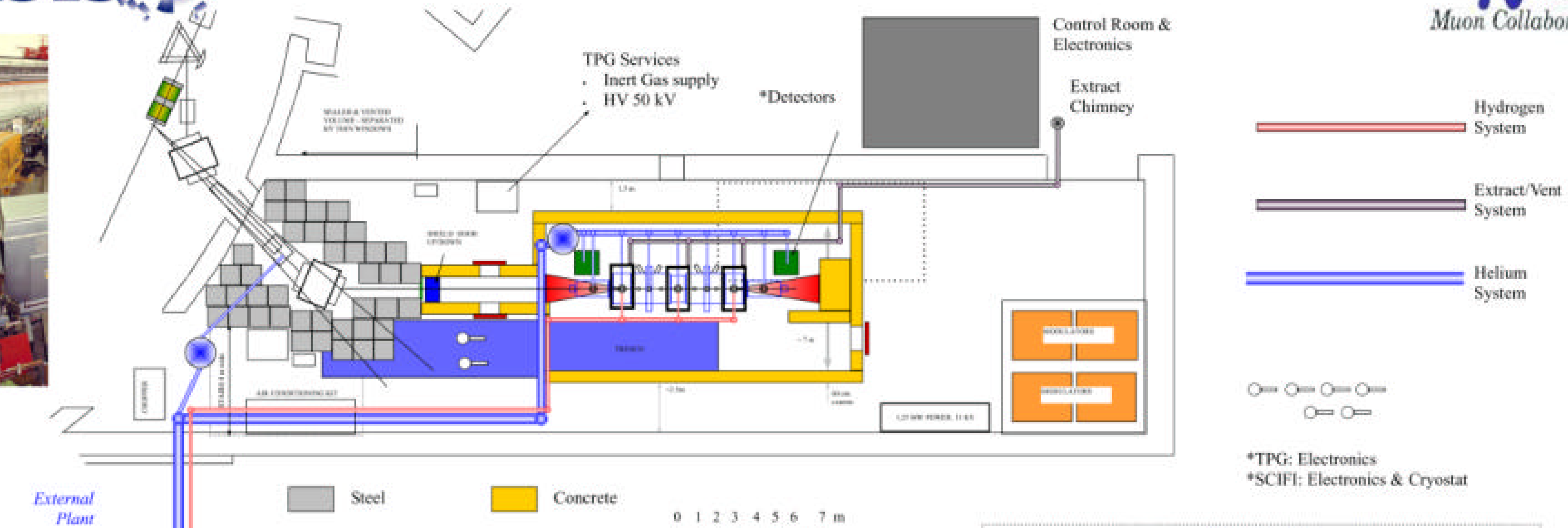
'Balbekov Ring'

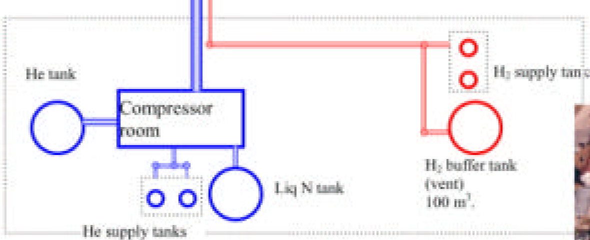
There are significant developments in achieving 6D phase space via ionization cooling (R. Palmer, MUTAC03), but still far from 10^6 cooling factor.

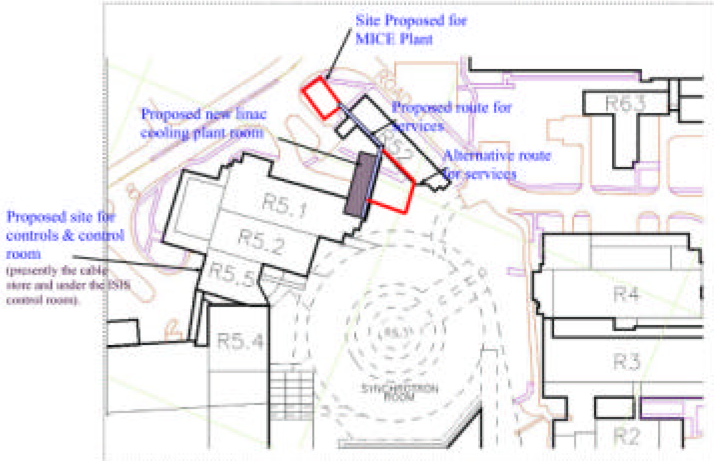


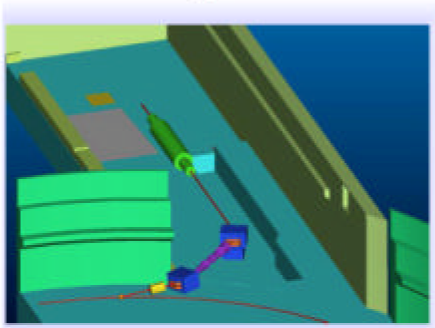
Muon Ionization Cooling Experiment





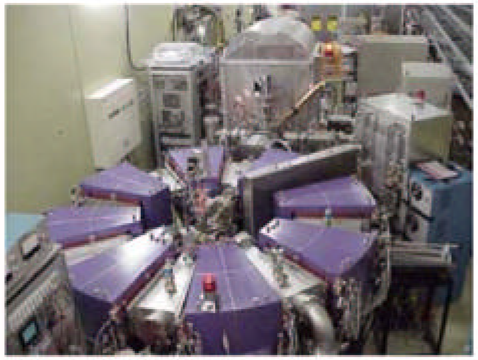






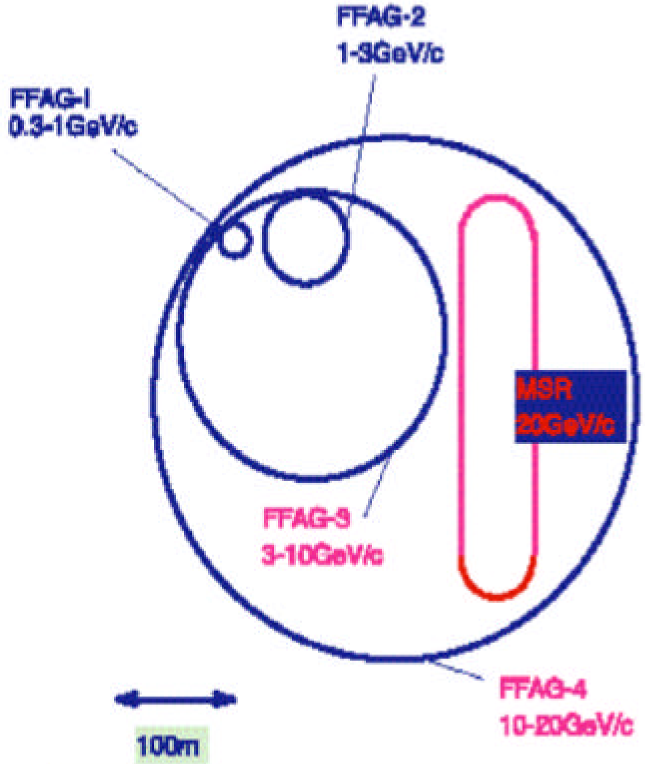
at the Rutherford Appleton Laboratory

KEK – focus on FFAG acceleration



0.5-MeV Proton FFAG POP at KEK

150-MeV Proton FFAG
Under construction at KEK



Series of FFAG acceleration

Frictional Cooling

Studies at Columbia University/Nevis Labs

Allen Caldwell, Raphael Galea

+

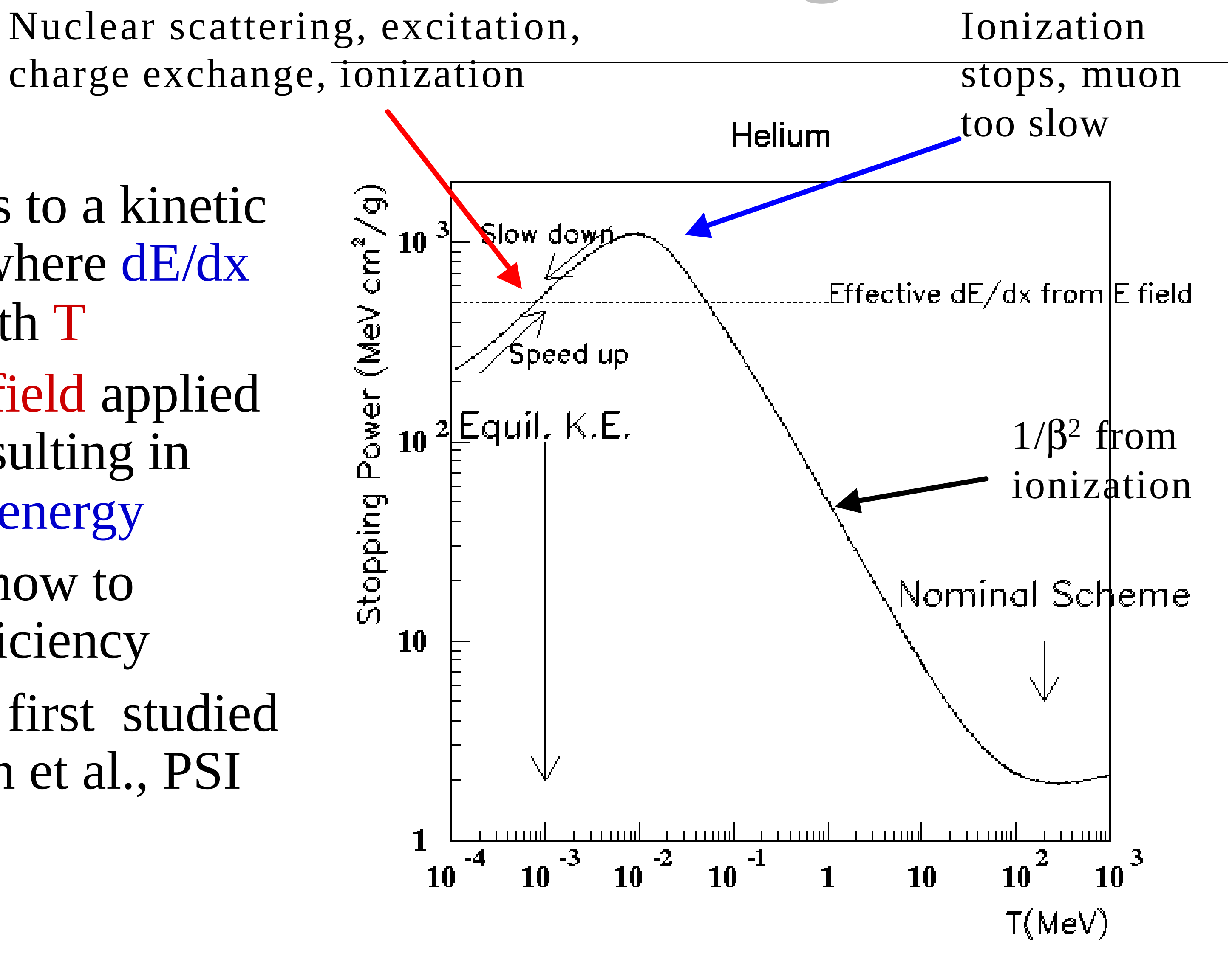
Stefan Schlenstedt (DESY/Zeuthen)

Halina Abramowicz (Tel Aviv University)

Summer Students: **Emily Alden**
Christos Georgiou
Daniel Greenwald
Laura Newburgh
Yujin Ning
Inna Shpiro
Will Serber

Frictional Cooling

- Bring muons to a kinetic energy (T) where dE/dx increases with T
- Constant E-field applied to muons resulting in equilibrium energy
- Big issue – how to maintain efficiency
- Similar idea first studied by Kottmann et al., PSI



Problems/comments:

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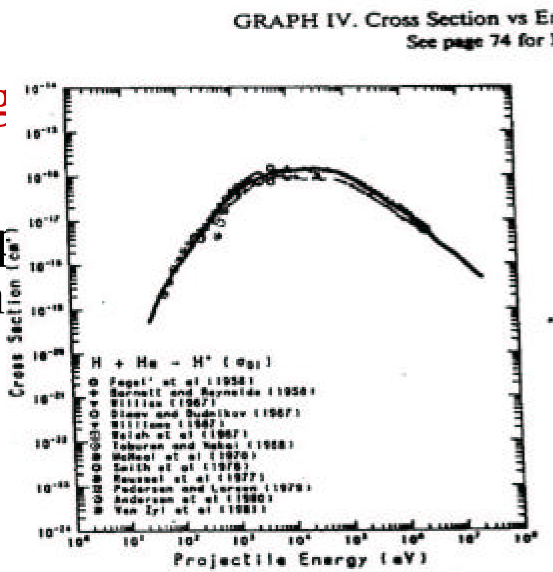
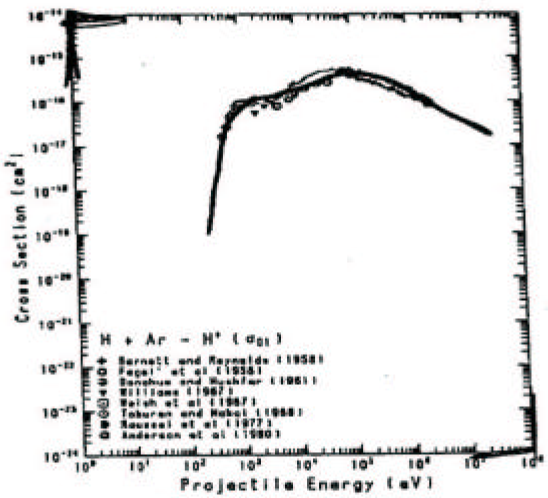
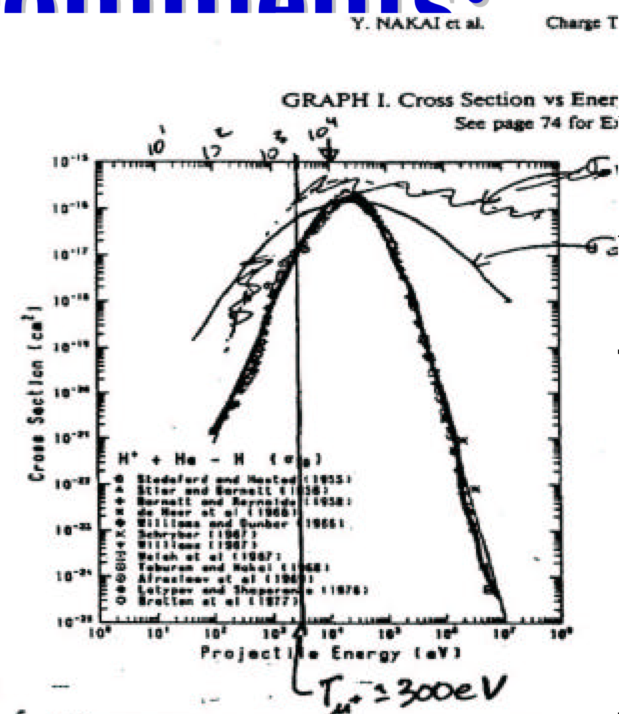
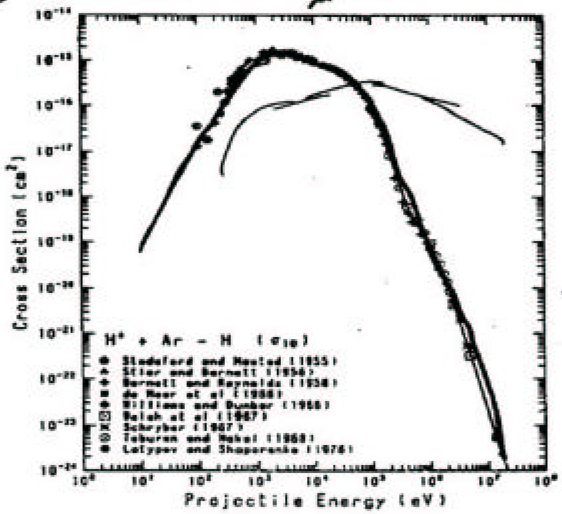
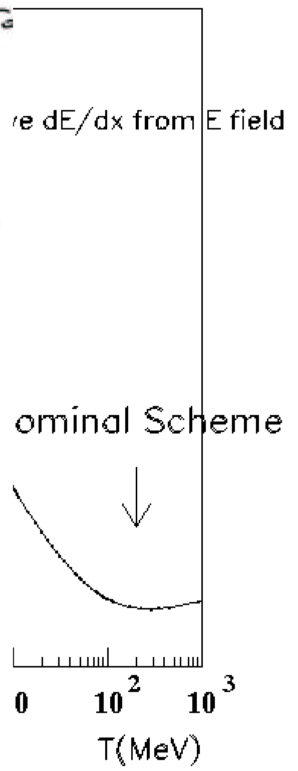


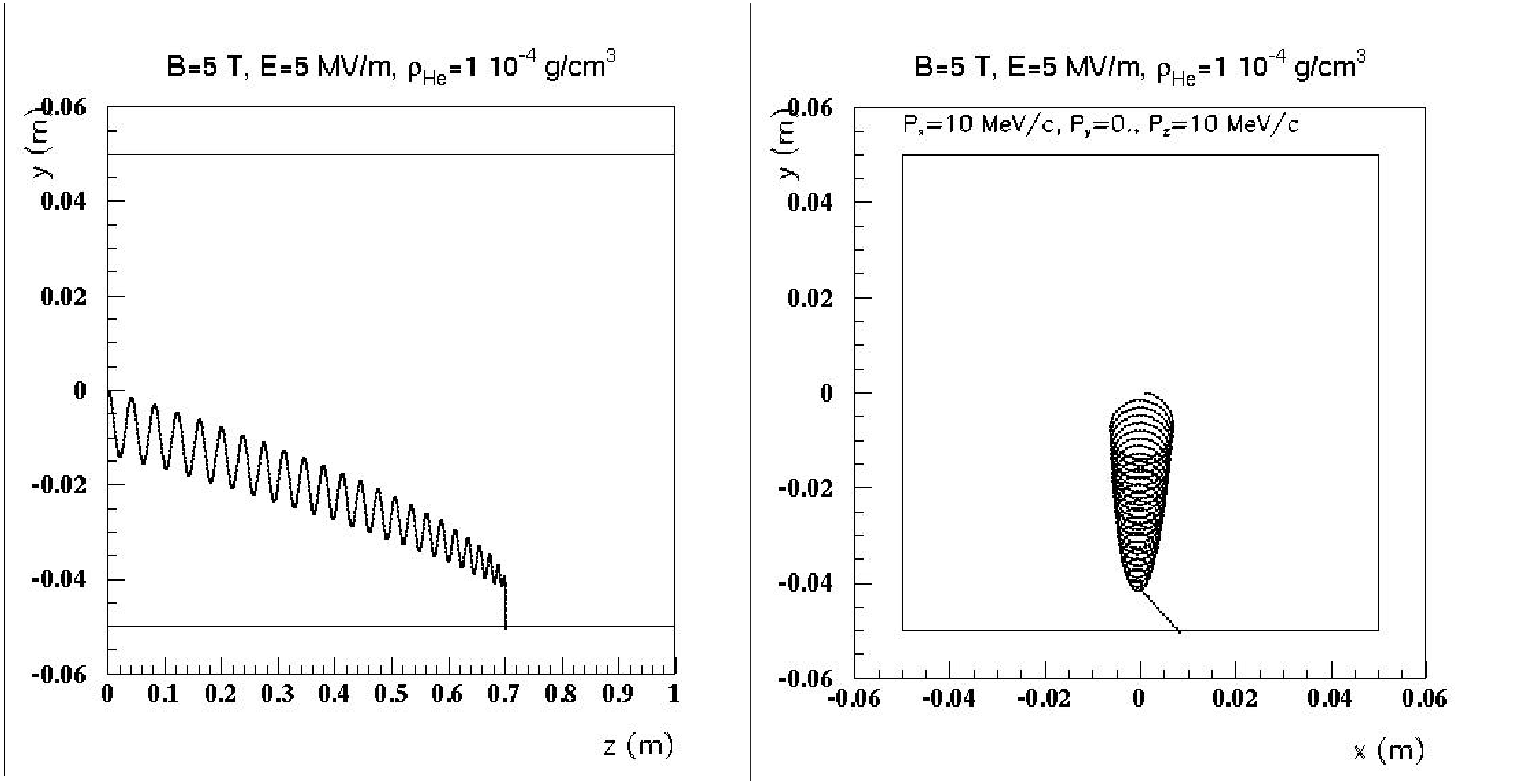








Frictional Cooling: particle trajectory

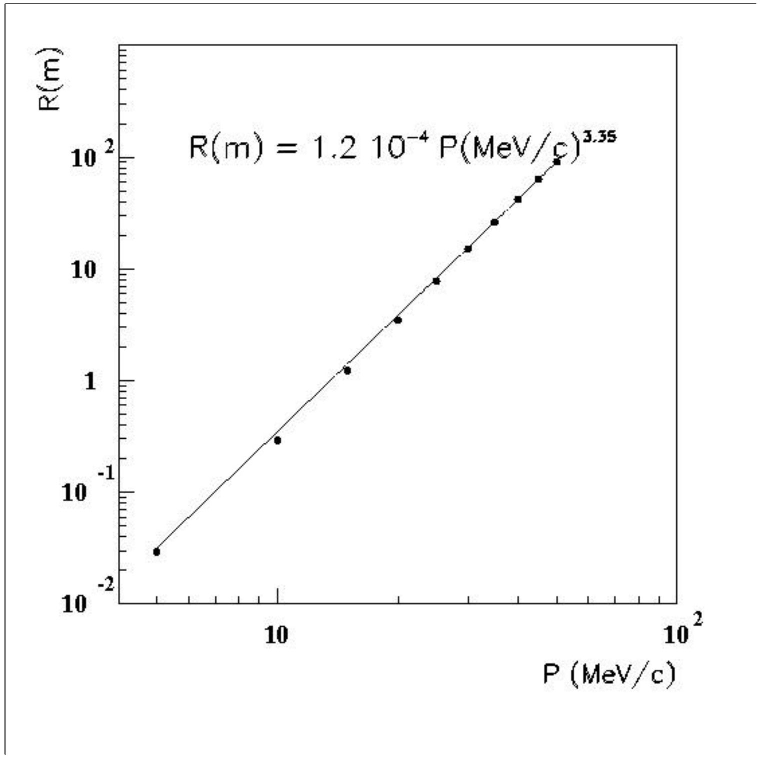


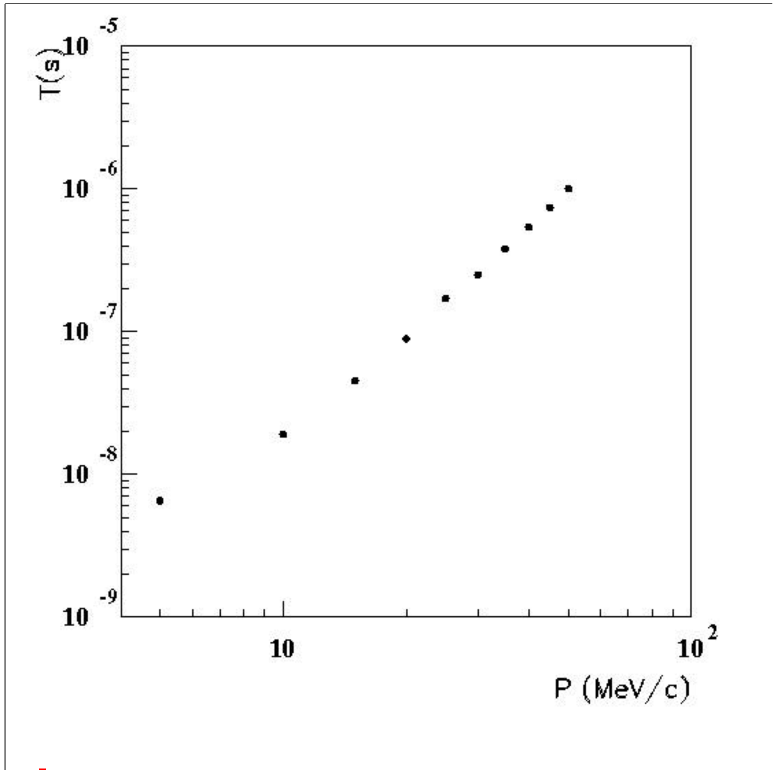
** Using continuous energy loss

Frictional Cooling: stop the m

- High energy μ's travel a long distance to stop
- High energy μ's take a long time to stop

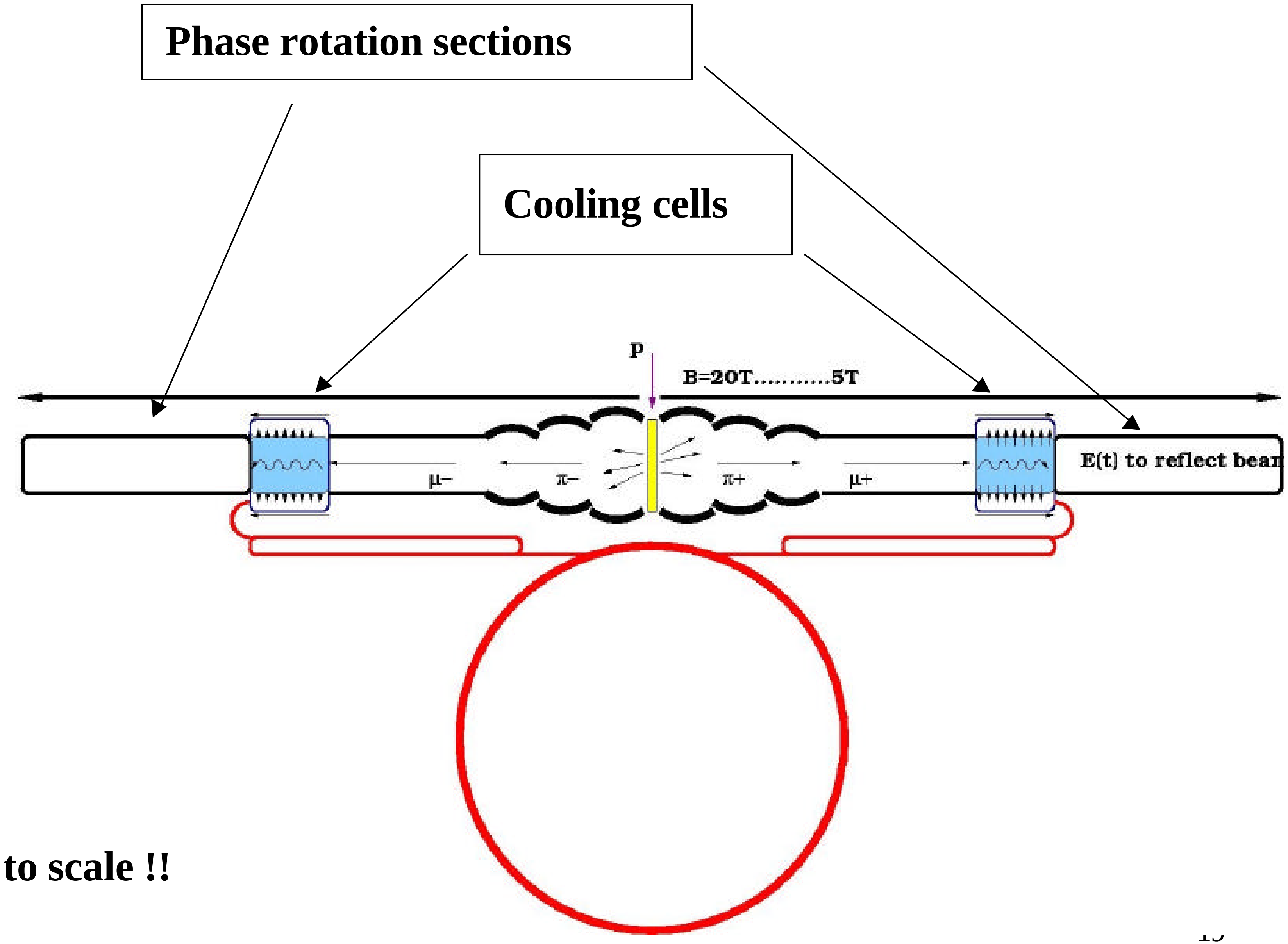
Plots for
1. 10^{-4} g/cm^3 He





Optimize for low initial muon momentum,
+ phase rotation

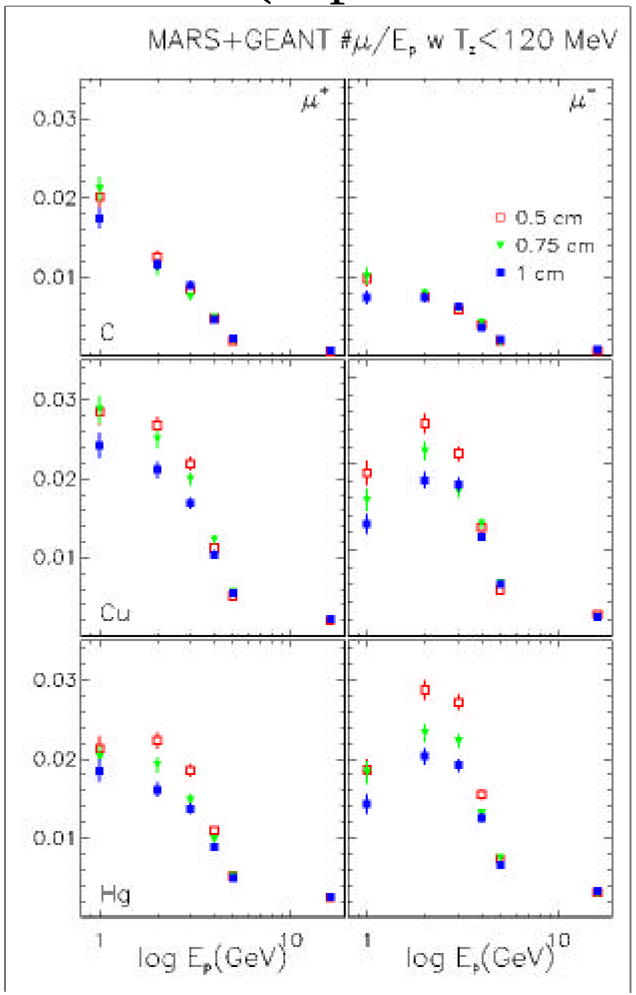
Schematic Layout for m Collider Scheme Studied

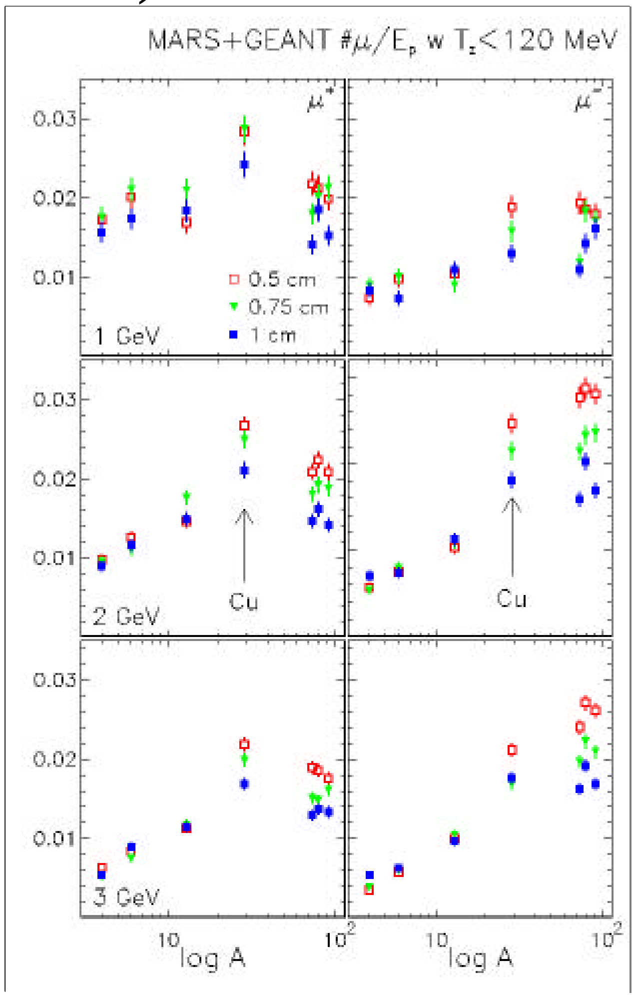


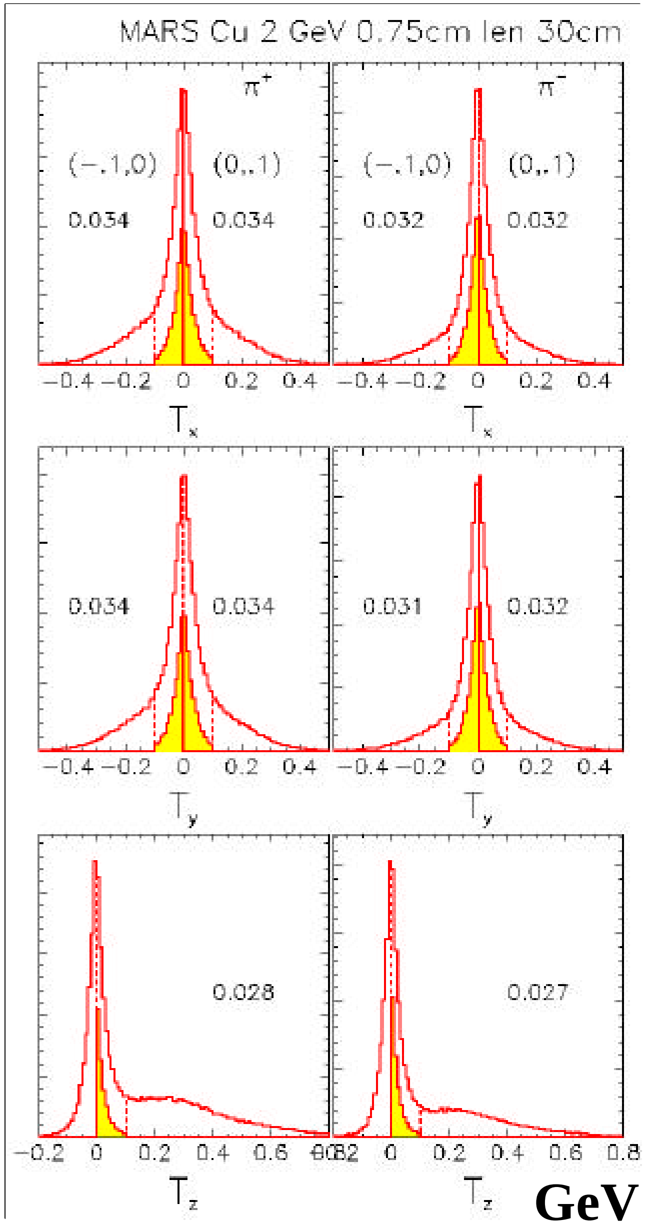
Not to scale !!

Detailed Simulation

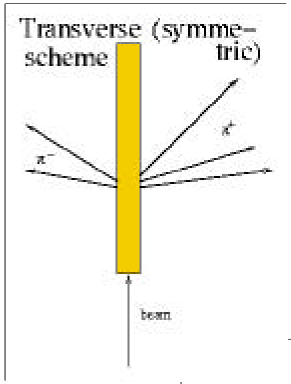
Full MARS target simulation, optimized for low energy muon yield: 2 GeV protons on Cu with proton beam transverse to solenoids (capture low energy pion cloud).



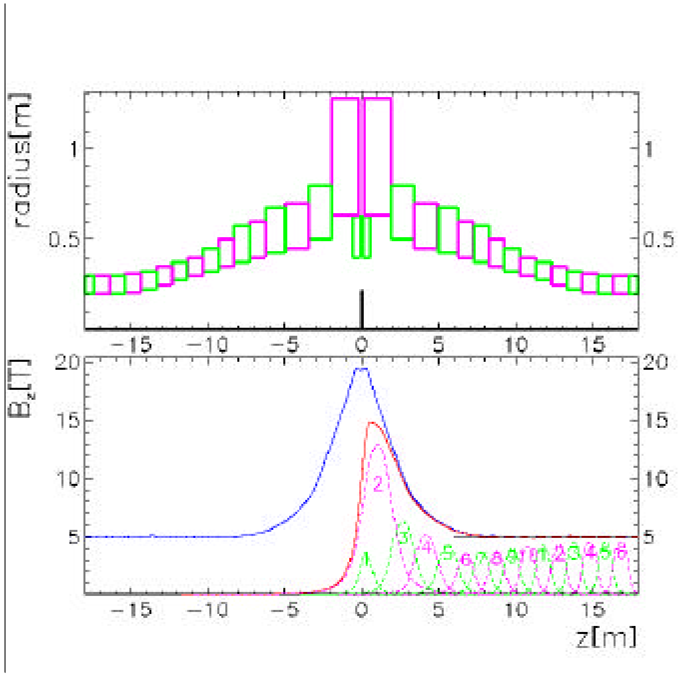




Target System

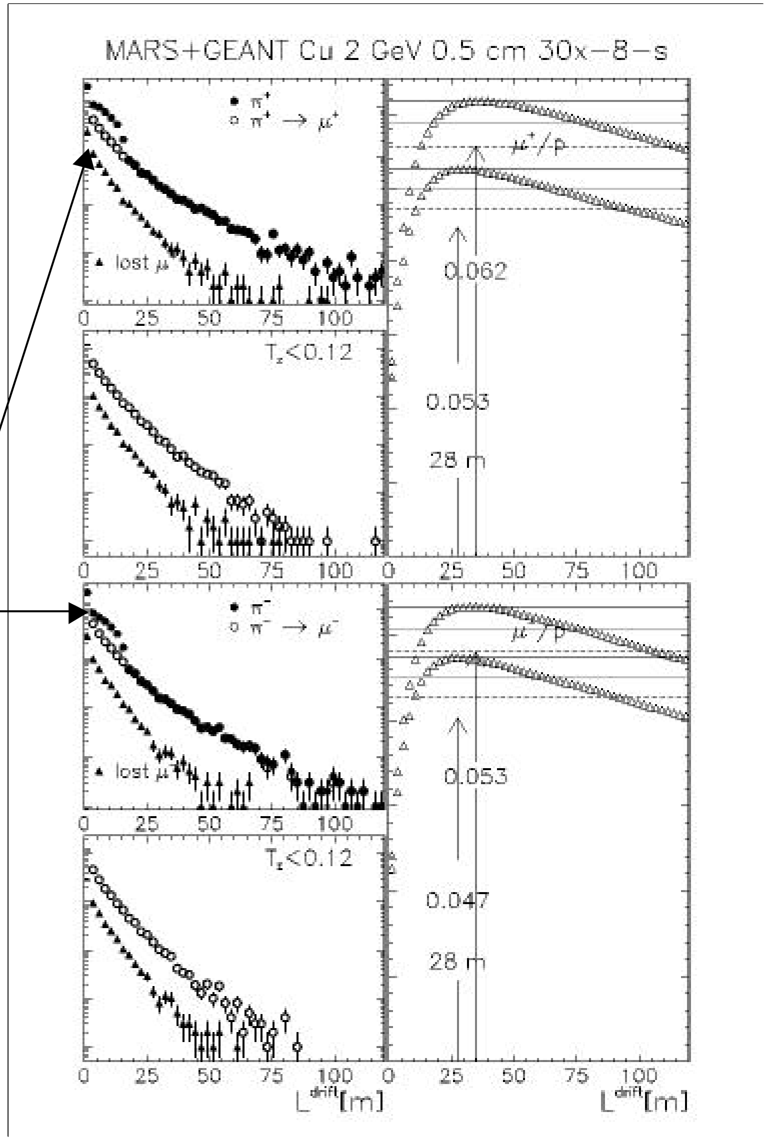


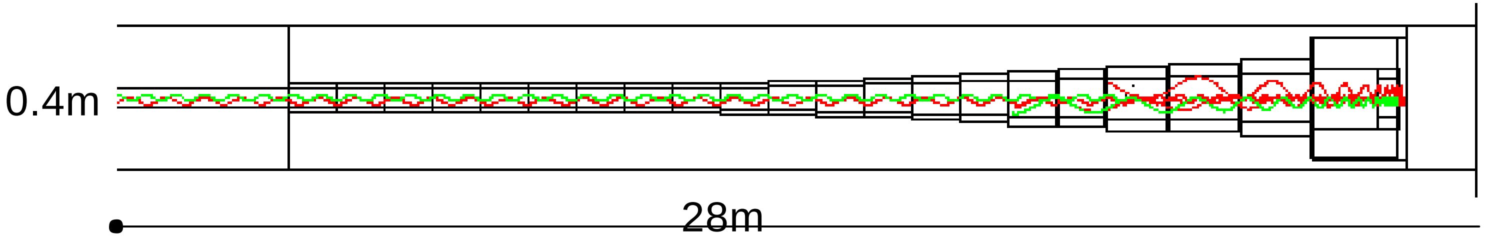
- cool μ^+ & μ^- at the same time
- calculated new symmetric magnet with gap for target

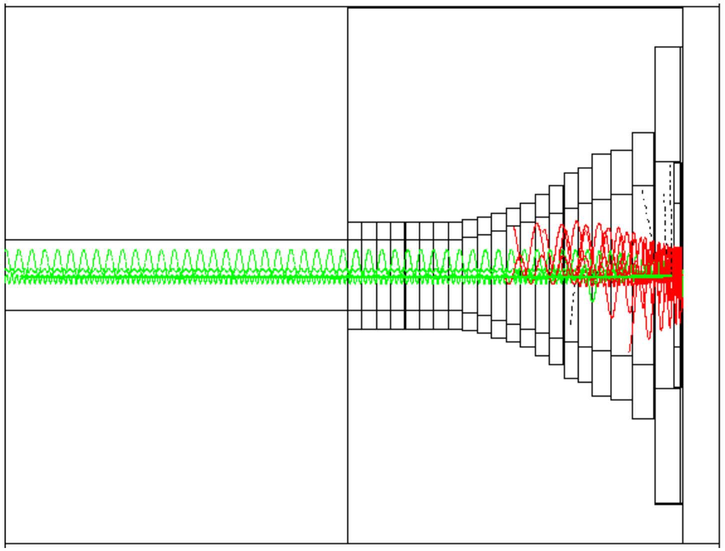


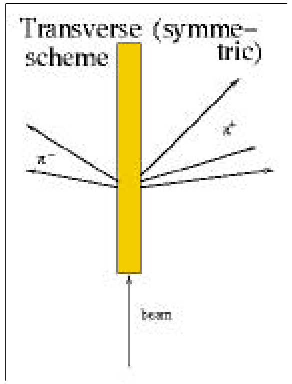
Target & Drift Optimize yield

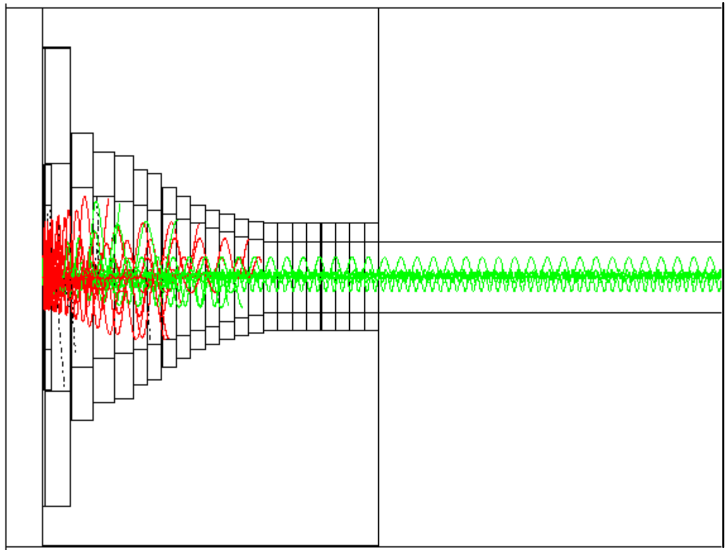
- Optimize drift length for μ yield
- Some π's lost in Magnet aperture





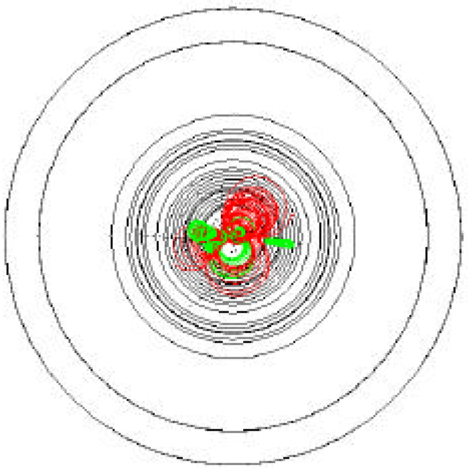






π's in red

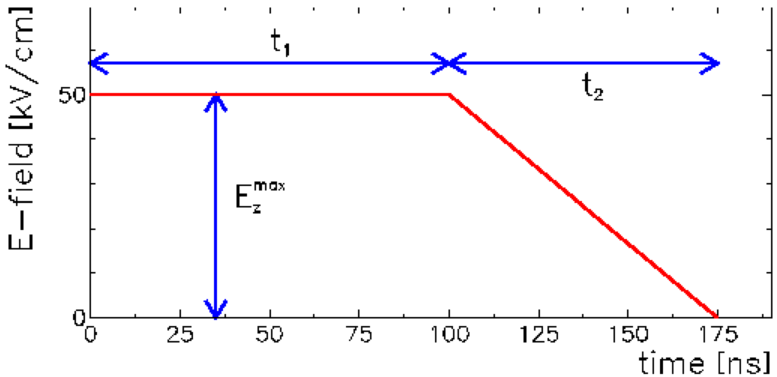
μ's in green

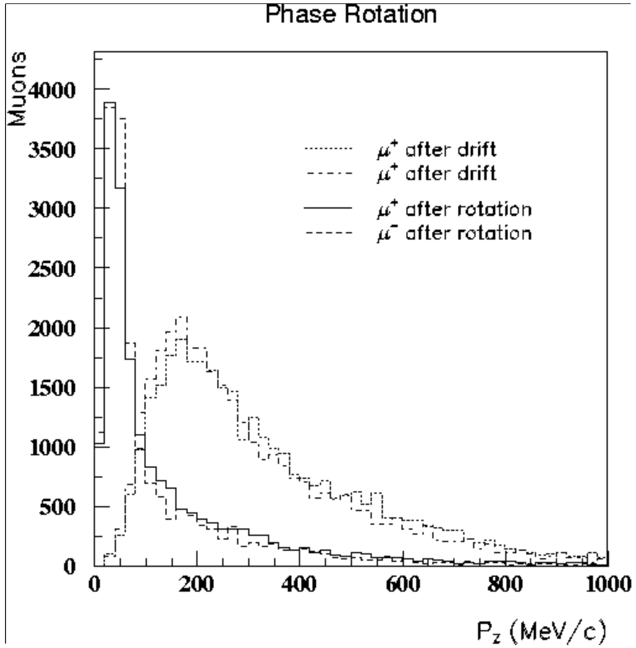


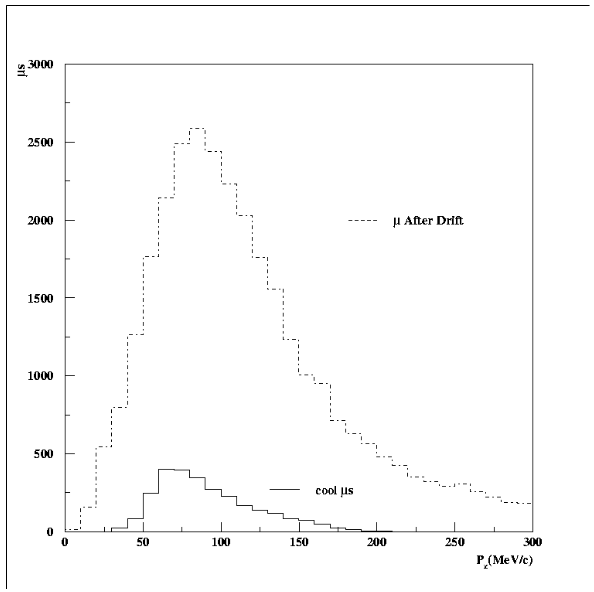
GEANT simulation

View into beam

Phase Rotation





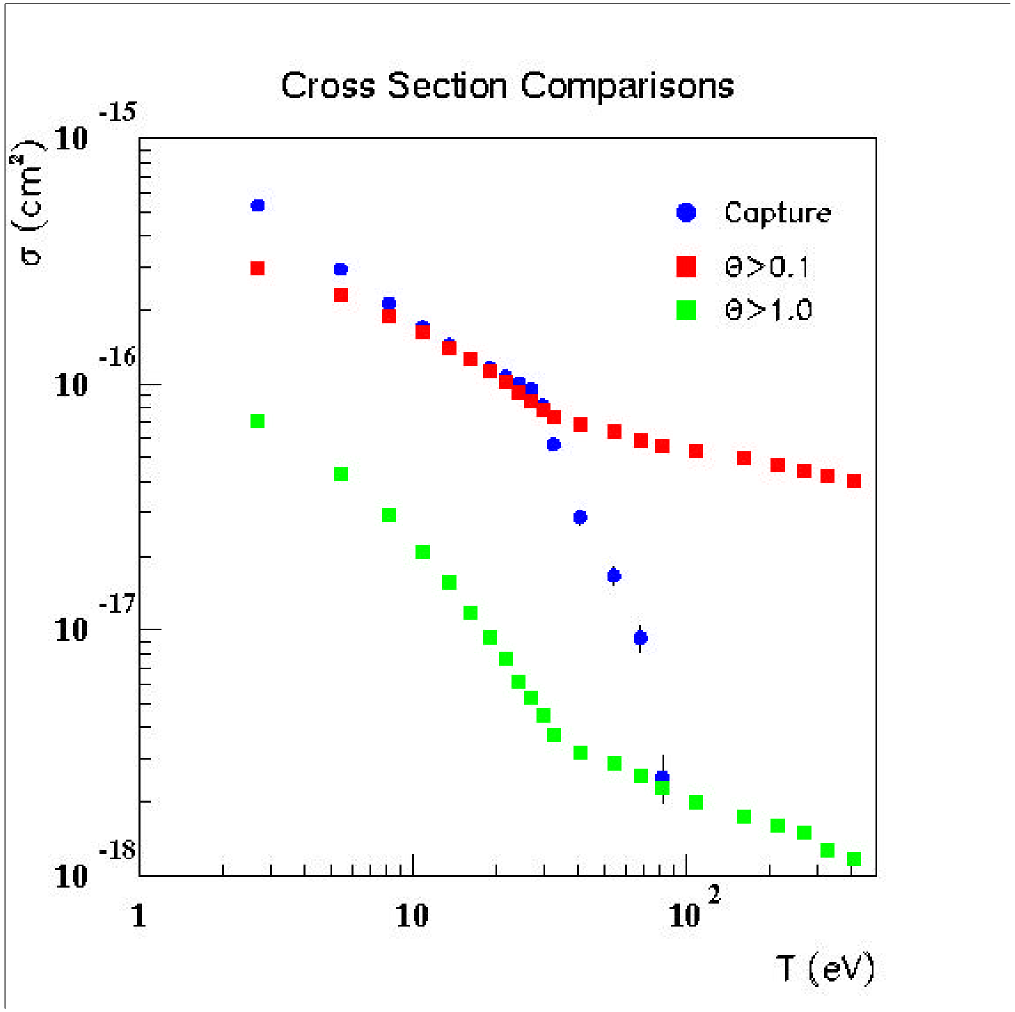


- First attempt simple form
- Vary t_1,t_2 & E_{max} for maximum low energy yield

Cooling cell simulation

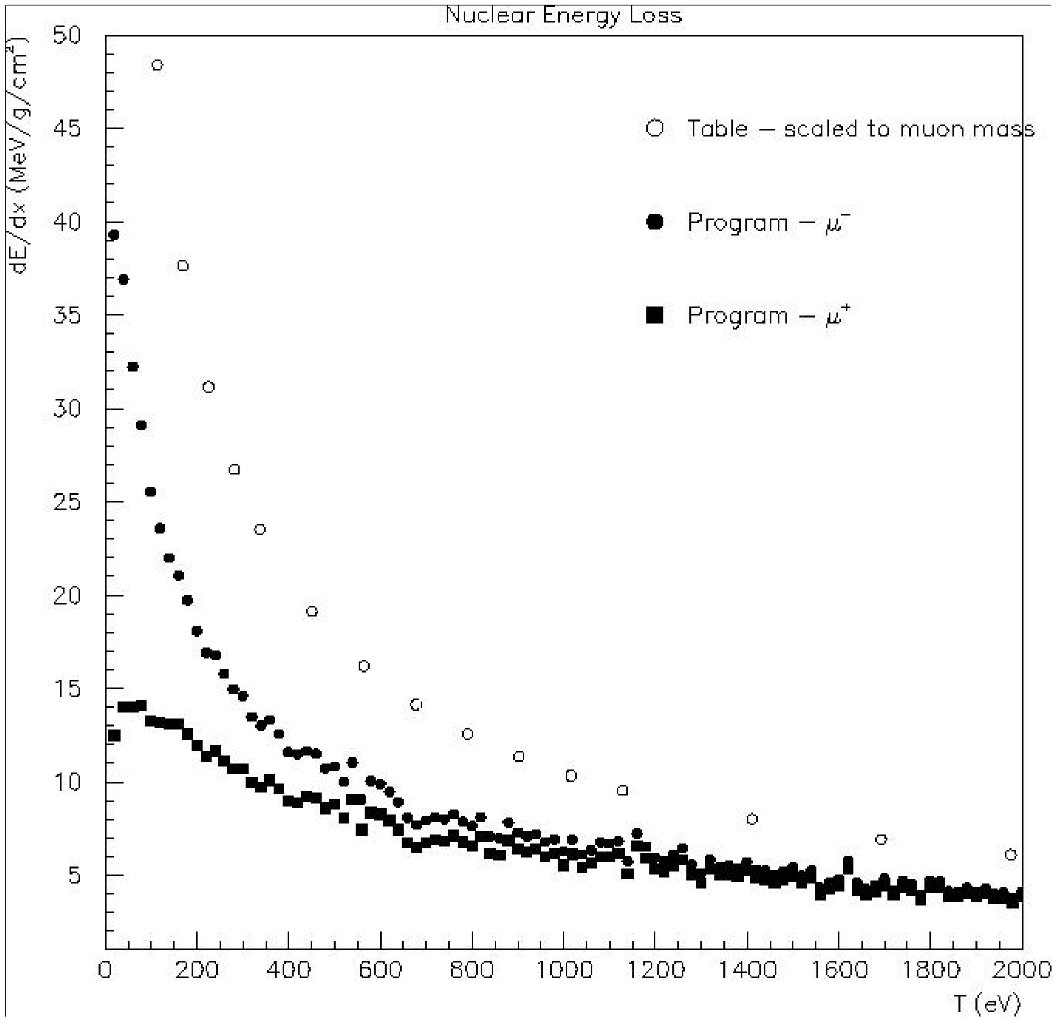
He gas is used for μ^+, H_2 for μ^-.

- 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

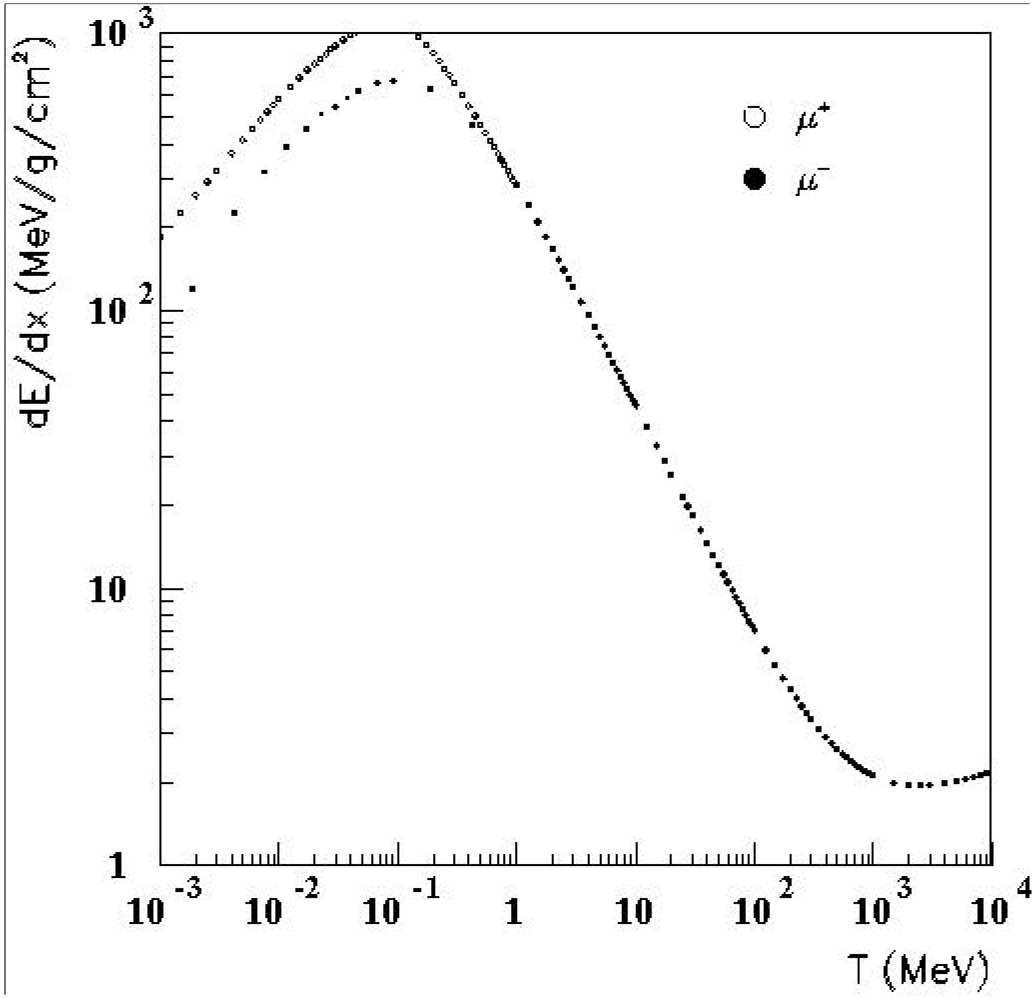


Scattering Cross Sections

- Scan impact parameter and calculate θ(b), dσ/dθ 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 θ>0.05 rad
- Simulation accurately reproduces ICRU tables



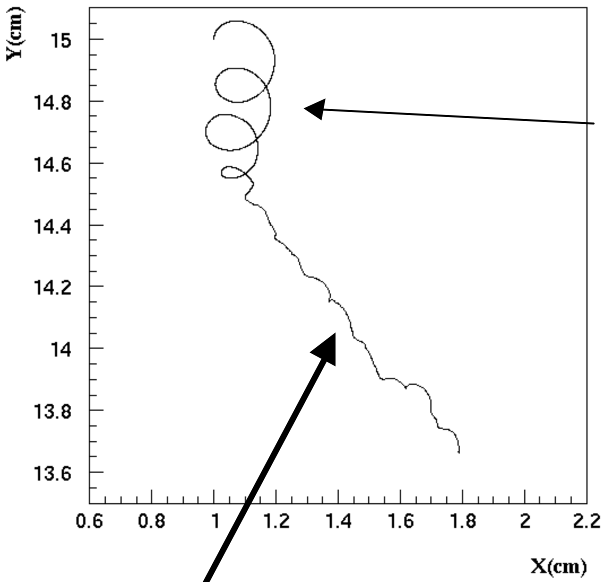
Barkas Effect



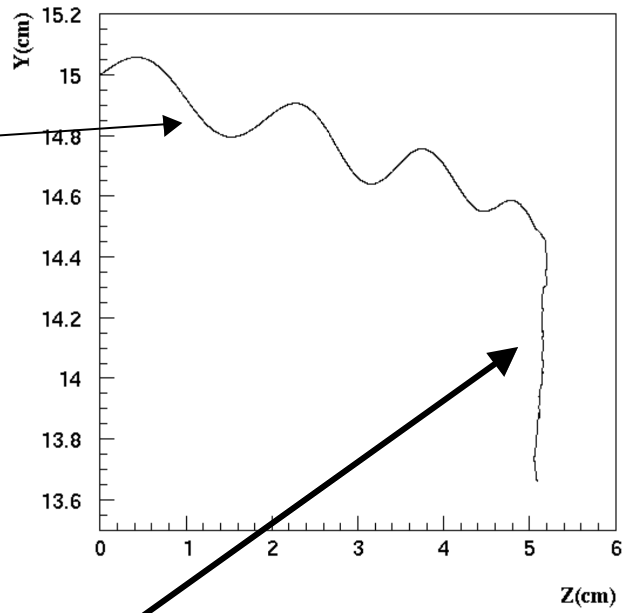
- Difference in μ^+ & μ^- energy loss rates at dE/dx peak
- Due to charge exchange for μ^+
- parameterized data from Agnello et. al. (Phys. Rev. Lett. 74 (1995) 371)
- Only used for the electronic part of dE/dx

Trajectories in detailed simulation

Transverse motion



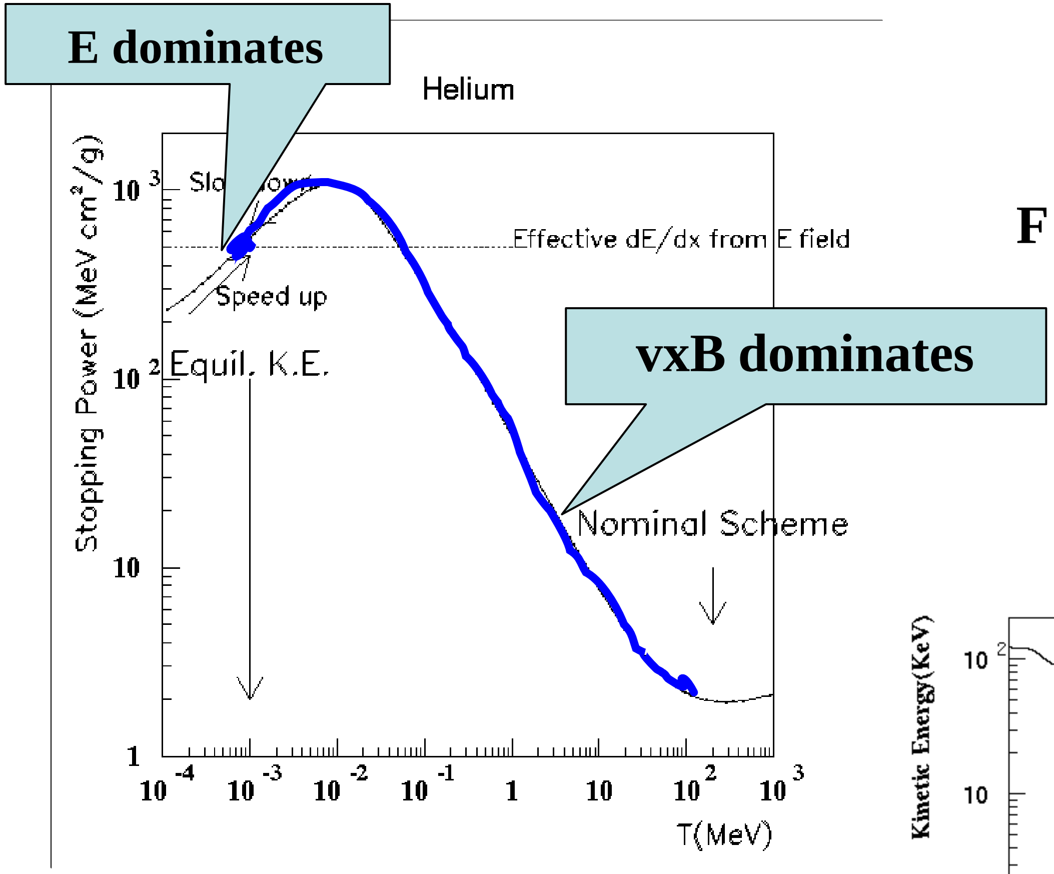
Longitudinal motion



Motion controlled by **B** field

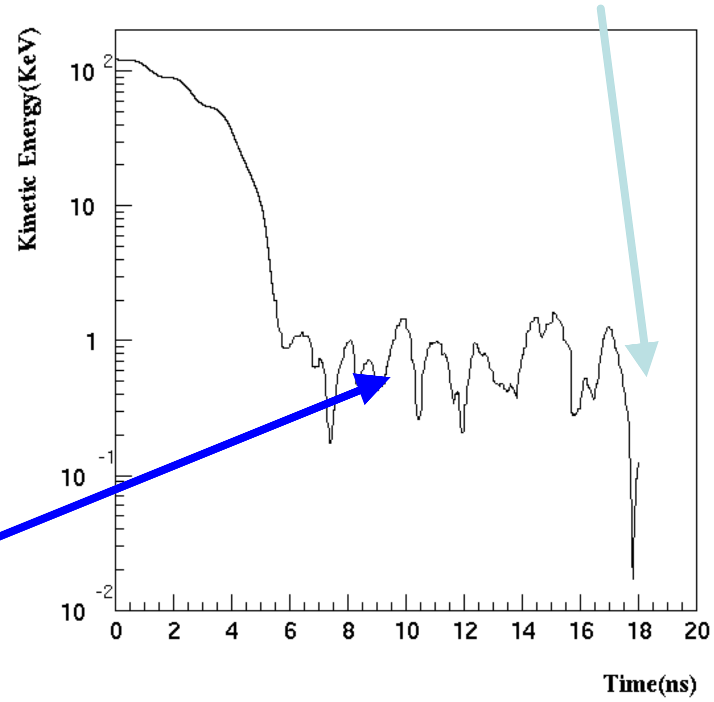
Lorentz angle drift, with nuclear scattering

Final stages of muon trajectory in gas cell



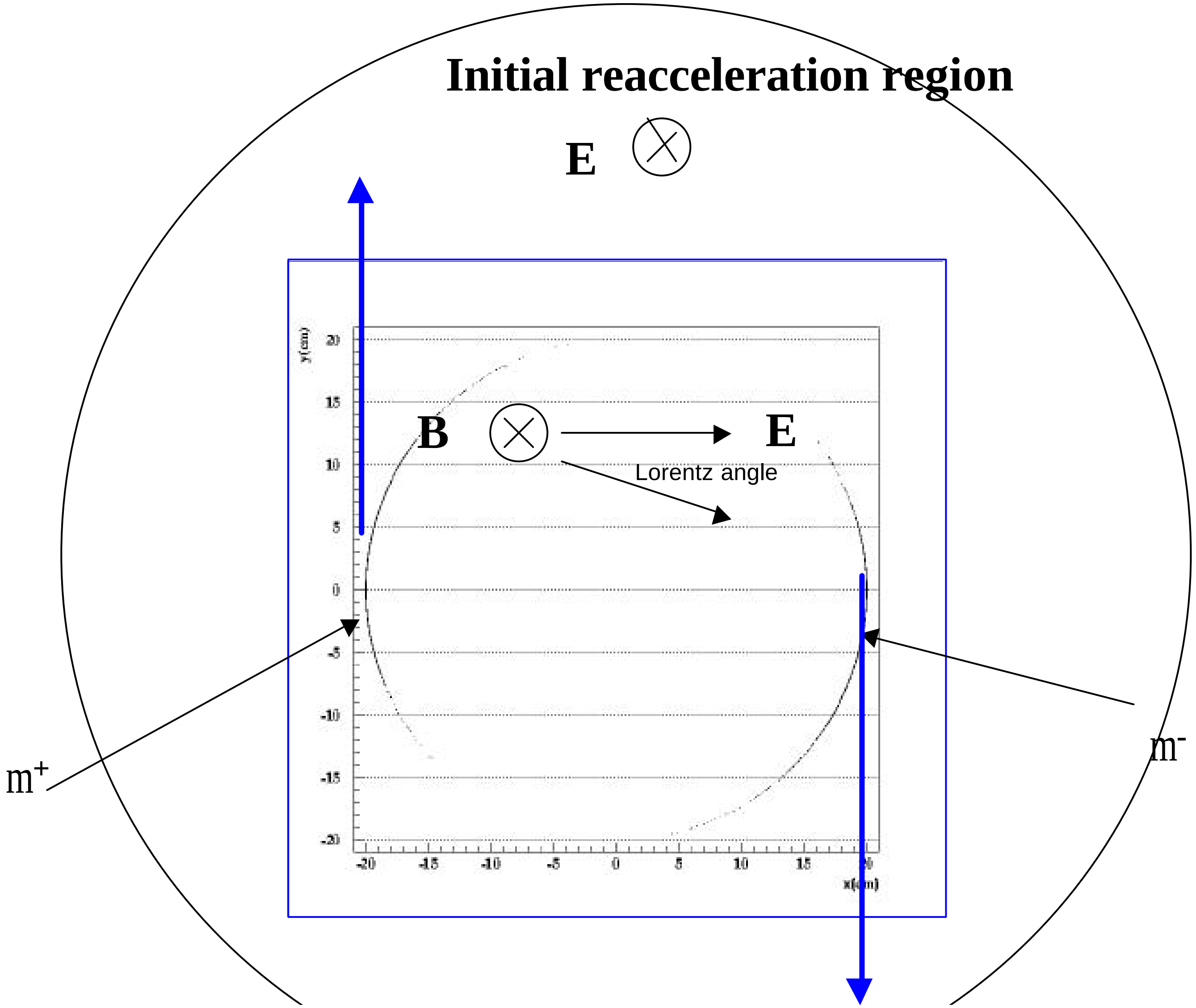
$$\mathbf{F} = q(\mathbf{E}+\mathbf{v}\times\mathbf{B})-d\mathbf{T}/dx$$

Dangerous because of μ^- capture possibility



Oscillations about equilibrium define emittance.

After the gas cell



Yields & Emittance

Look at muons coming out of 11m cooling cell region after initial reacceleration.

Yield: approx 0.002 μ per 2GeV proton after cooling cell.
Need to improve yield by factor 3 or more.

Emittance: rms

$x = 0.015$ m
$y = 0.036$ m
$z = 30$ m (actually βct)
$P_x = 0.18$ MeV
$P_y = 0.18$ MeV
$P_z = 4.0$ MeV

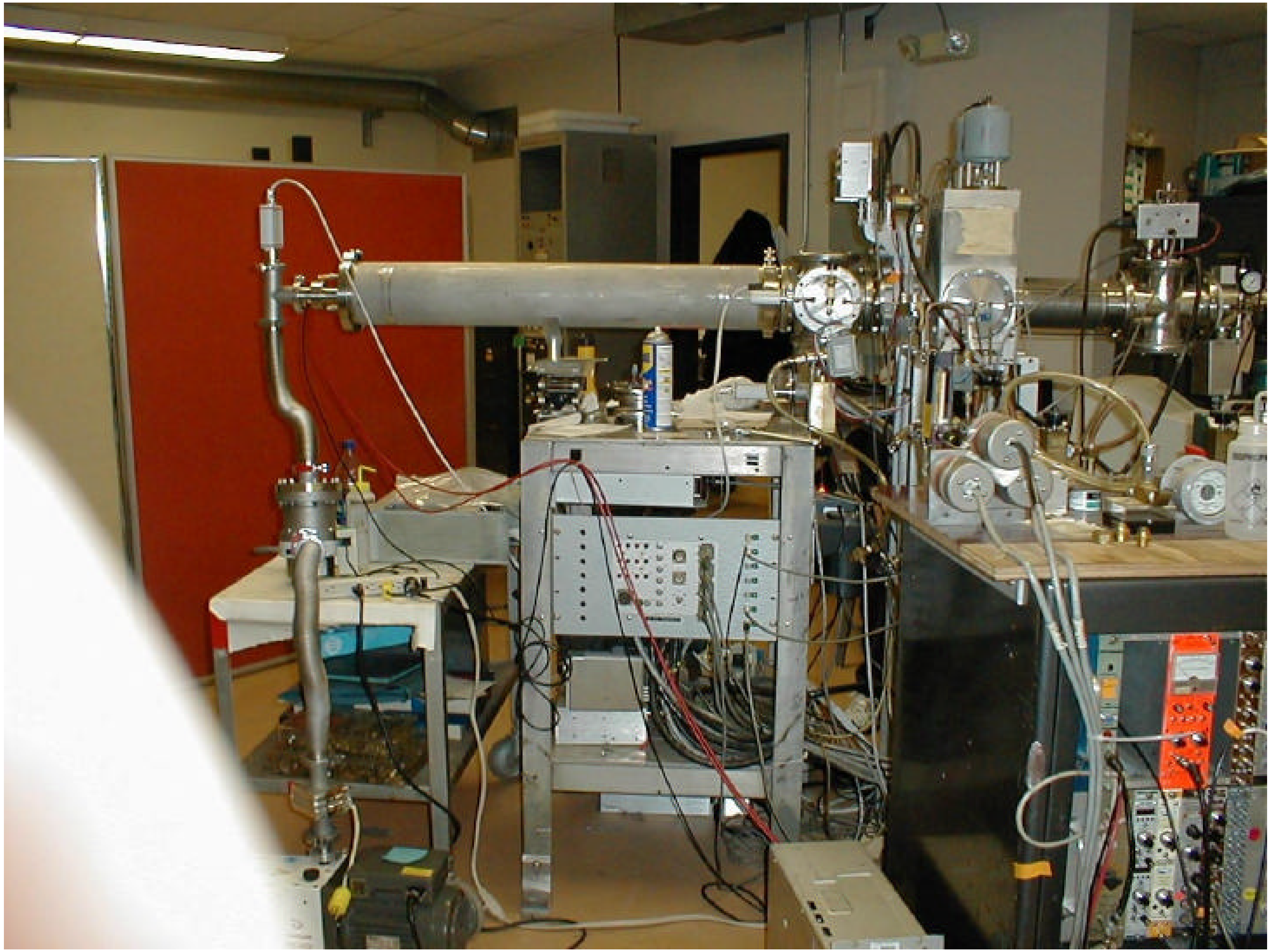
$$\varepsilon_{6D,N} = 5.7\ 10^{-11}\ (\pi m)^3$$

Problems/Things to investigate…

- Extraction of μs through window in gas cell
  - Must be very thin to pass low energy μs
  - Must be reasonably gas tight
- Can we apply high electric fields in gas cell without breakdown (large number of free electrons, ions) ? Plasma generation → screening of field.
- Reacceleration & bunch compression for injection into storage ring
- The μ^- capture cross section depends very sensitively on kinetic energy & falls off sharply for kinetic energies greater than e^- binding energy. NO DATA – simulations use theoretical calculation
- +…

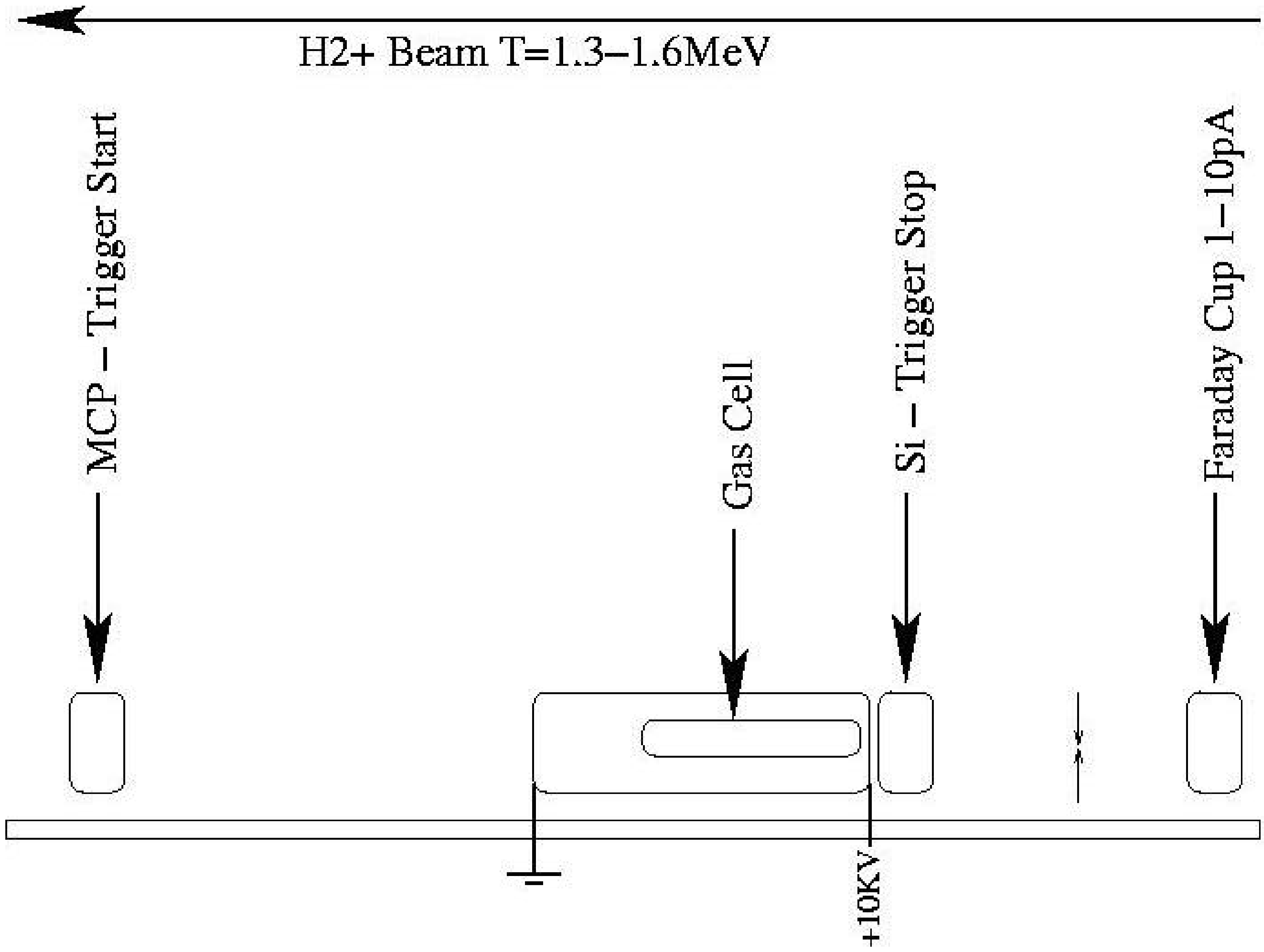
First try to demonstrate frictional cooling with protons.

RARAF Facility – Nevis Lab/Columbia University

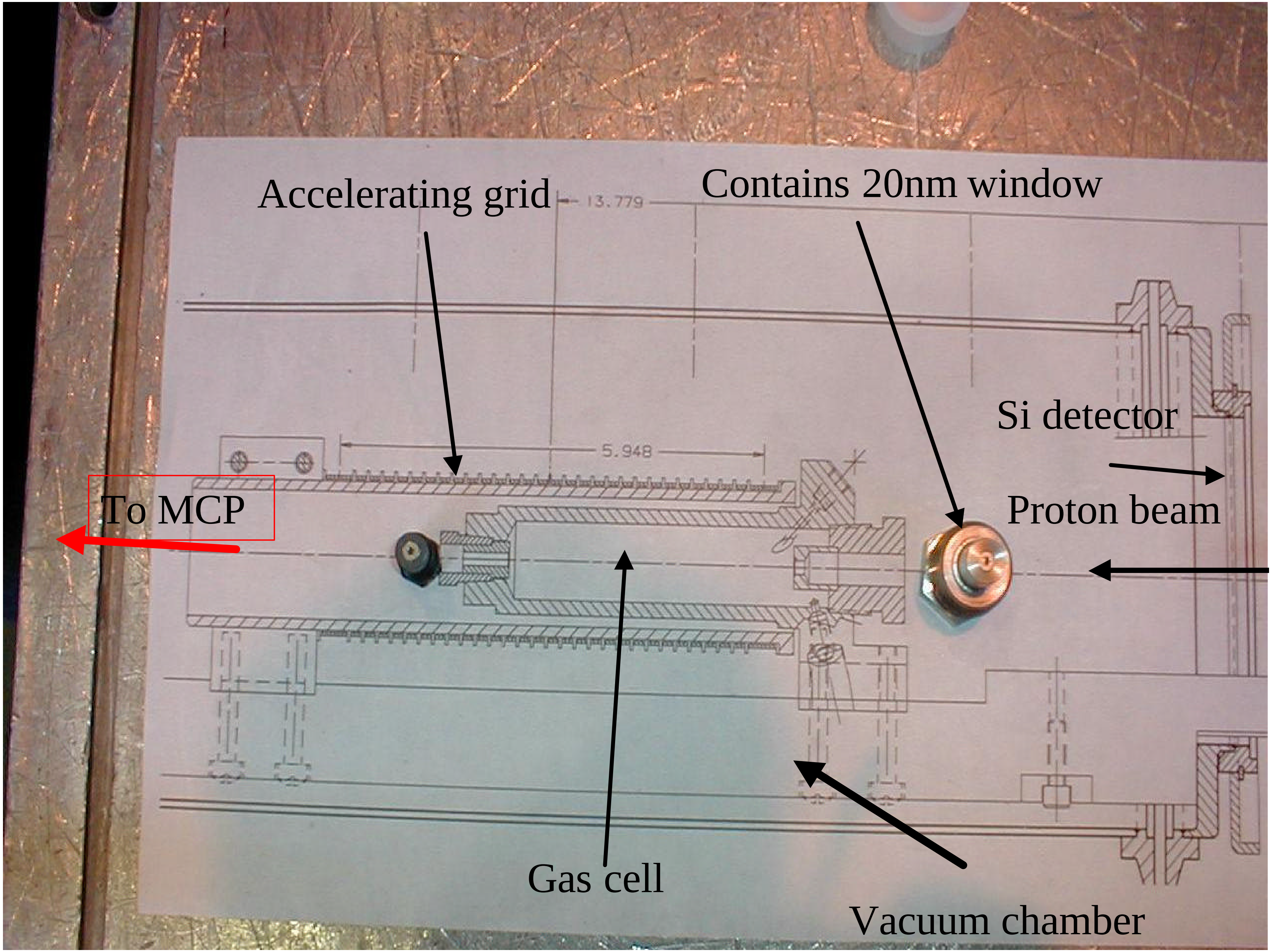


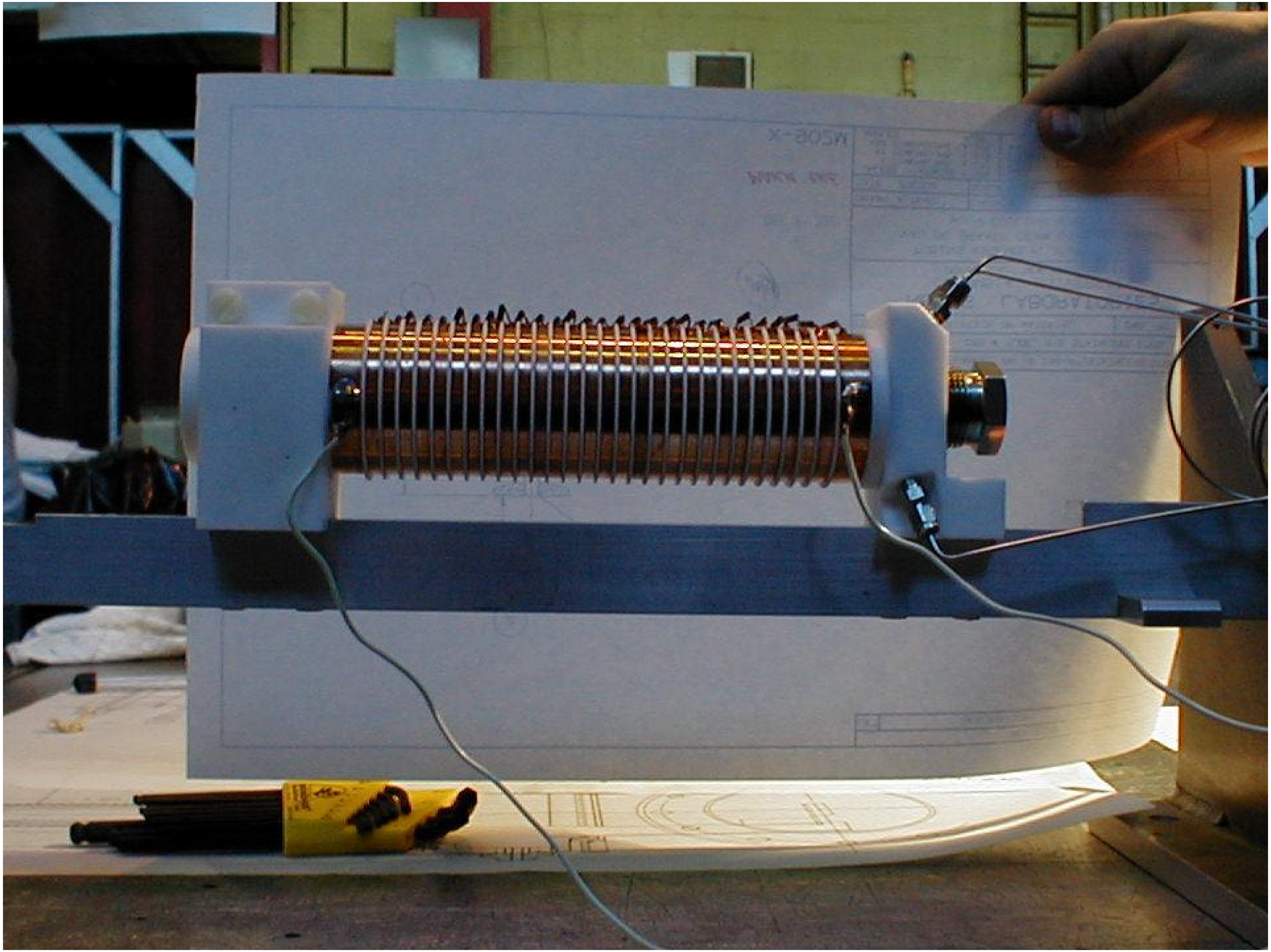
£ 4 MeV p

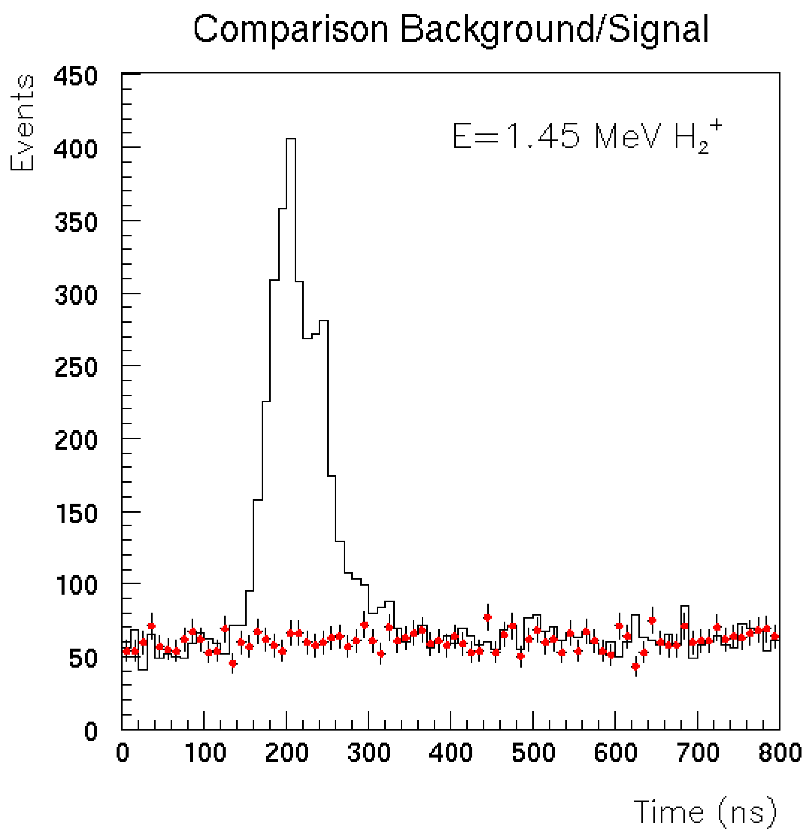
VandeGraaf accelerator for biomedical research

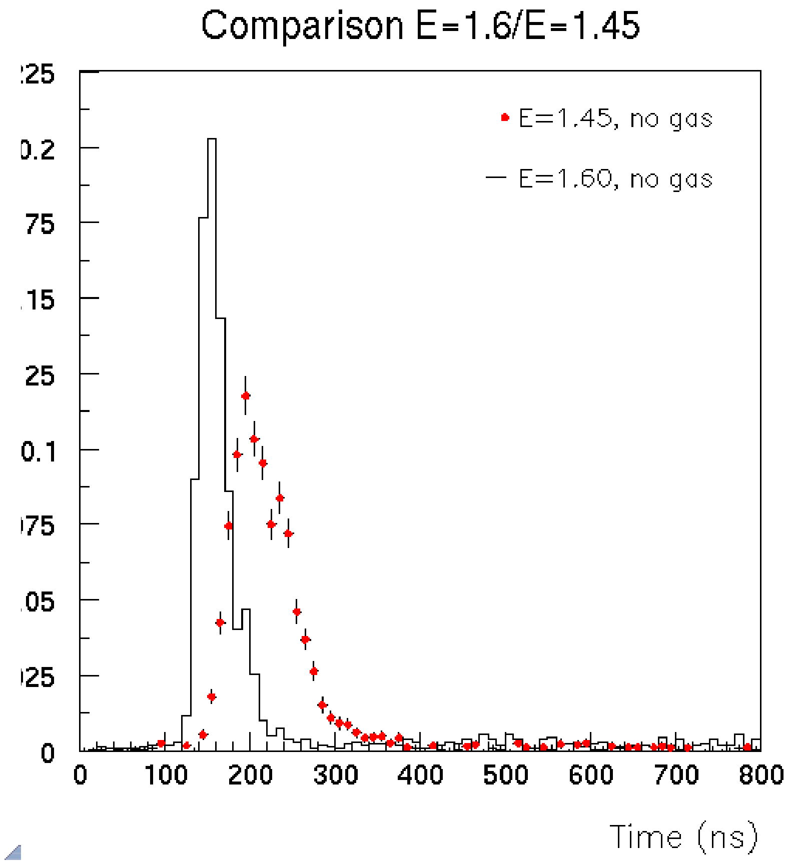


H2+ Beam T=1.3–1.6MeV
MCP – Trigger Start
Gas Cell
Si – Trigger Stop
Faraday Cup 1–10pA
+10KV

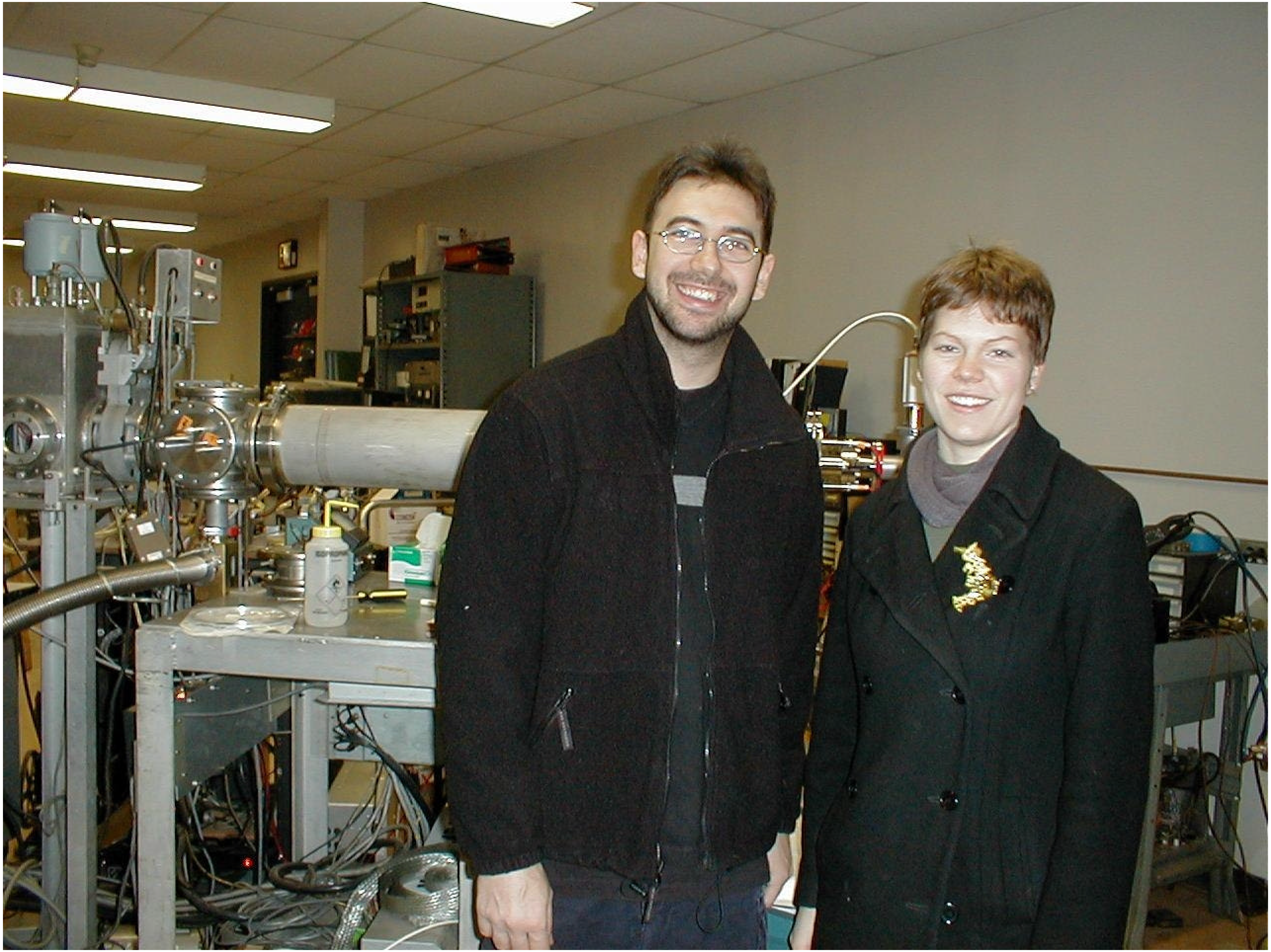

Accelerating grid
13.779
Contains 20nm window
Si detector
5.948
To MCP
Proton beam
Gas cell
Vacuum chamber







Initial conclusions: no obvious cooling peak, but very low acceptance due to lack of magnetic field. Use data to tune simulations. Redo experiment with a solenoidal magnetic field.

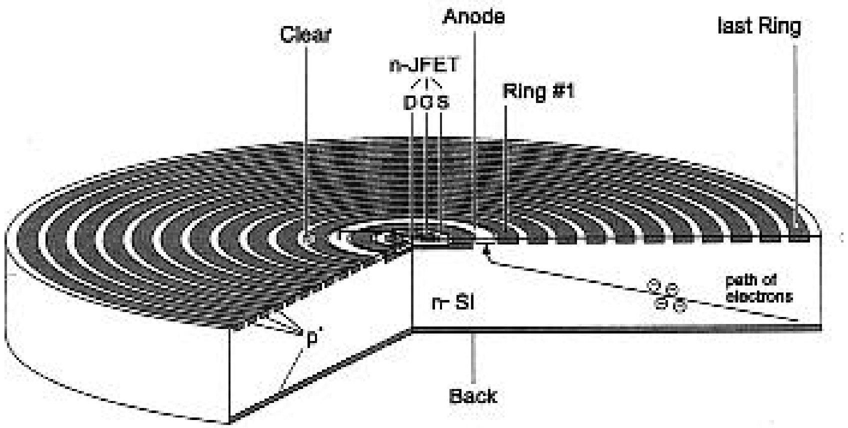


Future Plans

- Frictional cooling tests at MPI with 5T Solenoid, alpha source
- Study gas breakdown in high E,B fields
- R&D on thin windows
- Beam tests with muons to measure μ capture cross section

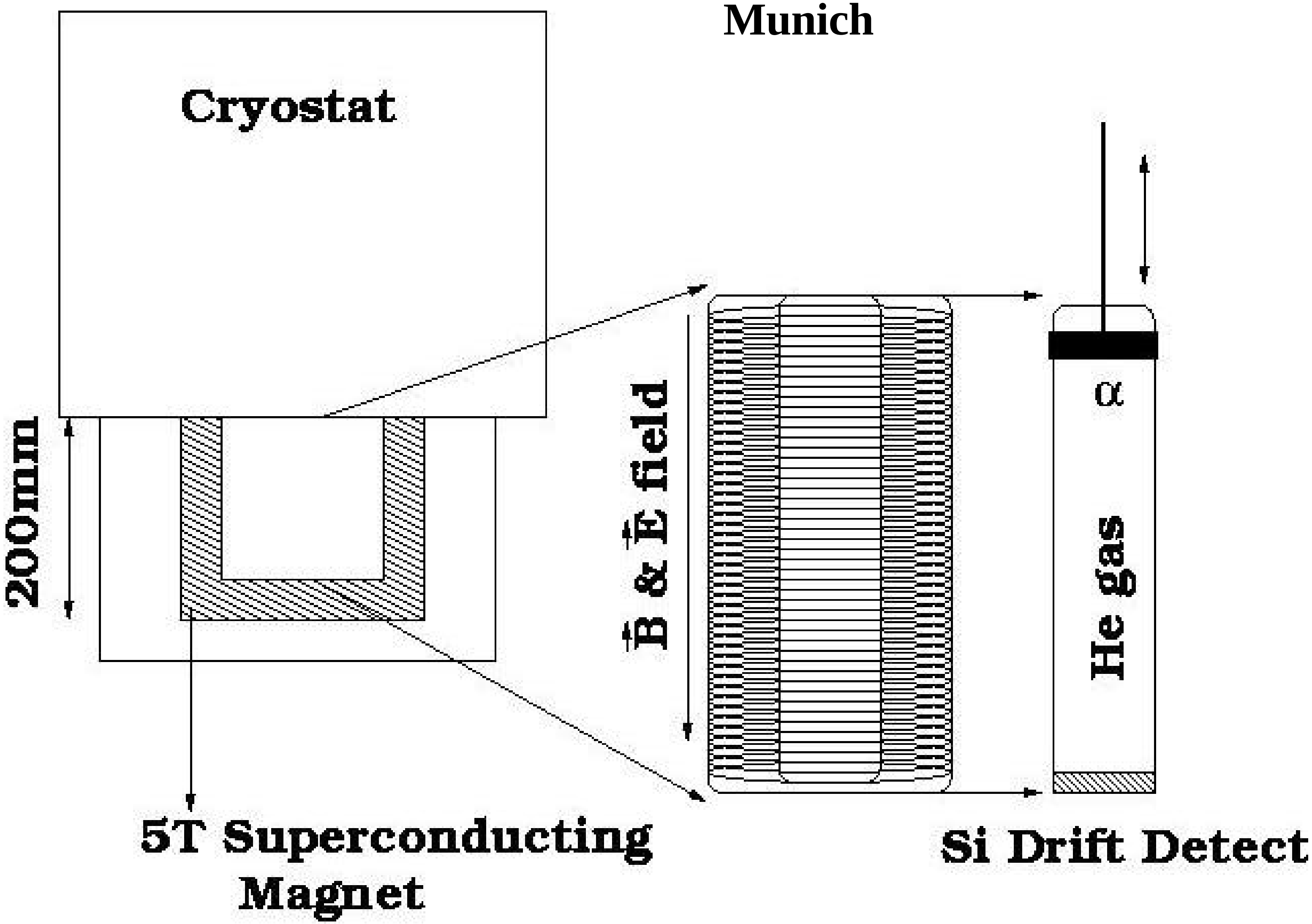
$$\mu^- + He \rightarrow He_\mu + e + \gamma\text{'s}$$

muon initially captured in large n orbit, then cascades down to n=1. Transition n=2→n=1 releases few KeV x-ray.



Si drift detector Developed my MPI HLL

Lab situated at MPI-WHI in Munich



Conclusions

- Muon Collider complex would be a boon for physics
- We need to solve the muon cooling problem
- Different schemes should be investigated
- We are doing some simulation and experimental studies of **frictional cooling**. So far, so good, but a long way to go !