Muon Frictional Cooling

D. Kollar, R. Galea, A. Caldwell, D. Greenwald

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Outline

→ Why a muon collider ?

→ What is the problem ?

→ Typical scheme

→ Frictional cooling

→ Demonstration experiment with protons

Why a Muon Collider ?

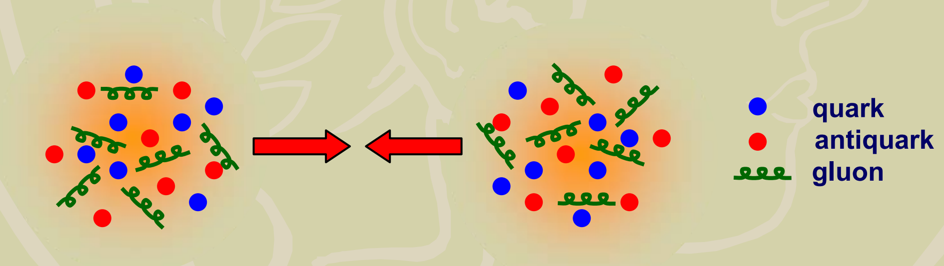
→ compared to electrons:

- no synchrotron radiation problem (as $m_\mu \approx 200\ m_e$)

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

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

→ compared to protons:



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

Why a Muon Collider ?

Physics

→ Higher energy frontier

- SUSY, GUT, etc.
- Higgs Factory $\sigma_{xx\to H} \propto m_x^2 \;\Rightarrow\; \sigma_{\mu\mu\to H} \approx 40.000\, \sigma_{ee\to H}$
- …

→ ν physics

- from target – π decay
- from stored – μ decay

→ Physics of slow μ

What is the Problem ?

Muons decay with lifetime **2.2 μs**

→ need a multi MW source

- large starting cost — maybe not a big problem

→ large experimental backgrounds

- lots of energetic $e^{\pm}$ from μ decay — should not be a big problem

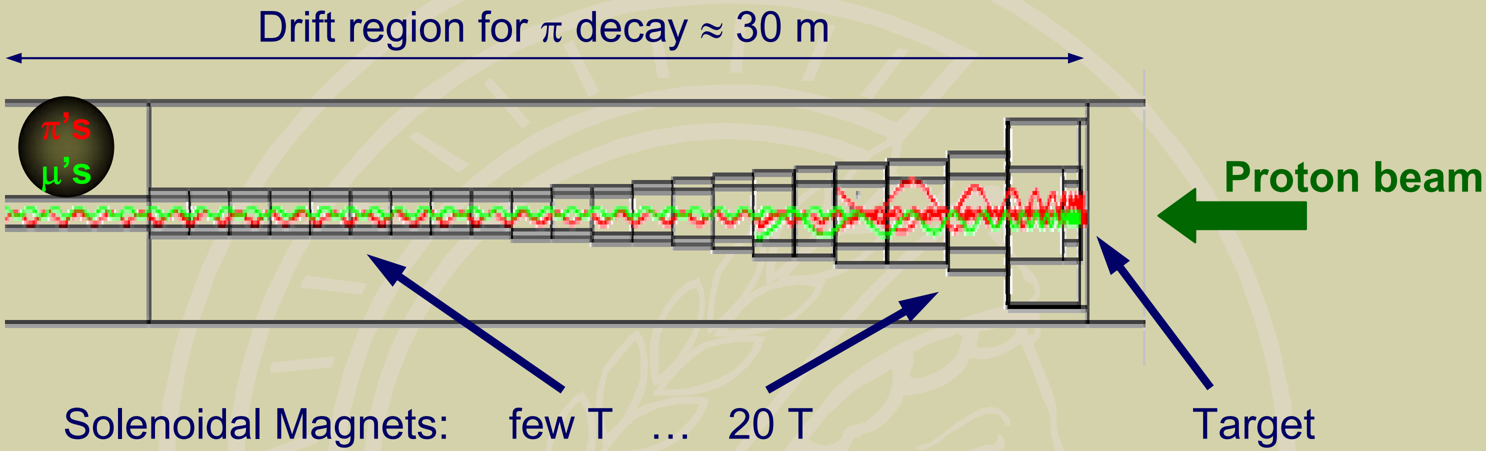
→ limited time for cooling, bunching, and accelerating

- need new techniques — seems to be a problem now

→ limitations due to neutrino induced radiation

- cannot be shielded — really a big problem

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

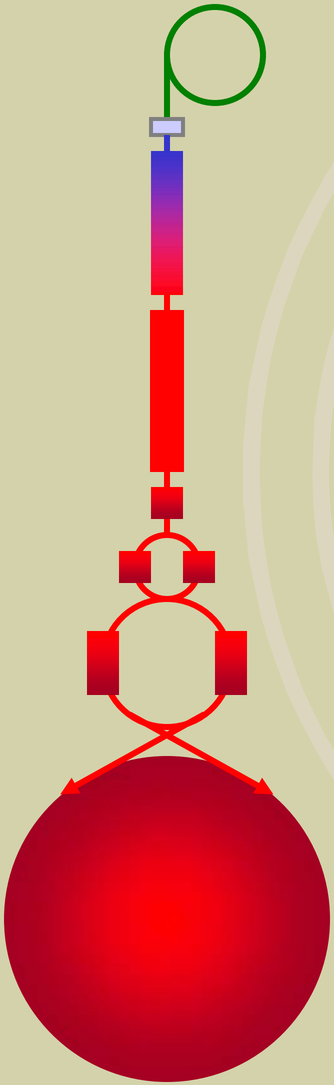
$\varepsilon_{6D,N} \approx \mathbf{1.7\times10^{-4}\ (\pi m)^3}$

COOLING

required

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

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

Typical muon cooling scheme

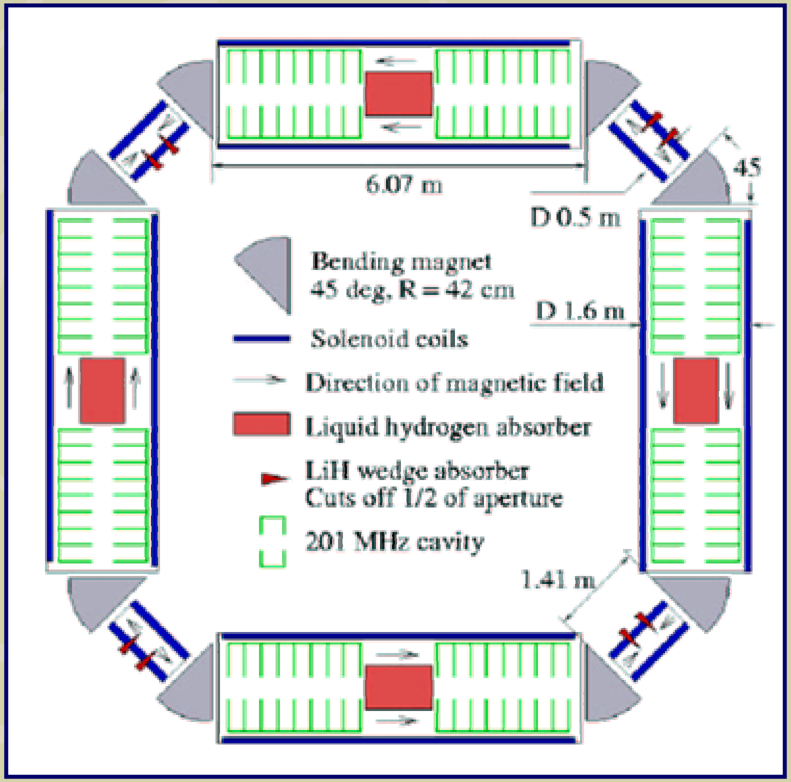
Ionization cooling

- muons are maintained at ca. 200 MeV while passed successively through an energy loss medium followed by an acceleration stage

- with simulations **cooling factors ~ 100** reached
  - → not enough for collider
  - → O.K. for ν factory
  - → still problems to be solved

- demonstration experiments in preparation

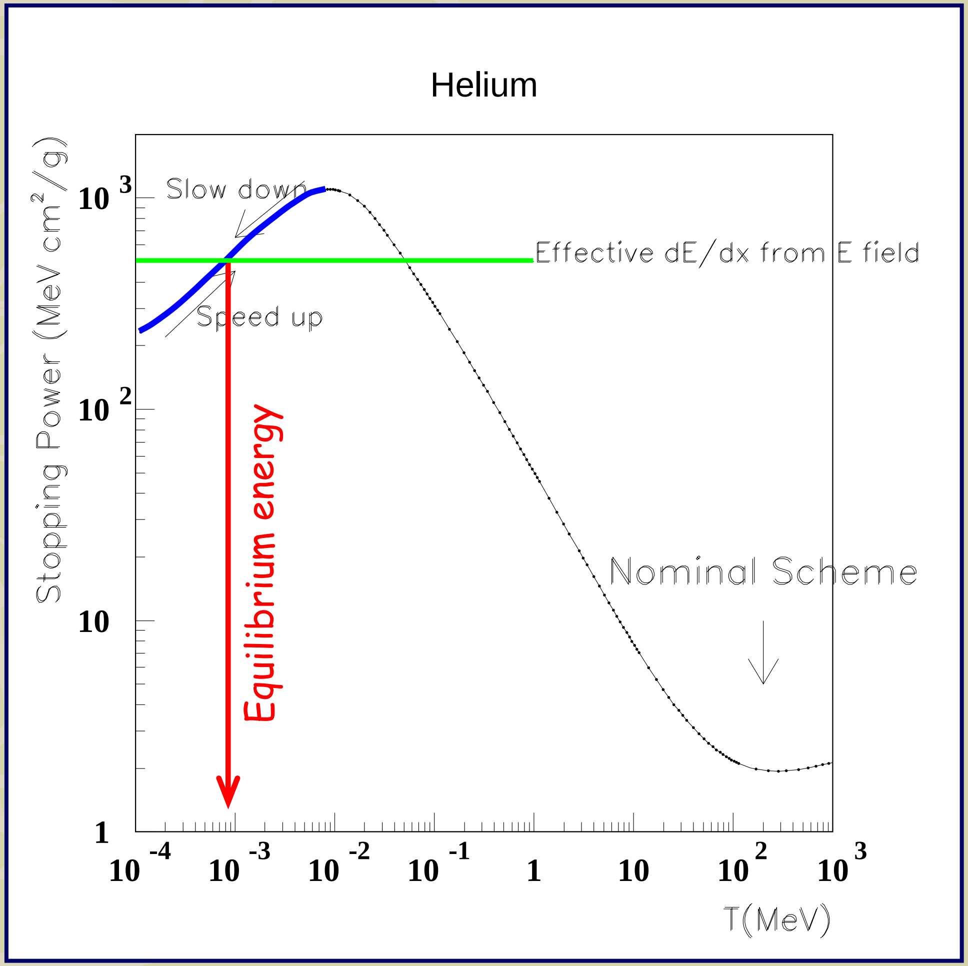
  e.g. **MICE**



Frictional cooling

Idea

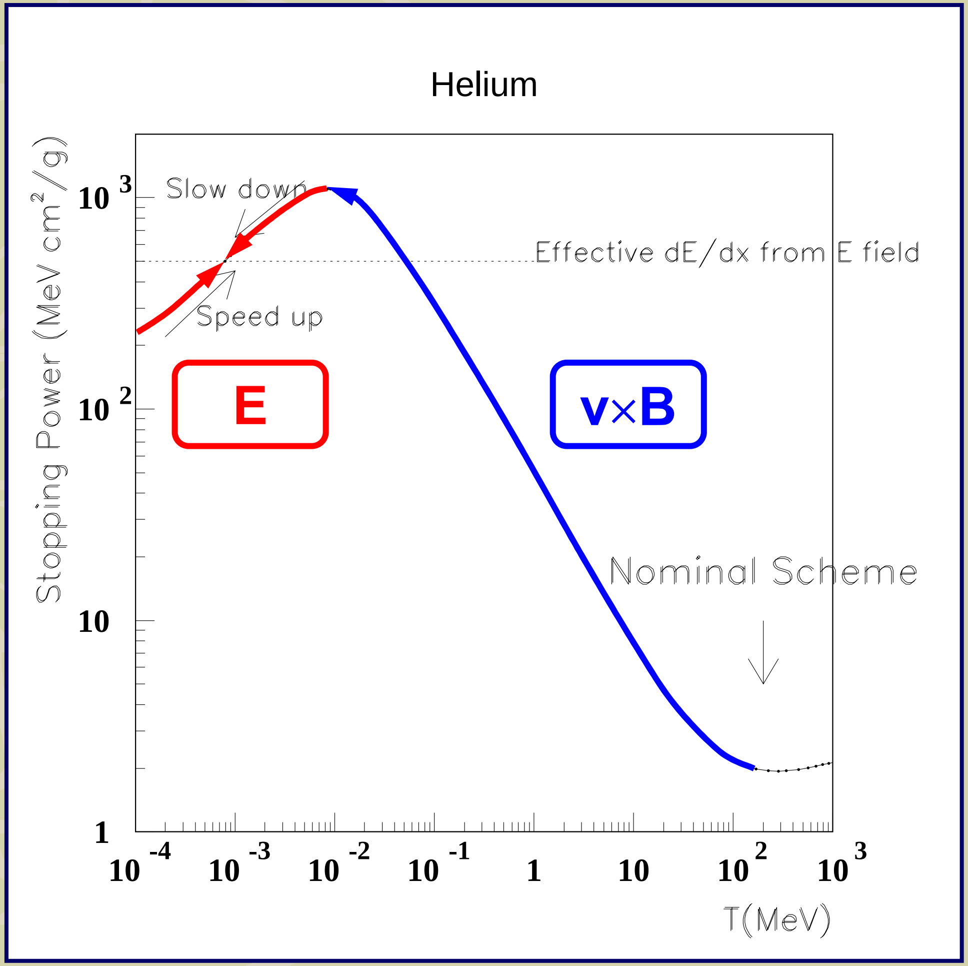
- bring muons to kinetic energy ***T*** where ***dE/dx*** increases with energy
- apply constant accelerating ***E*** field to muons resulting in **equilibrium energy**
- big issue – how to maintain efficiency
- similar idea first studied by Kottmann et al. at PSI



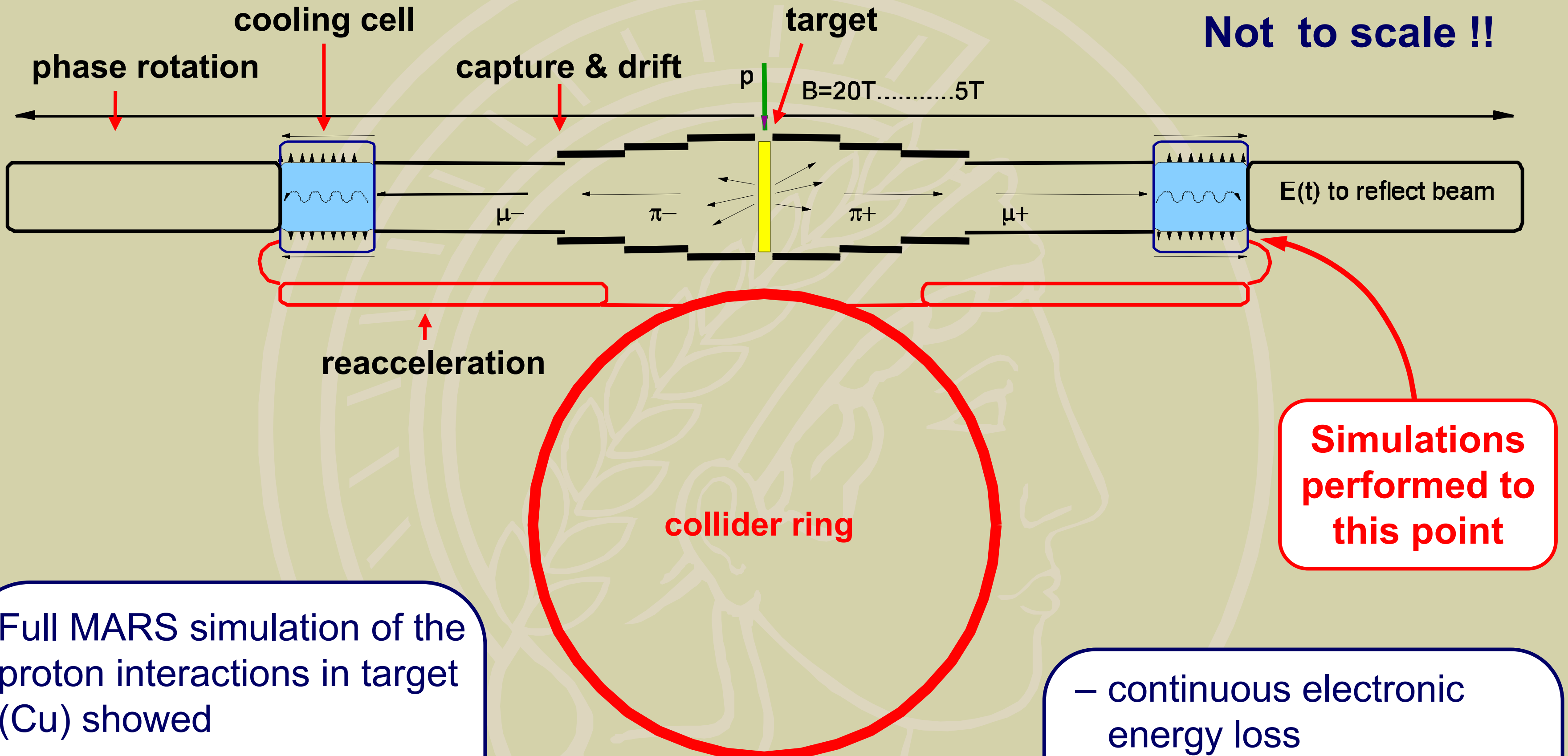
Frictional cooling

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



Muon collider scheme based on frictional cooling



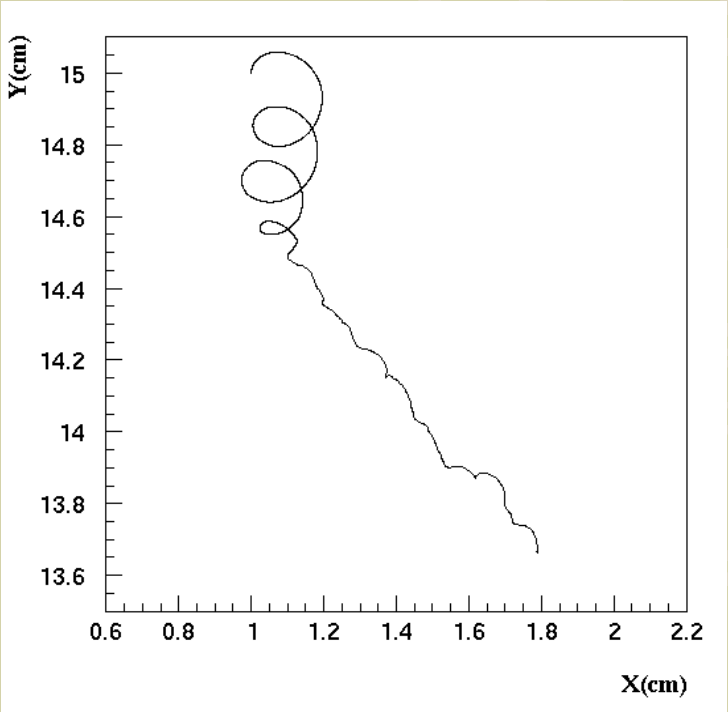
Full MARS simulation of the proton interactions in target (Cu) showed

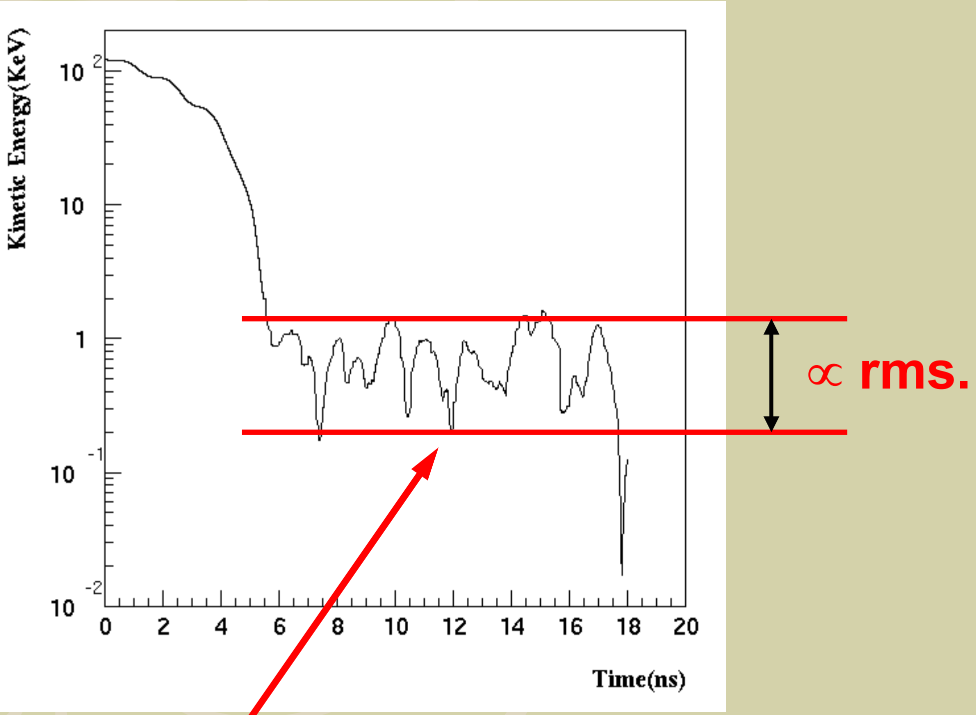
- larger low energy π yield in transverse directions
- nearly **equal** π^+ **and** π^- **yields** with T < 100 MeV

- **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

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

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

→ 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

Demonstration experiment with protons

RARAF

→ performed at Nevis Labs

→ to demonstrate the principle of frictional cooling
  - has to work for all charged particles $\Rightarrow$ **protons**

Results:

→ no cooled protons observed due to low acceptance (no ***B***) and **too thick windows**

→ however, including real thicknesses of windows into simulation reproduced the measured data

So the simulations seem to work but an experimental confirmation is still needed! ⇒ **MPI**

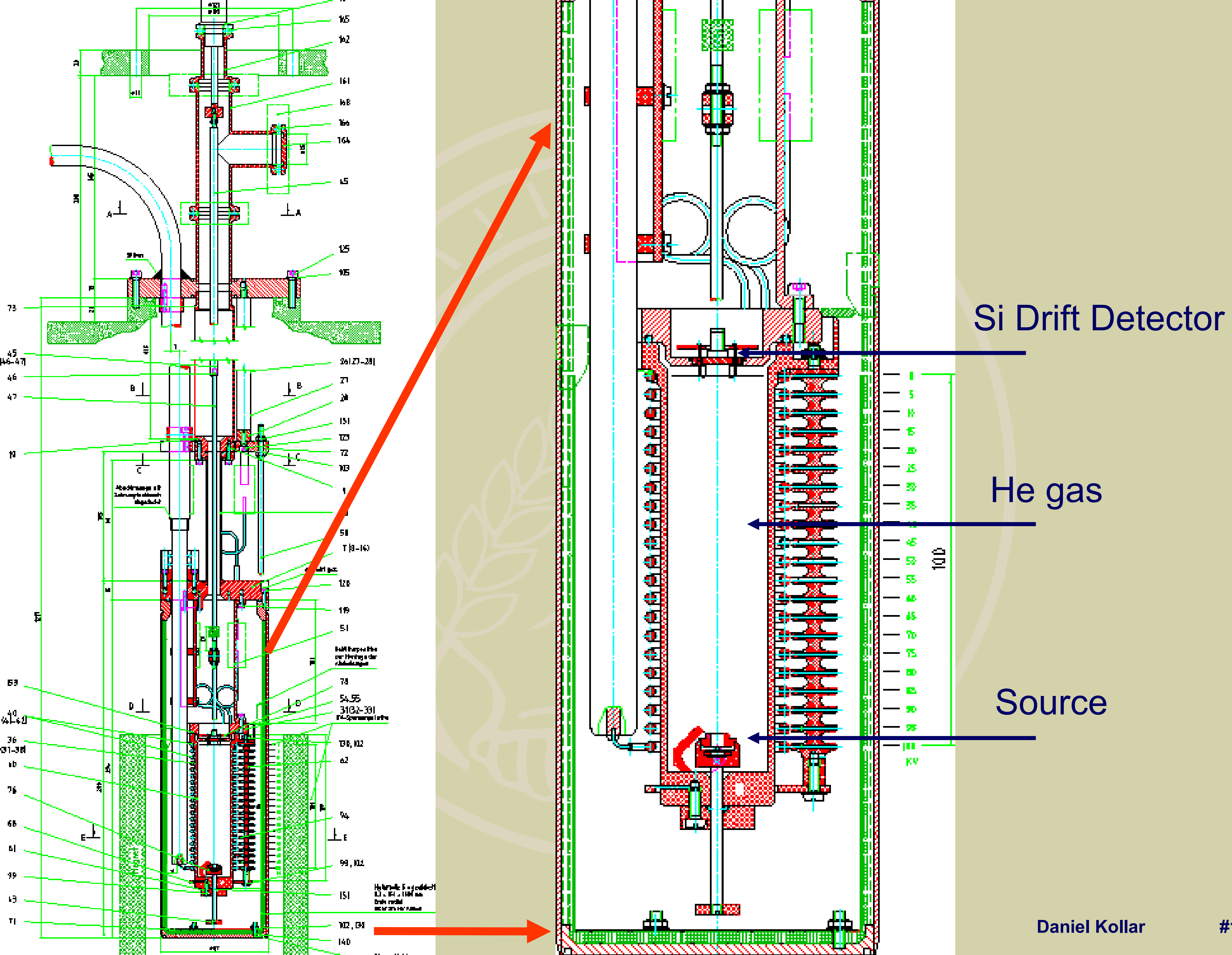
Demonstration experiment with protons

MPI für Physik

Repeat the demonstration experiment with improovements:

- no windows
- 5 T superconducting solenoid for high acceptance
- Silicon Drift Detector (SDD) to measure energy directly (was ToF at RARAF)

Cryostat housing 5 T solenoid in the lab at the MPI →

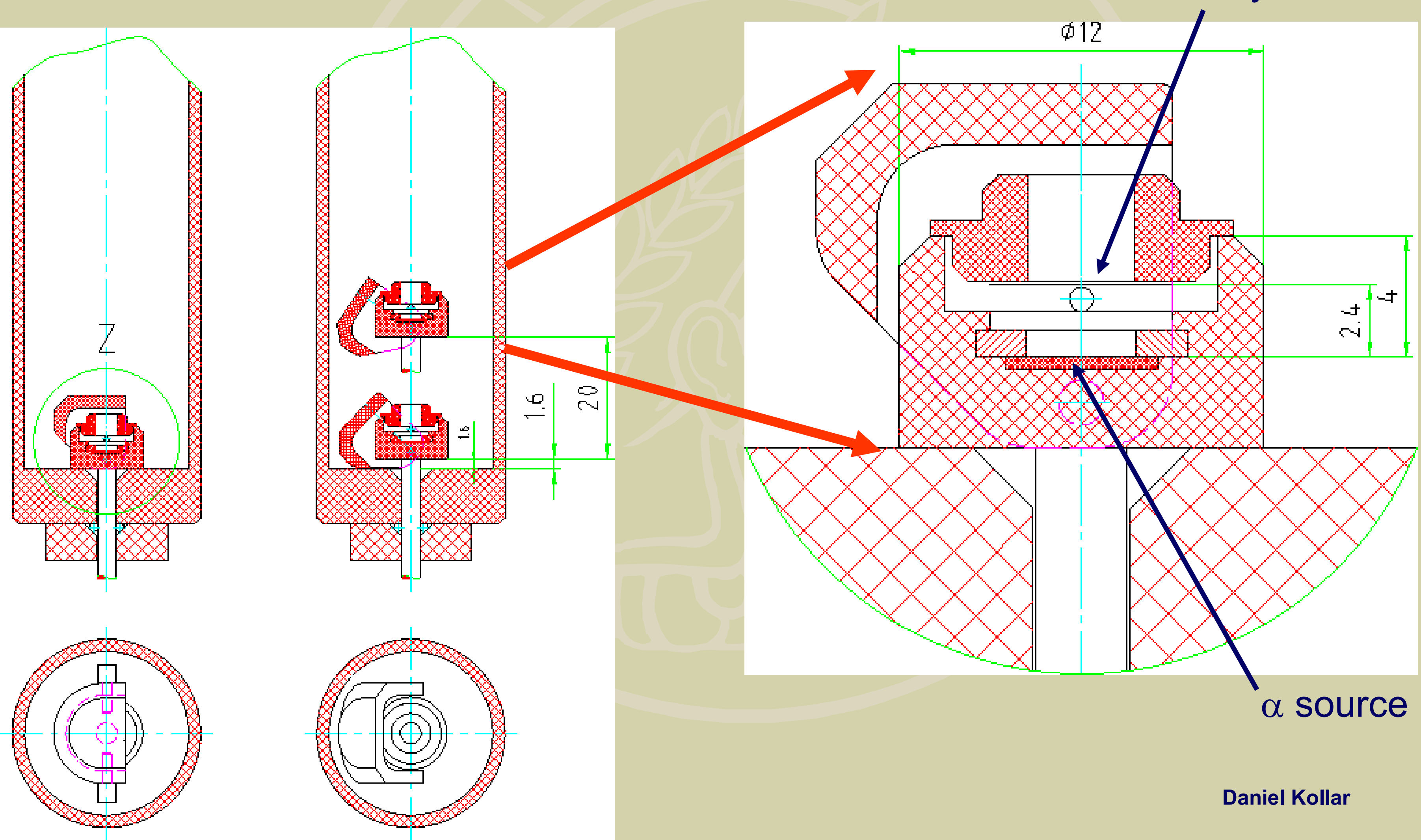


Si Drift Detector
He gas
Source

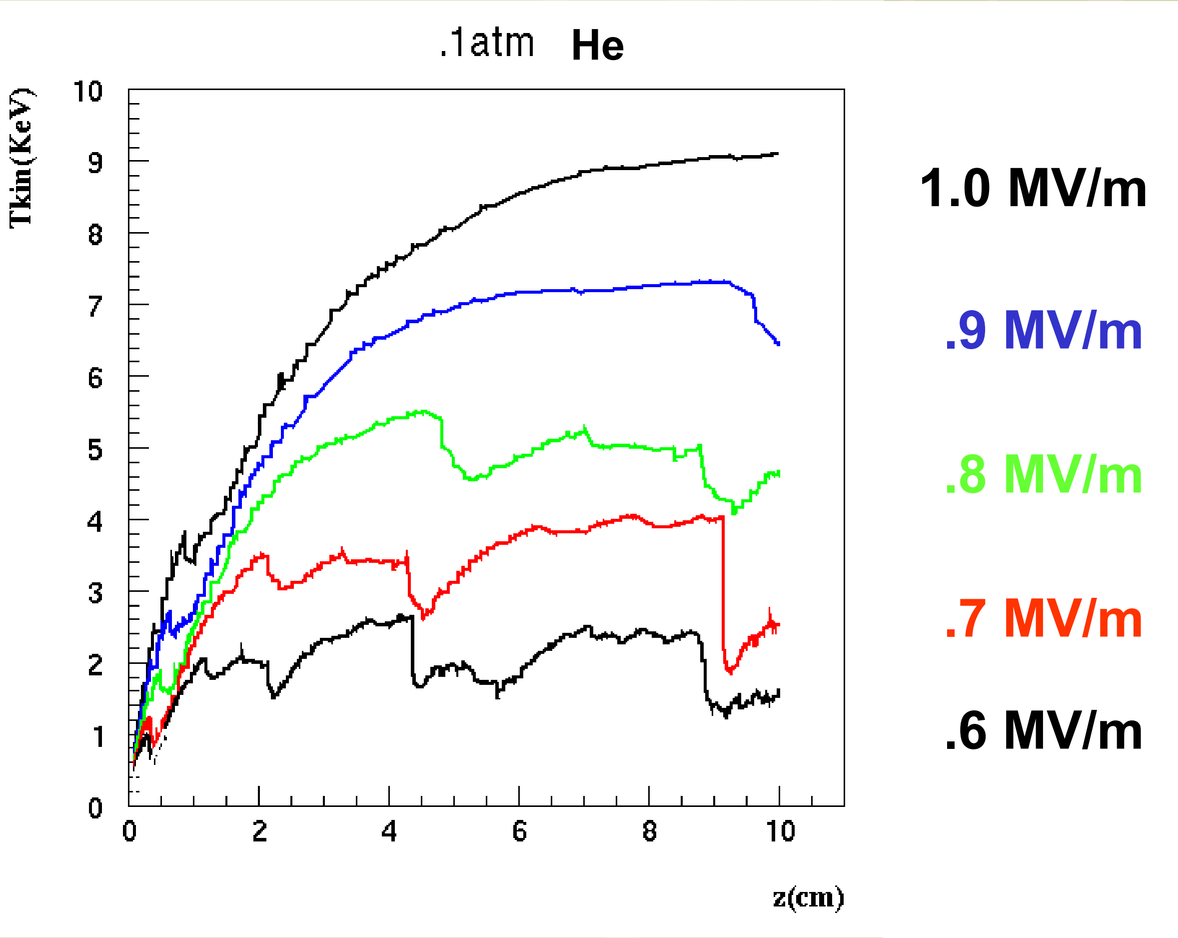
Where do we get protons ?

→ use strong α source + thin plastic (Hydrogen rich) foil

→ α's knock out H nuclei effectively at rest



What do we expect?



We are able to vary

- pressure/density of the gas
- distance between the source and detector
- strength of the *E* field

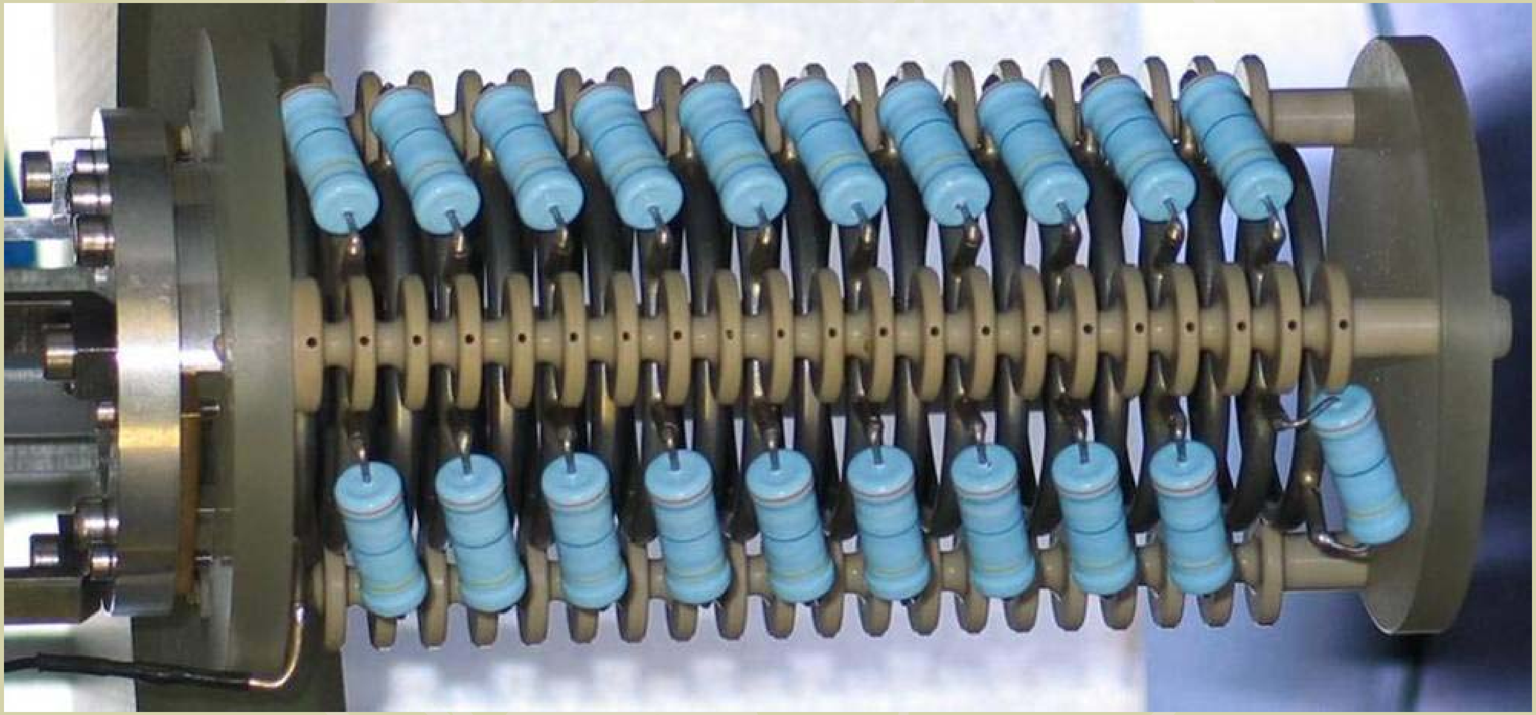
The ultimate question:

Can our MC simulation predict equilibrium energies?

Present status

→ the superconducting magnet commissioned

→ the accelerating grid is ready



We maintained up to 98 kV in vacuum.

Present status

→ the superconducting magnet commissioned

→ the accelerating grid is ready

→ all support structures are constructed

→ detectors and electronics are available

Do not work together at the moment !

Future plans

→ run the experiment
  – demonstrate the frictional cooling

→ muon capture cross section measurement

→ studies of breakdown in high **E⊥B** fields

→ R&D on thin windows

Build a muon collider.


Thank You for Your attention