Muon Colliders & Frictional Cooling

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MPP, Munich
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Why Build a Muon Collider?

Advantages over the electron:

$P_{synchrotron}$ goes as $1/m^4$.

$m_\mu = 200\ m_e$ => $P_\mu = 10^{-9}\ P_e$

meaning:

higher energies, smaller machines

Disadvantages:

Muon decay time (2.2 μs)

meaning:

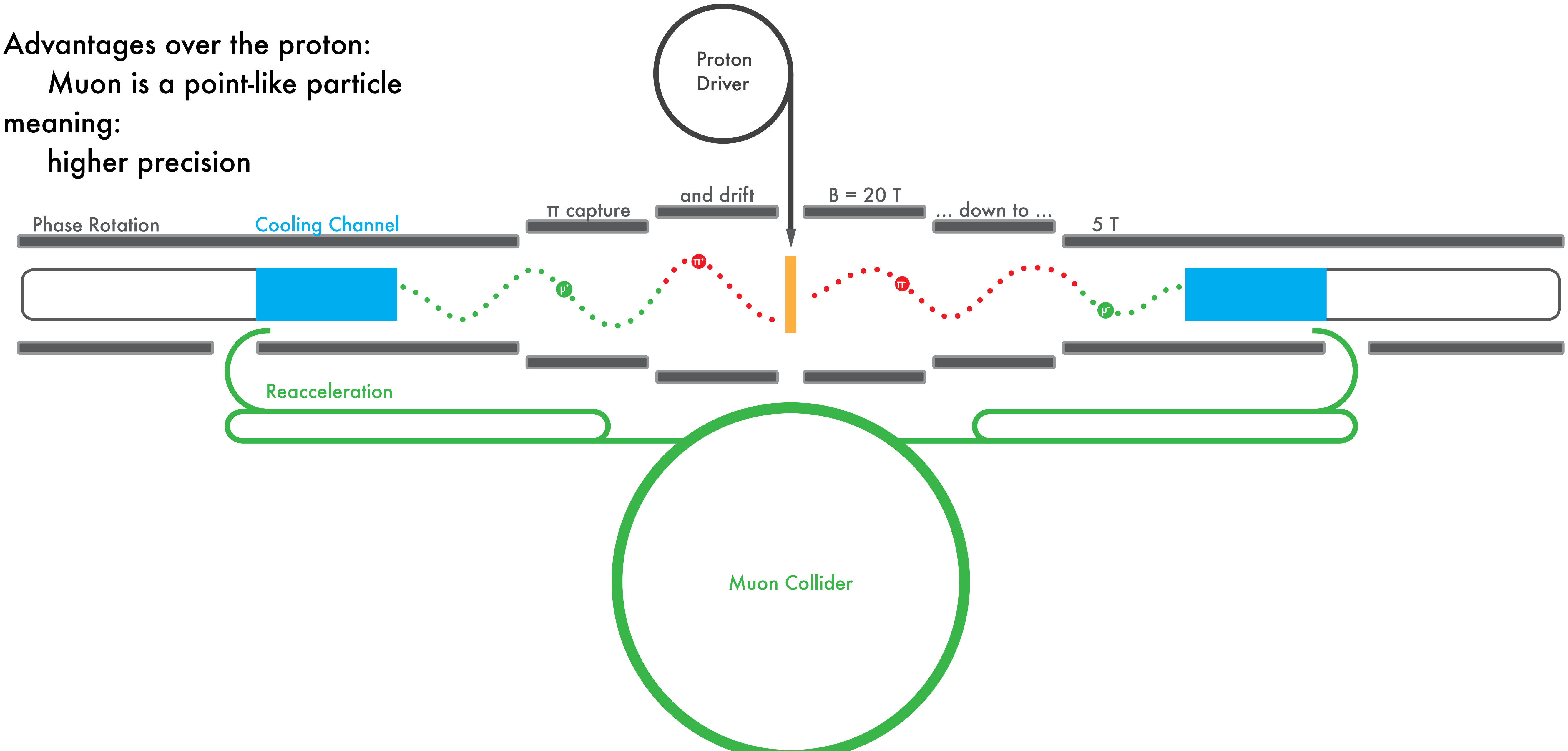
Fast schemes for beam preparation required

Advantages over the proton:

Muon is a point-like particle

meaning:

higher precision

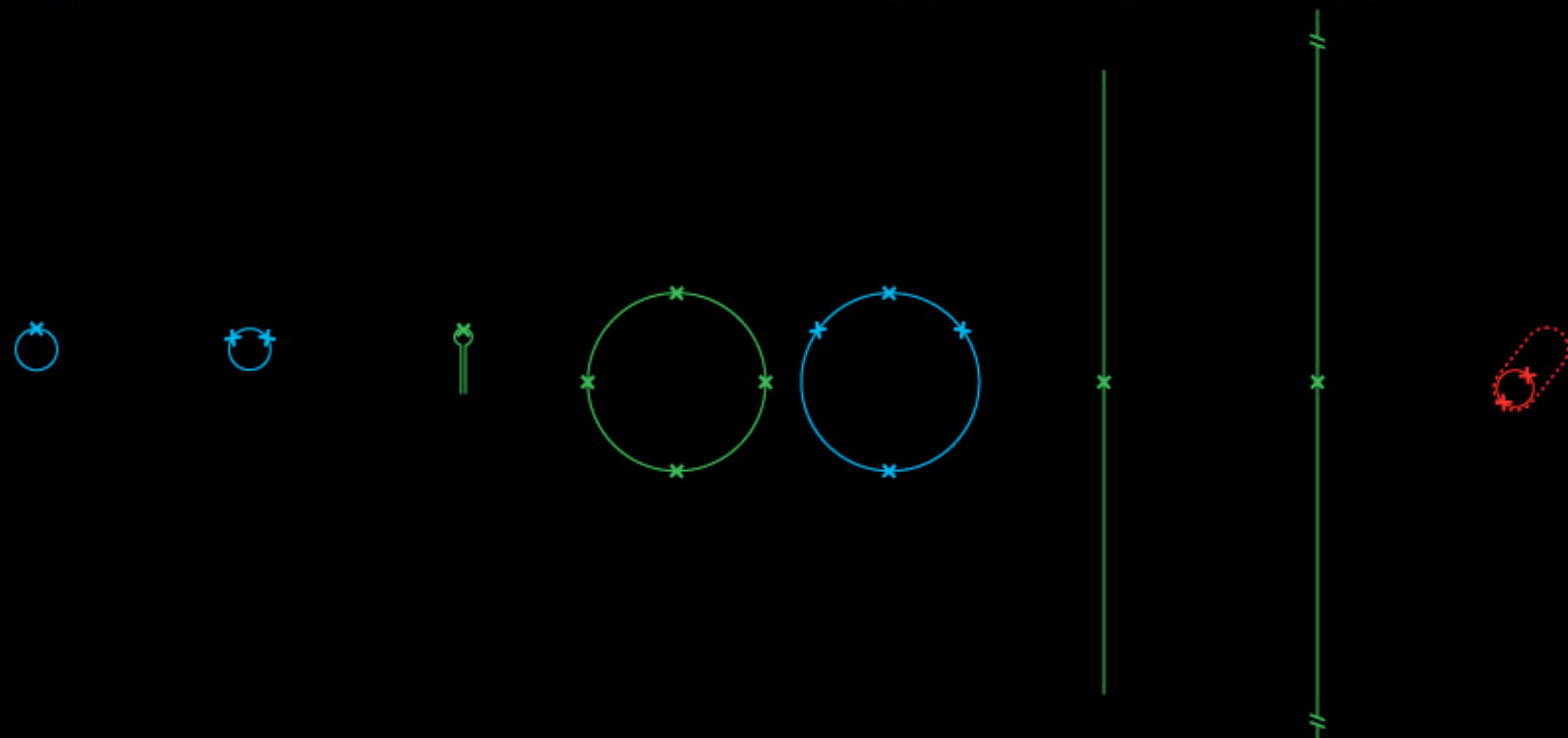


Collider Size

Name	SPPS	Tevatron	SLC	LEP I&II	LHC	ILC	CLIC	Muon Collider
	1981–1993	1985–present	1989–1998	1989–2000	First collisions 2009	proposed	proposed	proposed
Size	d=2.1km	d=2km	l=3km	d=8.4km	d=8.4km	l=30km	l=50km	d=2km
Type	$p\bar{p}$	$p\bar{p}$	e^+e^-	e^+e^-	pp	e^+e^-	e^+e^-	$\mu^+\mu^-$

Collision energy in TeV

Energy of constituent particles



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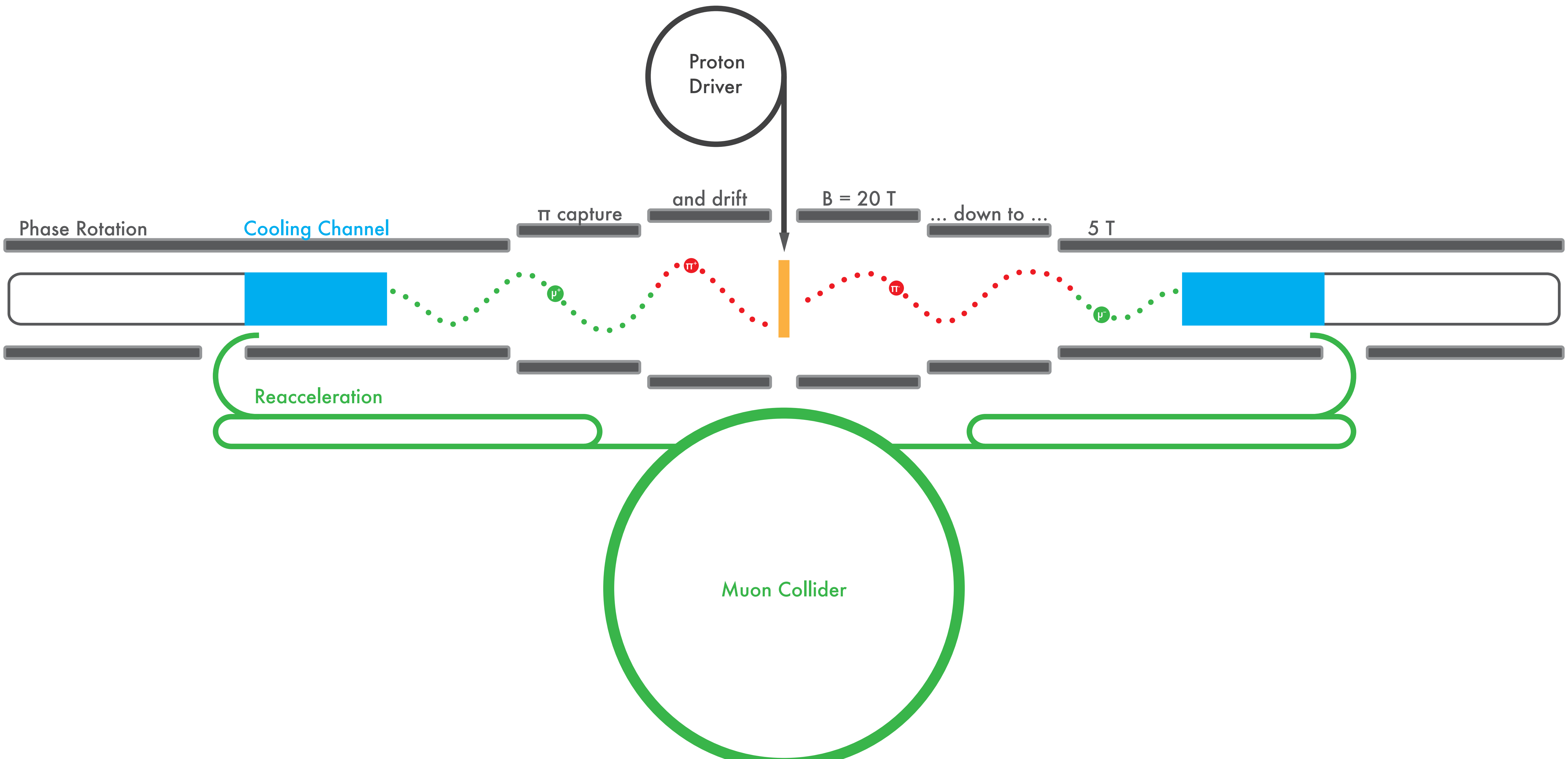
Muon Production

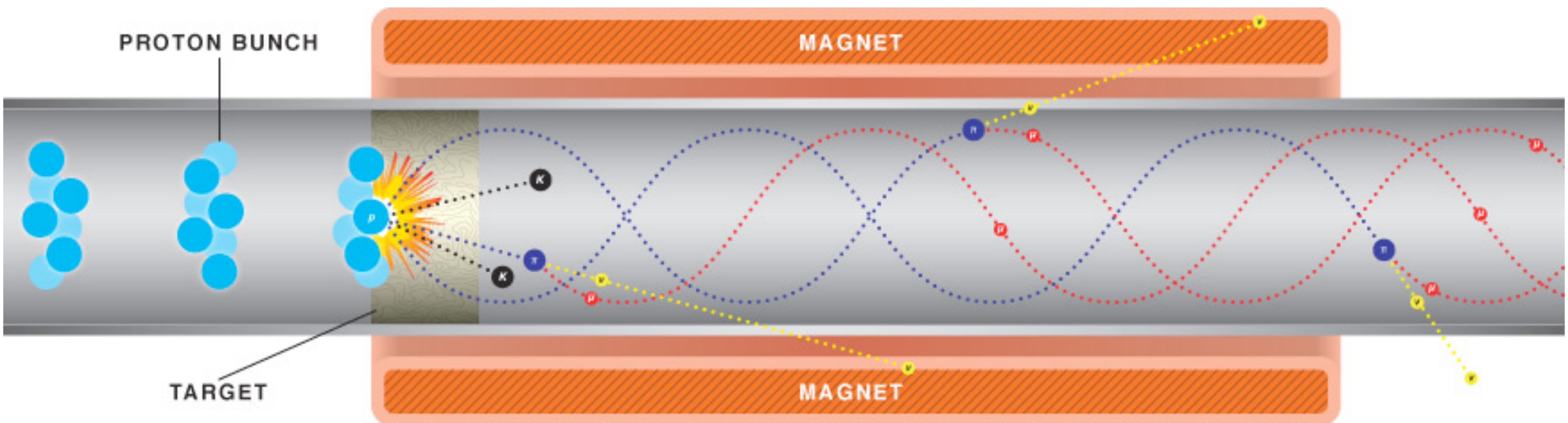
Multi-Megawatt proton beam produces pions in target



Muon Production

Multi-Megawatt proton beam produces pions in target

Strong magnetic field (20 T) captures pions
Pions drift, decay to muons.

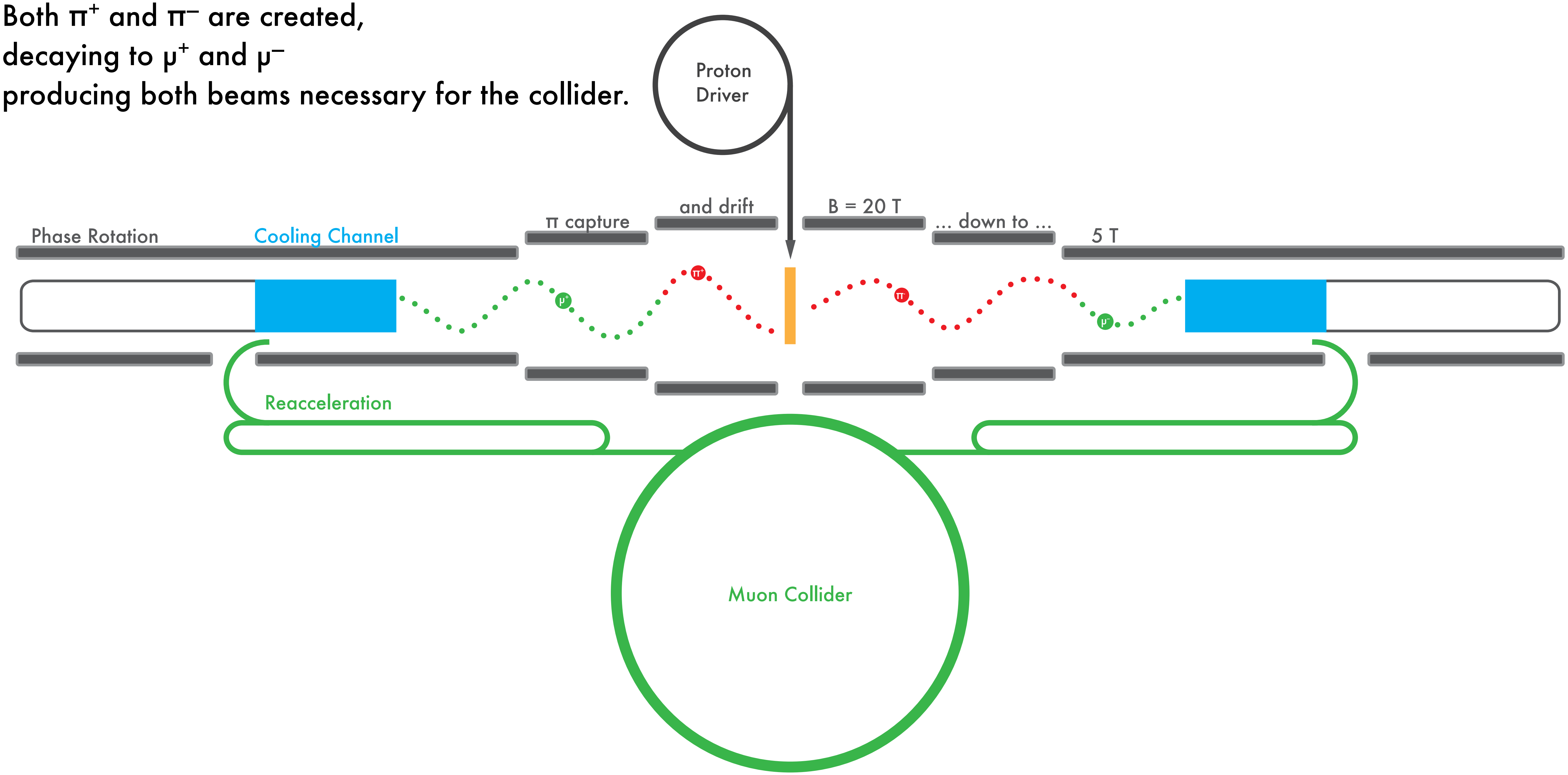


Muon Production

Multi-Megawatt proton beam produces pions in target

Strong magnetic field (20 T) captures pions
Pions drift, decay to muons.

Both π^+ and π^- are created,
decaying to μ^+ and μ^-
producing both beams necessary for the collider.



Luminosity & Emittance

Event Rate = Luminosity × Cross Section

$L = fN^2 / 4\pi\sigma_x\sigma_y$

Emittance = beam's size in phase space

$\varepsilon_{6D,N}$ = six dimensional normalized emittance

= $\sigma_x\sigma_y\sigma_z\sigma_{px}\sigma_{py}\sigma_{pz} / (\pi\ mc)^3$ [Assuming no correlations]

Example parameter set for a μC with a 3 TeV center-of-mass energy:

Bunches/fill	4
Rate	15 Hz
μ/bunch	2×10^{12}

for a

Luminosity	7×10^{34} cm^{-2} s^{-1}
one requires	
$\varepsilon_{6D,N}$	2×10^{-10} $(\pi m)^3$

After the pion decay channel, the muon beam has:

$\varepsilon_{6D,N}$ = (5cm)(5cm)(10m)(50MeV/c)(50MeV/c)(100MeV/c)

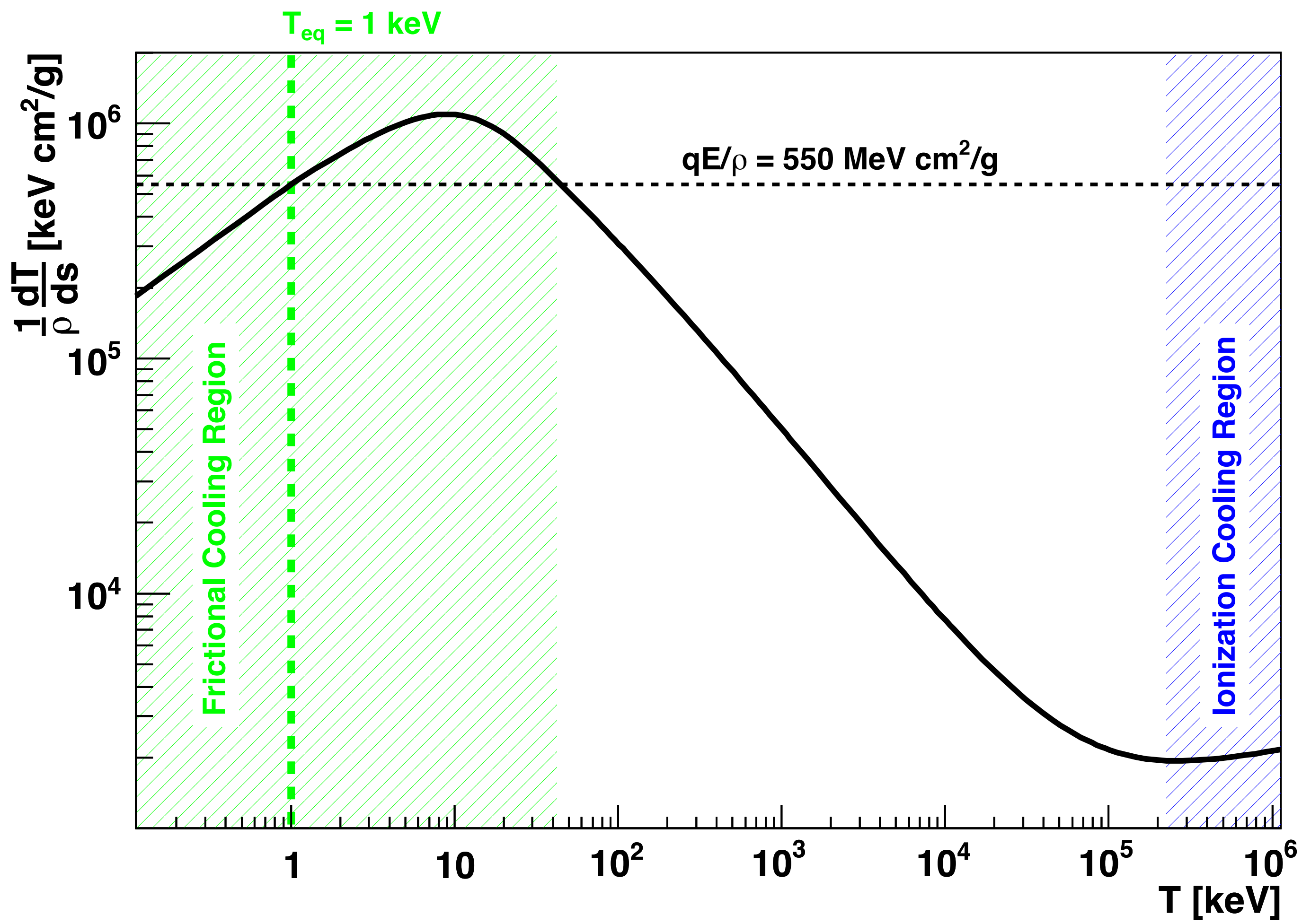
= 2×10^{-4} $(\pi m)^3$

6 orders of magnitude in emittance reduction ("cooling") is needed.

Frictional Cooling Concept

Frictional cooling is the bringing of charged particles to an equilibrium energy by the balancing of energy loss to a medium with energy gain from an electric field

In order to be cooled, muons must be in the low-energy energy region, where stopping power goes as $(T)^{1/2}$ and a stable equilibrium energy can be established.

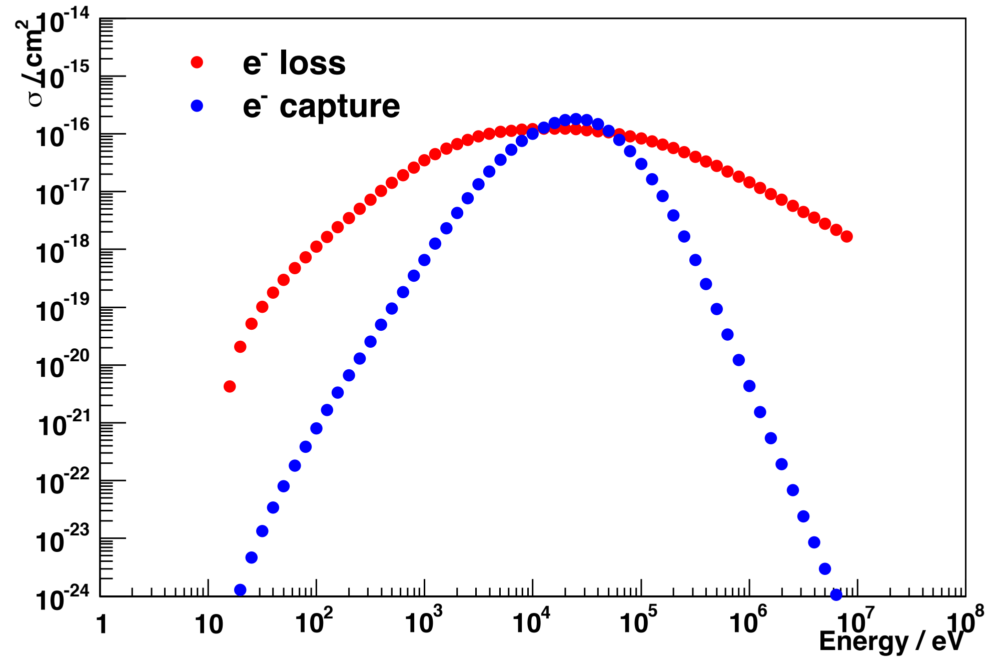


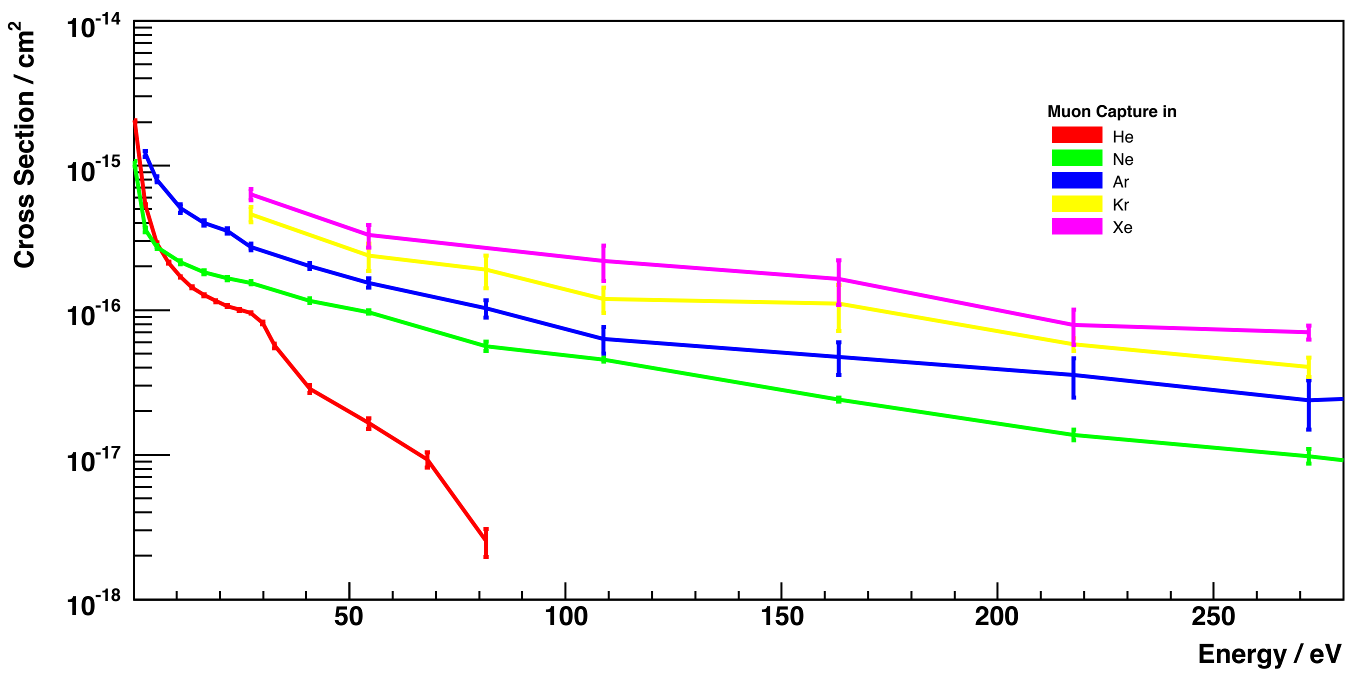
Because the stopping power is very large around T_{eq}, the density of the medium must be low; we use a gas.

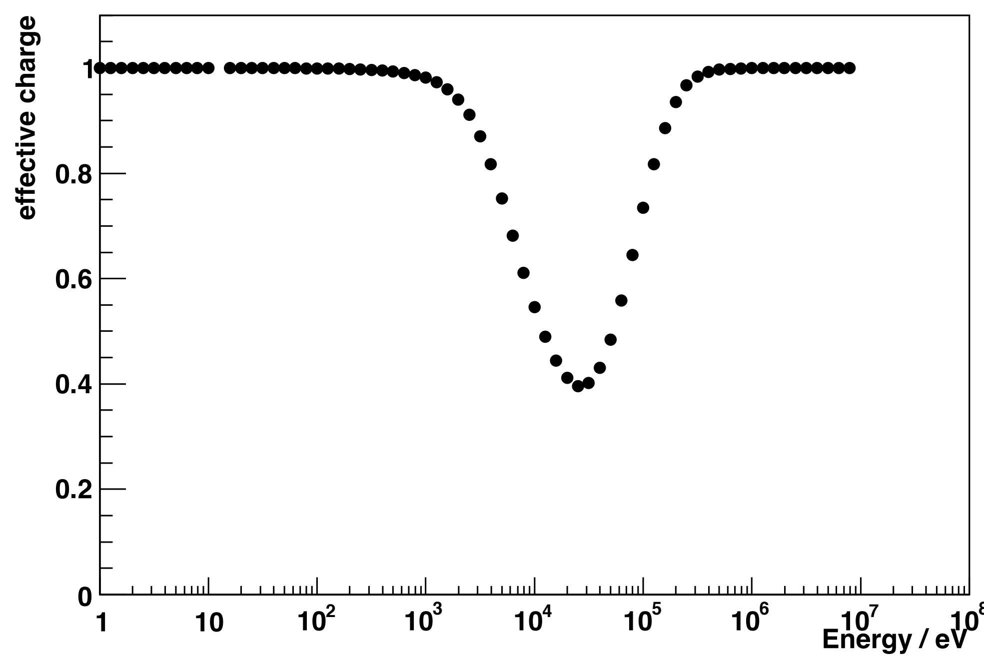
Cooling Medium

μ^+
charge exchange cross sections for helium make it the ideal gas

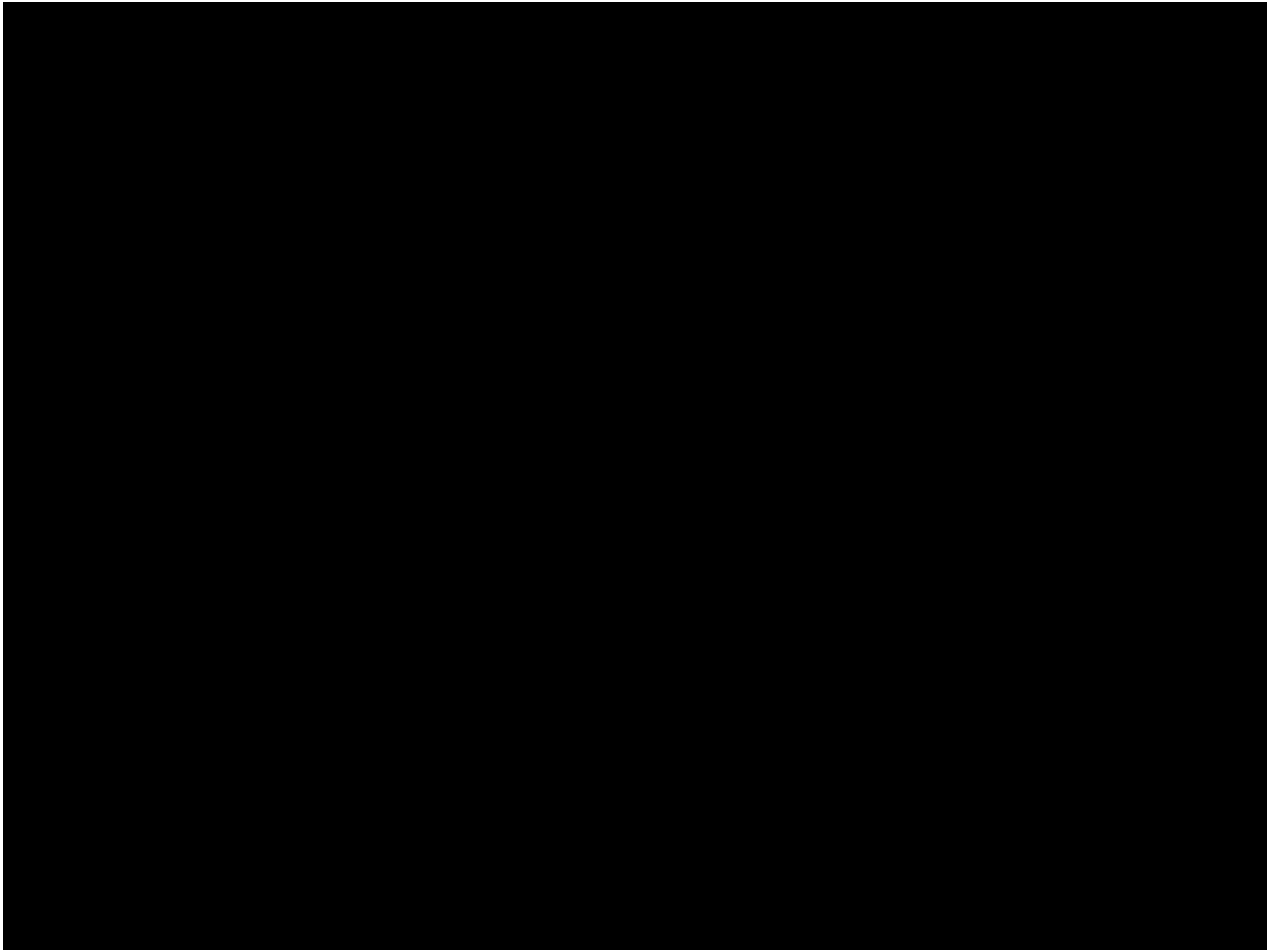
μ^-
capture cross sections for helium and hydrogen make them the ideal choices







Cooling Cell



First Simulation + Experiment

The front end scheme and this cooling scheme were simulated
(arXiv: physics/0410017)

An emittance of $\varepsilon_{6D,N} = 3 \times 10^{-11}$ $(\pi m)^3$ was acheived,
approximately 5 times better than what is needed
for $L = 7 \times 10^{34}$ cm^{-2} s^{-1}

The yield was 0.002 μ^+/p
unfortunately 5 times lower than what was aimed for,
but balances with the 5 times better emittance

New Simulation at MPP: CoolSim

- More flexible geometry control:
  - Easier optimization of scheme components
  - Testing of new schemes
- New physics at low energy:
  - Charge Exchange / Effective Charge / Neutralization

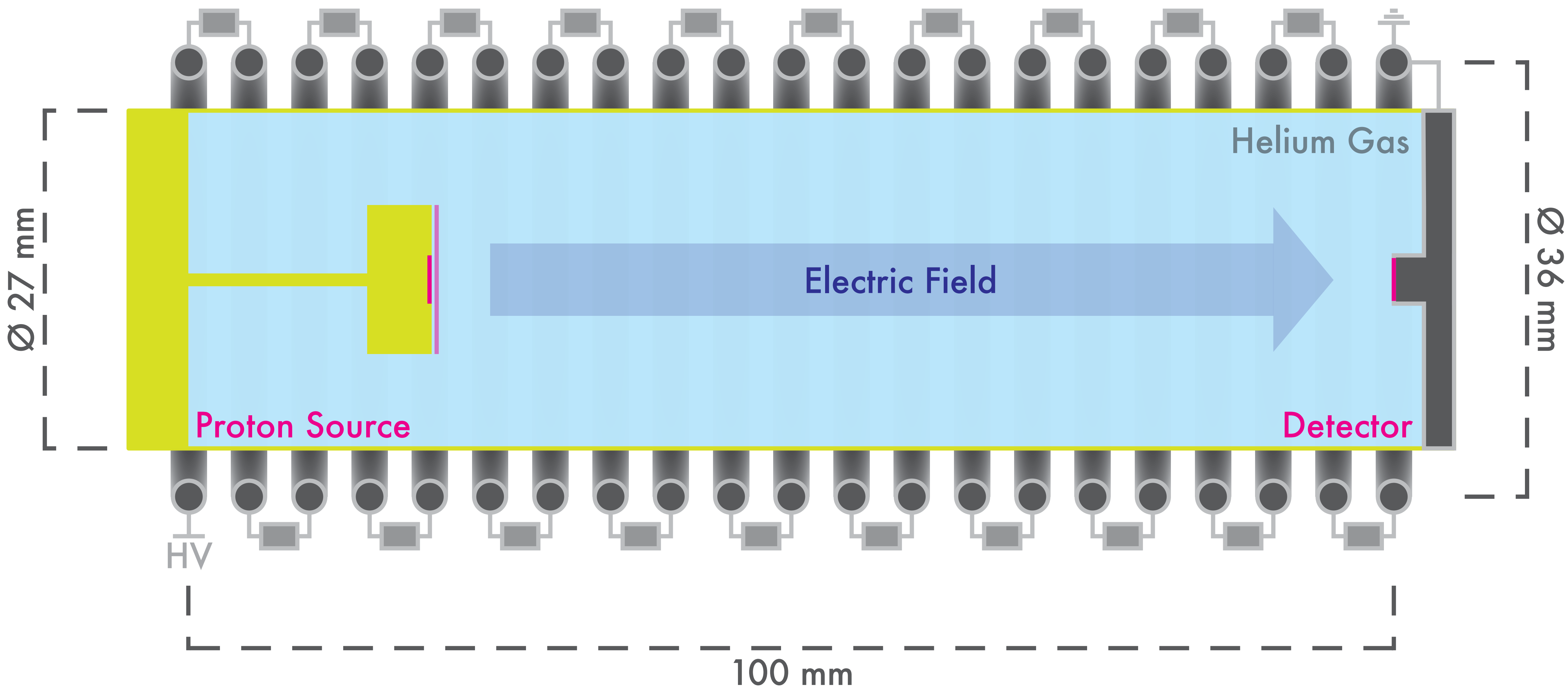
Frictional Cooling Demonstration Experiment

Motivated by the promising results of the first simulations, an experimental verification of frictional cooling using a proton beam was undertaken at Nevis Labs, 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.

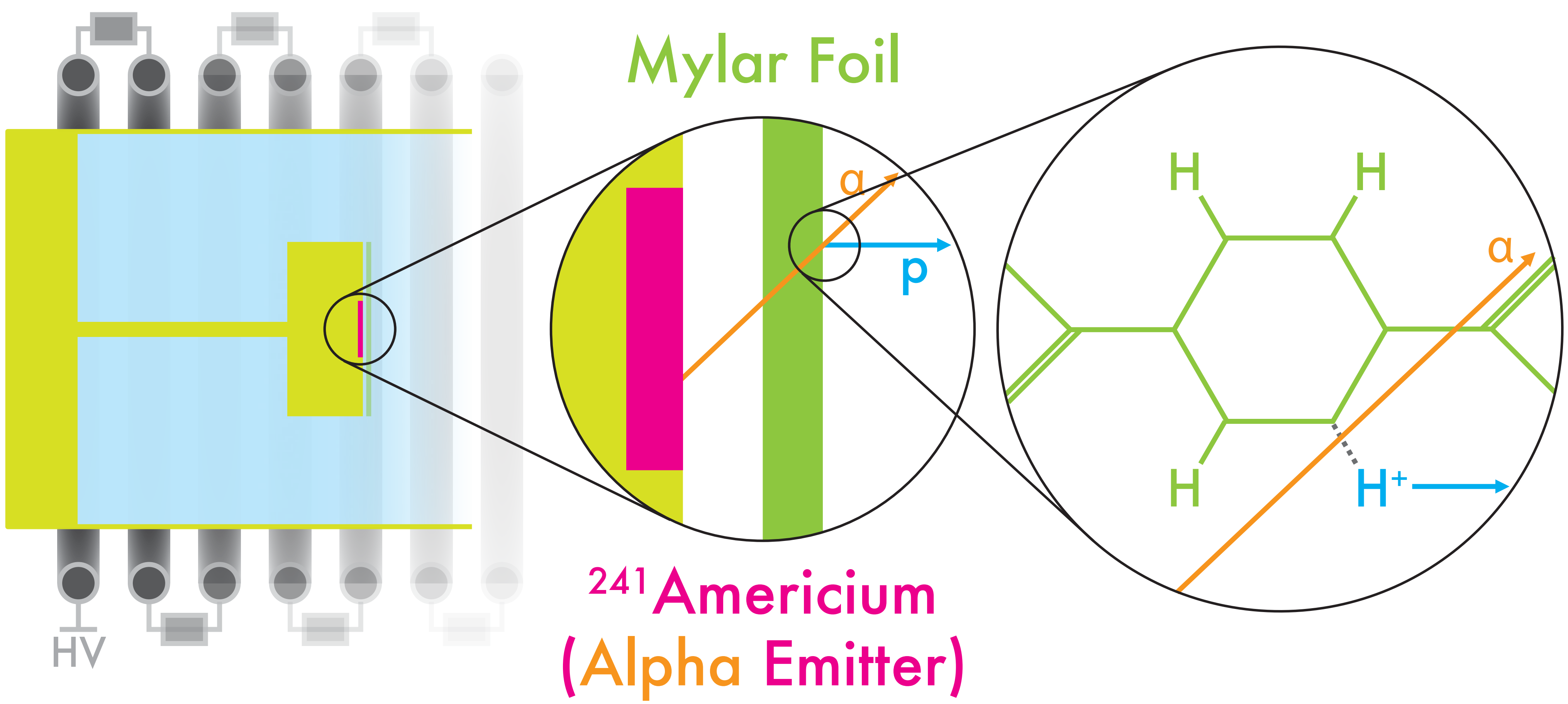
The FCD experiment at the MPP aims to test the basic principle behind frictional cooling, also using protons. The experiment has been designed to avoid the use of windows.

The proton source and detector are both mounted *inside* the cooling cell.

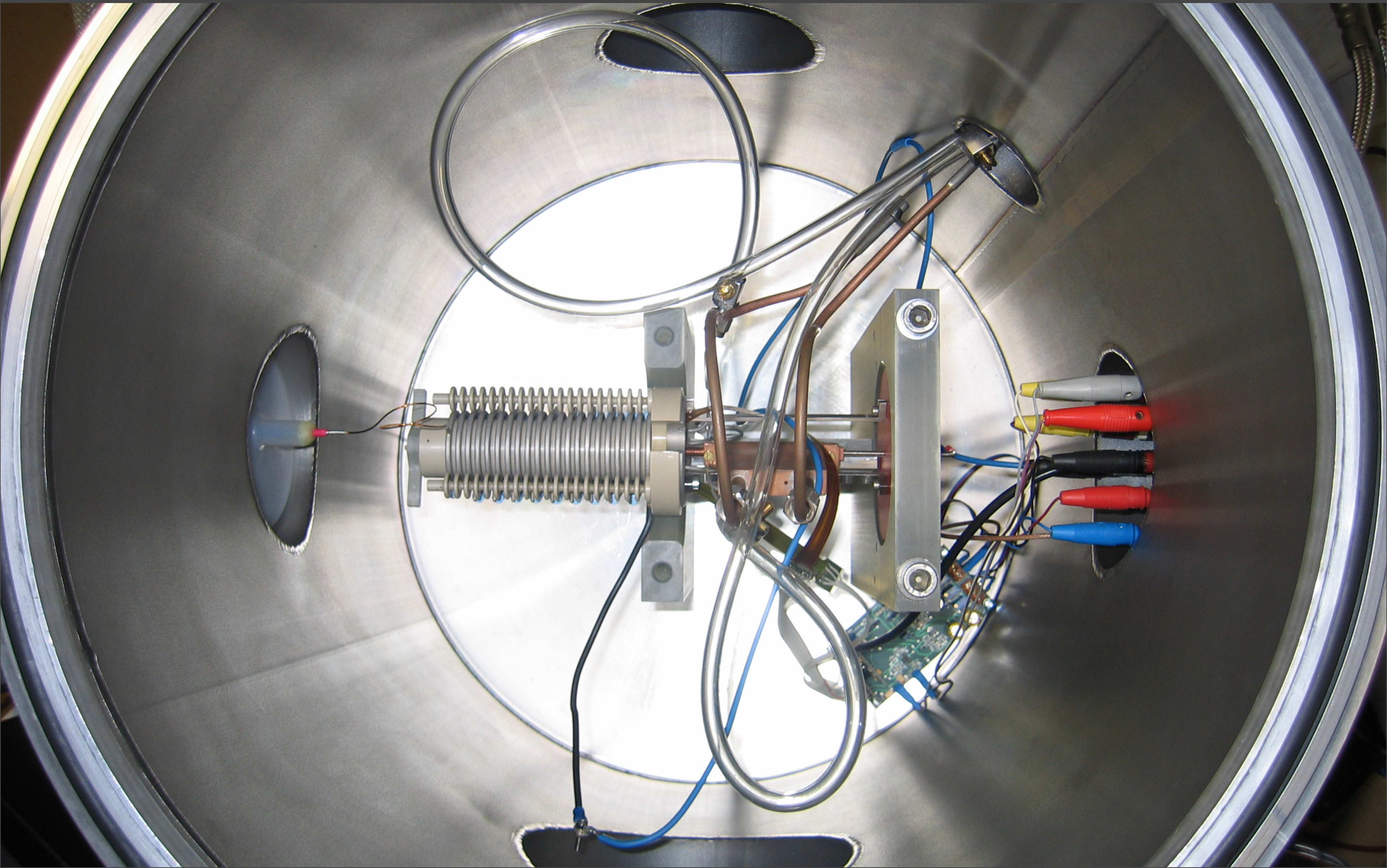


Proton Source

Alpha particles pass through a mylar foil, breaking the bonds between carbon and hydrogen, leaving the ionized hydrogen free to be accelerated away by the electric field in the cell.



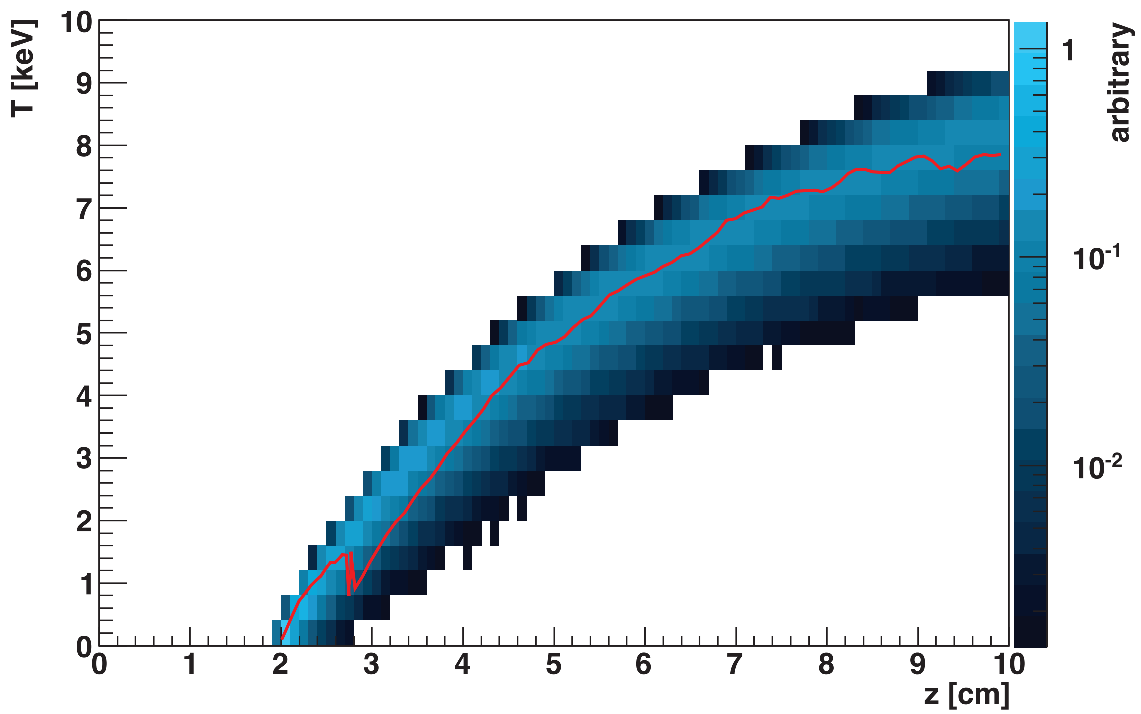
Experimental Setup



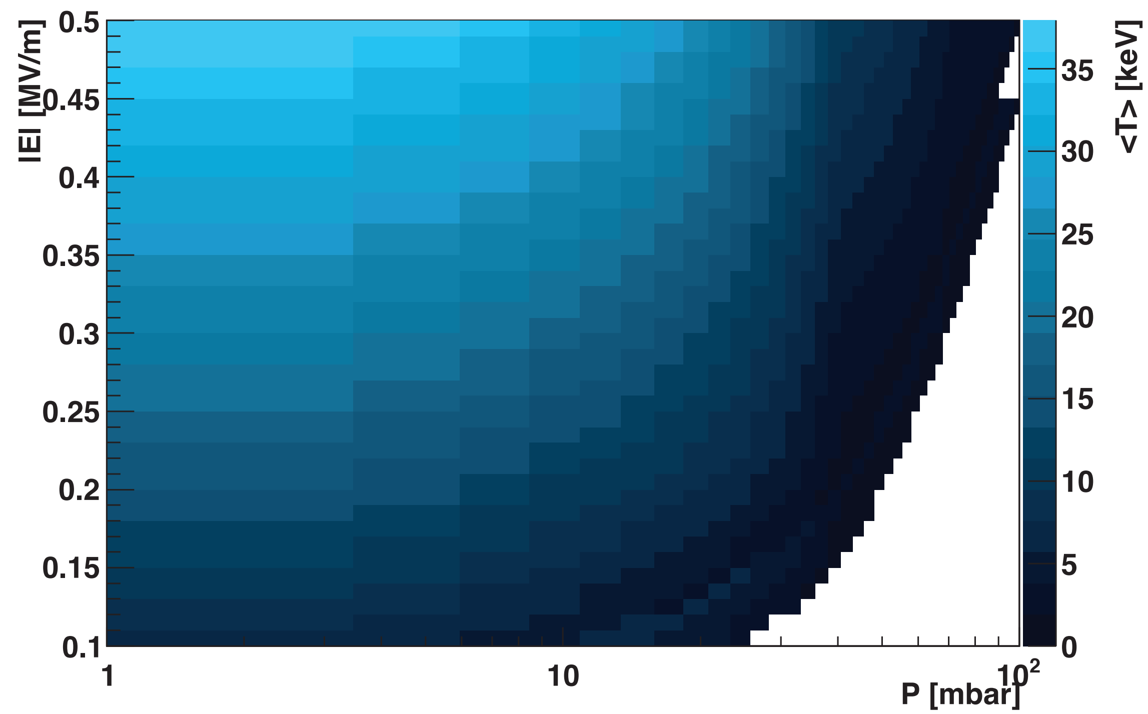
Proton Source

Simulation of the FCD cooling cell was made in CoolSim for the range of interesting pressures and electric fields that can be reached in the lab

The simulation determines the mean energy of the protons as a function of distance traveled in the gas cell.



It also calculates the mean energy of the protons at the detector plane (z=10cm) as a function of the electric field strength and the gas pressure.

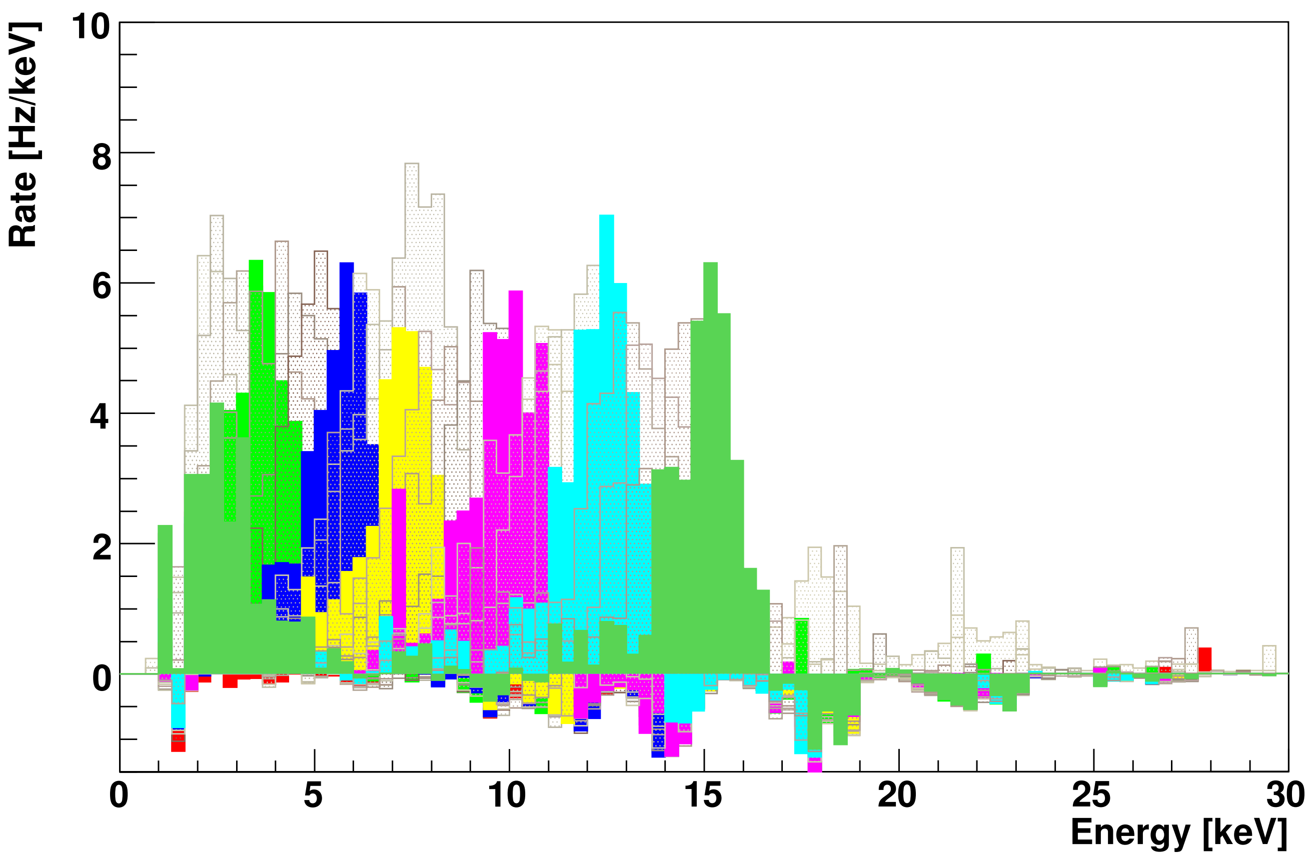


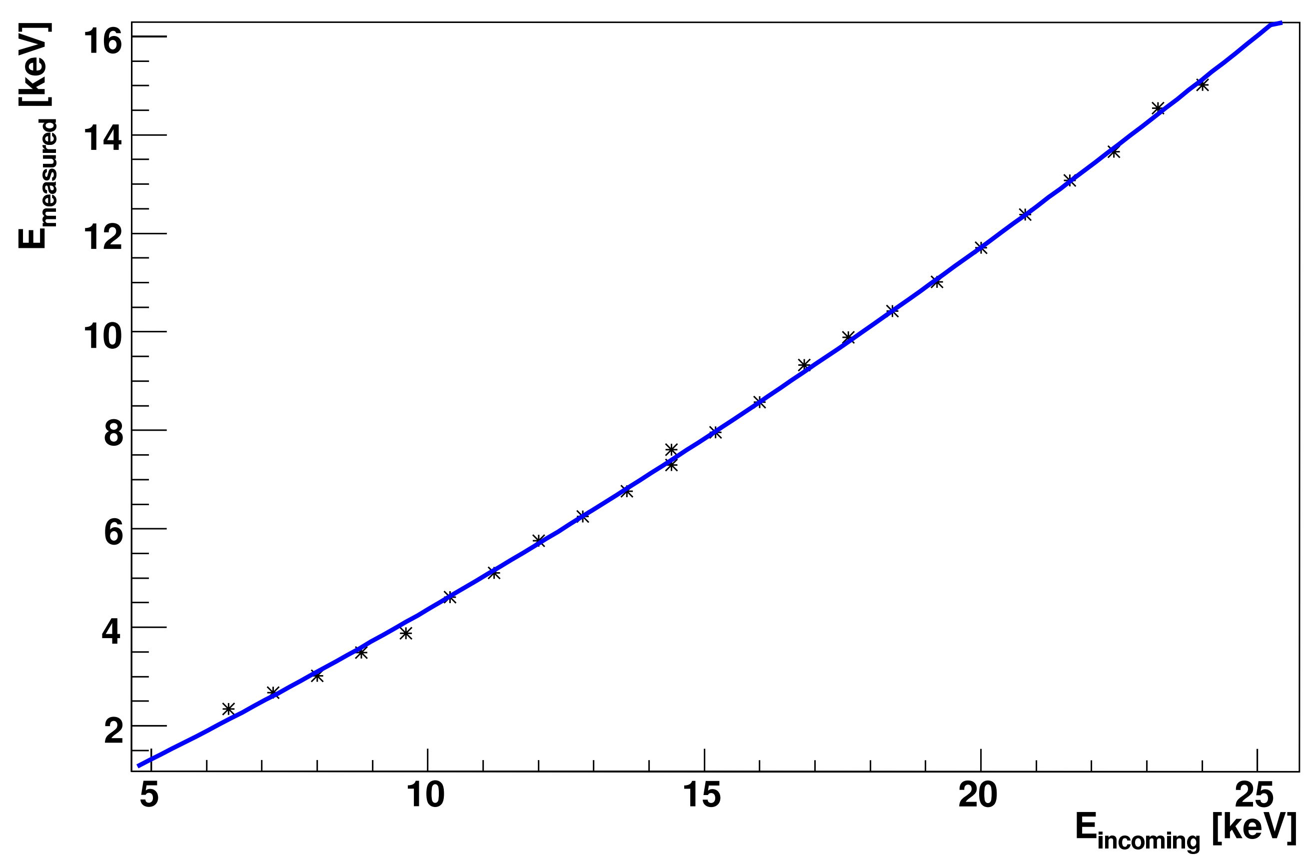
Most Recent Data

We aim to compare the simulation results from the previous slide to data from the lab.

Proton energy spectra have been measured for various strengths of the electric field, with the gas cell evacuated

These measurements confirm the production of protons at the source and allow us to calibrate the detector's response to protons.





Status & Future

The experiment construction has been successfully commissioned:

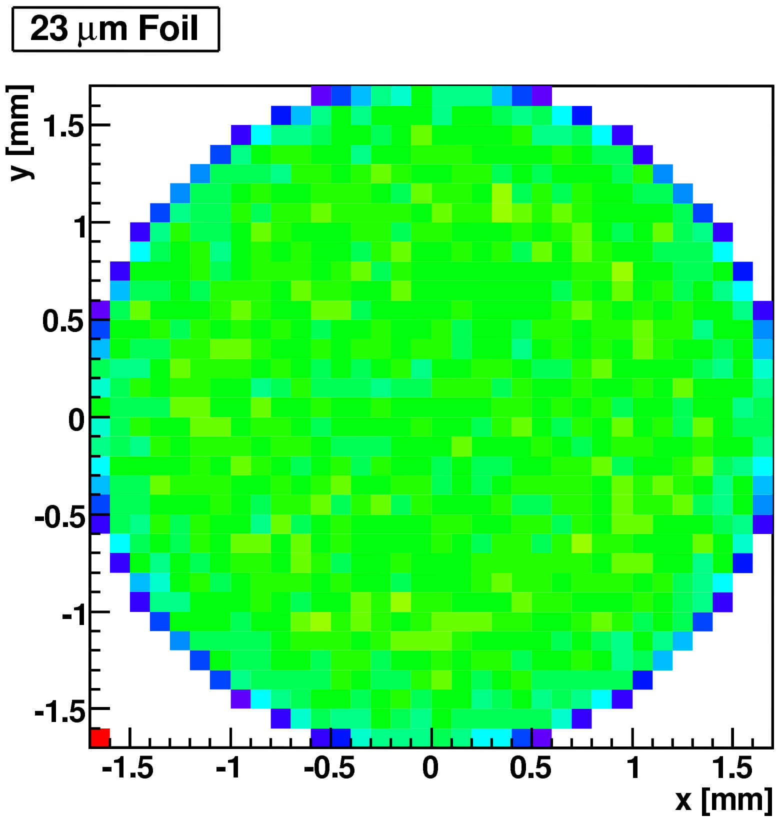
- the accelerating grid runs reliably, without breakdown between rings, at voltages up to at least 65 kV (0.65 MV/m) with an evacuated gas cell and at voltages below 50 kV (0.5 MV/m) for gas pressures between 10^{-3} mbar and 1250 mbar.
- the gas cell can hold steady pressures of Helium gas from 10^{-3} mbar to 1250 mbar,
- the proton source is constructed and operating
- detector response is well understood

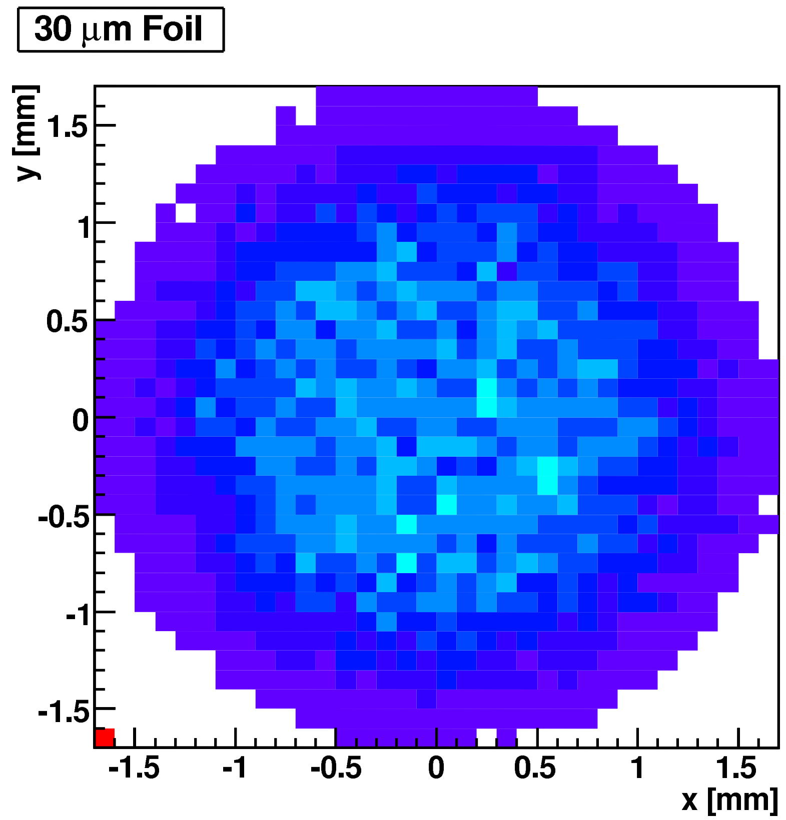
Current Issues:

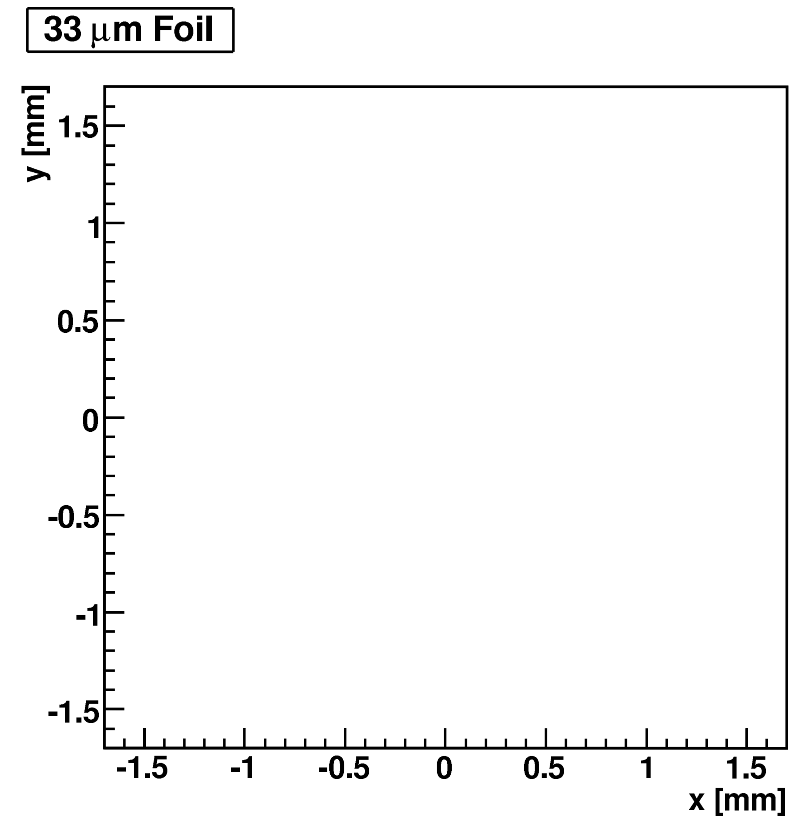
- increases of detector leakage current
- operation of the detector in helium gas

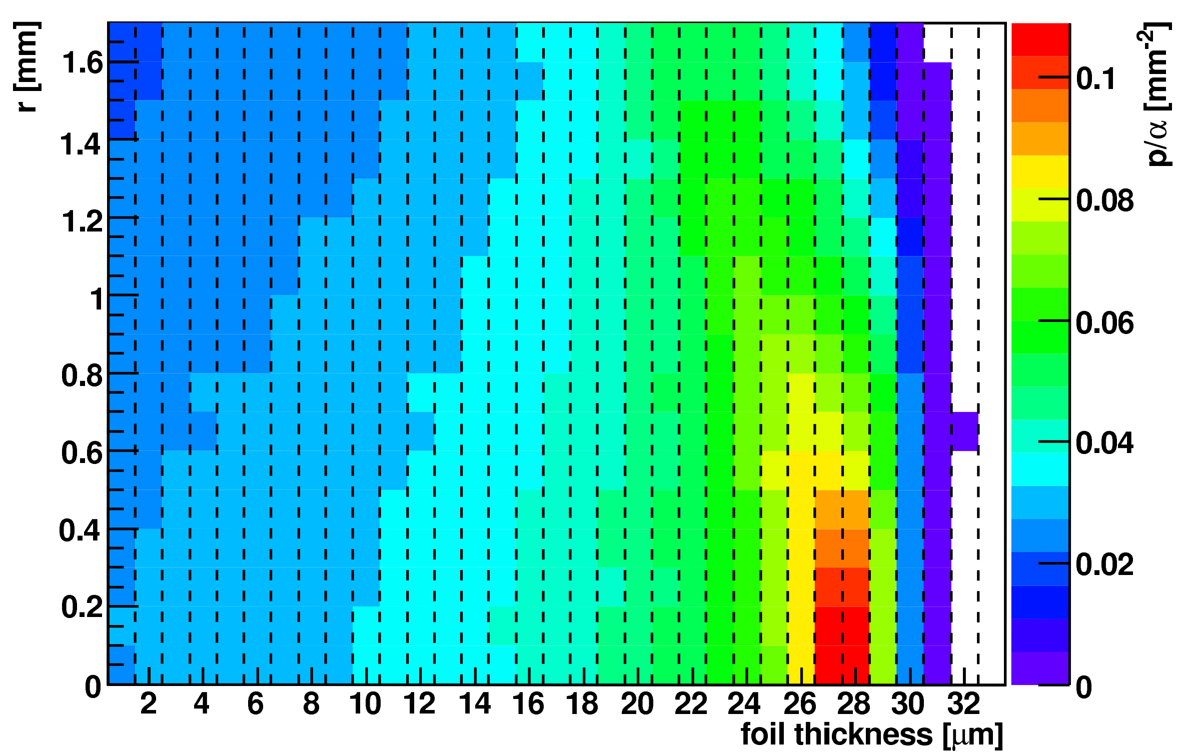
Once these are resolved, we will measure proton energy spectra for various strengths of the electric field and densities of the gas. These spectra will be compared to those that have been caclculated from the Monte Carlo simulations.

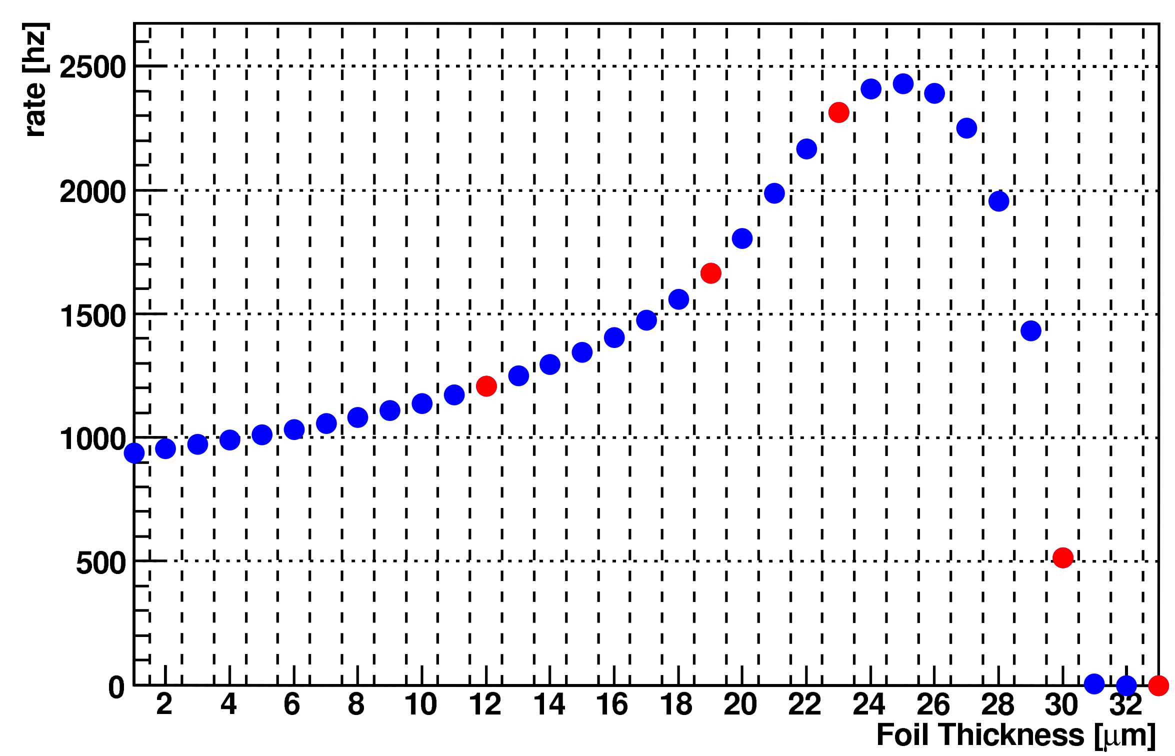
Proton Source Simulation



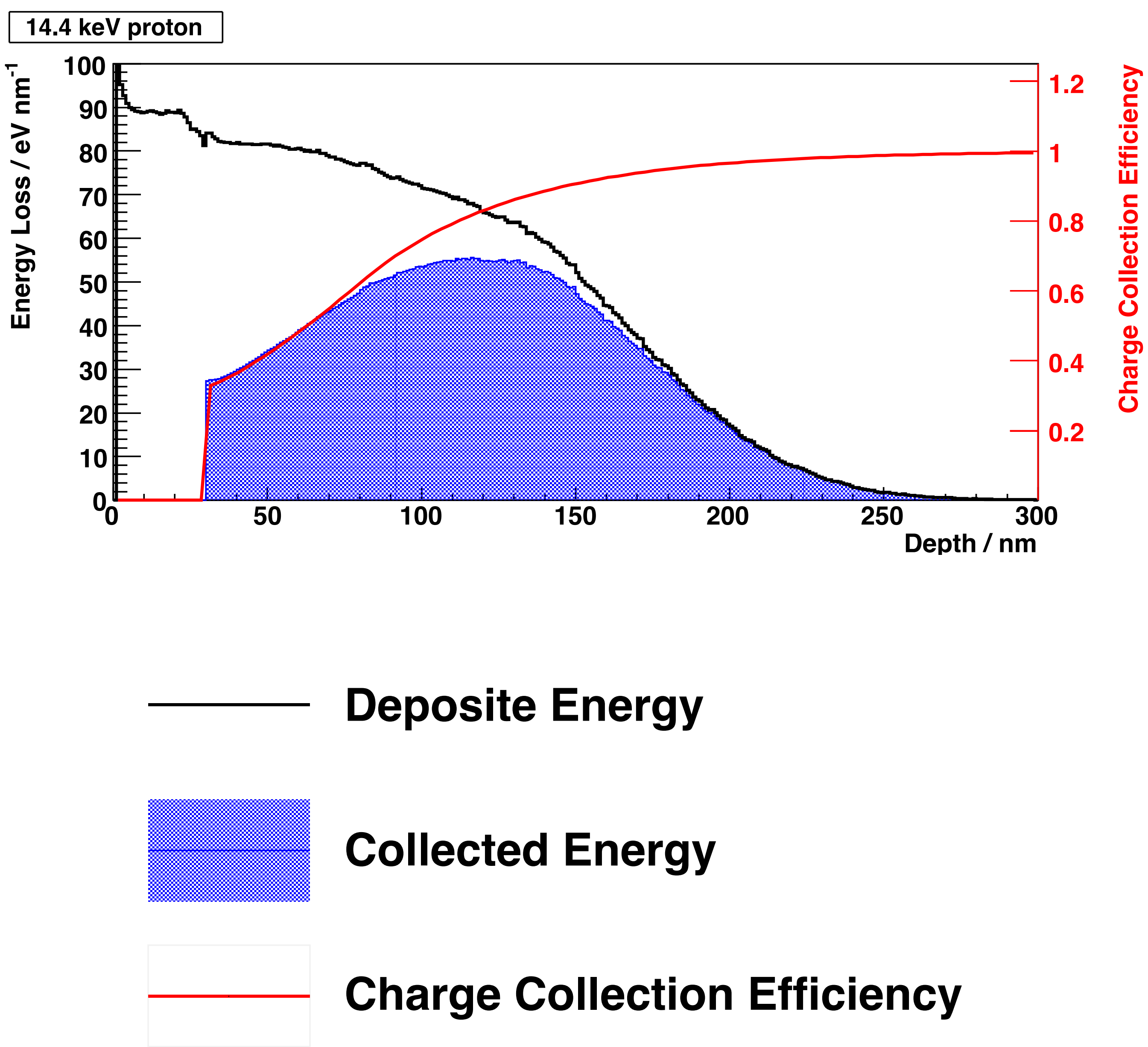


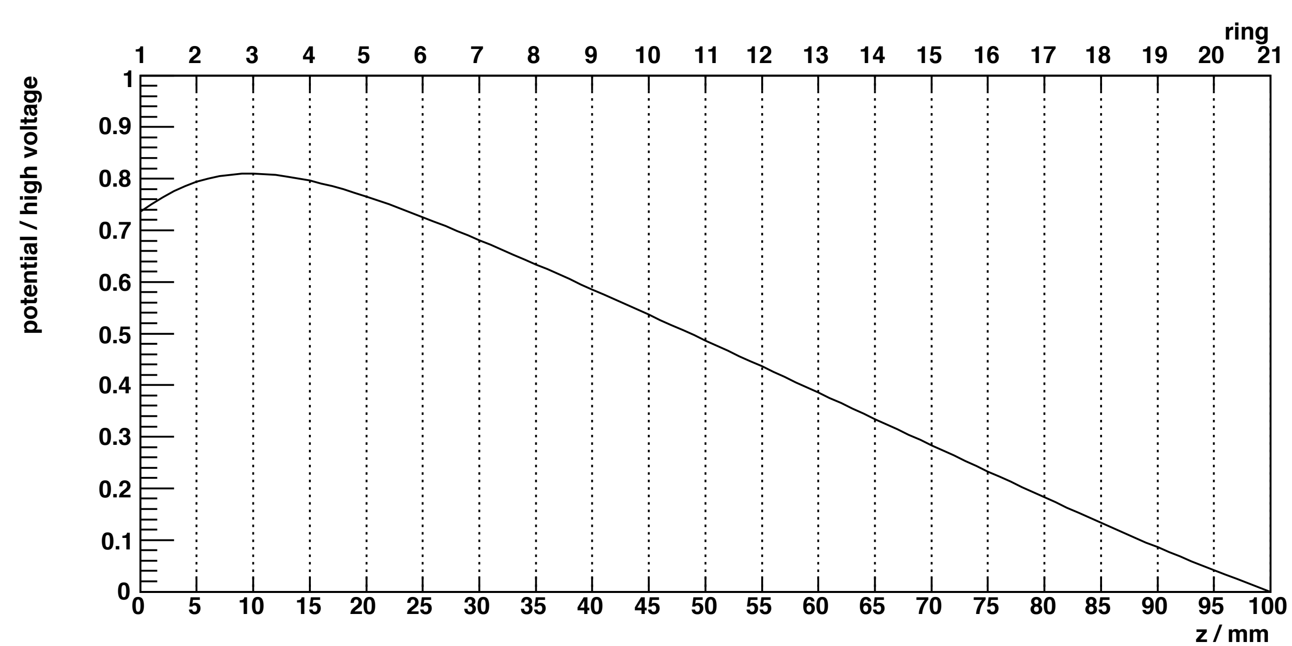






Detector Characterization

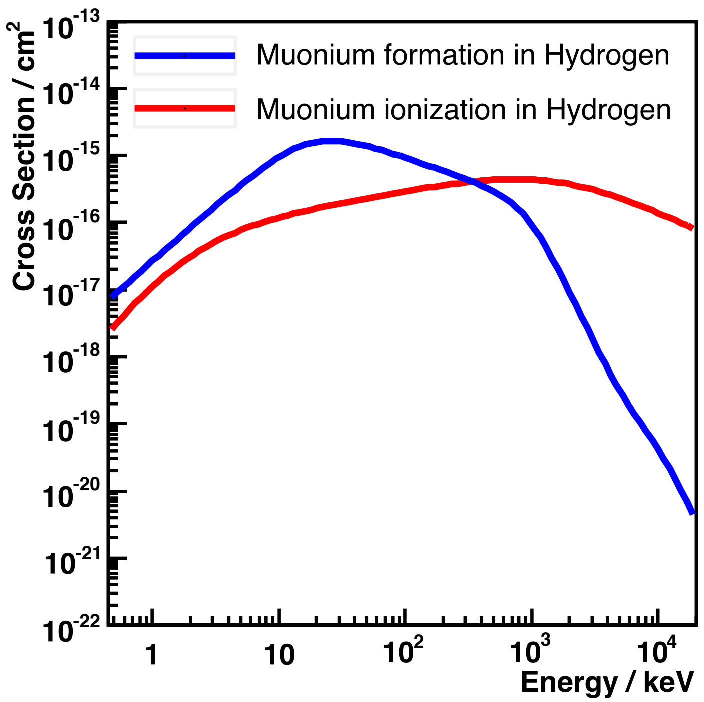


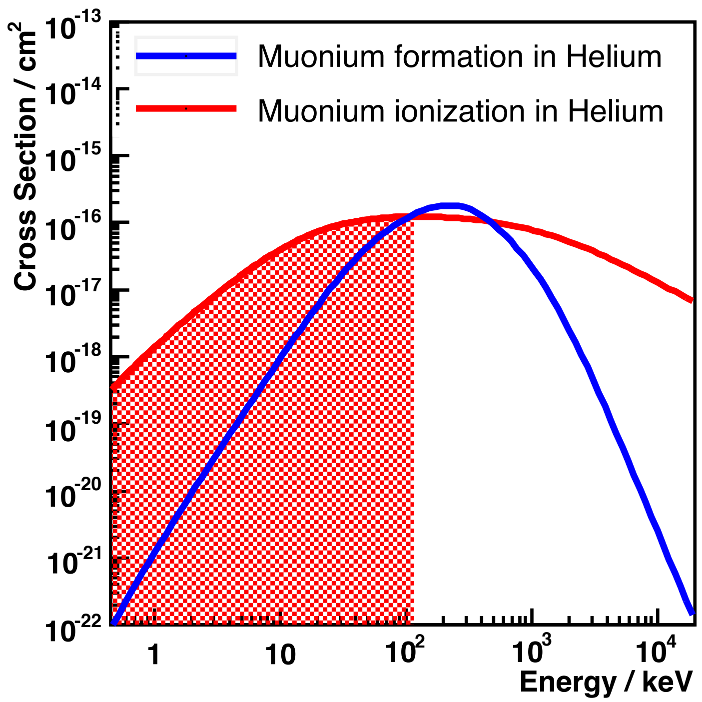


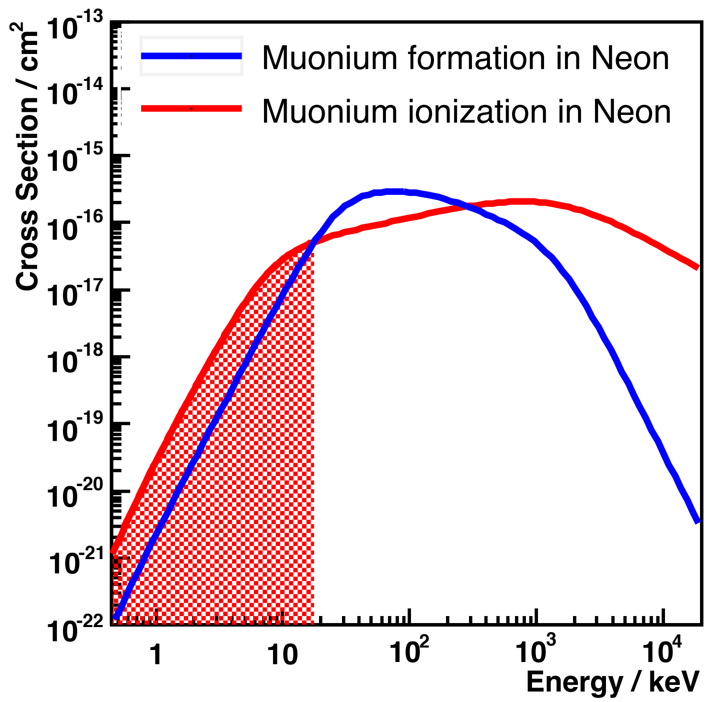
Effective charge

$$q_{\mathrm{eff}} = (\Sigma q_f \sigma_{if})/(\Sigma \sigma_{if})$$

σ_{if} = cross section for change from charge q_i to q_f







Collider Comparison

Fermilab's idea

Muon Collider Conceptual Layout

Project X
Accelerate hydrogen ions to 8 GeV using SRF technology.

Compressor Ring
Reduce size of beam.

Target
Collisions lead to muons with energy of about 200 MeV.

Muon Capture and Cooling
Capture, bunch and cool muons to create a tight beam.

Initial Acceleration
In a dozen turns, accelerate muons to 20 GeV.

Recirculating Linear Accelerator
In a number of turns, accelerate muons up to 2 TeV using SRF technology.

Collider Ring
Bring positive and negative muons into collision at two locations 100 meters underground.