Eidgenössische Technische Hochschule Zürich
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PAUL SCHERRER INSTITUT

Towards a Novel Muon Beamline for Next Generation Precision Experiments

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Overview

Why Muons are Interesting

Motivation

- Precise measurement of the muon g-2
- Search for the muon electric dipole moment
- Materials science using μSR techniques
- New Muonium (Mu $= \mu^+ e^-$) source
  - Mu spectroscopy
  - Lepton flavor violation via $Mu\text{-}\overline{Mu}$ oscillation
  - Antimatter gravity studies

Example: Muonium Spectroscopy

Measure 1S-2S energy interval and HFS

- Muon-electron mass ratio $\frac{m_\mu}{m_e}$ $\rightarrow$ important for next generation g-2 experiment
- Charge equality between the first two lepton families $\frac{q_{\mu^+}}{q_{e^-}}$
- Shed light onto the "Proton Radius Puzzle" (muonic hydrogen, pμ^-)
- In general: Test of bound-state QED

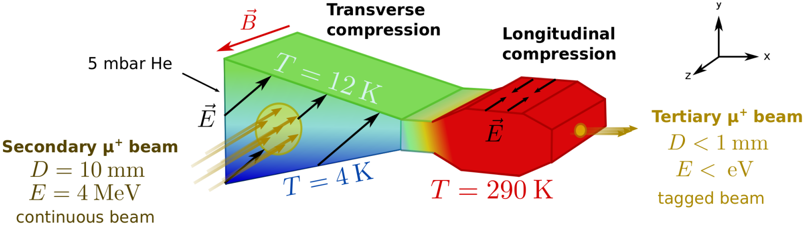
Working Principle

Facts and Figures

New low-energy μ^+ beamline is being developed at ETH & PSI

- Compressing the phase-space by a factor 10^{10}
- Sub-eV energy μ^+
- Beam size of $\mathcal{O}(\text{mm}^2)$
- Efficiency around $\mathcal{O}(10^{-3})$
- Add-on to existing standard surface μ^+ beamline

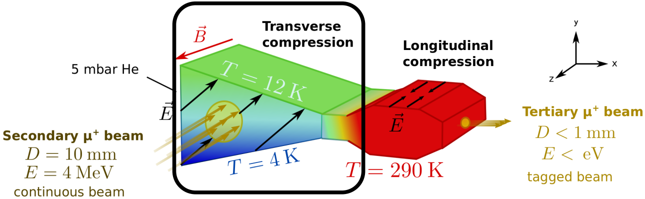
Overview



The compression process can be decomposed into three stages:

- Transverse compression
- Longitudinal compression
- Final compression and extraction into vacuum

Transverse Compression



Key point: position-dependent drift velocity vector $\vec{v}_D$ in gas

$$\vec{v}_D \propto \frac{|\mathbf{E}|}{1+\omega^2\tau^2}\left(\hat{\mathbf{E}} + \omega\tau\hat{\mathbf{E}}\times\hat{\mathbf{B}} + \omega^2\tau^2(\hat{\mathbf{E}}\cdot\hat{\mathbf{B}})\hat{\mathbf{B}}\right)$$

$\tau = \tau(p, T)$: mean free time

$\hat{\mathbf{E}} = \frac{1}{\sqrt{2}}(1,1,0),\ |\vec{E}| \approx 2\ \mathrm{kV/cm}$

$\omega = \frac{eB}{m_\mu}$: cyclotron frequency

$\hat{\mathbf{B}} = (0,0,1),\ |\vec{B}| = 5\ \mathrm{T}$

$\vec{E} \times \vec{B}$ fields and density gradient

Choose $\hat{\mathbf{E}} = \frac{1}{\sqrt{2}}(1,1,0)$ and $\hat{\mathbf{B}} = (0,0,1)$ to obtain drift vector

$$\vec{v}_D \propto \frac{|\mathbf{E}|}{1+\omega^2\tau^2}\left(\hat{\mathbf{E}} + \omega\tau\hat{\mathbf{E}} \times \hat{\mathbf{B}}\right)$$

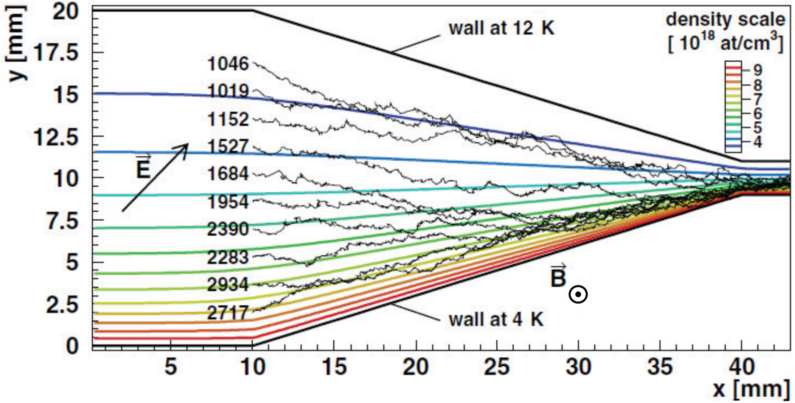
Establish a density gradient in the helium gas target by means of a temperature gradient:

bottom of the cell: ~4 K, **top of the cell:** ~12 K

Drift direction

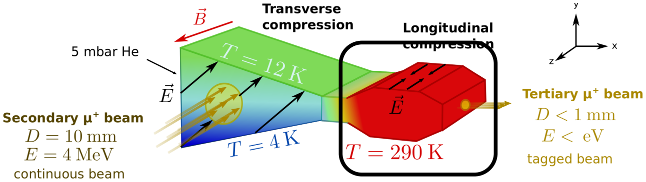
- μ^+ near the top: low density → τ big → $\hat{\mathbf{E}} \times \hat{\mathbf{B}}$ dominates
- μ^+ near the bottom: high density → τ small → $\hat{\mathbf{E}}$ dominates

Simulation



D. Taqqu, PRL **97**, *194801 (2006)*

Longitudinal Compression



Key point: position-dependent drift velocity vector $\vec{v}_D$ in gas

$$\vec{v}_D \propto \frac{|\mathbf{E}|}{1+\omega^2\tau^2}\left(\hat{\mathbf{E}} + \omega\tau\hat{\mathbf{E}}\times\hat{\mathbf{B}} + \omega^2\tau^2(\hat{\mathbf{E}}\cdot\hat{\mathbf{B}})\hat{\mathbf{B}}\right)$$

$\tau = \tau(p, T)$: mean free time

$\hat{\mathbf{E}} = (0, 0, \pm 1)$, $|\vec{E}| \approx 60$ V/cm

$\omega = \frac{eB}{m_\mu}$: cyclotron frequency

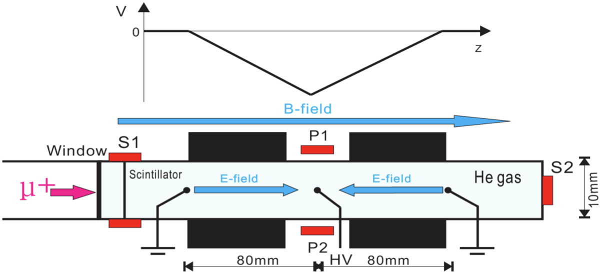
$\hat{\mathbf{B}} = (0, 0, 1)$, $|\vec{B}| = 5$ T

Experimentally tested in 2011 at PSI

Drift Direction

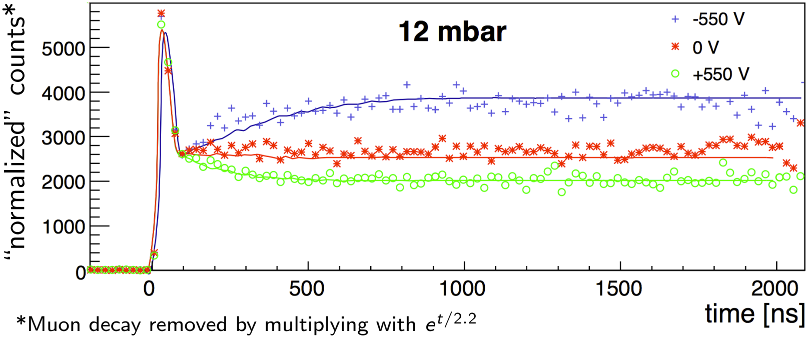
Choose $\hat{\mathbf{E}} = (0, 0, \pm 1)$ and $\hat{\mathbf{B}} = (0, 0, 1)$ to obtain drift vector

$$\vec{v}_D \propto \frac{|\mathbf{E}|}{1 + \omega^2\tau^2}\left(\hat{\mathbf{E}} + \omega^2\tau^2(\hat{\mathbf{E}} \cdot \hat{\mathbf{B}})\hat{\mathbf{B}}\right)$$



Y. Bao, PRL **112**, *224801 (2014)*

Results



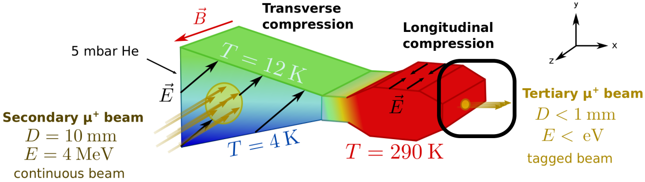
*Muon decay removed by multiplying with $e^{t/2.2}$

Conclusion for longitudinal compression

- 16 cm μ^+ swarm compressed to 0.5 cm wide swarm in 2 μs
- Improved experiment in December 2014

Y. Bao, PRL **112**, *224801 (2014)*

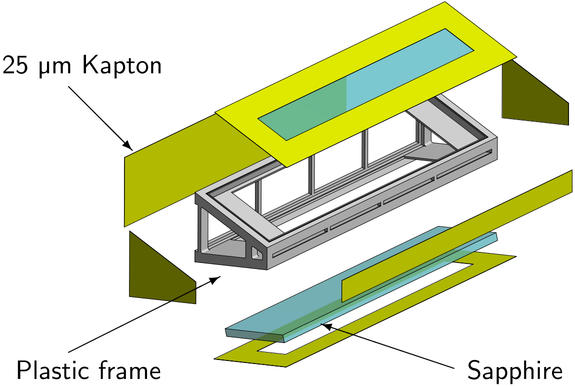
Extraction into vacuum



Technically very challenging but no showstopper found we could think of yet. The basic idea exist and its realization will start beginning next year.

Construction of the Cryogenic Helium-Target Cell for Transverse Compression

Cryogenic Helium-Target Cell

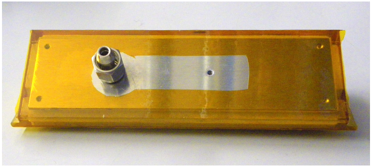


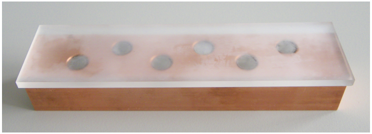
Cell dimensions $\approx 160 \times 50 \times 40$ mm^3

Difficult Environment

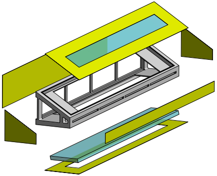
Challenging demands for the materials:

Have to deal with cryogenic temperatures, high $\vec{E}$ and $\vec{B}$ fields in helium gas as well as maintaining a static vertical density gradient.





- Sapphire or crystal quartz
- Plastic frame made by means of stereolithography
- 25 μm thick Kapton foil



Helium Gas Leak Rate

Problem: He gas leak rate through Kapton foil rather high
$\rightarrow$ problem for insulating vacuum!

An exponential temperature dependence of the permeability P is expected from theory:

$$P(T) \propto \exp \frac{-E_p}{RT} \quad : \quad \text{Permeability}$$

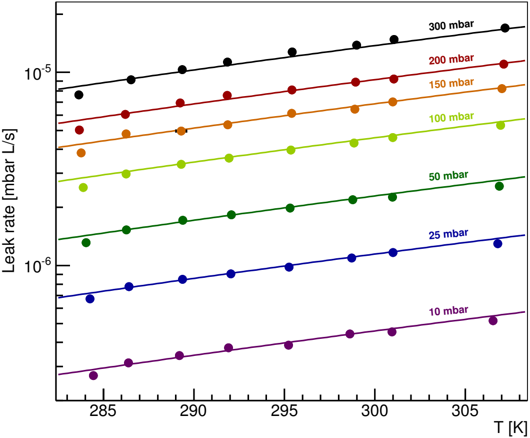
$$\text{Leak Rate } [\frac{\text{mbar L}}{\text{s}}] \quad = \quad P \cdot \frac{A}{d} \cdot \Delta p \cdot RT$$

A: area; d: foil thickness; Δp: pressure difference; R: gas constant; T: temperature

BUT: No conclusive literature values found!

Helium Gas Leak Rate

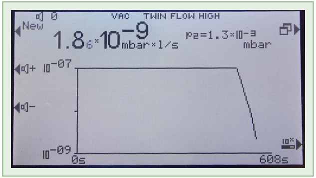
The leak rate of He gas through $A = 490\ \text{mm}^2$ Kapton foil (d =25 μm) was measured for various pressure differences Δp and temperatures T.



Helium Gas Leak Rate

Leak rate decreases by 3 - 4 orders of magnitude at LN_2.

T [K]	Δp [mbar]	Leak Rate $\left[\frac{\text{mbar L}}{\text{s}}\right]$
300	50	$2.2 \cdot 10^{-5}$
163	50	$3.0 \cdot 10^{-7}$
77	50	$\mathcal{O}(10^{-9})$

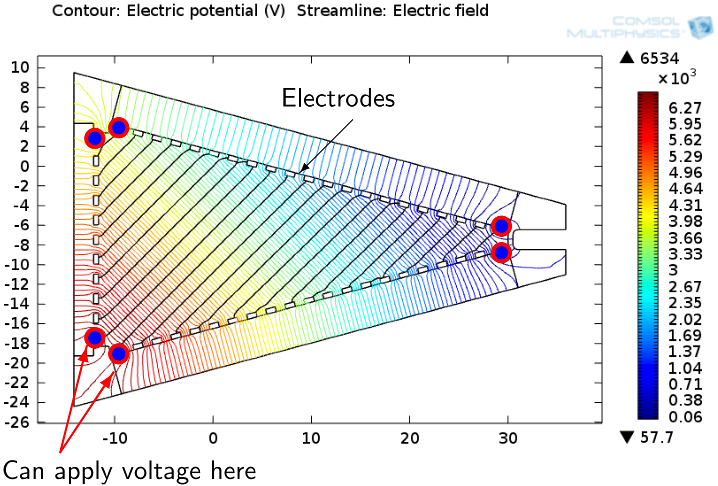


$\Rightarrow$ Helium gas loss at 77 K, 5 mbar and 50 cm^2 area:

$\mathcal{O}(10^{-4})$ mbar/day

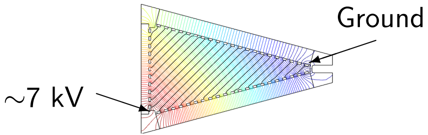
Required Electric Field

Ideally: $\hat{\mathbf{E}} = \frac{1}{\sqrt{2}}(1, 1, 0)$



Electric Fields

Electric fields of the order of 2 kV/cm create two central problems:



- Dielectric breakdown in gases. Need to consider $\vec{B}$-field, gas pressure and cryogenic temperature
- Joule heating: $P_{heating} = U^2/R$ with $U^2 \approx 10^8$ V^2

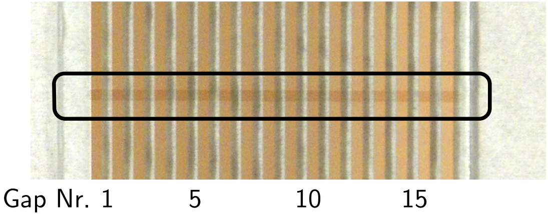
Cooling power of cryostat at 4 K: ∼1 W. Therefore

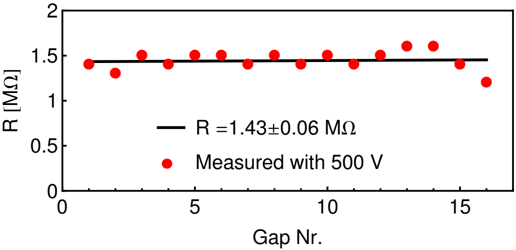
$$P_{heating} \overset{!}{\leq} 1W \Rightarrow R \overset{!}{\geq} 10^8\Omega$$

Using 1 mm spacing between 1 mm wide electrodes requires $R \approx 4$ MΩ between electrodes.

Electric Fields

Voltage divider:
20 Å graphite connecting the copper electrodes on Sapphire

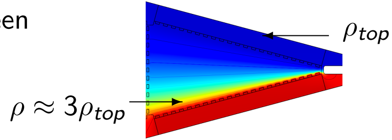




⇒ Sufficiently homogeneous resistance between copper electrodes

Gas Density Gradient

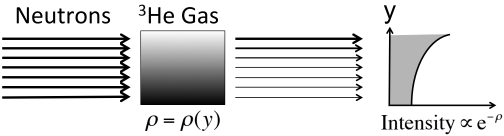
Need a factor $\geq$3 in density between top and bottom of the cell for position-dependent $\vec{v}_D$.



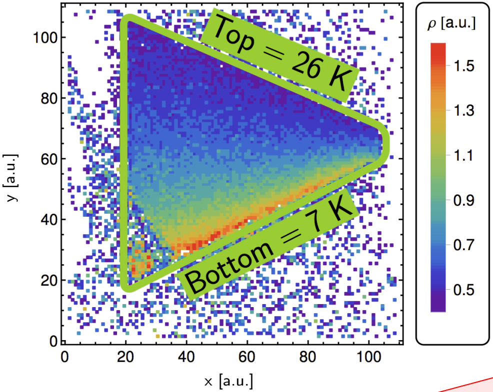
Neutron radiography

Huge absorption cross section for neutrons in ^{3}He. The transmitted neutron intensity through the gas cell as function of the density ρ:

$$I(y) = I_0 e^{-\sigma L \rho(y)}, \quad \rho(y) = \frac{p}{k_B \cdot T(y)}$$



Gas Density Gradient



See talk of G. Wichmann

Experiment in 2013 at PSI

A **stable gas density gradient** was demonstrated in ^{3}He gas.

Next Step:

Beam test to demonstrate feasibility of transverse compression in 12/2014

Two Major Difficulties

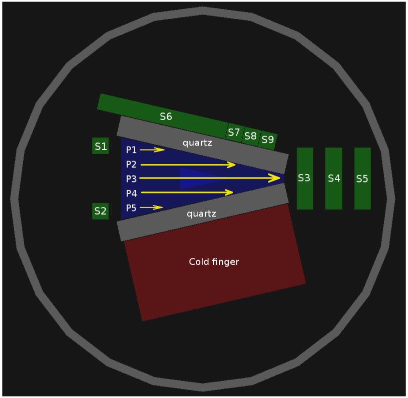
Electric field

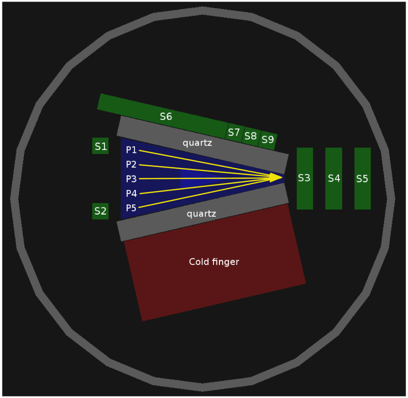
- Electric breakdown I: E-field of ∼200 V/mm required → close to the Paschen minimum
- Electric breakdown II: Tests require the 5 T B-field, cryogenic temperatures and 5 mbar He gas
- How close can we get to the ideal field $\hat{\mathbf{E}} = 1/\sqrt{2} \cdot (1, 1, 0)$?

Cooling the cell to 4 K

- Need ∼1 m long cold finger to get inside the magnet → what is the temperature at the end?
- How to couple the cell (i.e. the Sapphire) to minimize cooling power loss?

Data analysis...





Summary: Take away messages

- Compression of μ^+ beam relies on simple physical ideas
- Very challenging to build, but no showstopper so far
- Phase space compression by 10 orders of magnitude

Thank you for your attention!

Questions???

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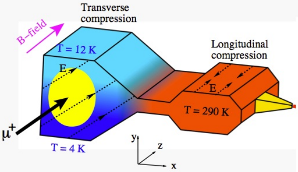

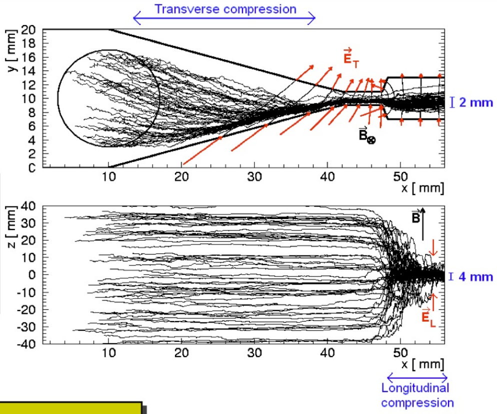

Stop μ^+ along z-direction
$\Rightarrow$ Large extension in z-direction

$\Rightarrow$ Compression over large z-distances
$\Rightarrow$ Need high μ^+ velocity for long. comp.

Selection of gas: He
+ Very low Muonium formation
− Low stopping power
+ High μ^+ velocity reachable

$\Rightarrow$ “run-away” conditions

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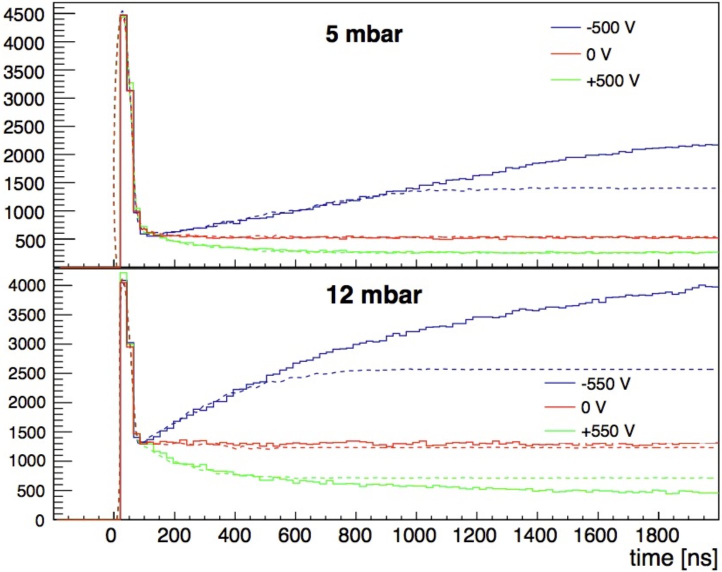

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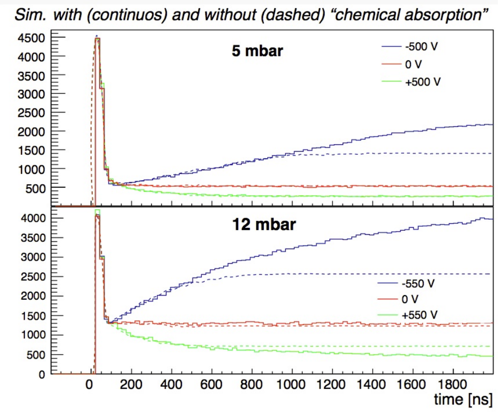

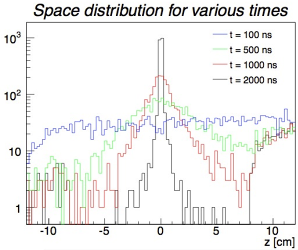

To fit simulations to measurements:

- introduce chemical absorptions for energies ∼eV
  → muons stick to impurities
- small misalignment beam/PSC

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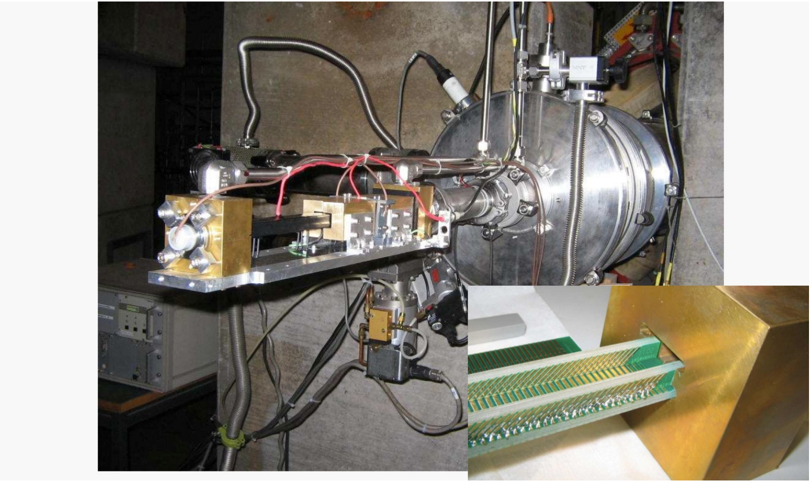

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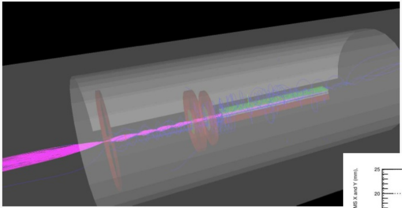
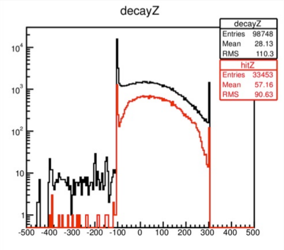
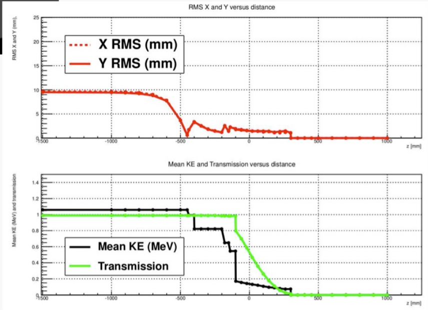


We need to tune the beam momentum (15 MeV/c) to avoid large fraction of stopping in foils

Make also shorter scintillator and use collimators for positrons





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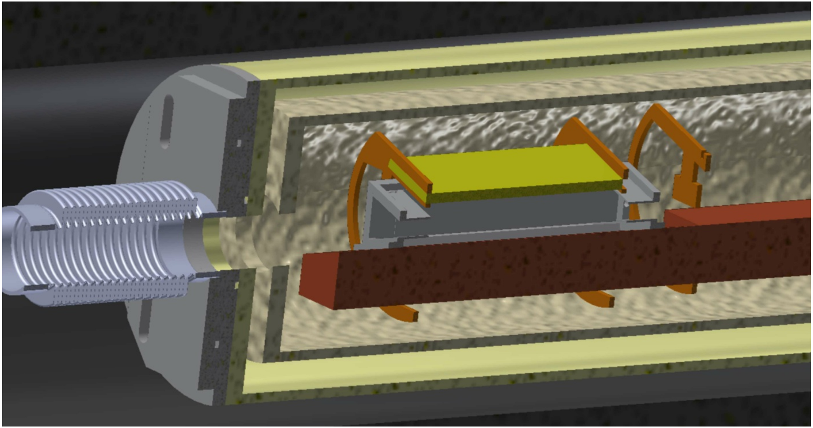

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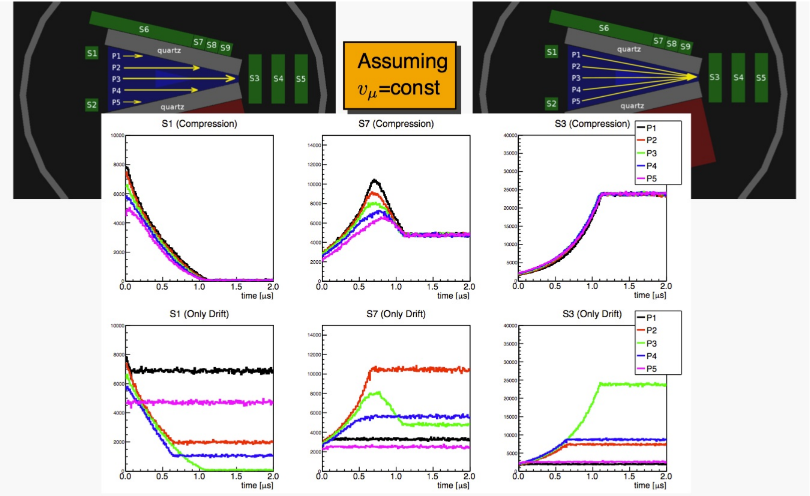

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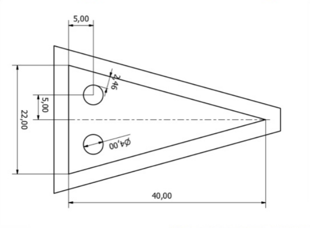
Alignment target/PSC



This is the minimal transverse size of the target:
$\rightarrow$ smaller HV at given E-field strength
$\rightarrow$ smaller electron-multiplication in the gas
$\rightarrow$ alignment target/beam difficult

Need a μ^+ entrance collimator with 3 holes of 4 mm diameter and target/beam parallelity within 2mm/400mm rad
Cold finger mechanics, moving while cooling etc...