Towards a Novel High-Brightness Muon Beamline for Next Generation Precision Experiments

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On behalf of the muCool Collaboration

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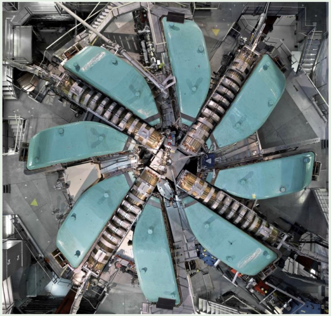
ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Outline

Facts and Figures

New low-energy μ^+ beamline is being developed at ETH Zürich & the Paul Scherrer Institute (PSI), Switzerland

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

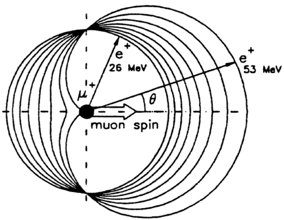


Ring Cyclotron at PSI

Why Muons?

$$\pi^+ \rightarrow \mu^+ + \nu_\mu : \qquad \mu^+ \sim 100\% \text{ polarized.}$$
$$\mu^+ \rightarrow e^+ + \nu_e + \overline{\nu_\mu} : \qquad e^+ \text{ preferentially emitted in } \vec{\mathbf{S}}_\mu$$

μSR → Materials research
Muon EDM → BSM search
Muon g-2 → BSM search
Muon lifetime → Determining G_F
Rare decays:
MEG, Mu2e, Mu3e, ... → BSM search



Create Muonium (Mu $= \mu^+ e^-$)
(see next slide..)

Muonic atoms: e.g. $H_\mu = p^+ \mu^-$ → e.g. "Proton Radius Puzzle"
Muon capture → weak interaction of proton

Why Muonium μ^+e^-?

Measure 1S-2S and 1S-HFS in $\mu^+\mathrm{e}^-$

- $\frac{m_\mu}{m_e}$ (120ppb) → input for g-2
- $\frac{q_\mu}{q_e}$ (120ppb) → test of Lepton family universality
- Determine fundamental constants: α, R_∞, μ_μ/μ_p, …
- Test of bound-state QED

- Mu-$\overline{Mu}$ oscillation → Search for cLFV: $e^-\mu^+ \rightarrow e^+\mu^-$
- Antimatter gravity (99.5%): sidereal, annual, interferometry
- Lorentz and CPT tests

See talk of Daniel Kaplan…

Working Principle

Phase Space Compression

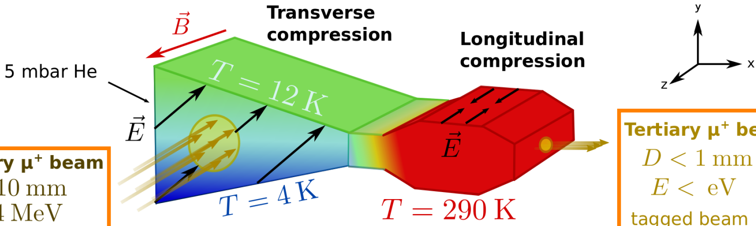
- To reduce phase space a dissipative mechanism is needed
  → slow down (stop) μ^+ in gas
- After slowing down in gas:
  → low energy
  → large volume
  ⇒ BUT μ^+ can be steered by $\vec{E}$- and $\vec{B}$-fields

Working Principle of our Beamline

- Stop a regular μ^+ beam in He gas target (dissipative mechanism)
- Compress the beam (transversally and longitudinally) in $\vec{E} \times \vec{B}$-field
- Extract the compressed beam again into vacuum, re-accelerate and send it to the experiment

Overview

Dimensions $\approx 10 \times 5 \times 50$ cm^3



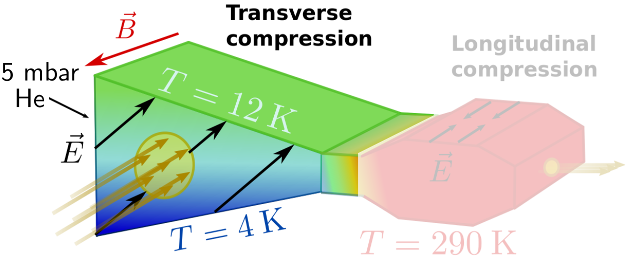
Secondary μ^+ beam
$D = 10\,\mathrm{mm}$
$E = 4\,\mathrm{MeV}$
continuous beam

Tertiary μ^+ beam
$D < 1\,\mathrm{mm}$
$E < \mathrm{eV}$
tagged beam

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

$\tau = \tau(p, T)$: mean free time
$\omega = \frac{e}{m_\mu}B$: cyclotron frequency
μ: muon mobility

Transverse Compression



low density → τ big
⇒ $\hat{\mathbf{E}} \times \hat{\mathbf{B}}$ dominates

high density → τ small
⇒ $\hat{\mathbf{E}}$ dominates

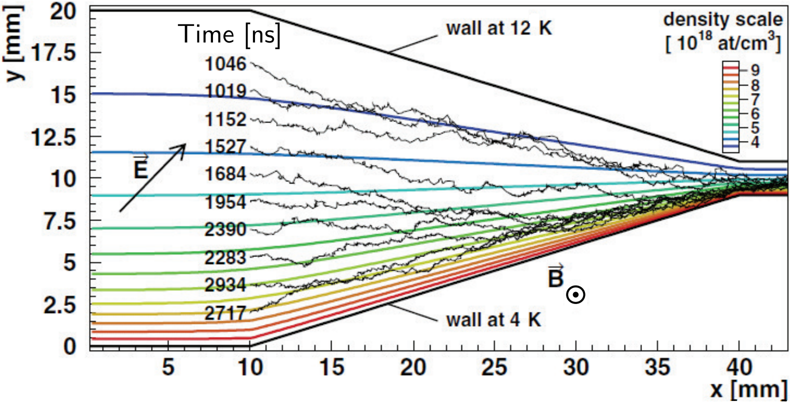
Key point: position-dependent drift velocity vector $\vec{v}_D$ in gas

$$\vec{v}_D = \frac{\mu|\mathbf{E}|}{1+\omega^2\tau^2}\left(\hat{\mathbf{E}} + \omega\tau\hat{\mathbf{E}}\times\hat{\mathbf{B}} + \omega^2\tau^2(\cancelto{0}{\hat{\mathbf{E}}\cdot\hat{\mathbf{B}}})\hat{\mathbf{B}}\right)$$

$\tau = \tau(p, T)$: mean free time
$\omega = \frac{eB}{m_\mu}$: cyclotron frequency
μ: muon mobility

$\hat{\mathbf{E}} = \frac{1}{\sqrt{2}}(1,1,0)$, $|\vec{E}| \approx 2\ \mathrm{kV/cm}$
$\hat{\mathbf{B}} = (0,0,1)$, $|\vec{B}| = 5\ \mathrm{T}$

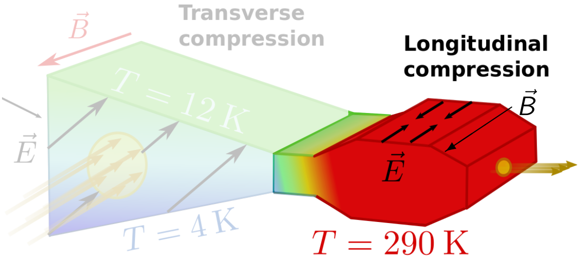
Simulation of Transverse Compression Stage



$$|\vec{E}| = 2 \text{ kV/cm}, \ |\vec{B}| = 5 \text{ T}$$

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

Longitudinal Compression



Compression along $\vec{E}$

Low, constant density

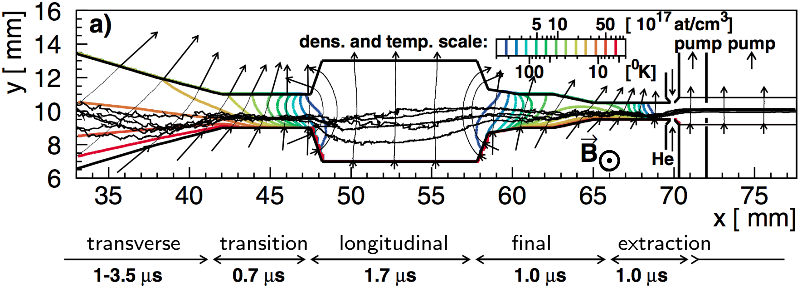
Key point: position-dependent drift velocity vector $\vec{v}_D$ in gas

$$\vec{v}_D = \frac{\mu|\mathbf{E}|}{1+\omega^2\tau^2}\left(\hat{\mathbf{E}} + \omega\tau\underbrace{\hat{\mathbf{E}}\times\hat{\mathbf{B}}}_{0} + \omega^2\tau^2(\hat{\mathbf{E}}\cdot\hat{\mathbf{B}})\hat{\mathbf{B}}\right)$$

$\tau = \tau(p, T)$: mean free time
$\omega = \frac{eB}{m_\mu}$: cyclotron frequency
μ: muon mobility

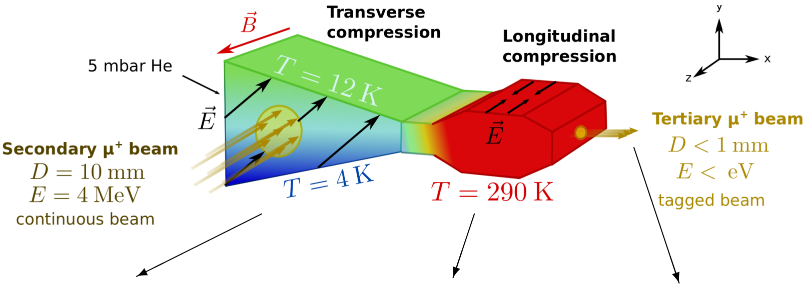
$\hat{\mathbf{E}} = (0, 0, \pm 1)$, $|\vec{E}| \approx 60\ \mathrm{V/cm}$
$\hat{\mathbf{B}} = (0, 0, 1)$, $|\vec{B}| = 5\ \mathrm{T}$

Full Simulation of Compression



- Full compression takes 6-8 µs
- Expected overall efficiency $\mathcal{O}(10^{-3})$
- Not discussed here: Final compression & vacuum extraction

Experimental Roadmap: Separate Tests of various Stages



Transverse compression:

Engineering run: Dec 2014
First test: Dec 2015

Longitudinal compression:

First test: 2011
Improved test: Dec 2014
Final test: Dec 2015

Extraction:

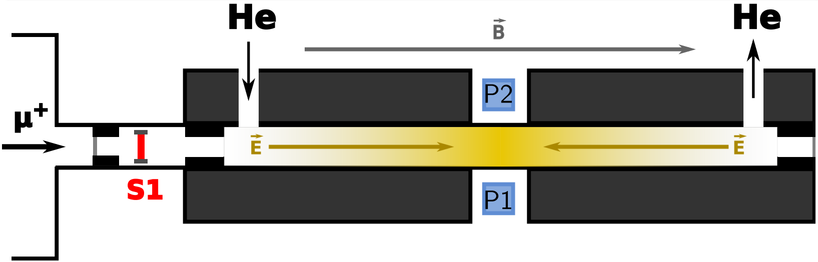
First tests: 2016

Demonstration of Longitudinal Compression

Preliminary Tests in 2011 at PSI

Drift Direction

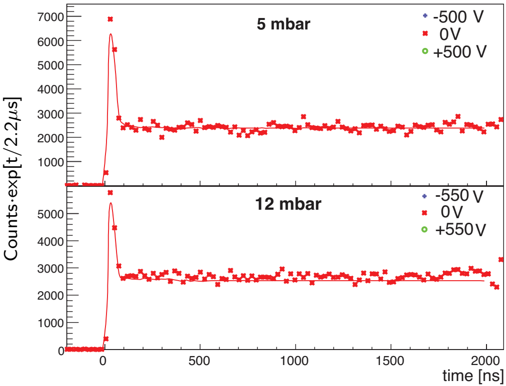
Set $\hat{\mathbf{E}} = (0, 0, \pm 1)$ & $\hat{\mathbf{B}} = (0, 0, 1) \Rightarrow \vec{v}_D = \frac{\mu |\mathbf{E}|}{1+\omega^2\tau^2} \left(\hat{\mathbf{E}} + \omega^2\tau^2 (\hat{\mathbf{E}} \cdot \hat{\mathbf{B}}) \hat{\mathbf{B}} \right)$



πE1 beamline @ PSI with 10 MeV/c

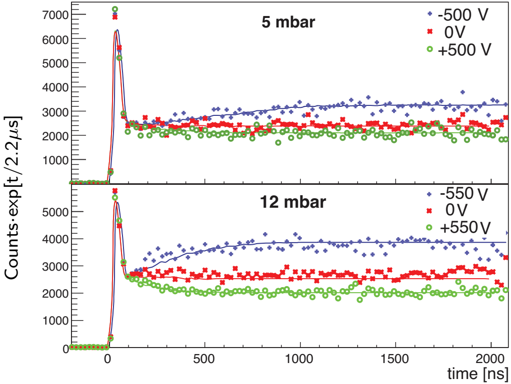
Count decay positrons in P1 & P2 vs. time relative to S_1 for $\text{HV} = \begin{cases} + \\ - \\ 0 \end{cases}$

Results (Measurement / Simulation)



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

Results (Measurement / Simulation)

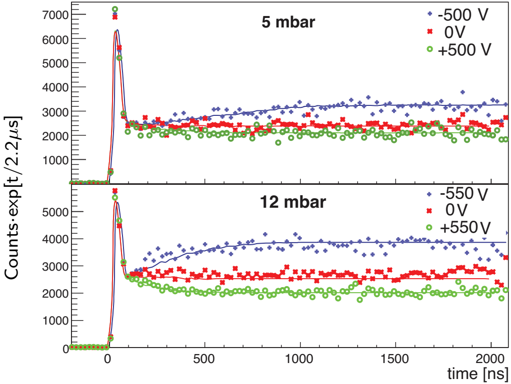


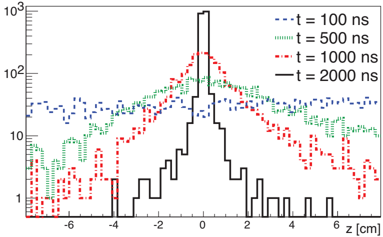
Simulation:

- Chemical absorption for $E_{\mu^+}<10$ eV
- Small missalignment

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

Results (Measurement / Simulation)





Simulation:

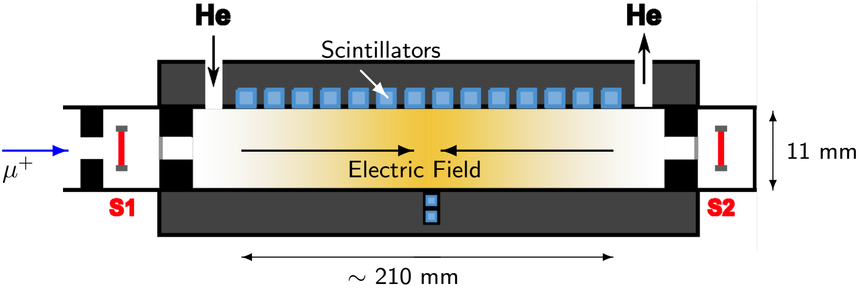
- Chemical absorption for $E_{\mu^+} < 10$ eV
- Small missalignment

NO chemical absorption

16 cm μ^+ swarm compressed to 0.5 cm wide swarm in 2 μs

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

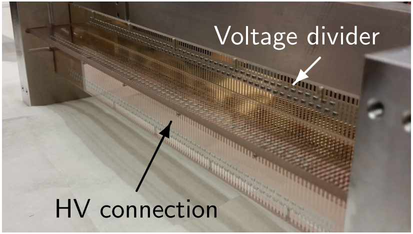
Improved Setup 2014



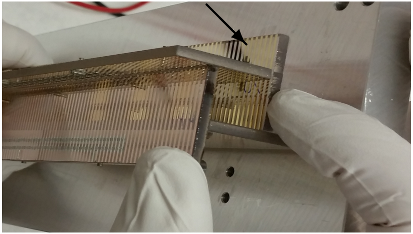
Improvements compared to 2011 beamtime:

- Use glass and special glue → much cleaner
- 21 + 2 scintillators
- Better shielding of scintillators to reduce background

Improved Setup 2014

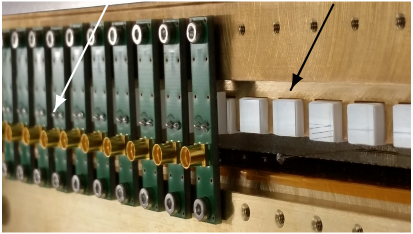


Glass with electrodes

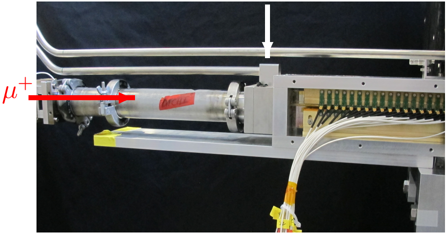


SiPM readout

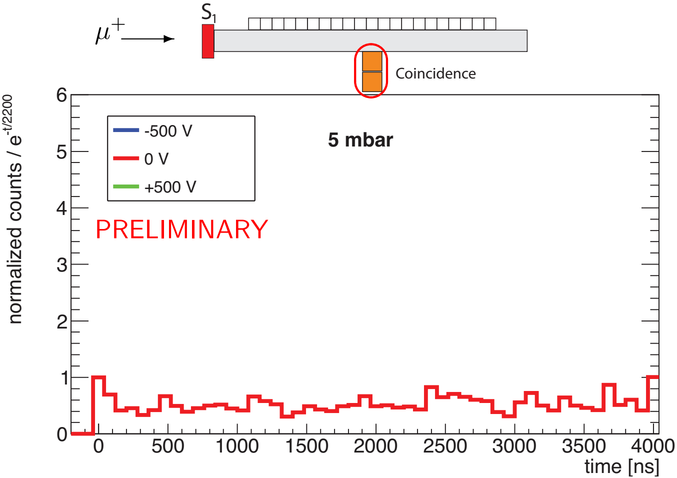
Scintillator bars



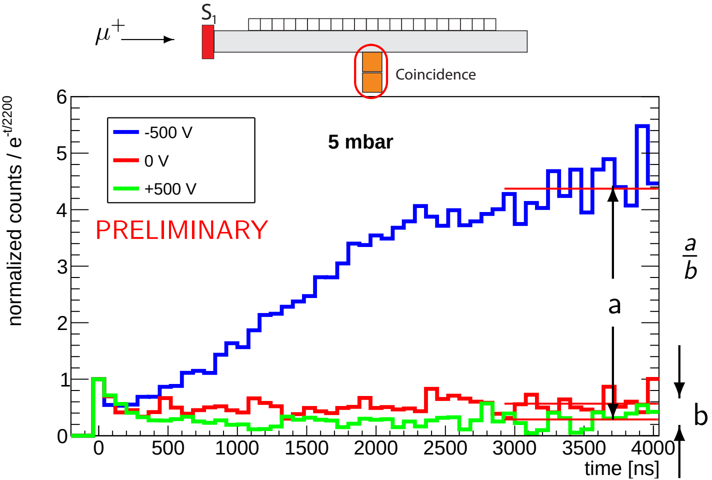
He connection



Longitudinal Compression – Result



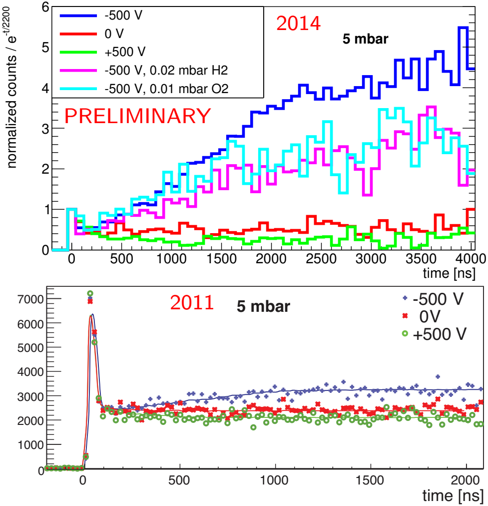
Longitudinal Compression – Result

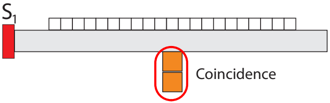


$$\frac{a}{b} \approx 14.5$$

$$\boxed{\text{Compression efficiency} \propto \frac{a}{b}}$$

2014 vs. 2011



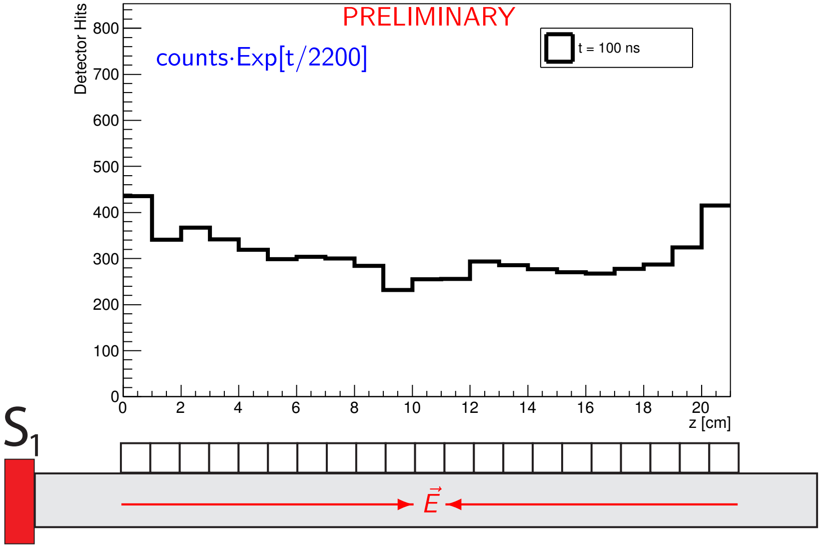


Comparison 2014 vs. 2011:

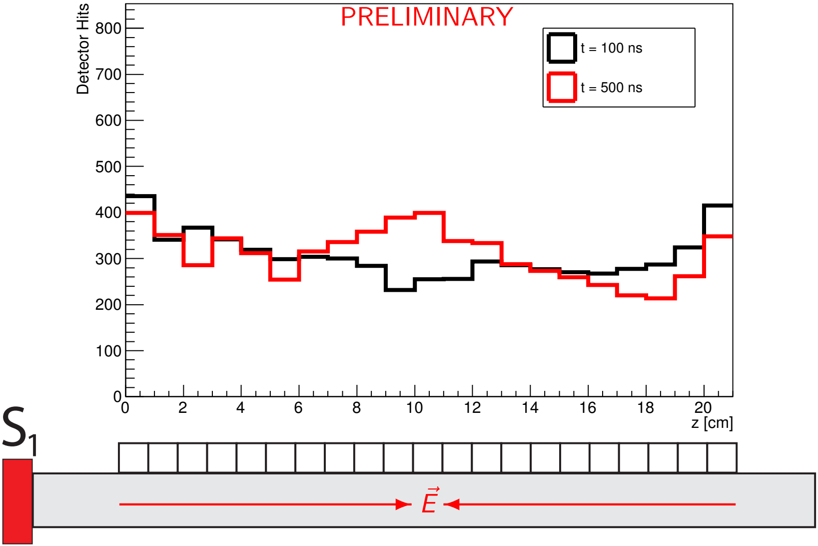
- Much larger effect
- Less impurities (less chemical absorption) → compression continues for t≥1 μs
- Reduced background

→ Confirmed impurity hypothesis

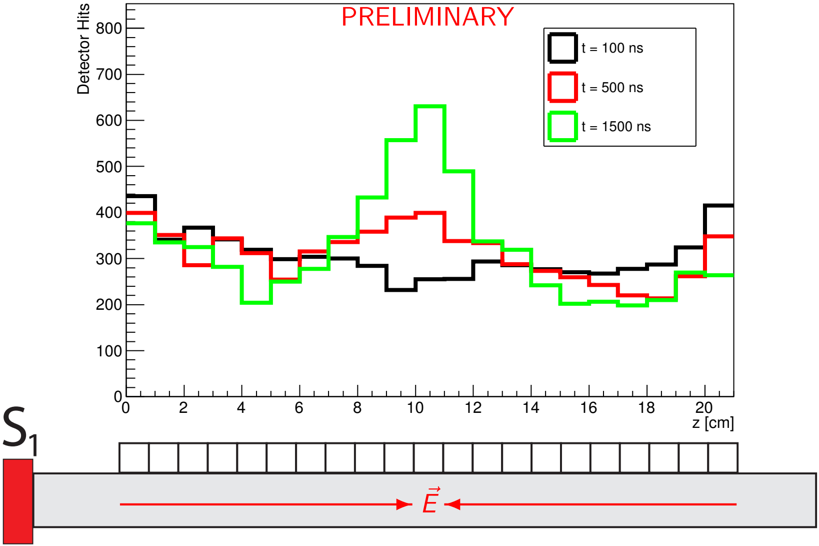
Measured μ^+ Swarm Compression



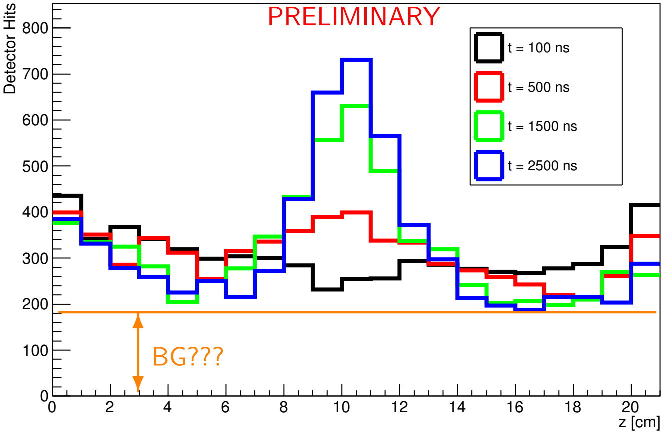
Measured μ^+ Swarm Compression



Measured μ^+ Swarm Compression



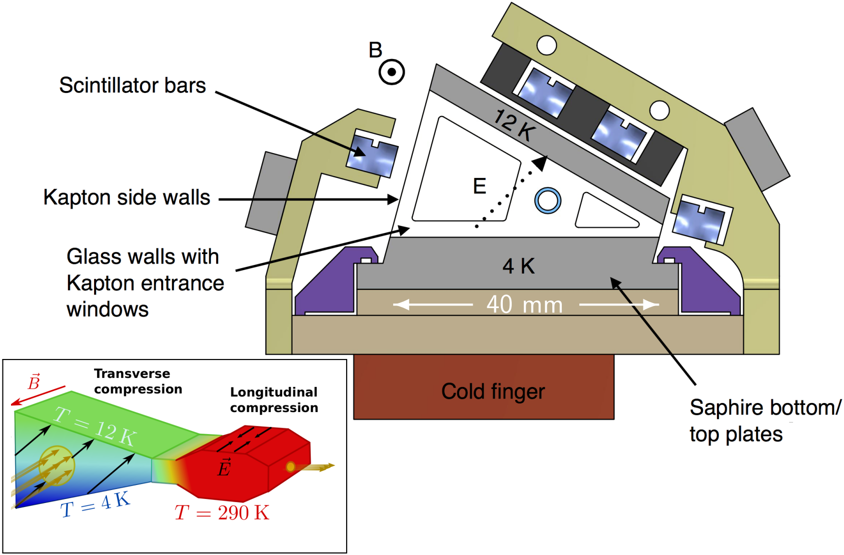
Measured μ^+ Swarm Compression



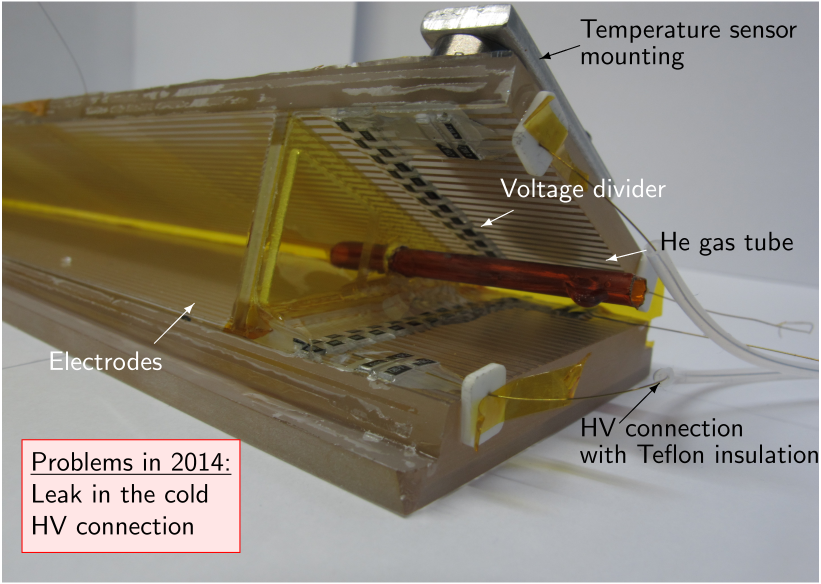
Width of distribution given by resolution & compression

Transverse Compression: Engineering Run

Transverse Compression - Concept

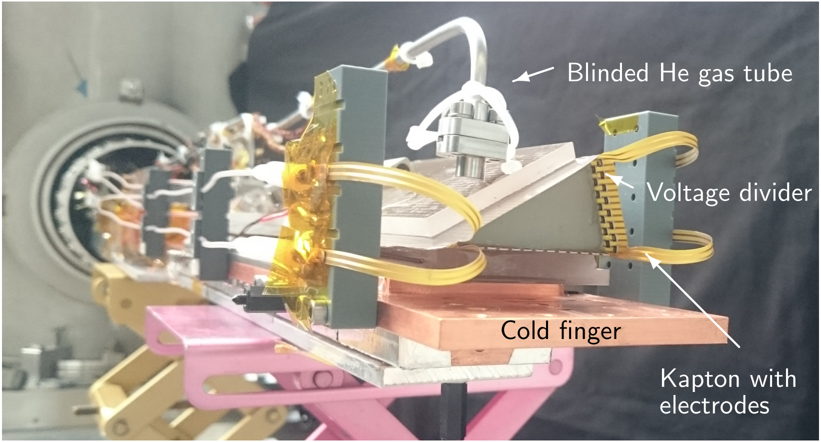


Testing Transverse Compression 2014



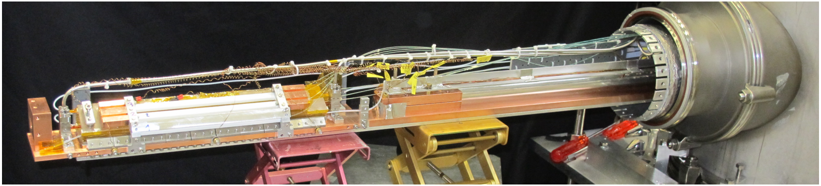
Problems in 2014:
Leak in the cold HV connection

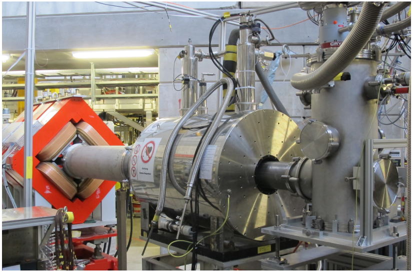
Latest Cell Design - 2015



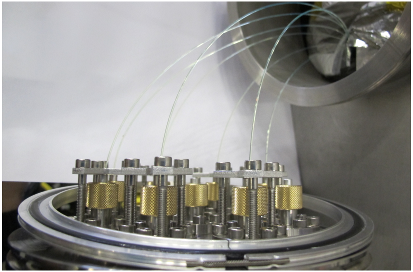
Testing Transverse Compression 2014

Target mounted on the 1.2 m long cold finger



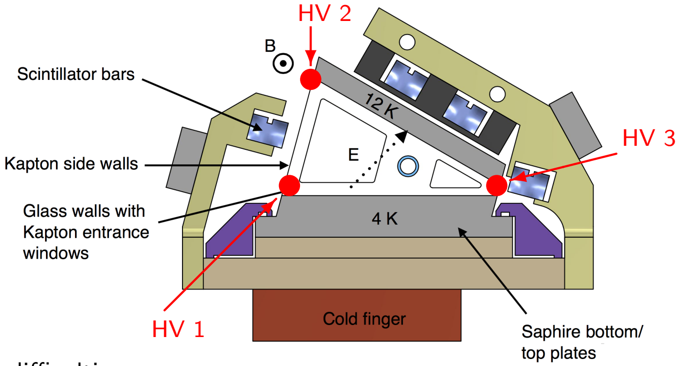


Setup PSI πE1



Wavelength shifting fibres

Testing Transverse Compression - Challenges

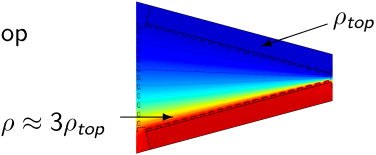


3 major difficulties:

- Cryogenic temp: $T_{\rm Up}$=21 K, $T_{\rm Bot}$<6 K, 0.5 W, B=0 T, 1.2 m ✓
- Establish gas density gradient (no He leak) ✓
- Establish high E-fields in gas → electrical breakdown?!

Gas Density Gradient: Tested with Neutron Radiography

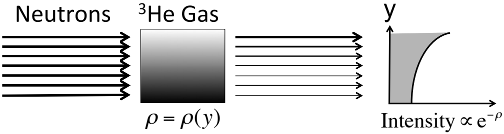
Need a factor ≥3 in density between top and bottom of the cell for position-dependent $\vec{v}_D$.



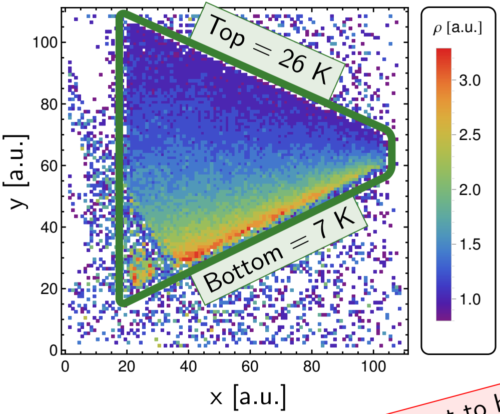
Neutron radiography

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



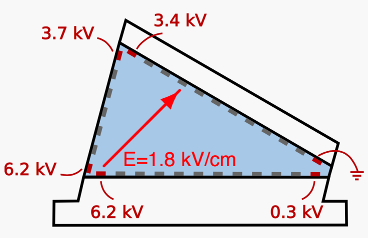
About to be published...

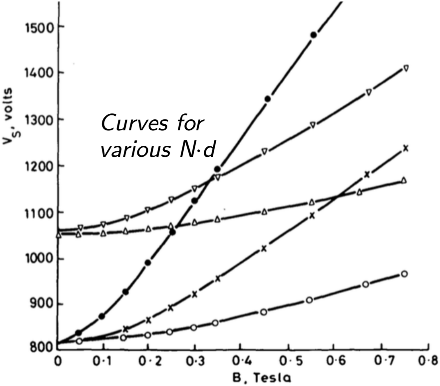
Experiment in 2013 at PSI

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

Electric Breakdown Studies

B-field is advantageous because of $\vec{E} \times \vec{B}$ drift of e^- and ions
→ increase effective density
→ increase breakdown voltage





V_{BD} between two parallel plates as function of B for N_2

A.E.D. Heylen et al.; IEE Proc. Vol 127, Pt. A, No. 4, May 1980

$$V_S = \frac{B \cdot N \cdot d}{\ln(Nd) + \ln(A / \ln(1+1\gamma))} \xrightarrow{N \rightarrow N/\cos(\theta)} V_S = \frac{B \cdot N \cdot d / \cos(\theta)}{\ln(Nd/\cos(\theta)) + \ln(A/\ln(1+1\gamma))}$$

Electric Discharge in our Setup

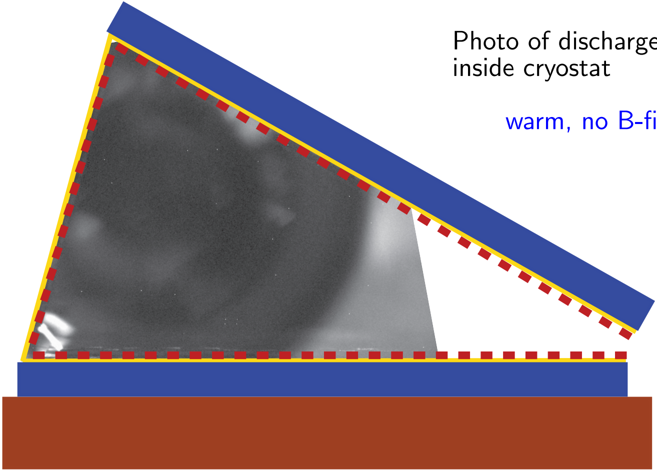


Photo of discharge inside cryostat

warm, no B-field

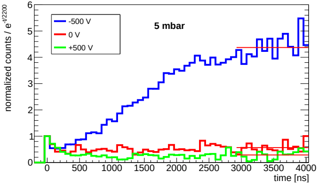
Outlook

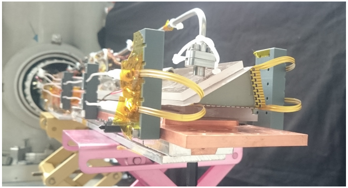
Path to muon beam compression

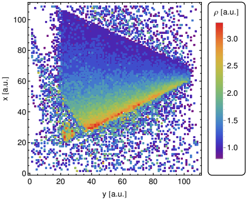
- 2015
  - Data analysis and conclusions of 2014 beamtime
  - Preparation for 2015 beamtime
  - In the 2015 beamtime:
    - Test transversal compression
    - Improve longitudinal compression
    - Test $E \times B$ drift after longitudinal stage
- 2016
  - First "mechanical" tests of vacuum extraction
  - Combine mechanically longitudinal and transversal stage

Take Away Messages

- Development of new beamline with high brightness is ongoing
- Very challenging to build, but no showstopper so far
- Longitudinal compression successfully demonstrated
- Test of transversal compression in December 2015







Thank you for your attention!

muCool Collaboration

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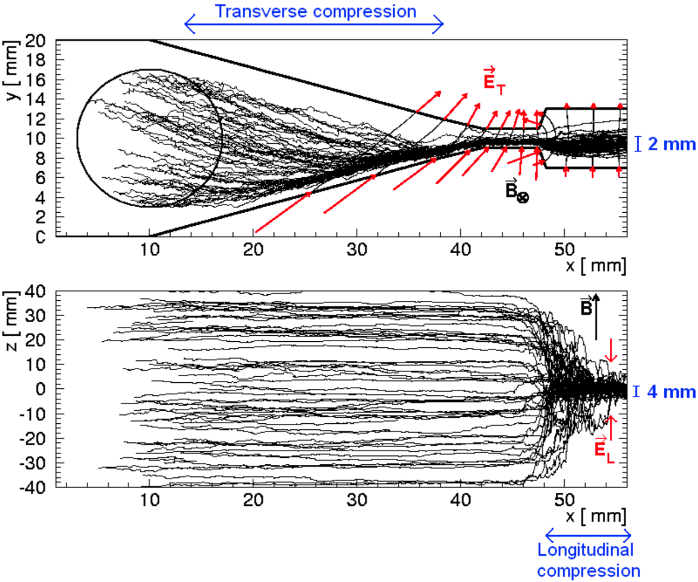
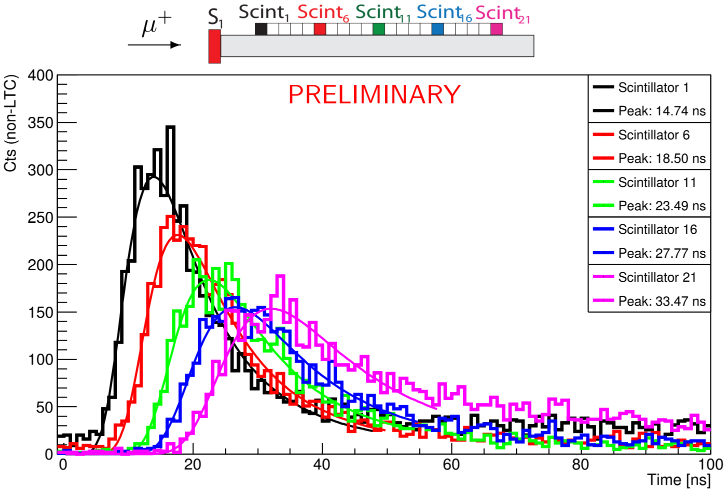
Back Up Slides

Simulation: Projections of Compression

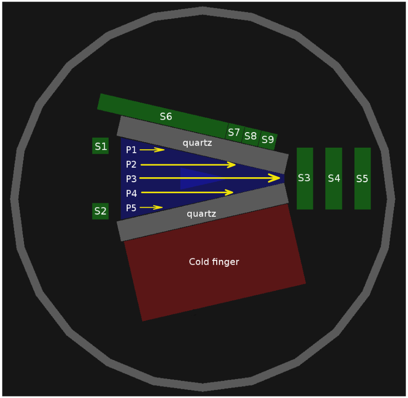


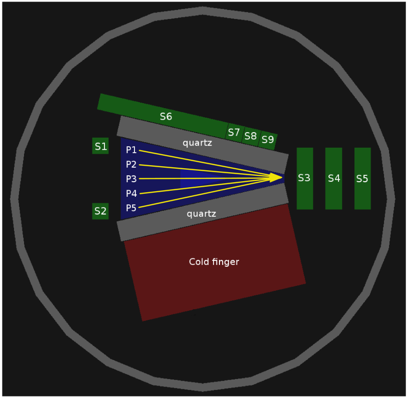
Time of Flight



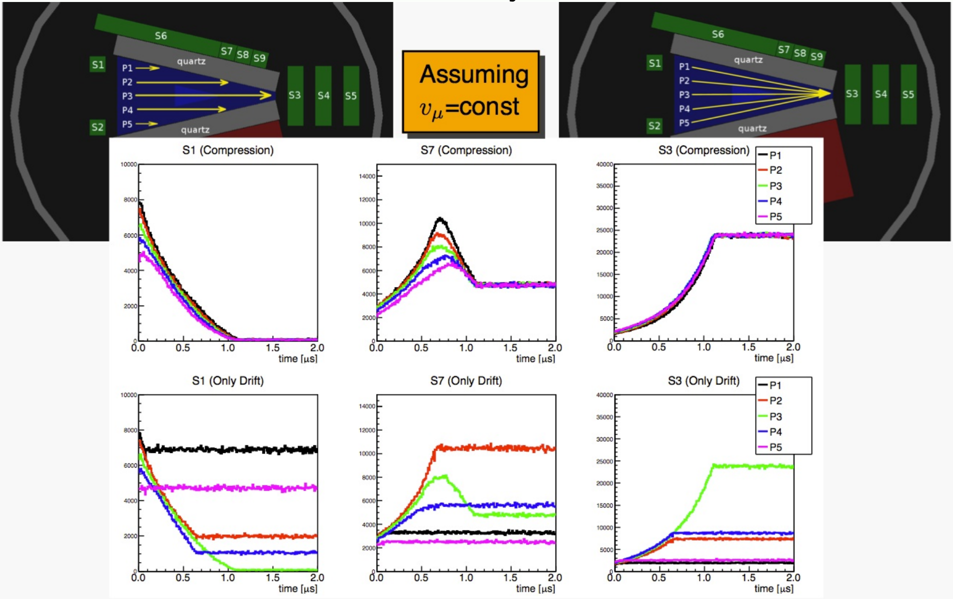
Calculated initial momentum: 11.55 MeV/c → ~20% stop in foils.

Data analysis...



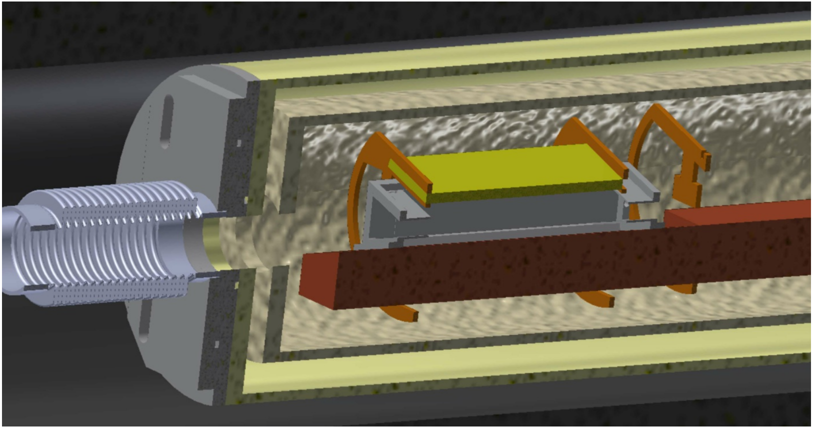


Data analysis...

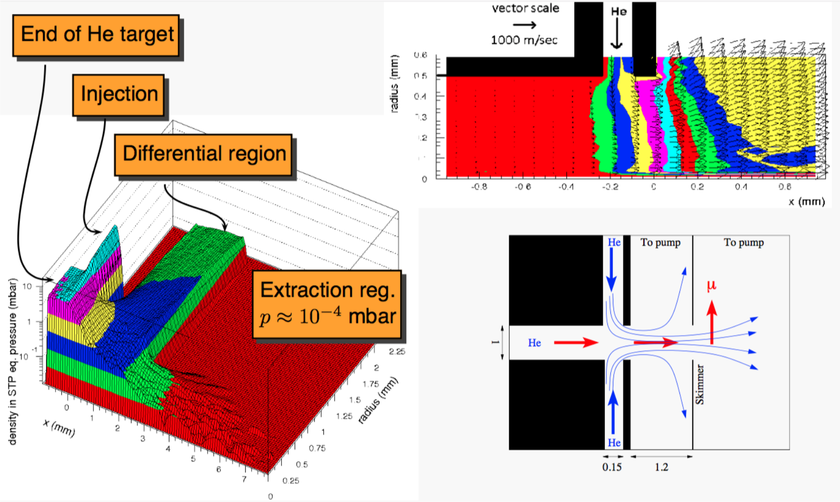


Assuming v_μ=const

Mounted on Beamline

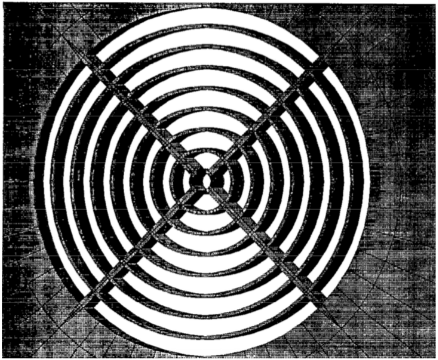


Vacuum Extraction

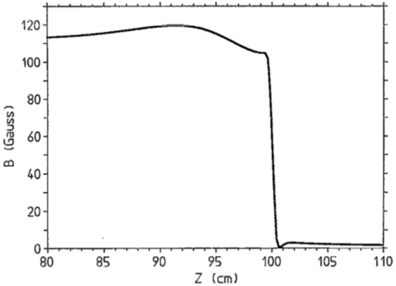


- No flow inside target!
- Reinjection of helium “blocks” outflow of helium from target cell and compensates losses

Extraction from Magnetic Field



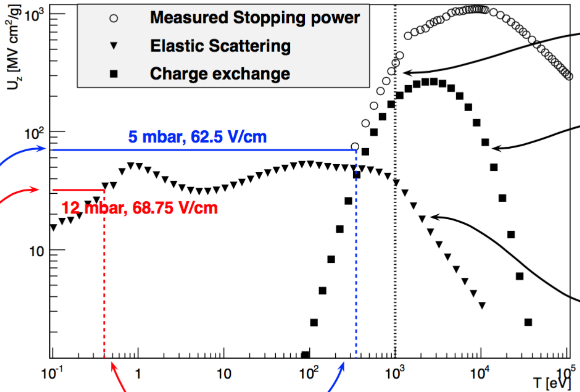
Gerola et al., Rev. Sci. Inst. **66**, 3819 (1995)



- Field termination with a magnetic grid
- Tested with slow positrons/electrons
- ~50% transmission and increased transverse energy by O(10 eV)

Stopping Power

Simulated energy loss per unit length along z-axis



Difference:
He ionization and excitation

Muonium formation and ionization
$\mu^+ + \mathrm{He} \to \mathrm{Mu} + \ldots$
$\mathrm{Mu} + \mathrm{He} \to \mu^+ + \ldots$

Elastic scattering:
$\mu^+ + \mathrm{He} \to \mu^+ + \mathrm{He}$

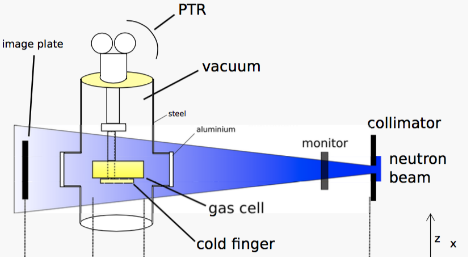
[Lin. et al., J. Phys. B **12**, 4179 (1979)]

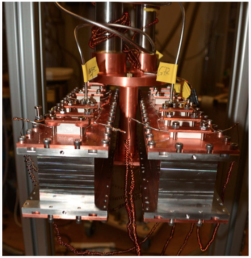
Kin. energy gained in E-field

Equilibrium kinetic energy

μ^+ cross sections at low energy are not know:
- velocity scaling from p data for the charge exchange
- energy scaling from p data for elastic scattering

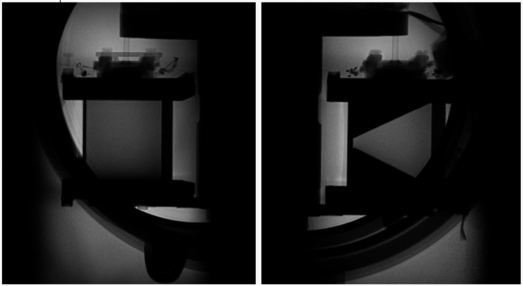
Stopping Power



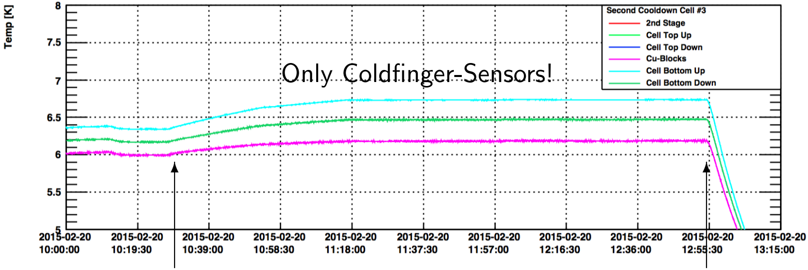


(Morpheus beam line, PSI)

(Raw data/images) →



Measured Temperatures of Target *with* B-Field



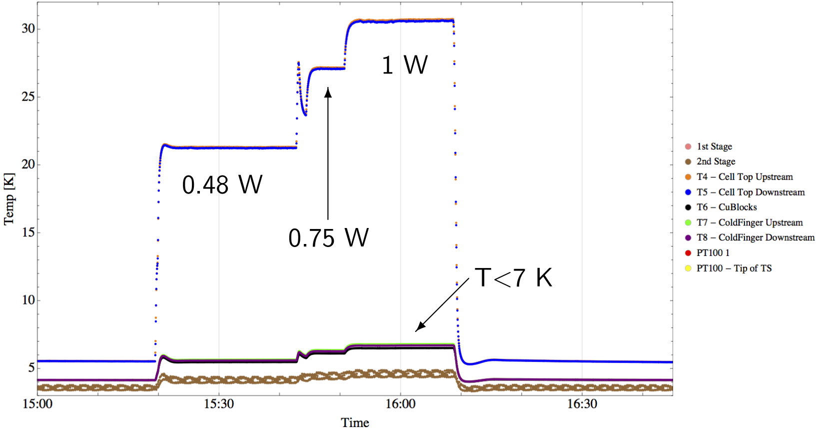
Only Coldfinger-Sensors!

B on

B off

	Top-US	Top-DS	Bot-US	Bot-DS
P=0, B=0	11	11	3.8	3.8
P=0.9 W, B=0	11.5	11.5	6.3	6.2
P=0.9 W, B=5 T	12.9	12.8	6.7	6.5
P=0, B=5 T	11.5	11.4	3.9	3.9

Heating with Heating Wire (Target 2014)



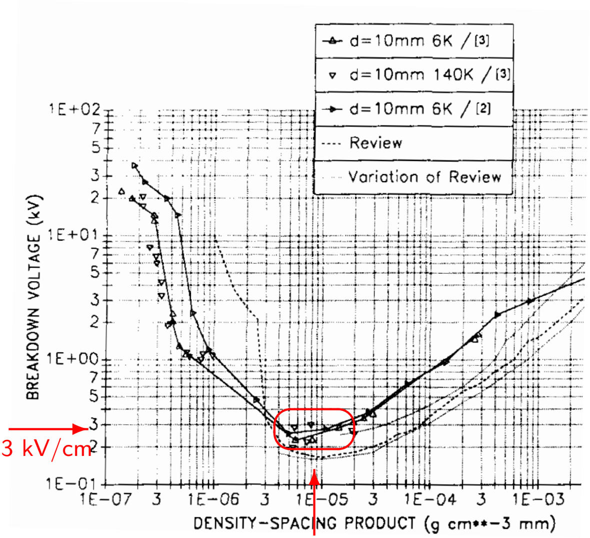
0.48 W

0.75 W

1 W

T<7 K

Electric Discharges



0.3 kV/cm

Our density: $\mathcal{O}(10^{-5})\mathrm{g}\cdot\mathrm{cm}^{-3}$

- Require 2 kV/cm
- Strong B-field!
    - $\vec{E} \times \vec{B}$-drift
    - Increase effective density
    - Increase breakdown voltage

V_{BD} at cryogenic temperatures for He

M. Irmisch et al.; IEEE Trans. on E. I. Vol 28, No. 4, Aug 1993

Muon Lifetime

Measured at MuLan and FAST experiment to be:

- $\tau_\mu^{MuLan} =$ 2'196'980.3±2.1(stat) ± 0.7 (sys) ps (overall 1.0 ppm)
- $\tau_\mu^{FAST} =$ 2'197'083 ± 32 (stat) ± 15 (sys) ps (overall 16 ppm)

Muon lifetime τ_μ required for the Fermi constant G_F

$$G_F = \sqrt{\frac{192\pi^2}{\tau_\mu m_\mu^5} \frac{1}{1 + \Delta q^0 + \Delta q^1 + \Delta q^2}}$$

m_μ: muon mass (known to 33 ppb according to PDG)
Δq^i: theoretical corrections

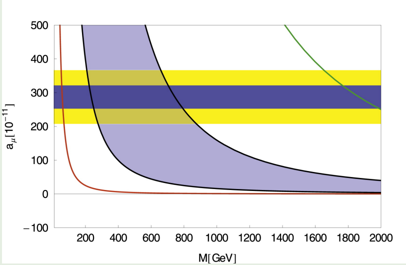
$\Rightarrow G_F = 1.166\ 378\ 7(6) \times 10^{-5}\ \text{GeV}^{-2}$ (0.5 ppm)

Muon g-2

Dirac Equation $\Rightarrow g_\mu \equiv 2$ for structureless, spin-1/2.
So-called *"anomalous magnetic moment"* $a_\mu \equiv (g-2)/2$; $a_\mu = \mathcal{O}(10^{-3})$.

Most precise value: BNL E821 with 0.54 ppm; Theory 0.43 ppm.

3.6 σ discrepancy between theory and experiment!



Increased precision with two new experiments: FNAL E989 with goal 140 ppb and J-PARC E24 with goal 400 ppb.
J-PARC uses muonium ionization. Improved muonium production rate would increase precision significantly!

Example: The Muon Electric Dipole Moment μEDM

Permanent electric dipole moment violates P and T → also CP.

$$\vec{\omega} = -\frac{e}{m} \left\{ \underbrace{a\vec{B} + \left(\frac{1}{1-\gamma^2} - a \right) \frac{\vec{\beta} \times \vec{B}}{c}}_{\text{from (g-2)}} + \underbrace{\frac{\eta}{2} \left(\frac{\vec{E}}{c} + \vec{\beta} \times \vec{B} \right)}_{\text{from EDM}} \right\}$$

"Frozen spin technique": Cancel (g-2)-precession by with radial $\vec{E}$-field

Improvement in almost tabletop experiment by up to $\mathcal{O}(10^4)$ possible.

Frozen spin techique: Farley F. J. M, *et al*, 2004, Phys. Rev Lett. **93**, 05 2001
Compact storage ring for μEDM search: Adelmann A *et al*, 2010, J. Phys. G: Nucl. Part. Phys. **37** 08 5001