Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

PAUL SCHERRER INSTITUT

Development of a novel muon beam line for next generation precision measurements

This work is supported by the SNSF grant 129600 and 146902.

Kim Siang Khaw
on behalf of the Muon Compression Group (ETHZ and PSI)

Institute for Particle Physics, ETH Zurich, Switzerland

Zurich PhD Seminar 2013
ETH Zurich
29th August 2013

Introduction

Precision measurements of muon (μ^+) interactions

- best determination of fundamental constants like $\frac{m_\mu}{m_e}$ (0.8 ppb), $\vec{\mu}_\mu$ (120 ppb) and $\frac{q_{\mu^+}}{q_{e^-}}$ (2.1 ppb) from muonium [Mu=($\mu^+ e^-$)] spectroscopy
- new physics searches like lepton flavor violation via Mu-$\overline{\mathrm{Mu}}$ oscillation
- lack of high quality μ^+ beam and Mu source has prevented progress of this promising field

What is needed for the next generation experiments?

Development of a high quality slow positive muon beam line

- phase space compression of 10^{10}
- sub-eV energies
- sub-mm beam size

Optimization of μ^+ to Mu conversion

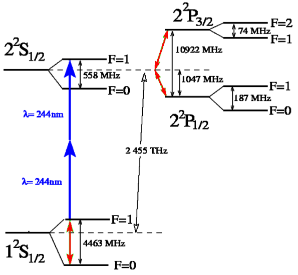
- new materials (porous silica materials and superfluid helium)

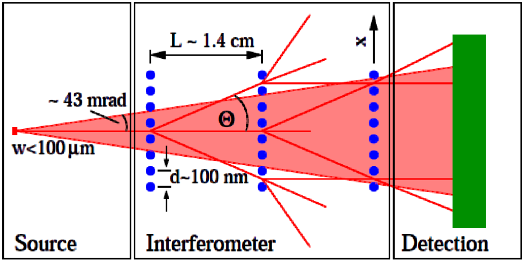
Application

Such a beam line would allow us to further improve previous precision measurements and open up new types of measurements.

Muonium spectroscopy and interferometry

High precision Mu 1S-2S transition frequency measurement, observation of its seasonal changes and Mach-Zehnder atom interferometer for antimatter gravity studies.

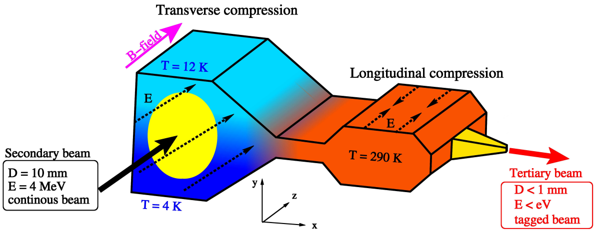




Solid state applications

Investigation of the physics of thin films using muon spin rotation (μSR) techniques, by varying the implantation depth from 1 to 500 nm.

Overview



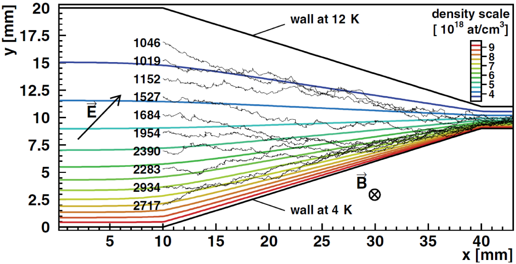
The proposed beam line is based on a position-dependent muon drift velocity v_D in gas. It is divided into 3 parts: transverse compression, longitudinal compression and extraction of the muon beam.

Muon drift velocity in the helium gas

$$v_D \propto \frac{E}{1+\omega^2\tau^2}\{\hat{\mathbf{E}} + \omega\tau\hat{\mathbf{E}}\times\hat{\mathbf{B}} + \omega^2\tau^2(\hat{\mathbf{E}}\cdot\hat{\mathbf{B}})\hat{\mathbf{B}}\}$$

$\tau = \tau(p, T)$: average time between collisions, $\omega = \dfrac{eB}{m_\mu}$: cyclotron frequency

Concept of transverse compression



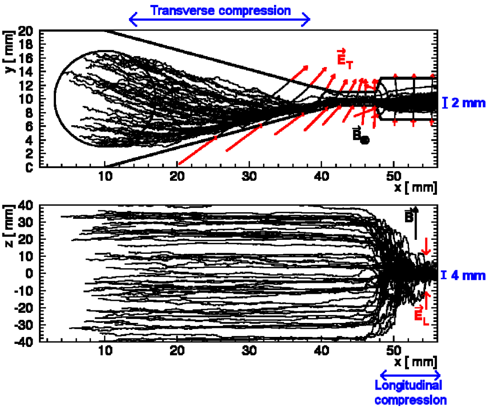
Density gradient and $\vec{E} \times \vec{B}$ field

Density gradient in the helium gas target is introduced by the temperature gradient, 4K at the bottom plate, 12K on the upper plate. With the following configuration,

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

muon at low density is drifted downwards (less collisions), at high density is drifted upwards (lots of collisions). However, it is technically challenging!

Concept of longitudinal compression

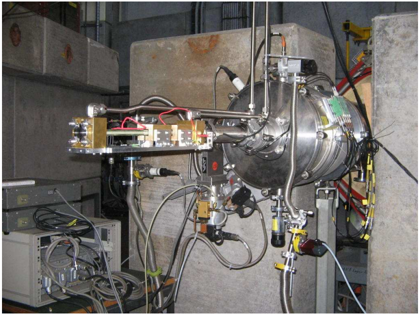


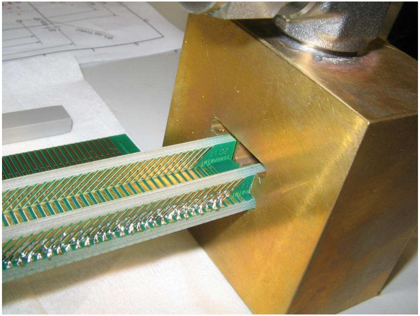
Center-focusing longitudinal electric field

At room temperature and low gas density, the long muon swarm is squeezed into swarms of a few mm diameter by a center-focusing longitudinal electric field. It is technically easier.

Feasibility test at ETHZ and PSI

Due to the technical difficulties, we have first tested longitudinal compression and now preparing for transverse compression.

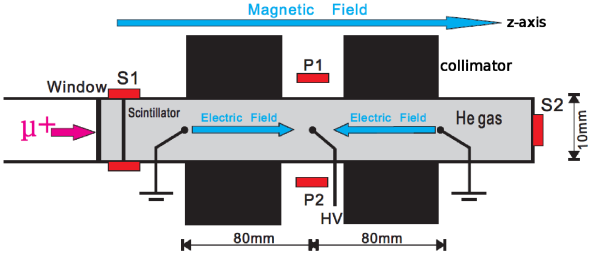


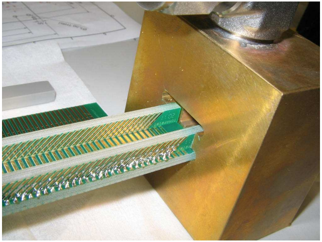


Beam time 2011 - testing longitudinal compression

- Experiment was done at πE1 at PSI
- 2×10^4 μ^+/s @ 10 MeV/c (500 keV energy)
- The target was surrounded by a 5 T solenoid magnet

Experimental setup

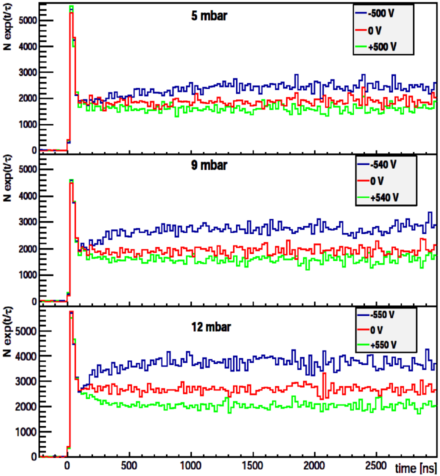


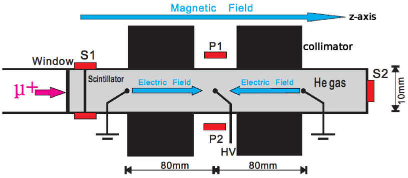


Apparatus

- 30 μm thick plastic scintillator (S1 - start)
- PCB with metallic strips to define potential (-550 V to 550 V)
- 2 scintillators to tag e^+ from μ^+ decay (P1, P2 - stop)
- Time of flight measurement with another scintillator (S2 - stop)
- Helium gas pressure was varied from 5 mbar to 12 mbar

Raw results





Measured positron time spectra

- The histograms are scaled with $\exp(t/\tau)$ to remove μ^+ decay effect
- The prompt peaks are coming from high energy μ^+ decaying in flight
- -HV: μ^+ are being attracted to P1 and P2
- +HV: μ^+ are being pushed away from P1 and P2

MC simulations

Standard GEANT4 at low energy

Energy loss

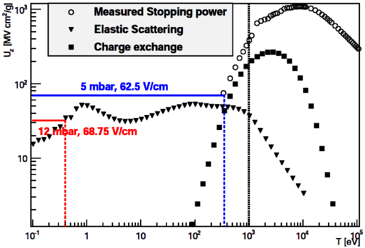
- > 1 keV: stopping power according to NIST data
- 10 eV - 1 keV: free electron gas model ($E_{loss} \propto v$)
- < 10 eV: particle is killed and tracking is stopped

Scattering

- Multiple scattering, no energy loss

Elastic scattering at energy < 1 keV

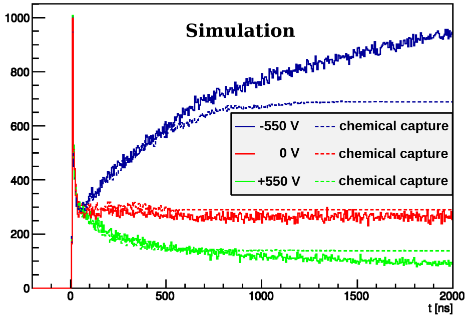
- The cross section is much larger than the ones of inelastic processes
- Energy loss due to this process is dominant
- This process was studied in detail by plasma physicists



Extended GEANT4 at low energy

- Low energy elastic collision process is implemented by scaling the p-He interaction
- Charge exchange process is implemented by scaling the p-He interaction
- MuMultipleScattering and MuIonisation are turned off at $E < 1$ keV

Comparison of MC and data



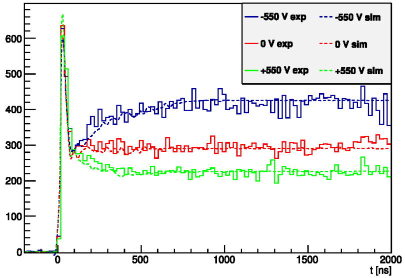
Disagreement

- Time spectra do not have flat region at later time in the simulations
- Smaller flat background in the simulation than in the experiment

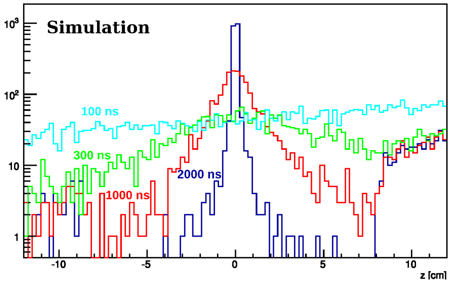
Solutions

- Implement "chemical capture" where very slow muon interacts with impurities in the target and stops there
- Add a constant background to the simulated spectra - small misalignment between magnetic field and target

Preliminary results



(a) simulation and data



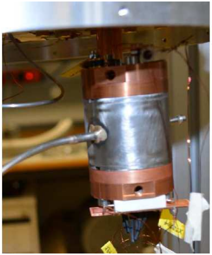
(b) muon swarm at different times

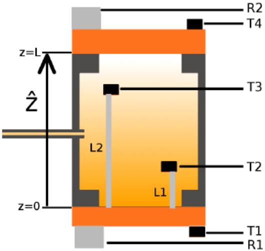
Good agreement between MC and data

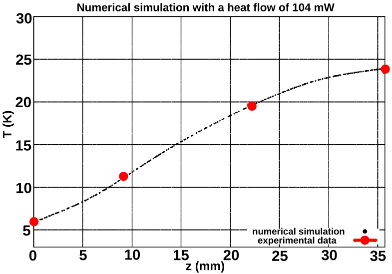
- Data are fitted with the simulations where the "chemical capture rate" and the background are the free parameters
- No unknown physical process is needed to reproduce the experiment results
- The compression of the 16 cm wide muon swarm into a 0.5 cm width region occurs in less than 2 μs
- Realization of longitudinal compression is then feasible

Gas density gradient

We have done our first test on the feasibility of gas density gradient.







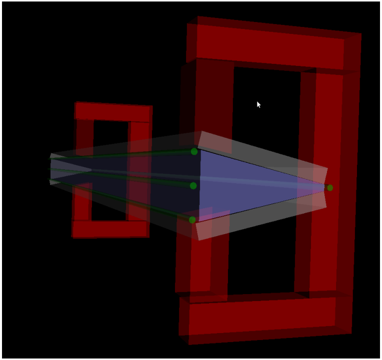
Simple gas cell

- Leak-proof cylinder made of copper (top, bottom) and stainless steel (sides)
- Resistors to heat up the cell and sensors to measure the temperatures
- Helium gas pressure can be varied from 0.01 mbar to 50 mbar
- Copper plate temperatures can be varied from 3 K to 50 K
- Good agreement achieved between COMSOL simulation and our experimental data

Towards the test experiment for transverse compression

To do list

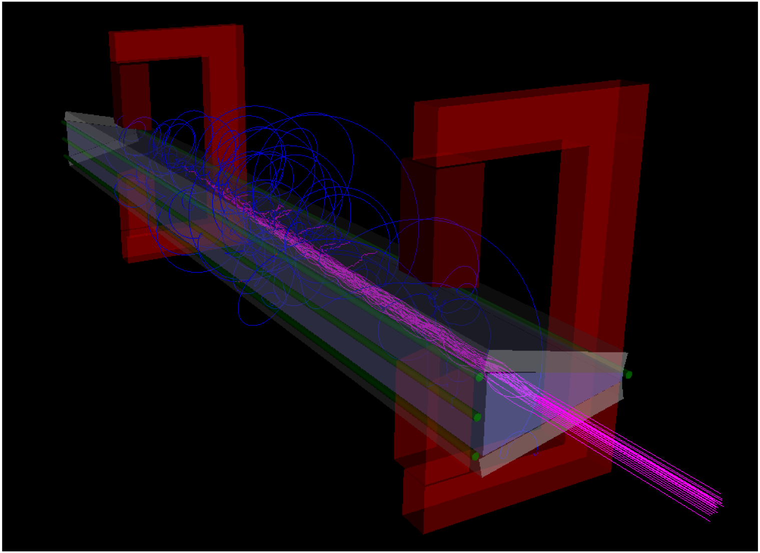
- Appropriate materials to construct the target
- A positron detection scheme that is suitable for our experimental setup
- Implementation of the gas density gradient in GEANT4 (or mimic the effect)



Sketch of test experiment for transverse compression

- Quartz plate with metallic strips to define electric potential (3-5 mm)
- Thin mylar foil to contain helium gas (2-5 μm)
- Plastic scintillators to detect e^+ from μ^+ decay (simple or tracker)

Towards the test experiment for transverse compression



Summary and Future Plan

Summary

- Working towards next generation precision measurements by developing a slow positive muon beam of high brilliance
- Longitudinal compression has been demonstrated to be feasible and transverse compression is under development

Future Plan

- Realization of full compression scheme

If it is feasible,

- Production of muonium from superfluid helium (mono-energetic muonium)
- Precision measurement of 1S-2S energy interval of muonium to extract fundamental constant with higher precision
- Studies of antimatter gravity using this novel beam line by measuring the seasonal changes of 1S-2S energy interval of muonium, and/or by observing the interference pattern of the beam in Mach-Zehnder interferometer