Research Plan

for a Doctoral Study in Physics at the D-PHYS of ETH Zurich

Doctoral thesis:

Doctoral thesis title (provisional):
Towards a novel high-brightness low-energy muon beamline

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1 Introduction and motivation

Muon beams have important applications in particle and solid state physics [1]. In particle physics, experiments with muons allow us to perform fundamental physics research, e.g. testing electroweak interaction and searching for physics beyond the Standard Model [2]. Such experiments include measurements of the anomalous muon magnetic moment or searches for the muon electric dipole moment and charged lepton flavor violation in forbidden muon decays.

Furthermore, the experiments with muonium atoms (Mu $= \mu^+e^-$) open possibilities for very sensitive spectroscopy measurements [3]. A big advantage of the muonium atom is that hadronic effects can be eliminated since it consists of only two leptons. This allows precise tests of the bound-state QED and measurements of fundamental constants, e.g. muon mass, muon magnetic moment and fine structure constant. The muonium atom can also be used to search for CPT-invariance violation and muonium-antimuonium conversion, which violates lepton number conservation. The measurement of the gravitational acceleration of antimatter could also be achievable with muonium [4].

These experiments would benefit from better quality muon beams, i.e. higher intensity slow muon beams with small phase space [2, 5]. Such a beam would enable, for example, better statistics in these experiments, which could then lead to a greater precision of the measurements.

2 Working principle

The proposed new muon beamline [6] consists of three stages: transverse compression, longitudinal compression and mixed longitudinal-transverse compression followed by the extraction into the vacuum (Fig. 2.1).

Compression in all stages is achieved by making the muon drift velocity $\vec{v}_D$ position-dependent. The drift velocity of a charged particle in a gas and electric and magnetic fields ($\vec{E}$, $\vec{B}$) is given by the following equation [7]:

$$\vec{v}_D = \frac{\mu E}{1 + \left(\frac{\omega}{\nu_c}\right)^2} \left[\hat{E} + \frac{\omega}{\nu_c} \hat{E} \times \hat{B} + \left(\frac{\omega}{\nu_c}\right)^2 \left(\hat{E} \cdot \hat{B}\right) \hat{B} \right], \tag{2.1}$$

where $\omega = eB/m$ is the muon cyclotron frequency (m is muon mass), $\mu = e/\nu_c m$ is the muon mobility in the gas and ν_c is the collision frequency, which depends on the temperature and pressure of the gas. The drift velocity vector can be made position dependent by using a position-dependent electric field $\vec{E}$ and/or a temperature gradient. The temperature gradient produces the density gradient that changes the weight of the three components in eq. (2.1), leading to the position dependent $\vec{v}_D$.

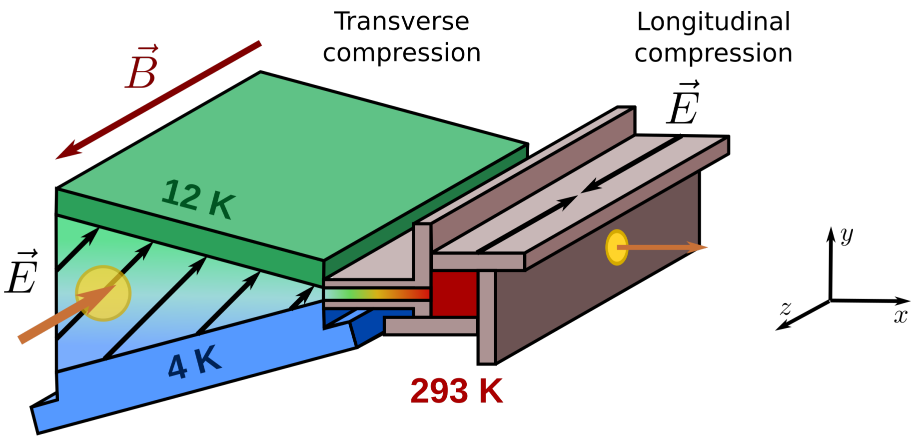

Figure 2.1: Scheme of the proposed muon compression beamline. Muons from the secondary μ^+ beam enter the transverse compression stage, where they are first stopped in the helium gas and then compressed in transverse (y) direction by using the combination of a vertical temperature gradient and the electric and magnetic fields. After that, they enter the longitudinal compression stage, where they are compressed in the longitudinal (z) direction and then extracted into the vacuum.

Transverse compression stage: In the transverse compression stage, the secondary μ^+ beam is stopped in a few mbar of cryogenic helium gas. A magnetic field of 5 T points in the z-direction and the electric field has direction $\hat{E} = 1/\sqrt{2}\,(\hat{x} + \hat{y})$. The upper wall of the target is kept at 12 K and the lower at 4 K which creates a temperature gradient in the y-direction.

According to eq. (2.1), the drift velocity of muons has only two components: in the direction parallel to the electric field ($v_\parallel$) and in the $\hat{E} \times \hat{B} = 1/\sqrt{2}\,(\hat{x} - \hat{y})$ direction (perpendicular to the electric field, $v_\perp$). The ratio of these two components is $\frac{v_\parallel}{v_\perp} = \frac{\nu_c}{\omega}$, which means that muons are moving at an angle θ relative to the $\hat{E} \times \hat{B}$ direction, given by the relation:

$$\tan\theta = \frac{v_\parallel}{v_\perp} = \frac{\nu_c}{\omega}. \tag{2.2}$$

In the middle of the cell, the gas density is chosen such that $\frac{\nu_c}{\omega} = 1$. It follows from (2.2) that the two drift velocity components have the same magnitude and the muons drift in the $x-$direction. In the top part of the cell, the gas density is lower, which means that $\frac{\nu_c}{\omega} < 1$ and muons drift diagonally in $-y$ and $+x$ direction. In the lower part of the cell, at larger gas densities, $\frac{\nu_c}{\omega} > 1$ and muons drift in $+y$ and $+x$ direction. The result is transverse (y) compression of the muon beam.

Longitudinal compression stage: After the transverse compression stage, muons enter the longitudinal compression stage, which is at room temperature. The electric field in this case has a component parallel to the magnetic field and points towards the center of the target, which causes a muon drift into the center of the target and gives rise to the longitudinal (z) compression of the muon beam.

Additionally, there is component of electric field perpendicular to the magnetic field, in $+y-$direction. Therefore, muons also drift in $\hat{E} \times \hat{B}$ direction, which in this case points in $+x-$direction, towards the final compression stage and extraction into the vacuum.

Extraction into vacuum: After the transverse and longitudinal compression stages, the final compression is occurring, both in y and z direction and again at cryogenic temperature. The beam is then extracted into the vacuum through a 1 mm orifice. To keep the pressure in the target stable, without turbulences, helium gas needs to be continuously injected into the target.

3 Research activities

Different stages of the novel muon beamline can be tested independently of each other.

In the beamtime 2011 longitudinal compression stage was tested and demonstrated for the first time [7].

In the beamtime 2014 we tested again the longitudinal compression with an improved setup. Additionally, we also attempted a first engineering run for the transverse compression stage.

Unfortunately, due to the problems with a helium leak from the transverse target at cryogenic temperatures and breaking of the electrical contacts during the cooldown, we were not able to test the transverse compression of the muon beam.

In 2015 the effort was invested in solving the aforementioned problems with the transverse target. The target design was optimized to prevent the voltage breakdown when applying high electric fields in the helium gas. In another beamtime in December 2015, we successfully demonstrated the transverse compression for the first time. Also, we tested the longitudinal compression with additional $\hat{E} \times \hat{B}$ drift, which is needed to later extract the beam into the vacuum.

Currently, the analysis of the data from the beamtimes 2014 and 2015 is ongoing.

In order to correctly interpret the data, a GEANT4 simulation of the low-energy muon beamline has to be done. This requires implementing low-energy muon physics processes in GEANT4, mainly low energy elastic collisions and charge exchange. The simulation also has to be validated by comparing its results with our experimental data and theory. Preliminary results show compatibility of the experiment and the simulation.

For the simulation of the transverse compression, it is necessary to model the density gradient of the helium gas in the simulation. The simulation then allows us to optimize the compression of the muon beam by tuning the electric fields, helium gas pressure and temperature gradient.

In 2017, another beamtime is planned to test the combined transverse and longitudinal compression stages and/or extraction of the muon beam, depending on the R&D progress over the next months.

4 Schedule of the research work

2014 (done)

- Preparation for the beamtime 2014 to the test improved longitudinal compression and engineering run for the transverse compression
- Participation in the beamtime 2014

2015 (done)

- Data analysis for the paper "Temperature dependence of the leak rate and permeability of helium gas through Kapton foils" [8]
- Development of the longitudinal and transverse targets for the beamtime 2015
  - Simulation of the electric fields for the transverse and longitudinal target
  - Optimization of the high voltage connections for both targets
  - Study of the breakdown properties in the helium gas at cold temperatures and in the magnetic field
  - Various cryogenic tests of the transverse target temperature distribution
  - Optimization of the detector system using GEANT4
- Design and realization of the longitudinal and transverse targets
- Preparation for the beamtime 2015
  - Programming the slow control for the high voltage, temperature control, pressure readout
  - preparing DAQ for the beamtime (MIDAS)
  - setting up area (beamline, solenoid, cryocooler, infrastructure)
  - gas installation
- Simulation of the μ^+ diffusion in the helium gas target
  - preliminary simulations considering only elastic low energy cross sections
  - simulation of the two experiments
- Data taking in December 2015

2016 (partially done)

- Improving the simulation of the low energy μ^+ diffusion
  - debugging the code
  - extend the code to include additional physical processes
  - compare the results of the simulation using transport and differential cross sections
  - validate the results by comparing with SRIM tables [9]
- Analysis of the data from the beamtime 2015 (transverse compression)
- Writing paper about transverse compression
- Preliminary design/simulation of extraction into vacuum
- Preliminary design/simulation of connecting the transverse and longitudinal stages

2017

- Writing paper about simulations
- Offline tests of the extraction into vacuum
- Development of the combined transverse-longitudinal target
  - simulation of the thermal properties
  - simulation of the complex electric field distribution
  - simulation of the detector system
  - related offline tests
- Preparation for the beamtime 2017
- Data taking and data analysis of the results from the beamtime 2017
- Writing thesis

5 Teaching activities

Previous teaching duties were:

- 2015 - Teaching assistant for General Physics 2 (FS, Prof. K. Kirch) and Vorgerücktenpraktikum VP (HS, Prof. C. Grab and Prof. T. Ihn)
- 2016 - Teaching assistant for General Physics 2 (FS, Prof. K. Kirch)

Further activities are planned in the VP within the Advanced Students' Lab in IPP and as needed at 20-25% total load.

References

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[9] J. F. Ziegler et al. SRIM - The stopping and range of ions in matter (2010). *Nucl. Instruments Methods Phys. Res. Sect. B: Beam Interactions with Mater. Atoms*, 2010.