PROCEEDINGS OF SCIENCE

Development of next generation muon beams at the Paul Scherrer Institute

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The Paul Scherrer Institute (PSI) provides the world's highest intensity muon beam of $\mathscr{O}(10^8)\,\mu^+/\mathrm{s}$ at 28 MeV/c. The HiMB project aims to improve this rate by two orders of magnitude. Meanwhile, the muCool collaboration is developing a device which converts a standard surface μ^+ beam of cm-size and MeV-energy into a beam of 1 mm-size and 1 eV energy spread by achieving a compression of 6-dimensional phase space by 10 orders of magnitude with a prospected efficiency of 10^{-3}.

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1. Introduction

The PSI has been leading physics with DC muon beams utilising a cyclotron based proton accelerator complex delivering a proton beam of 590 MeV energy and 1.4 MW power. The 28 MeV/c surface muons from positive pion decays at rest are most widely used for the experiments. Currently, the highest rate of surface muons, over 10^8 μ^+/s, is available at πE5 and μE4 beamlines for particle physics and material science. Two projects at PSI are advancing the performance of these muon beams; the muCool collaboration is aiming at increasing the quality of the positive muon beam by reducing its phase space, the HiMB collaboration is aiming at improving the total muon rates by optimising the production target and beam transport.

2. muCool project

Experiments with low energy muons are largely limited by the poor phase space quality of standard muon beams. Stochastic cooling [1] or electron cooling [2] can be applied for stable particles, however, a much faster scheme is required for muons because of their short lifetime of 2.2 μs. The muCool collaboration is developing such a cooling technique that compresses the phase space of the standard beam by 10 orders of magnitude in 6-8 μs with an efficiency of $\mathscr{O}(10^{-3})$ [3]. In this scheme, a standard muon beam with cm-size and MeV-energy spread is first stopped inside the helium gas at cryogenic temperatures and then it is compressed by complex fields and a gas density gradient. The beam that emerges from this device has a sub mm-size and eV-energy. After acceleration to keV energy, this new beam can be used for searching for the muon electric dipole moment with efficient magnetic trapping, for producing high quality muonium beam to test the gravitational interaction of anti-matter [4] and for laser spectroscopy. The beam can be used also for solid state physics investigation using the μSR techniques, especially suited for thin and small samples.

2.1 Working principle

Figure 1 shows a scheme of the device where phase space compression is occurring, consisting of two compression stages and an extraction stage. Muons are stopped in several mbar of helium gas at cryogenic temperatures where high electric and magnetic fields are applied. In the presence of such fields and helium gas atoms, the average drift velocity of muons can be described as

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

where $\tilde{\mu}$ is the muon mobility in the gas, $\omega = eB/m_\mu$ is the muon cyclotron frequency, τ_c is the mean time between a collision of the muon with a helium gas atom and $\hat{E}$ and $\hat{B}$ are the unit vectors along $\vec{E}$ and $\vec{B}$, respectively [5].

In the first stage, muons are compressed in y-direction while drifting in x-direction. In this stage, the helium gas is at cryogenic temperatures with a temperature gradient between 4 K and 12 K, while the direction of the electric and magnetic fields are $\hat{E} = (\hat{x}+\hat{y})/\sqrt{2}$ and $\hat{B} = \hat{z}$, respectively. Hence in this stage $\hat{E}\cdot\hat{B} = 0$ and the third term in equation (2.1) vanishes. As a result (see Figure 2 (left)), in the lower part of the target (y < 0) where the gas density is larger, muons drift

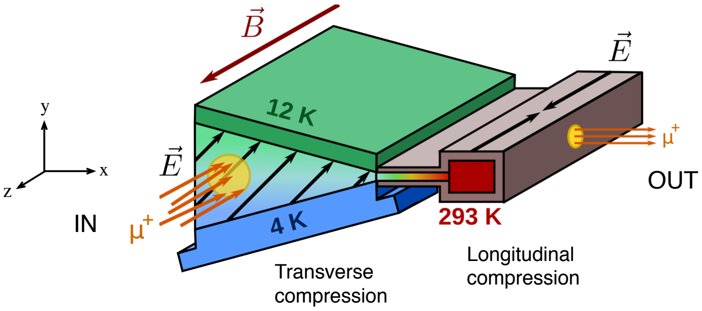

Figure 1: Principle of the proposed muCool setup. Muons are stopped in the cryogenic part of the target. From there, they drift in +x-direction compressing first in y-direction (in the green-blue region) and then in z-direction (in the brown region). After about 8 μs, they exit the gas target through an orifice. From there, re-acceleration can occur.

approximately along the $\hat{E}$-direction. In the upper part of the target (y > 0) where the gas density is lower, muons drift approximately along the $\hat{E} \times \hat{B}$ direction. Thus, as visible in Figure 2 (left), muons drift in the x-direction while compressing in the y-direction.

In the second stage shown in brown in Figure 1 which is at room temperature, muons are compressed along the z-direction (longitudinal compression). Here the electric field is parallel to the magnetic field and directed to the mid-plane of the target. Because $\hat{E} \cdot \hat{B} \neq 0$ and the density is low, the third term in equation (2.1) becomes dominant resulting in muons drifting toward the mid-plane at $z = 0$. The electric field in the second stage is also having a non-vanishing component in the +y-direction. This component, via the $\hat{E} \times \hat{B}$ term of equation (2.1) guarantees a drift in the +x-direction. Hence in this stage, as shown in Figure 2 (right), muons drift in the +x-direction while compressing in the z-direction.

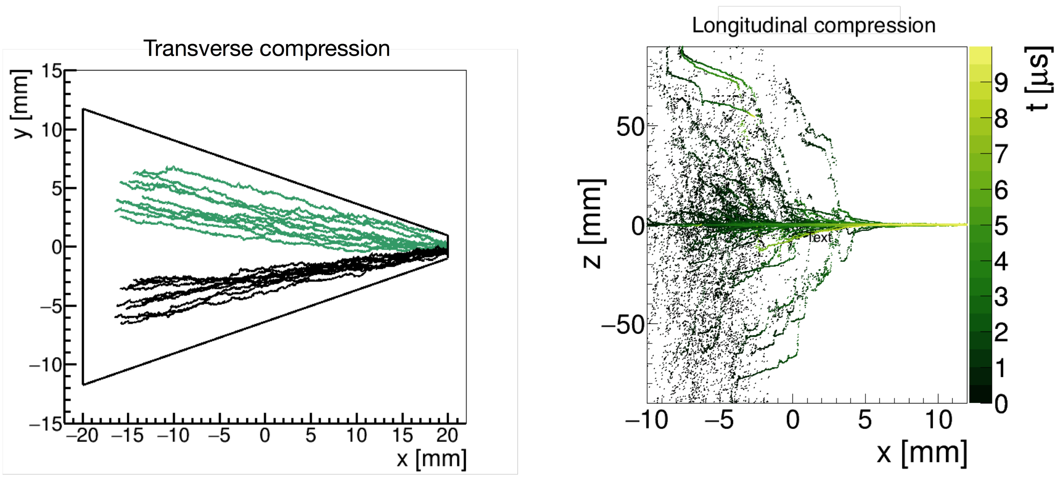

Figure 2: Simulated muon trajectories. (Left) Transverse compression. Muons initially stopped at $x \simeq -20$ mm over a wide distribution in the y-direction are drifting in the +x-direction while being compressed in the y-direction. (Right) Longitudinal compression. Muons initially stopped at $x \simeq -10$ mm over a wide distribution in the z-direction are drifting in the +x-direction while being compressed in the z-direction.

After the two muon compression stages described above, the compressed muon distribution is guided through a windowless orifice into vacuum. At the orifice, helium gas is continuously injected transversally with respect to the muon drift direction to keep the target pressure to a certain value. The orifice region has to be efficiently evacuated so that the muons after passing the orifice will be in a short time in a low pressure region where they can be re-accelerated with pulsed electric fields parallel to the magnetic field. After the re-acceleration, the muons are extracted from the 5 T solenoid and delivered to an experiment.

2.2 Status of the muCool development

Until now, the longitudinal and transverse compression stages have been separately demonstrated. Recently, we have also demonstrated efficient compression where both transverse and longitudinal compressions occur simultaneously in a single stage. To better illustrate the status of the development, we summarise the main milestones reached so far:

2011 First test of the longitudinal compression stage [5]. The compression was successfully observed but limited by gas impurities and misalignment between the beam and the target.

2013 Test of the feasibility to establish a gas density gradient in a cryogenic target. The method used was neutron imaging on a ^{3}He cryogenic target. A density gradient as needed for the transverse compression (Figure 1) was successfully measured [6][7].

2014-1 Improved test of the longitudinal compression. An efficiency as predicted by simulations has been obtained. The impurity effects have been quantified [8].

2014-2 Engineering run to test the transverse compression stage. Detectors, cryostat and beamline were successfully tested but the cryogenic target was having issues (He tightness at cold temperatures and electrical breakdown when applying HV).

2015-1 Improved test of the longitudinal compression with the addition of an $\hat{E} \times \hat{B}$ field to drift the muons in the x-direction while compressing them in the z-direction [8].

2015-2 Test of the transverse compression. Transverse compression as expected from simulations was observed. Analysis of the data is ongoing.

2017 Test of simultaneous longitudinal-transverse compression in a cryogenic target. The measurements indicated feasibility of the mixed compression. Yet, the measurements were severely limited by the electrical breakdown that limited strength of the applied electric field.

2019 Improved test of the simultaneous compression. The design electrical field was obtained and mechanical issues were solved. Measurements indicate efficient compression. Data analysis is ongoing.

As a next step, the muCool collaboration will address the extraction of the muons from the gas target and their re-acceleration.

3. HiMB project

The HiMB project aims to provide a 100 times higher surface muon rate of $\sim 10^{10}\,\mu^+/\mathrm{s}$ at 28 MeV/c by upgrading production targets and beamlines [9]. This unprecedented intensity is essential for next generation rare muon decay searches such as Phase-II of the Mu3e experiment [10] as well as novel muon spin rotation techniques (μSR). The first phase of the project is a geometric optimisation of the graphite production targets, target E and target M. By having a small slanted angle against the proton beam axis to increase the surface area, the surface muon rate is expected to be increased by 30 to 60 %, depending on the beamline. The new proposed geometry was successfully tested and the results will be published soon.

In the next step, rebuilding the target station M is considered by replacing the existing beamlines by radiation-hard, normal-conducting capture solenoids followed by a solenoidal beamline. The first simple beam optics shows that transporting a large number of surface muons of $\mathscr{O}(10^{10})\,\mu^+/\mathrm{s}$ is feasible for a proton current of 2.3 mA.

4. Conclusion

The potential of DC muon beams at PSI will be extended by the muCool and HiMB projects. The muCool collaboration already demonstrated efficient transverse and longitudinal compression. The HiMB collaboration has optimised the meson production target geometry to increase the surface muon rate. Furthermore, the HiMB collaboration is planning to replace standard beamlines with solenoidal-based beamlines to improve the efficiency of the beam transport.

5. Acknowledgement

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