PROCEEDINGS OF SCIENCE

Towards muon cooling at the Paul Scherrer Institute

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At the Paul Scherrer Institute, the muCool device is being developed to compress the 6D phase space of a standard μ^+ beam by a factor of 10^9 with up to 10^{-4} efficiency. Efficient compression has been observed using a cryogenic helium gas target and a complex geometry of E and B-fields. Once compressed, the beam has to be extracted through a windowless orifice into vacuum and a field-free region. This article outlines the status of the muCool device with a focus on the muons extraction stage, currently under development.

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1. Introduction

High-precision experiments using muons and muonium atoms offer promising opportunities to challenge the Standard Model. Such experiments including the measurement of the muon EDM, muonium spectroscopy and muonium gravity would benefit from intense high-quality and low-energy muon beams [1]. However, standard muon beams have poor phase space quality due to scattering in the muon production target combined with the large acceptance of the secondary beamlines [2].

The goal of the muCool device is to implement a fast cooling scheme to reduce the 6D phase space of a standard μ^+ beam by a factor of 10^9 with an efficiency up to 10^{-4}, i.e. a boost in brightness up to 10^5. Typical parameters of the initial beam (before compression) and the final beam (after compression) are indicated in Fig. 1. In this article, we highlight the working principle of the muCool device and we report on its current status.

2. Working principle

Figure 1 shows a diagram of the muCool apparatus. It consists of a cryogenic helium gas target with a pressure of several mbar placed inside a 5 T solenoid magnet. Positive muons of few MeV energy are initially injected into the target and are slowed inside the gas to O(eV) energies. Then they are steered into a sub-mm spot due to a special arrangement of E and B-fields in combination with a gas density gradient [3]. From here, they are extracted into vacuum, accelerated electrostatically and extracted through an iron grid to a magnetic field-free region. The entire process takes less than 10 µs, which is crucial given the short 2.2 µs muon lifetime.

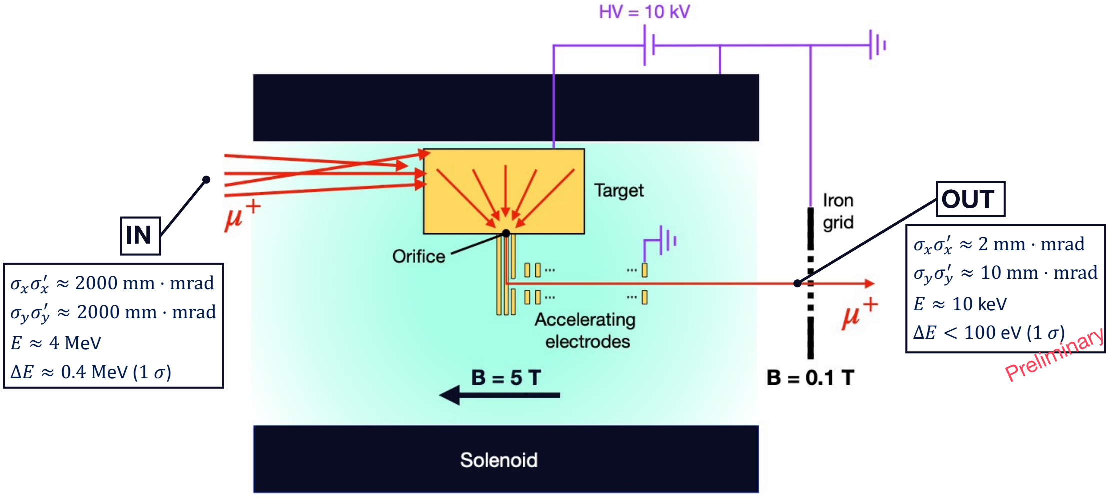

Figure 1: Schematic (not to scale) of the muCool setup showing injection of the positive muon beam into the gas target, phase space compression inside the target, reacceleration and extraction from the surrounding high magnetic field solenoid. The input beam parameters are from simulations of the High-Intensity Muon Beams (HIMB) beamline planned at the Paul Scherrer Institute [1]. The output beam characteristics have been computed propagating the extracted beam until the B-field drops to 0.1 T [4].

2.1 Compression scheme

The phase space compression is achieved with strong electric and magnetic fields. The E-field can be decomposed in a *transverse* and *longitudinal* part: $\vec{E} = \vec{E}_T + \vec{E}_L$, where transverse and longitudinal refer to the orientation with respect to the B-field direction, as depicted in Fig. 2 [5]. The muon beam initially travels along the $B-$field lines in the $-z$-direction and enters the helium gas target. The drift velocity $\vec{v}_D$ of a muon inside a helium gas and in the presence of E and B-fields is [6]:

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

where $\mu = \frac{e}{m_\mu \nu_c}$ is the muon scalar mobility, ν_c is the average μ^+-He collision frequency, $\omega = \frac{eB}{m_\mu}$ is the muon cyclotron frequency with the muon mass m_μ. $\hat{E}$ and $\hat{B}$ are the unit vectors along $\vec{E}$ and $\vec{B}$ respectively.

The *transverse* electric field $\vec{E}_T = \frac{E_T}{\sqrt{2}}(\hat{x} + \hat{y})$ leads to $\vec{E}_T \cdot \hat{B} = 0$ so the last term of Eq. (1) vanishes. It follows that the muon trajectories in the gas, when averaged over many collisions, are at an angle θ with respect to the $\hat{E} \times \hat{B}$-direction according to [3]:

$$\tan\theta = \frac{\nu_c}{\omega}. \tag{2}$$

By employing a temperature gradient as shown in Fig. 2, the gas density and in turn the collision frequency ν_c is lower at the top of the target and higher at the bottom of the target. Therefore, the muons drift angle θ becomes position-dependent and the beam gets compressed in the y-direction.

The *longitudinal* electric field $\vec{E}_L$ is along the B-field such that $\vec{E}_L \times \hat{B} = 0$. As a result, Eq. (1) simplifies to a drift motion along the electric field lines leading to a compression in the z-direction. Hence, the superposition of transverse ($\vec{E}_T$) and longitudinal ($\vec{E}_L$) electric fields yields a simultaneous compression in the y- and z-direction as the beam drifts in the x-direction. A GEANT4 simulation of the muon trajectories in the muCool target is displayed in Fig. 2.

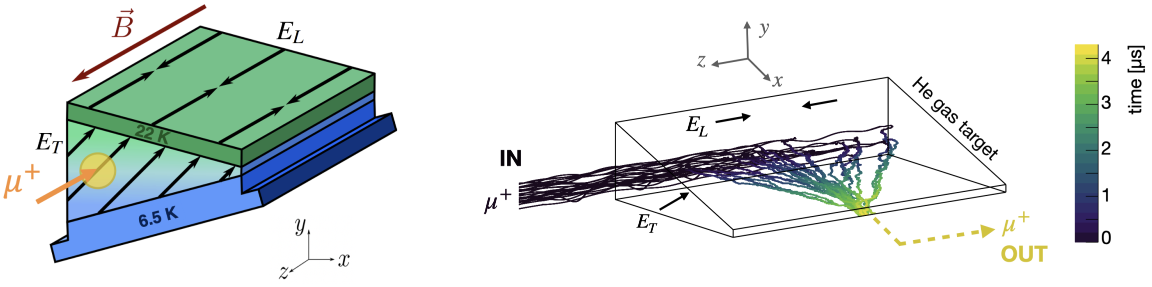

Figure 2: (Left) Schematic of the muCool setup. Muons enter a cryogenic helium gas target placed in a homogeneous magnetic field pointing in the $+z$-direction. The electric field generated in the target has transverse ($\vec{E}_T$) and longitudinal ($\vec{E}_L$) components to obtain simultaneous compression in the y- and z-direction. (Taken from [5]). (Right) Particle trajectories in the muCool target simulated with GEANT4: the injected muons are stopped in the gas and are guided in $\lesssim 5$ μs to a sub-mm spot at the tip of the target, where extraction into vacuum occurs.

2.2 Extraction into vacuum

After the phase space compression, the muons approach the tip of the target and are extracted through a small windowless orifice guided by an electric field. Since the gas exits continuously from the orifice, the target needs to be refilled to maintain a constant gas pressure and to preserve the density gradient inside the target.

When the extracted muons enter a region of sufficiently low gas density, after passing through a series of differentially pumped regions, they are accelerated electrostatically by ring electrodes along the $-z$-direction, as shown in Fig. 1. Finally, a metallic grid terminates the B-field lines so that the μ^+ are extracted into a magnetic field-free region before being transported to an experimental setup.

3. Status of the muCool project

The muon motion inside the target, as defined in Sec. 2.1, has been demonstrated by a series of experiments [7–10]. Good agreement was found between experimental measurements and GEANT4 simulations that were extended to include low-energy processes (μ^+- He elastic scattering and charge exchange) [5].

The muCool target with dimensions of $50 \times 20 \times 90$ mm^3 was realised by folding a kapton foil around a triangular wedge plastic support [10]. The electric field necessary for the compression scheme was produced by electrode lines printed on the kapton foil. A helium pressure of 10 mbar was maintained inside the target and temperature boundaries were set at the upper wall (22 K) and the lower wall (6.5 K) of the target using sapphire plates: heated on top, cooled on the bottom.

The next objective is to develop a target with an extraction orifice in which the muon beam is compressed, extracted through the orifice and coupled to the acceleration stage. This would be a demonstration of the complete muCool scheme. The compressed μ^+ beam is guided through an orifice of $1{\times}1.3$ mm^2 transverse size using the electrodes displayed in Fig. 3 (left), while injecting He gas, as shown in Fig. 3 (right).

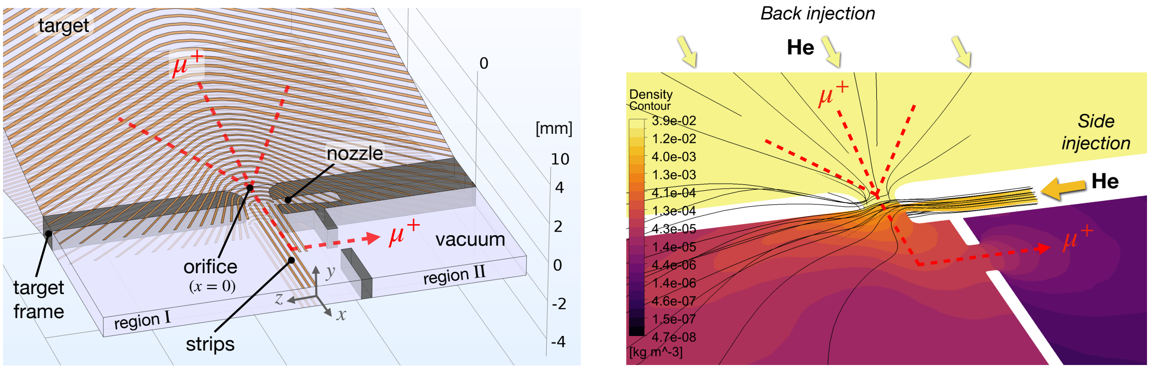

Figure 3: (Left) Scheme of the extraction stage. In orange are given the electrodes producing the electric field to guide the muons and in grey the plastic frame defining the orifice channel and two differentially pumped regions (region I and region II). (Right) Density contours of the helium gas around the orifice region simulated with ANSYS. The black lines are velocity streamlines of the gas.

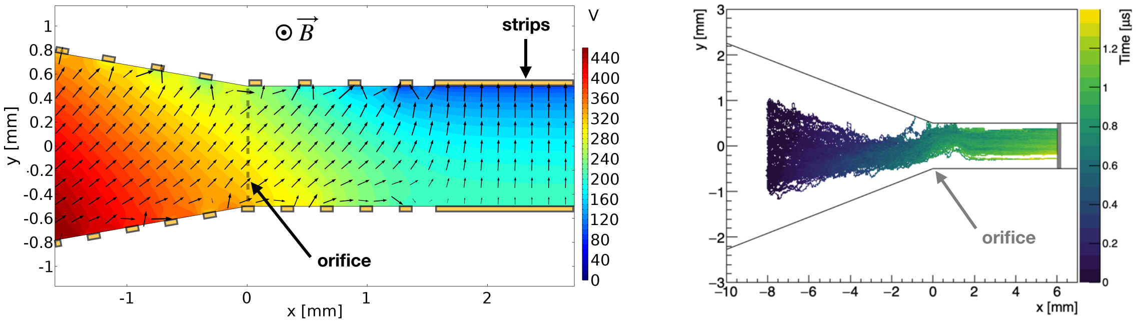

Figure 4: (Left) Electric field (arrows in log scale) and electric potential (colour map) in the xy-plane at $z = 0$ of the extraction stage simulated with COMSOL Multiphysics. (Right) GEANT4 simulation of μ^+ trajectories projected on the xy-plane performed using the He gas density of Fig. 3 (right) and the E-field of the left panel. The particles are generated at $x = -8$ mm with an uniform distribution for $-1 < y < 1$ mm and 10 eV energy. The μ^+ reach the plane at $x = 6$ mm after approximately 1 µs with a transport efficiency (without muon decay) of about 90 %.

The gas in the target is injected in part from the back of the target at 6.5 K - 14 K *(back injection)* and in part at the orifice with a temperature of 100 K - 300 K perpendicularly to the μ^+ motion (*side injection)*, as indicated in Fig. 3 (right). This injection scheme has been designed to minimise the density of the He gas in the reacceleration region and the He flow while preventing gas turbulence in the target disrupting the temperature gradient.

As the muons approach the tip of the target, the electrodes are shaped to generate an E-field that smoothly increases the intensity of the z-compression and thus reduce the muon losses on the target frame. These culminate in a series of parallel electrode strips that generate a vertical E-field in the y-direction and a confining E-field in the z-direction. Figure 4 (left) shows a view of the electric field in the xy-plane at $z = 0$. The vertical E-field in the y-direction gives rise to an $\hat{E} \times \hat{B}$ drift in the x-direction, while the z-component of the E-field confines the muons in the z-direction. Outside the target, the gas density is sufficiently low so that the muons merely drift in the $\hat{E} \times \hat{B}$-direction. Hence, the electric field in this region requires a vanishing E_x component to prevent muons from hitting the top strips. However, in the orifice region the μ^+-He elastic collisions still govern the muons motion. Here, the gas density drops along the muon trajectory and the drift angle θ of Eq. 2 is strongly position dependent. The E-field given in Fig. 4 (left) is derived so that the muons drift in in the $+x$-direction.

Figure 4 (right) displays the muon trajectories inside the gas target as simulated in GEANT4 using the field maps of Fig. 4 (left). A transport efficiency of about 90 % (without muon decay) was obtained at $x = 6$ mm away from the orifice.

4. Conclusion

The muCool device aims to cool and compress the phase space of a standard μ^+ beam by a factor of 10^9 with an efficiency up to 10^{-4}. The compression scheme has been validated with a helium gas target featuring complex E and B-fields in combination with a vertical gas density gradient. The next step is to extract the muon beam from the target into vacuum through a windowless orifice and reaccelerate it to $\mathcal{O}$(keV) energies.

Currently, a new target geometry with an extraction orifice is being developed. The main challenge is to design a helium gas injection system that maintains the density gradient inside the target, while minimising the gas density in the extraction and acceleration regions. Realising electrodes to generate the desired electric field in the extraction region is another major design challenge.

Simulations of He gas flow, electric fields and muon trajectories have been performed. They show that muons can be efficiently extracted from the target through the orifice. Implementations are ongoing.

Acknowledgement

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