

# MODERATION OF POSITIVE MUONS BY HELIUM GAS\*

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## Abstract

Efficiently creating beams of spin-polarized positive muons with energies between eV and keV (so-called slow muon beams) is important for further development and application of muon spin rotation, relaxation, and resonance techniques. One existing moderation method involves the use of wide-band-gap materials as moderators such as rare gas solids and solid nitrogen thin films (band-gap energy between 11 eV and 22 eV). Based on this moderation method, we have studied the use of helium gas as a moderator, with the goal of producing the slow muon beam more efficiently. Because of helium's high (24.6 eV) ionization energy and because the cross section for muonium formation is suppressed in helium gas, we expect the production of slow muons using helium gas to be highly efficient.

## INTRODUCTION

Muon beams are tertiary beams. They originate from the decay of charged pions, which are produced by proton beams striking the production target. Surface muons are produced by pions that stop and decay near the surface of the production target. There are only positive muons ( $\mu^+$ ) in the surface muons, since  $\pi^-$  interact with nuclei before decay. Surface muons are 100% polarized, with  $\sim 4.1$  MeV kinetic energy in the rest frame of  $\pi^+$ . Slow  $\mu^+$  are produced by moderating surface muons to thermal or epithermal energy and subsequently reaccelerate them to keV energy (0.5 keV–30 keV). Slow  $\mu^+$  beams are a great tool for many researches such as depth-sensitive (1 nm–300 nm) Muon Spin Rotation, Relaxation, and Resonance ( $\mu$ SR) studies [1].

We are planing to produce slow  $\mu^+$  beams for the Experimental Muon Source (EMuS) at the China Spallation Neutron Source (CSNS) [2], dedicated to  $\mu$ SR applications. The EMuS project is in the conceptual design phase. According to the current baseline design, the surface muon beam intensity is about  $10^8 \mu^+$ /s with a relatively large beam spot size of about 72 mm  $\times$  80 mm (full width at half maximum). Therefore, a novel muon moderation scheme is required for the production of slow  $\mu^+$  at EMuS. In this paper, we will present a preliminary scheme based on frictional cooling of  $\mu^+$  by helium (He) gas within an electric field. We will also present some progress on both simulation and experiment, as well as the future planning.

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## FRICITIONAL COOLING

The low energy processes of  $\mu^+$  implanting into the moderator materials can be summarized as follows: (a) Between 4 MeV and 10 keV, the ionization and multiple scattering dominate. (b) Between 10 keV and 10 eV, the ionization [3], charge exchange [4], and elastic scattering [5] dominate. Most of the low energy  $\mu^+$  are neutralized and form Muoniums (Mu) during these processes due to the large  $e^-$ -capture cross section. Energy loss due to Mu formation is strongly suppressed when the  $\mu^+$  energy is close to the band-gap energy  $E_g$  of the moderator, since the  $\mu^+$  energy must, at least, be comparable to  $E_g$  to ionize an atom. In epithermal energy region, the energy loss is mainly due to elastic scattering, which is not so efficient because of the small  $\mu^+$  mass. This results in a large escape depth of a few tens of nanometers [6].

In order to suppress the Mu formation for a higher moderation efficiency, wide-band-gap materials, such as argon, neon, or nitrogen cryosolids ( $E_g$  between 11 eV and 22 eV), have been used as the moderator. Among several possible noble gases, we select He because (a) the ionization energy is high,  $E_g \sim 24.6$  eV, and (b) the cross section of Mu ionization is greater than that of Mu formation when the  $\mu^+$  energy is below keV region. The mass stopping power of  $\mu^+$  in He gas is shown in Fig. 1 [7]. As seen, the processes of  $\mu^+$ -He interactions mainly include: (a) in high energy region, the ionization and multiple scattering; (b) in intermediate energy region, the ionization and charge exchange; and (c) in low energy region, the elastic scattering, dominating the energy loss contribution at energies down to  $\sim 1$  eV.

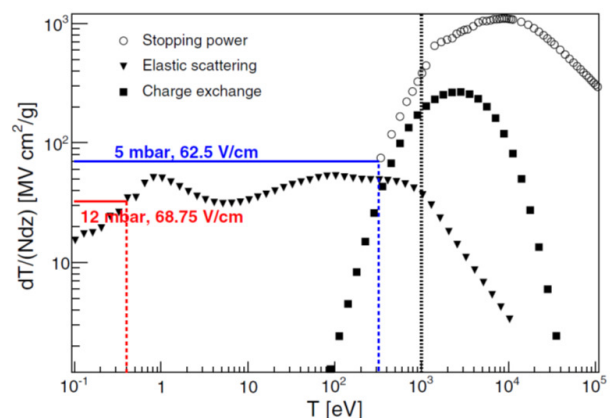


Figure 1: The mass stopping power of  $\mu^+$  in He gas. The vertical blue and red dashed lines show the resulting equilibrium energies at two experimental conditions, respectively [7].

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First, the fast  $\mu^+$  beams need to be slowed down into the energy region where the frictional cooling [8, 9] works effectively, i.e., where the mass stopping power increases with increasing energy. Then, an electric field is applied in the He gas to bring the  $\mu^+$  energies in the longitudinal direction to an equilibrium energy  $T_{eq}$  with a smaller energy spread. When the energy gain from the electric field is greater (less) than the energy loss in the He gas,  $\mu^+$  are continuously accelerated (decelerated) until reaching  $T_{eq}$ .

## PRELIMINARY SCHEME

Figure 2 shows a preliminary scheme based on frictional cooling of  $\mu^+$  by He gas within an electric field. The incident surface muon beams are degraded by a thin foil (e.g., a 780  $\mu\text{m}$  thick carbon foil) before moderated in the gas cell. The  $\mu^+$  lose their kinetic energy through collisions with the He atoms and meanwhile transport along an accelerating and focusing electric field towards the exit of the cell. In the upstream part of the cell, the cylindrical electrode rings define the electric field for accelerating the  $\mu^+$ . The  $\mu^+$  scatter with the atoms of He gas causing a beam expansion inside the cell. In the downstream part, close to the exit, the conical electrodes define the field for focusing the  $\mu^+$ . In the current simulation, (a) the cylindrical gas cell is 155 mm long with an inner diameter of 150 mm; (b) the exit of the cell is a pinhole of 3 mm diameter; and (c) the pressure of the He gas filled the moderator cell is 5 mbar. At the exit the  $\mu^+$  are extracted from the moderator gas into vacuum. The slow  $\mu^+$  are subsequently deflected by 90 degree by the electrostatic mirror, while the fast  $\mu^+$  with energies above several tens of keV are only slightly influenced by the mirror. Then a high voltage (HV) up to a few tens of kV is applied to accelerate the slow  $\mu^+$  beam before implantation.

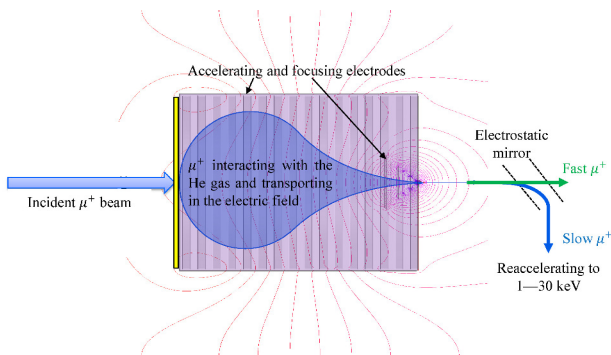


Figure 2: Preliminary scheme for frictional cooling of  $\mu^+$ .

## Simulation

As a preliminary study of this frictional cooling scheme, a gaussian beam of  $\mu^+$  with the mean kinetic energy of 5 keV and the energy spread of 20% was simulated and used as the incident beam. In total,  $10^6$   $\mu^+$  were generated, and the beam sigmas in both x- and y- directions were set to 20 mm. The energy degrader before the gas cell was not simulated. We set the  $T_{eq}$  to 1 keV, corresponding to an applied electric

field of  $\sim 320$  V/cm in the longitudinal direction, which was determined from the mass stopping power curve shown in Fig. 1. The simulation of the electric field was based on ANSYS, and the simulation of the  $\mu^+$  moderation in He gas was based on G4beamline. Figures 3(a)–(d) show the energy distribution and the beam spot at the entrance and at the exit, respectively. As seen, both the energy spread and the beam spot size were improved after the moderator gas cell, i.e., the energy spread from  $\sim 1$  keV to  $\sim 0.4$  keV and the beam spot size from  $\varnothing \sim 80$  mm to  $\varnothing \sim 6$  mm. The efficiency, defined as  $N_{mod}/N_{gen}$ , is about 0.2%, where  $N_{mod}$  and  $N_{gen}$  are the number of  $\mu^+$  passing through the exit of the cell and of the generated  $\mu^+$  (i.e.,  $10^6$ ), respectively. In order to increase the efficiency, some technical improvements can be made, such as: (a) the design optimization of the focusing electrodes; (b) the optimum settings of the He gas pressure in the moderator, the length of the moderator, and the applied HV; and (c) an additional magnetic field for increasing the longitudinal path length of  $\mu^+$  with transverse momentum and meanwhile limiting the transversal spread of the beam.

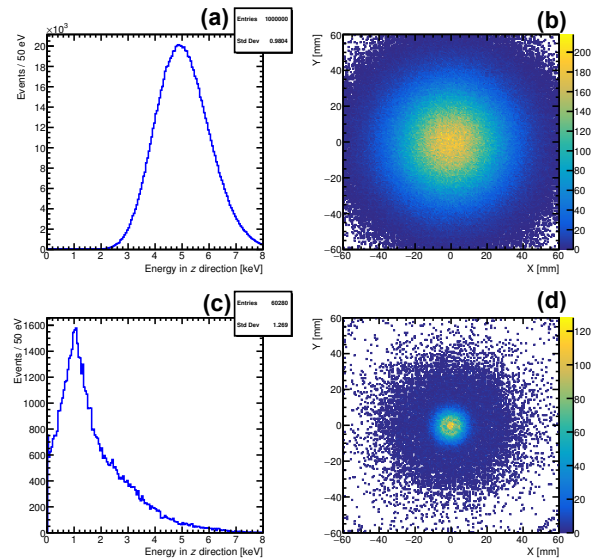


Figure 3: (a) The energy distribution and (b) the beam spot of the  $\mu^+$  beam at the entrance of the gas cell. (c) The energy distribution and (d) the beam spot at the exit of the gas cell.

## DEMONSTRATION EXPERIMENT

As a first step, we plan to perform a frictional cooling demonstration (FCD) experiment with protons in He gas, which aims to verify the working principle behind the frictional cooling. The behavior of other charged particles in this low energy regime is similar to that shown in Fig. 1. Thus, the frictional cooling method for  $\mu^+$  should work for a variety of charged particles including protons [8–10].

A simulation of free protons accelerated in He gas by an electric field has been performed based on our modified version of MuSim, in which additional low energy physics models were implemented. In this simulation, the pressure of

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the He gas in cell is 5 mbar and the longitudinal electric field is 336 V/cm. Figure 4 shows the proton energy as a function of the proton drift distance in longitudinal direction. Based on this result, we have designed a gas cell of 400 mm length for the FCD experiment, since an accelerating distance of 400 mm in the gas leads to a final proton energy of about ~6 keV, which can be precisely measured by the silicon drift detector (SDD). The proton source that we have produced consists of an  $^{241}\text{Am}$   $\alpha$  source and a Mylar foil.

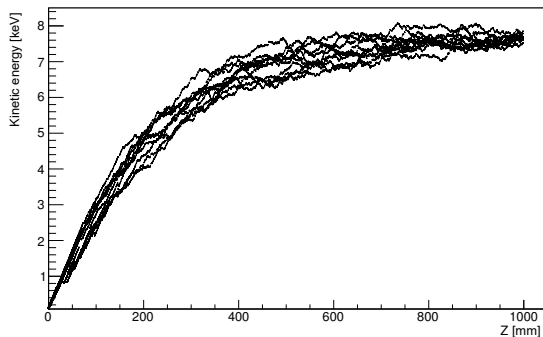


Figure 4: The kinetic energy of protons as a function of the drift distance in the longitudinal direction with an electric field of 336 V/cm in the He gas at a pressure of 5 mbar.

We have designed and produced the first version of the accelerating grid and tested its HV stability, as shown in Fig. 5. The test result shows that it operates reliably up to 65 kV in the vacuum chamber at a pressure of  $10^{-5}$  mbar.

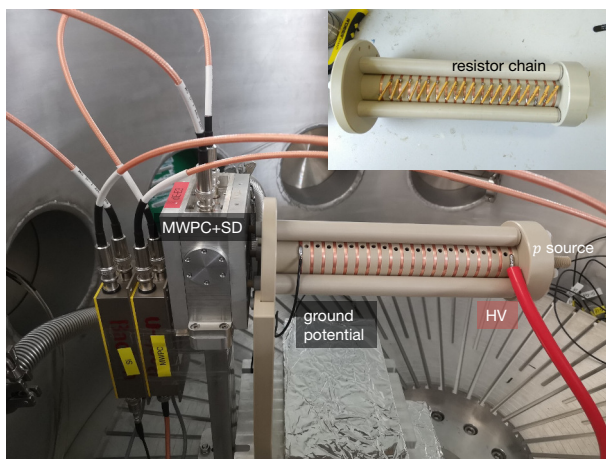


Figure 5: The experimental setup for the HV stability test of the accelerating grid. The inset shows the resistor chain welded to the accelerating grid. The Silicon Detector (SD) together with the MultiWire Proportional Chamber (MWPC) was used for the proton energy measurement. However, due to a low signal-to-noise ratio, there was a large uncertainty in the proton energy measurement. This would be greatly improved by using the SDD in future experiments.

One of the most critical issues in this frictional cooling scheme is the electric discharges inside the He gas. Thus far, one of our potential solutions to this issue is by replacing

the welded resistor chain with a thin and smooth foil resistor coated on the whole inner surface of the cylindrical gas cell using, e.g., vacuum sputtering technique. Then the metallic electrode rings are coated on the thin foil resistor surface such that the shielding effect against the external electric field can be resolved. Otherwise, once the electrodes are placed outside the gas cell, the ionized electrons in the He gas would accumulate onto the inner surface of the gas cell, resulting in an unwanted shielding of the applied electric field. Recently, we have succeeded in coating a layer of germanium (Ge), about hundreds of nanometers thick, on an acrylic substrate. The uniformity of the resistance has met the baseline requirement of the FCD experiment. In the next step, we will try coating the Ge foil resistor on the inner surface of the cylindrical gas cell and check the uniformity of the resistance in detail. For a further verification of the frictional cooling, we plan to use positrons for the FCD experiment in addition to protons. In the meantime, we are applying for the surface muon or low energy muon beam time at PSI.

## CONCLUSION

In conclusion, we have presented the working principle of the frictional cooling of  $\mu^+$  by He gas within an electric field and performed a simulation study based on a preliminary scheme. The result shows that frictional cooling with He gas could be a promising method for the slow  $\mu^+$  production at EMuS. For the FCD experiment with protons, progress on both simulation and experiment has been shown. We have also presented the current status and future planning on the resolving of the critical issue in our frictional cooling scheme, i.e., the electric discharges inside the He gas.

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