muCool: A novel high-brightness low-energy muon beam

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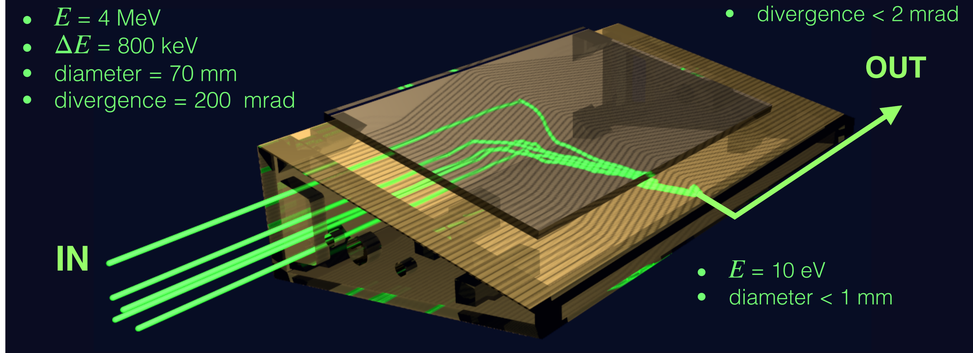
Motivation and goal

- Compact device to compress the phase space of a standard μ^+ beam
- Fast compression scheme within 8 µs
- Compression efficiency of $\approx 10^{-4}$
- Phase space improved by $\approx 10^{9}$

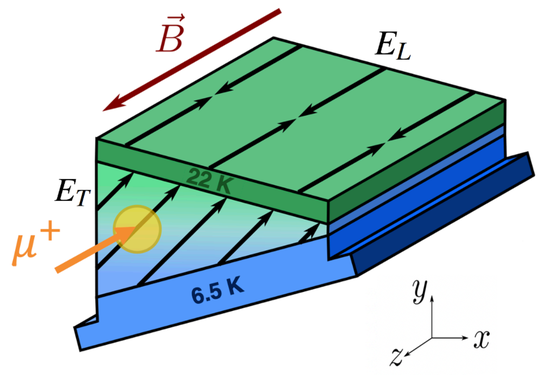


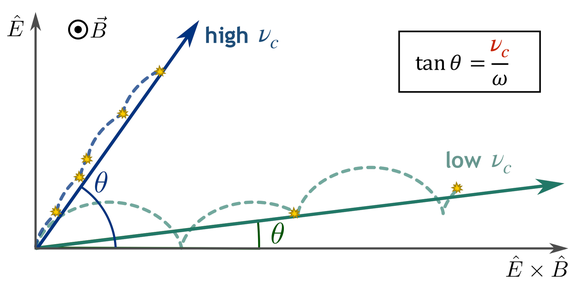
Applications

- Muon spin spectroscopy
- Muon g-2 / EDM
- Muonium spectroscopy
- Muonium gravity

Working principle

- Muon cooling in a cryogenic He gas target at 10 mbar pressure
- Compression is achieved with complex *E*- and *B*-fields in combination with gas density gradient





Collisions with gas atoms with frequency ν_c

- The muon drift velocity in He gas and electric and magnetic fields ($\vec{E}$, $\vec{B}$) is:

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

μ : muon scalar mobility
w : muon cyclotron frequency
ν_c : μ^+ - He collision frequency

Position dependent due to gas density gradient

Transverse compression E_T + Longitudinal compression E_L = Mixed compression with simultaneous compression in the y and z direction

Status

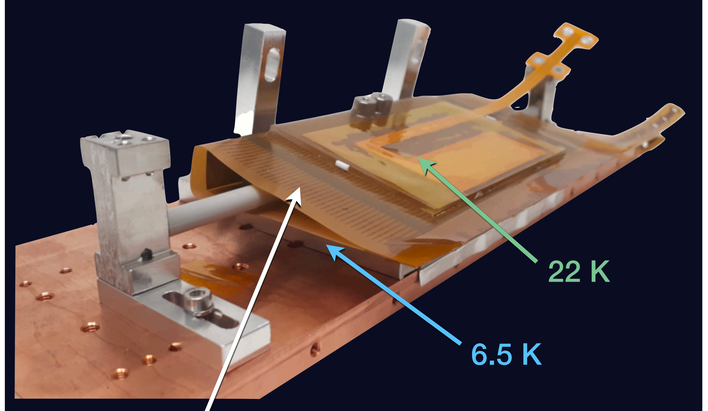
- Demonstration of density gradient with n-imaging ✓
- Transverse compression ✓
- Longitudinal compression ✓
- Mixed compression ✓

Tools

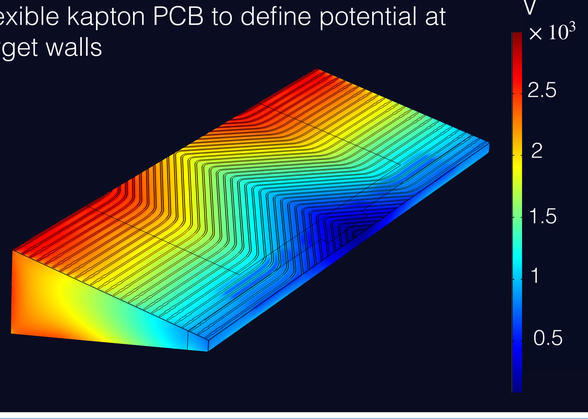
- Simulations of muons in He gas with Geant4
- Simulations of E- and B-fields and density gradients with COMSOL
- Simulations of gas flow dynamics with Ansys

Mixed compression target

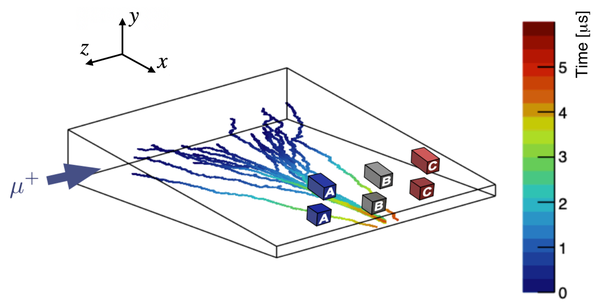
- Sapphire plates to define temperature gradient



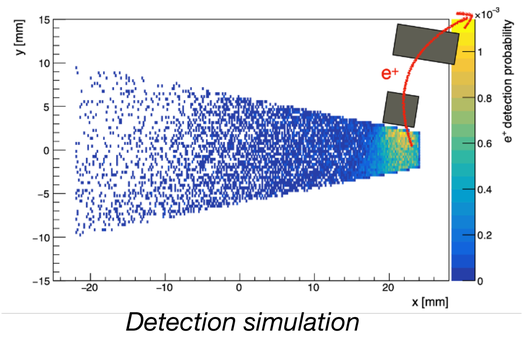
- Flexible kapton PCB to define potential at target walls



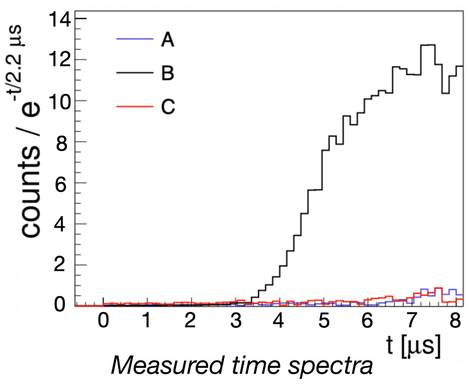
Demonstration of mixed compression



Simulated muon trajectories



Detection simulation

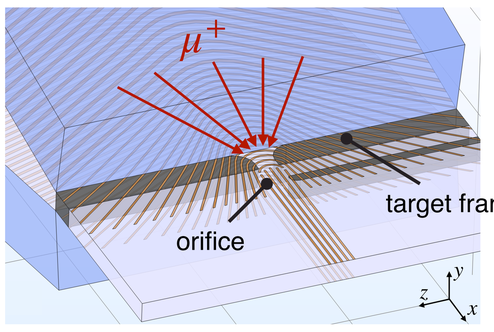


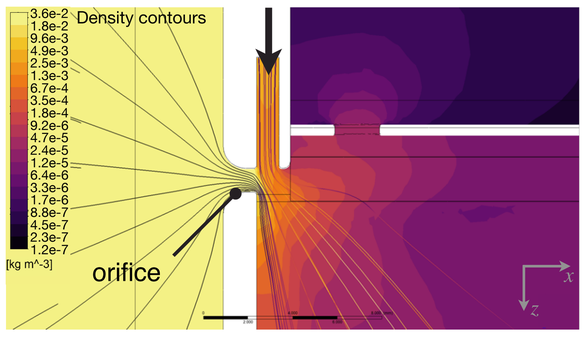
Measured time spectra

Positive muons at ~15 MeV/c momentum are injected and stopped into the muCool mixed compression target.
Inside the target, muons are guided to a single point independently of their initial stopping position.

The muons motion is “indirectly" measured by plastic scintillators at the tip of the target that detect Michel positrons.
A large increase of counts is only observed by detectors B demonstrating mixed compression.

Extraction from the target





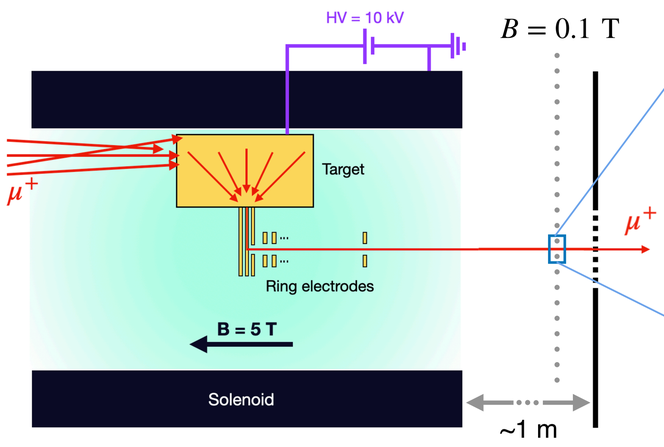
After the phase space compression, the muon “swarm” is extracted through a 1×1 mm^2 windowless orifice.
Injection of He gas perpendicularly to the µ⁺ motion creates a gas barrier at the orifice and maintains the same pressure inside the target.

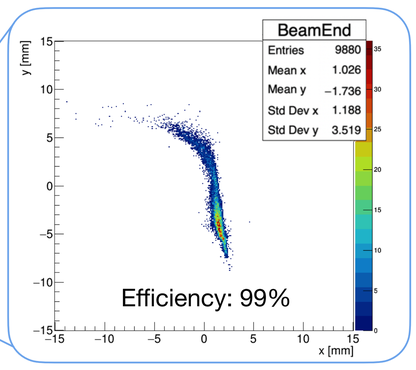
To guide muons out of the target, the existing electrode lines from the target are extended and terminate with pairs of parallel electrode strips.

The muons transport efficiency can be maximised by optimising the electric field profile given the muon drift angle θ at a certain gas density. Preliminary simulations of particle trajectories through the orifice yield 80-90% transmission (without muon decay).

Complete apparatus

- Injection of muon beam into 5 T solenoid
- Phase space compression inside the target and extraction into vacuum
- Re-acceleration to 10 keV by ring electrodes
- Termination of magnetic field lines with metallic grid and extraction from solenoid





Preliminary simulation of beam profile after acceleration at B = 0.1 T

Publications

[1] Taqqu, D. *Phys. Rev. Lett.* 97.194801 **(2006)**
[2] Bao, Y. et al. *Phys. Rev. Lett.* 112.224801 **(2014)**
[3] Wichmann, G. et al. *Nucl. Instr. Meth. Phys. Res. A:* 814 **(2016)**
[4] Belosevic, I. et al. *Eur. Phys. J. C* 79:430 **(2019)**
[5] Antognini, A. et al. *Phys. Rev. Lett.* 125.164802 **(2020)**

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