Frictional Cooling of Muons

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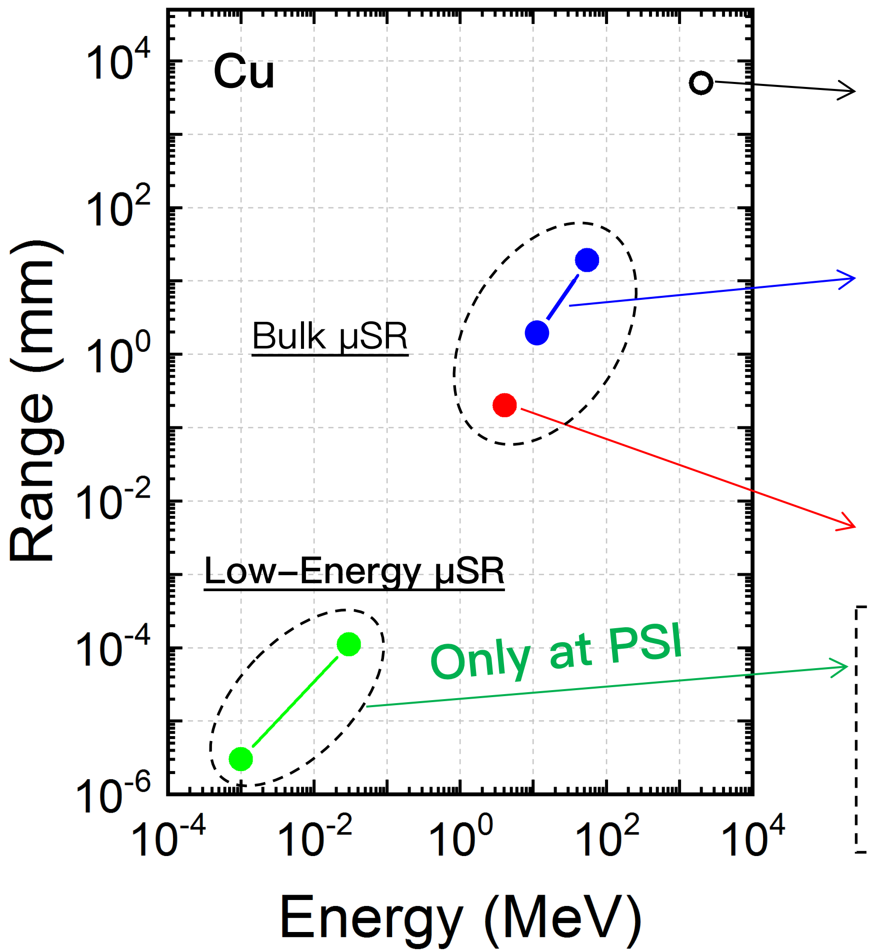
Muon Moderation

Slow Muons

Moderate surface μ^+ to (epi–)thermal energies
and reaccelerate them to a few tens of keV



Cosmic–ray muon, 2 GeV
Muography: image interior of large objects (pyramids …)

Decay muon, 10—80 MeV
Implantation depth: 0.2—4 cm

<u>"Bulk" μSR</u>: sub–mm sample

Suface muon, 4.1 MeV
Implantation depth: ~ 100 μm

Slow muon, 1—30 keV tunable
Depth: 1—300 nm
<u>Depth sensitive μSR:</u> magnetic spin microprobe for thin films, multilayers, nanomaterials …

Moderation Method

PSI SμS

Solid rare–gas (Ar / Ne)

- Highly polarized μ^+ (>90%)
- Efficiency $<10^{-4}$

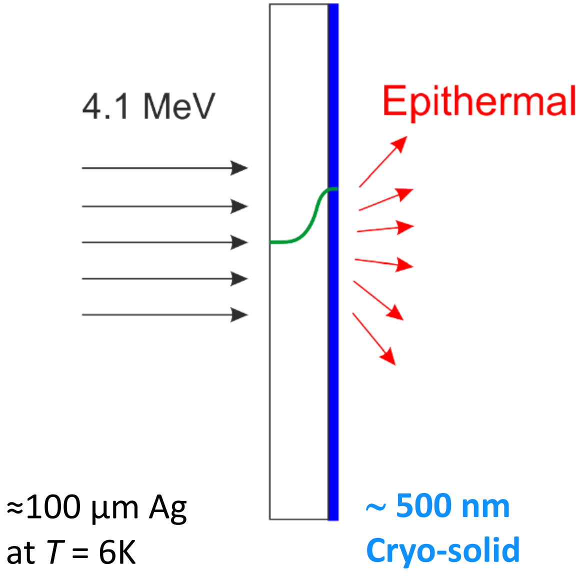
LEM: ~6000 LE–μ^+ /s

J–PARC MLF MUSE

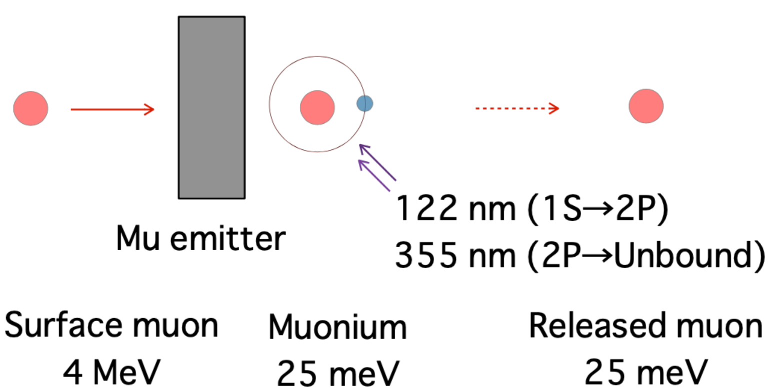
Laser ionization of muonium

- High efficiency $(\sim 10^{-3})$
- Polarization <50%
- Complex laser system

U–Line: 10^5 LE–μ^+/s expected



A. Amato, presentation at 2nd *Workshop on CSNS Muon Source Multidisciplinary Applications*, Hefei, China, 2019

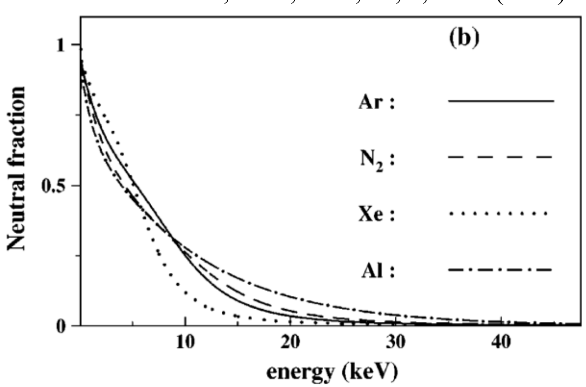


S. Kanda, presentation at *ICANS XXIV*, Dongguan, China, 2023

Physics Process

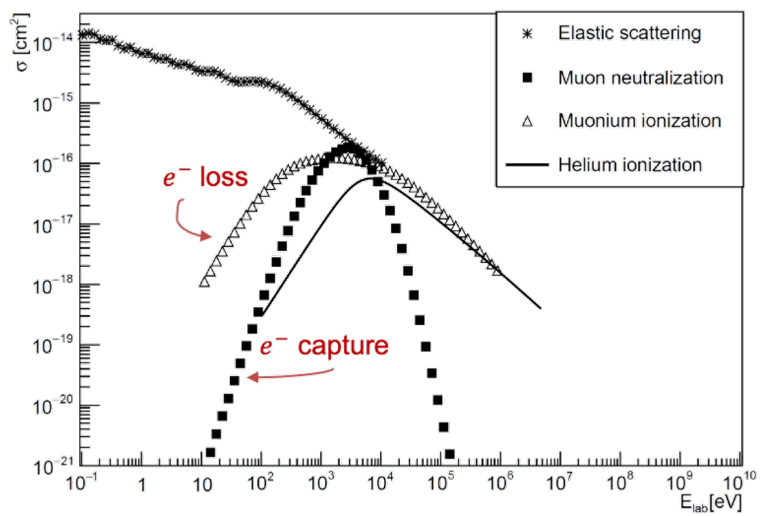
- 4 MeV – 10 keV
  - Ionization of atoms
  - Coulomb collisions with e^-
- 10 keV – 10 eV
  - Ionization
  - Charge-exchange cycles ($\mu^+ \rightleftharpoons \mathrm{Mu}$)
  - Elastic scatterings
- LE-μ^+ loss mainly due to neutralization

T. Prokscha, *et. al*, PRA, 58, 5, 3739 (1998)



- Helium
  - Wide band gap (24.6 eV)
  - Cross section of Mu ionization > formation below keV energy

μ^+-He cross sections vs. E_{μ^+}

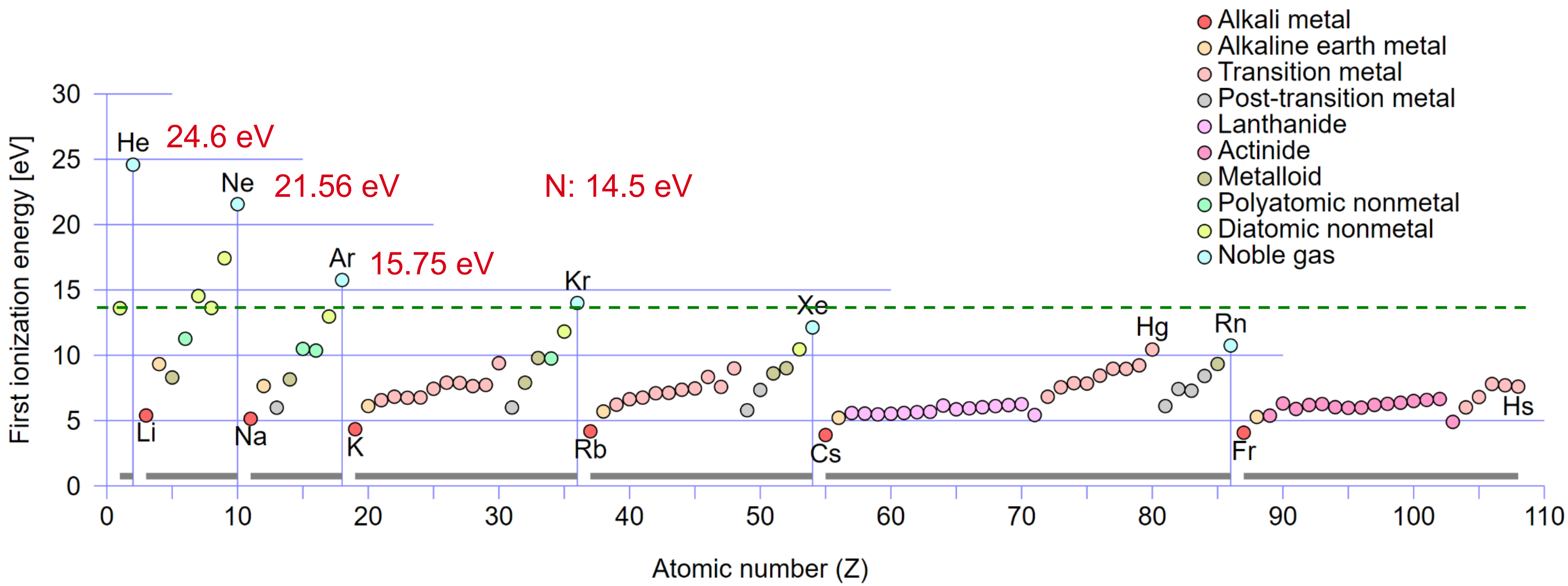


Moderator

Moderator	Moderation efficiency	E_g [eV]
Ne	$1.4 \pm 0.2 \times 10^{-4}$	21.58
Ar	$8.6 \pm 1.2 \times 10^{-5}$	14.16
Kr	$1.7 \pm 0.2 \times 10^{-5}$	11.61
Xe	$5.7 \pm 1.1 \times 10^{-7}$	9.33
N_2	$6.3 \pm 1.1 \times 10^{-5}$	15.1
O_2	$1.4 \pm 0.2 \times 10^{-5}$	12.08
CH_4	$1.4 \pm 0.2 \times 10^{-5}$	12.51
LiF	$1.9 \pm 0.5 \times 10^{-7}$	14.1
SiO_2	$3.0 \pm 1.0 \times 10^{-7}$	~9
Al	$2.0 \pm 0.4 \times 10^{-7}$	0
Cu	$1.0 \pm 0.3 \times 10^{-7}$	0

- Experimental data show that moderation efficiency increases with increasing band-gap energy of the moderator

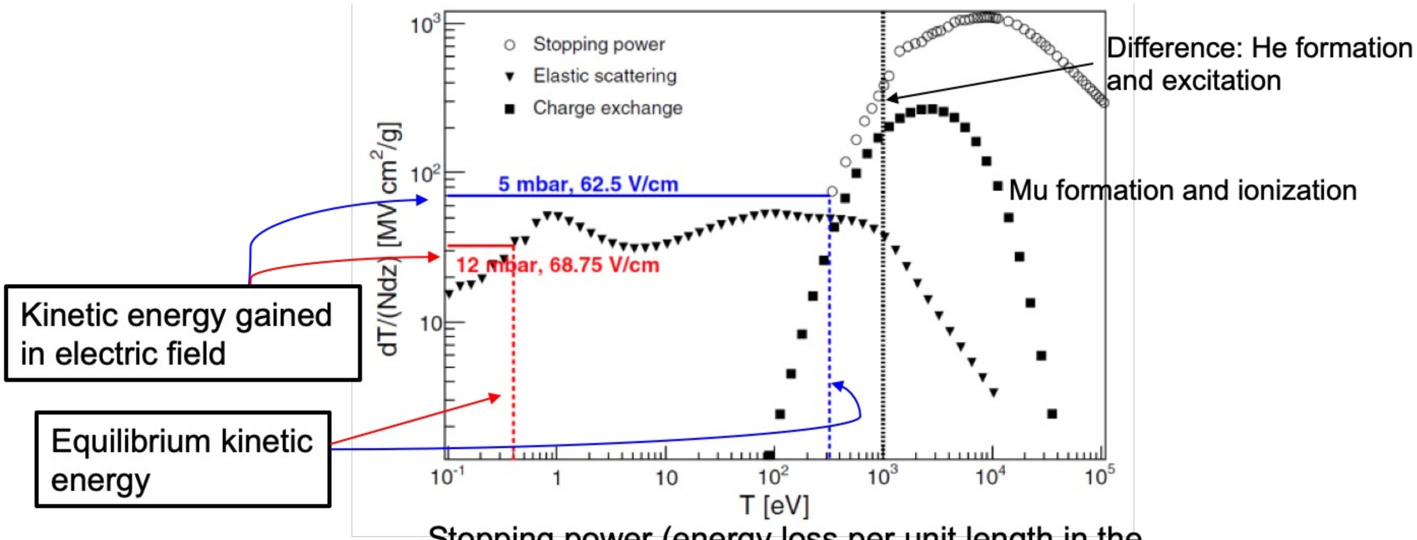
E. Morenzoni, Physics and applications of low energy muons, Muon Science: Muons in Physics, Chemistry and Materials (Bristol and Philadelphia, 1999), vol. 51, eds. by S.L. Lee, S.H. Kilcoyne, R. Cywinski, pp. 343–404 (1998)



Y. Bao *et al.*, PRL 112, 224801 (2014)
A. Antognini *et al.*, PRL 125, 164802 (2020)

μ^+ Frictional Cooling

- He gas moderator
- Apply electric field in He gas
  - Compensate for energy loss, reaching equilibrium
  - Electric discharges inside the He gas
  - Charge build-up on the gas cell wall
  - Beam extraction into vacuum



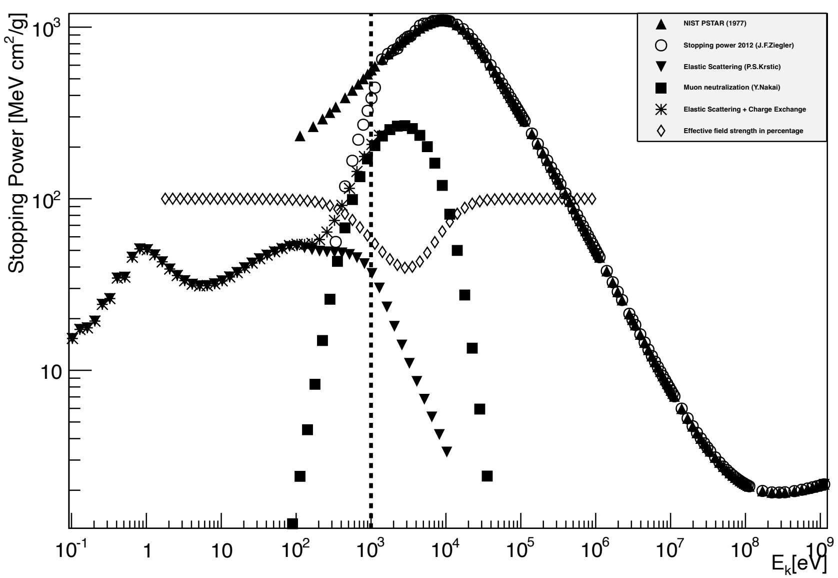
Stopping power (energy loss per unit length in the electric field direction) of μ^+ in He gas

Simulation

Simulation Software

- Investigate low-energy muon processes in materials and implement them in simulation
  - Geant4-based code
  - Implemented into G4beamline
- LE μ^+-He interaction (cross sections scaled from proton-He cross sections)

Muon in Helium



Charge exchange

- Electronic stopping power (SP) depends only on the velocity of the projectile, but not on its mass
- Therefore, the electronic SP for muons in He is same as that for protons in He at the same velocity (velocity-scaling)

Elastic collisions

- Differential and total cross sections for elastic collisions are the same for muons and protons at the same center-of-mass energy (energy-scaling)
- $\sigma_{\text{el}}^{\mu\text{He}}(\frac{M_{p\text{He}}}{M_{\mu\text{He}}}E_{\text{CM}}) = \sigma_{\text{el}}^{p\text{He}}(E_{\text{CM}})$
- $M_{A\text{He}} = \frac{M_A M_{\text{He}}}{M_A + M_{\text{He}}}$

- At the same E_{CM}, SP due to elastic collisions with target nuclei (nuclear SP) for protons in He is larger by a factor of $\frac{M_p}{M_p + M_{\text{He}}} \cdot \frac{M_\mu + M_{\text{He}}}{M_\mu} \approx 7.3$ than that for muons in He

Implementation

$\geq$ 1 keV

Use standard Geant4 processes:

- `G4MuIonisation`
- `G4MuMultipleScattering`
- `G4MuBremsstrahlung`
- `G4MuPairProduction`

< 1 keV, switch to custom low-energy processes:

Elastic collisions

✓ Elastic energy loss in the laboratory frame

- $\mathrm{d}E = \frac{2m_{\mathrm{A}}m_{\mathrm{B}}}{(m_{\mathrm{A}}+m_{\mathrm{B}})^2}(1-\cos\theta)E_{\mathrm{A}}$
- A is projectile, θ the scattering angle in the center-of-mass frame

✓ Mean free path $\lambda = \frac{1}{N\sigma_{\mathrm{el}}}$, N is the gas density

Charge exchange

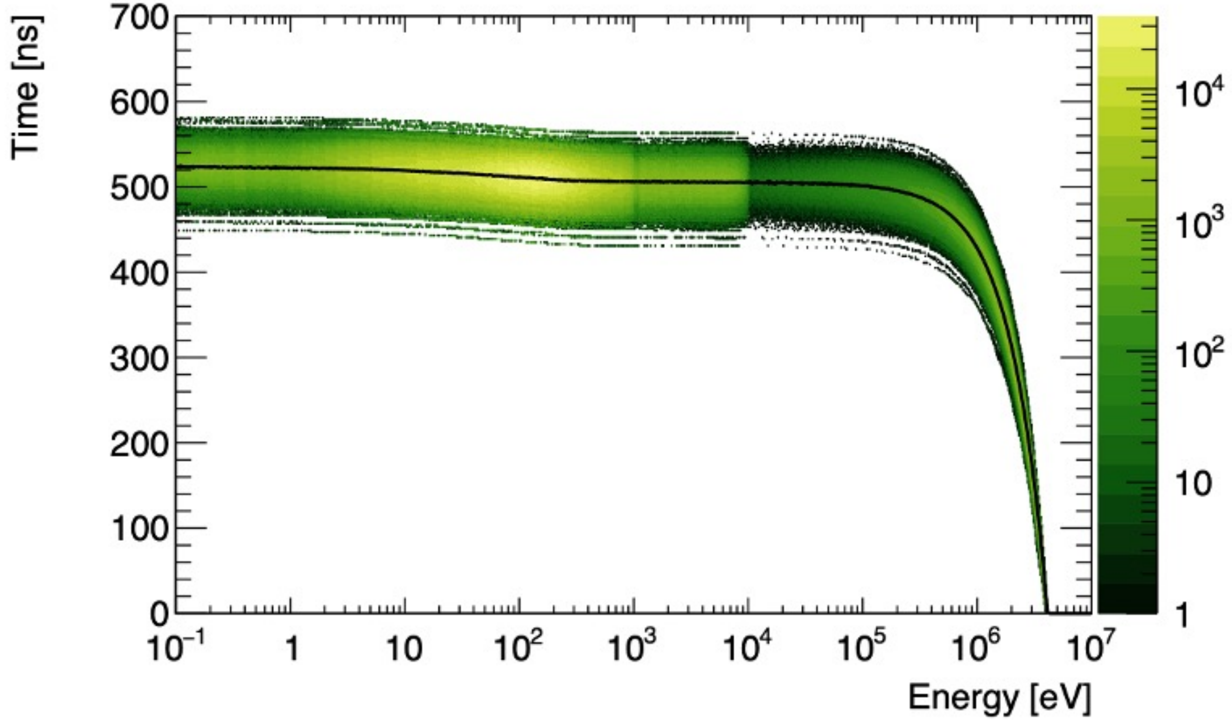
- Electron-capture: Average inelastic energy loss 11 eV (-24.6 eV to ionize He atom, +13.6 eV in Mu formation)
- Electron-loss: Average inelastic energy loss 13.6 eV (ionization energy of Mu)

✓ In one charge-exchange cycle, $\mathrm{d}E$=24.6 eV, mean free path $\lambda = \frac{1}{N\sigma_{\mathrm{capt}}} + \frac{1}{N\sigma_{\mathrm{loss}}}$

✓ $\frac{dE}{Ndx} = 24.6\ \mathrm{eV} \cdot \frac{\sigma_{\mathrm{capt}}\,\sigma_{\mathrm{loss}}}{\sigma_{\mathrm{capt}}+\sigma_{\mathrm{loss}}}$

Simulation Example (1)

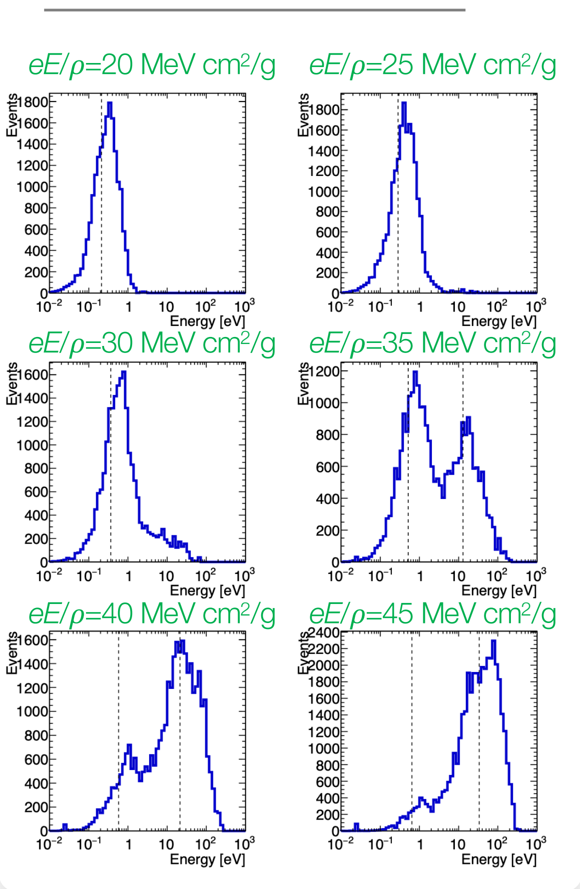
- The evolution of μ^+ kinetic energy with time for μ^+ starting with 4 MeV energy at $t = 0$.



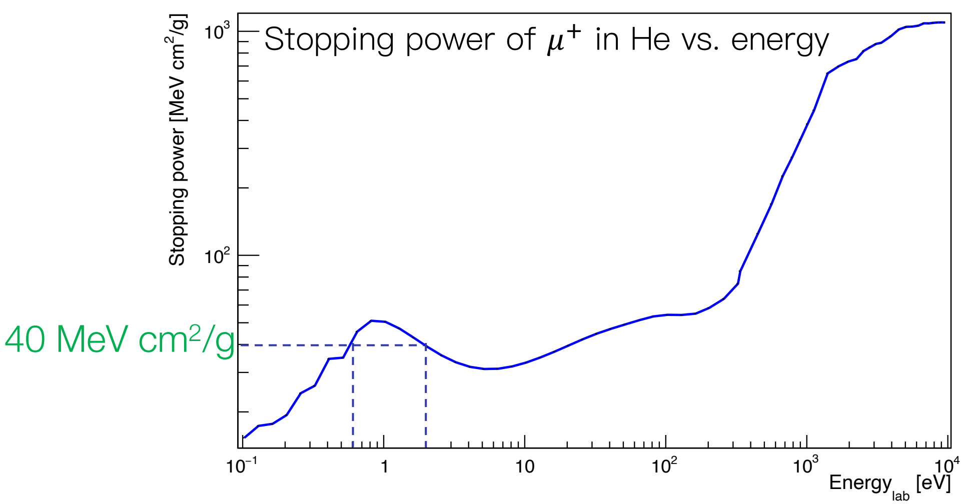
Simulation Example (2)

- Muon drift in He gas and uniform electric field
  - μ^+: 0.1 eV initial energy
  - He gas: 5 mbar，293 K

Muon energy distributions at equilibrium



- Muon energy distributions for various reduced electric field strength values
- Average equilibrium energies (peaks) consistent with stopping power curve's predictions (dashed lines)

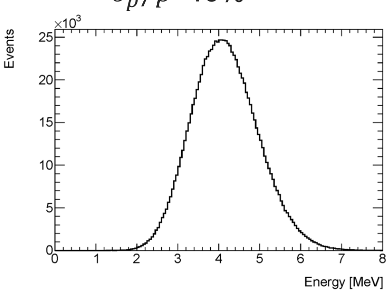


Simulation Example (3)

➢ Frictional cooling of surface μ^+ to below 1 keV energy

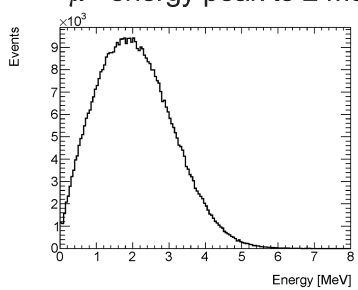
① Muon beam

- 29.8 MeV/c (~4 MeV)
- σ_p/p=10%



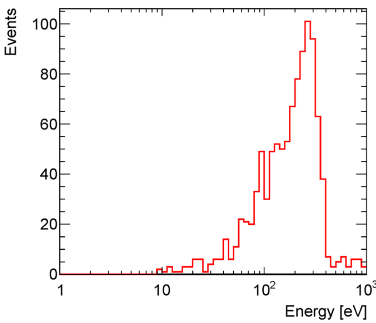
② Degrader

- 0.78 mm thick C foil
- μ^+ energy peak to 2 MeV



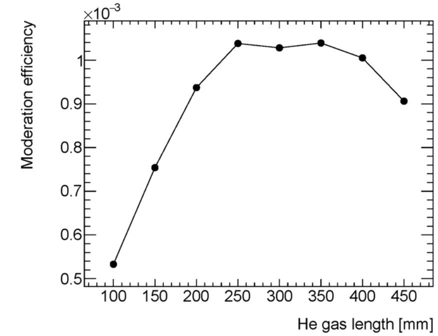
③ Frictional cooling

- He gas 20 mbar，293 K (density ~3.29 $\mu g/cm^3$), 300 mm long
- E-field 0.023 kV/mm
- Equilibrium ~295 eV



④ Efficiency

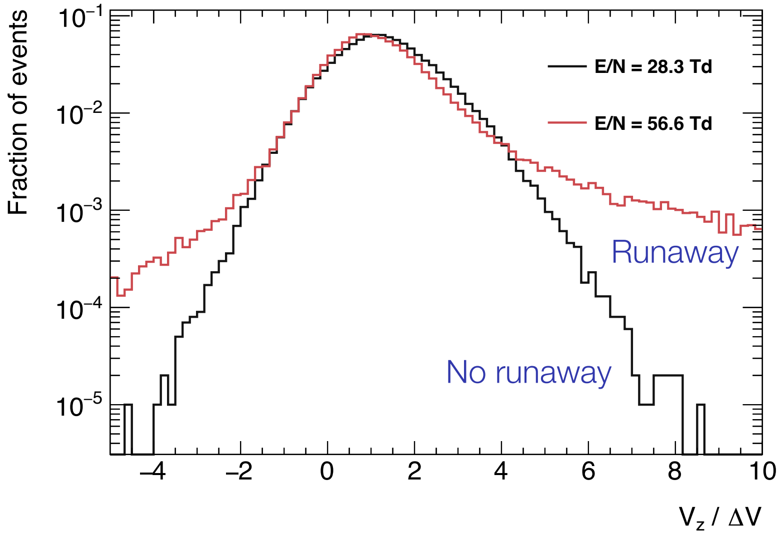
- Efficiency vs. gas length
- Up to ~1×10^{-3}



Efficiency of beam extraction into vacuum not yet considered

Simulation Example (4)

- Proton drift in He gas and uniform electric field
  - Proton velocity distributions consistent with (Ushiroda *et al.* 1988)



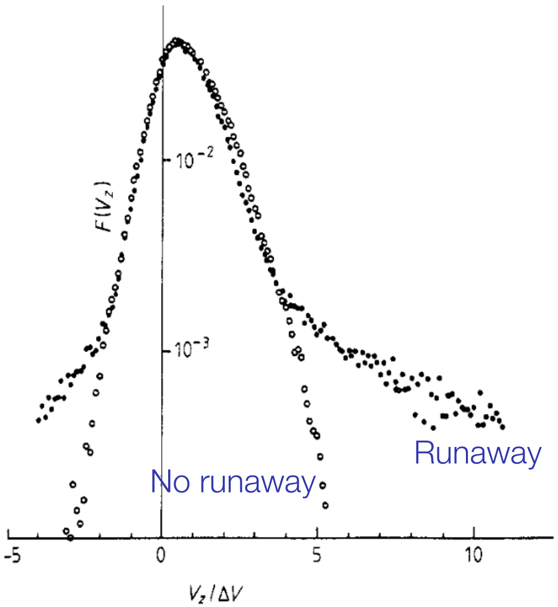


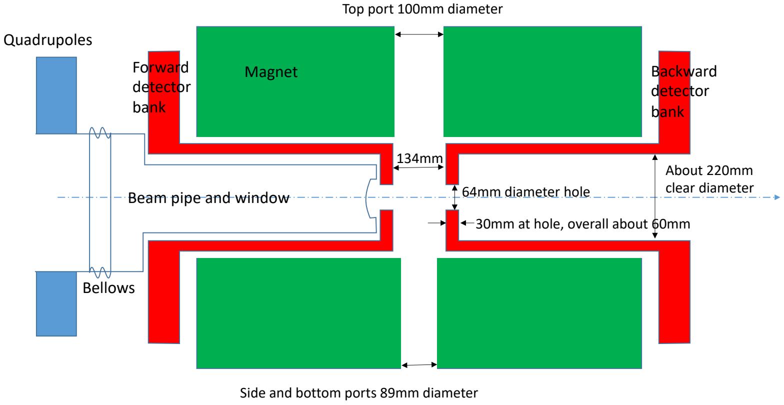
Figure 4. The distribution of the H^+ ion velocity in the direction of the field in 0.2 Torr of helium 10 μs after ions left the anode. The velocity axes are normalised with respect to Δ*V*, and are 2.5×10^5 and 5.0×10^5 cm s^{-1} for 28.3 (○) and 56.6 Td (●), respectively.

Experimental Progress

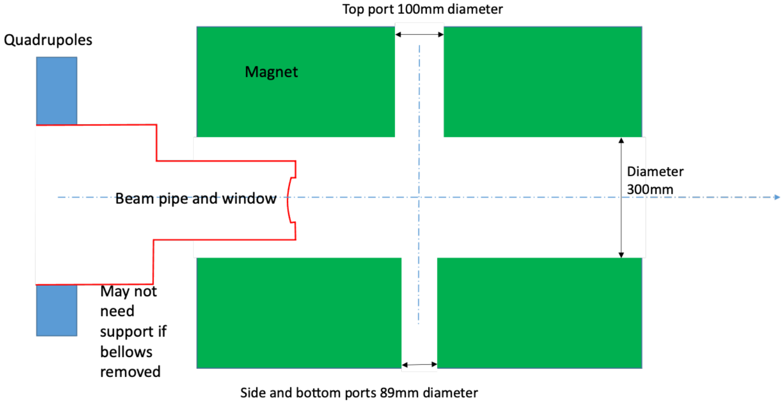
Muon Beam Test

- CW muon source: Frictional cooling experiment at PSI (Y. Bao *et al.* 2014)
- Plan to conduct frictional cooling test at ISIS under CSNS-ISIS collaboration MoU, as MELODY to be a pulsed muon source
- Extensive discussions with ISIS muon group this year
- Tend to utilize ISIS HiFi instrument's 5T superconducting magnet (Sep. next year)
- Simulation with HiFi's magnetic field map

Complete HiFi instrument for normal user experiments



Detectors removed and new snout and new window



From J.S. Lord

Simulation

➢ Use full HiFi magnet to reduce incidence of muons hitting gas cell wall

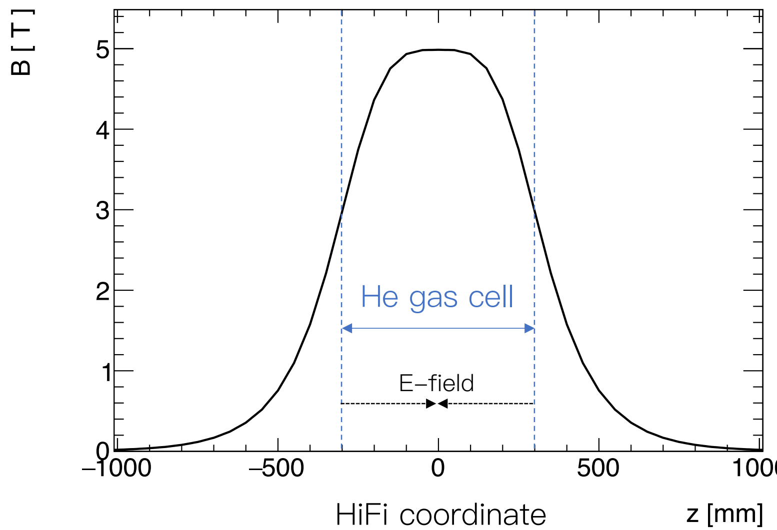
HiFi magnet
- Diameter = 1488 mm, length = 1078 mm
- Main bore diameter = 300 mm

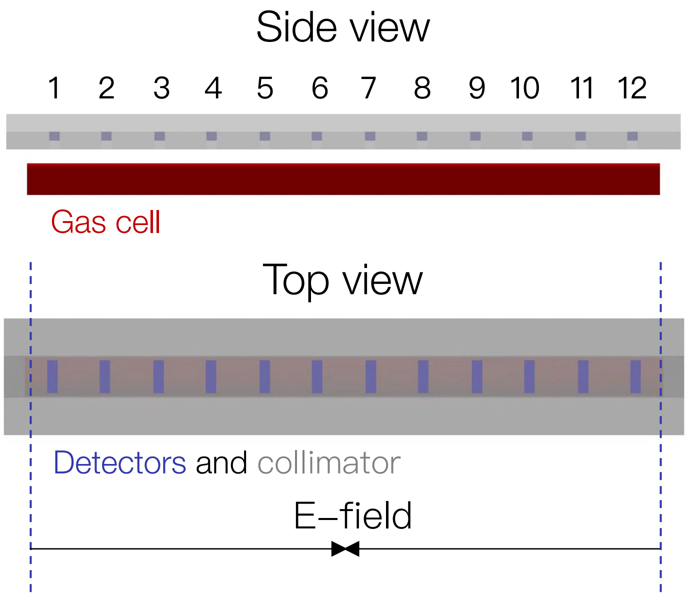
μ^+ beam
- 28 MeV/c, $\frac{\Delta p}{p} = 8\%$ (FHWM), 10^9 μ^+ simulated
- Beam spot ϕ10 mm (sigmaXY=–5, sigmaXpYp=–0.25)
- Beam time structure: meanT=70 ns, FHWM=70 ns
- Energy degrader: 0.78–mm–thick carbon foil

Gas cell
- Diameter = 30 mm, length = 600 mm or 400 mm
- Material: POM
- He gas: 100 mbar, 293 K
- E–field: 0.115 kV/mm

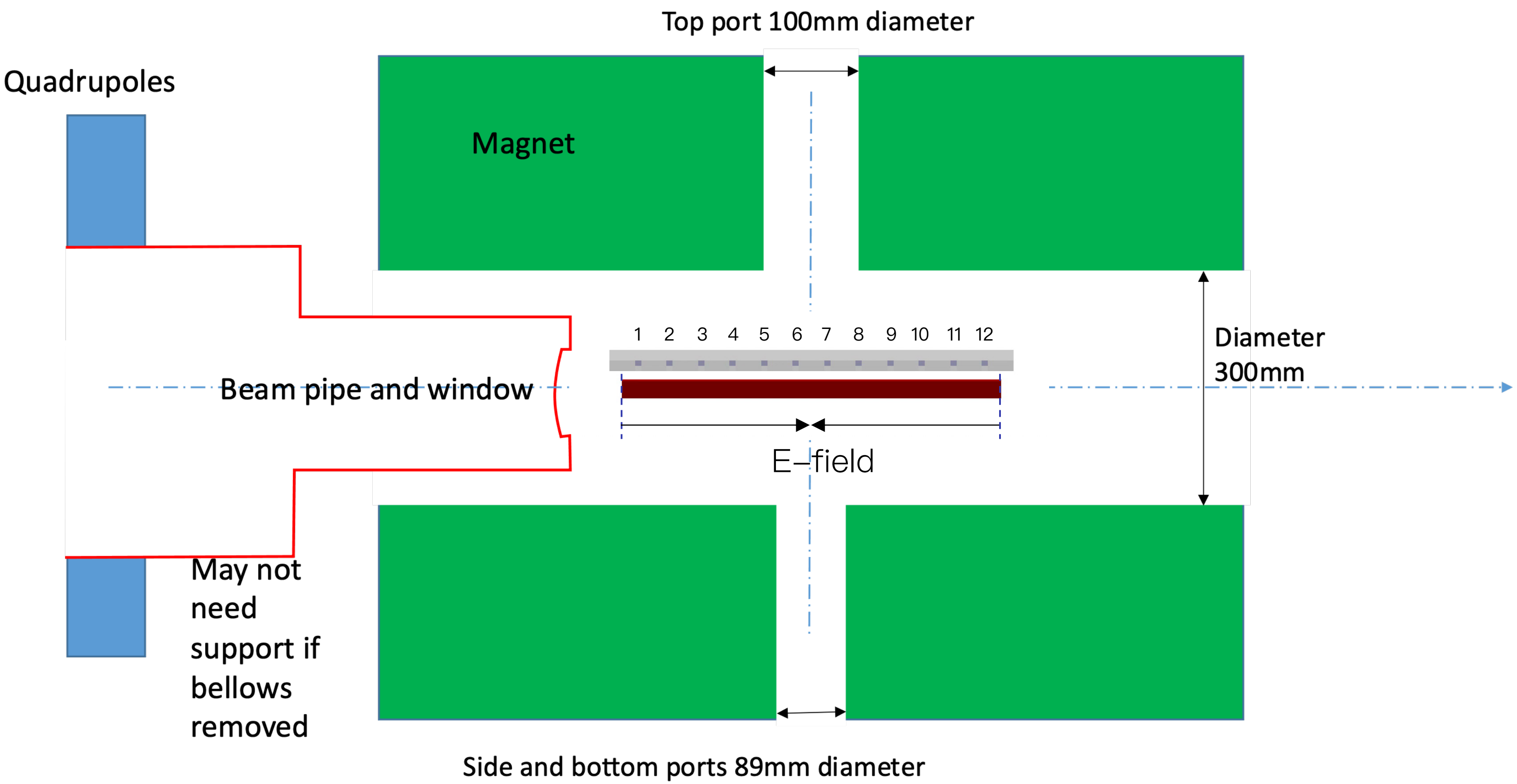
Scintillation detector
- Purpose: To detect positrons from muon–decay
- Size: 10×10×30 mm^3
- Detector collimator: 40–mm–thick copper
- Number of detectors: 12

HiFi Field Map



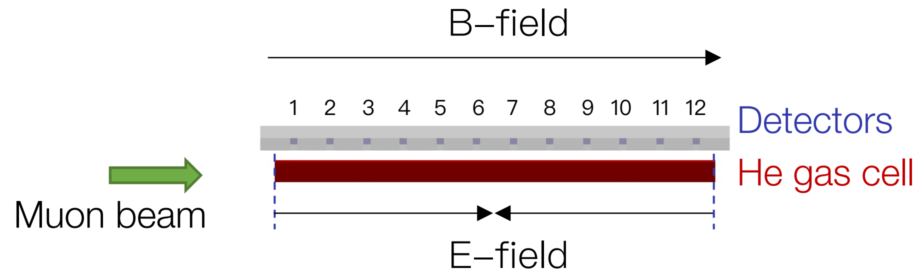


Sketch

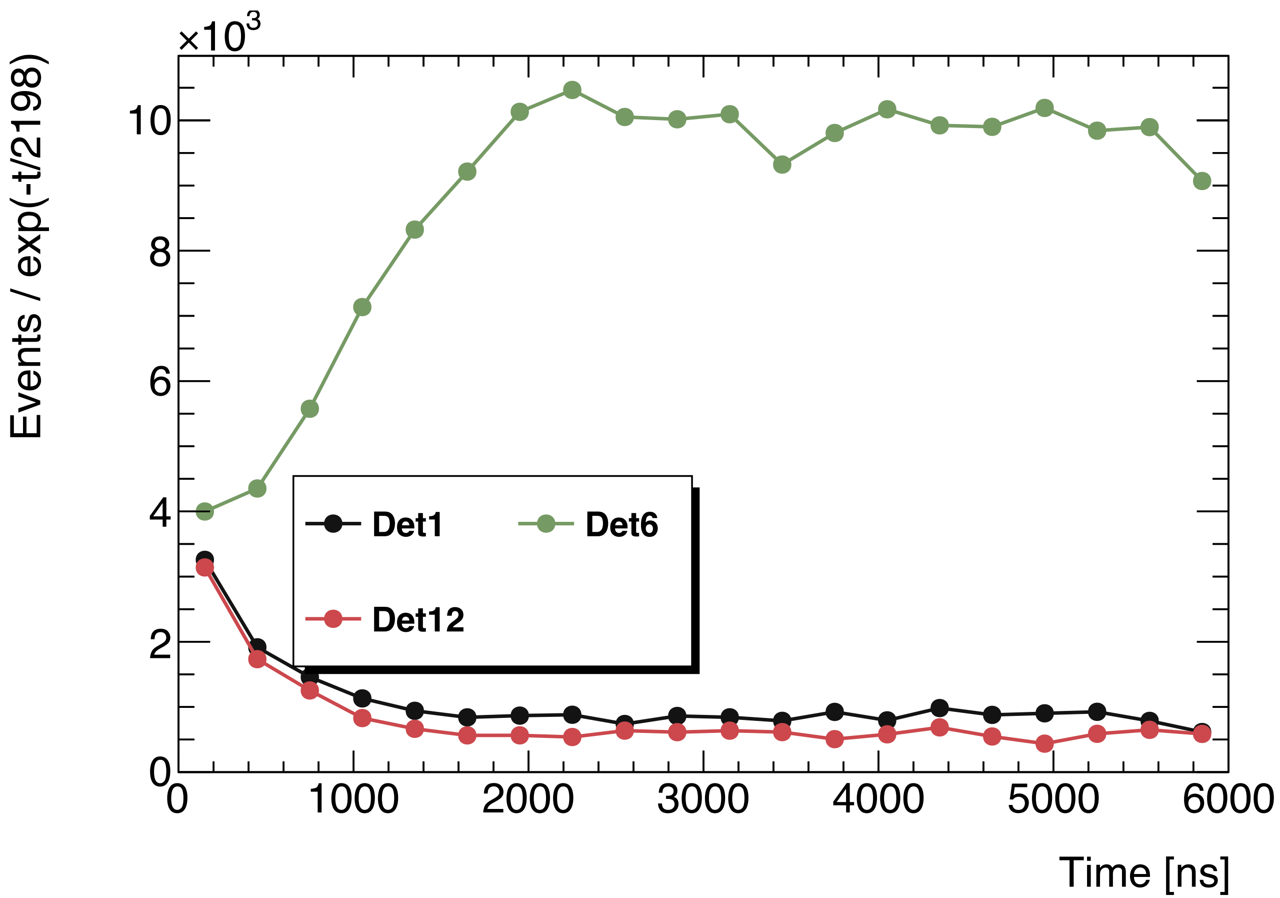


Not to scale

Simulation Result



- Detected positron counts vs. time



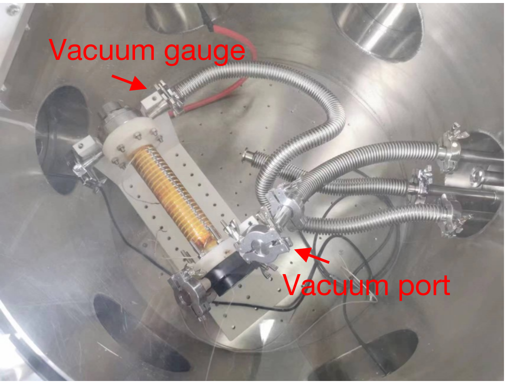
center detector

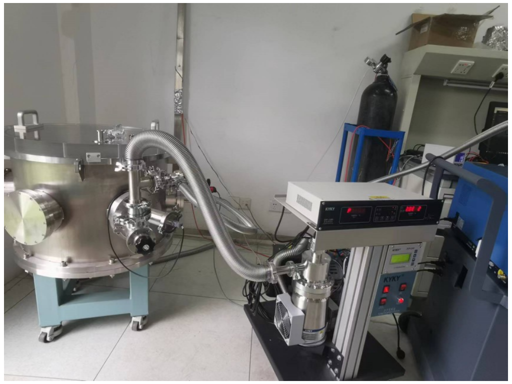
✓ Muons stopped in He gas, steered to center by electric field

end detectors

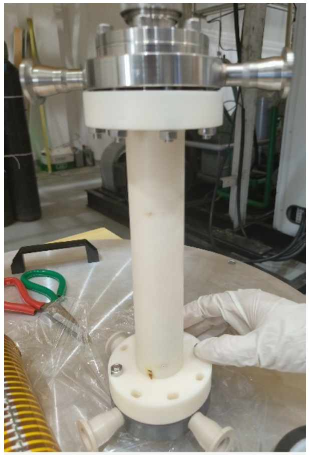
Test at CSNS

- ➢ Accelerating grid: Copper tapes on Kapton foil with resistor chain
- ➢ Gas cell material: ElectroStatic Discharge Polyoxymethylene (ESD POM) to mitigate charge build-up on the wall
- ✗ Accelerating grid (~2 kV/cm) inside a few tens of mbar He gas ⇒ electrical breakdown
- ✓ Accelerating grid wrapped around gas cell
- ■ High voltage stability test
- ■ Outgassing rate test
- □ Demonstration test with protons in He gas

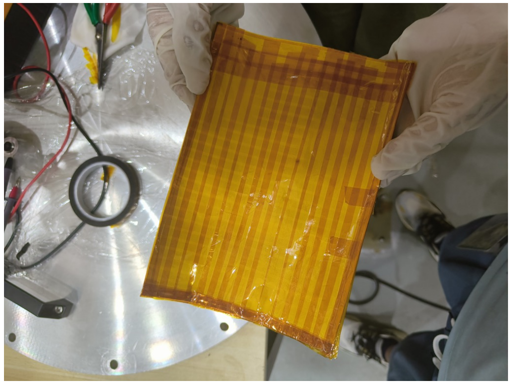




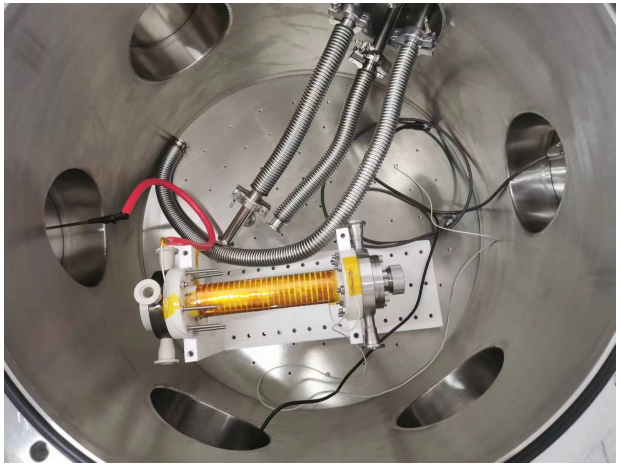
Gas cell prototype
ϕ 3 cm, 24 cm long



Accelerating grid



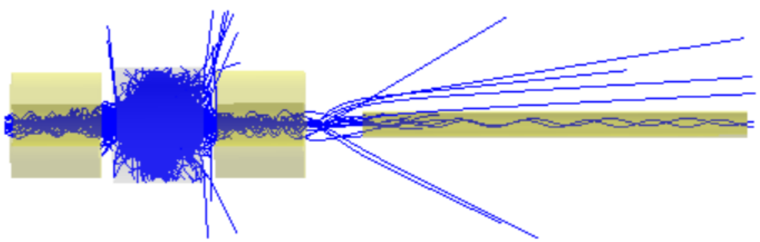
Up to 34 kV

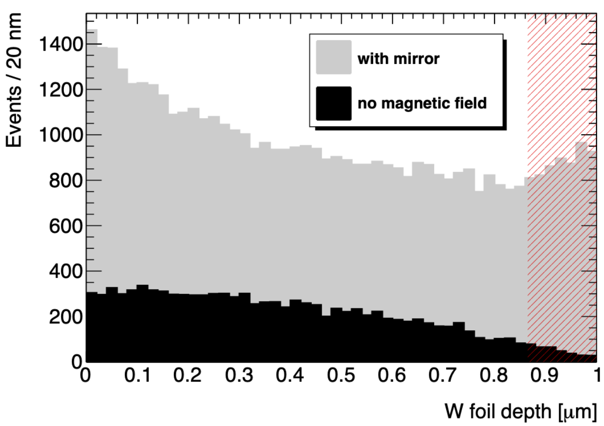


- ➢ Outgassing rate: $1.21\times10^{-8}\ (133.3\mathrm{Pa}\cdot\mathrm{L}\cdot\mathrm{s}^{-1}\cdot\mathrm{cm}^{-2})$
- ➢ >0.25 sccm gas flow to keep contamination <0.1%

Positron Moderation

- Magnetic mirror assisted positron moderation to improve efficiency, recycling the wasted fast positrons
- Prototype set up and tested at USTC positron lab
  - $B_{\max}$ = 0.1 T, magnetic mirror ratio = 2.5
- Potential use-case: Muonium production



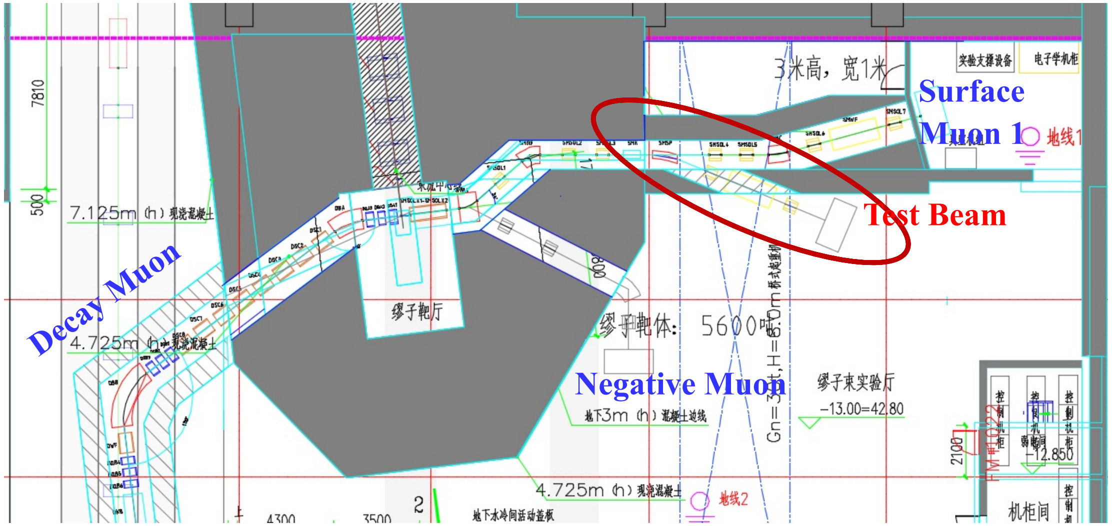


Simulation

Experiment

Summary

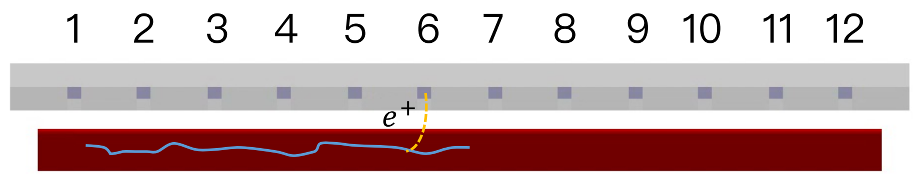
- PSI and J-PARC provide low-energy muons using different methods.
  - PSI: Solid rare-gas moderator
  - J-PARC: Laser ionization of thermal muonium
- At CSNS, R&D of muon frictional cooling with helium gas is currently underway.
- First test with pulsed muon beam is planned at ISIS HiFi next year; in future: at the Test Port of MELODY.
- The use of magnetic mirror is being considered for efficient muonium production.



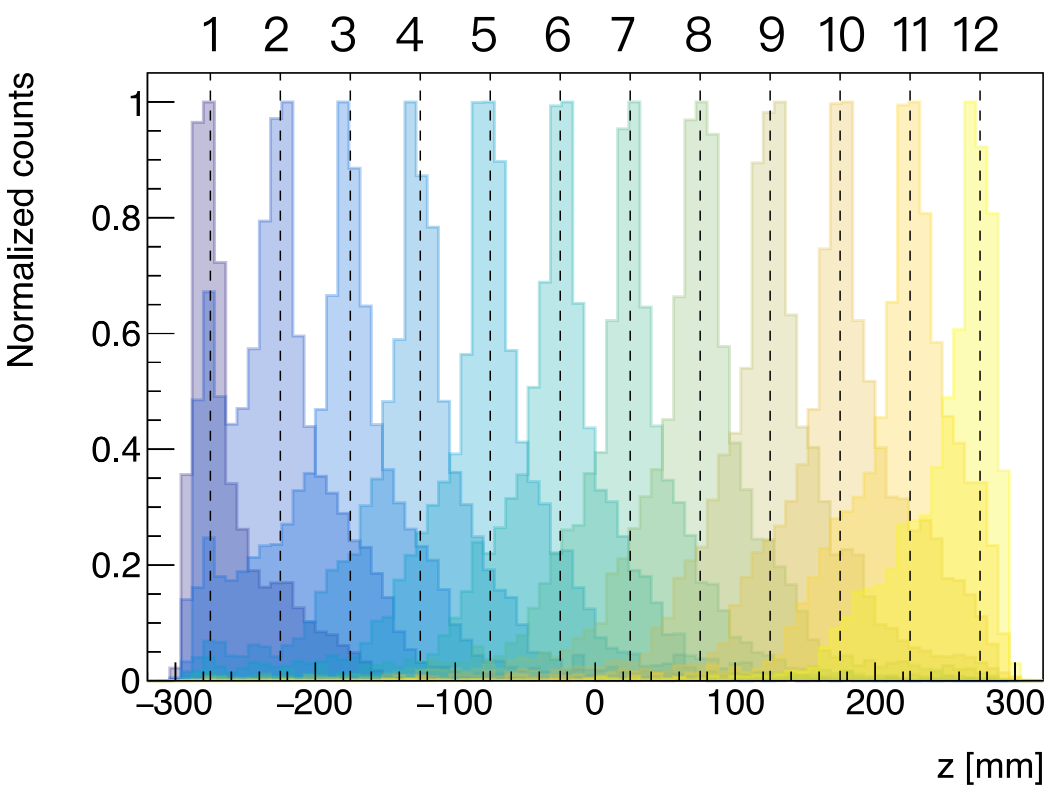
- **Energy：4 MeV**
- **Intensity：10^5~$10^7 \mu^+/s$**
- **Polarization: >95%**
- **Time Resolution: 120ns**

Backup Slides

Simulation Result



- z resolution



- Dashed line: detector position
- Filled area: initial z of the detected positron ⇒ muon-decay position