Progress on μ^+ Moderation R&D at CSNS EMuS

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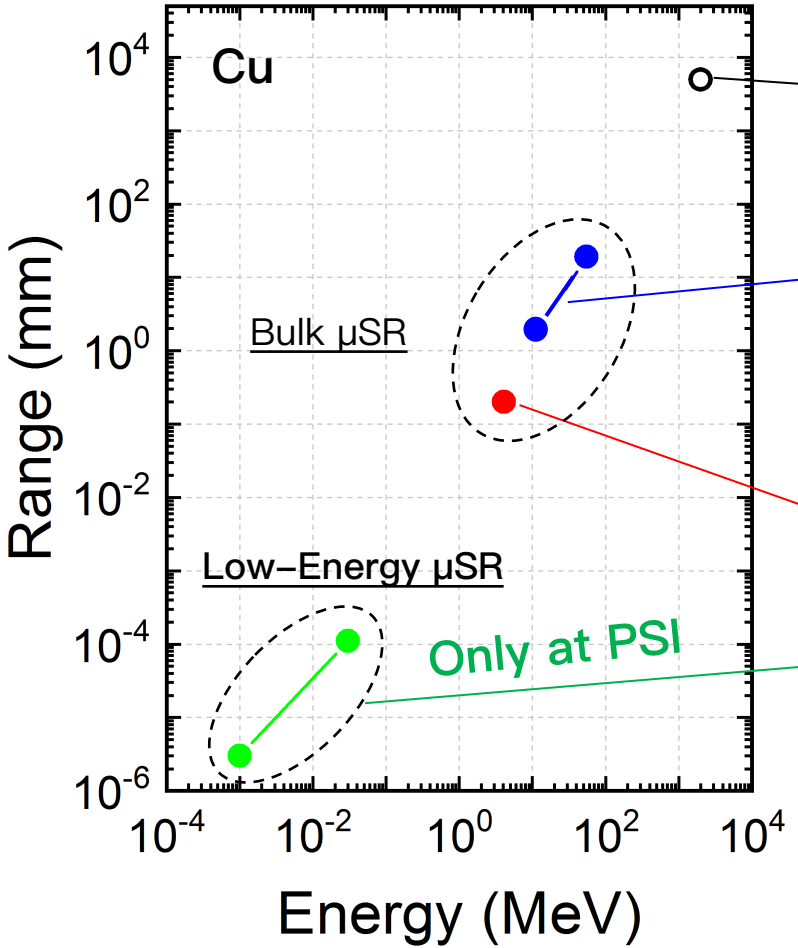
Outline

1. Slow muon introduction
2. Status of muon moderation R&D at EMuS
    - Frictional cooling (FC) demonstration experiment
    - Cryogenic moderation method
    - Electrostatic mirror
3. Summary and outlook

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

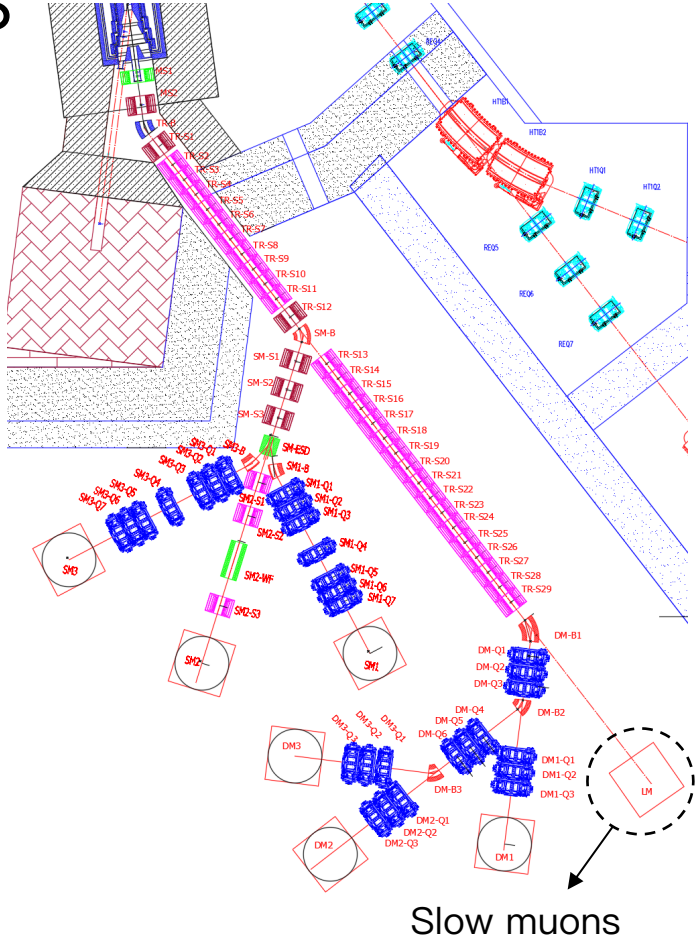
"Bulk" μSR: sub–mm sample

Suface muon, 4.1 MeV
Implantation depth: ~ 100 μm

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

Slow Muons at EMuS

- Only one slow muon beam line for μSR at present (PSI LEM)
- Slow muon beam designed in EMuS baseline scheme
  - Incident surface $\mu^+ \sim 4\times10^7/s$
  - Moderation efficiency $\geq 10^{-4}$
  - Frictional cooling with helium gas
  - Cryogenic moderation



Moderation Methods

PSI SμS

Solid rare gas (Ar / Ne)

✓ Highly polarized μ^+ (>90%)

✗ Low efficiency $<10^{-4}$

LEM: ~5000 slow μ^+ /s

J-PARC / RIKEN-RAL

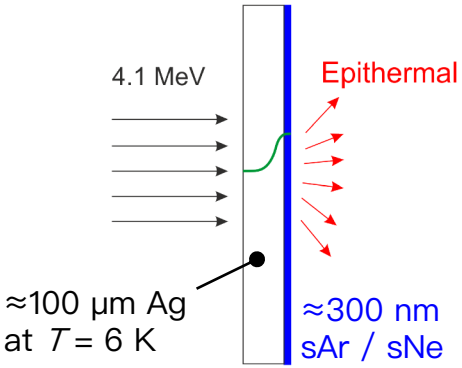
Laser ionization of Mu (μ^+e^-)

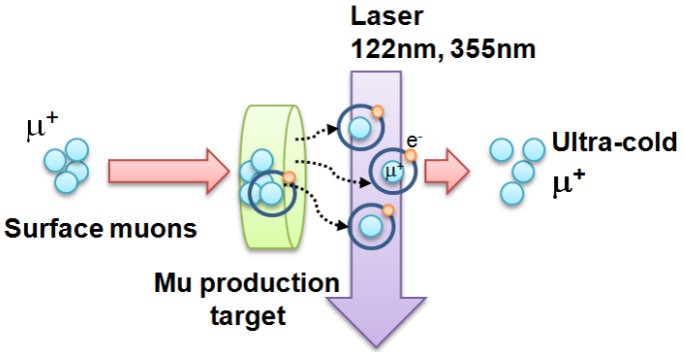
✓ Higher efficiency ($\sim 10^{-3}$)

✗ Polarization <50%

✗ Complex high-intensity laser system

U-Line: $> 10^5$ μ^+ /s expected





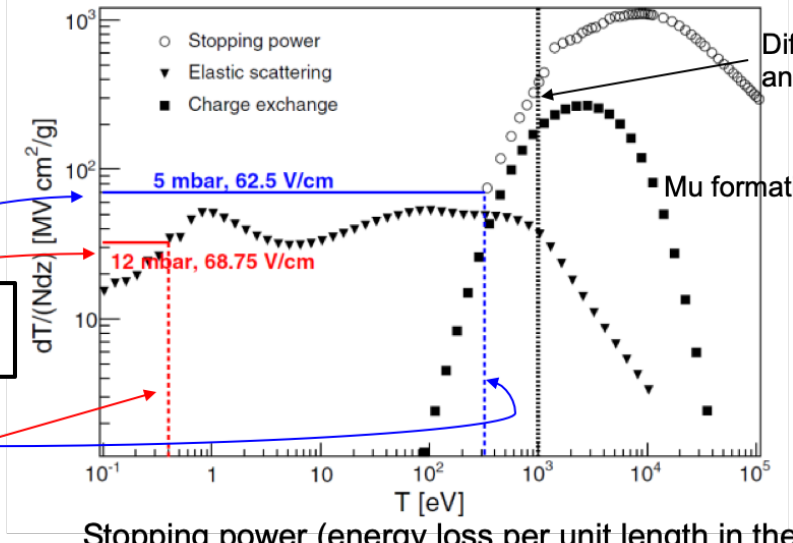
μ^+ Frictional Cooling

Y. Bao *et al.*, PRL 112, 224801 (2014)
I. Belosevic *et al.*, Eur. Phys. J. C 79, 430 (2019)
A. Antognini *et al.*, PRL 125, 164802 (2020)

He gas moderator

Apply E–field in He gas (muCool experiment by ETHZ & PSI, $\epsilon \sim 10^{-3}$)

- Compensate energy loss; reach equilibrium energy
- Electric discharges inside the He gas



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

FC Experiment Plan

Simulation and design

- Accelerating E–field, moderation process, beam focusing, *vacuum–extraction*, and reacceleration

2018–2022

Demonstration experiment (proton/positron)

- FC working principle, *discharges, muon extraction* …

2019–2022

Frictional muon cooling

- PSI, RIKEN–RAL muon beam time

2022–

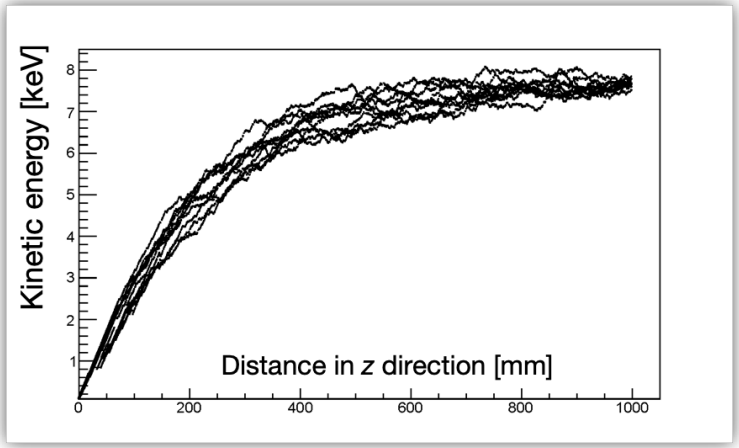
Data analysis

- Moderation efficiency, beam energy spread …

Status of FC R&D

FC demonstration experiment with protons

- Simulation
- Accelerating test in vacuum
- FCD experiment in He gas
- Vacuum–extraction



Proton energy vs. drift distance in 5 mbar He gas and 336 V/cm longitudinal E–field

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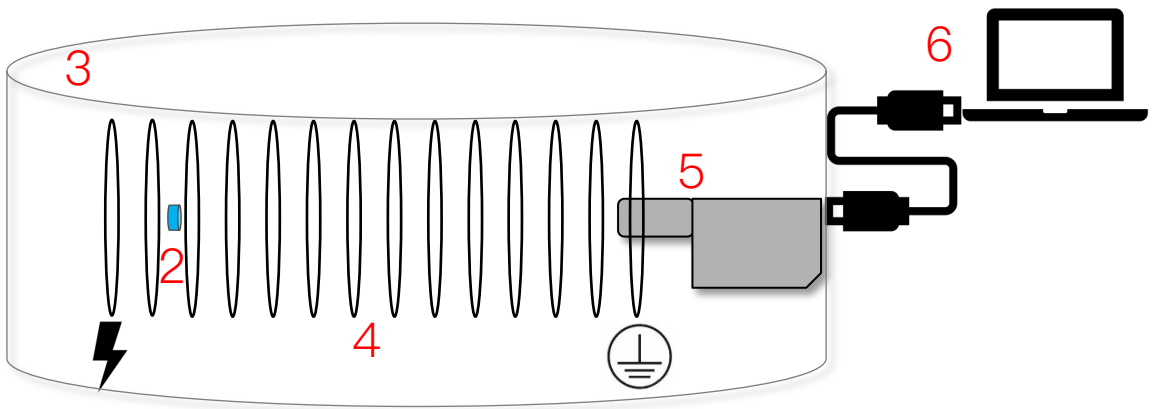
1. Laboratory
2. Compact proton source
3. Vacuum system
4. Accelerating grid & HV
5. Detector
6. Proton energy spectrum



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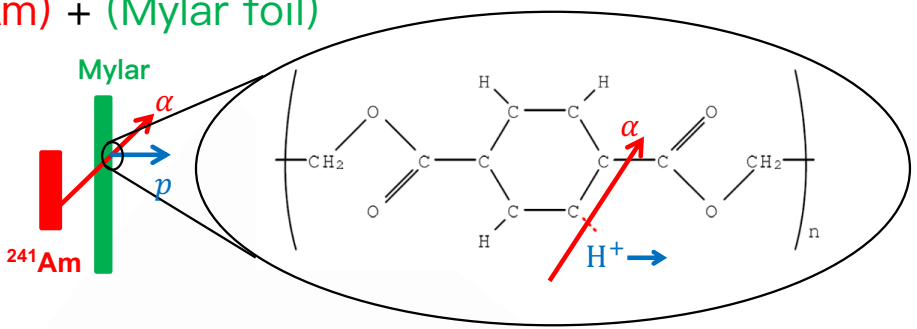
(^{241}Am) + (Mylar foil)



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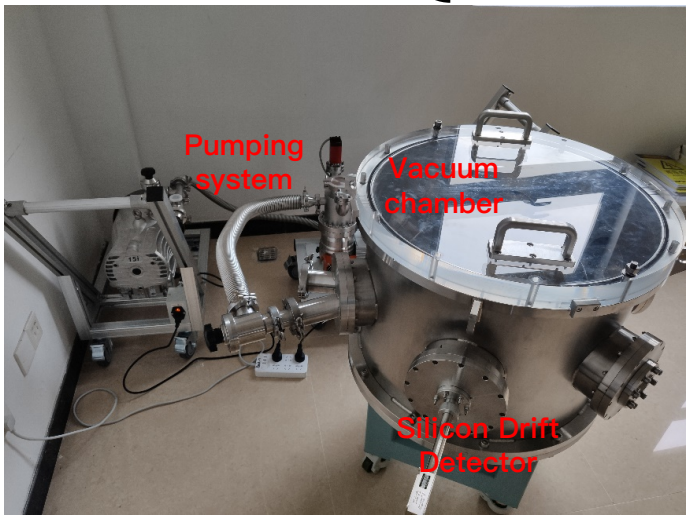

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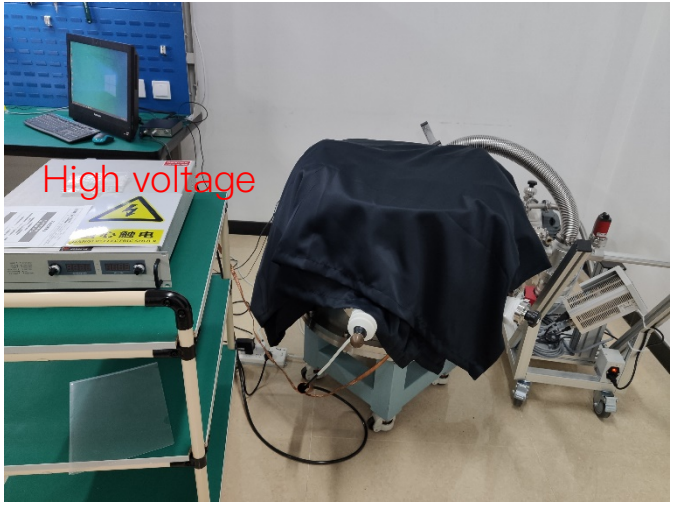
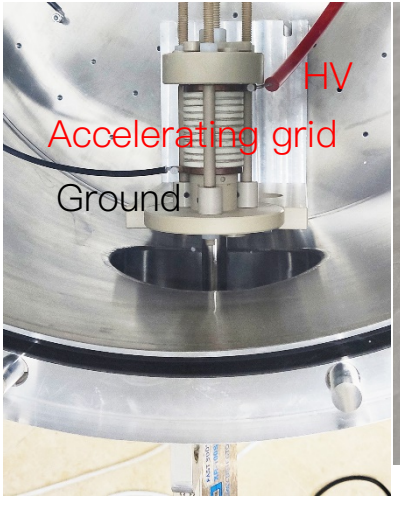




Status of FC R&D

FC demonstration experiment with protons

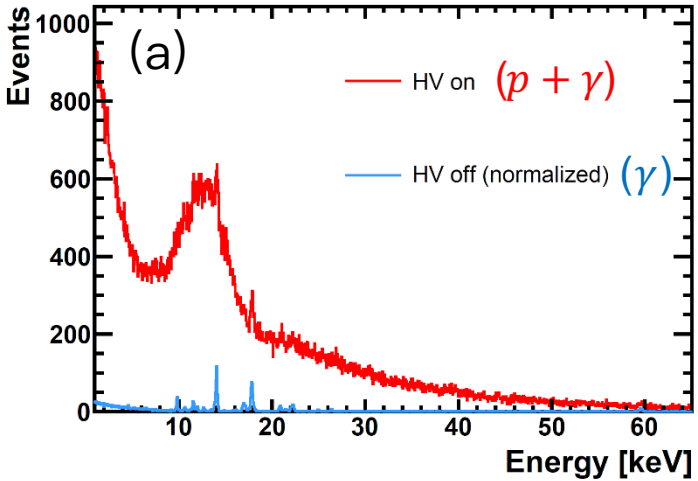
- Accelerating test in vacuum

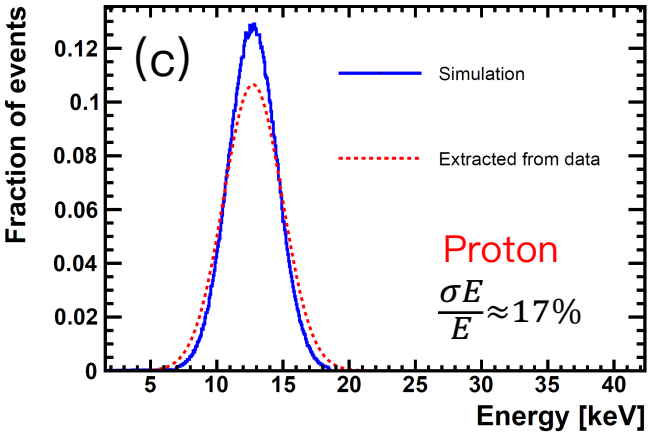
  HV: 25 kV

  Acceleration length: 55 mm

SDD energy calibration (50 mm^2 active area)

^{241}Am 14 keV & 60 keV photopeaks





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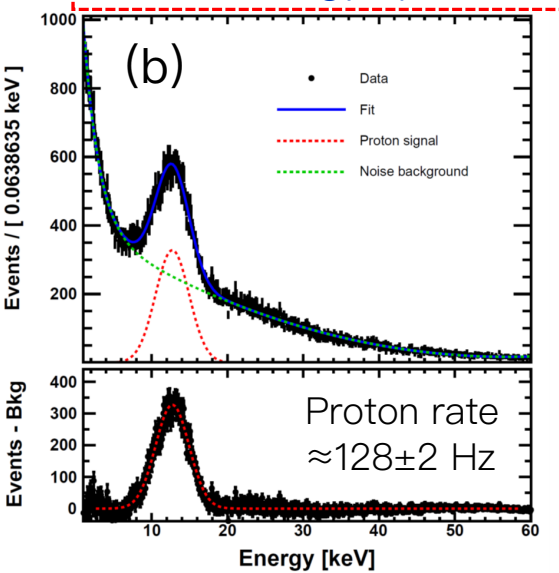
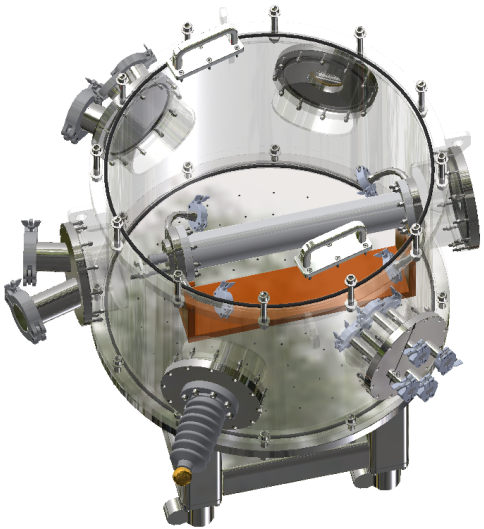


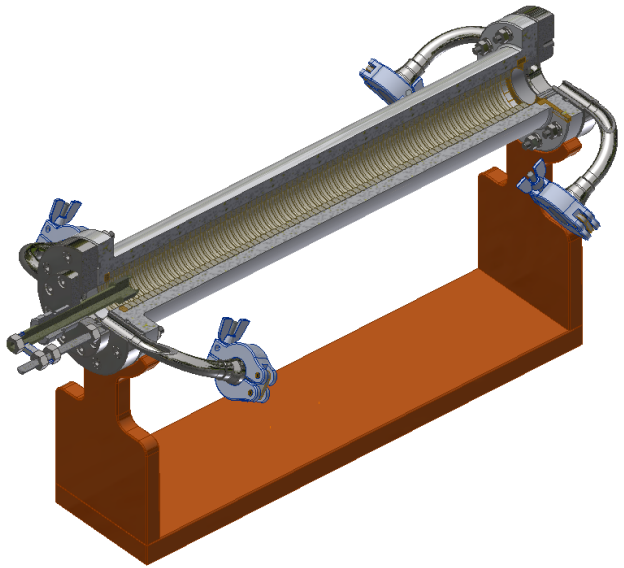
Status of FC R&D

FC demonstration experiment with protons

- Simulation
- Accelerating test in vacuum
- FCD experiment in He gas
- Vacuum–extraction

1. Gas cell design & fabrication
2. Discharge test at different gas pressure: 5—20 mbar …
3. Proton energy measurement, data–MC comparison

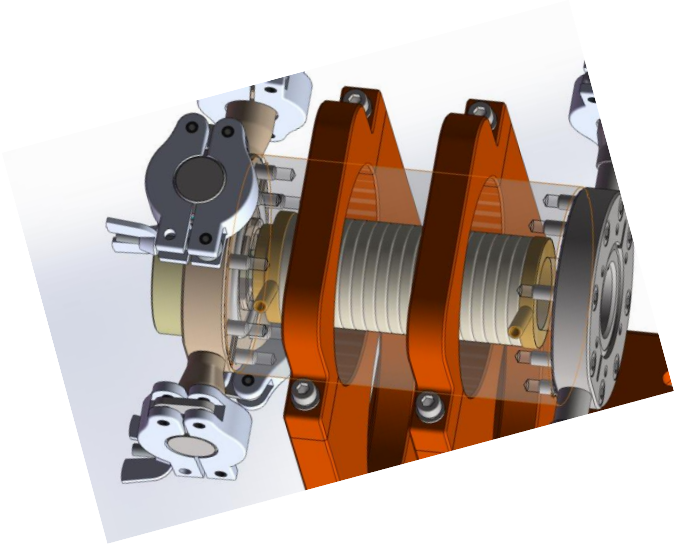




Gas Cell Molding

Two types of resistors

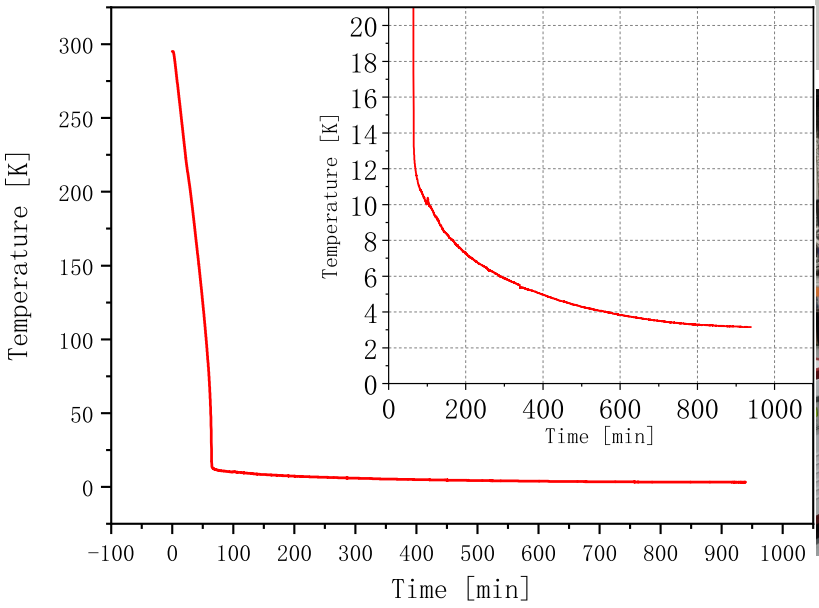
- Ceramic rings
- Normal resistor chain

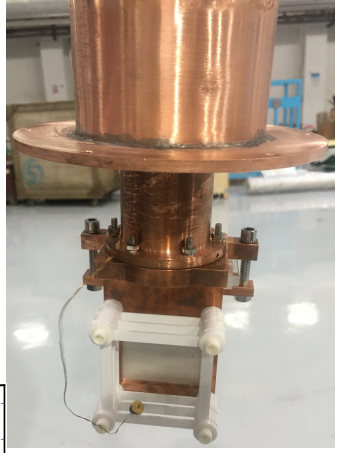


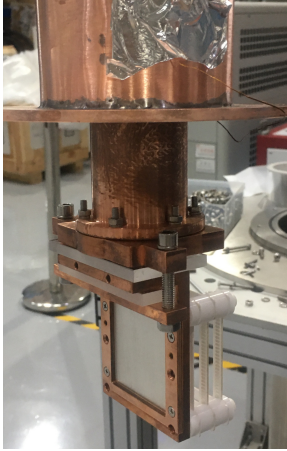
Cryogenic Moderator

50×50×0.3 mm^3 Ag foil substrate

Cold head (~ 3.2 K) ⇢ 2 sapphires ⇢ moderator frame (< 4 K)

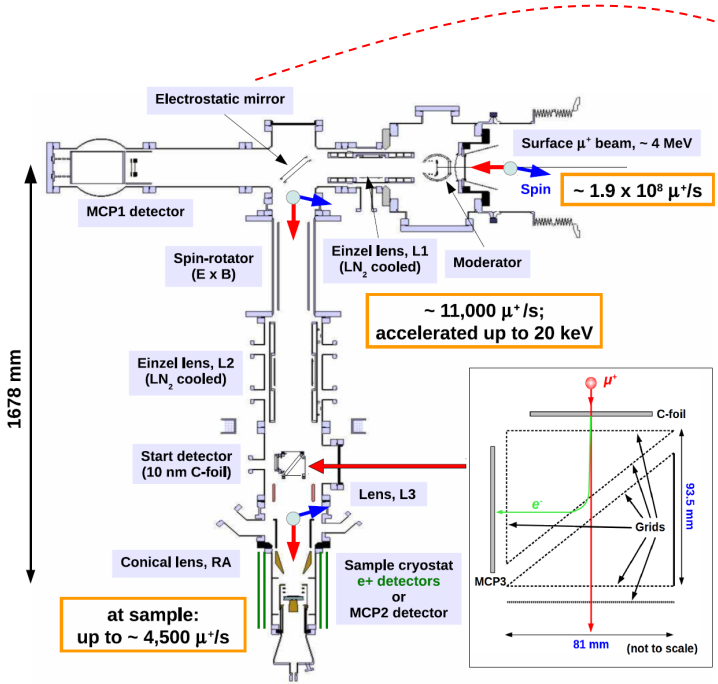


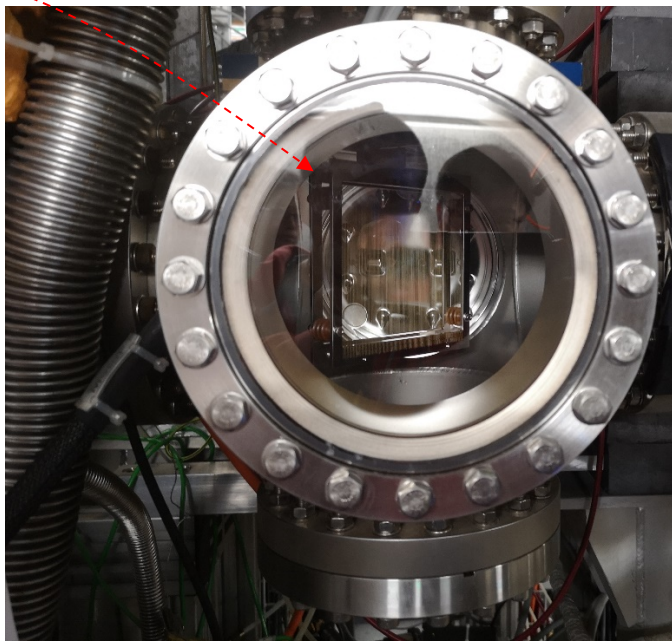




PSI LEM

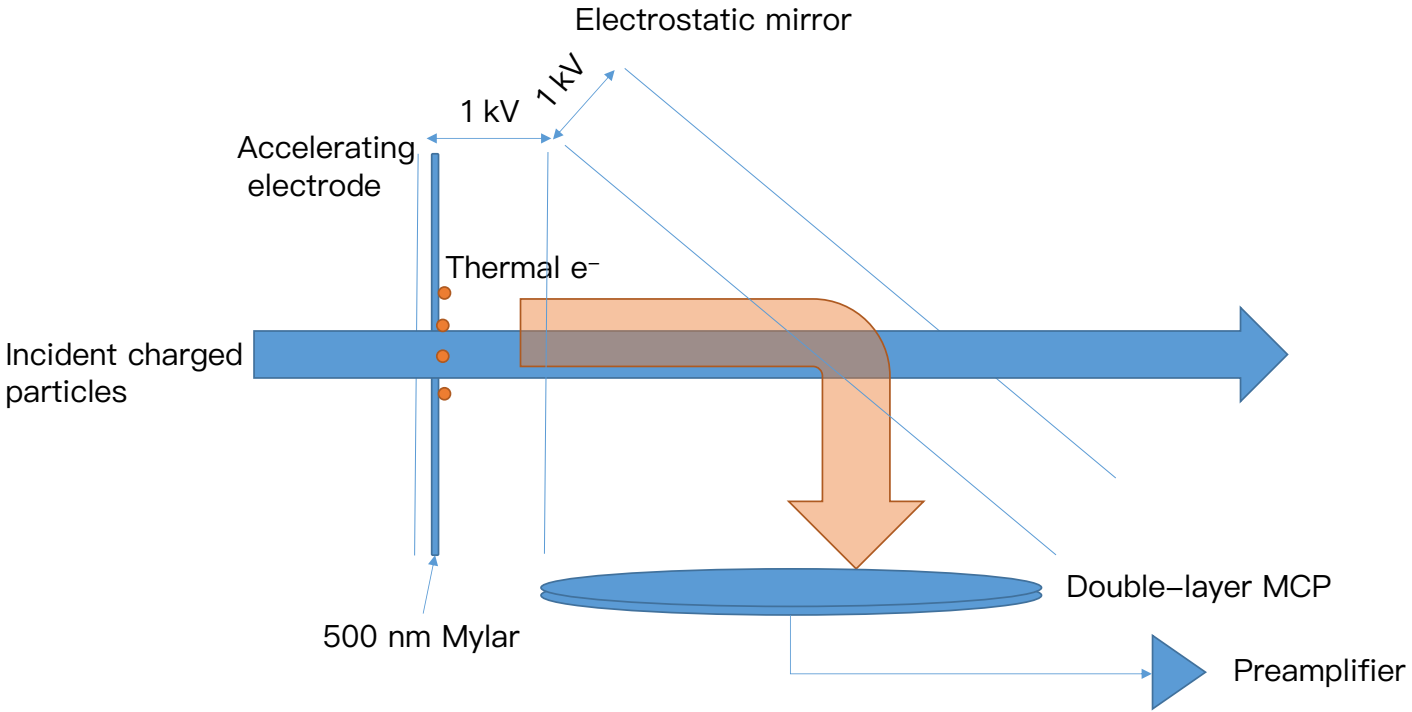
- After moderation, slow μ^+ are deflected and separated from fast μ^+ by an electrostatic mirror.





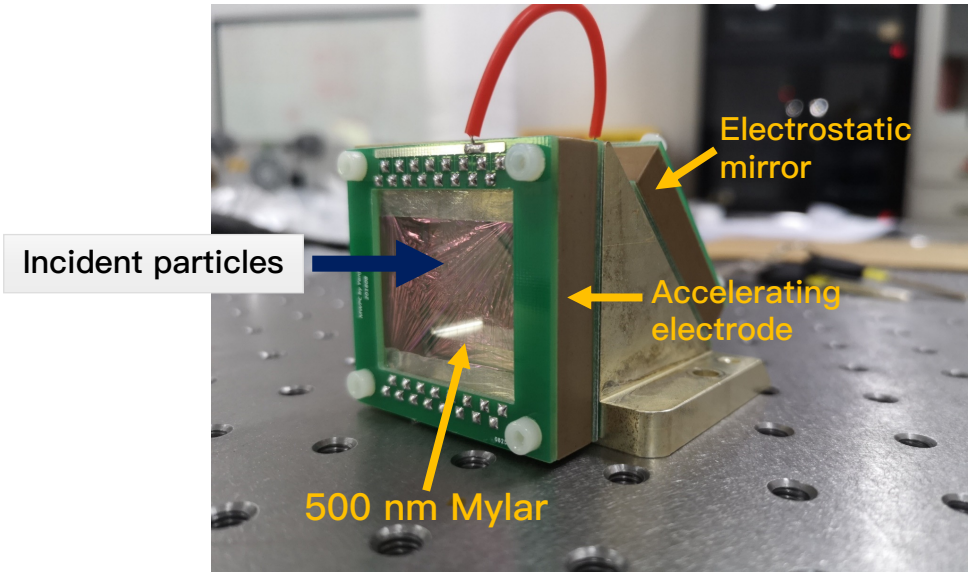
Electrostatic Mirror R&D

- Schematics

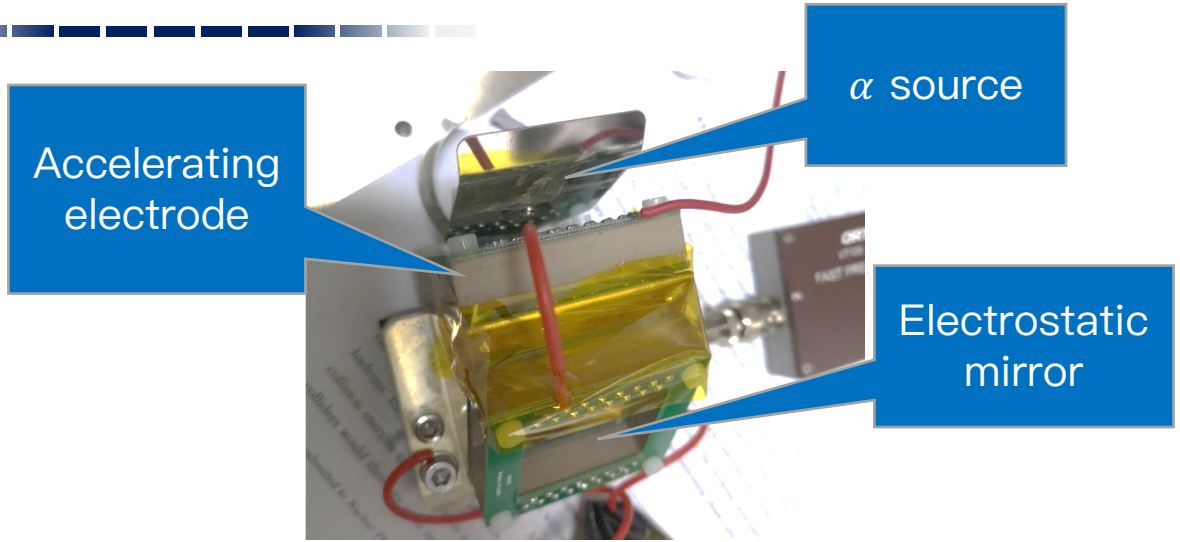


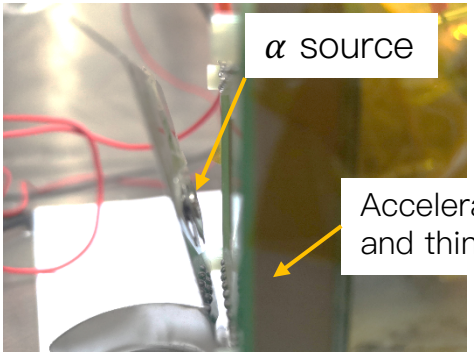
Electrostatic Mirror R&D

- Grid area 30×30 mm^2
- ϕ 20 μm wires
- Wires distance 2 mm



Test with α source

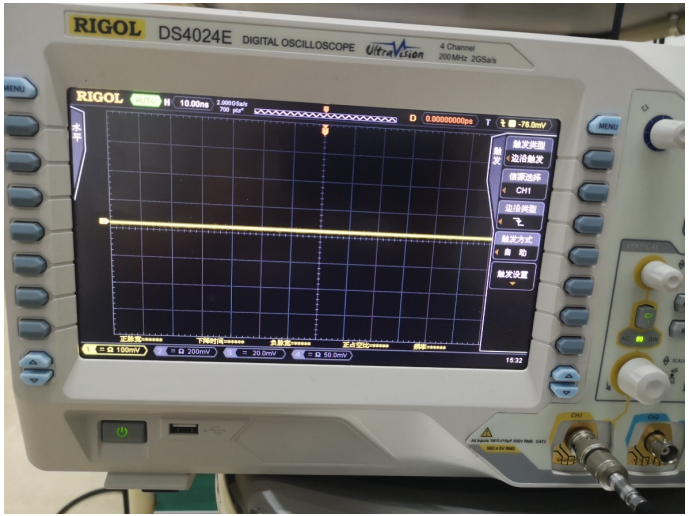




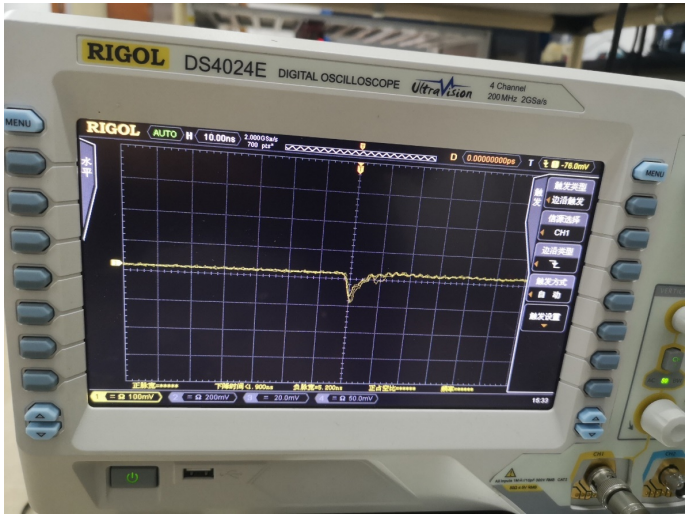
Tilted to avoid α hitting MCP directly

Test with α source

- HV off → no signal → no α hitting the MCP directly



- HV on → signals → thermal e^- from thin film surface ionized by α



Summary & Outlook

- μ^+ moderation method for EMuS: frictional cooling with He gas / cryogenic moderation
- R&D in progress using protons and positrons
- Electrostatic mirror tested with electrons
- Gas cell fabrication improvement
- HV discharge test in He gas
- Differential pumping experiment for extraction stage