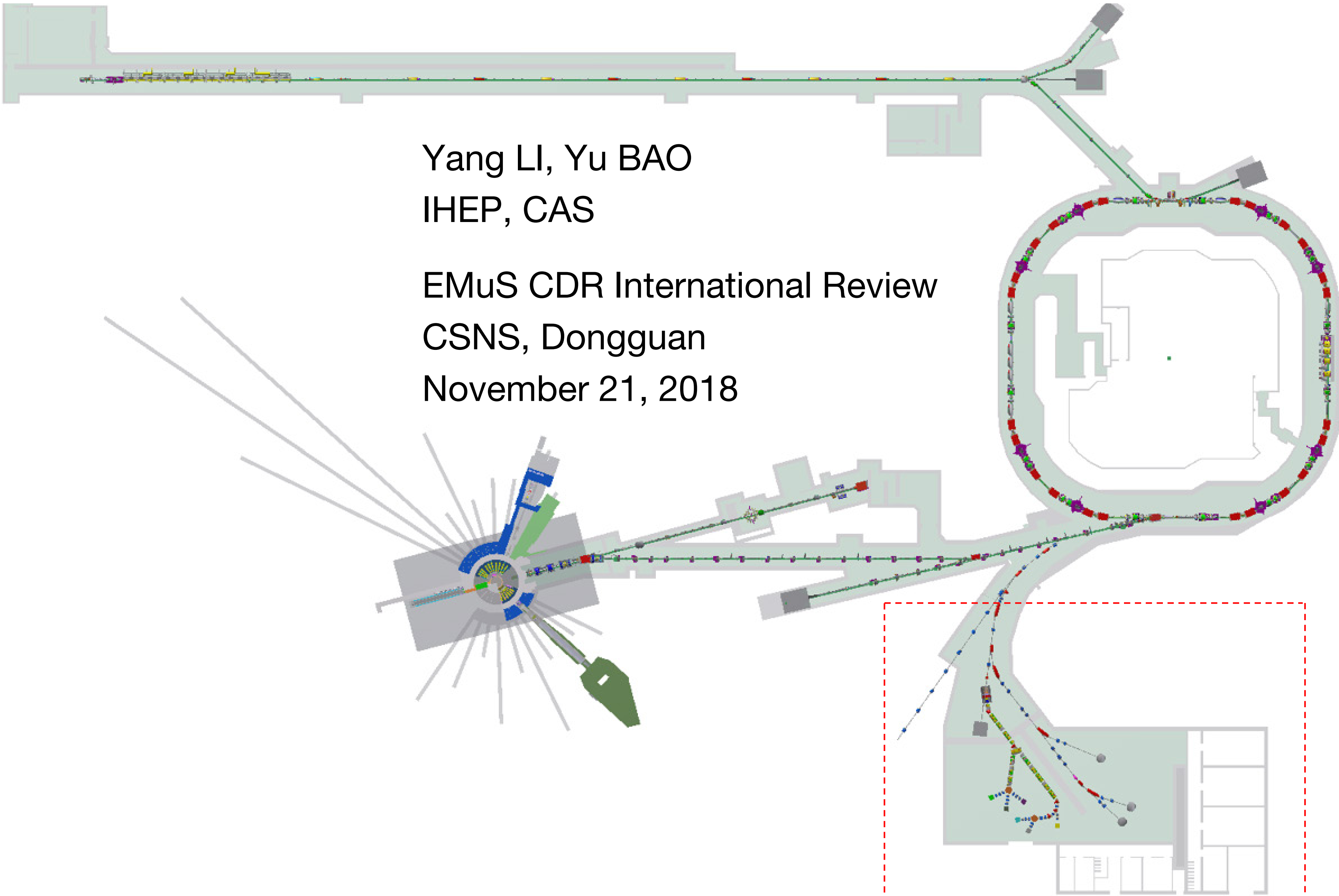
μ^+ Beam Moderation Methods and R&D Efforts for EMuS



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EMuS CDR International Review

CSNS, Dongguan

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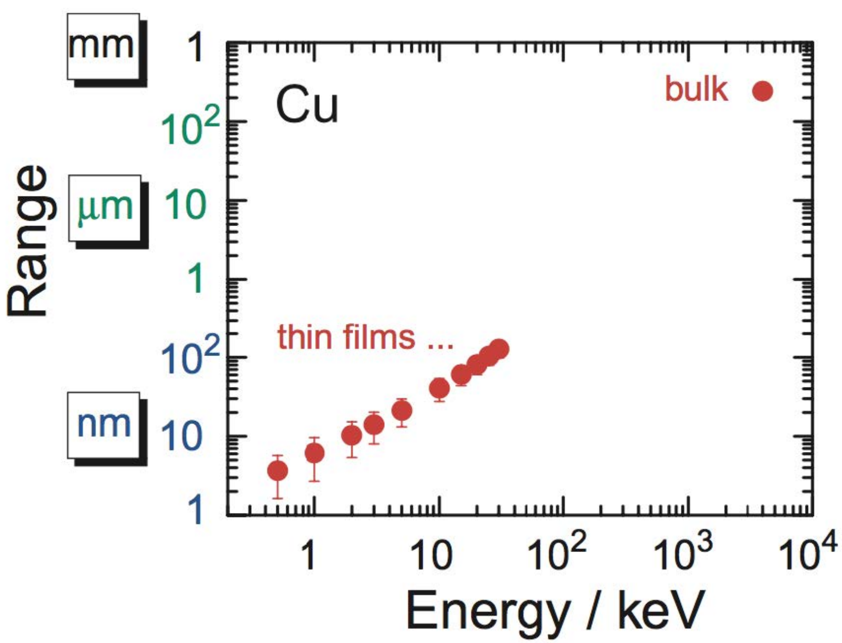
Outline

1. Background
2. Physics Processes of μ^+ Moderation
3. Current μ^+ Moderation Methods
4. Low-Energy μ^+ Production Plans for EMuS
   i. Frictional Cooling Method
   ii. Cryogenic Moderator Method
   iii. Current Status of the R&D
5. Summary

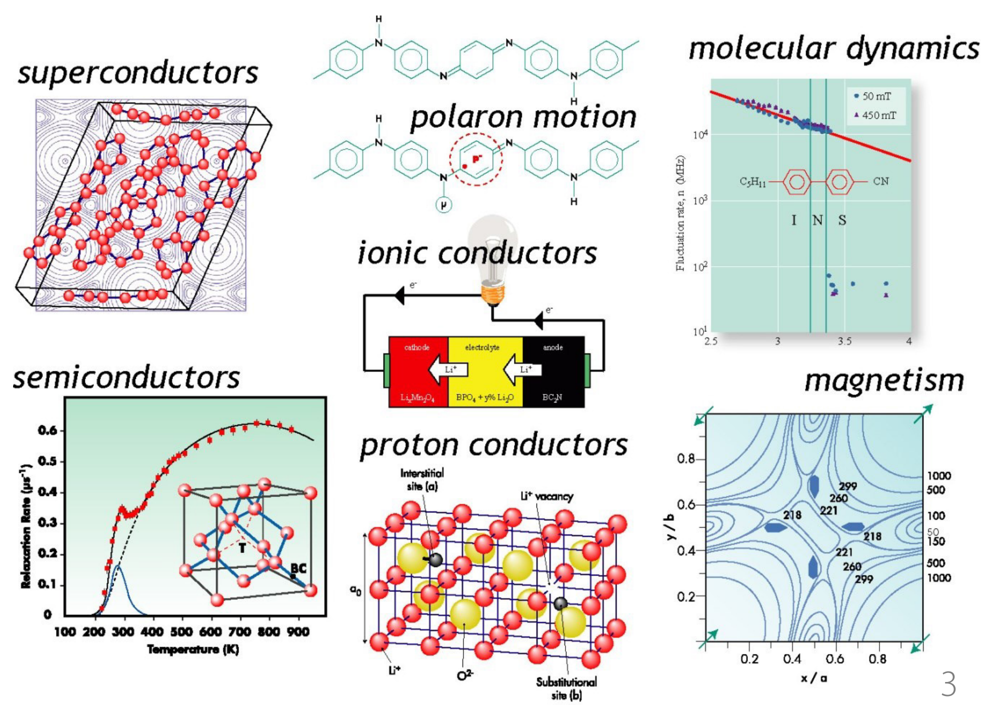
Muon Implantation Range in Material

- Surface muons: pions stop and decay near the surface of the production target
  - μ^+ only, since π^- interact with nuclei before decay
  - 100% polarized, 4.1 MeV in the rest frame of π^+: bulk μSR studies (sub-mm)
- Slow or Low-Energy μ^+ (LE-μ^+): moderate surface muons to thermal/epithermal energy and reaccelerate them to keV energy (0.5–30 keV)
  - Depth-sensitive μSR studies (1–300 nm): thin films, surfaces, nanomaterials...

μ^+ penetration range in Cu

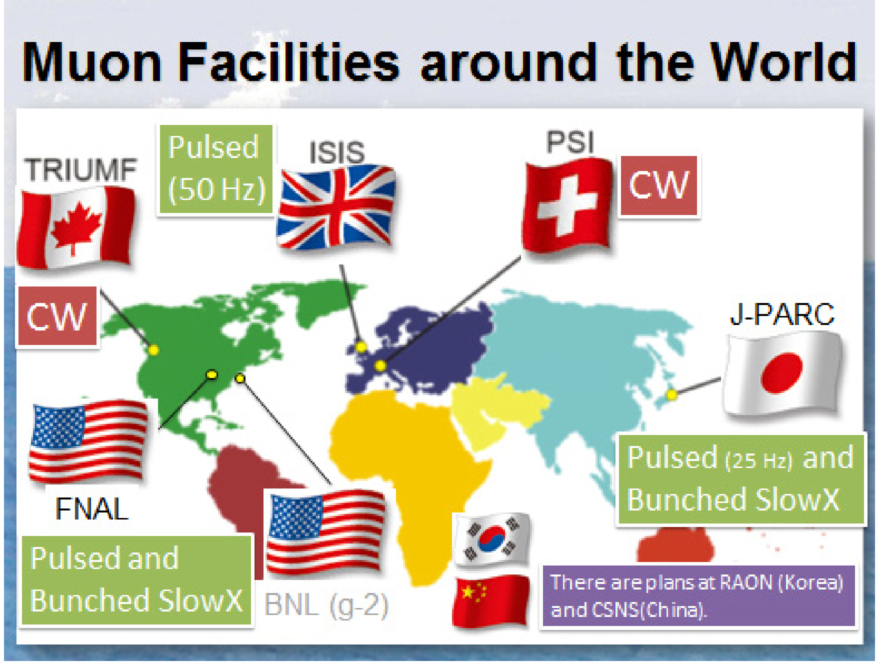


Muon: various science areas



Slow Muon Source

- Production of slow muon
  1) High-intensity surface muon beam
  2) Moderation efficiency
- RIKEN-RAL muon facility: surface muon intensity $\sim 6 \times 10^5/s$, moderation efficiency $\sim 3 \times 10^{-5}$
- **PSI low-energy muon (LEM) beam: worldwide unique slow muon source available for user experiments,** surface muon intensity $\sim 10^8/s$, moderation efficiency $\sim 5 \times 10^{-5}$



μ^+ Moderation Process in Material

Surface μ^+ — $E_{\mu^+} \approx 4$ MeV

surface of material

Ionization of atoms — $E_{\mu^+} \approx 2$–30 keV

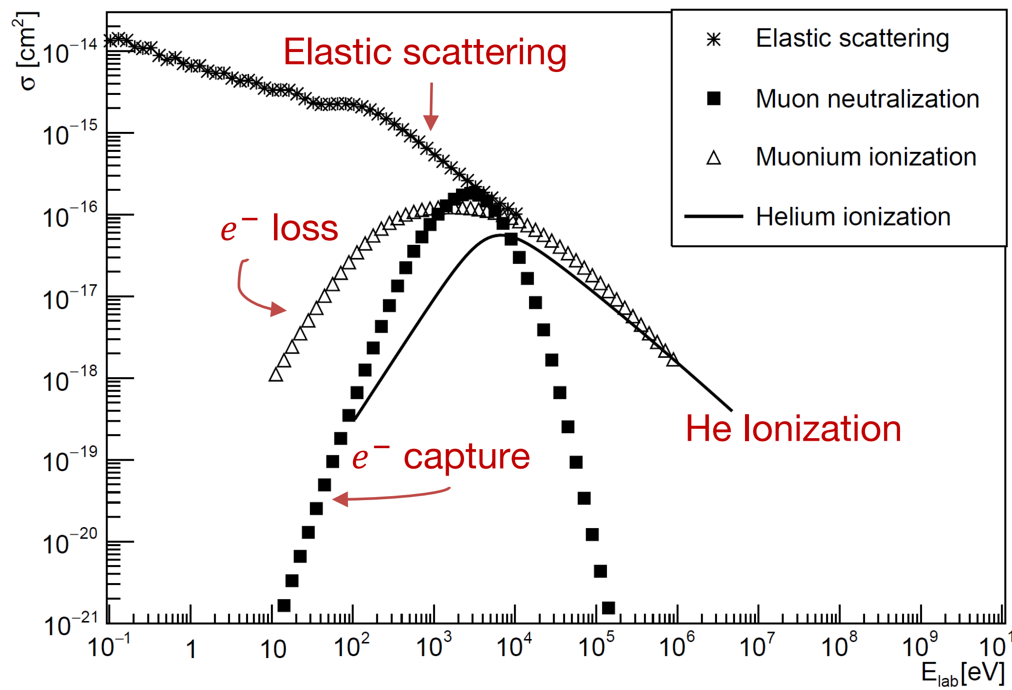
Coulomb collisions with e^-

Charge-exchange cycles

- excess e^- capture and loss, i.e., muonium (Mu) formation and ionization — $E_{\mu^+} \approx 100$ eV

Elastic scatterings

μ^+-He cross sections as a function of E_{μ^+}



At low energy, μ^+ cross sections not known

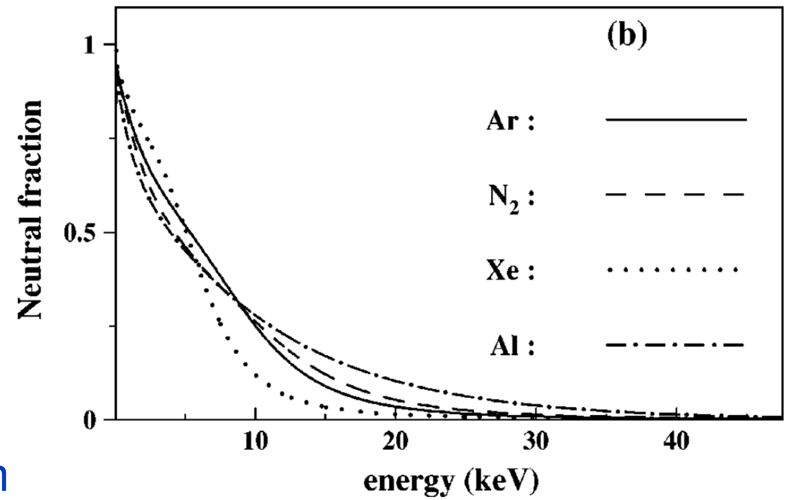
- Charge exchange: velocity scaling from proton data
- Elastic scattering: energy scaling from proton data

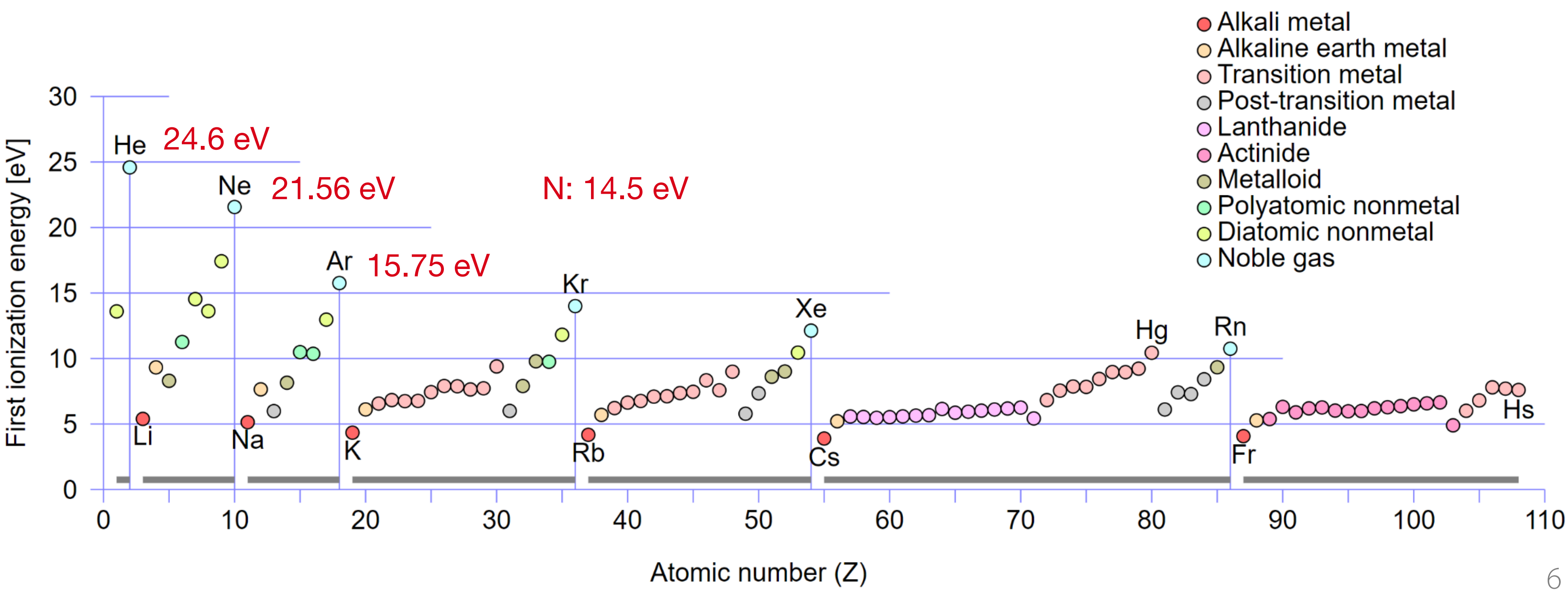
S.L. Lin, I.R. Gatland, and E.A. Mason, J. Phys B 12, 4179 (1979)
M. Senba, J. Phys B 31, 5233 (1998)

Suppression of Mu ($\mu^+ e^-$) Formation

- Moderator: wide-band-gap perfect insulators (e.g., solid Ar, N_2, and Ne, band-gap energy E_g between 11 and 22 eV)
  - Energy loss from Mu formation strongly suppressed once μ^+ energy ~ E_g
  - Because μ^+ energy must, at least, be comparable to E_g in order to ionize an atom

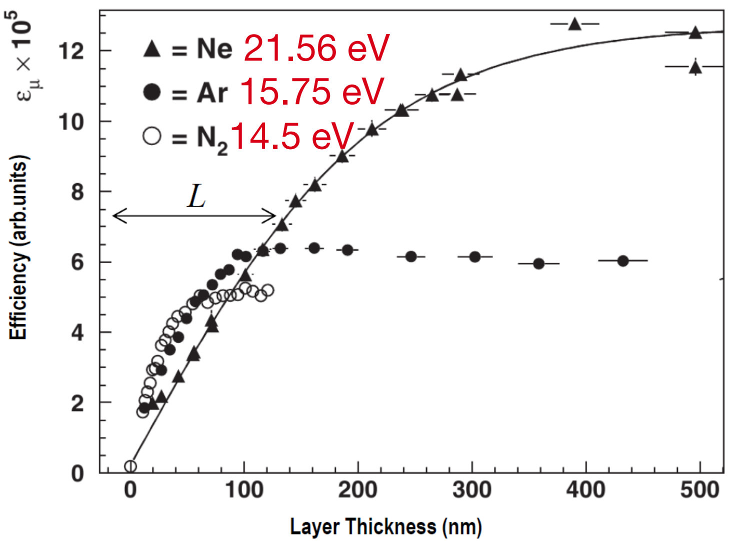
T. Prokscha, *et. al*, PRA, 58, 5, 3739 (1998)





Moderating Materials and Moderation Efficiency

- Moderation efficiency increases with increasing band-gap energy of the moderator



Moderation efficiency vs. thickness of the solid van der Waals layer

Moderator	Moderation efficiency	E_g [eV]
Ne	$1.4\pm0.2\times10^{-4}$	21.58
Ar	$8.6\pm1.2\times10^{-5}$	14.16
Kr	$1.7\pm0.2\times10^{-5}$	11.61
Xe	$5.7\pm1.1\times10^{-7}$	9.33
N_2	$6.3\pm1.1\times10^{-5}$	15.1
O_2	$1.4\pm0.2\times10^{-5}$	12.08
CH_4	$1.4\pm0.2\times10^{-5}$	12.51
LiF	$1.9\pm0.5\times10^{-7}$	14.1
SiO_2	$3.0\pm1.0\times10^{-7}$	$\sim$9
Al	$2.0\pm0.4\times10^{-7}$	0
Cu	$1.0\pm0.3\times10^{-7}$	0

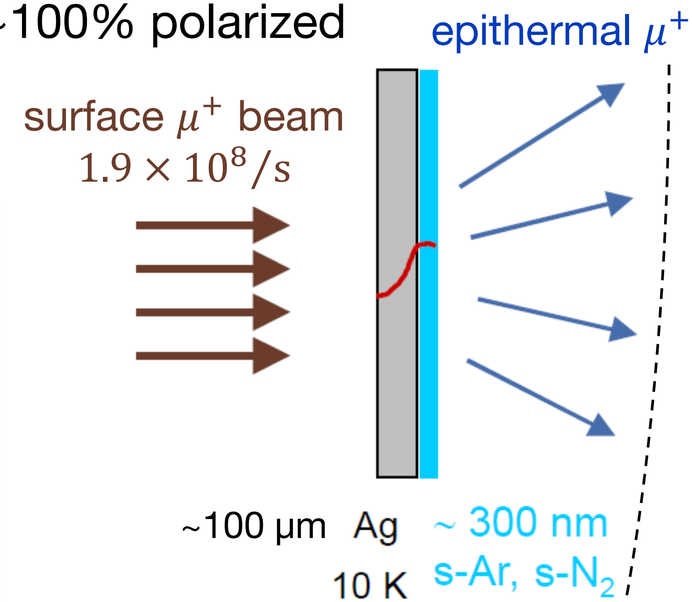
E. Morenzoni et al., J. Phys.: Condens. Matter 16, S4583 (2004)
Morenzoni E. Physics and applications of low energy muons. Muon Science: Muons in Physics, Chemistry and Materials (Bristol and Philadelphia, 1999), SL Lee, SH Kilcoyne, and R. Cywinski, Eds, 1998, 51:343–404.

Current μ^+ Moderation Methods

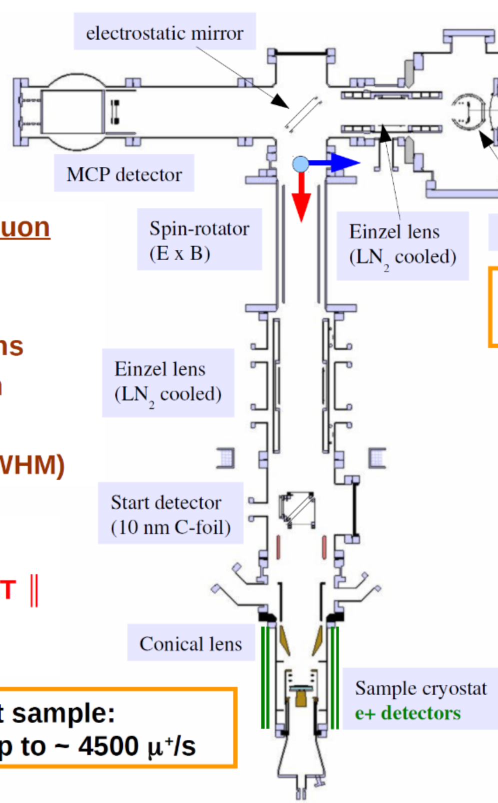
T. Prokscha *et al.* Appl. Surf. Sci. **172**, 235 (2001)
E. Morenzoni *et al.* J. Appl. Phys. **81**, 3340 (1997)
D. Harshmann *et al.*, Phys. Rev. **B 36**, 8850 (1987)
E. Morenzoni, *et al.*, PRL, 72 (17), 2793 (1994)

- ***Cryogenic moderator method***
  - PSI LEM

1) ~300 nm thick solid noble gas moderator layer on a cold substrate
2) Deliver epithermal (~15 eV) μ^+ for LE-μ^+ beam, ~100% polarized
3) Moderation efficiency $\varepsilon_{\mu^+} \equiv \frac{\mathrm{N_{epith}}}{\mathrm{N_{4MeV}}} \approx 10^{-5}$–$10^{-4}$



- UHV system, 10^{-10} mbar
- some parts LN_2 cooled



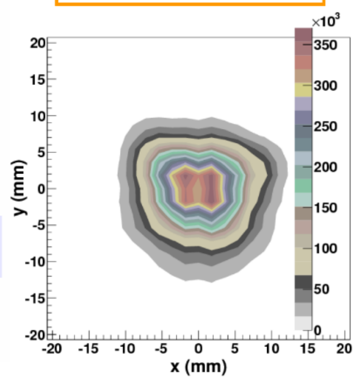
Polarized Low Energy Muon Beam

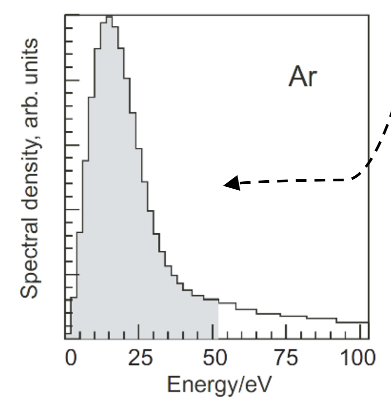
Energy:	0.5-30 keV
ΔE, Δt:	400 eV, 5 ns
Depth:	1 – 300 nm
Polarization	~100 %
Beam Spot:	12 mm (FWHM)

Sample environment:

B = 0 – 0.3 T ⊥, 0 – 0.03 T ∥ sample surface
T = 2.5 – 320 K

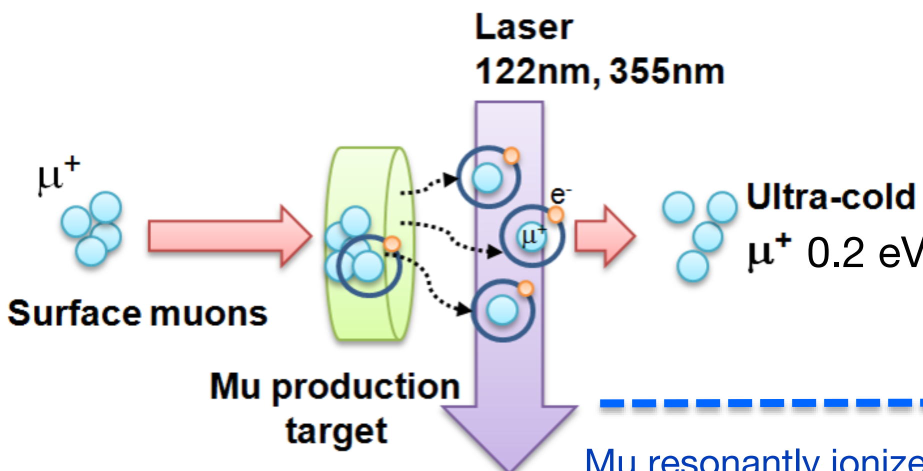
Beam spot at sample





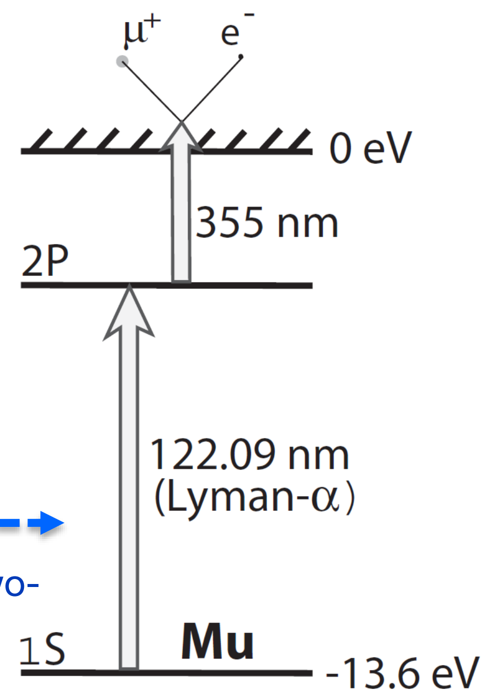
Current μ^+ Moderation Methods

- ***Laser resonant ionization of Mu***
  - RIKEN-RAL muon facility
  1) Intensity: ~15 slow μ^+/s out of $1.2 \times 10^6/s$ surface muons
  2) Spin polarization: ~50%
  3) Beam size at sample: 4 mm
  - J-PARC MUSE
  1) Intensity: $> 10^4/s$ expected



Mu formed by stopping surface muons on the rear surface of a hot W foil

Mu resonantly ionized via two-photon 1S→2P→unbound process

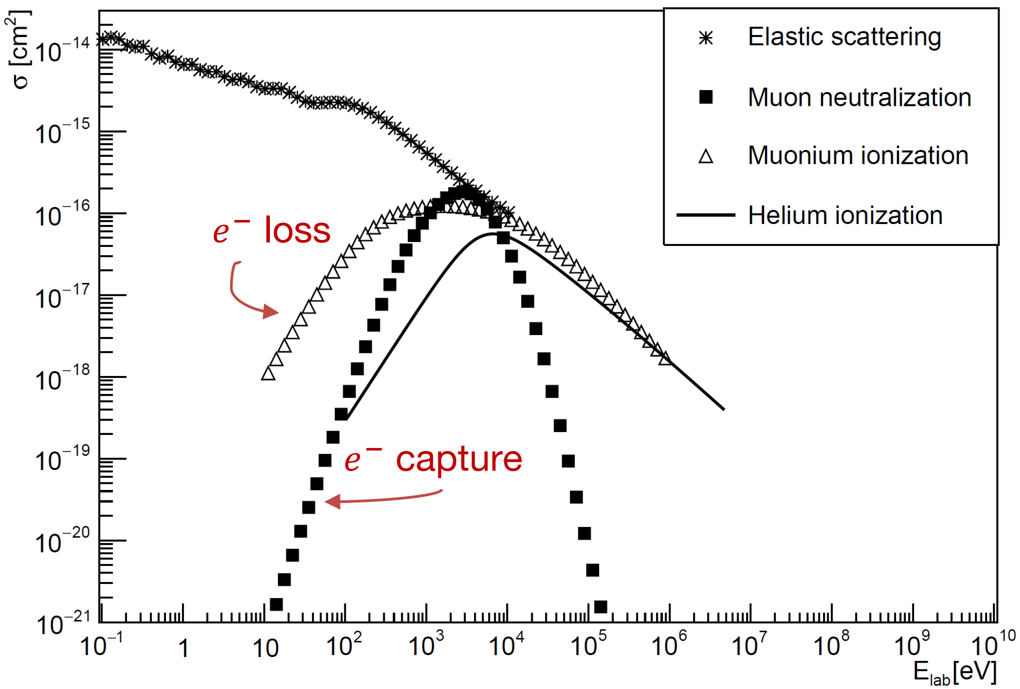


K. Nagamine, *et al.* Phys. Rev. Lett. 74 (24) 4811–4814 (1995)
P. Bakule, *et al.* Nucl. Instr Meth. B 266, 335 (2008).

LE-μ^+ Production Plans for EMuS

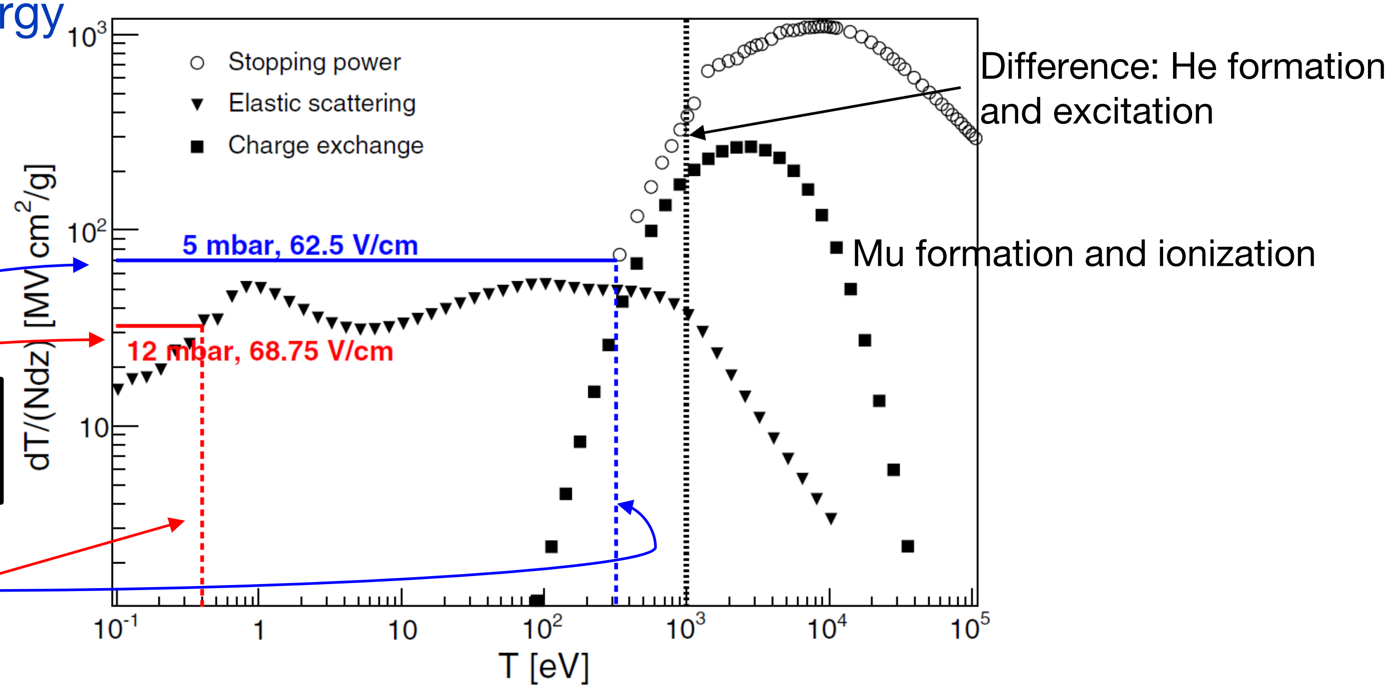
- Laser ionization method:
  - High efficiency $\geq 10^{-4}$, narrow energy resolution
  - Complex high-intensity laser system, polarization loss
- Cryogenic moderator: moderation efficiency is the key
  - Helium: 1) wider band gap (24.6 eV), 2) cross section of Mu ionization > formation below keV energy
  - Helium gas
  - Liquid helium (LHe)
  - Aim to achieve $\varepsilon_{\mu^+} \geq 10^{-4}$

μ^+-He cross sections vs. E_{μ^+}



Frictional Cooling of μ^+ in He Gas

- Slow down μ^+ into an energy range where the stopping power increases with energy
- Below a few hundreds of eV, energy loss by elastic scattering nonnegligible
- Apply an electric field in He (muCool experiment at PSI→aim: $\varepsilon_{\mu^+} \sim 10^{-3}$)
  - Energy gain in the electric field > energy loss, μ^+ continuously accelerated until slowed down by charge exchange and inelastic collisions
  - Equilibrium energy
- Electric discharges inside the gas

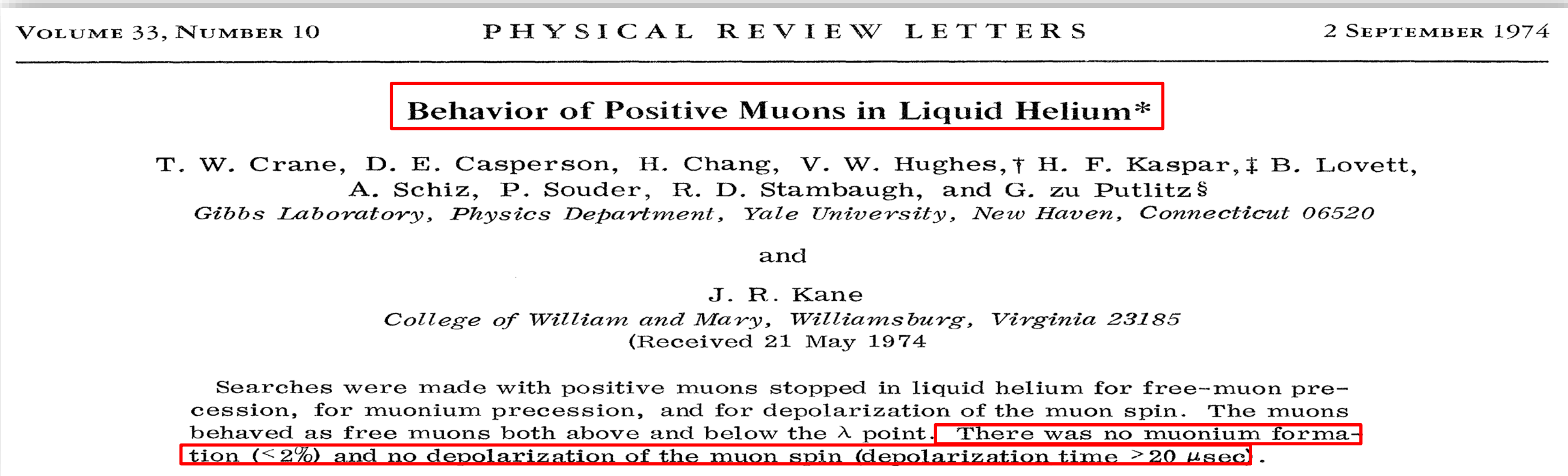


Stopping power (energy loss per unit length in the electric field direction) of μ^+ in He gas

Y. Bao et al., PRL 112, 224801 (2014)

LHe Moderator on Low-Density Graphite Aerogel Substrate

- LHe as the moderator
  - Low Mu formation in LHe, larger muon escape prob. from LHe (125 mg/cm^3)



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Behavior of Positive Muons in Liquid Helium*

T. W. Crane, D. E. Casperson, H. Chang, V. W. Hughes,† H. F. Kaspar,‡ B. Lovett, A. Schiz, P. Souder, R. D. Stambaugh, and G. zu Putlitz§
Gibbs Laboratory, Physics Department, Yale University, New Haven, Connecticut 06520

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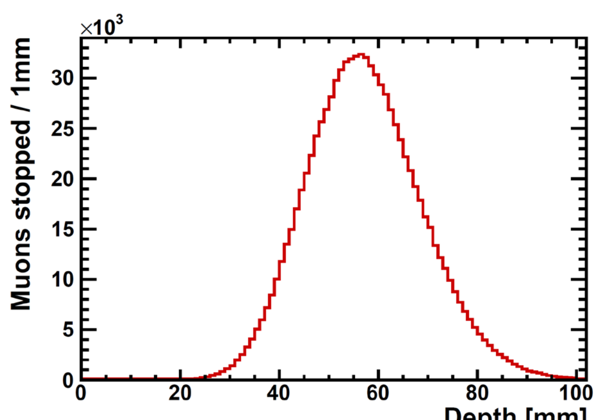
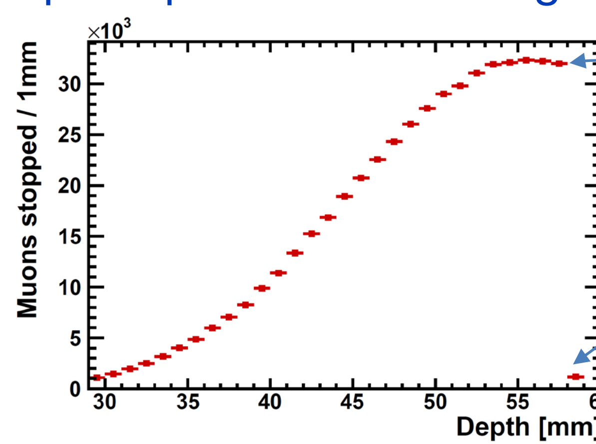
J. R. Kane
College of William and Mary, Williamsburg, Virginia 23185
(Received 21 May 1974)

Searches were made with positive muons stopped in liquid helium for free-muon precession, for muonium precession, and for depolarization of the muon spin. The muons behaved as free muons both above and below the λ point. There was no muonium formation (<2%) and no depolarization of the muon spin (depolarization time >20 μsec).

- ~20 mg/cm^3 graphite aerogel as substrate
  - Increase the mean free path→larger escape depth of muons→higher efficiency

μ^+ stopping distribution in 100mm thick graphite aerogel substrate



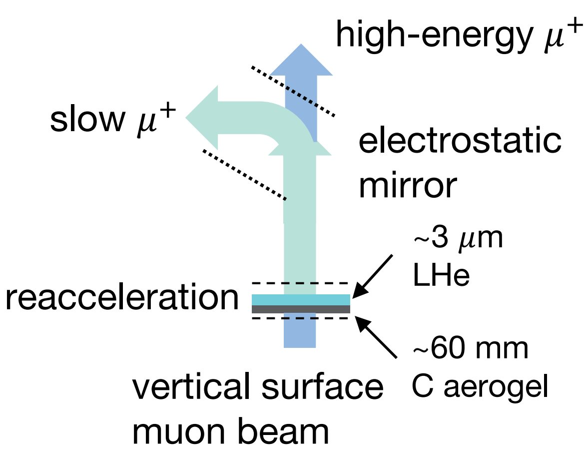


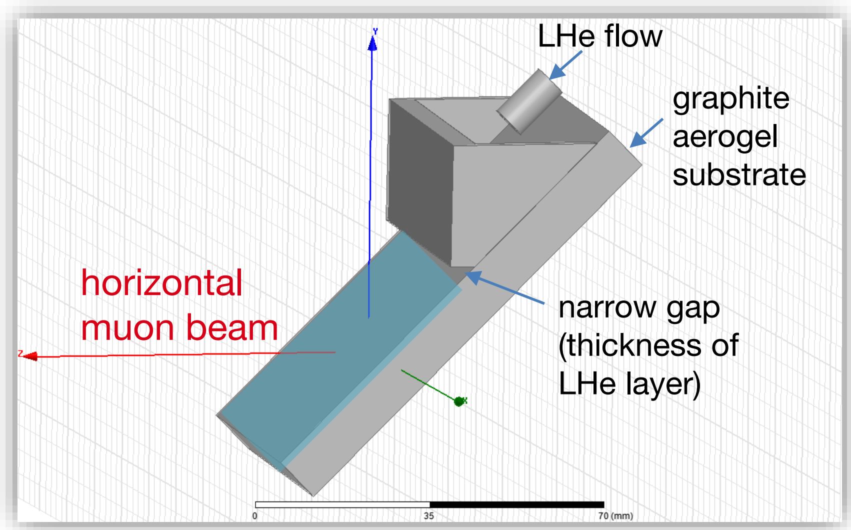
58mm thick graphite aerogel + 3μm LHe

Current Status of the R&D

- Frictional cooling
  - He gas cell as the moderator

- Low-density graphite aerogel + LHe



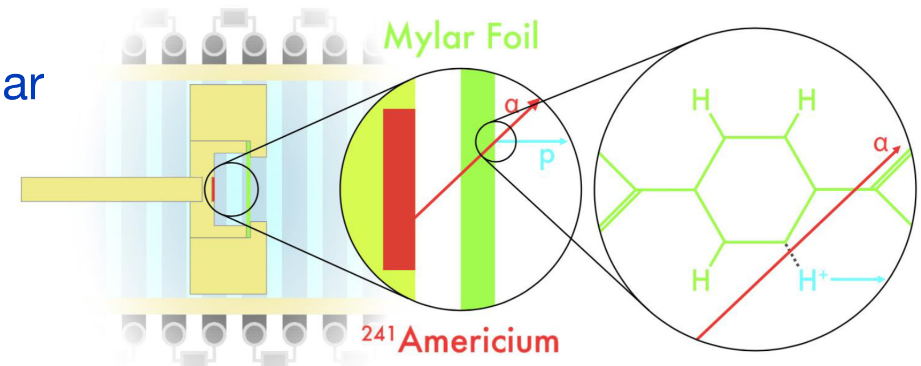


- Use protons to demonstrate the frictional cooling
  - Construct a compact test platform with proton source
  - Silicon drift detector (SDD) for keV proton energy measurement

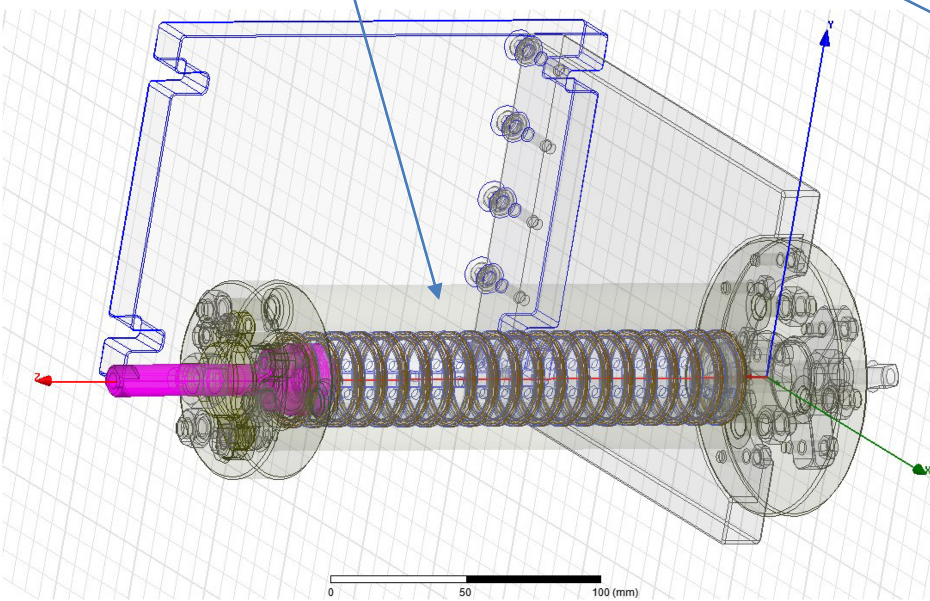
Proton Source

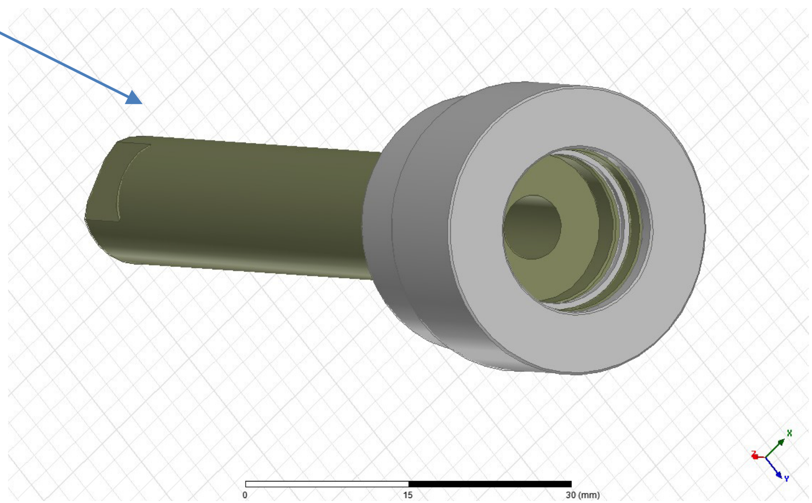
- Am-241 (α source) + Mylar (Hydrogen rich foil)
- Free p created by stripping e^- from H atoms in Mylar
- Apply an electric field (accelerating grid) to accelerate protons up to 60 keV

Am-241 + Mylar



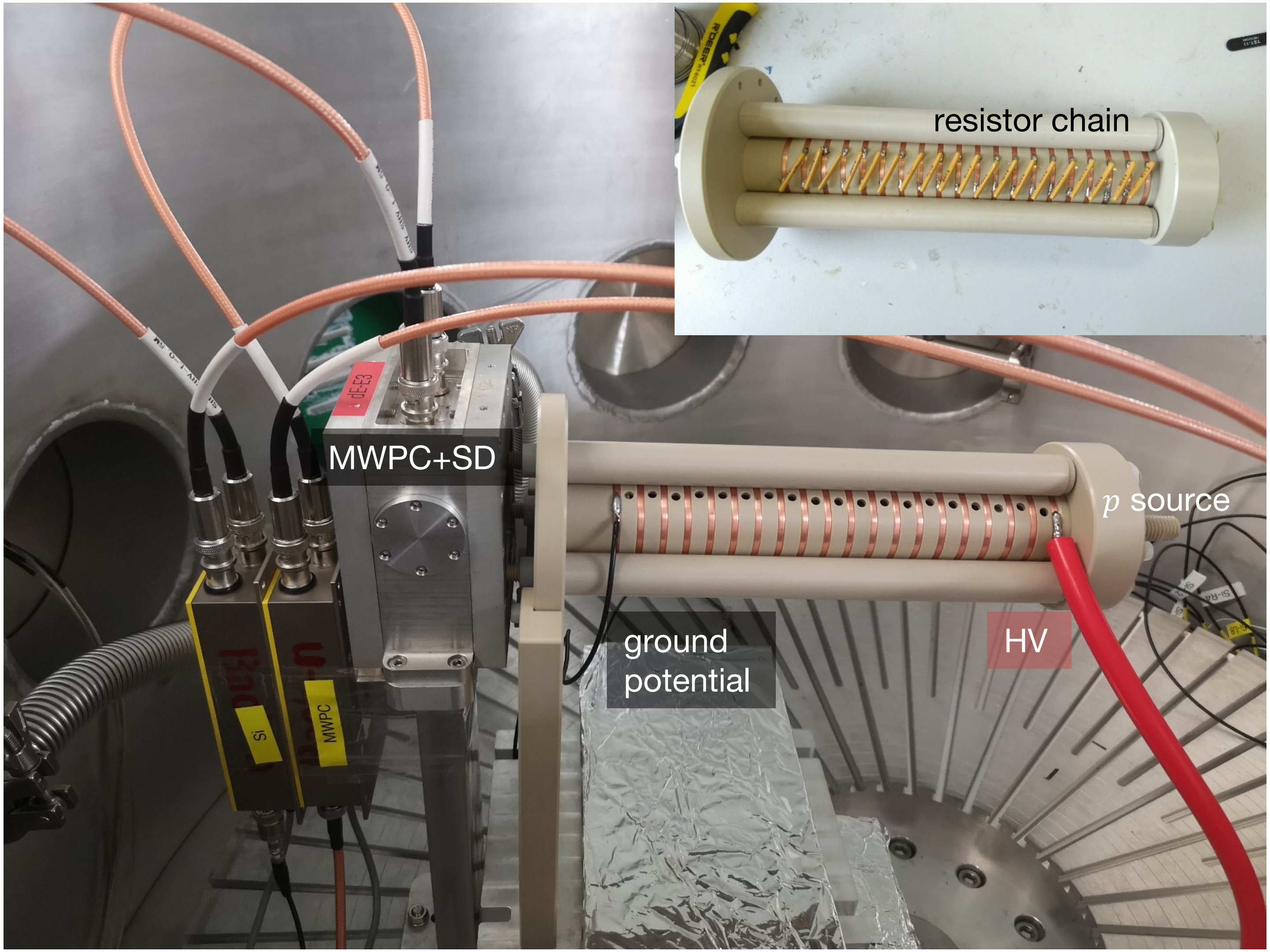
Accelerating grid and p source holder





HV Stability Test of the Accelerating Grid

- Runs reliably up to 65 kV in the vacuum chamber (10^{-5} mbar)



Current Status of the R&D

- Frictional cooling
  - Proton source constructed
  - High voltage stability of the accelerating grid at 65 kV
  - SDD ordered and to be delivered next month
- Liquid helium + graphite aerogel
  - Low-density graphite aerogel substrates will be provided by collaborators from Zhejiang University (浙江大学)
    - Aerogels of 10 $\mathrm{mg/cm^3}$ and 20 $\mathrm{mg/cm^3}$ are ready
  - Ongoing study on the simulation of the moderation process
  - Challenges
    - Experiment: ultra high vacuum environment for the LHe flow
    - Simulation: porous material as the substrate would absorb the LHe
  - Proton- or positron-moderation test in China; apply for muon beam and muCool facility at PSI next year

Summary

- An introduction of slow μ^+ production was presented
- Currently there are two plans for slow μ^+ production for EMuS
  1) Frictional cooling in He gas
  2) Liquid He moderator with low-density graphite aerogel substrate
- The current status of both the experiment and the simulation was summarized for these two plans

THANK YOU!