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Muon Penning Trap at J-PARC

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  - Conceptual design
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J-PARC muon facility

- MUSE (MUon Science Establishment) in the MLF

S line
- surface μ^+
- S1 for μSR
- **S2 for Mu 1S-2S**
- S3 will be constructed this year.
- S4 is planned

3GeV proton from RCS

2e15 /s @1MW

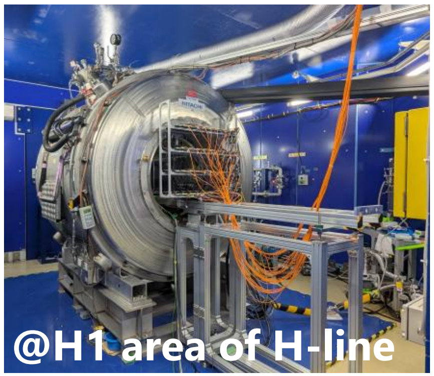
H line
- surface μ^+ (~10^8 μ^+/s, 100% polarization),
- cloud μ^- (~10^7 μ^-/s)
- for high intensity & long beamtime experiments
- **H1 for MuHFS & μ trap**
- H2 for g-2/EDM & TμM

Muon target
(graphite, ^{t}20mm)
Rotating target

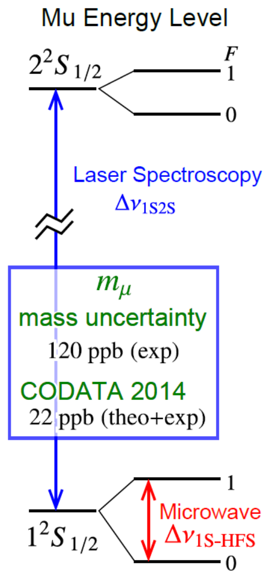
U line
- **ultra slow μ^+**
- U1A for nm-μSR
- U1B for μ microscopy
- under commissioning

D line
- decay μ^+/μ^-, surface μ^+
- D1 area for μSR
- D2 for variety of science

Precision muon physics at J-PARC



MuHFS(MuSEUM)
Muon magnetic moment μ_μ
Fine-structure constant α



μ_μ, α, g_μ

$$\overrightarrow{\mu_\mu} = g_\mu \frac{eh}{2m_\mu c} \vec{s}$$

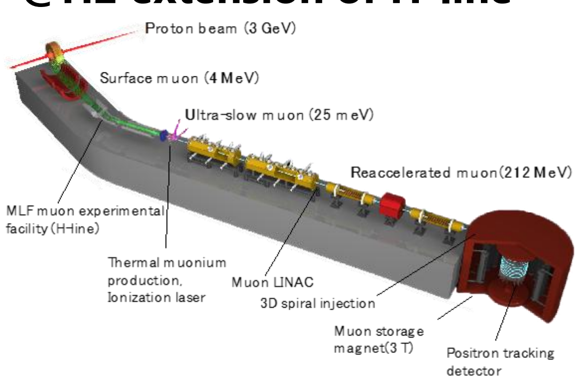
m_μ

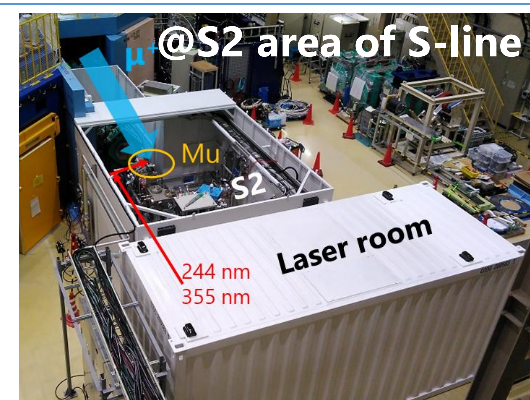
Muon $g-2$
New physics beyond SM

m_μ

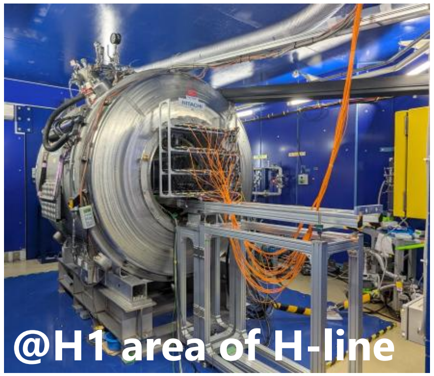
Mu 1s-2s (AMuLET)
Muon mass m_μ

@H2 extension of H-line





Precision muon physics at J-PARC



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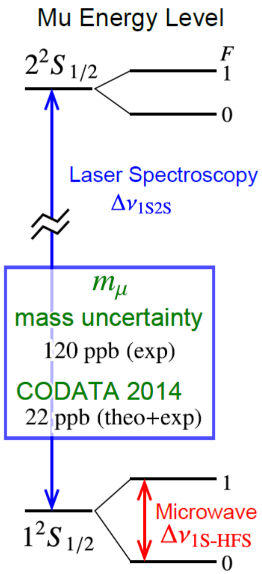

μ_μ, α, g_μ

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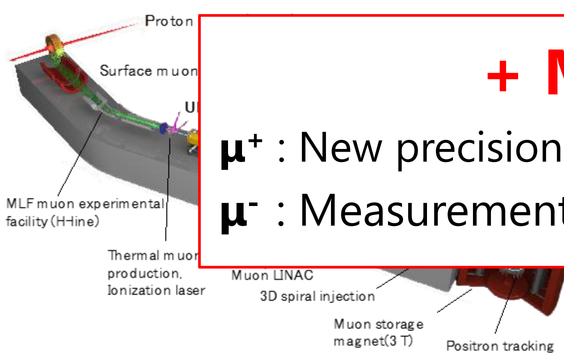
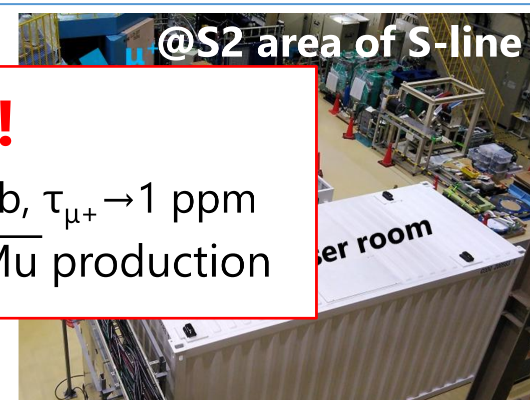


+ Muon Penning trap!

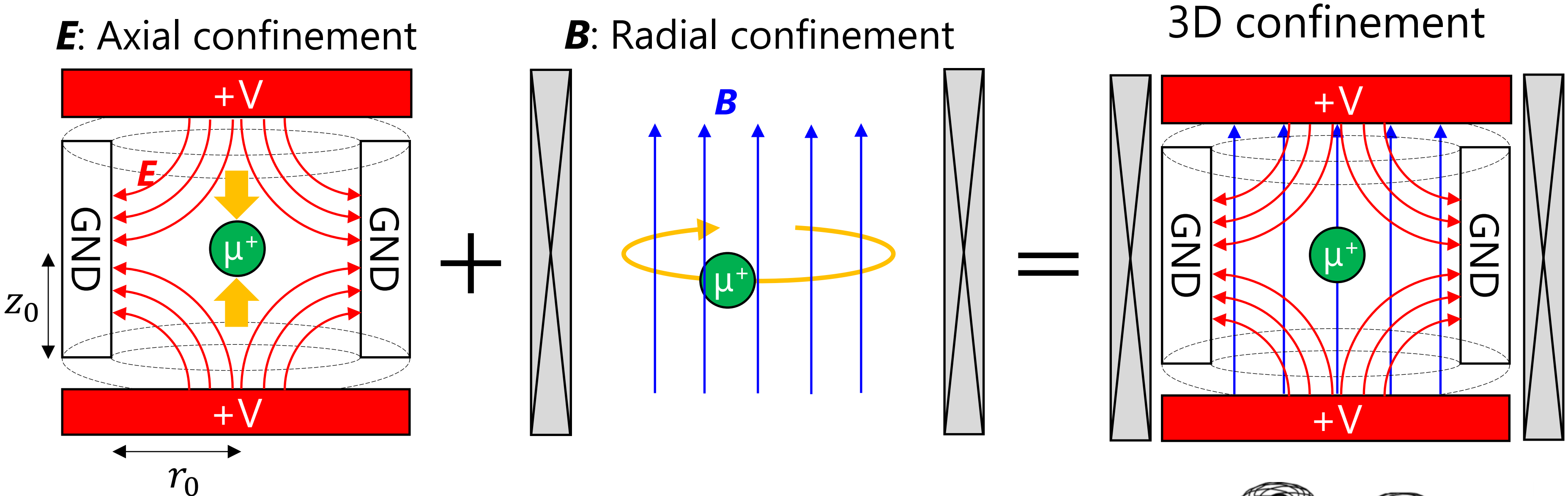
μ^+ : New precision measurement: $\mu_{\mu+}$, $m_{\mu+}$→1 ppb, $\tau_{\mu+}$→1 ppm

μ^- : Measurement of $\tau_{\mu-}$ in vacuum →1 ppm, $\overline{\text{Mu}}$ production



Penning Trap

- Charged particles are confined using a quadrupole electric field and a uniform magnetic field.

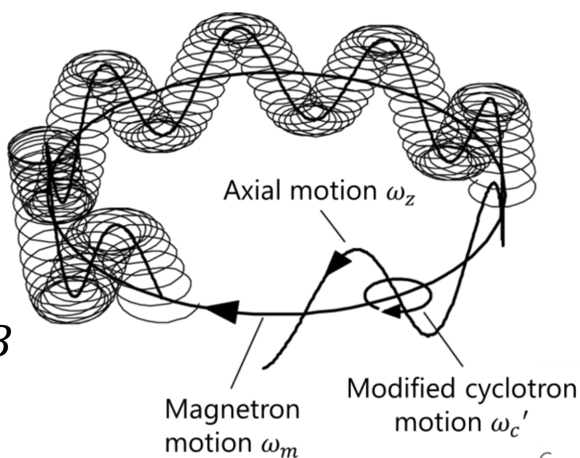


- Particle motion in a Penning trap
  - ✓ Axial motion

    $\omega_z = \sqrt{4eV/mR^2}, R^2 = {r_0}^2 + 2{z_0}^2$
  - ✓ **Modified cyclotron motion**

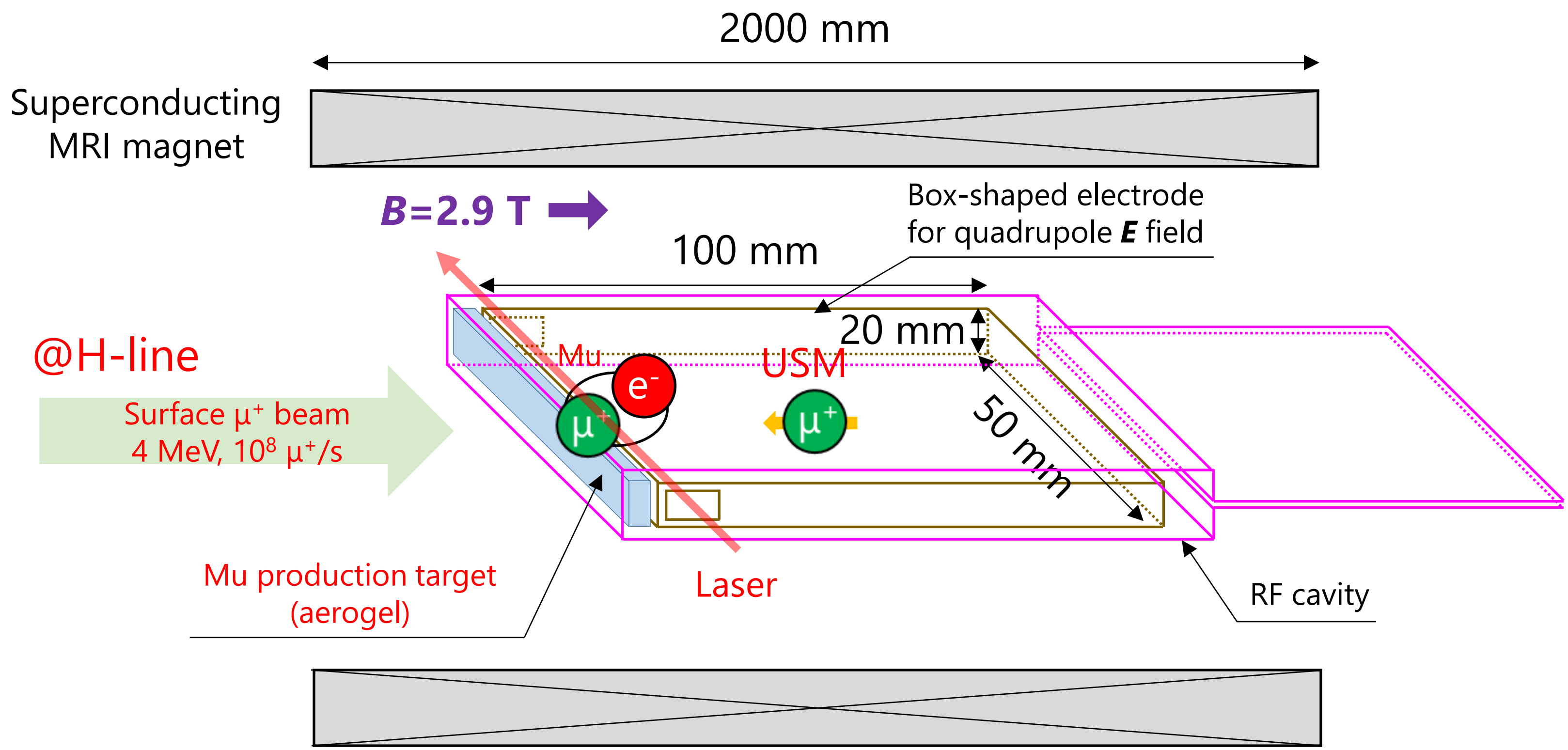
    $\omega_c' = \omega_c/2 + \sqrt{(\omega_c/2)^2 - {\omega_z}^2/2} \sim \omega_c = (e/m) \cdot B$
  - ✓ Magnetron motion ($\boldsymbol{E} \times \boldsymbol{B}$ drift)

    $\omega_m = \omega_c/2 - \sqrt{(\omega_c/2)^2 - {\omega_z}^2/2}$



Positive muon (μ^+)

μ^+ Penning trap at J-PARC

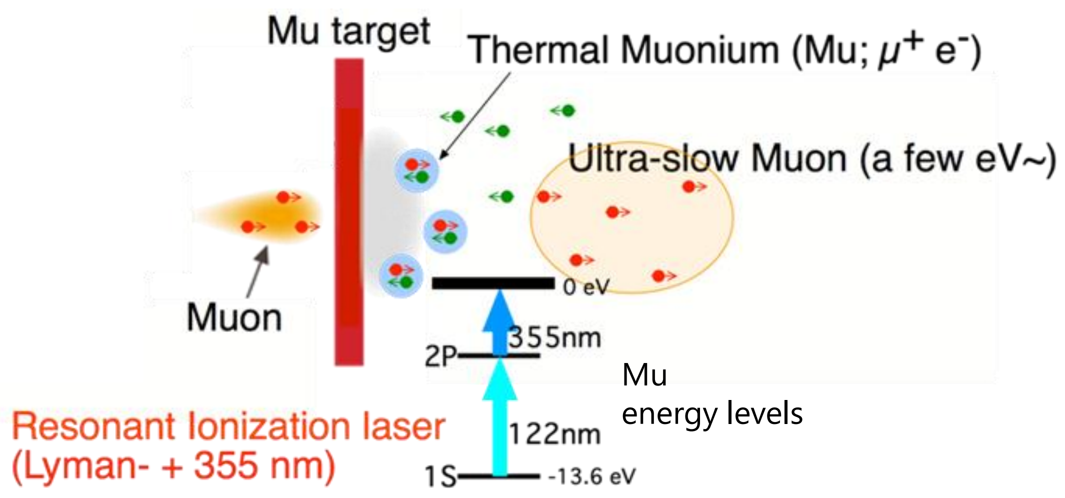


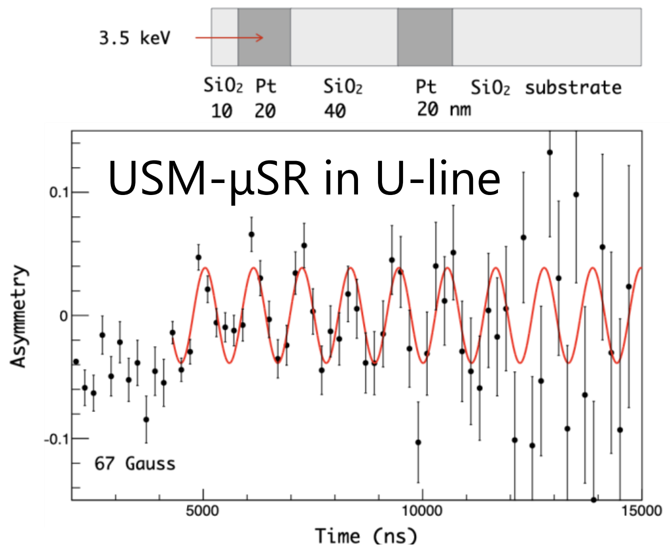
Muons need to be slowed down efficiently before entering trap region!

- Surface muons (4 MeV, 10^8 /s) are stopped in a laser-ablated aerogel target to produce muonium atoms (Mu). Pol = 100% in a high magnetic field.
- Ultra-slow muons (USM, 30 meV, 10^5 /s) are generated by laser-ionizing muonium atoms.

Ultra-slow muon (USM) generation

USM generation has been developed in U-line, and O(100) muons/s on a sample was already observed.

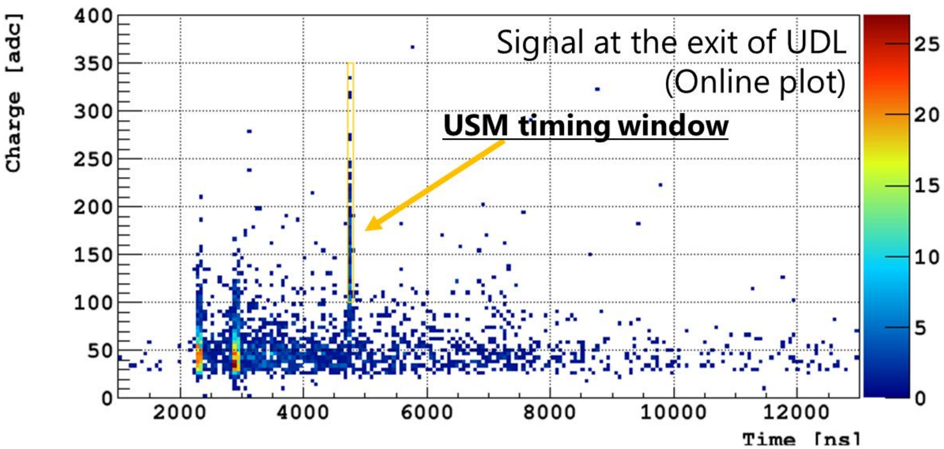




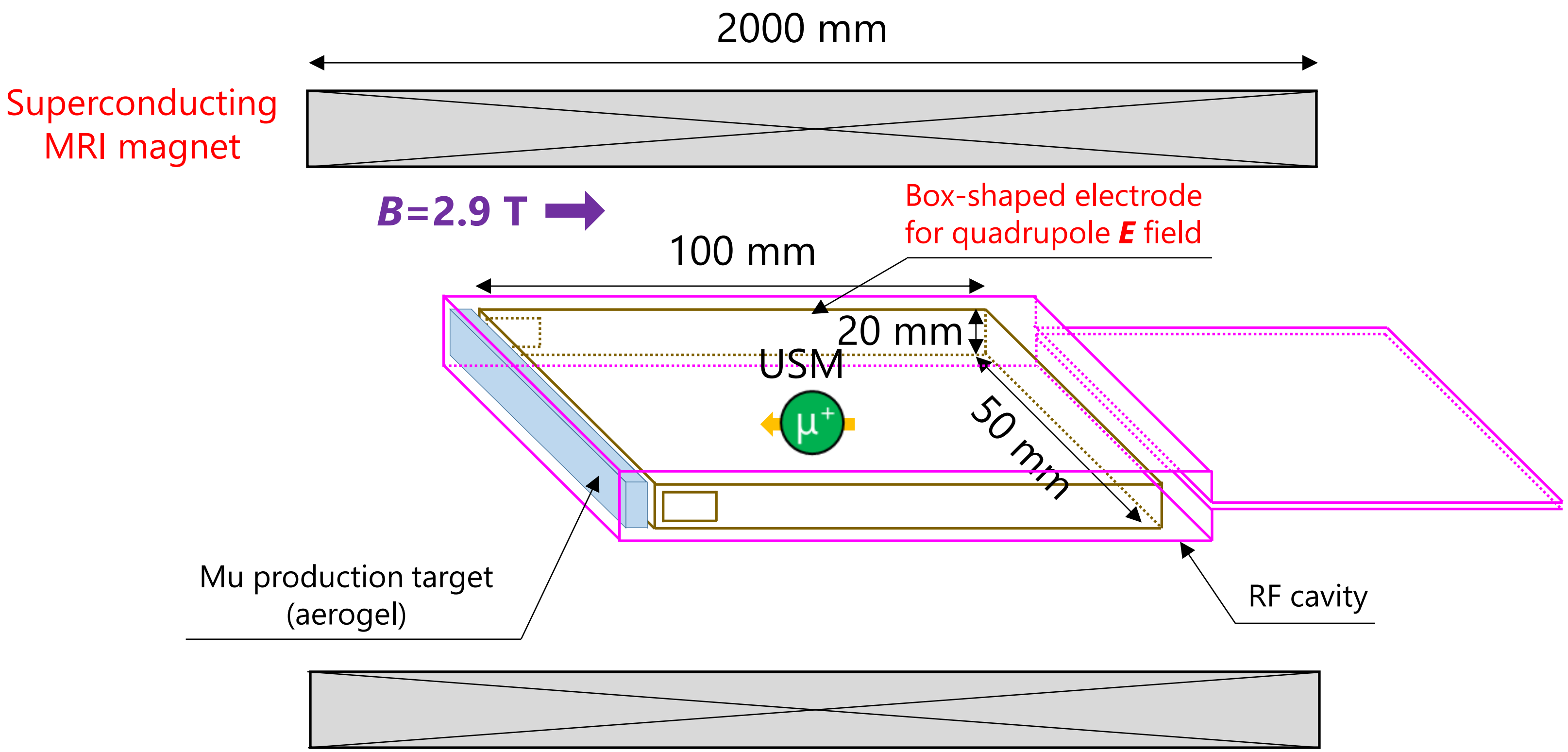
New 122nm and 355nm light sources for H-line is being developed.

In Dec. 2025, we observed the first USM signal in H-line! (only 0.15 USM/s)

- Laser upgrade is underway to achieve ~10^5 USM/s.



μ^+ Penning trap at J-PARC

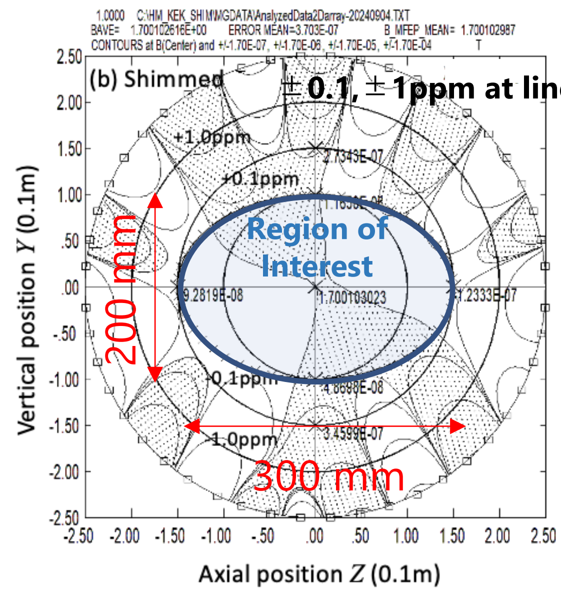


- Ultra-slow muons are confined in a Penning trap using a superconducting MRI magnet and a box-shaped electrode which generates quadrupole electric field.

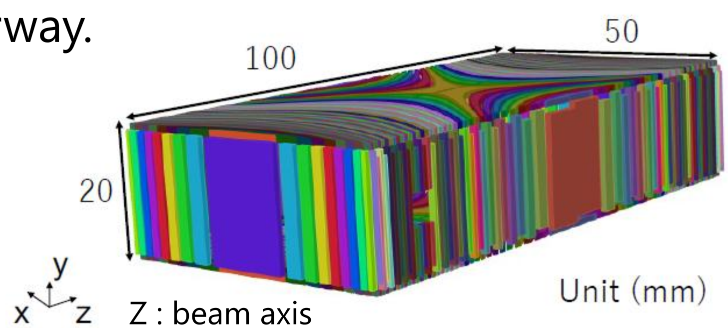
Magnetic and electric field

- A superconducting MRI magnet is installed in H1 area
  - Solenoid, Max. 2.9 T in beam direction (z axis)
  - Uniformity < ±0.1 ppm after passive shimming with Fe and Ni plates

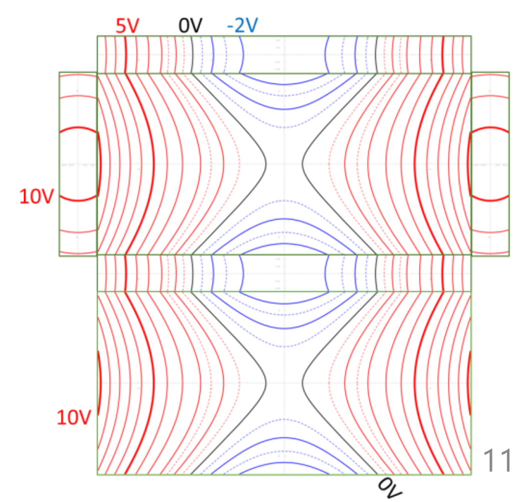
field X-Z map



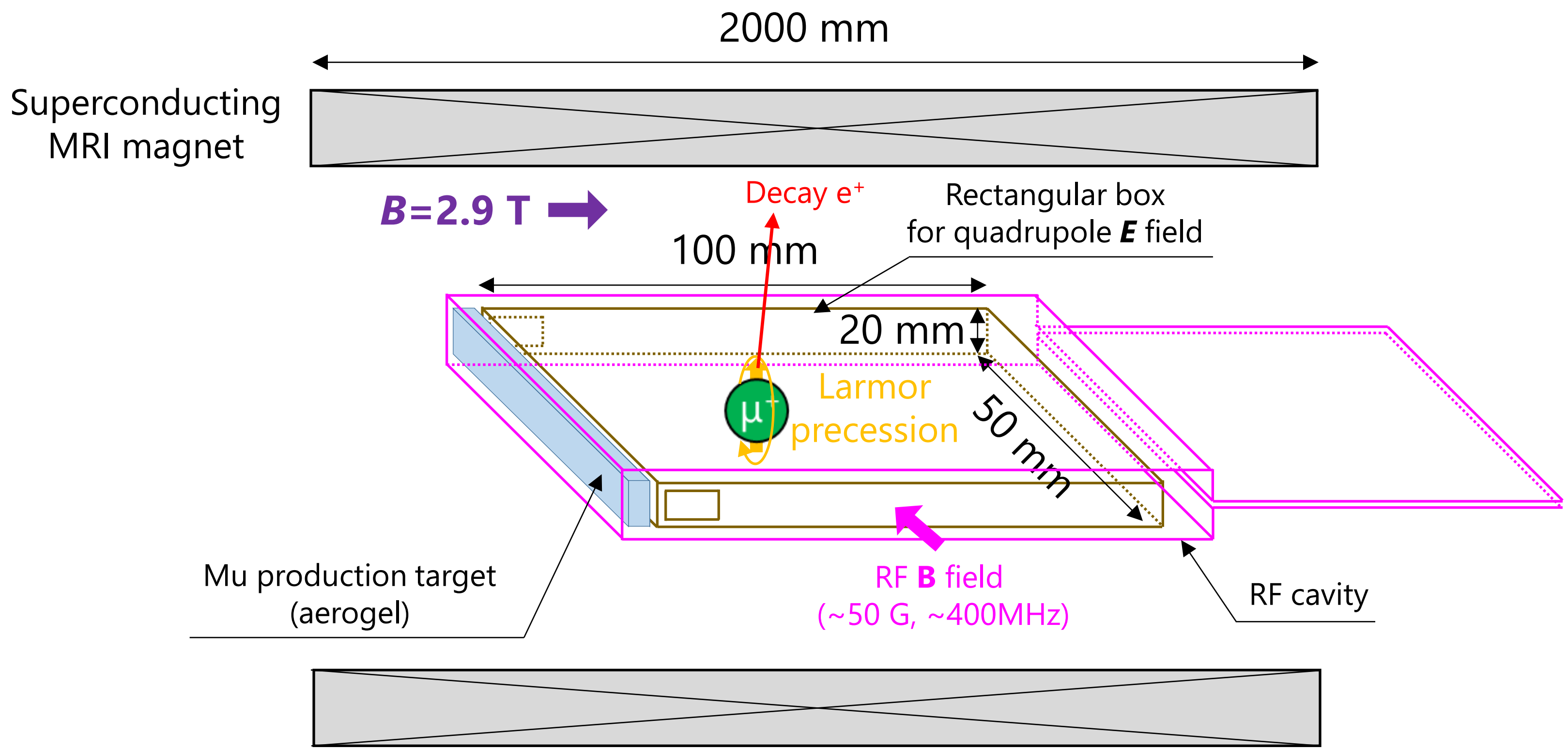
- A box-shaped segmented electrode is used to apply a quadrupole electric field.
  - Box-shape can capture more ultra-slow muons.
  - Translational symmetry in y-axis (vertical), but trapped muons decay before escaping the box.
  - Design is underway.



Net of the electrode



μ^+ Penning trap at J-PARC



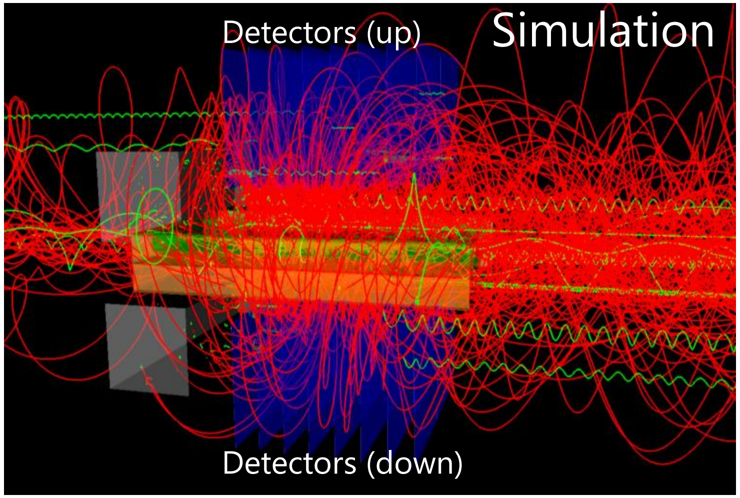
- An RF magnetic field (B~50 Gauss, f~400 MHz matches the Larmor frequency due to the static magnetic field) is applied for ~1 μs to make their spins orthogonal to the static magnetic field. RF cavity design is in progress.
- Decay positrons are detected by positron counters placed above and below the trap region to measure Larmor precession due to the static magnetic field (T~2.5 ns in B=2.9 T).

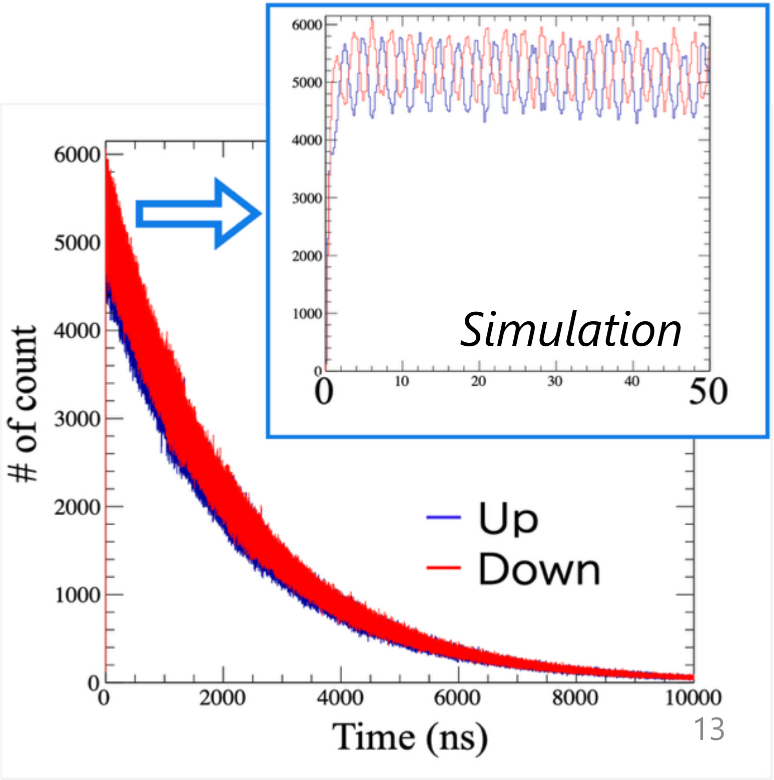
μ^+ Penning trap at J-PARC

- The magnetic moment $\mu_{\mu+}$ and the lifetime $\tau_{\mu+}$ are measured from the time spectrum of decay e^+.
- If we can generate 10^5 USM/s and confine them, we can observe ~10^{12} events in 100 days DAQ.
  - ✓ Stat. uncertainty of the gyromagnetic ratio γ_μ is 6 ppb in a MC simulation
- If we can measure decay positions, m_μ (e/m_μ) is also obtained from ω_c.
- We will conduct studies on systematic uncertainties.

Based on the calculation by T. Adachi (RIKEN)

	Efficiency	# of muons /sec
Injection to H1 area		1.0×10^8
Beam transportation	19%	1.9×10^7
Stop at aerogel target	15%	4.1×10^6
Muonium evacuation	20%	6.0×10^5
Passing mesh electrode	90%	5.4×10^5
Muonium in laser region	24%	1.3×10^5
Ionization rate by laser	80%	1.0×10^5

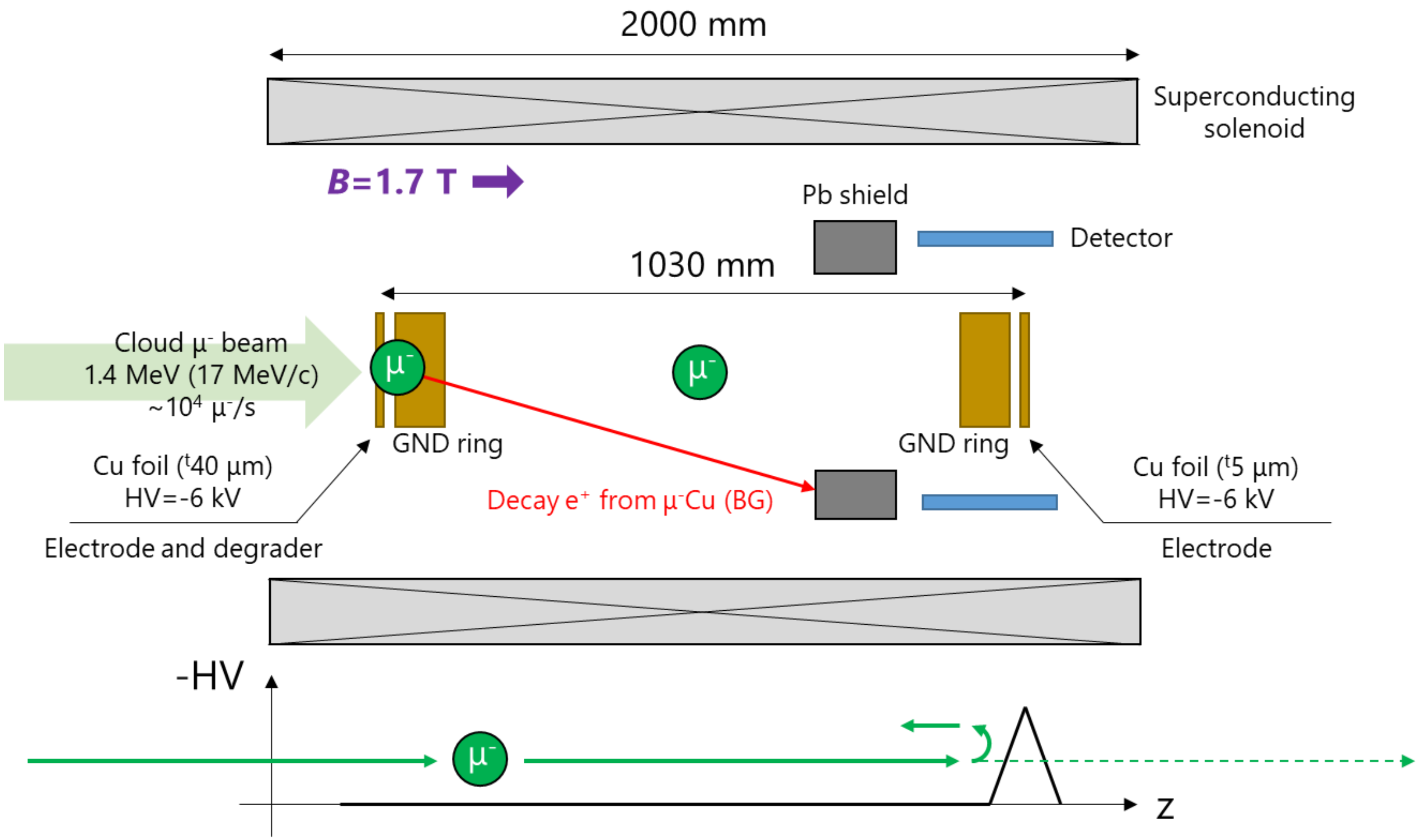




Negative muon (μ^-)

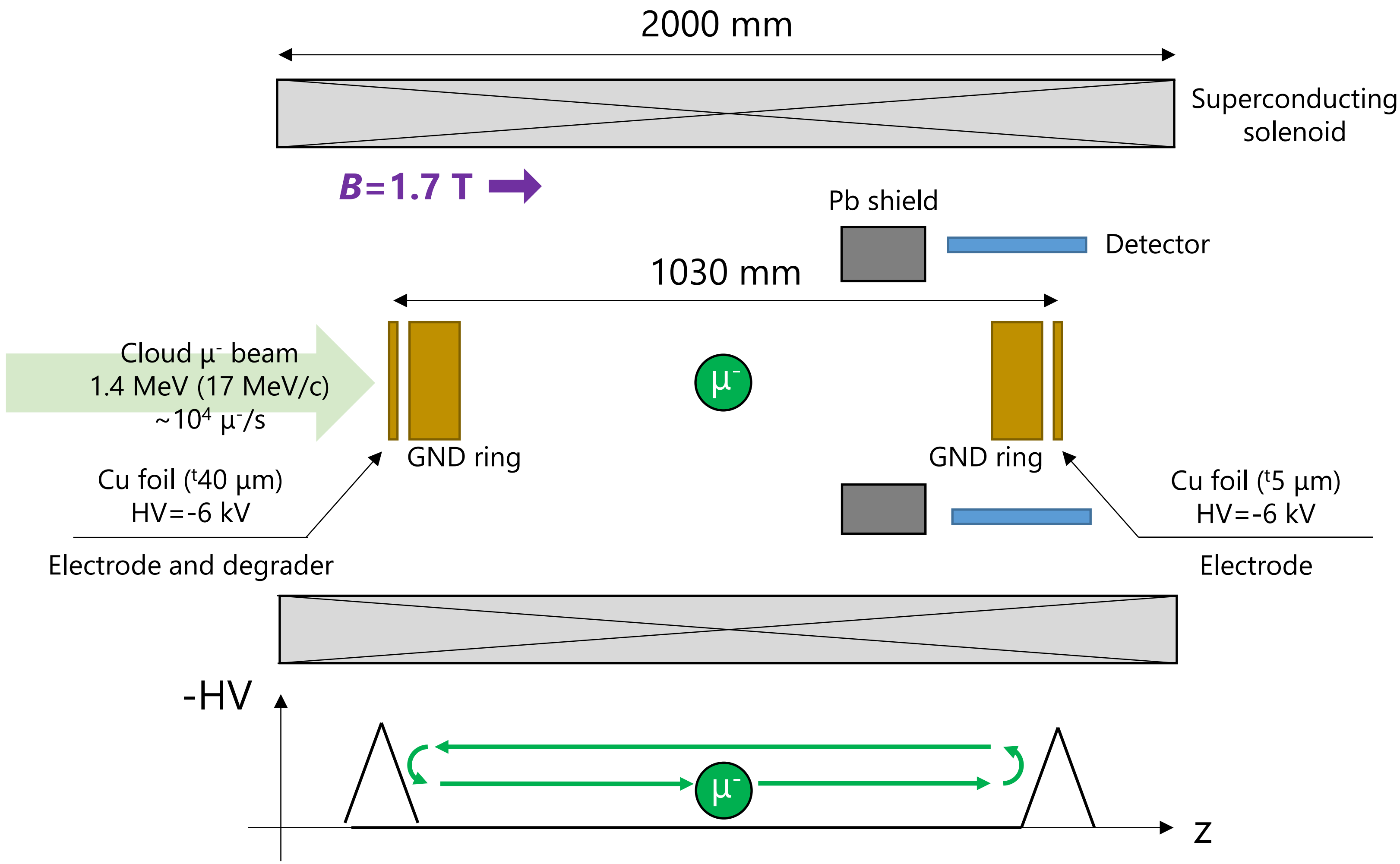
First demonstration of μ^- trap

- Demonstration of confining short-lived particles in EM field



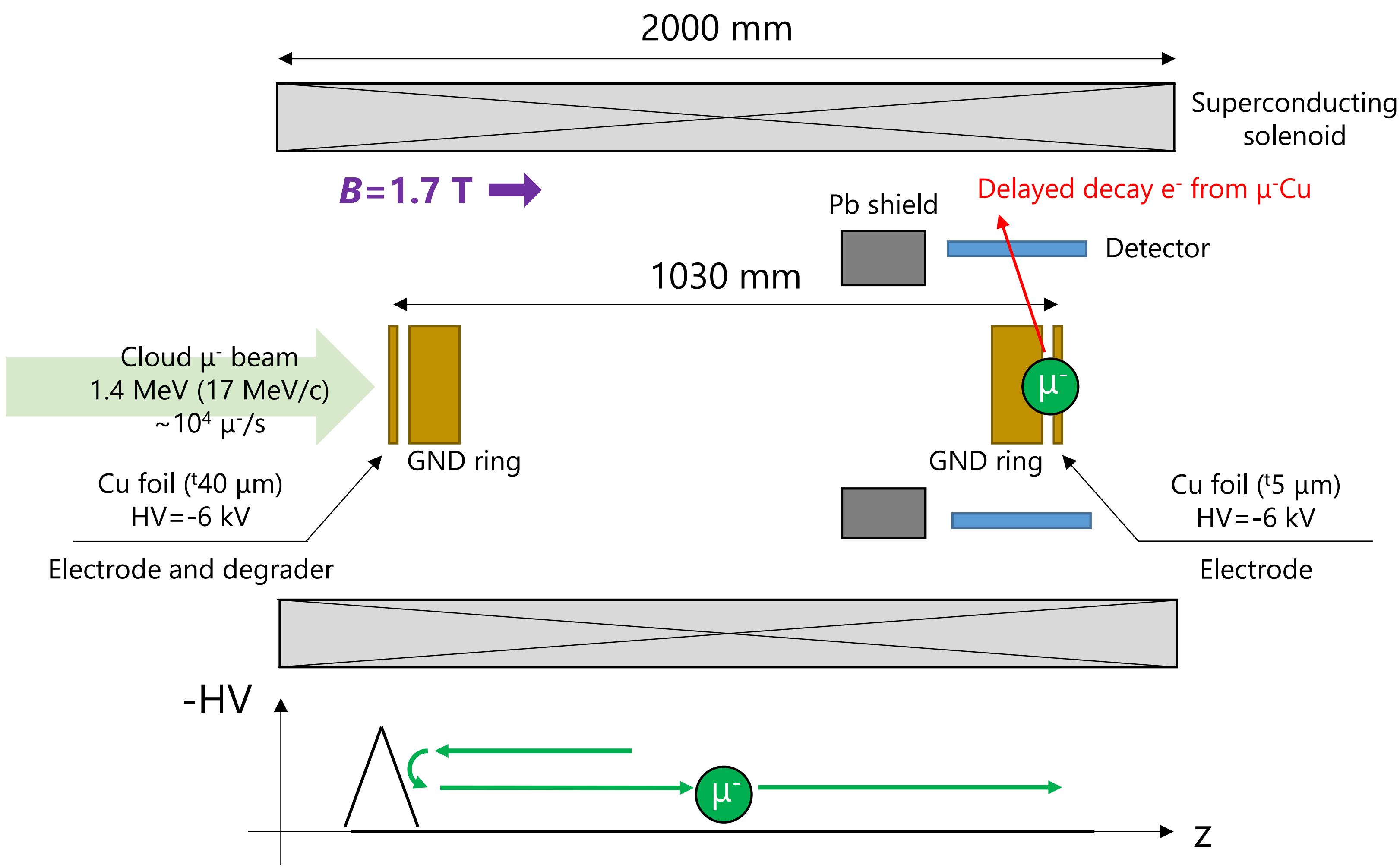
- The energy of pulsed μ^- beam is degraded using a 40 μm-thick Cu degrader. Negative muons with energies below 6 keV are reflected at the downstream electrode.

First demonstration of μ⁻ trap



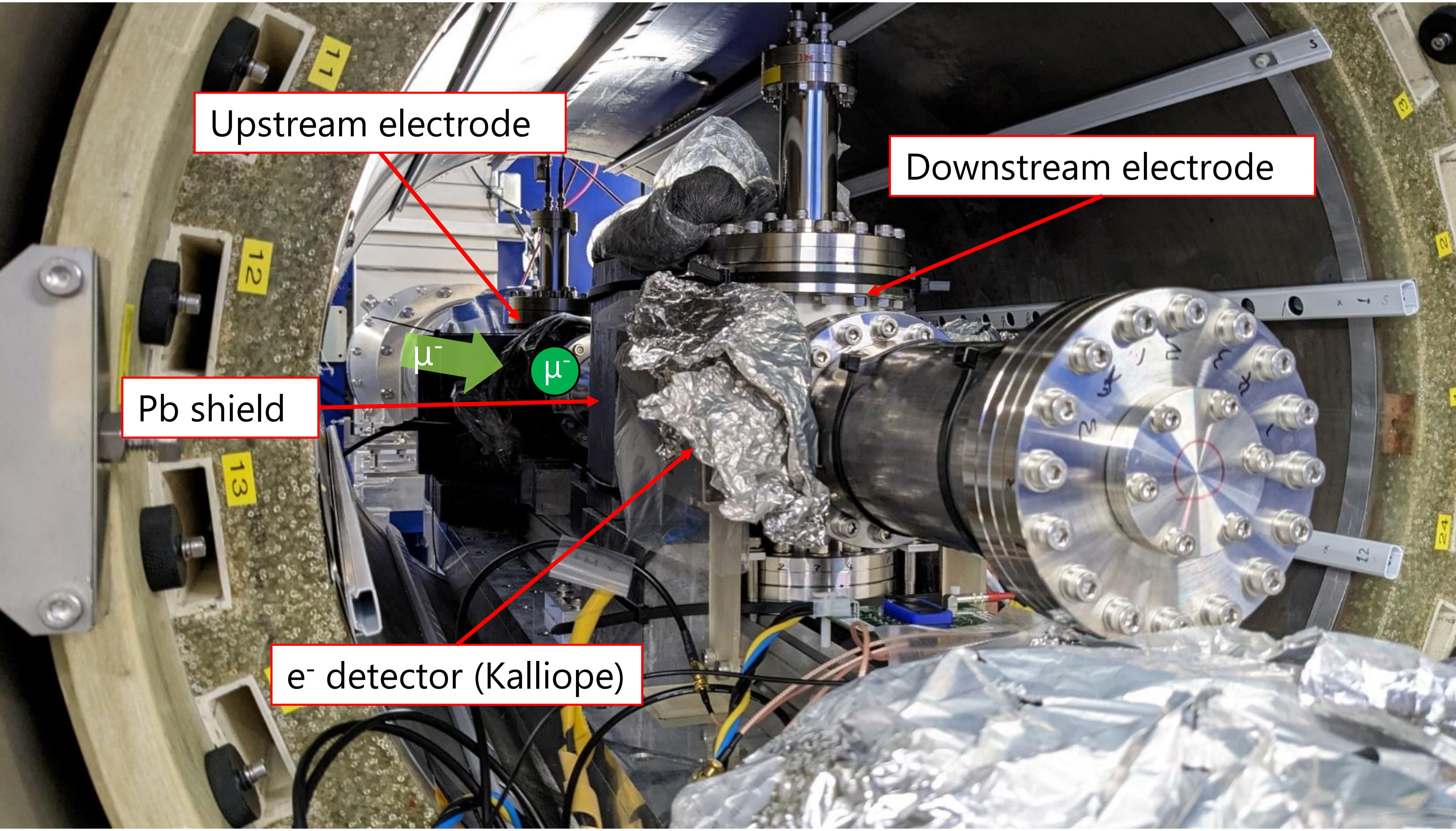
- After the μ⁻ injection, high voltage is applied to the upstream electrode, and then μ⁻ are trapped.

First demonstration of μ⁻ trap



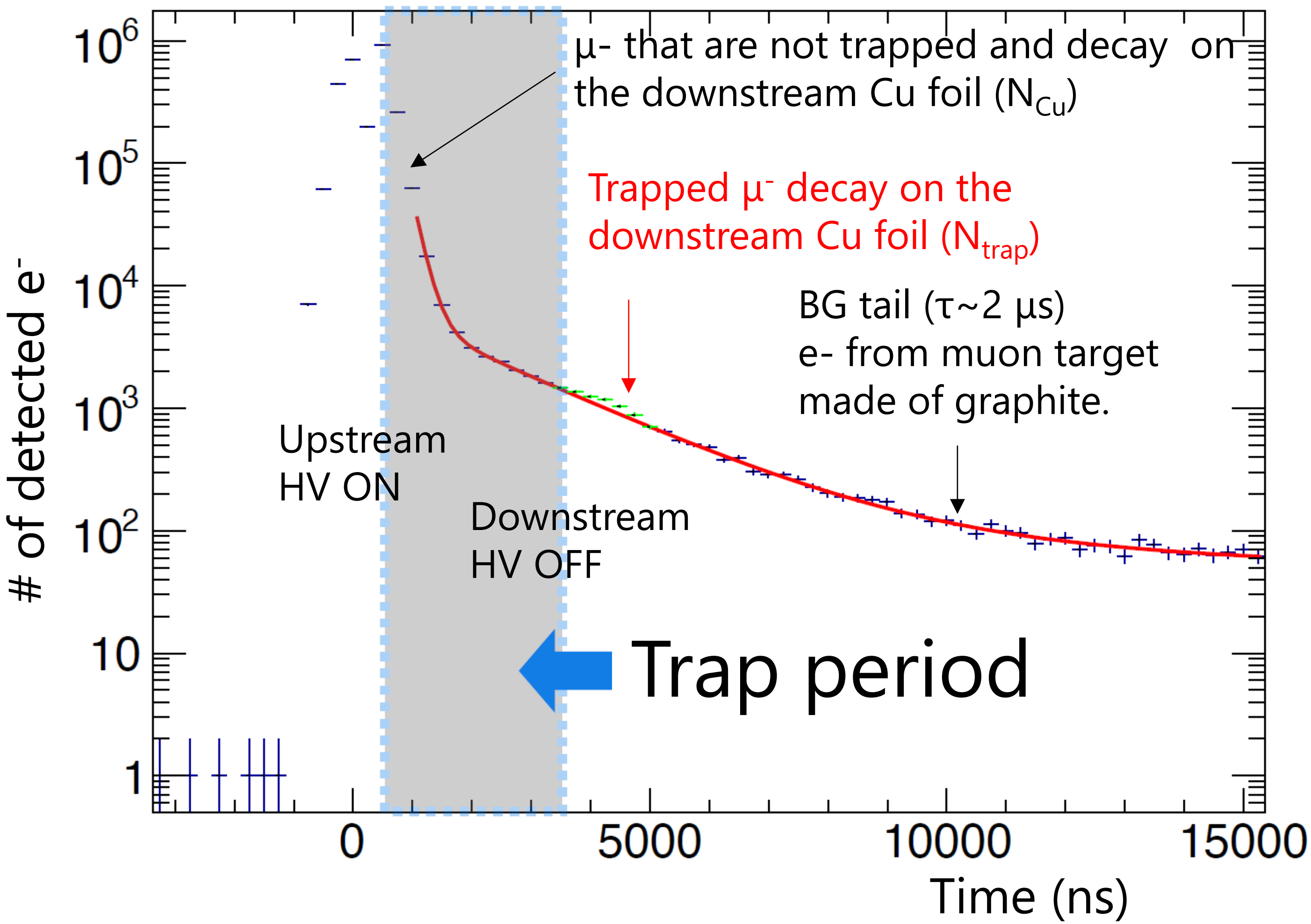
- HV of the downstream electrode is turned off after a few μs. Then, trapped μ⁻ hit the downstream electrode, and e⁻ are emitted with the μ⁻ lifetime in Cu (160 ns). Signal = Delayed, short-lived component

First demonstration of μ⁻ trap



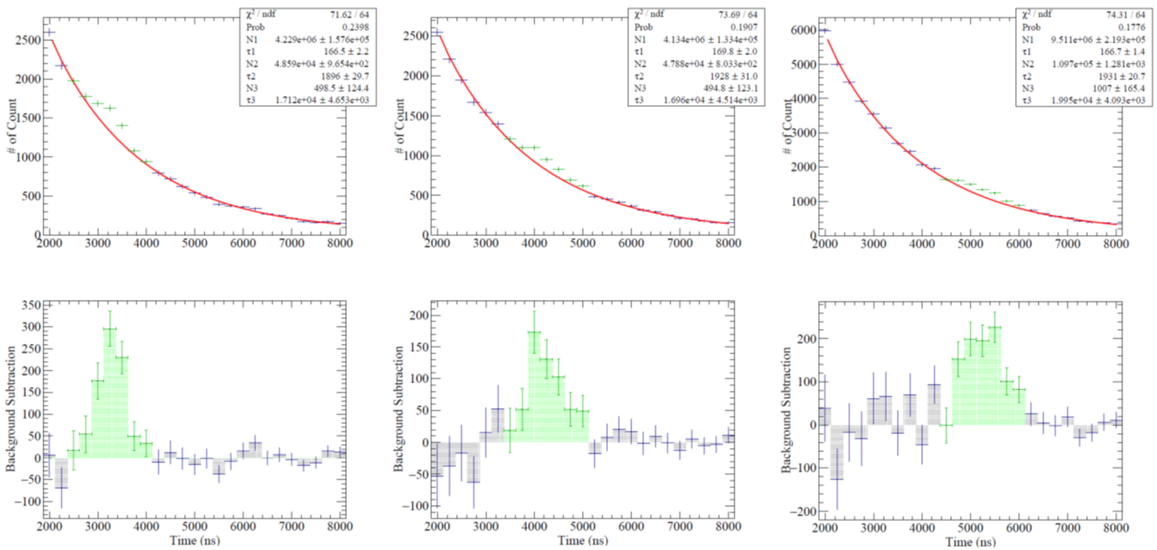
Results

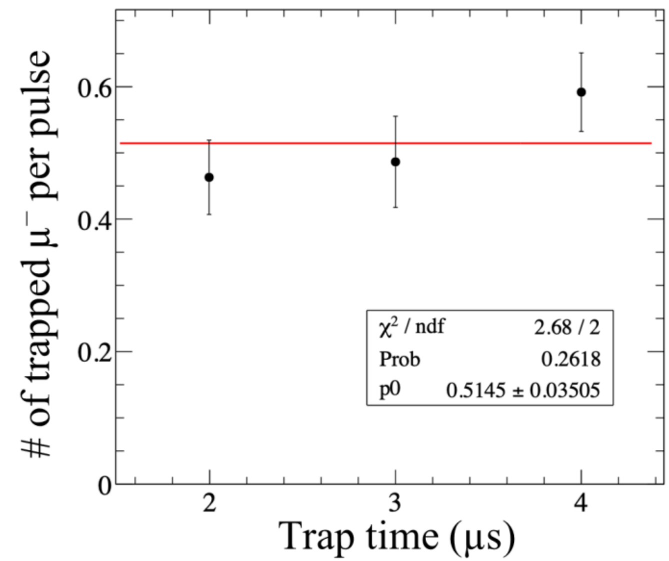
- μ-, 17 MeV/c, HV=-6 kV, Trap period=3 μs



Results

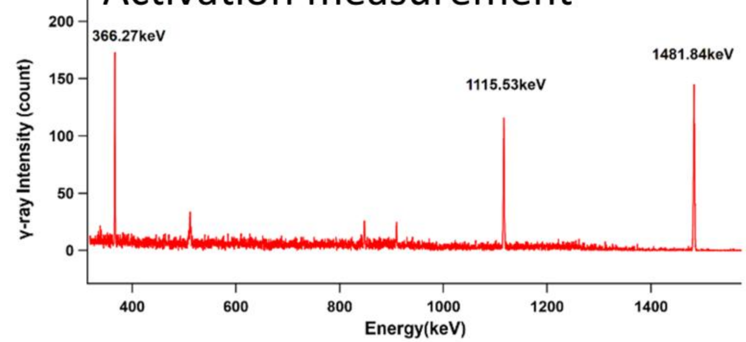
Trap period=2 μs Trap period=3 μs Trap period=4 μs





- The timings of the signal peaks changed according to the trap periods.
- Detection efficiency of our setup was estimated using Geant4, and # of trapped μ- is estimated as 0.52 μ^-/pulse.
- # of injected μ- was also estimated to be 600 μ^-/pulse (P=17 MeV/c) from activation of Cu.
- Trapped μ^- / Injected μ^- = 0.09 %.

Activation measurement



Prospects of μ^- trap

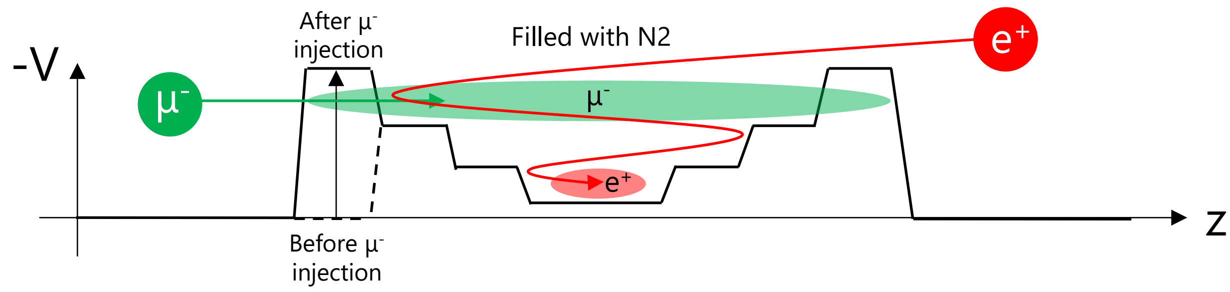
μ^- lifetime measurement

- Current world record is 70 ppm by correcting the lifetime in liquid hydrogen using the muon nuclear capture rate (G. Bardin, et al., Phys Lett. 137B, 135 (1984)).
- We aim to measure μ^- lifetime in vacuum using an upgraded Penning trap with a multi-ring electrode and large acceptance e^- detectors.

$\overline{\text{Mu}}$ production

- Antimuonium ($\overline{\text{Mu}}$, $\mu^- e^+$) could be produced by confining μ^- and e^+ in a Penning trap simultaneously.
- Toward first observation of $\overline{\text{Mu}}$, we aim to improve the efficiency of μ^- cooling (Muon decelerator, frictional cooling, …).

$\overline{\text{Mu}}$ production



Summary

- We aim at a precise measurement of μ_μ, τ_μ, and m_μ by confining ultra-slow muons in a Penning trap.
- Recently, we demonstrated μ^- trap at J-PARC muon H-line.
- As a next step, we plan to measure μ^- lifetime in vacuum and develop an efficient method to cool μ-.