Progress and prospect of the thermal muon source at J-PARC

S. Kamioka

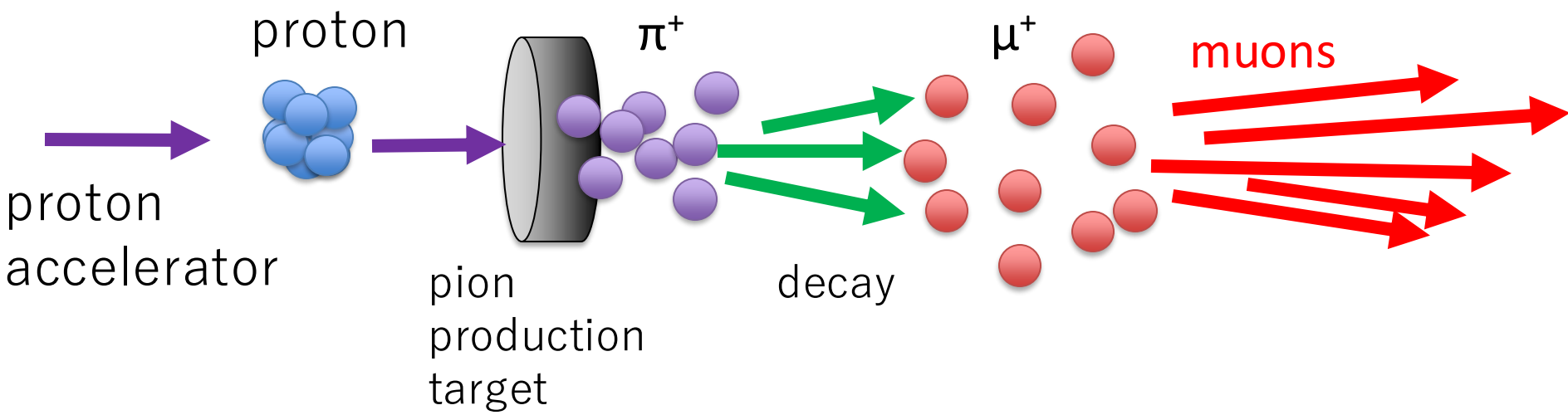
KEK, IPNS

On behalf of the collaboration

Towards a low emittance (positive) muon beam

- Conventional surface muon beam: high intensity but **its beam quality is not very good**
  - Normalized transverse emittance: **1000 π mm-mrad (typ.)**
  - Longitudinal: **Δp/p ~5% & Δt ~ 100ns (at J-PARC)**

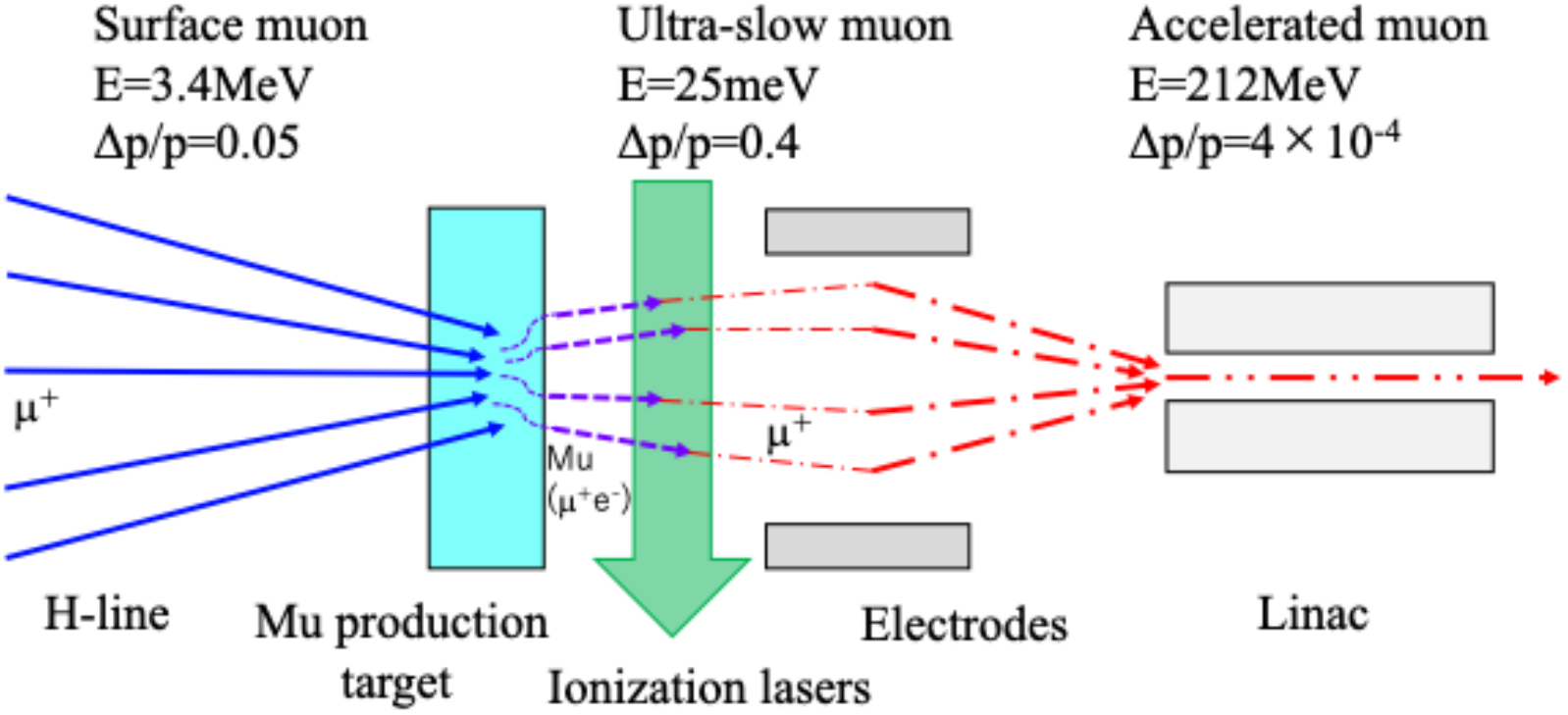
✓ **<u>Muon cooling</u>** is essential for next-gen muon experiments



Production of conventional muon beam

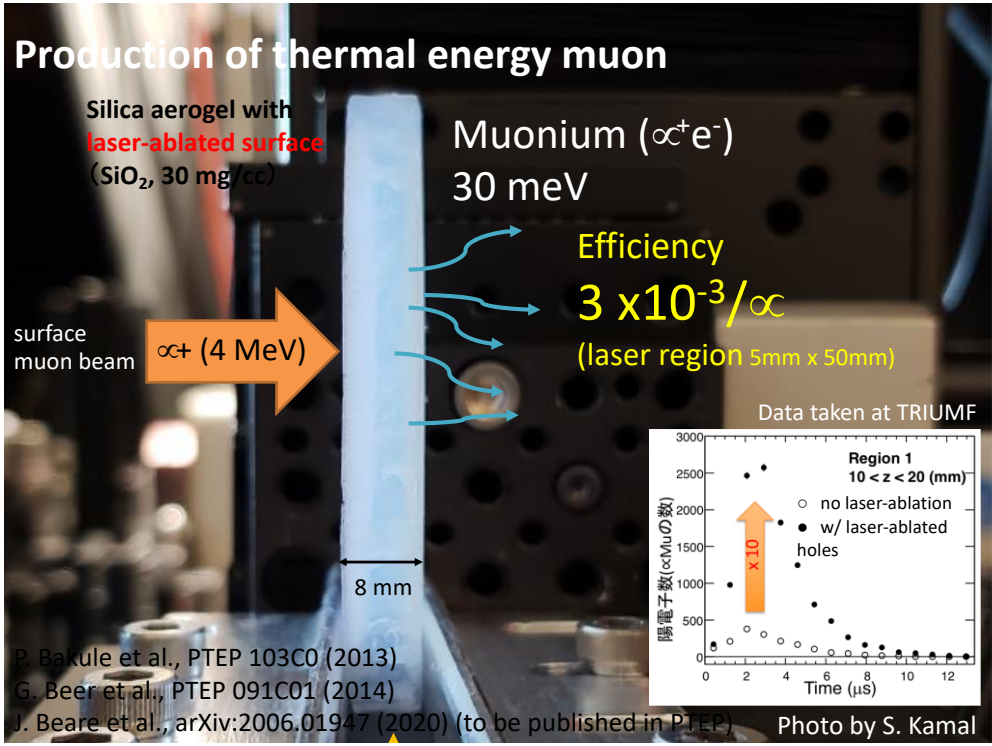
Muon cooling at J-PARC

- ✓**The ultra-slow muon (USM) and its re-acceleraiton**
  - ➢ **ultra-slow muon: thermal energy muon source**
- ➢Surface μ^+ → Mu Target & Mu emission → Resonance multi-photon ionization → Init. transport → Linac
- ✓~1/1000 reduction of normalized transverse emittance



Key technology 1: muonium production target

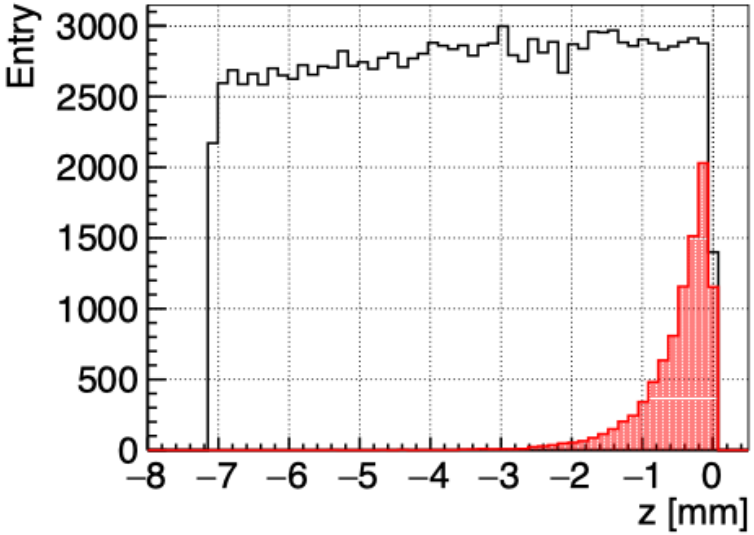
- **Laser-ablated aerogel**
  - Drilled by short-pulse laser
  - ×10 emission compared to a conventional aerogel
  - Mu formation eff: 52%
- **Established diffusion model**
  - 3D random walk inside a uniform material
  - T~320K -> production of thermal Mu (E_{kin} **=25 meV**)
- Spin pol. becomes **1/2**
  - Hyperfine structure of Mu



Expected performance of the target

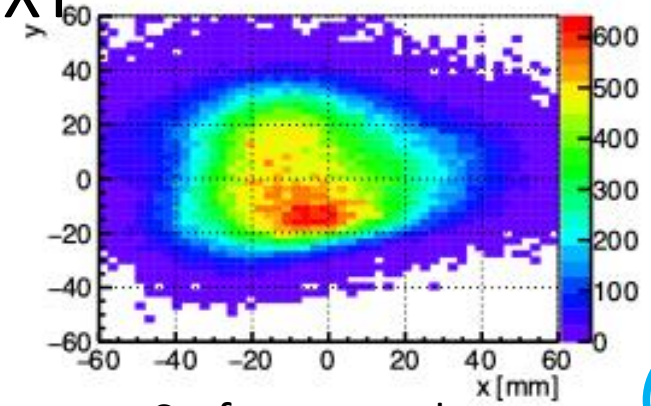
- Simulation assuming H-line of J-PARC MLF (pulse, double bunch)
- Vacuum emission efficiency: **6%**
  - In addition: Mu formation eff (52%), Stopping eff (40%)

Black: total stopped Mu
Red: those emitted to vacuum



Simulation: Typical emission profile at laser irradiation timing

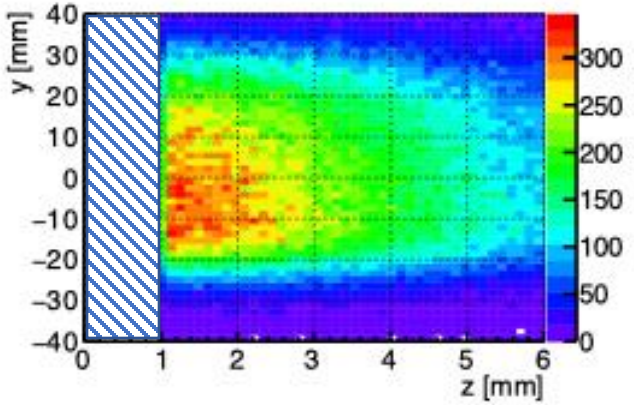
XY



Surface muon beam

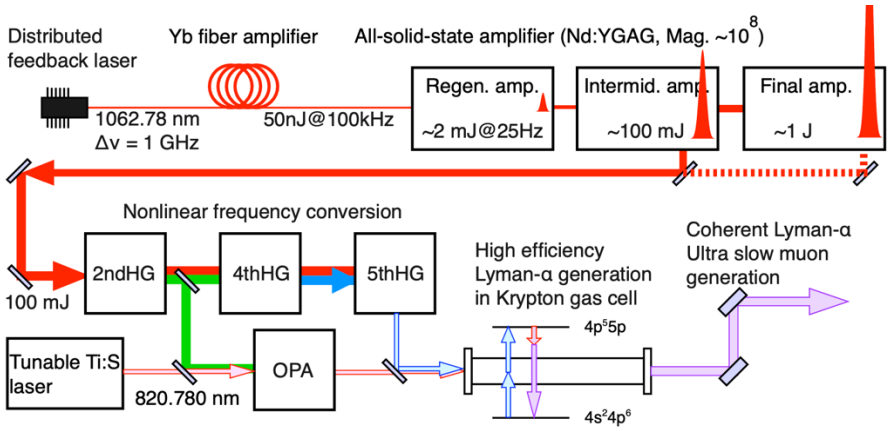
ZY

muon beam

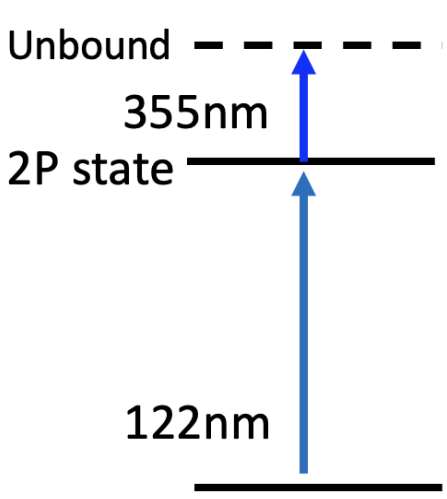


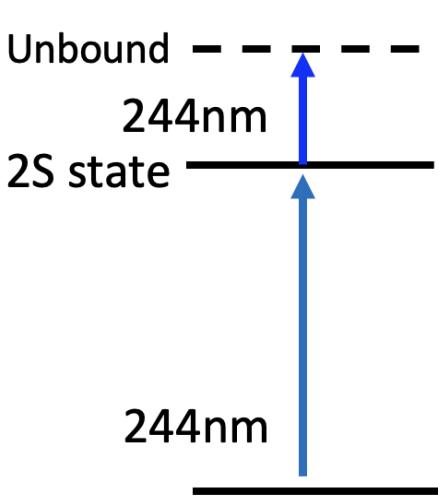
Key technology 2: Photo-ionization of muonium

- **Ionization of muonium is very challenging**
  - Resonant multi-photon ionization via 2S or 2P
    - ✓ Still, **VUV (122nm) or DUV (244nm)** laser is necessary
  - Large spatial spread & doppler width: **~2cm² & 80GHz**
- **25Hz rep & 2ns pulse duration is required**
  - To synchronized with J-PARC beam & to keep muon bunch short



Solid-state high-energy UV laser development

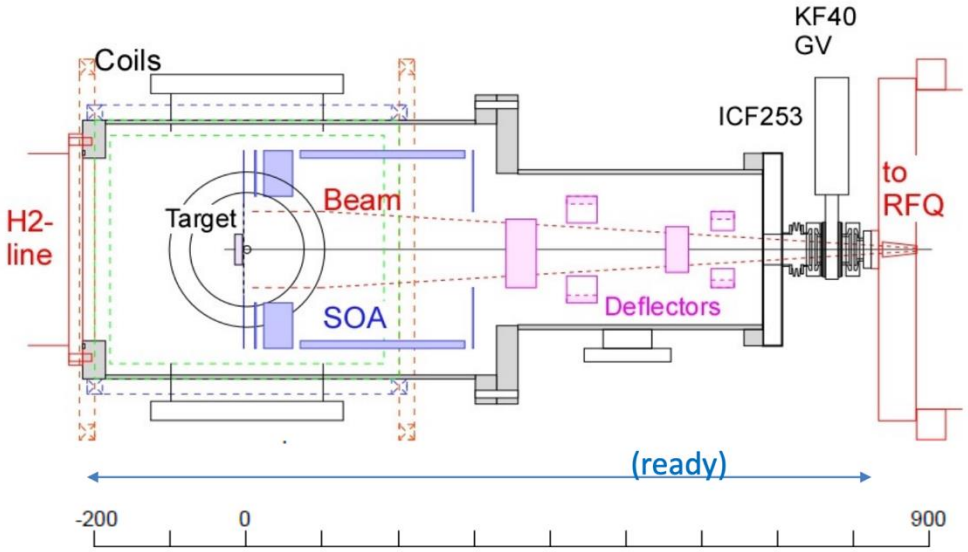


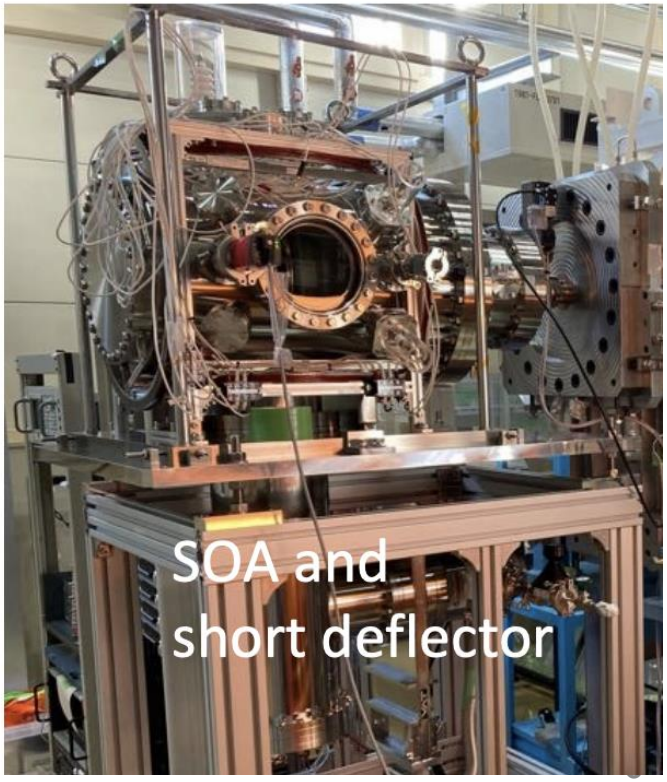


Electrostatic transport

- Thermal muons are electrostatically accelerated to 5.7keV and focused to the entrance of following rf-cavities.
- **Soa-lens**, originally developed for positron transport
- Diagnostic line for these 5.7keV muon is also equipped

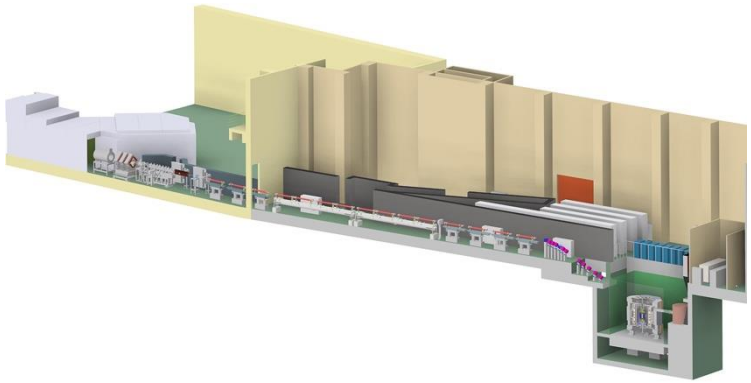
Schematic

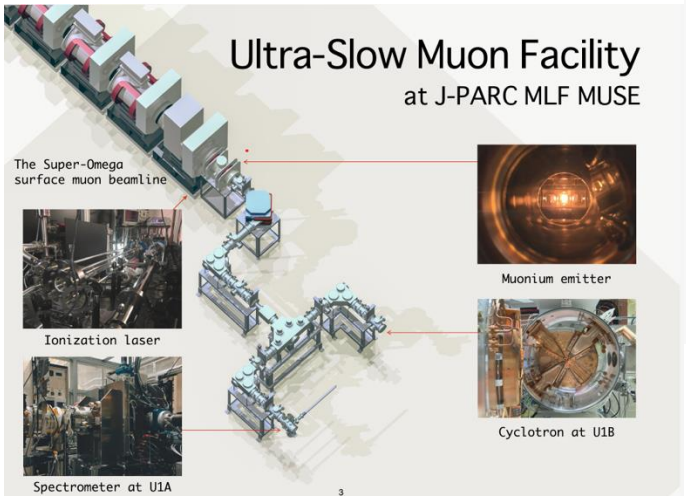


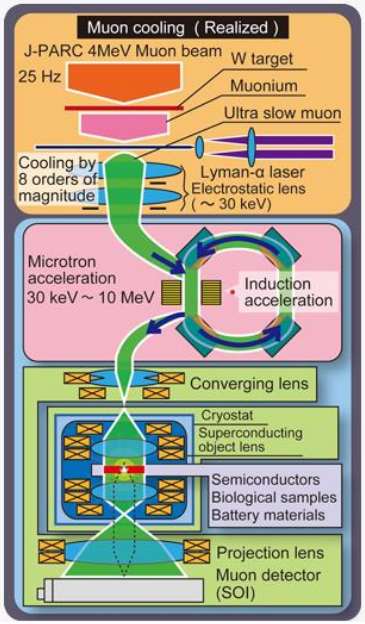


Expected performance & Application

- Specification,
  - **25Hz, 2ns**
  - **E=30meV (300K)**
  - **Up to ~10^5 /s**: depending on laser energy
  - Norm. transverse emittance: **<1π mm-mrad**
  - Spin polarization is **50%**
- Application
  - J-PARC muon g-2/EDM exp
  - μSR
  - Muon microscope



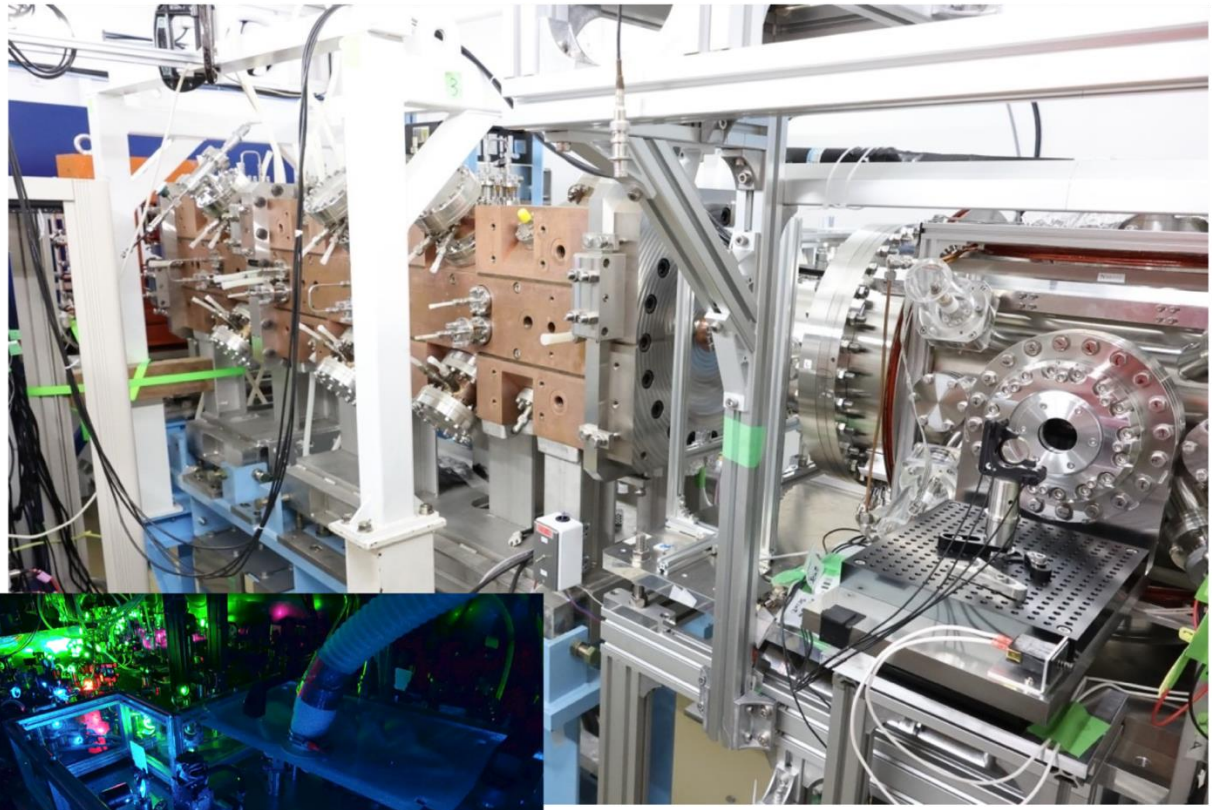




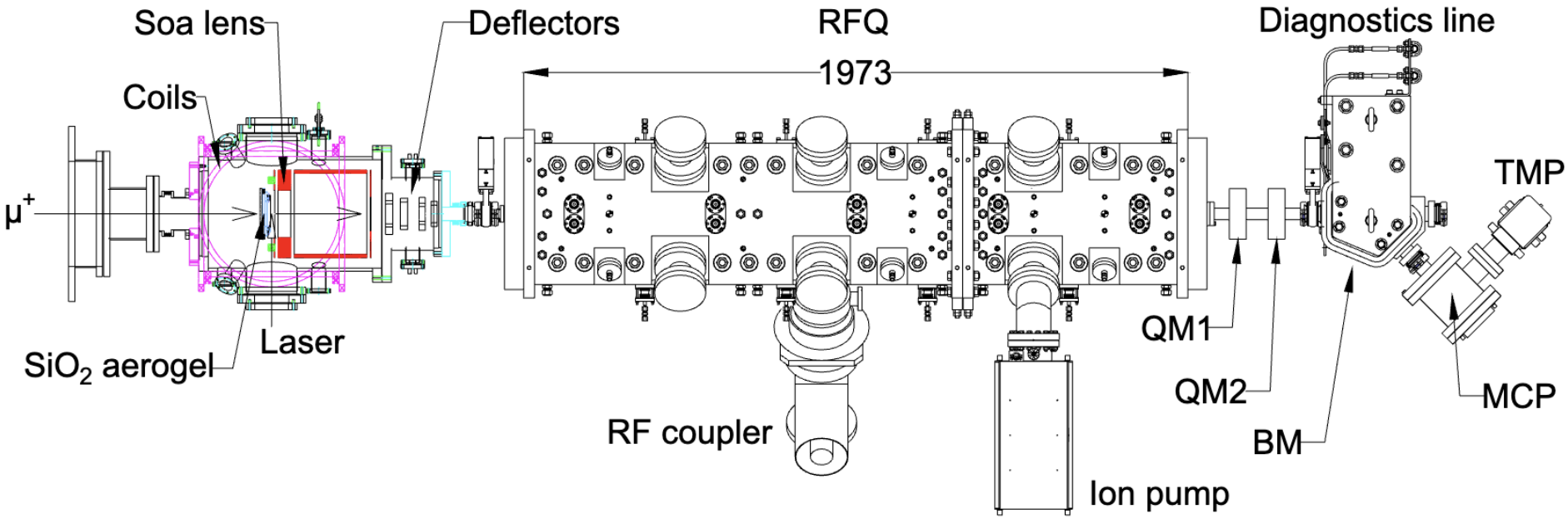
Muon cooling & acceleration demonstration experiment

✓Performed in Mar~Apr. 2024

- arXiv:2410.11367, Accepted for the publication in PRL



Overview of demonstration experiment



- ✓Incoming muon: 9.5×10^4 /pulse. E= 3.6MeV
- ✓244nm laser by Okayama group for Mu spectroscopy
- ✓Electrostatic lens for initial transport: **30meV→5.7keV**
- ✓J-PARC prototype RFQ: **5.7keV→100keV**
- ✓Beam diagnostics line

Evaluation of 5.7keV muon

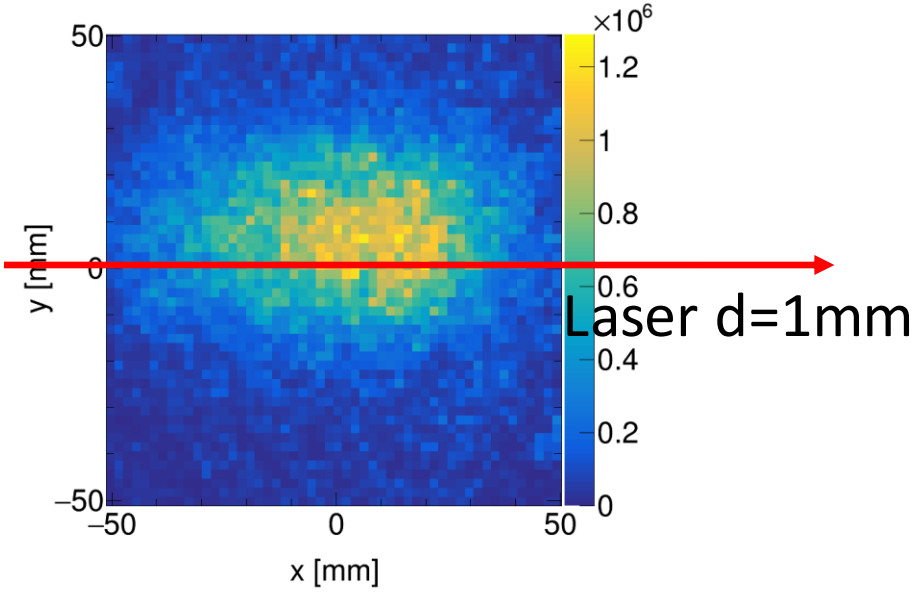
- Prior to rf-acceleration, a slow-muon diagnostic line was installed after Soa lens to evaluate 5.7keV muon beam

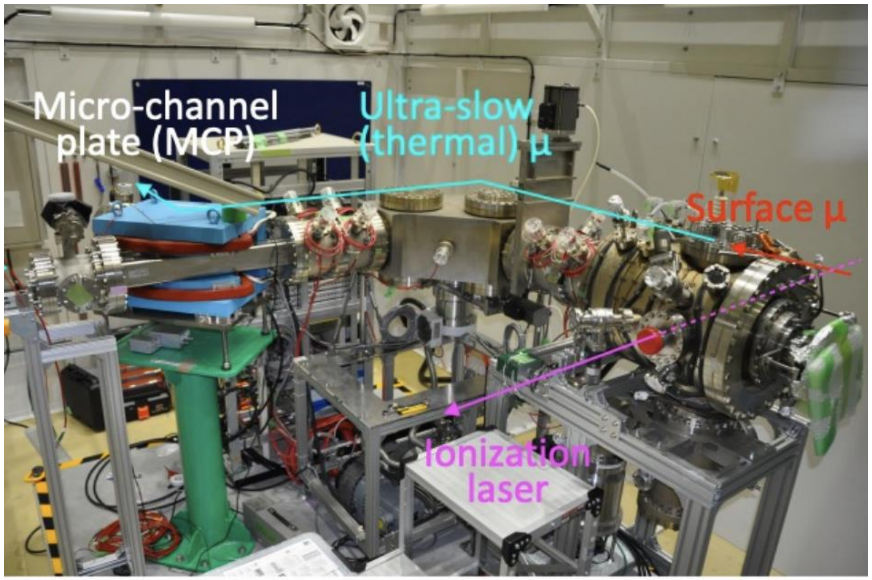
➢ Tuning of laser timing, frequency, position

- Laser for spectroscopy (1S-2S transition): very narrow resonance width: O(10MHz) of 1000THz

➢ Successfully **observed ionized muon signal at 5.7keV**

Profile of incident surface muon





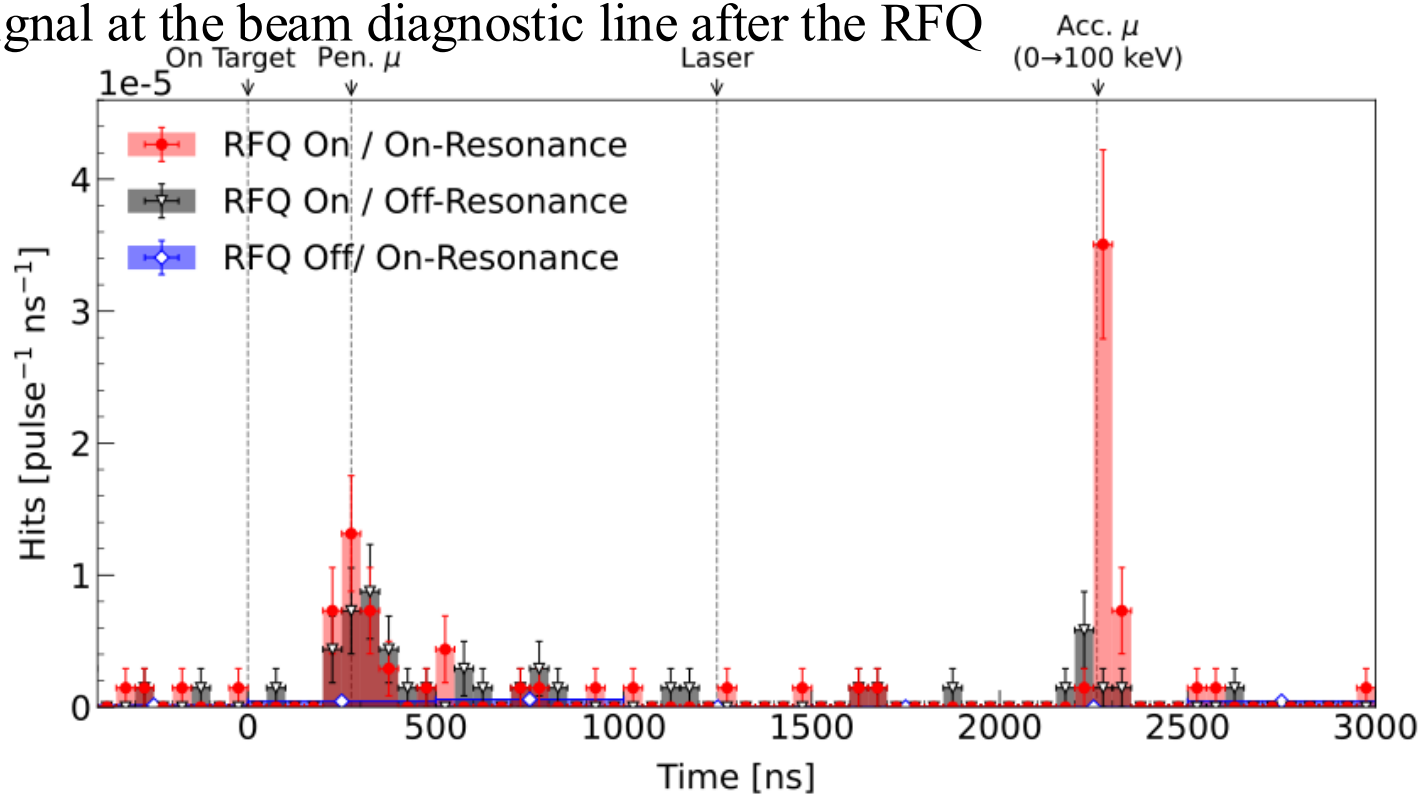
Acceleration of positive muon!!

- **RF-cavity is installed for 5.7keV→100keV acceleration**

✓**World first rf-acceleration of cooled muon !!**

- Clear peak only when laser on-resonance & RFQ ON
- μ^+ rate: 2×10^{-3} /pulse

MCP signal at the beam diagnostic line after the RFQ

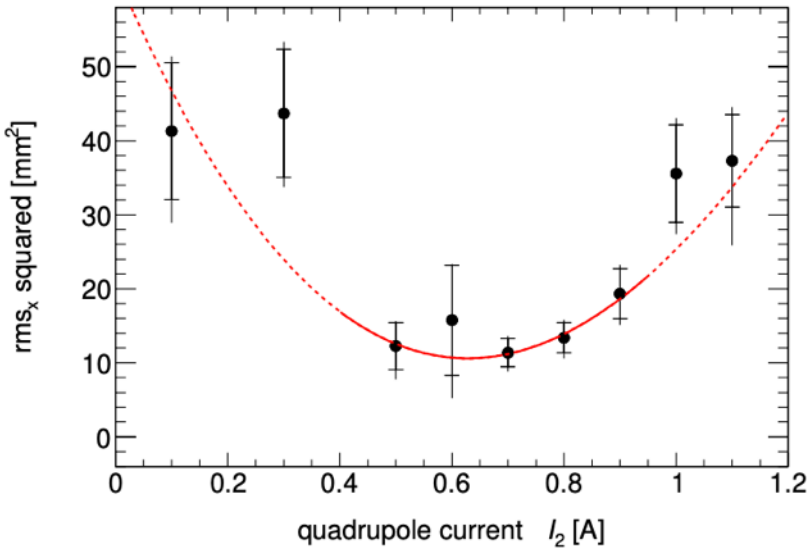


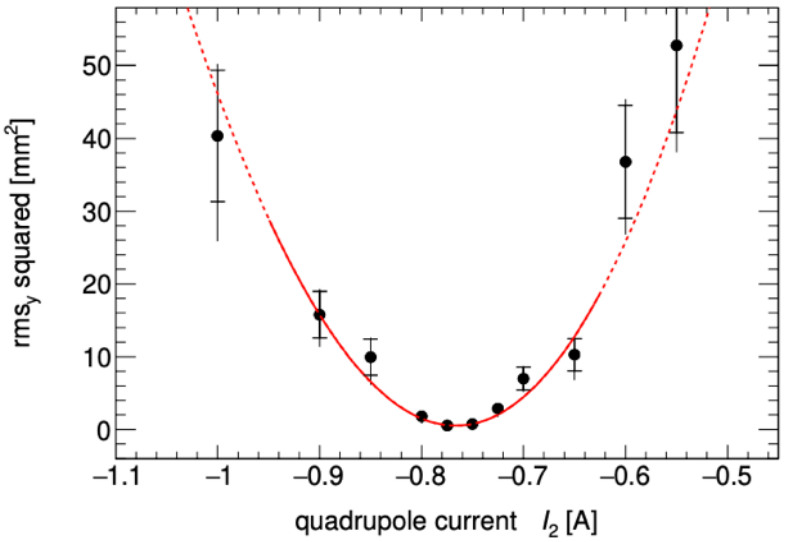
Emittance measurement

- Emittance measurement: Q-scan method
  - Muon beam size vs quadrupole strength → beam parameter
- Measured normalized rms emittance
  - **Horizonal: $0.85 \pm 0.25\ ^{+0.22}_{-0.13}$ π mm mrad → ×1/200**
  - **Vertical: $0.32 \pm 0.03\ ^{+0.05}_{-0.02}$ π mm mrad → ×1/400**

➢ ***Birth of low emittance muon beam!!***

arXiv:2410.11367





Next steps

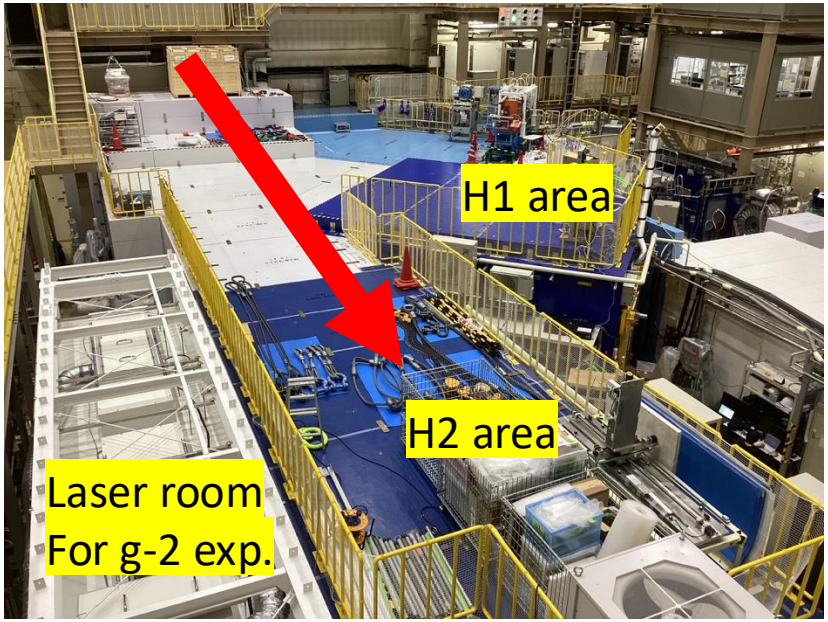
- ***More muon and higher energy !!***

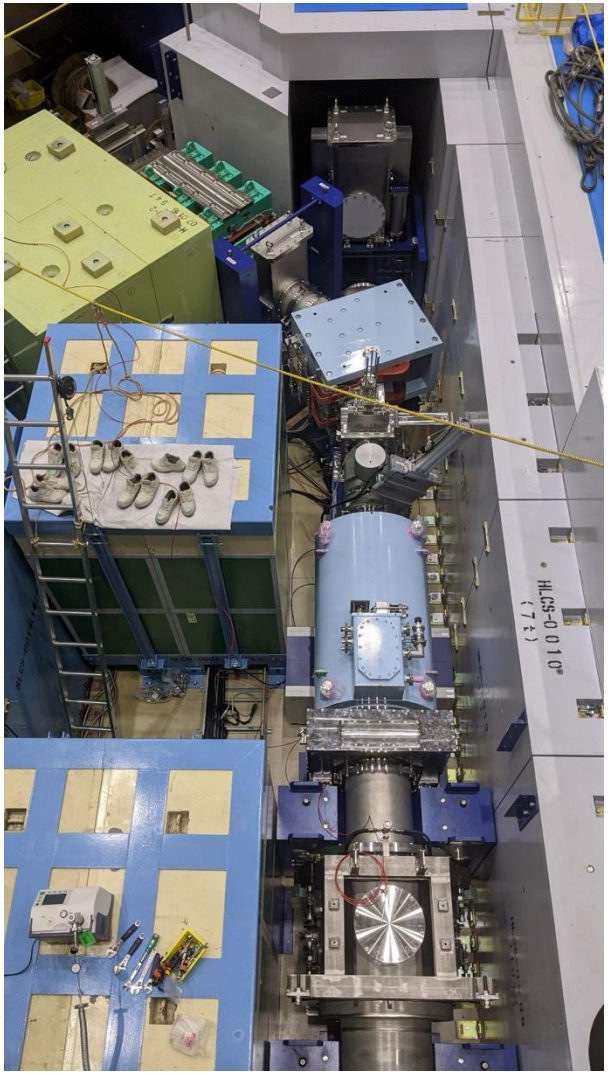
➢ Muon rate: ~10^5 μ^+/s for J-PARC g-2/EDM experiment
  - ✓ More intense surface muon beamline
  - ✓ Laser dedicated for muonium ionization
    - The laser for the demonstration experiment is developed for muonium spectroscopy, very precise laser but low ionization efficiency

➢ Energy: Up to 212 MeV
  - ✓ Another accelerating cavities

Surface muon beamline

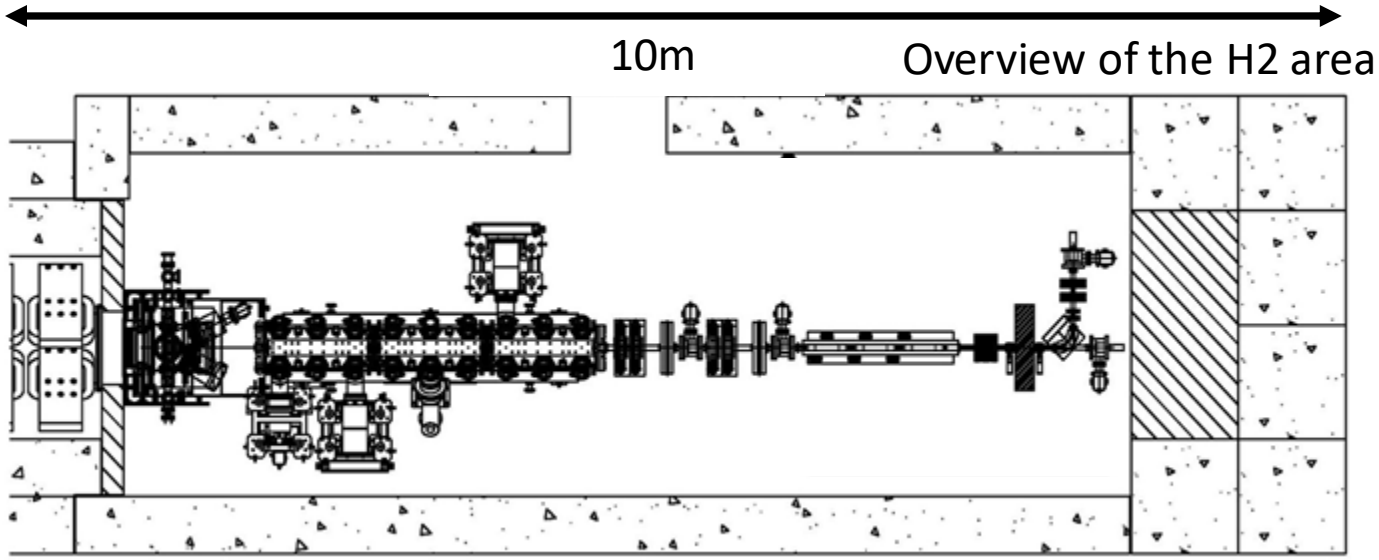
- H2 area of H-line: for g-2/EDM experiment and muon microscope
  Large solid angle: ~100mSr → × **70 more μ^+**
- Current status: Sato-san's talk





Experimental area and 5.7keV muon diagnostic line

- An experimental area for acceleration up to 4MeV is ready. (H2)
  - The cavities are not installed yet.
- A new 5.7keV muon diagnostic line is prepared and being tested
  - Compact enough to fit into the new experimental area



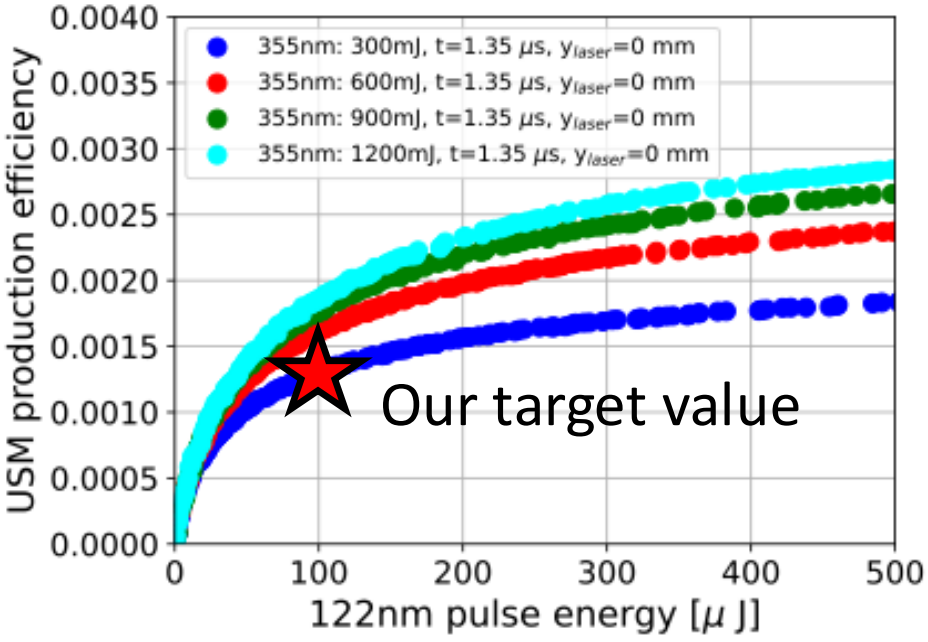
Ionization light sources

✓New lasers based on those at MLF U-line→ × **10^3~10^4 USM**

- 122nm for 1S-2P trans.: ~20μJ → Our goal is 100μJ
- 355nm for unbound from 2P: ~10mJ → Our goal is 300mJ

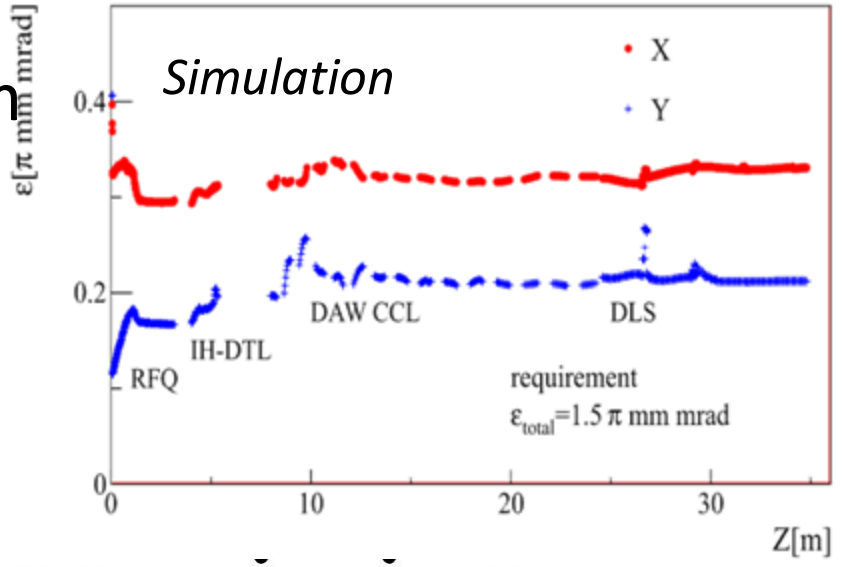
✓ A new laser room & optical bench is ready at H-line

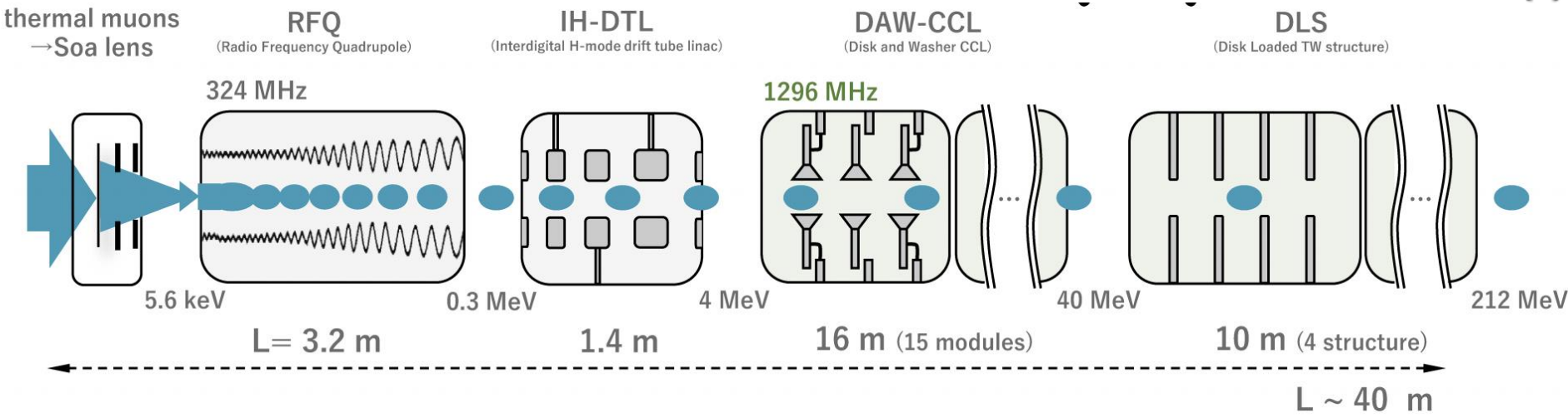
- KEK, Riken, Ibaraki univ
- First (low energy) VUV light in this Nov
- Upgrade from FY2026 to FY2028



Muon accelerator

- 212MeV with four systems in 40m
- **20% decay loss** in total
- **Accelerating cavities are under development**
- See also Sato-san's talk

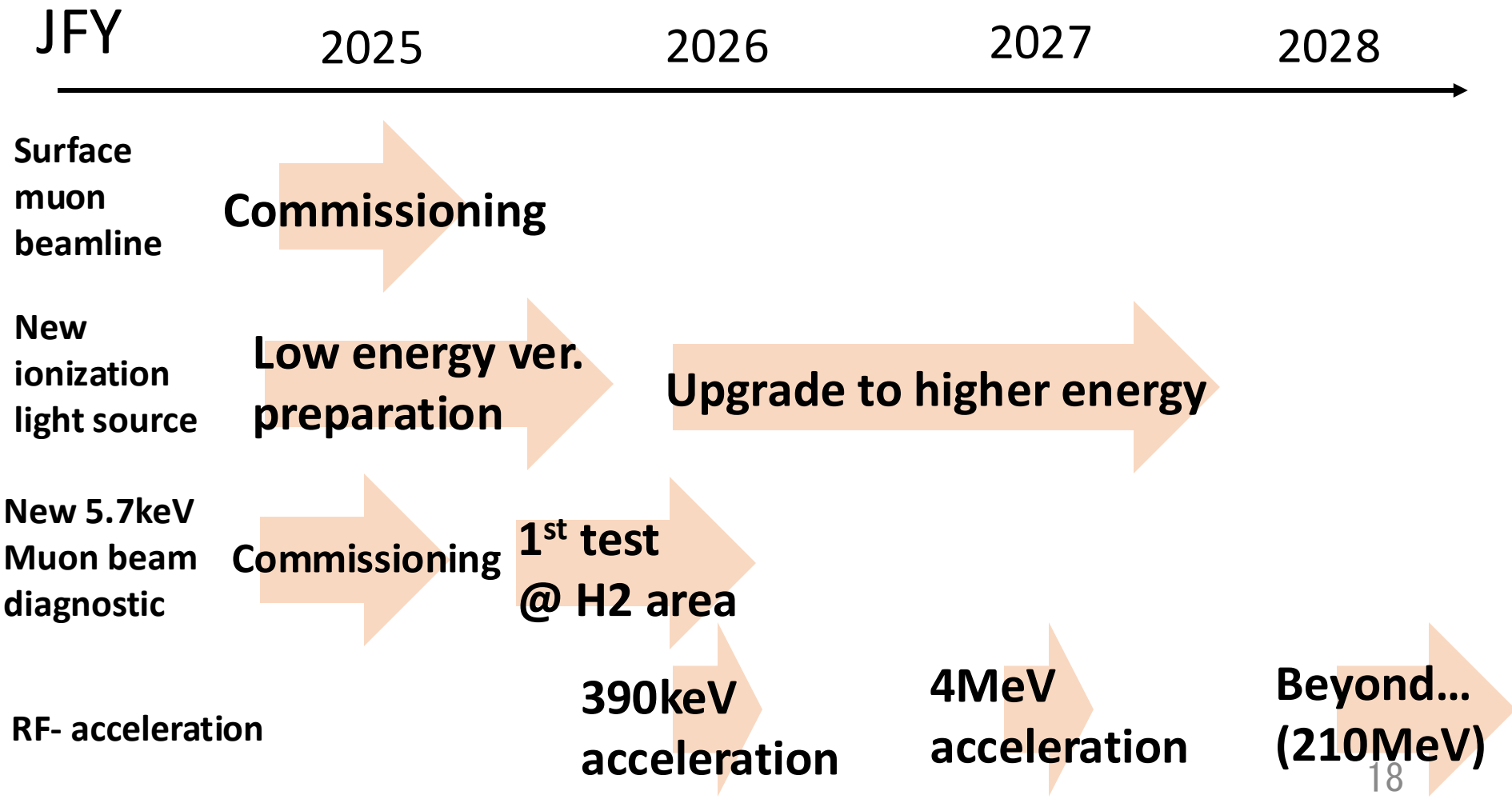




→ Sato-san's talk

Next milestone(s)

- ✓ ***4MeV acceleration at H2 area***
  - 4MeV with RFQ & IH-DTL , ~1000 μ^+/s

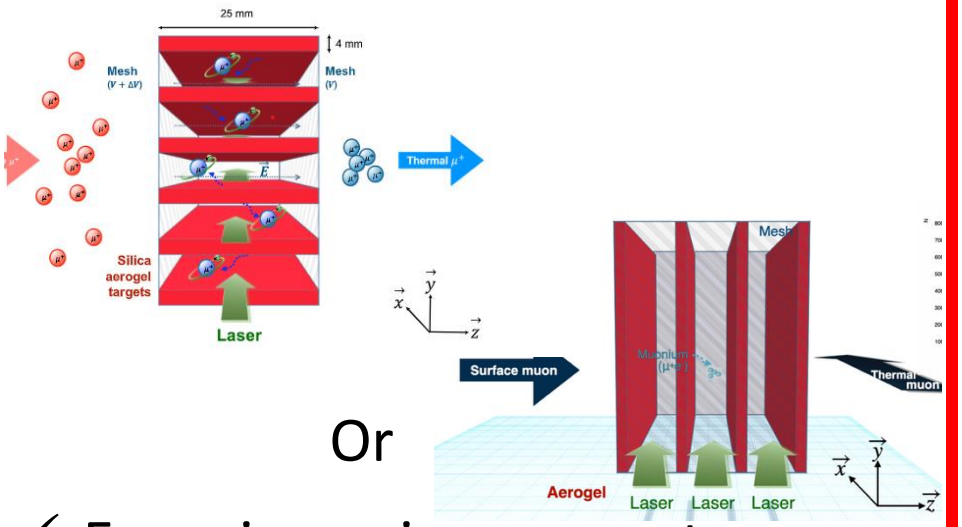


Future improvement

- *More muonium and more spin polarization!!*
  - Spin polarization of muon in muonium becomes half times smaller due to the hyperfine structure

Proposal of multi-layered Mu target

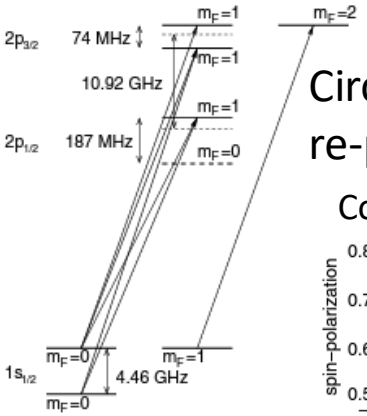
C. Zhang et al, NIM. A, 1042 (2022) 167443



Or

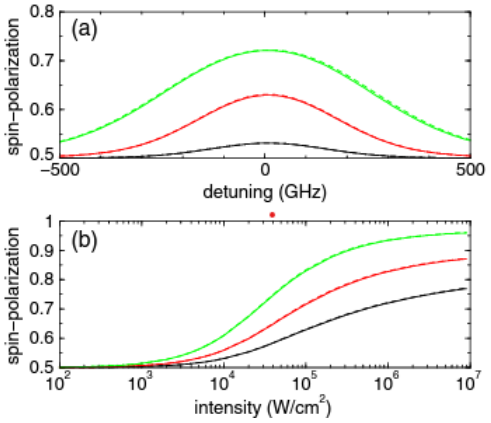
✓ Every incoming muon stops near the surface of one of the thin targets

Proposal of optical pumping of Mu



Circularly polarized laser→ re-polarization of spin

Color: # of pulse (one, two, three)



T. Nakajima. Journal of the Optical Society of America B 2012, 29(9): 2420-2424

Summary

- Muon cooling and acceleration technique is being developed at J-PARC.
  - Production of thermal muonium
  - Laser ionization
  - RF-acceleration to 200MeV
- The world first acceleration of positive muon has been demonstrated last year
- Preparation of new beamline/laser/diagnostic line/accelerator are underway
- Next milestone: 4MeV acceleration in 2027.
- ***Any other interesting applications ???***