Results on muon cooling and acceleration at J-PARC

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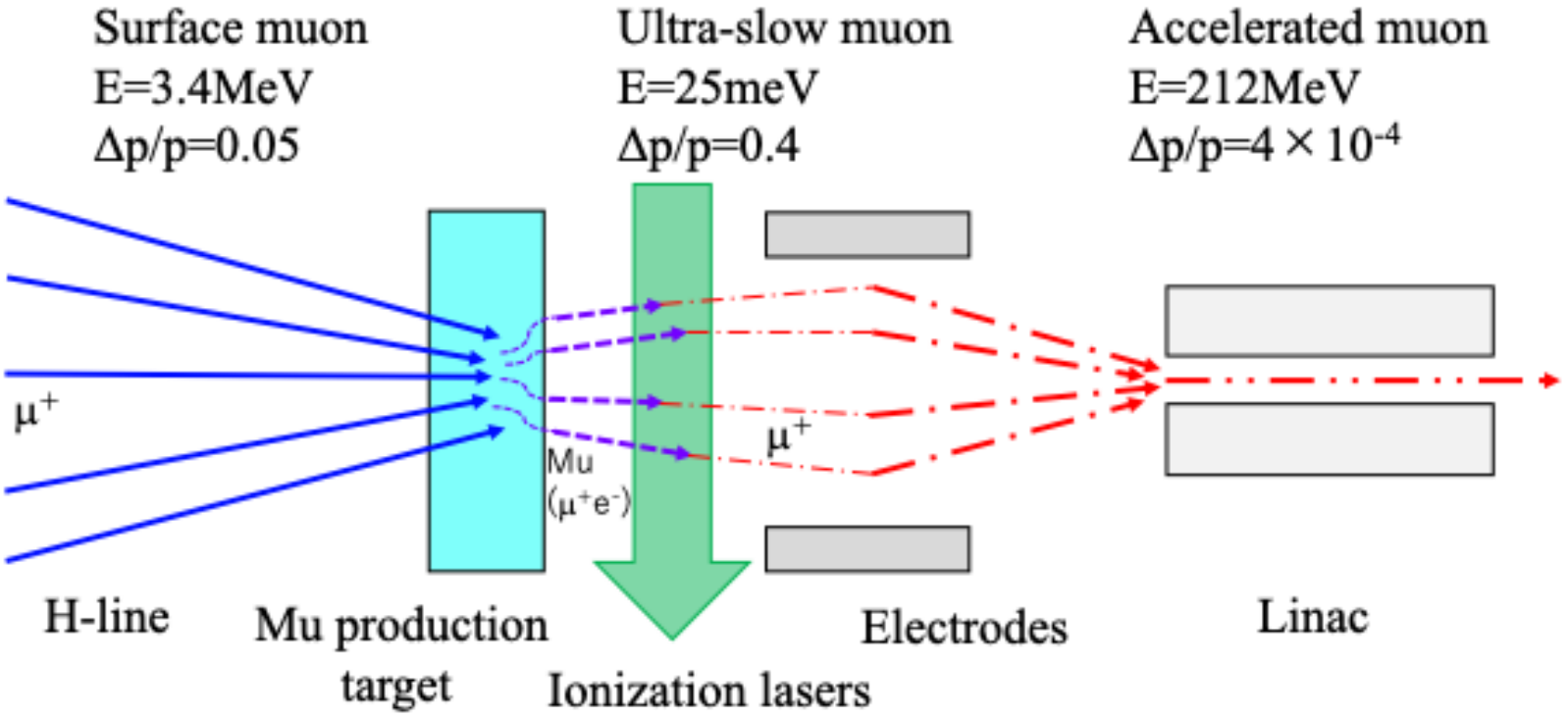
On behalf of the collaboration

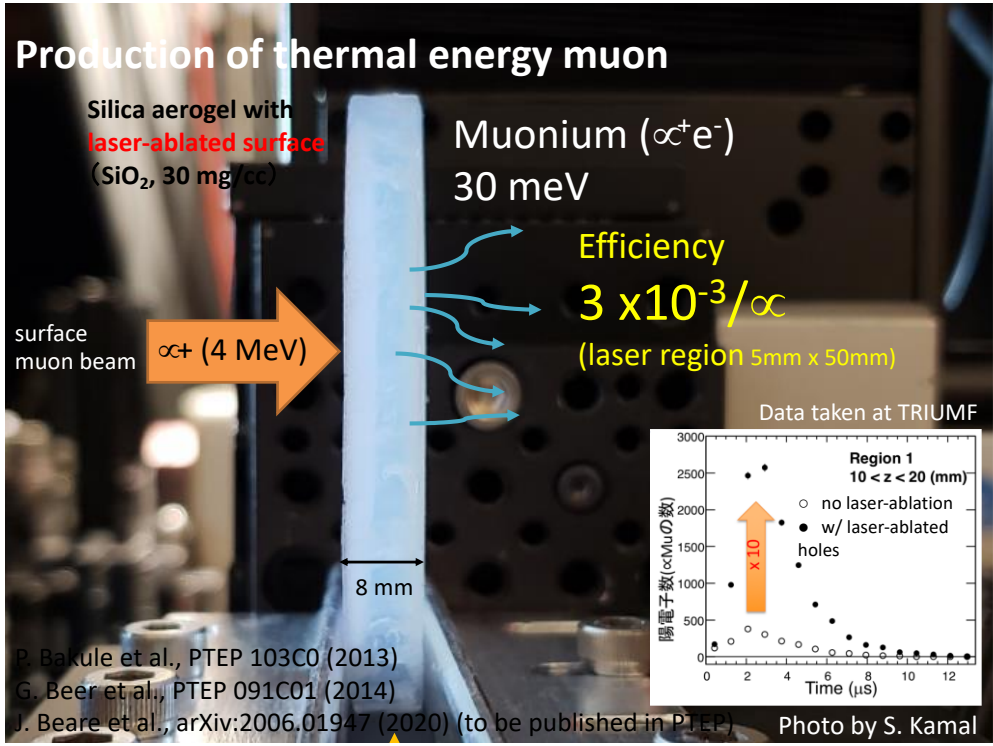
Muon cooling at J-PARC

- ✓**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

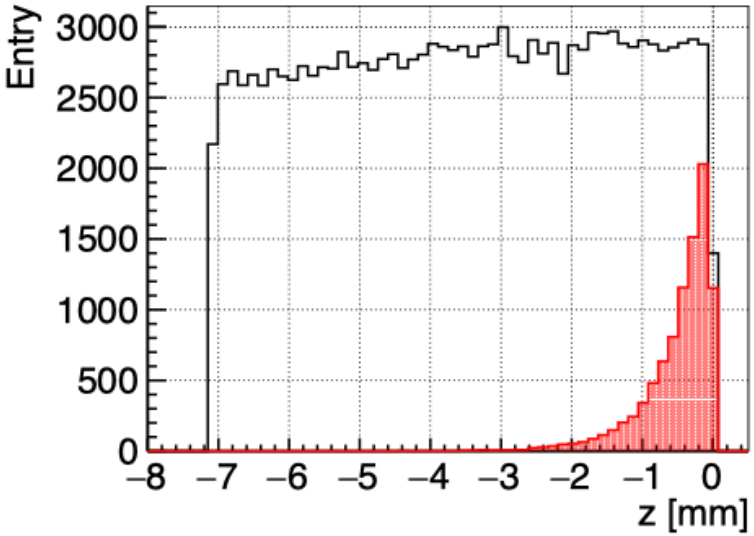


Expected performance of the target

- Simulation of H-line of J-PARC
- **Efficiencies:**
  - Stopping eff.: **40%**
  - Mu formation eff.: **52%**
  - Vacuum emission eff.: **6%**
  - Overlap with laser: **27%**

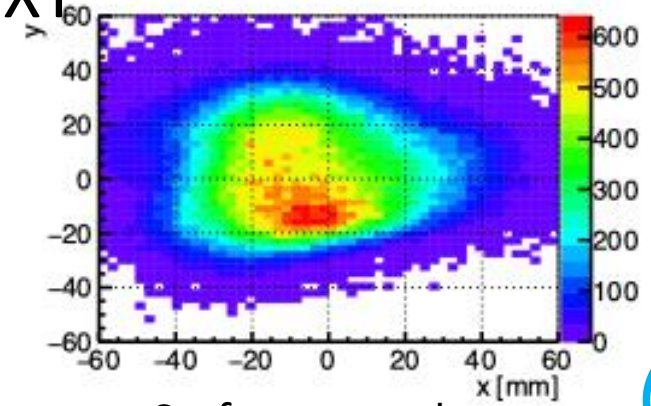
Black: total stopped Mu

Red: those emitted to vacuum



Simulation: Typical emission profile at laser irradiation timing

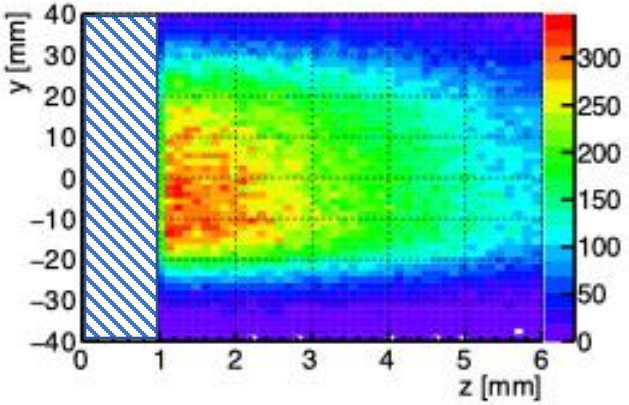
XY



Surface muon beam

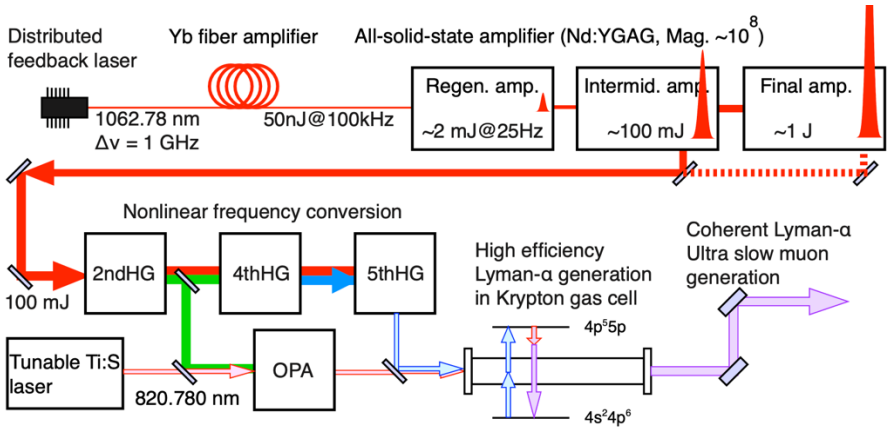
ZY

muon beam

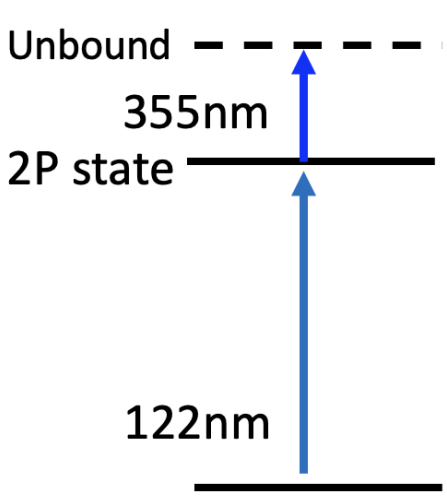


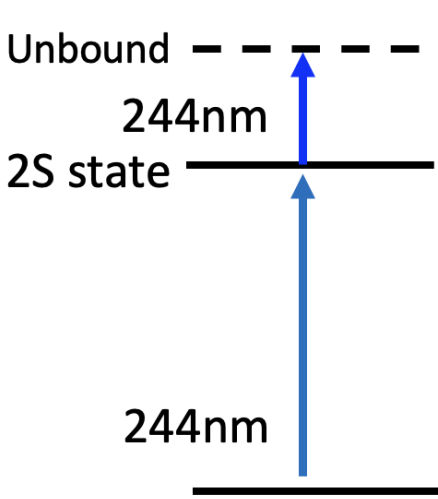
Key technology 2: Photo-ionization of muonium

- **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

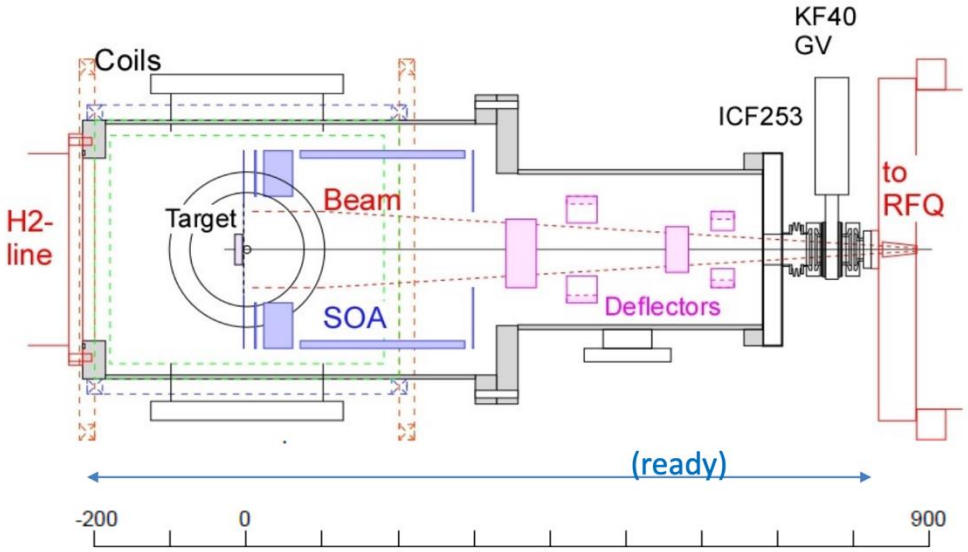


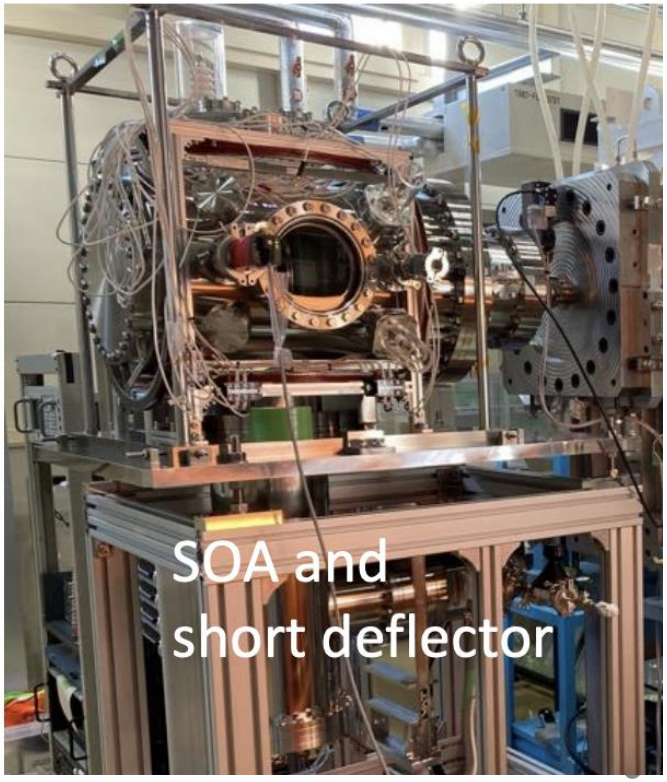


Electrostatic transport

- 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

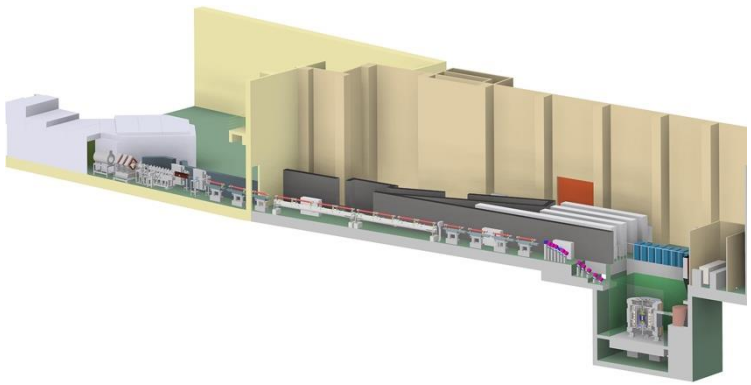
Schematic

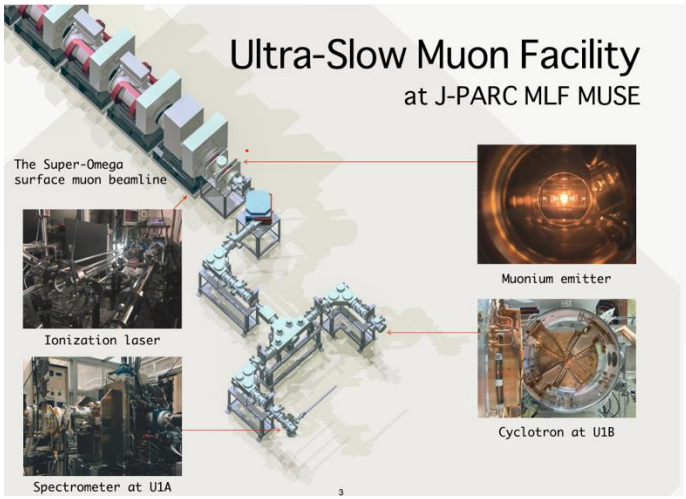


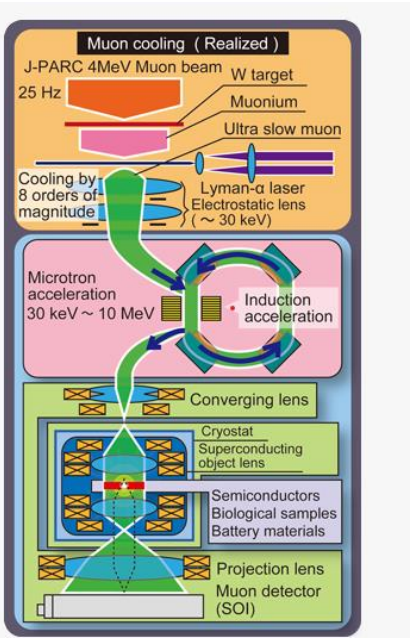


Expected performance & Application

- 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



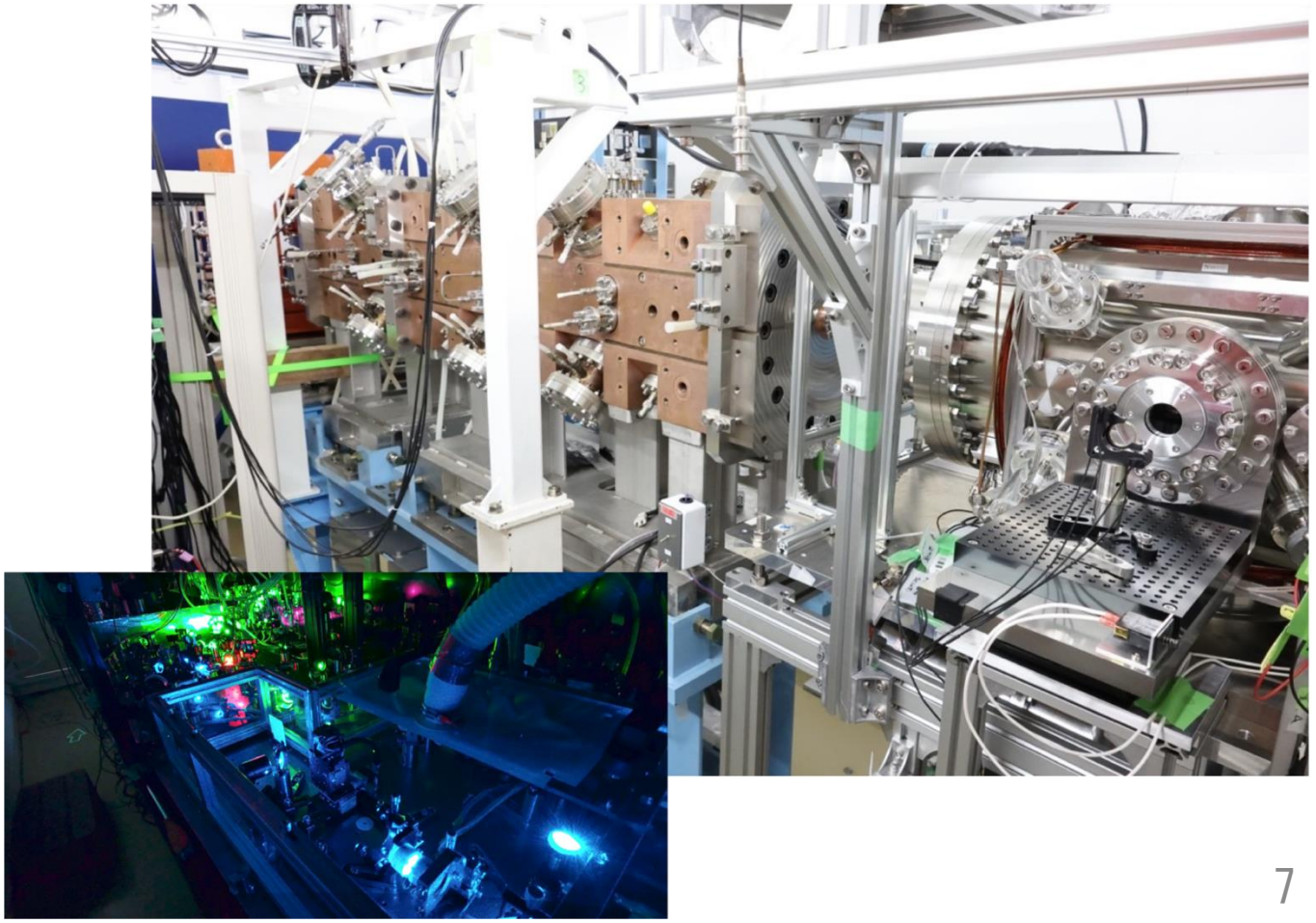




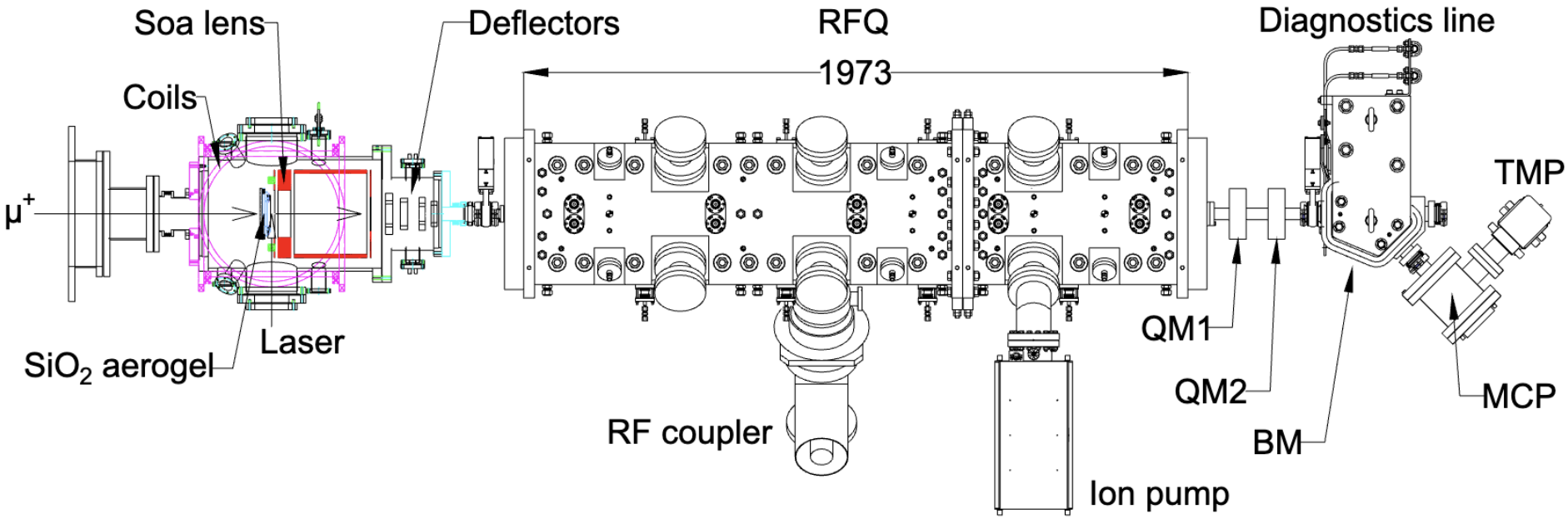
Muon cooling & acceleration demonstration experiment

✓Performed in Mar~Apr. 2024

- arXiv:2410.11367, Accepted for the publication in PRL



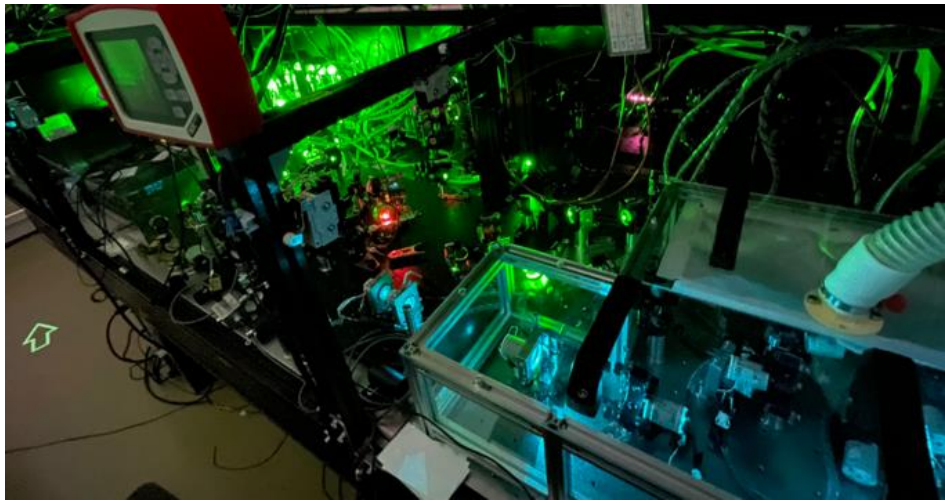
Overview of demonstration experiment

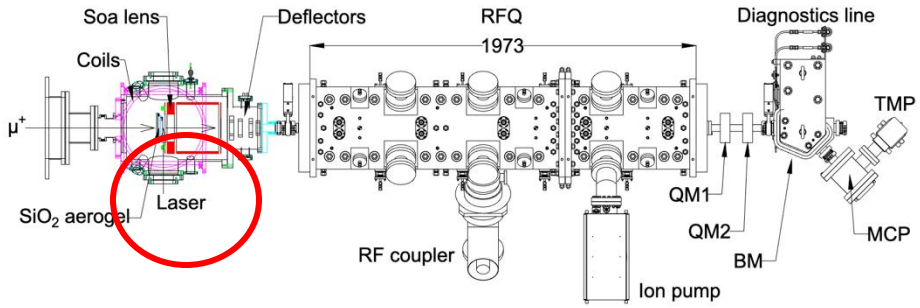


- ✓Incoming muon: 9.5×10^4 /pulse. E= 3.6MeV
- ✓244nm laser
- ✓Electrostatic lens for initial transport: **30meV→5.7keV**
- ✓J-PARC prototype RFQ: **5.7keV→100keV**
- ✓Beam diagnostics line

Ionization laser

- **Narrow linewidth 244 nm pulsed laser**
  - Developed by Okayama univ. (pump laser by KEK)
- Not for high-efficiency ionization (→ laser for spectroscopy), but enough muon rate for our demonstration experiment
- Typical parameter
  - Pulse energy: 1mJ
  - Pulse duration: 57ns
  - $1/e^2$ diameter: 1mm
  - Doppler free excitation
  - OFC for freq. stabilization





Evaluation of 5.7keV muon

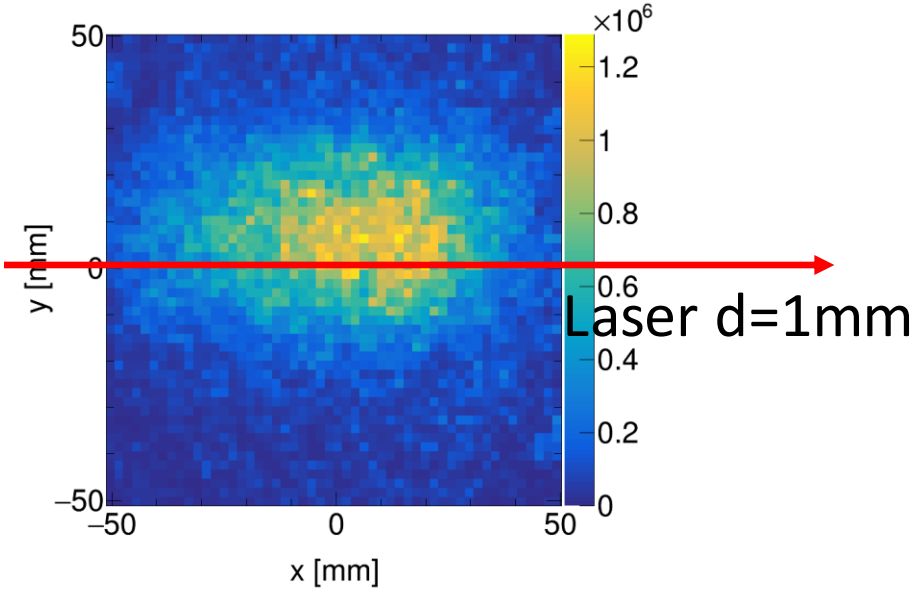
- Prior to rf-acceleration, a slow-muon diagnostic line was installed after Soa lens to evaluate 5.7keV muon beam

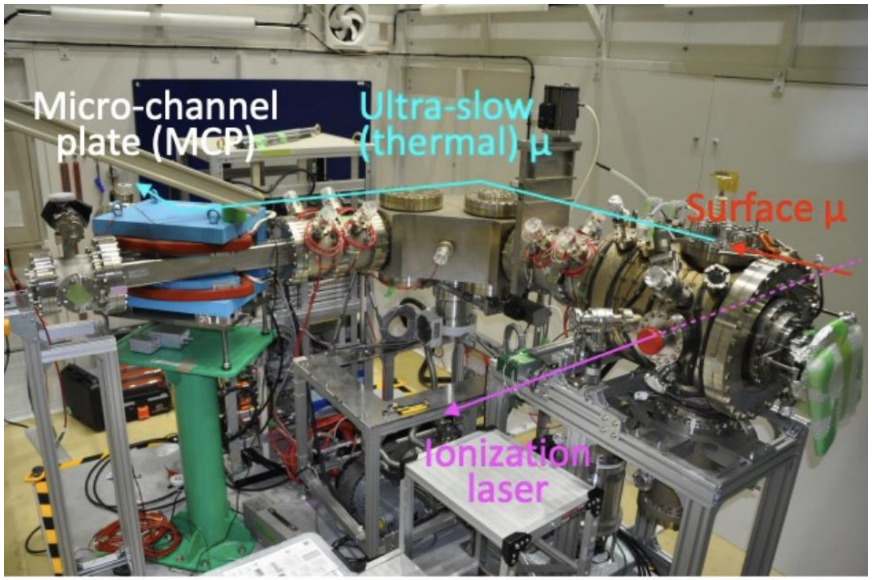
➢ Tuning of laser timing, frequency, position

- 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





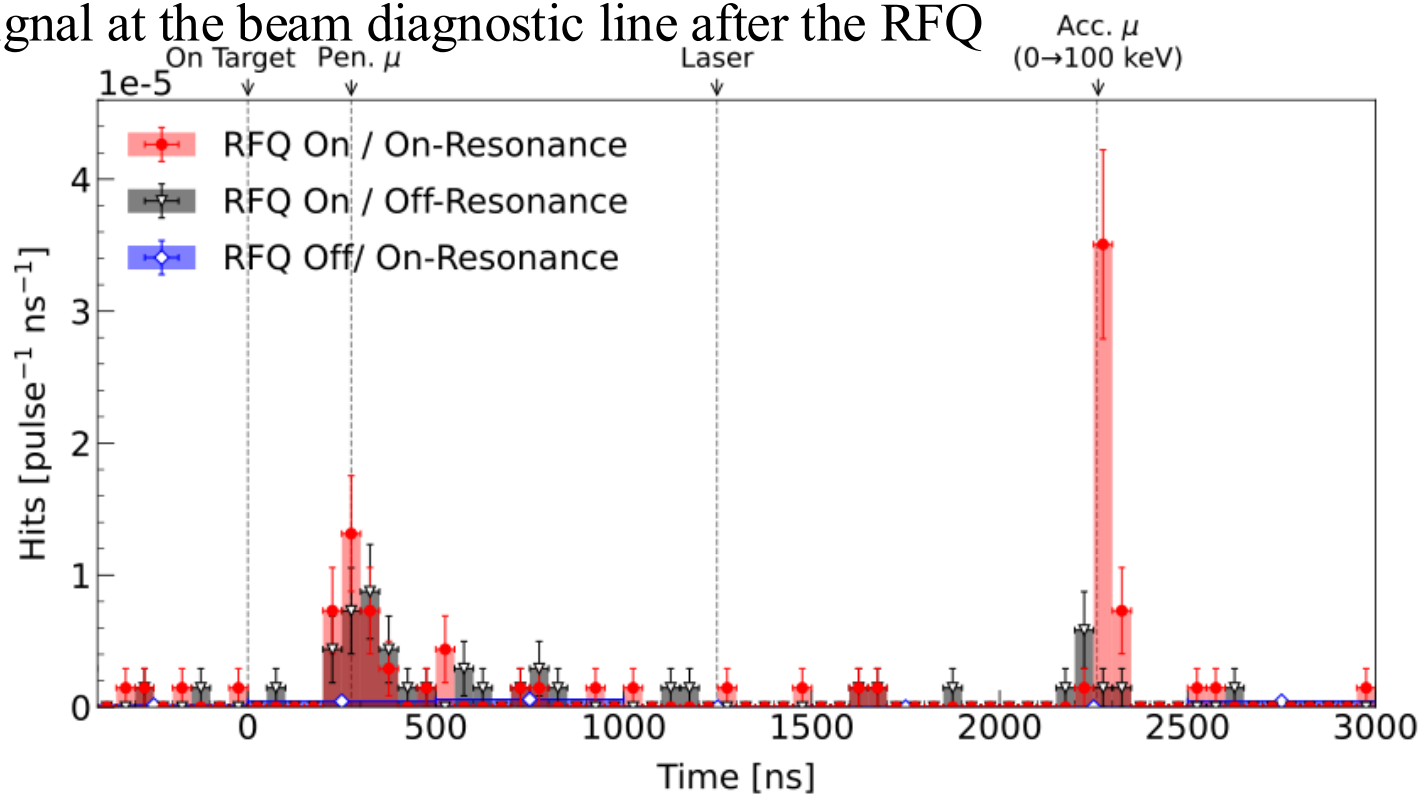
Acceleration of positive muon!!

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

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

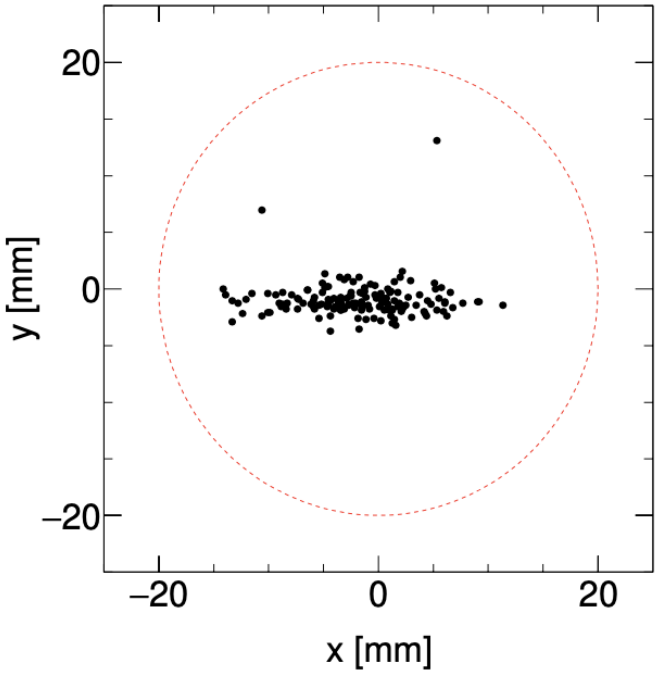
- Clear peak only when laser on-resonance & RFQ ON
- μ^+ rate: 2×10^{-3} /pulse

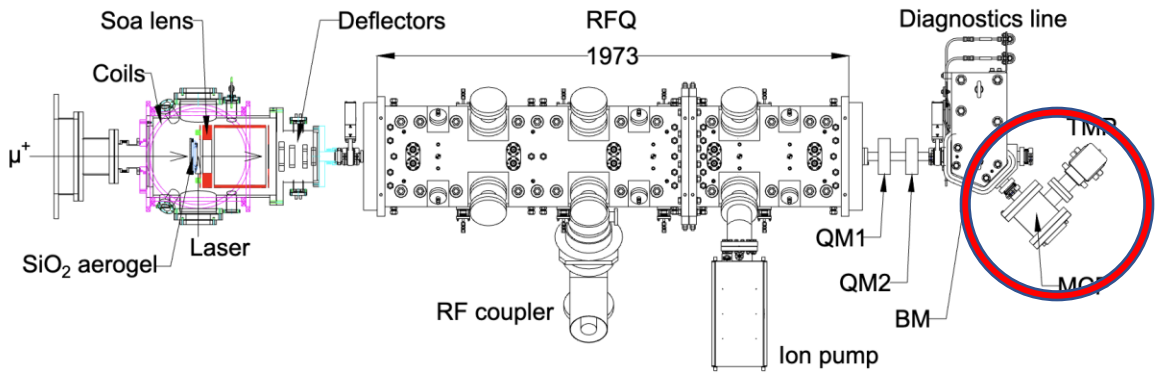
MCP signal at the beam diagnostic line after the RFQ



Muon beam profile measurement

- A BPM based on MCP at end of the setup
- Succeeded to measure the beam profile of the accelerated muon
- The profiles are used for the emittance measurement





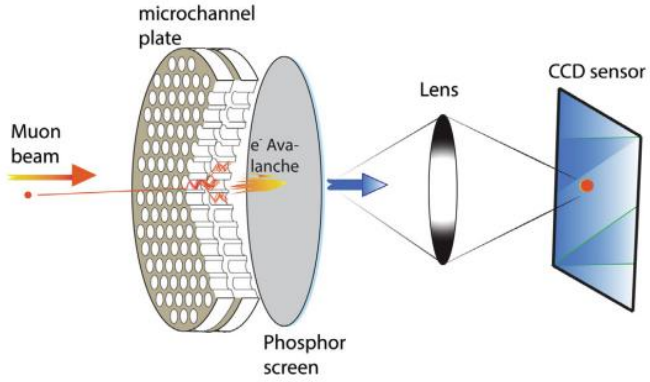


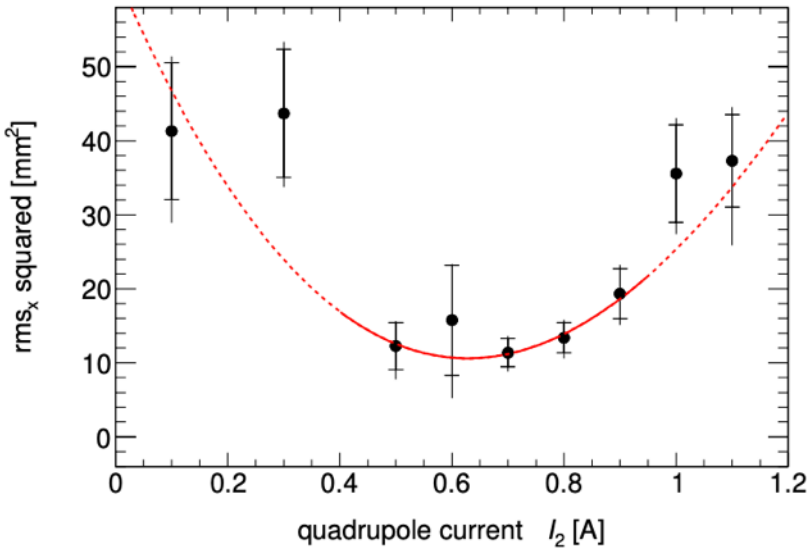
Fig. 1. A schematic view of the MCP based BPM.

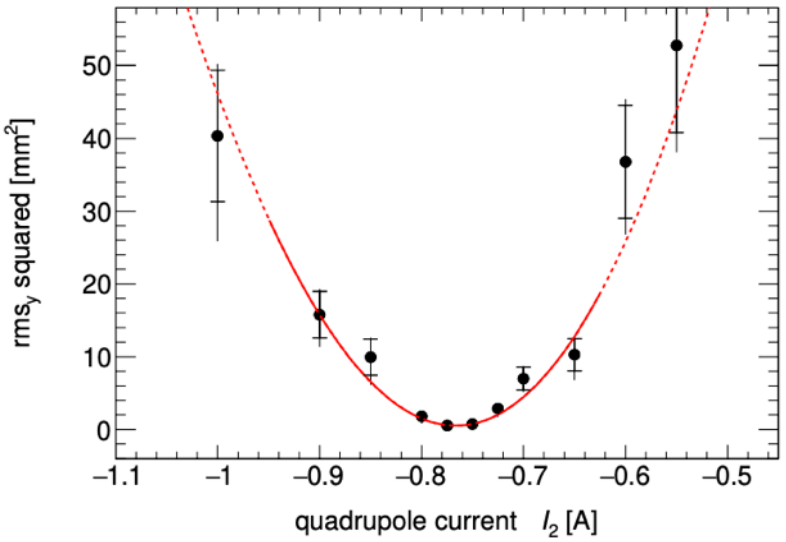
Emittance measurement

- 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

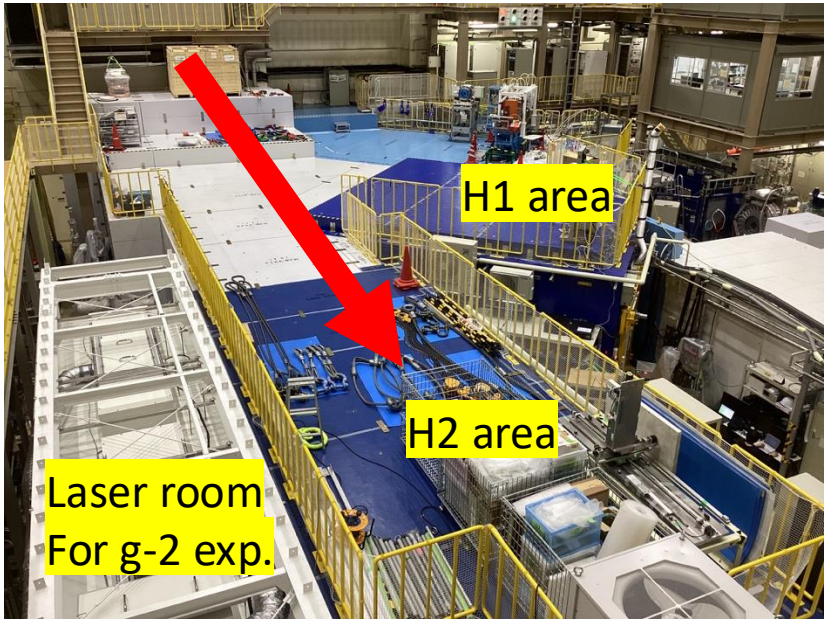
✓ Laser dedicated for muonium ionization

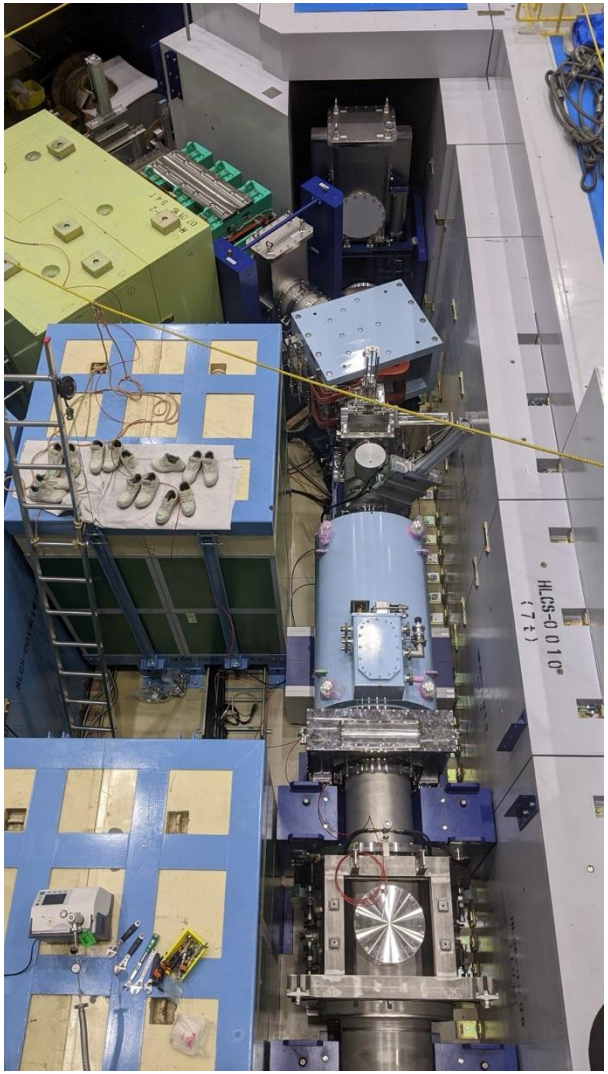
➢ Energy: Up to 212 MeV

✓ Another accelerating cavities

Surface muon beamline

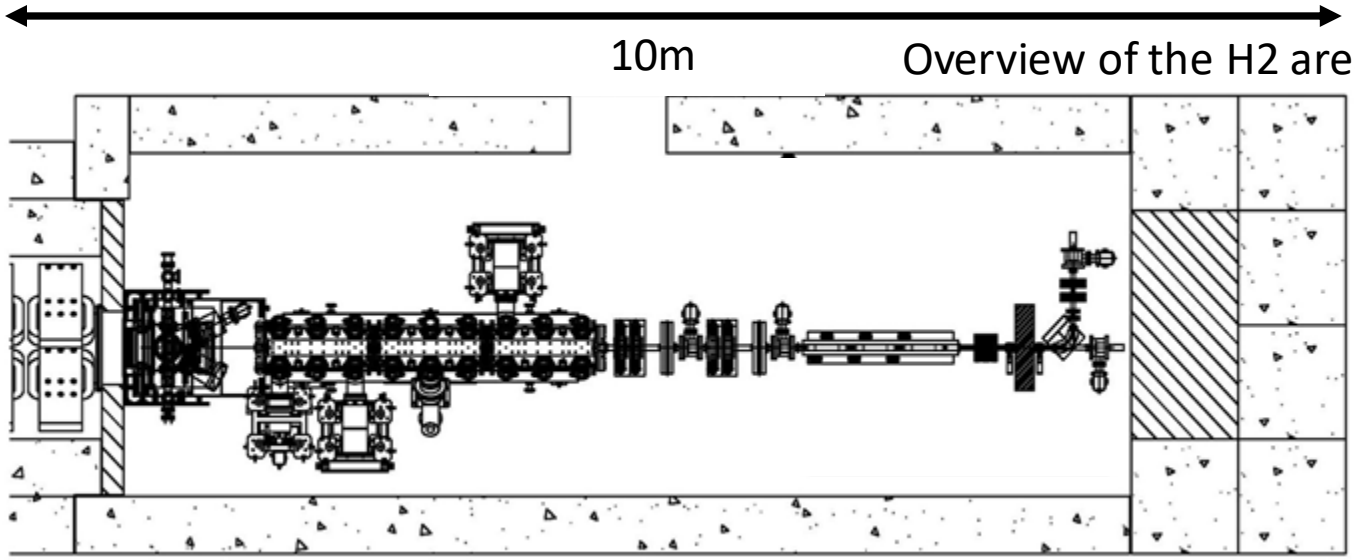
- H2 area of H-line: for g-2/EDM experiment and muon microscope
  Large solid angle: ~100mSr → × **70 more μ^+**
- Detail of H-line: talk by Kawamura-san





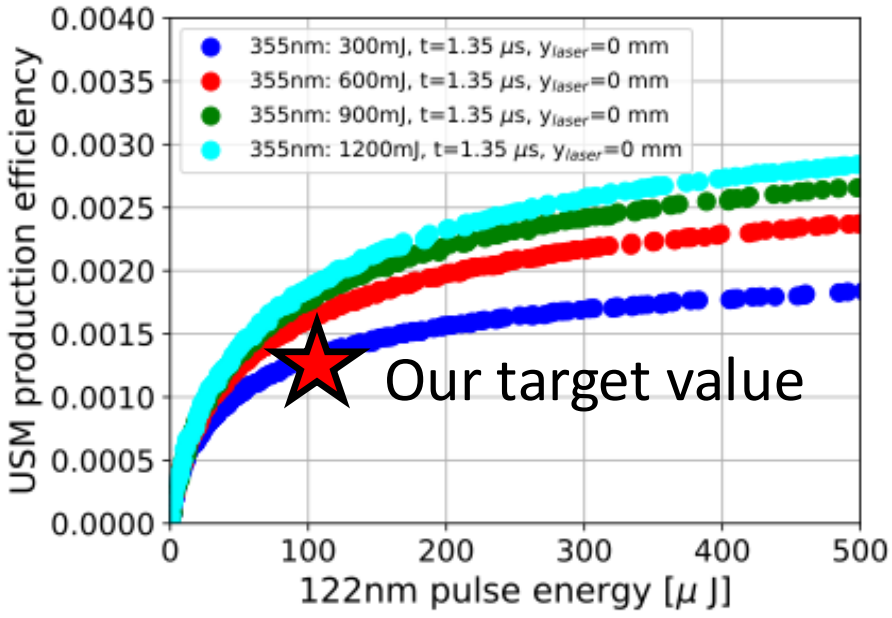
Experimental area and 5.7keV muon diagnostic line

- 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

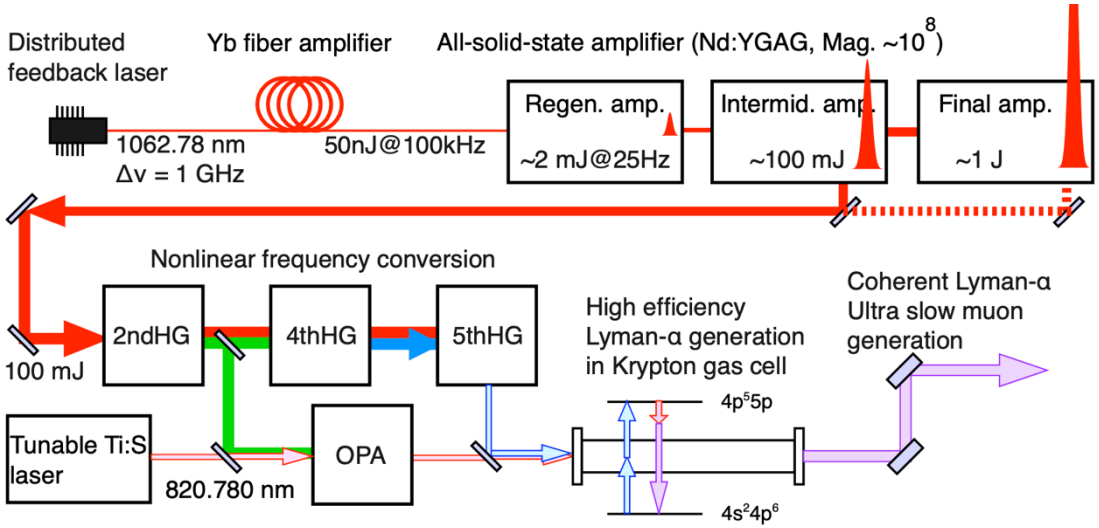
- ✓ **New lasers for Mu ionization→ ×10^3~10^4 USM**
  - 122nm for 1S-2P trans.: 100μJ
  - 355nm for unbound from 2P: 300mJ
- ✓ **A new laser room & optical bench is ready at H-line**
  - KEK, Riken, Ibaraki univ
  - Start the development from 2024



Development strategy

- ✓ **Now~FY2026:** preparation of a "copy" of light source operated at another beamline of MLF
  - ➢ **Expecting >1000 μ^+/s**, enabling the next acceleration text

- ✓ **FY2026~2027: upgrade for ~10^5 ionized muon**
  - ➢ Increase energy of 122nm light source from O(10)μJ to **100μJ** with new amps
  - ➢ Independent 355nm light source to increase energy from 10mJ to **300mJ.**

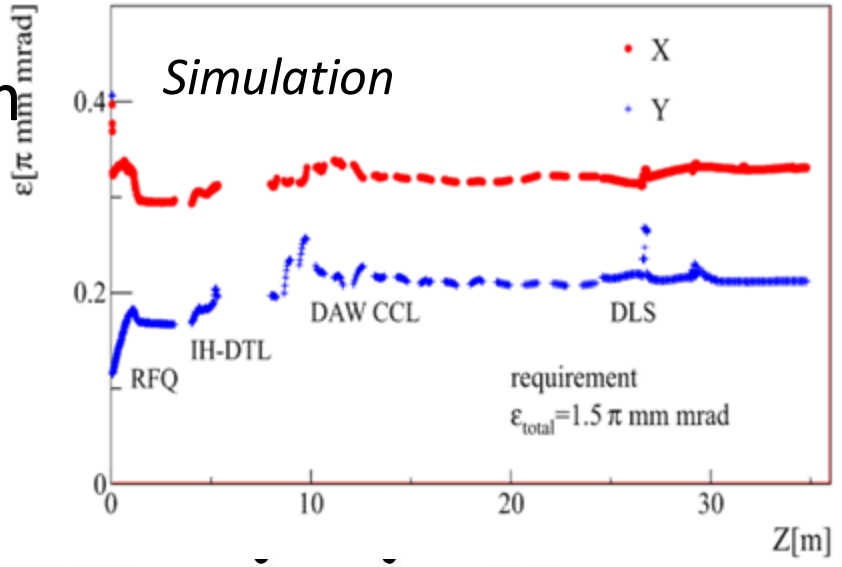


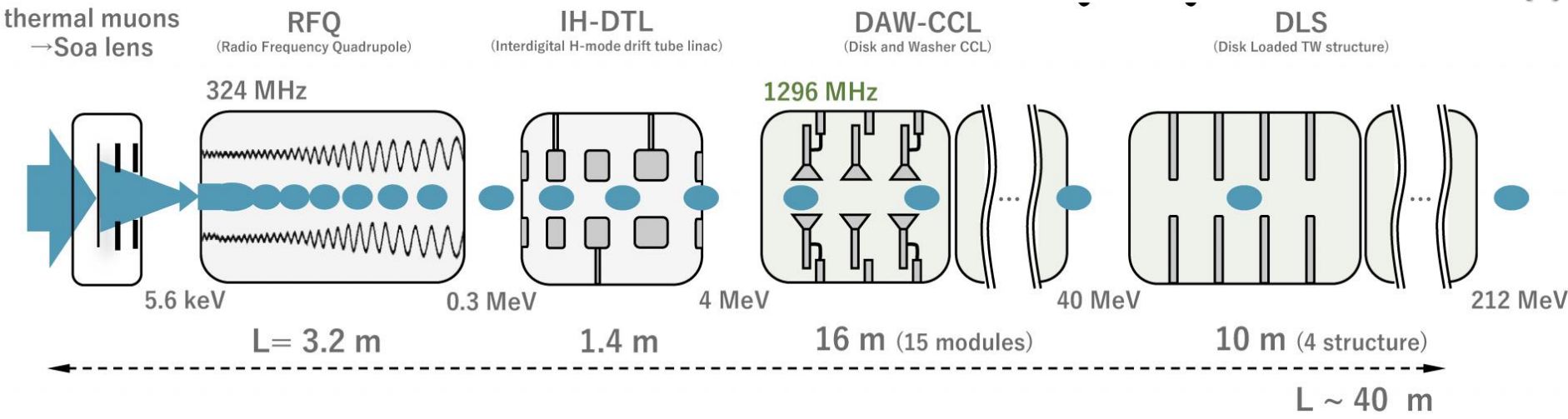
Desing of 122nm/355nm light source at U-line

※355nm pulse is produced from the non-used energy of 122nm system

Muon accelerator

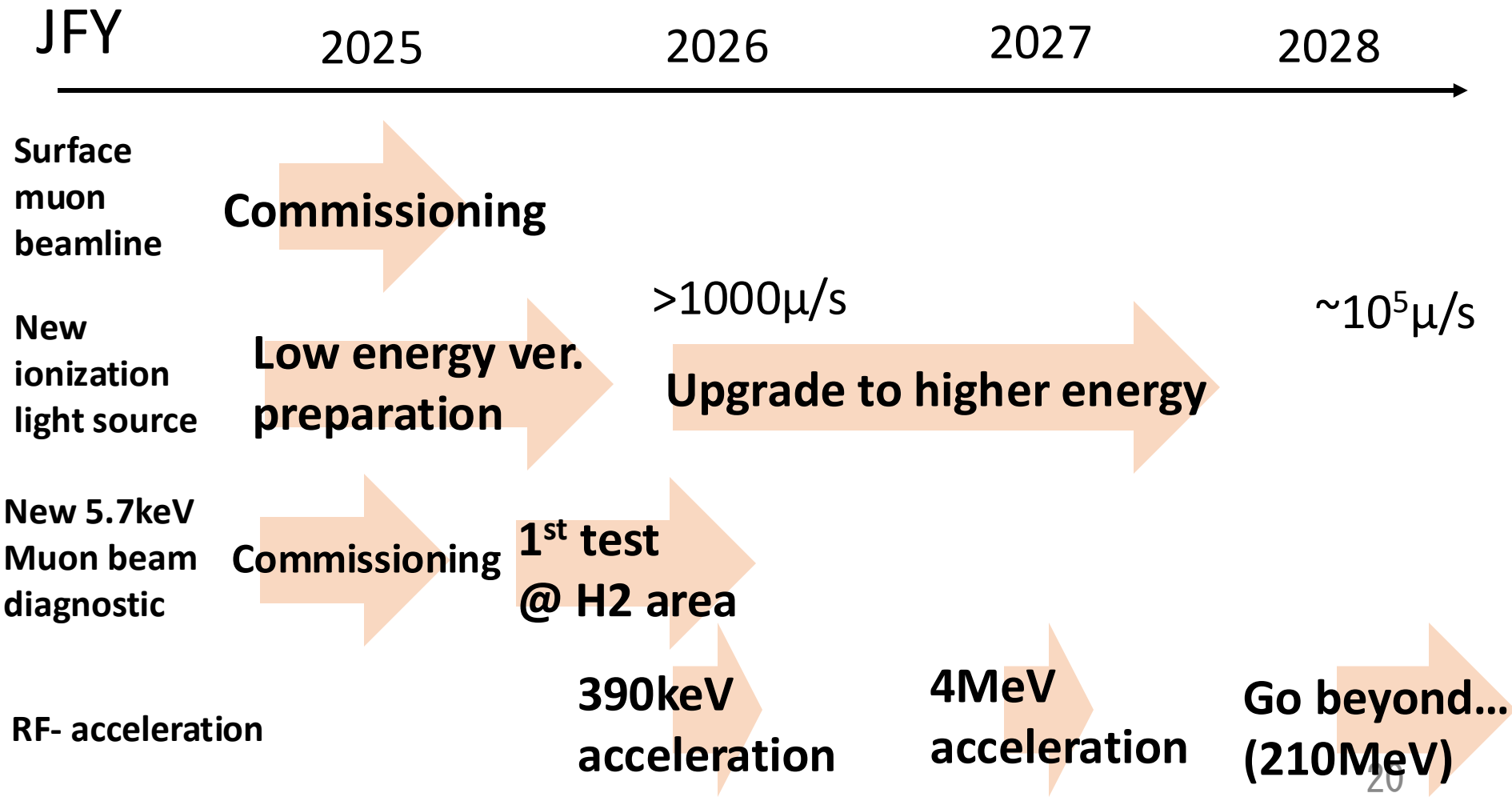
- 212MeV with four systems in 40m
- **20% decay loss** in total
- **Accelerating cavities are under development**
- (See overview talk of g-2/EDM exp.)





Next milestone(s)

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

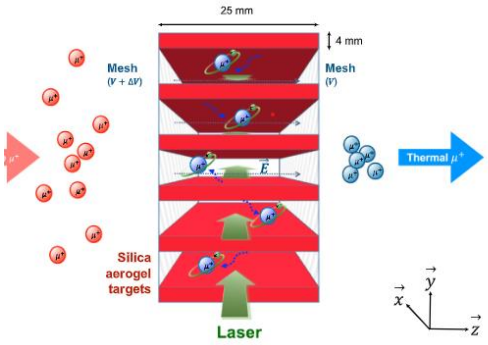


For Future

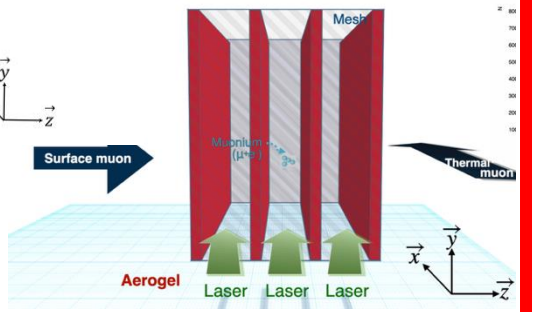
- *More muonium and more spin polarization!!*
  - Spin polarization of muon in muonium becomes half times smaller due to the hyperfine structure

Proposal of multi-layered Mu target

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

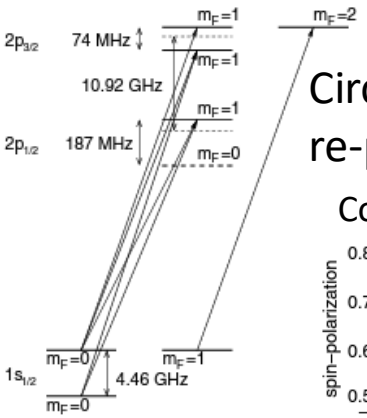


Or



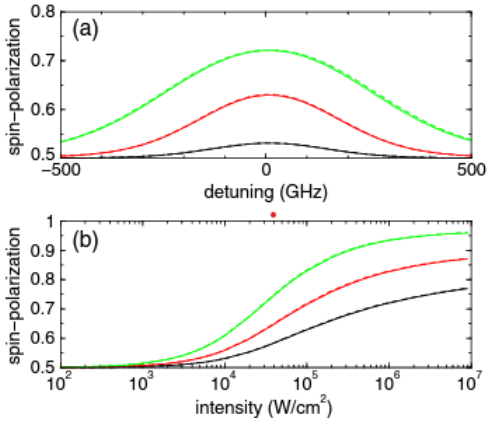
✓ Every incoming muon stops near the surface of one of the thin targets

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 ???***