Muon cooling at J-PARC

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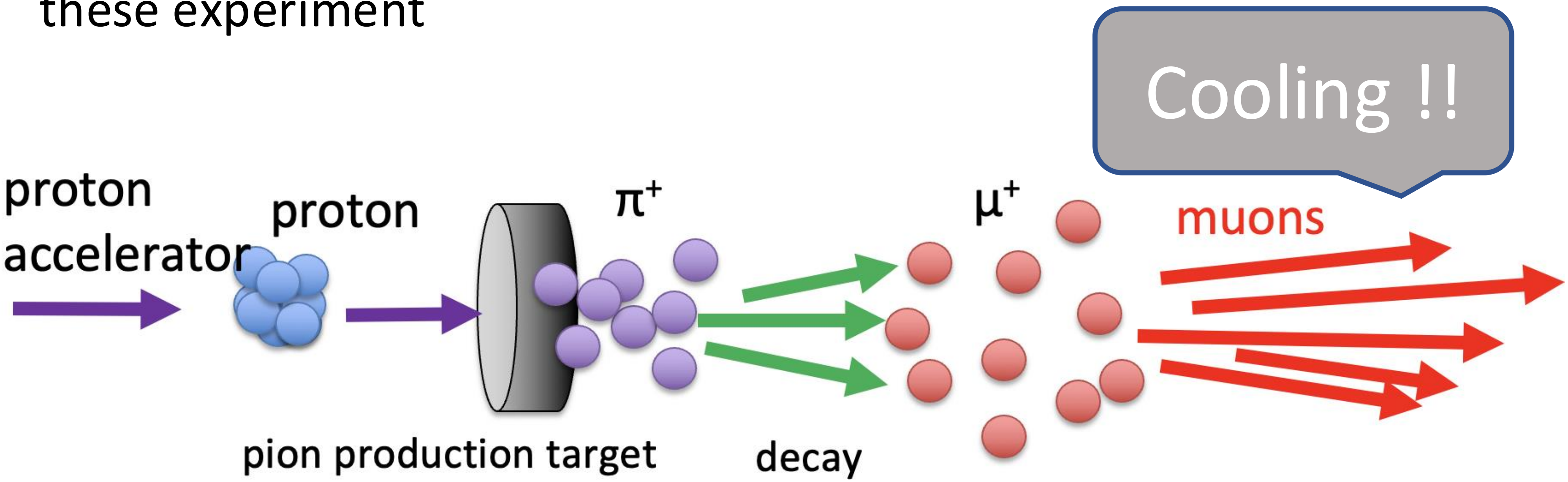
On behalf of the collaboration

Overview

- J-PARC/MLF: one of the most intense **muon facility** for general use.
  - ✓ **~10% of 1MW proton beam→Pion → Muon production**

➢ This muon beam is utilized for **material and life science experiments** and **precision measurements of particle physics**.

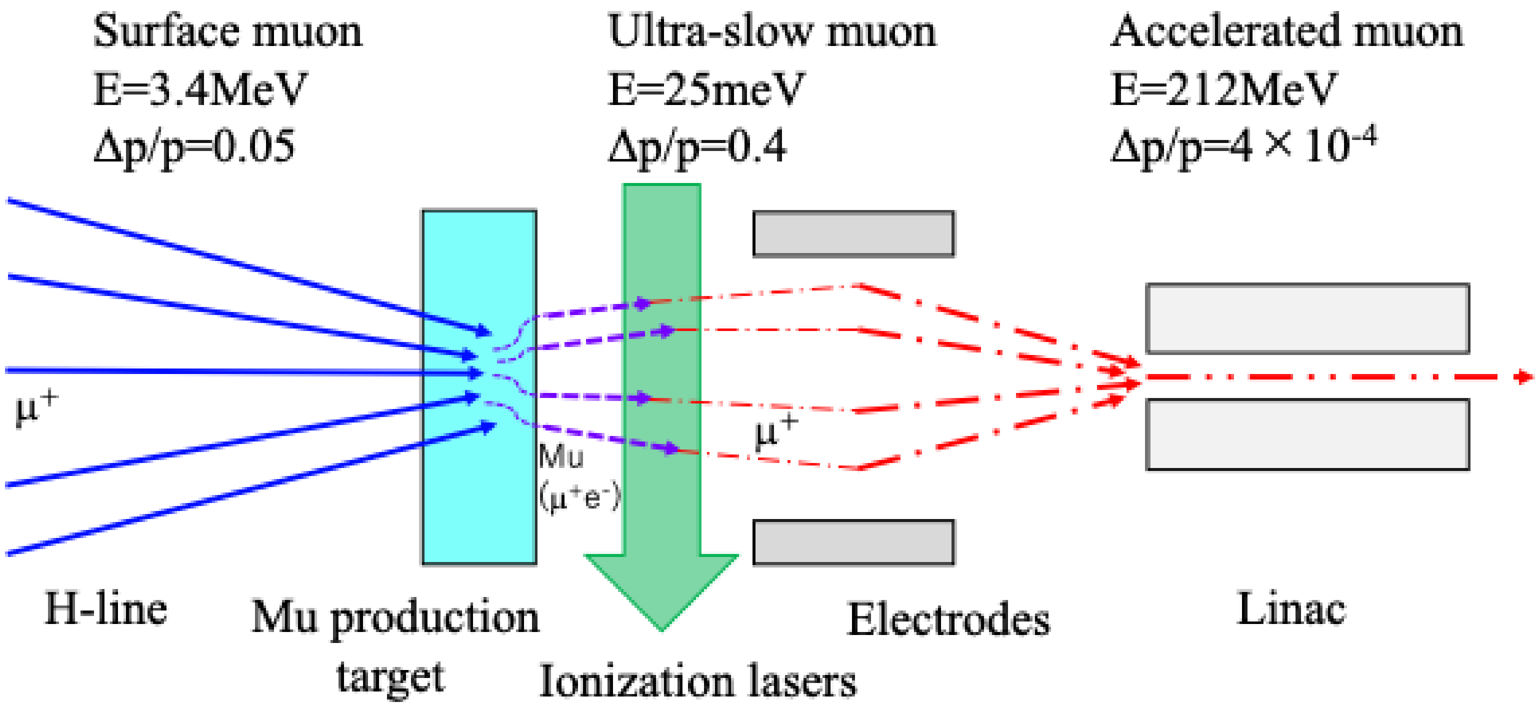
✓ Cooling of muon beam is important for better precision/resolution of these experiment



Muon cooling at J-PARC: Ultra-slow muon (USM) source

- **Laser ionized thermal muonium (μ^+e^-,** Mu**)**
- Primary μ^+ beam→ thermal Mu production → laser ionization → Extraction → rf-Acceleration

✓ Very good beam quality is expected. **Muon is once "stopped".**



Specifications/Features

- **Energy: 30 meV**
- **Normalized RMS emittance : ~ 0.5 π mm mrad.**
  - Determined by Mu spatial distribution and energy
  - One of the smallest emittance among proposed techniques
- **Production Efficiency: ~10^{-3}/μ**
  - Detail shown later.
- **Timing profile: short pulse. FWHM ~ 2 ns**
  - Determined by laser pulse.

- **Only positive muon can be cooled**
- **Polarization: ×1/2**
  - Due to hyperfine structure of muonium (4GHz)

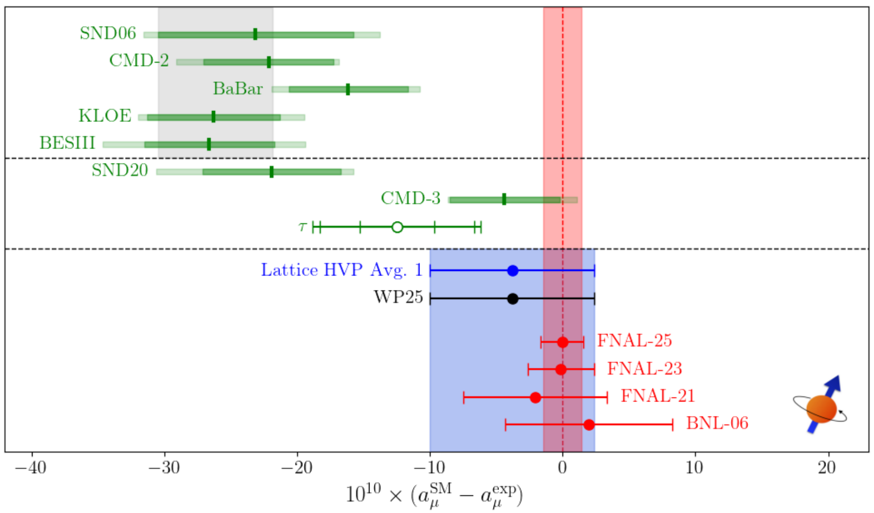
Application of USM

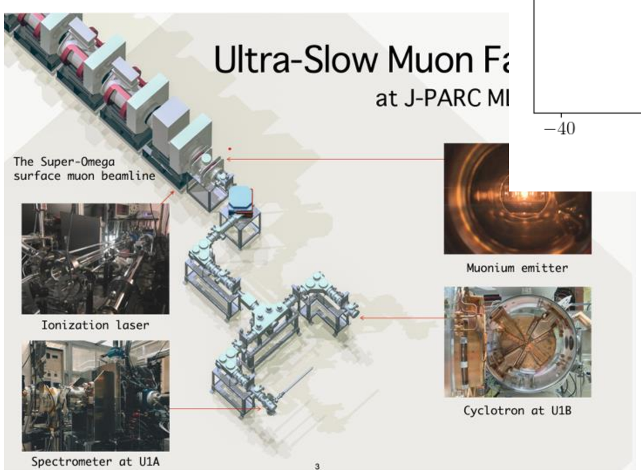
- **A lot of proposal for low energy application**

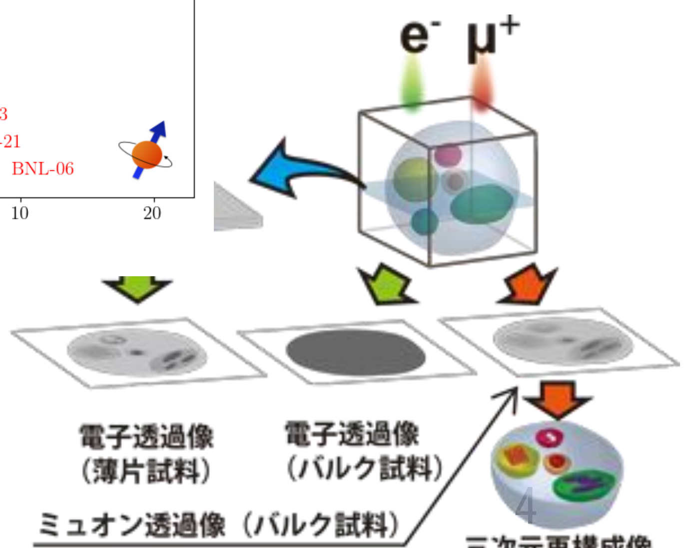
✓ **keV~MeV**: µSR for thin material with good timing/spatial resolution

✓ **O(10)MeV**: transmission muon microscope

✓ **O(100)MeV**: new muon g-2 measurement

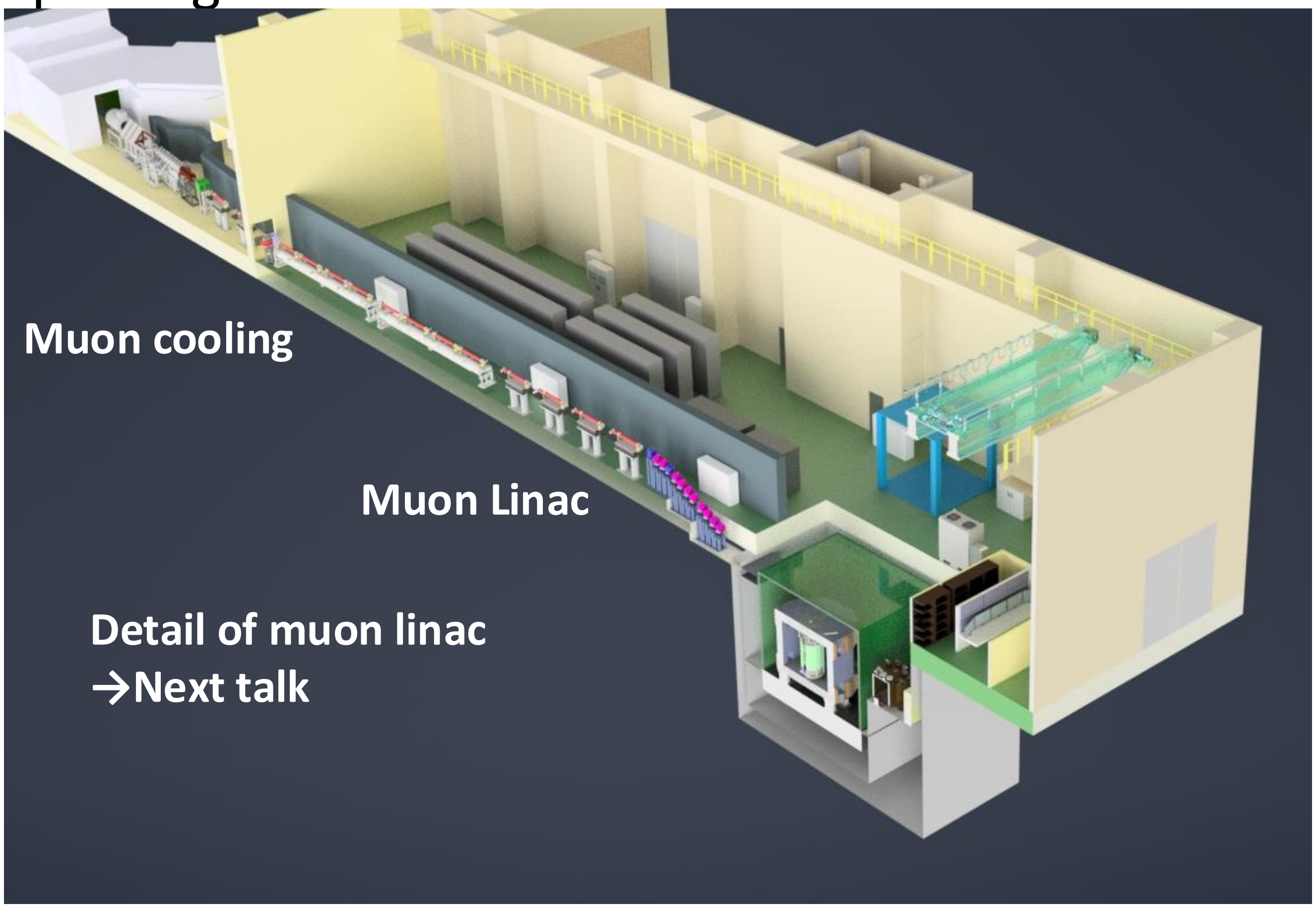






Flagship facility

- World's first Accelerated muon facility, including
  - **Muon g-2/EDM measurement**
  - **Muon microscope**
  - And so on: muonium spectroscopy? μSR?
- Expecting its realization in 2030s



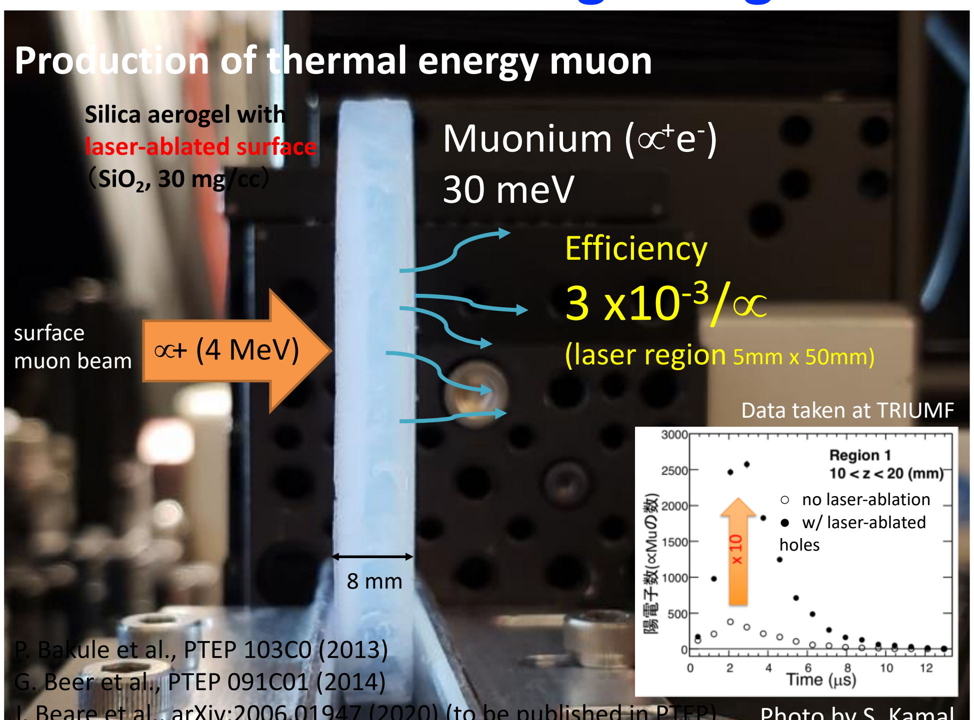
Key technology 1: Muonium emission target

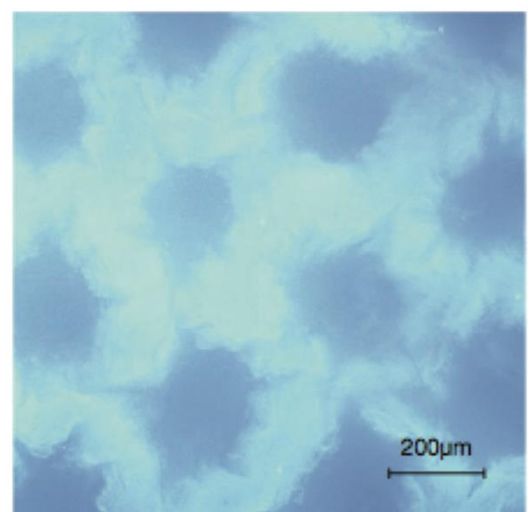
✓ Challenge is **increasing the cooled muon production efficiency**

- ↔ By nature, good emittance is expected

- Muonium production target is one of them.
  - Lower temperature, better emission efficiency, stability

➢ **Laser ablated aerogel target has been invented.** → × 10 efficiency





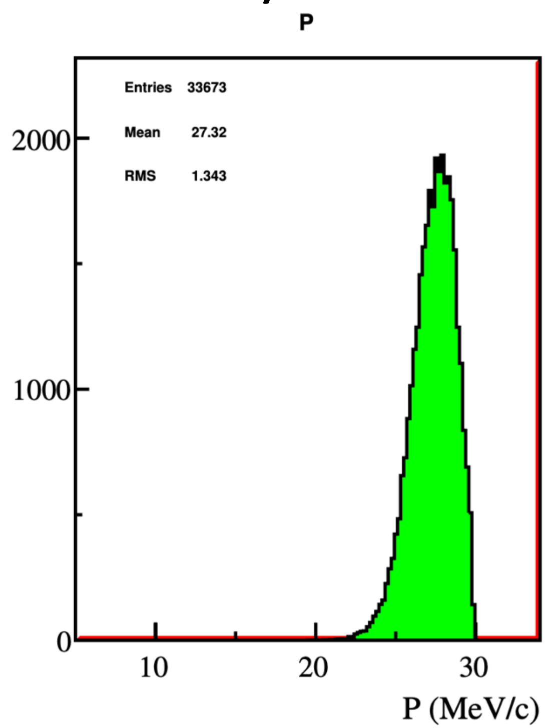
Detail of the target

- The behavior of Mu inside the target is modeled **as 3D random walk**
  - Diffusion parameters is determined from the experiment.

✓ **Mu only near the target surface** is emitted to vacuum before decay

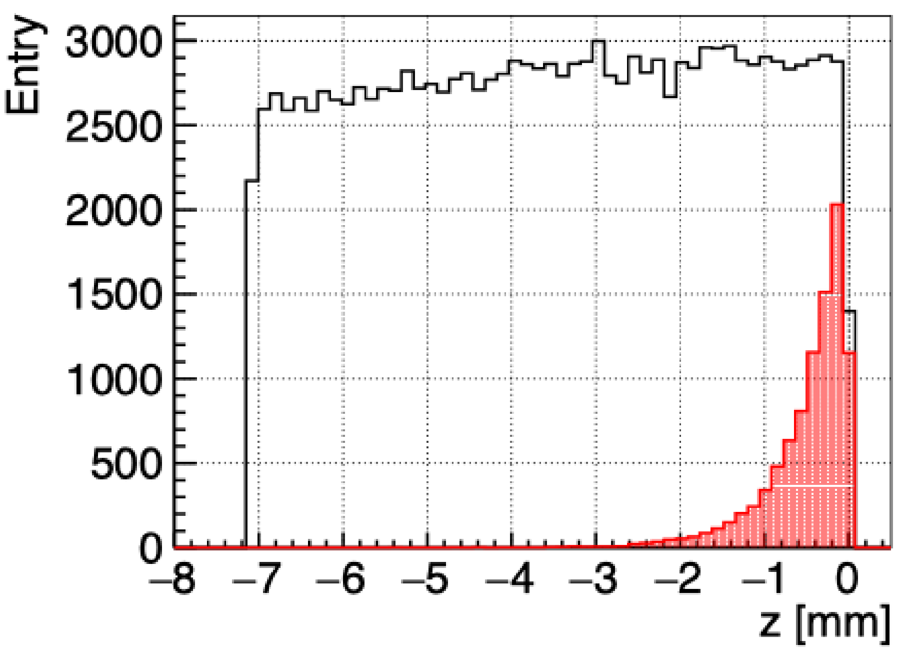
➢ "Vacuum emitted Mu/Mu in target" is about 6%

Primary muon beam



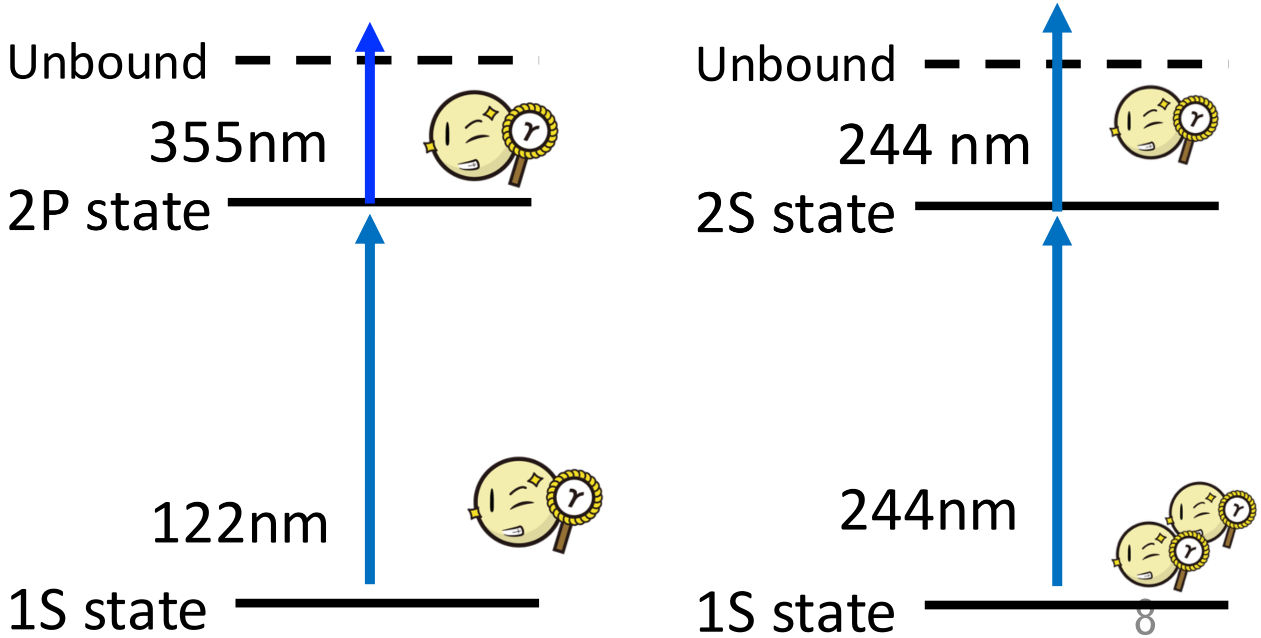
Mu stopping distribution (Black)

Emission before decay (red)



Key technology 2: Resonant multi-photon ionization

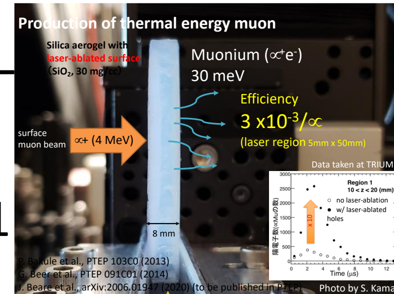
- ✓ Muonium is ionized by absorption of multiple photons
  - **122nm + 355nm photon** → ionization via 2P state
  - **244nm photon ×(2+1)** → ionization via 2S state
- ✓ Two challenge:
  - **Short wavelength (UV/VUV)**
  - **Large beam size = high energy**; due to the large beam size of incident muon



Hisotry

Proposal of cooling technique: PRL 74, 4811 (1995).

Muonium target PTEP 2013, 103C01 (2013)



Laser for Mu 1S-2S spectroscopy is installed to MLF

Previous Hokkaido workshop

1995 — 2013 — 2017 — 2021 — 2024 — 2025

Acceleration of negative muonium ion: PRAB 21, 050101 (2018)

First acceleration of μ⁺: PRL.134.245001 (2025)

First USM event in the new experimental area.

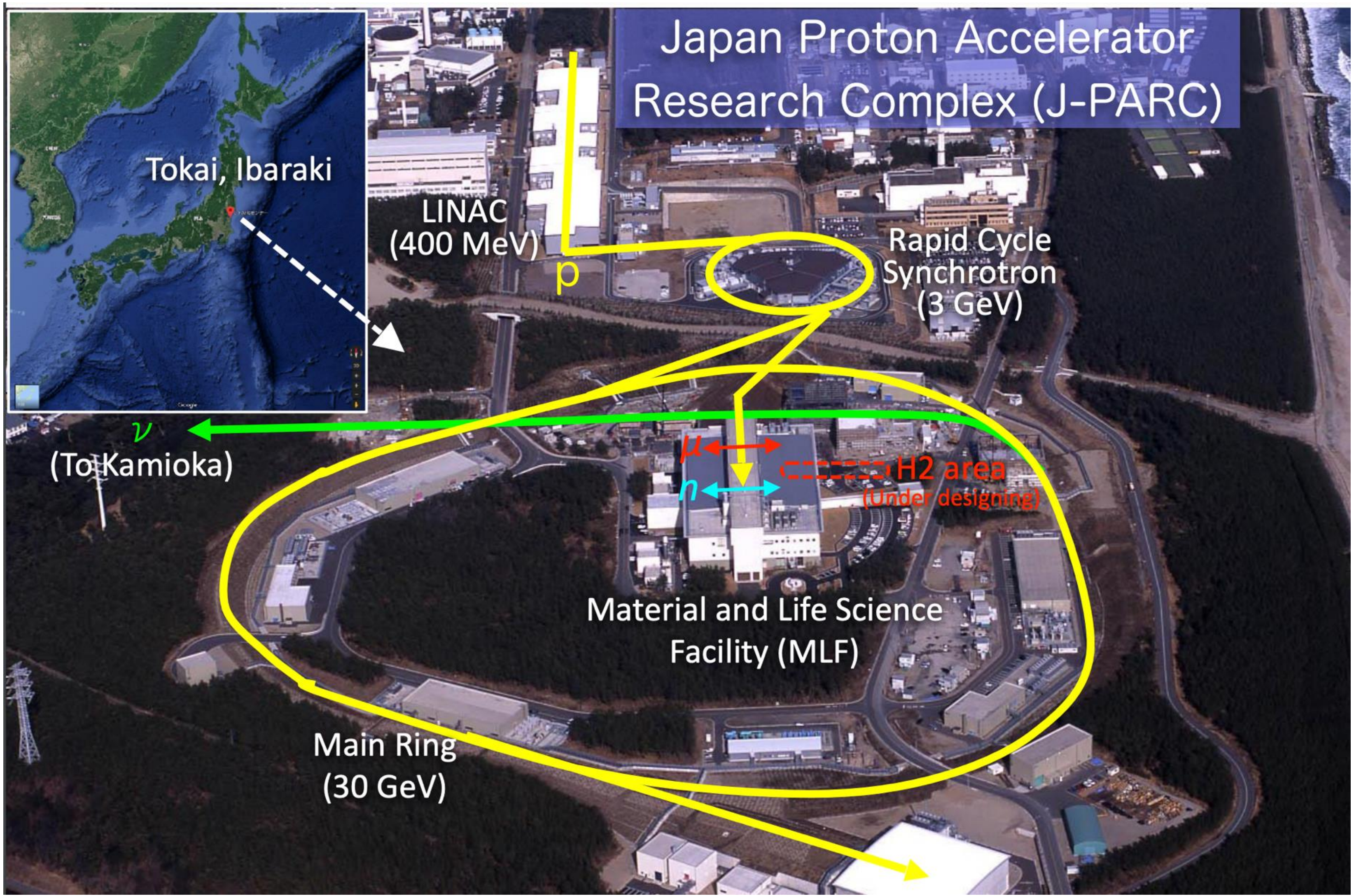
Recent highlights

Recent highlight: world's first rf-acceleration of cooled muon

- Performed in April 2024.

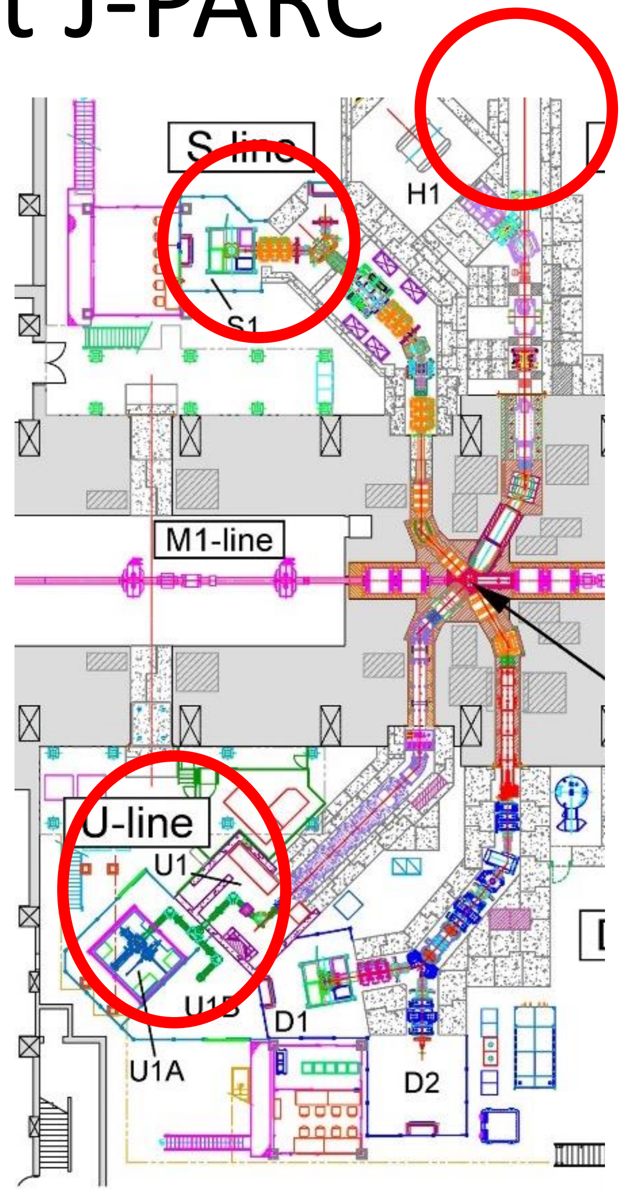
J-PARC

High intensity proton beam facility
neutrino, hadron, neutron, muon

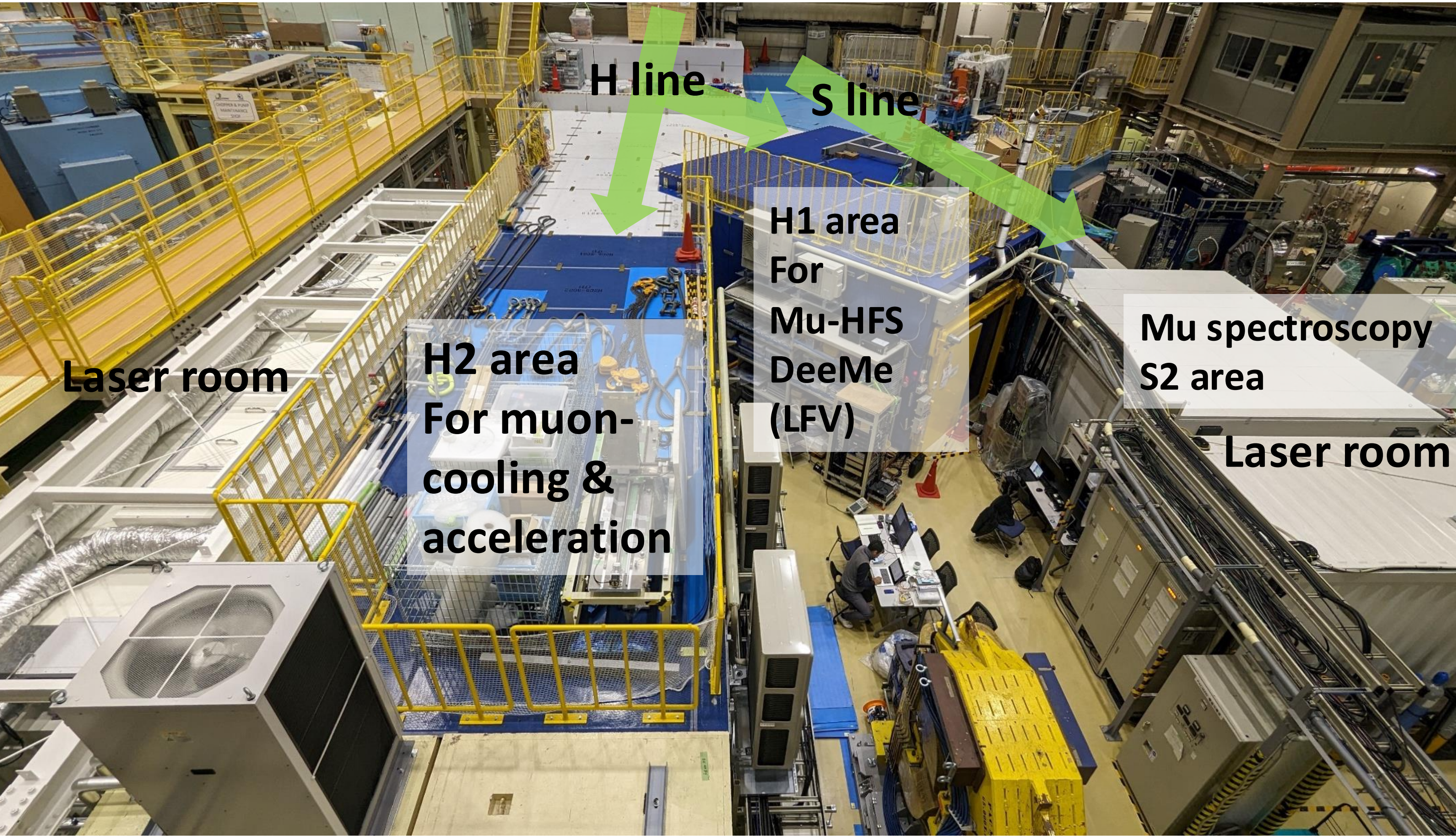


MLF: Muon facility at J-PARC

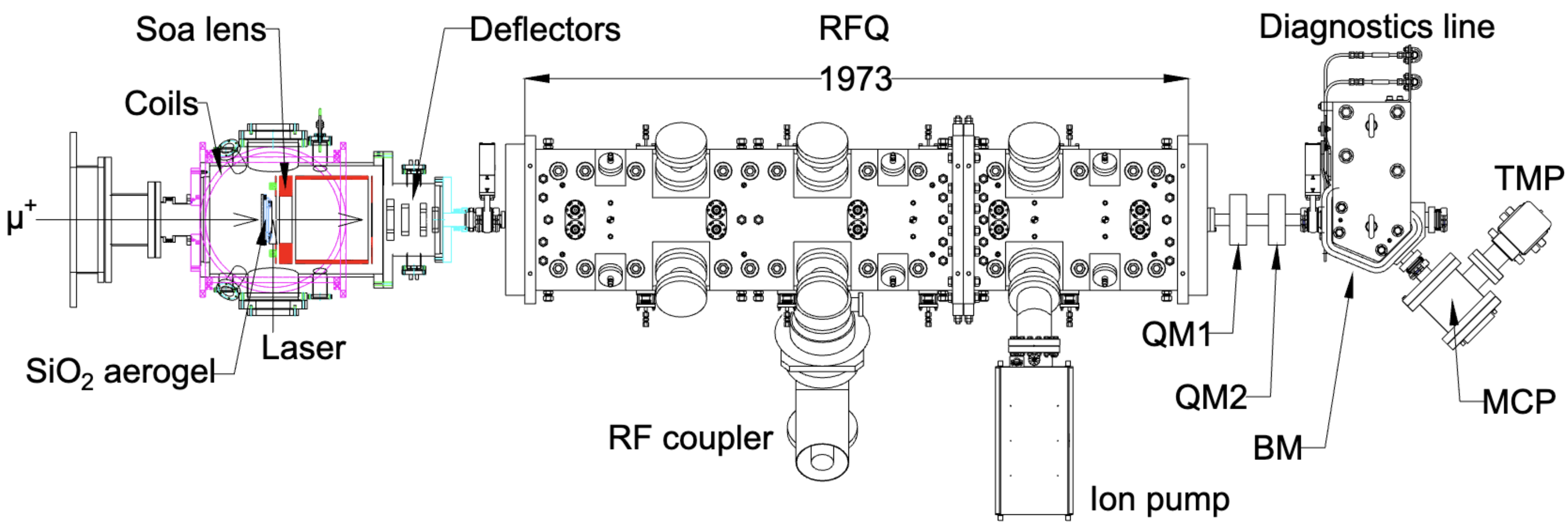
- ***4 beamlines and 8 experimental area***
  - ***~10% of 3GeV, 25Hz, 1MW proton beam***
- 10^8 muon/s (4MeV positive muon beam)
- Multiple programs featuring USM
  - Muonium spectroscopy
  - Muon acceleration
  - USM μSR



Experimental hall



Experimental setup



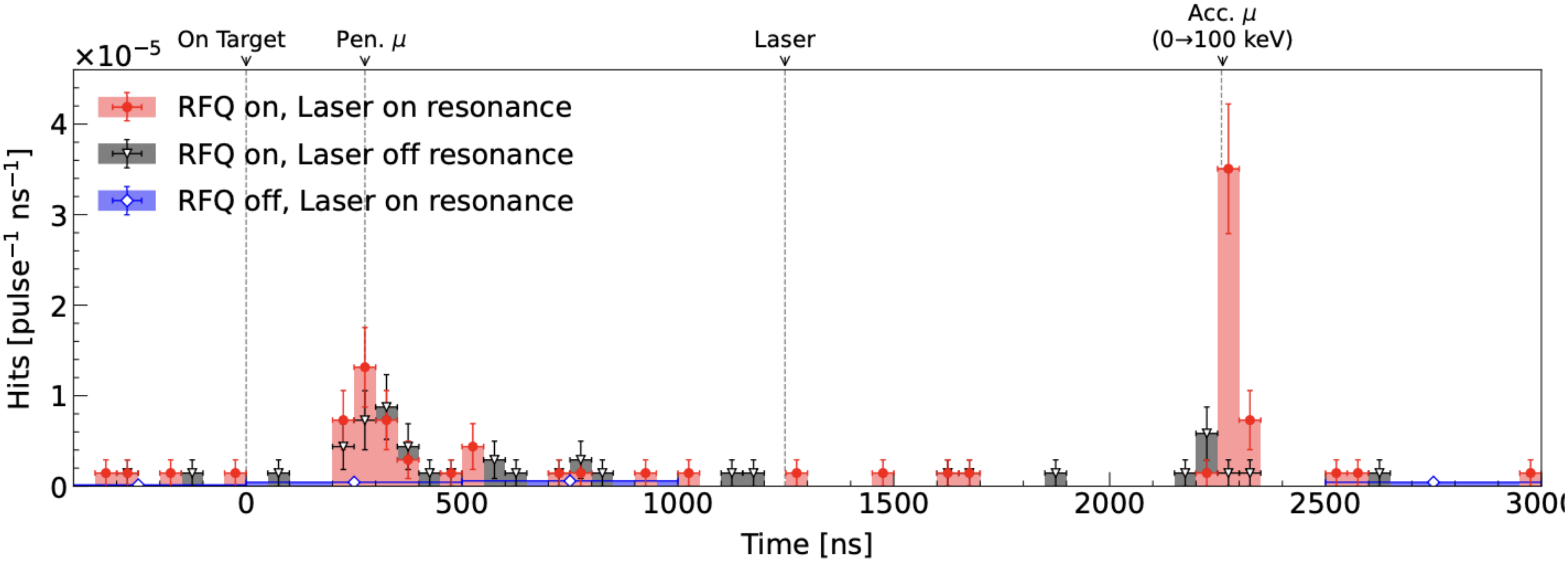
- Incoming muon: 9.5×10^4 /pulse. E= 3.6MeV
- 244nm laser by Okayama group for Mu spectroscopy
- Electrostatic lens for initial transport: **30meV→5.7keV**
- J-PARC prototype RFQ: **5.7keV→100keV**
- Beam diagnostics line

Result

- Timing spectrum of the MCP signal at the end of RFQ
- Intense peak when laser is on-resonance and RFQ is ON

✓ **First rf-accelerated cooled muon signal!!**

  - **We also measured the transverse emittance of the beam and confirmed the reduction of emittance**



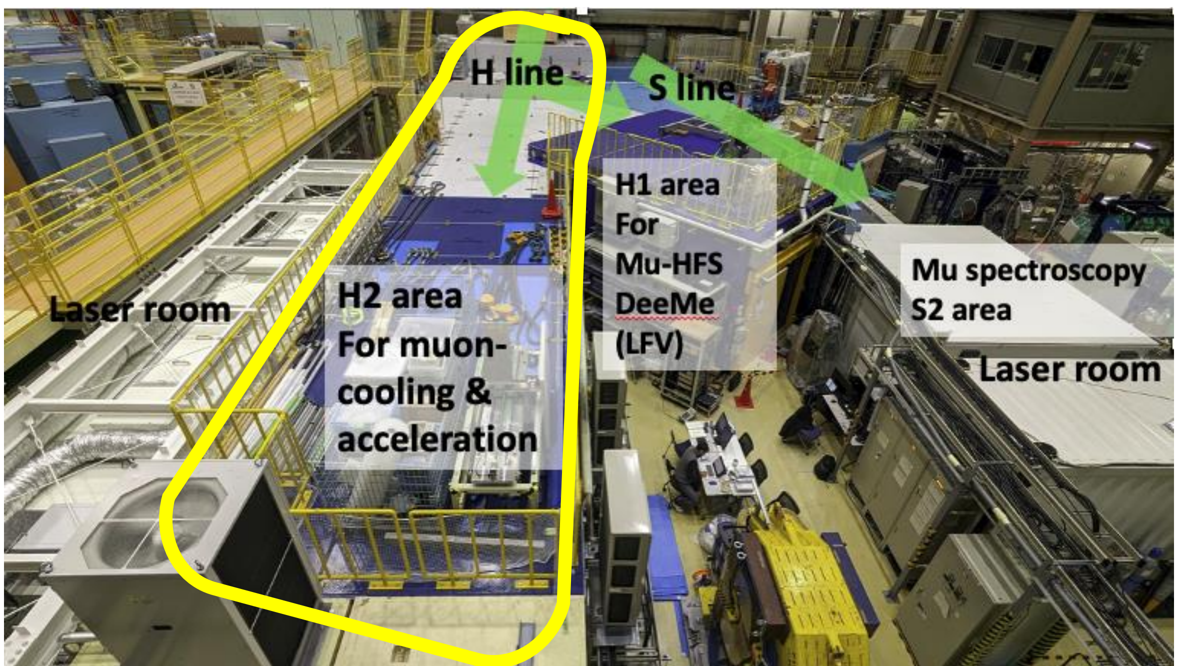
Next step

- The demonstration experiment was performed at a general-purpose experimental area.

➢ Production efficiency of cooled muon was **$10^{-7}/\mu^{+}$**

- We used a light source for precision laser spectroscopy, but not for efficient ionization & limited space for accelerating cavity

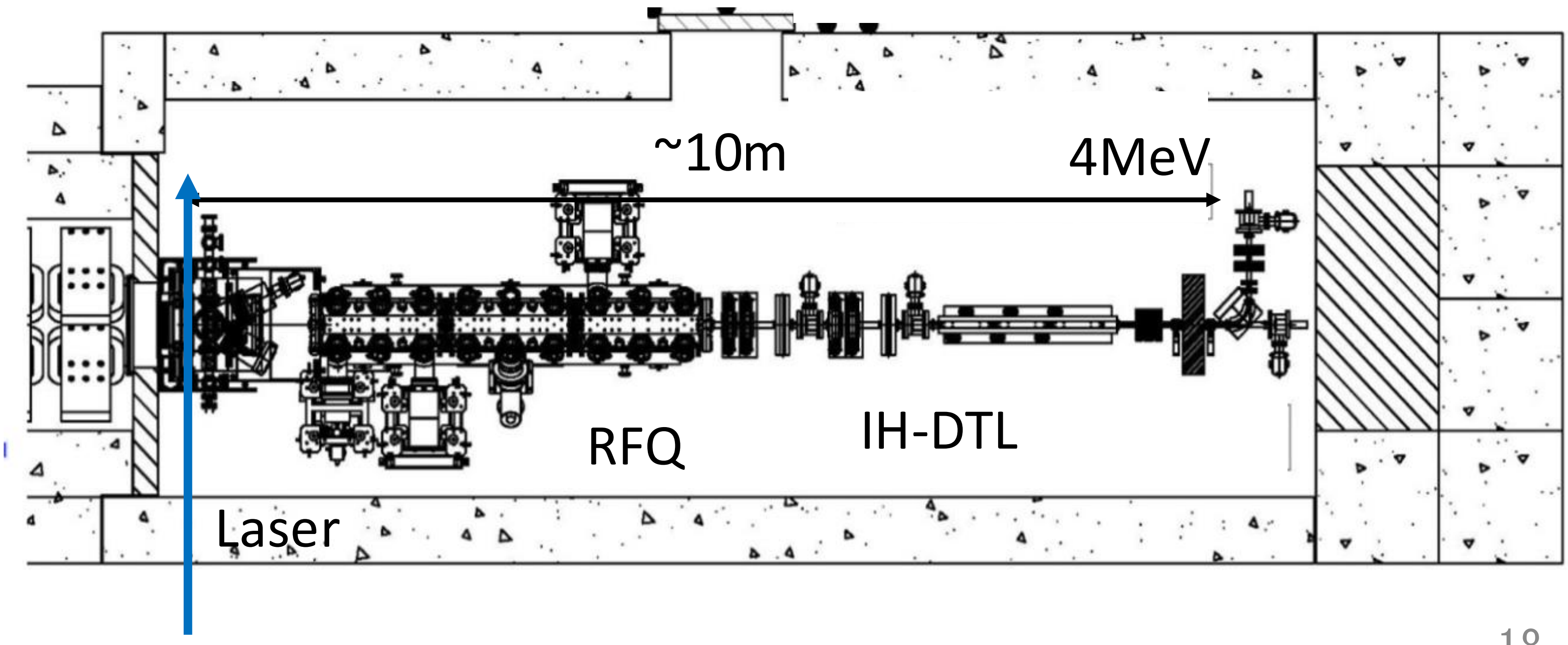
✓ We need **a dedicated experimental area** with a high energy light source and with muon accelerators



First primary muon beam in 2025 April

H2 area

- **New experimental area for muon cooling and acceleration.**
  - Accelerating cavities for 4MeV acceleration can be installed.
  - Laser room next to the experimental area.
- Extension of the area towards higher energy (more accelerating cavities!) in the future

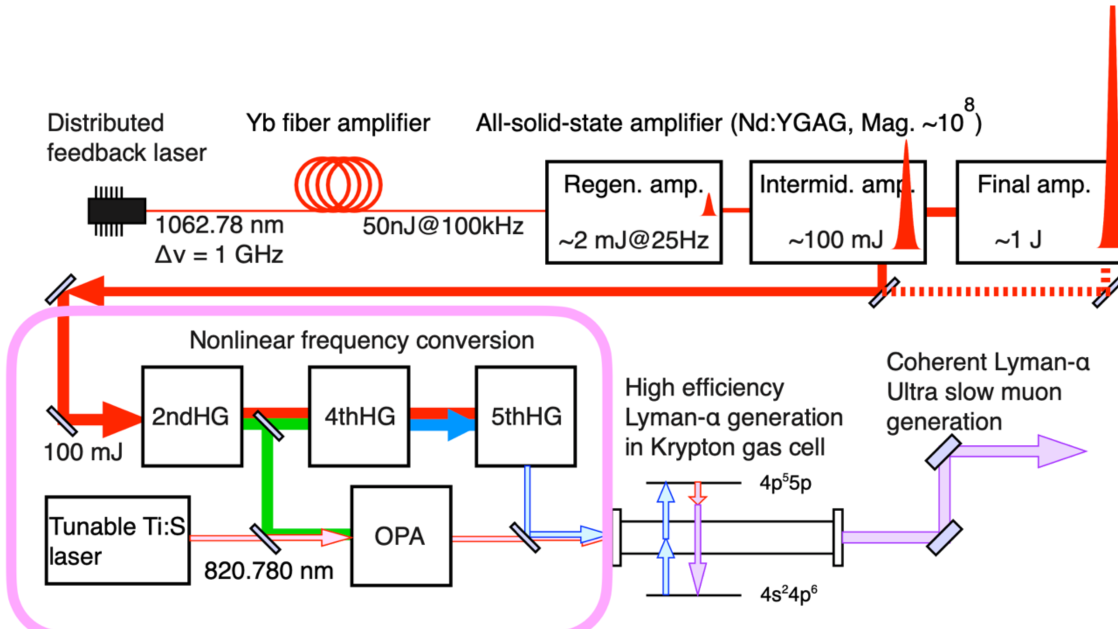


A new light source

- 122nm & 355nm light source has been constructed.
- 122nm→ Long development history in KEK, and still in progress.

✓**A new light source based on the existing system** has been prepared.

- "Copy" of the current version→Energy upgrade in the future.

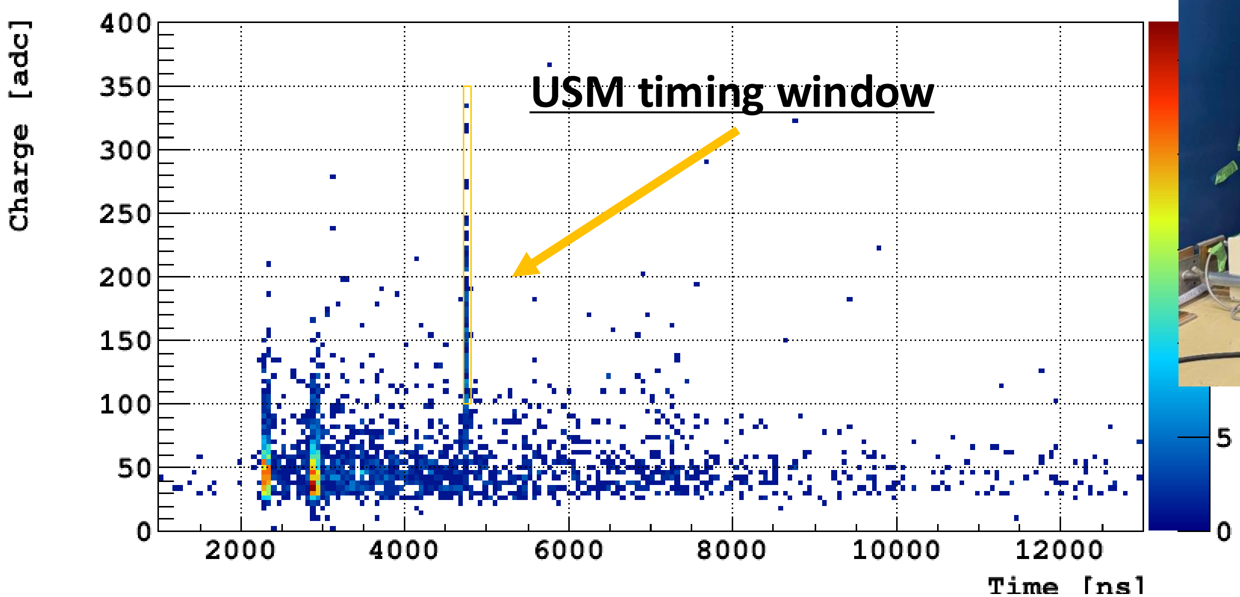


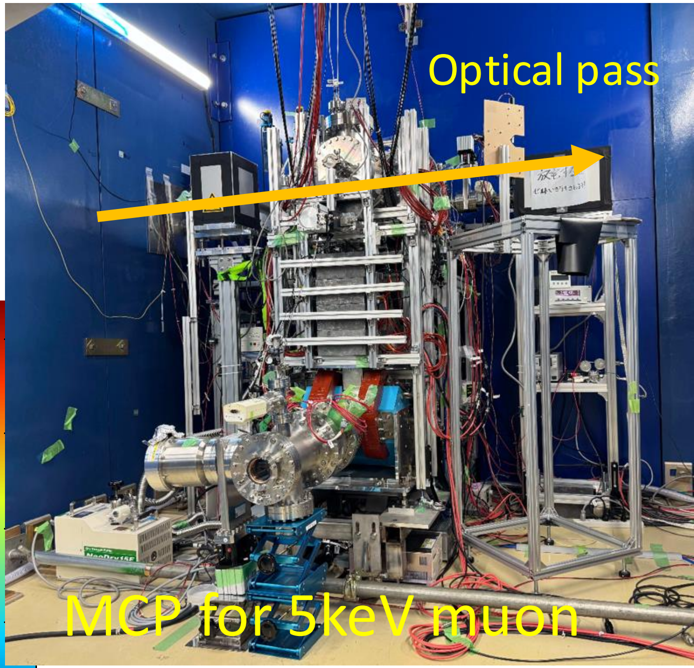
First USM commissioning

- We had our first beamtime in the H2 area in 2025 December.
  - (We ran the world's first (?) official muon accelerator operations shift)
- A new diagnostic line for USM was also installed to the area

✓ Tough beamtime, **but we observed first USM signal in new area.**

- First 122nm light **during the beamtime**.
- Cooling efficiency was O(10^{-9}) due to limited time for tuning, alignment and study
- **Anyway, we made it!!!**

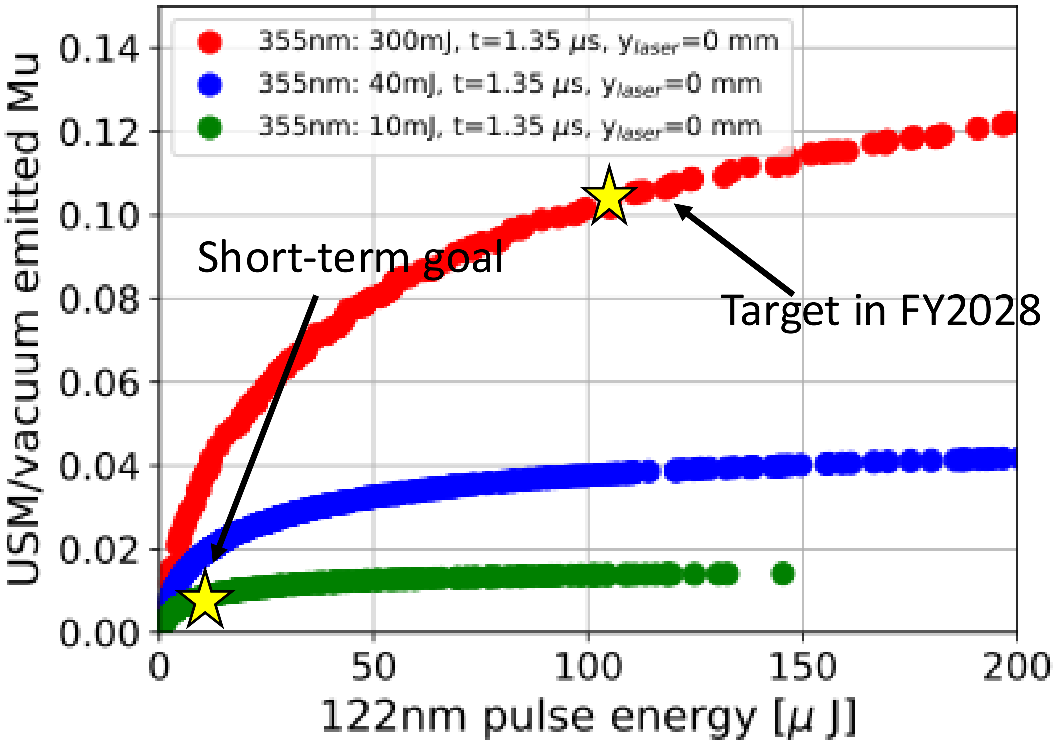




Next steps

- **Every components are ready** → The exciting part starts now! R&D towards the understanding of our cooling system can be started.
  - **USM production efficiency can be as high as O(10^{-5}), based on simulation. This is our short-term goal.**

✓After that, upgrade of light source to increase pulse energy will be started → **Aiming USM production efficiency of 10^{-3} in FY2028**



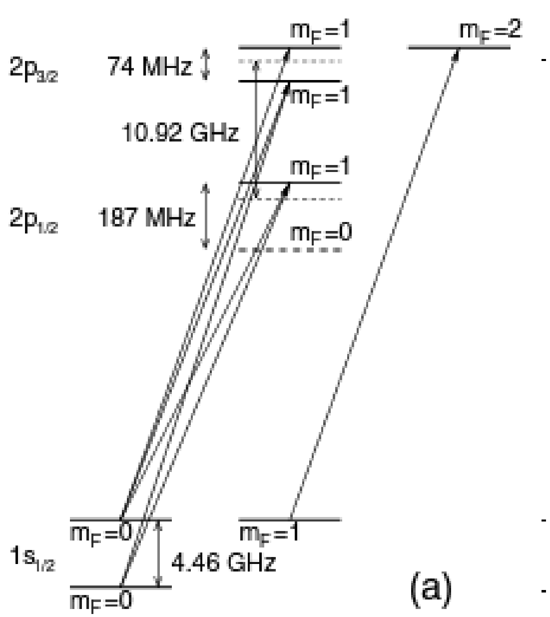
← Simulation of Muonium ionization efficiency

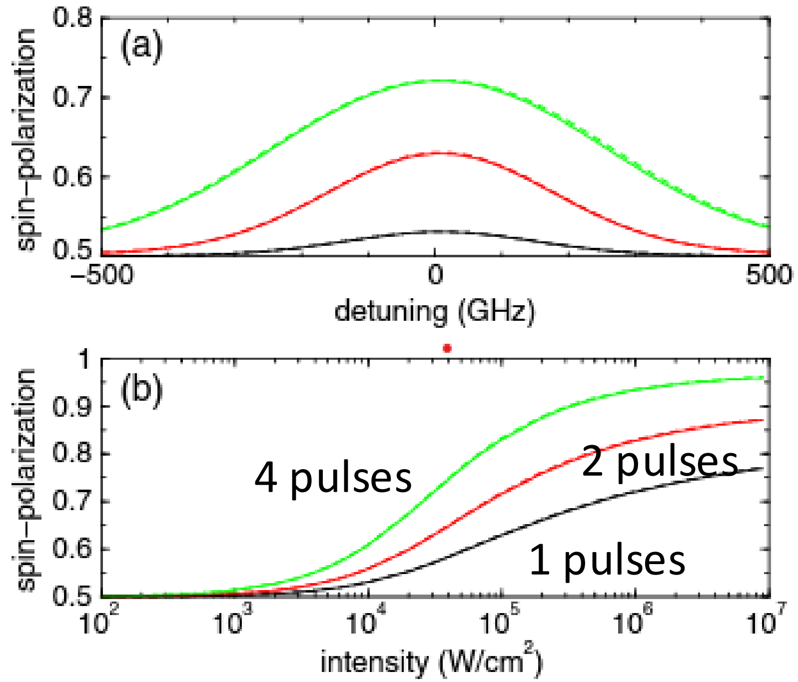
USM production eff.
= Ionization eff.× Mu production eff.

Future

Spin polarization

- As we use an atomic system, **we can polarize the muon spin inside the atom (muonium)** using AMO technique.
  - By the absorption of circularly polarized 122nm photon, angular momentum of photon is transferred to muon spin = optical pumping
- Shooting multiple circularly polarized 122nm pulse could increase muon spin polarization from 50% to >70%





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

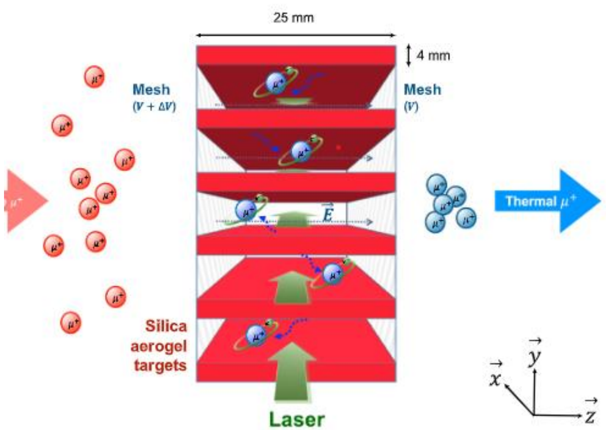
Towards higher beam intensity?

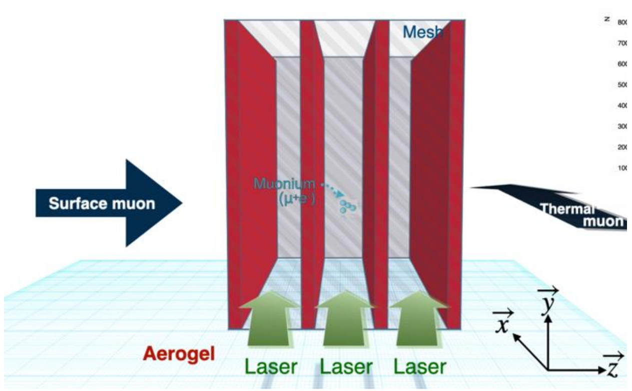
- **Muonium near the target surface is emitted to vacuum** = our efficiency is limited by momentum acceptance of the system
- We need a new idea to stop more muon near the "surface" of target.
  - **Installing multiple thin target?**
  - Any ideas for narrowing the momentum spread??

Proposal of multi-layered Mu target

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

We can expect factors of increase o Mu emission efficiency



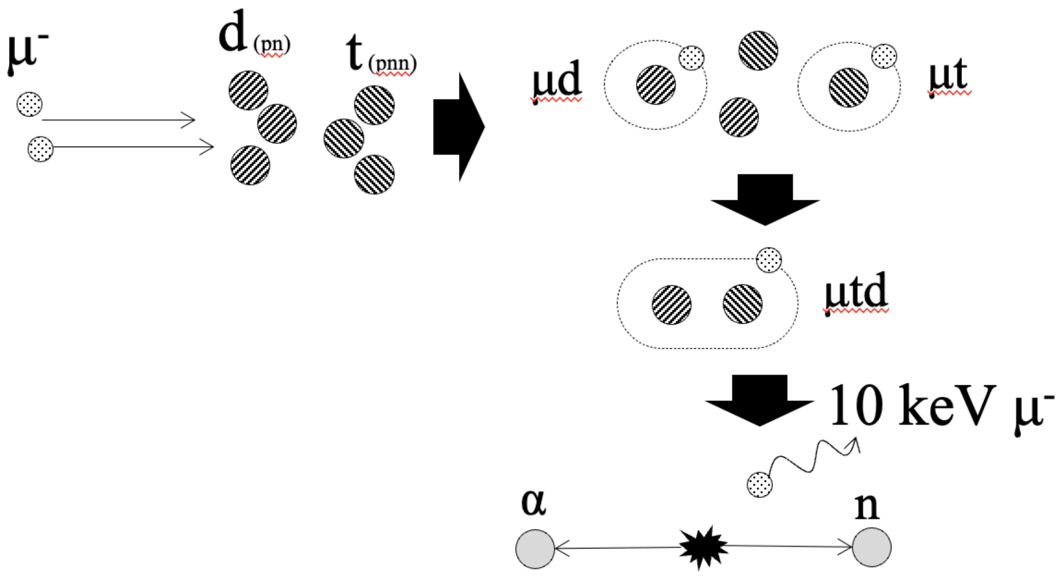


Cooling of negative muon?

- In Japan, there are no intense activity of μ^- cooling for particle physics/high energy application.

✓ **For material science, μ^- cooling using μCF is under discussion.**
  - Application: μ^- microscope
  - As a result of μCF, 10keV negative muon is emitted.

✓ Will be demonstrated in the future(I hope), but expected flux is 30 μ^-/s



Muon catalyzed fusion

Summary

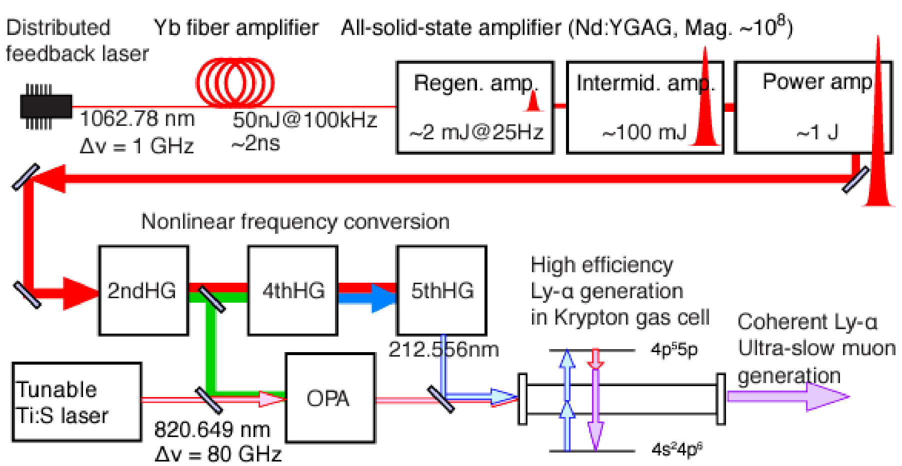
- Muon cooling at J-PARC: production of the ultra-slow muon
  - Laser ionization of thermal muonium
- A lot of proposal for precision measurements
- We've demonstrated the world first rf-acceleration of cooled muon in 2024
- A new experimental area and light source is being developed to achieve the USM production efficiency of 10^{-3}
- Additional proposal to increase the spin polarization or better production efficiency.

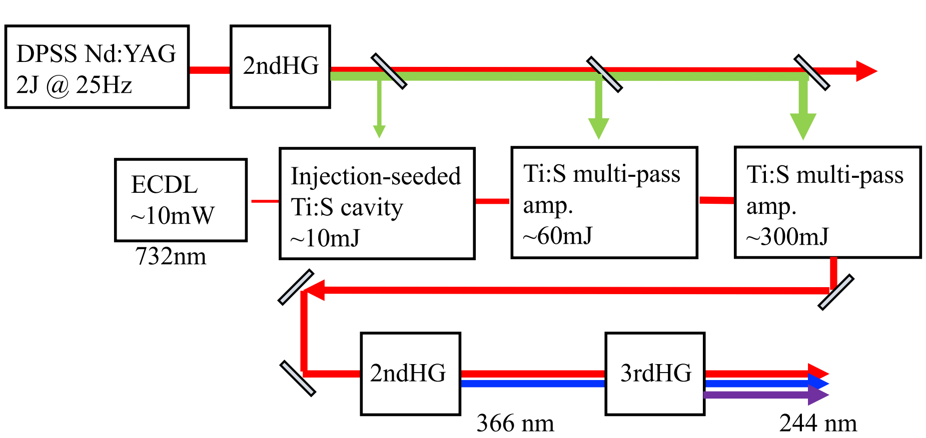
- Next talk: detail of muon accelerator in J-PARC

Backup

Requirements on Lasers

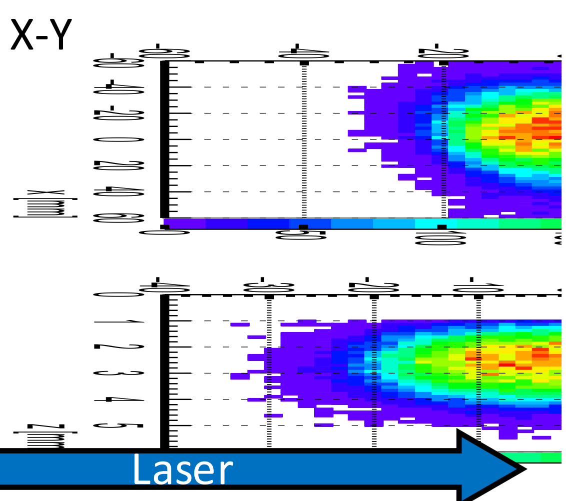
- **Ionization via 2P state:** to saturate the transition…
  - 122 nm for excitation: I=100μJ, Δv: 80GHz, Δt=2ns
    - **Very challenging (×~100 of typical energy of table-top scale ly-α laser)**
  - 355 nm for ionization: I=300mJ, Δt=2ns
    - **Easier, but still challenging for table-top scale laser**
- VUV light source is technically challenging → Alternative method (ionization via 2S state) is also under development in parallel
  - ✓ I=60mJ, Δt=40ns, >10 Multiple reflections to cover Mu cloud
    - **Challenging + (another R&D of USM extraction is required)**

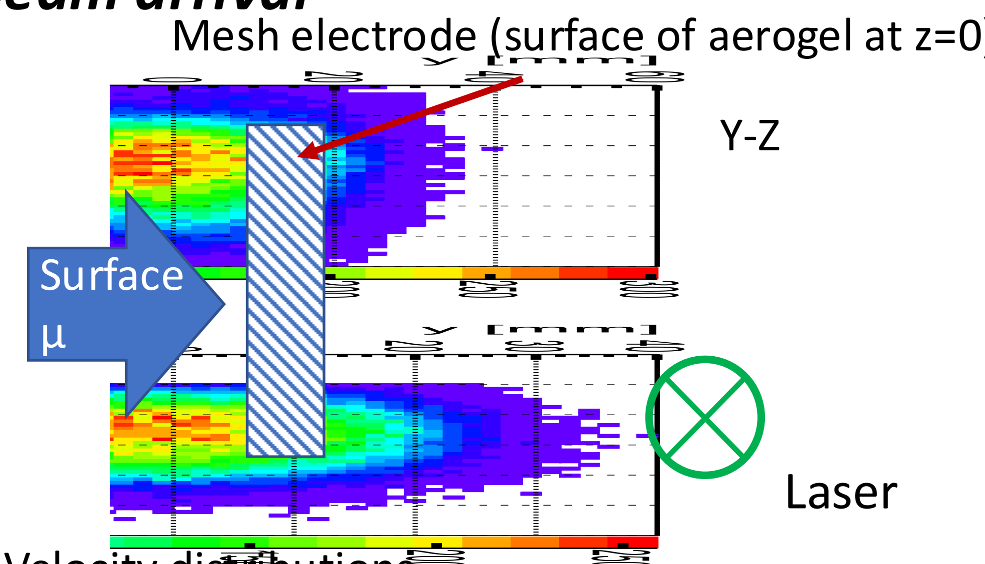




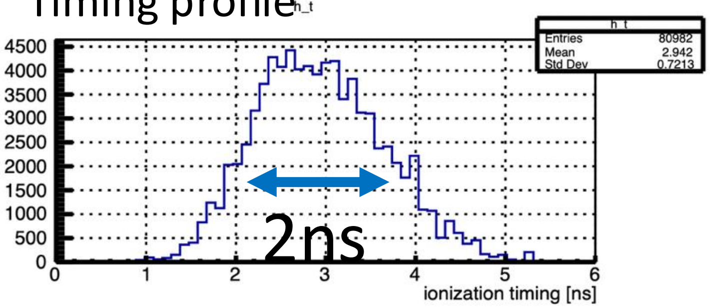
Expected performance at MLF H-line

- Simulation assuming J-PARC MLF H-line (for g-2 experiment)
  - Simulation from surface muon transport to laser ionization
- ***Laser fires 1.3 μs after beam beam arrival***

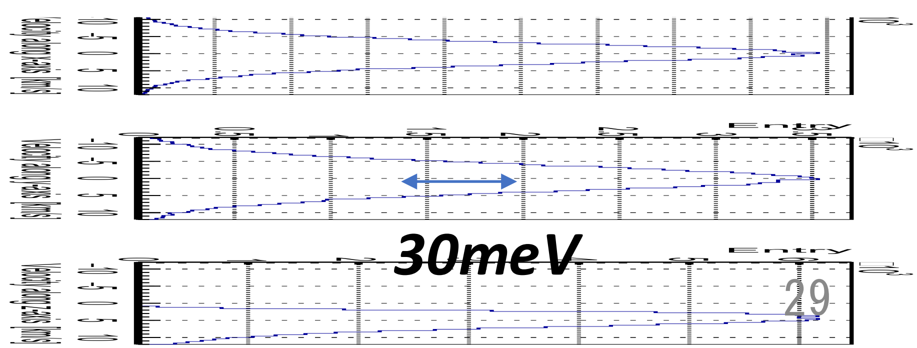




Timing profile



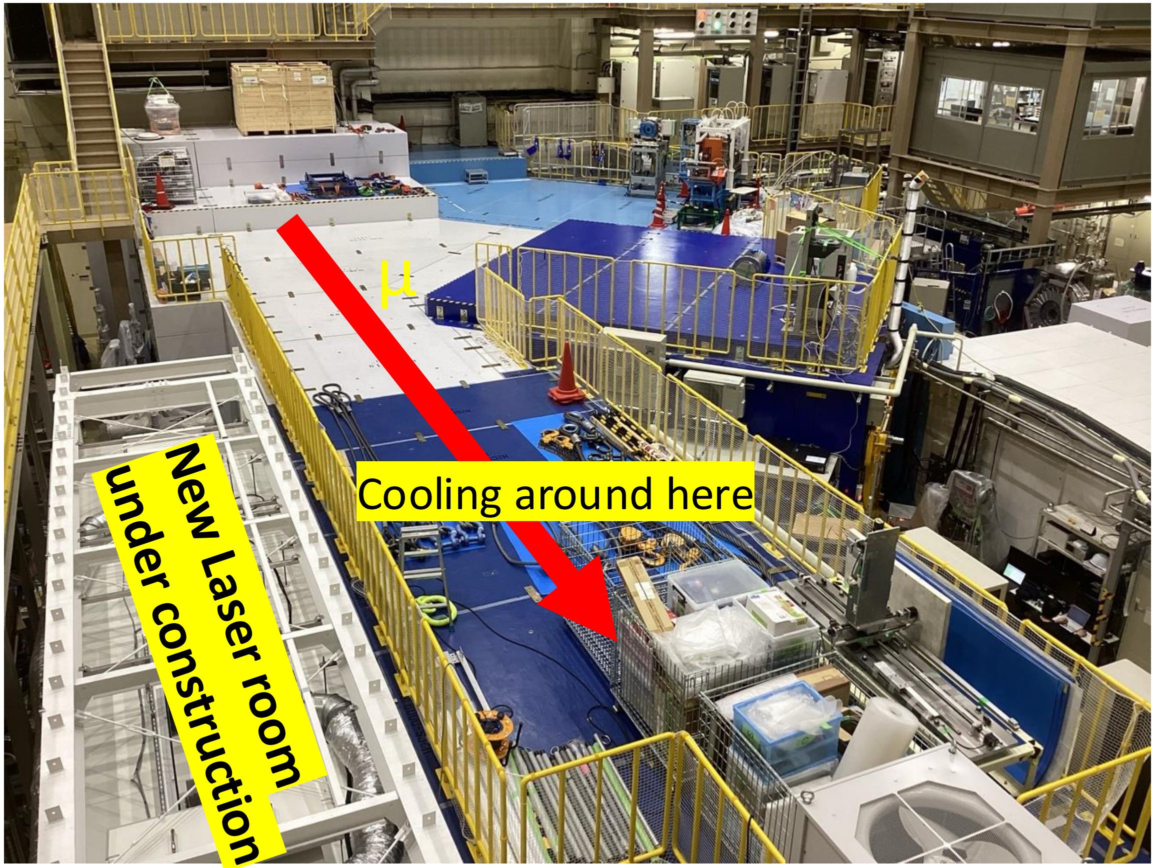
Velocity distributions



Towards high-intensity USM

- New beamline & laser room is under construction for $>10^5$ USM/s
  - One of the branch of beamline is already being operated.
- All of transport magnets will be installed in next FY.

➢ First muon cooling at the new area will be performed in FY2025



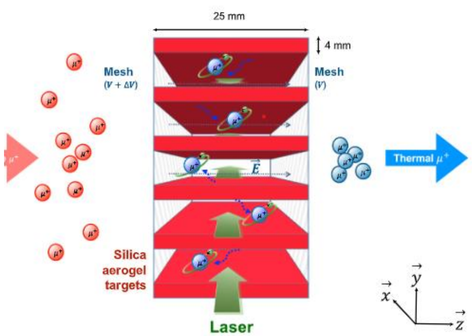
Based on R&D so far, Upgraded laser system is now being designed

Possible upgrade of USM source

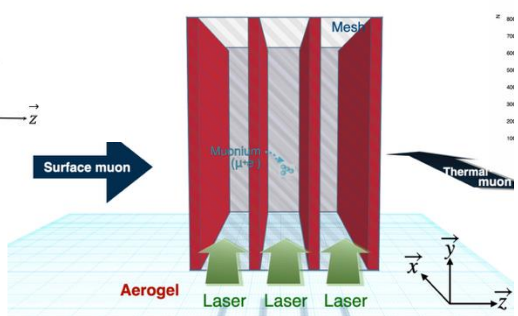
- Proposals to achieve more USM flux or better spin polarization.
  - Interesting ideas to increase the FoM of the muon source further

Proposal of multi-layered Mu target

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

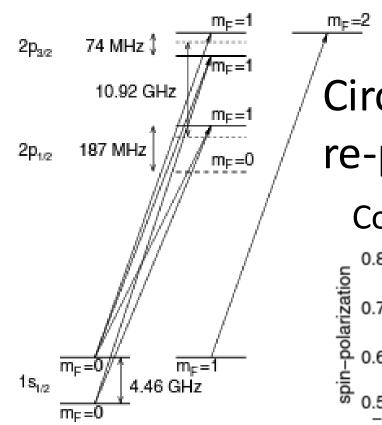


Or



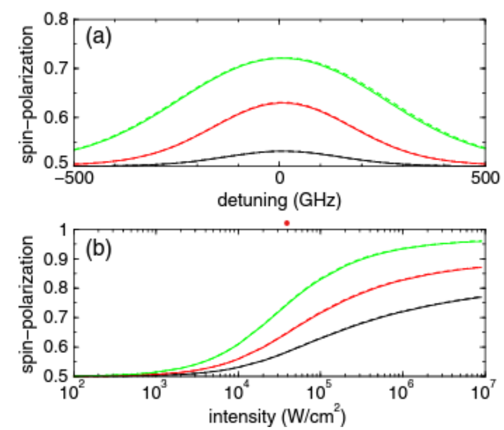
✓ Every incoming muon stops near the surface of one of the thin targets

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

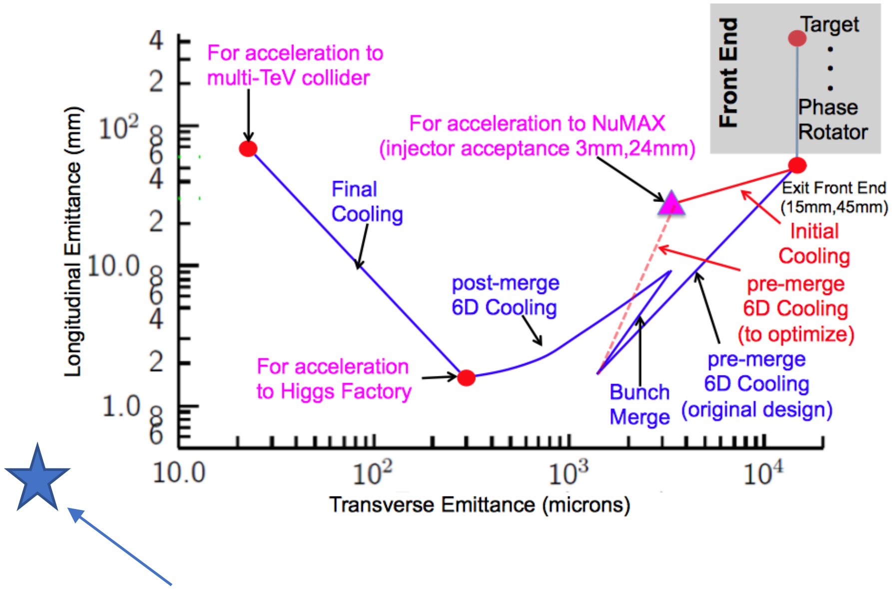
Application to muon collider?

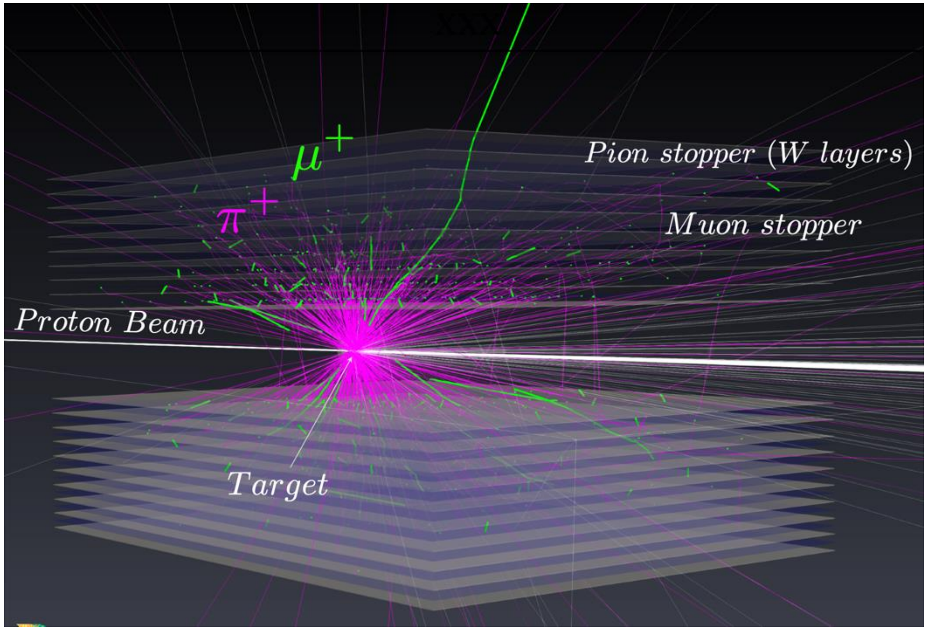
- Low emittance is advantage for muon collider

➢ How do we increase the flux of USM further ?

- Need to address the challenge of limited momentum acceptance of cooling system = π & μ^+ should be stopped near the surface

➢ Drastic change of target system: μTristan (Yoshida-san's talk)





Emittance of USM beam for g-2/EDM experiment (200MeV) is around here

Any other application ?

- Even if USM can be a source for a MuC, it is very long way to go..
  - $>10^5$/s & 220MeV for g-2 ↔ 10^{13}/s & 1 TeV for MuC

➢ We are (or I am) happy if there are any other application in between them.

  ✓ Good motivation of USM development towards ultimate goal.

✓ Compared to conventional muon beam…

  ◎ : **much better emittance**

  ○ : **demonstration up to 220MeV will be soon.**

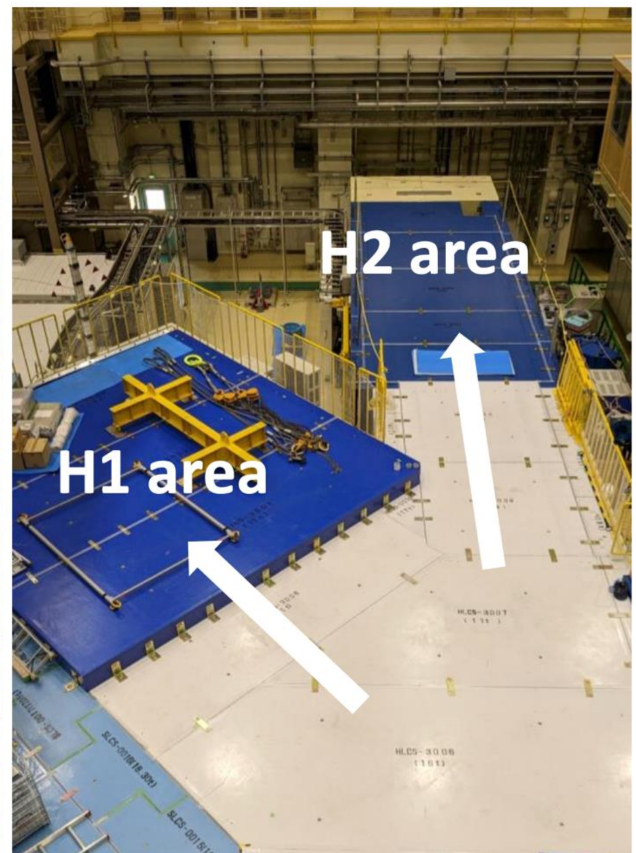
  △ : **lower flux (decay + emission/ionization eff. during cooling)**

  △ : **Only positive muon**

Surface muon beamline

- **H-line: a new, high intensity muon beamline**
  - H1-area: one of the branch of H-line → Under operation
  - H2-area: the other branch for g-2/EDM and muon microscope
  - ➢ Design intensity: 1.6×10^8 /s

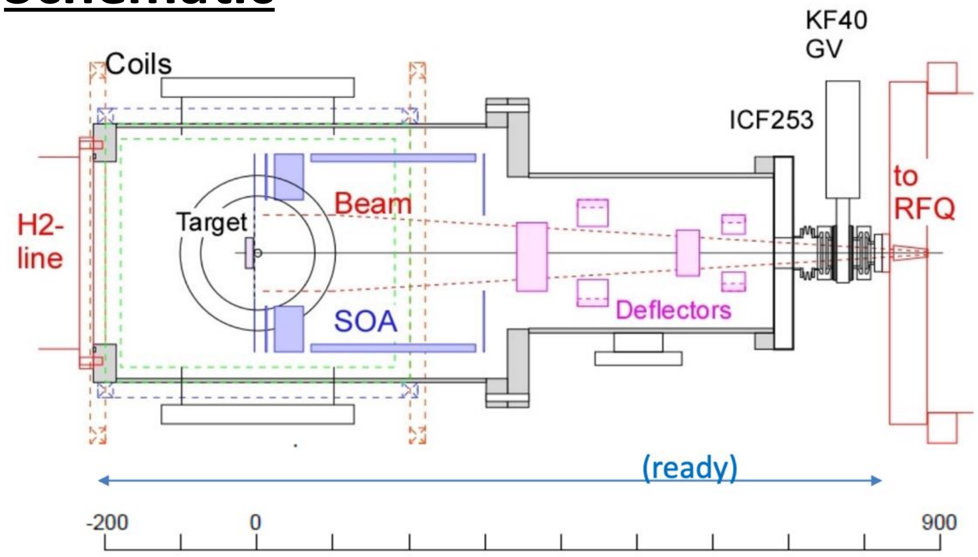
First beam in next year

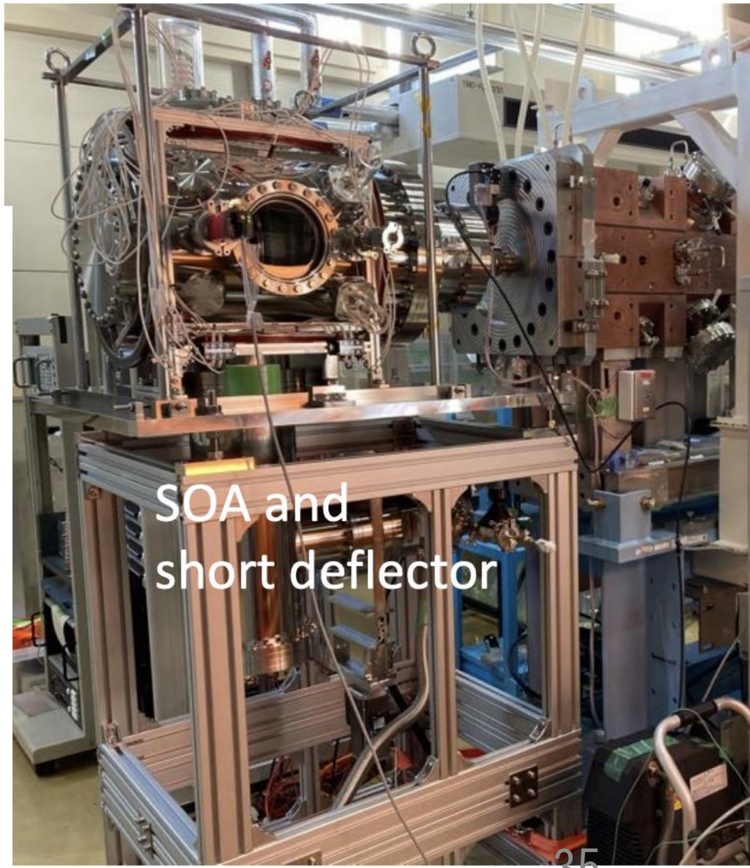


Development of muon source chamber

- Including…
  - Target holder + mesh electrode
  - Electrostatic immersion lens for extraction (5.7keV)
  - Electric deflector
  - Field compensation 3axis coil
    - ➢ B-field → spin polarization

Schematic





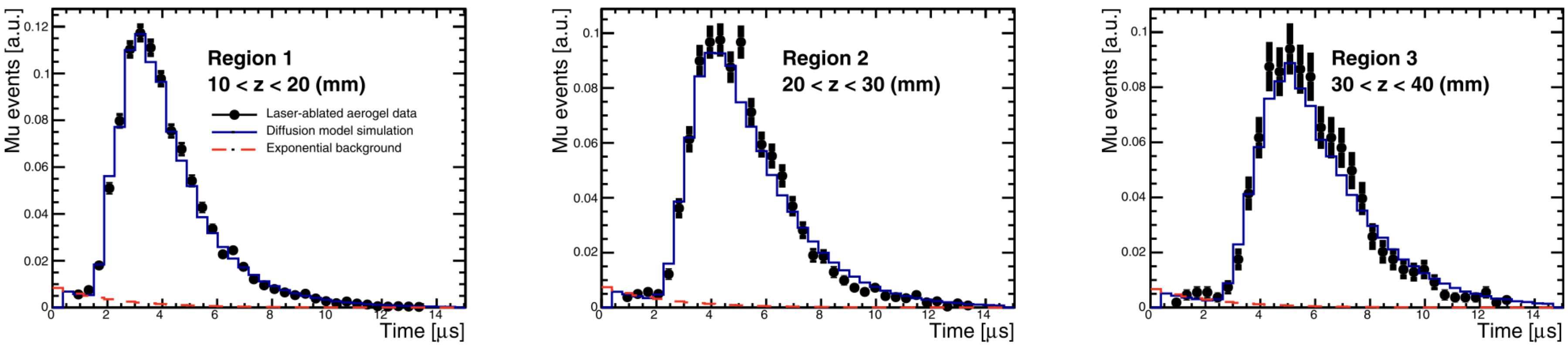
Modeling of the target

✓ 3D random walk inside an isotropic material to describe diffusion of Mu inside the aerogel.
  - Comparison with measured Mu emission profile

➢ **Diffusion constant: 870 cm^2/s, T=320K, Mu formation eff: 0.52**

➢ **Expected Mu emission efficiency per surface μ @ H-line is 0.013**

Comparison with data & model

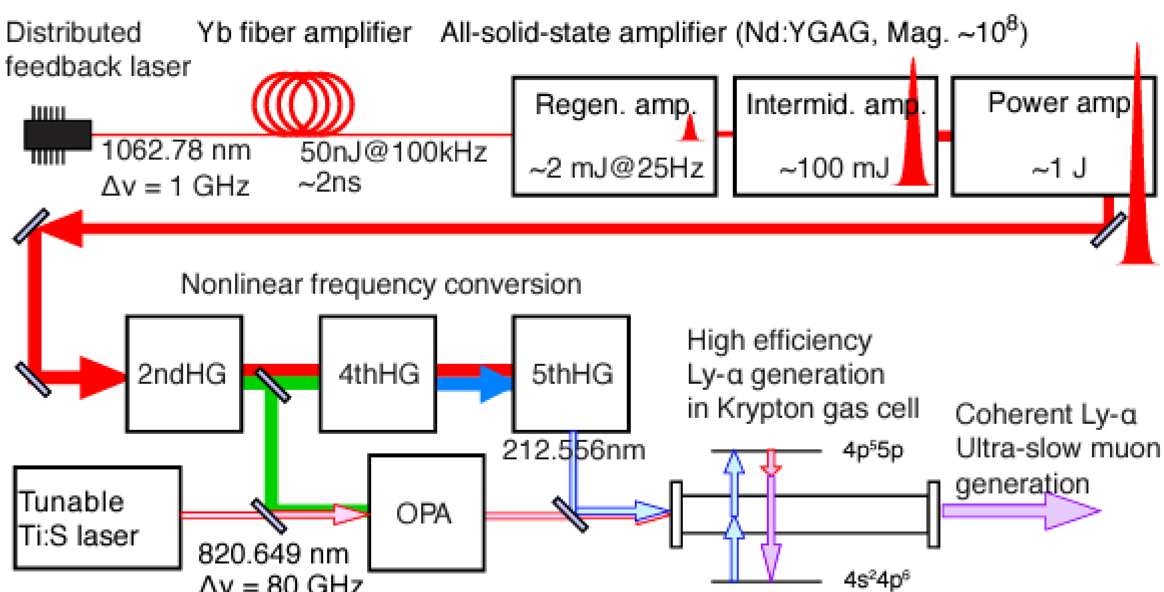


Breakdown of the expected efficiency

Surface muon stopping in the aerogel	0.418
Mu formation	0.52
Mu vacuum yield	0.058

1S-2P-unbound scheme

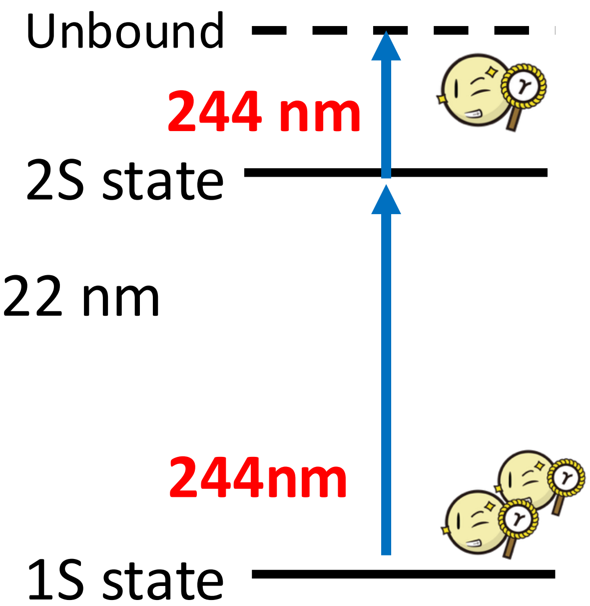
- Main scheme of the laser ionization of Mu
- Requirement on laser specification
  - **122 nm (Ly-α) for excitation: I=100μJ, Δv: 80GHz, Δt=2ns**
    - **Very very challenging**
  - **355 nm for ionization: I=300mJ, Δt=2ns**
    - **Challenging**
- Most intense ly-α laser system is now under operation.



Recently, mainly developed by Y. Oishi

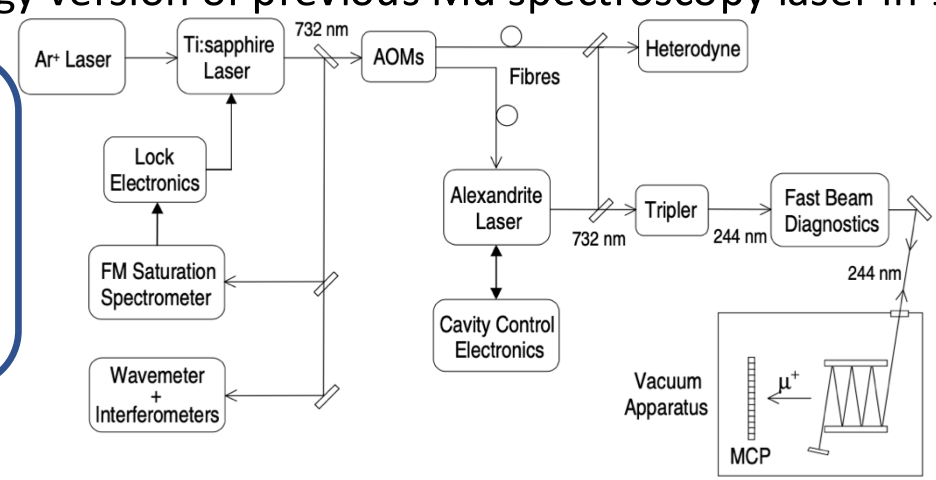
1S-2S-unbound scheme

- Less efficient two photon transition
    - High energy is required
        - Very challenging
    - Easier handling & more established than 122 nm
- Several 244nm laser developments
    - For spectroscopy (Okayama univ.)
    - For efficient ionization (KEK)



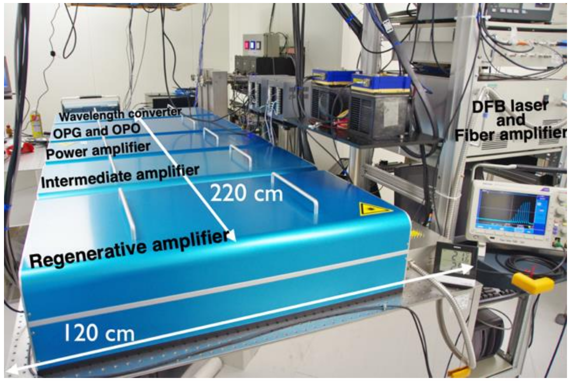
- ✓ I=60mJ
- ✓ Δt=40-60ns
- ✓ >10 Multiple reflections to fully cover Mu cloud

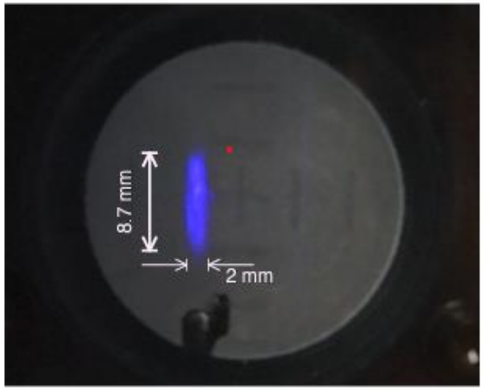
High energy version of previous Mu spectroscopy laser in 1999

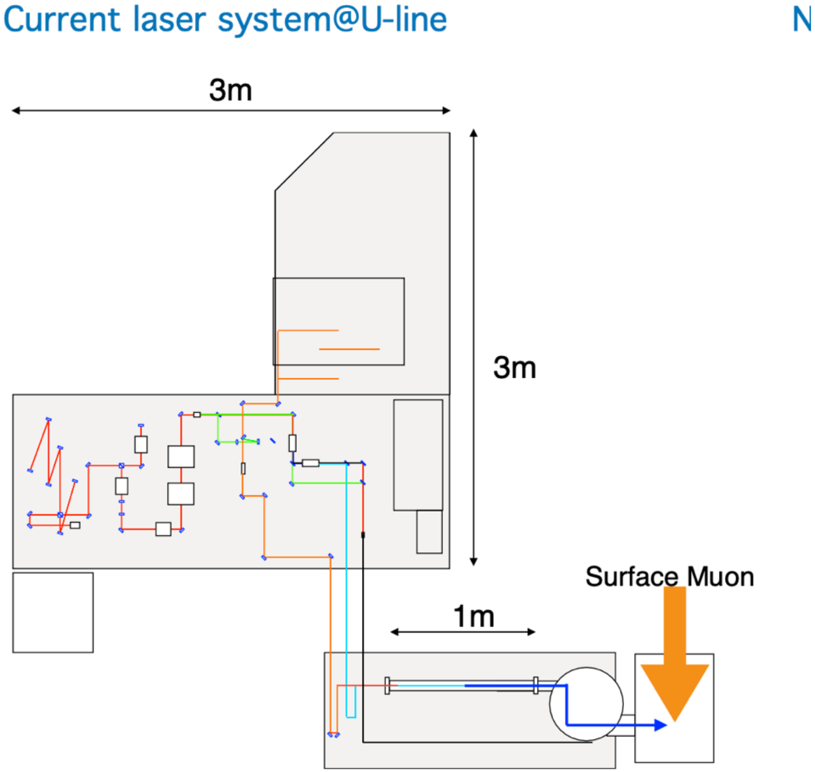


Laser development @ Tokai: 122nm

- **All solid-state laser for long term operation.**
  - **5μJ @ 122nm** is stably produced at MLF U-line.
  - **New amplifier to double the pulse energy is being installed**
  - **Another ×2 improvement is expected → Integration is underway**



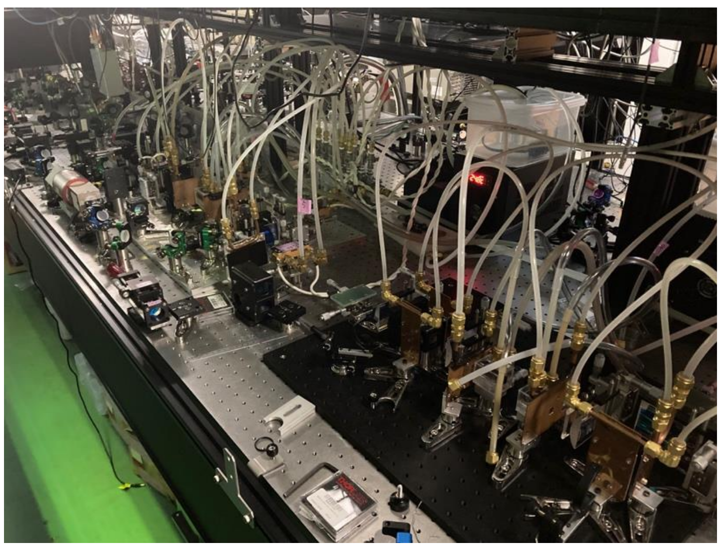




From Y. Oishi (reported in J-PARC Laser Review 2023 for Muon Science Advisory)

Laser development @ Tsukuba: 244nm

- Operated at 5Hz to demonstrate the entire system so far.
    - **30mJ @ 244nm was produced**: ~ ½ of requirement
        - **Very short-term result** & just after a frequency conversion crystal
- **R&D for transition to 25Hz is underway: thermal issues**
    - **First full power test will be performed in this spring**



355nm pulse for ionization from 2P can be also produced from the same system

Recent proposal

- **Install multi-layer of pion stopping & muon stopping targets**

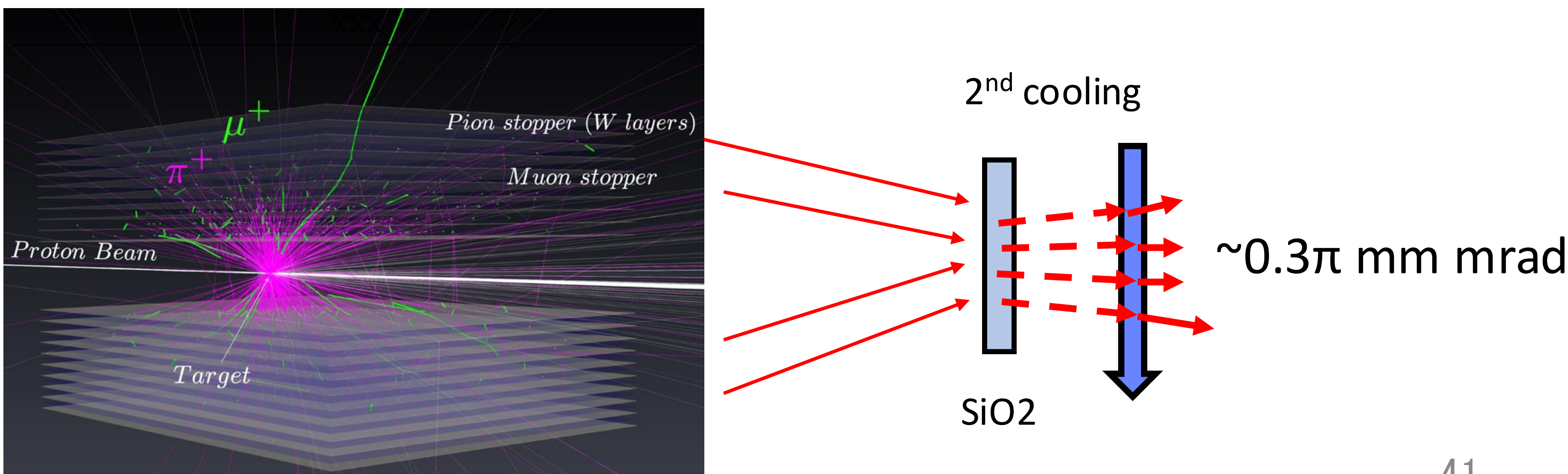
➢ Every emitted pion stops one of the targets, then decay muon also stops one of the target and forms Mu

  ➢ Mu could have larger spatial spread, but every muon can be cooled

➢ Then the Mu is ionized, extracted and cooled again.

➢ A lot of things to be studied: Ongoing

How to Extract? Detailed eval. of efficiency? Practical difficulty?



Comparison of various cooling method

- I tried to fill the table bellow. I am sorry if I make a mistake.

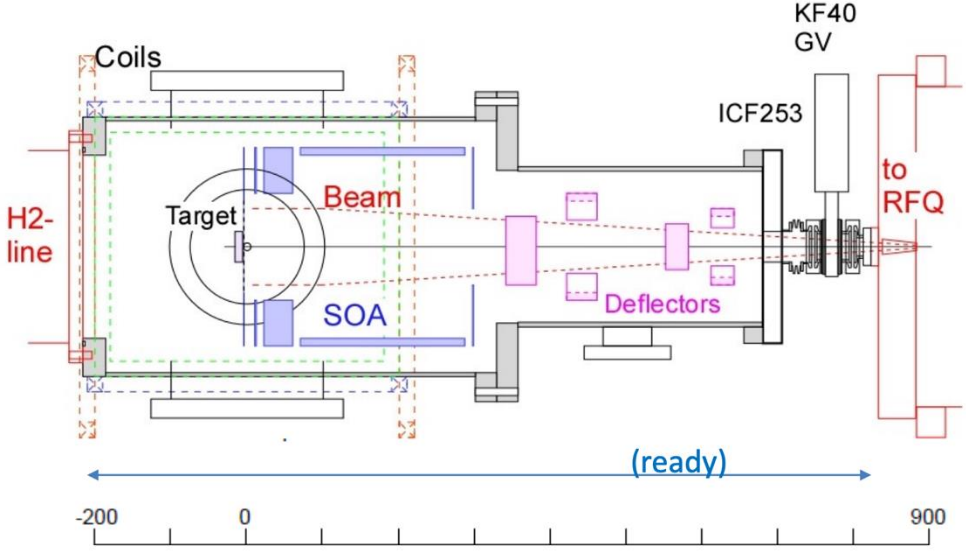
	Surface μ^+ (J-PARC)	Cold moderator	Ionization cooling	Laser ionization	muCool @PSI
Application	-	μSR	collider	**g-2, μSR**	g-2, μSR
Efficiency*	-	10^{-4} - 10^{-5}	0.1	**10^{-3}**	10^{-4}-10^{-5}
charge	μ^+	μ^+	μ^+/μ^-	**μ^+**	μ^+
Polarization	100%	100%	100% ?	**50%**	~100%
RMS $\varepsilon_{L,N}$ [μrad]	1000	~10	25	**0.3**	0.55
ε_L [mm]	?	-	50	**0.1**	?
Status	operation	operation (CW)	R&D	**R&D/ operation**	R&D

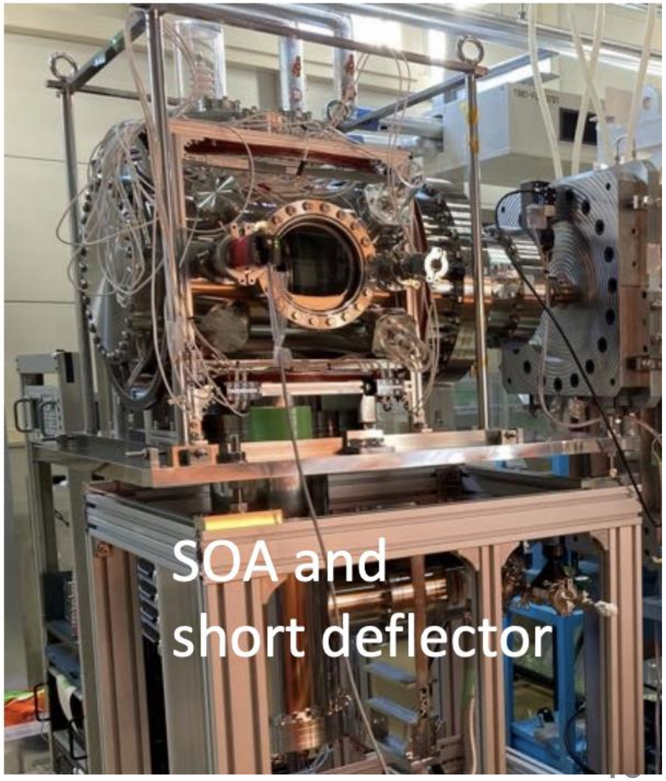
*: assumed incoming μ beam is different each other

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

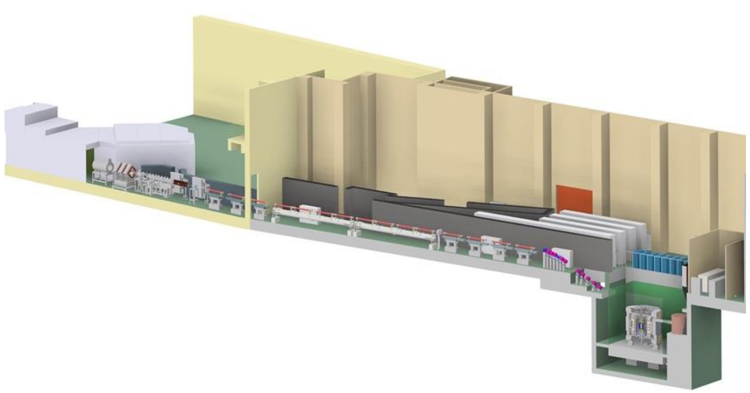
__Schematic__

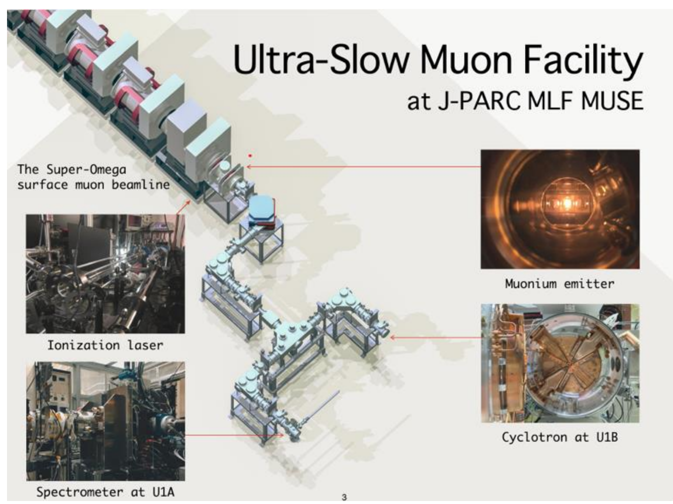


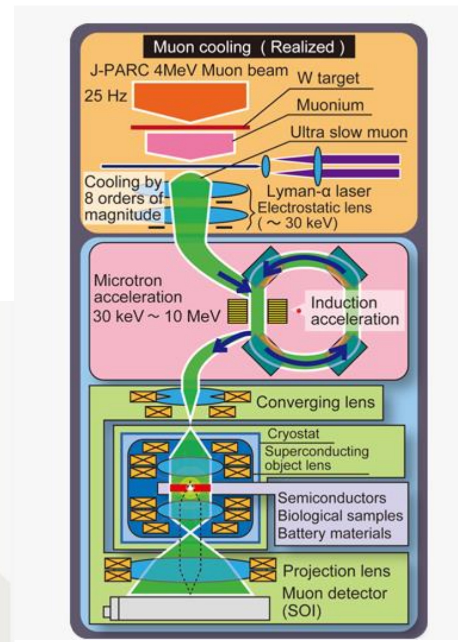


Expected performance & Application

- 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

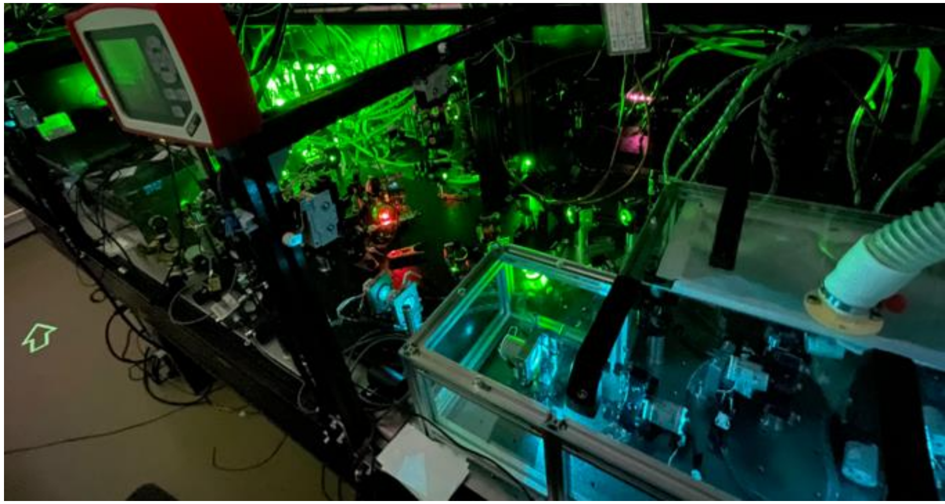


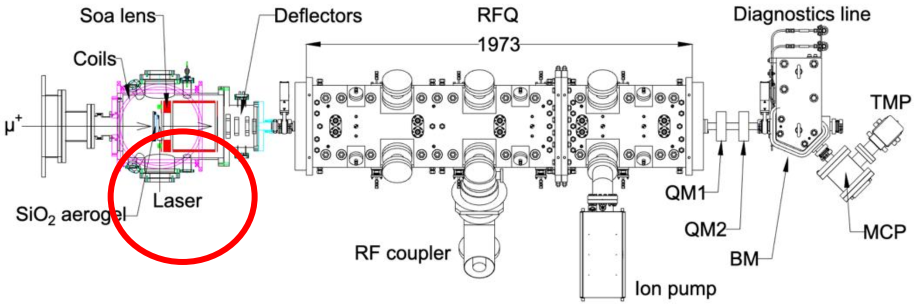




Ionization laser

- **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

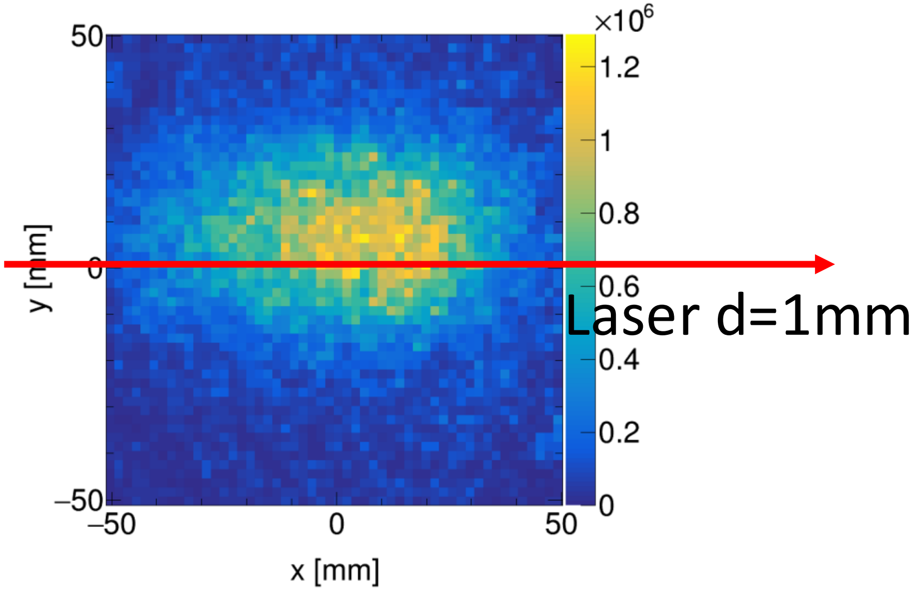
- Prior to rf-acceleration, a slow-muon diagnostic line was installed after Soa lens to evaluate 5.7keV muon beam

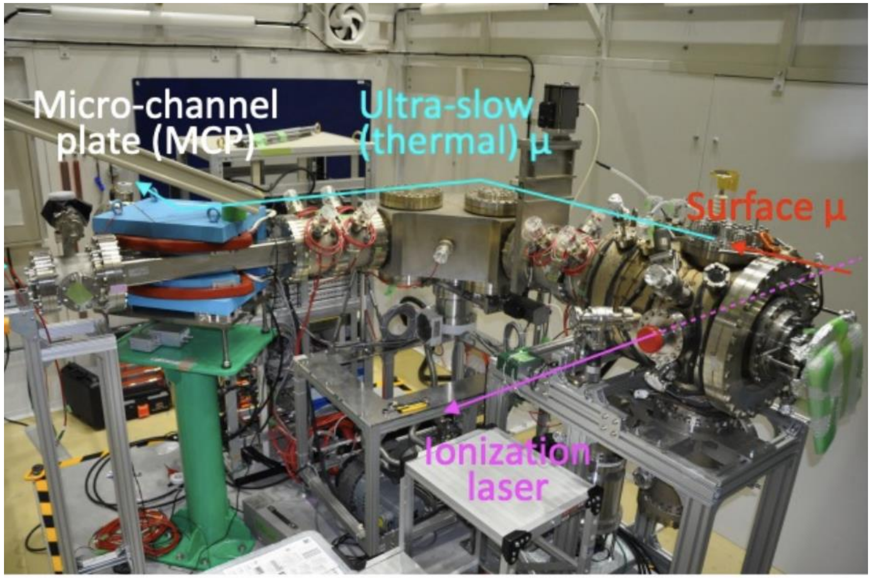
➢ Tuning of laser timing, frequency, position

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

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

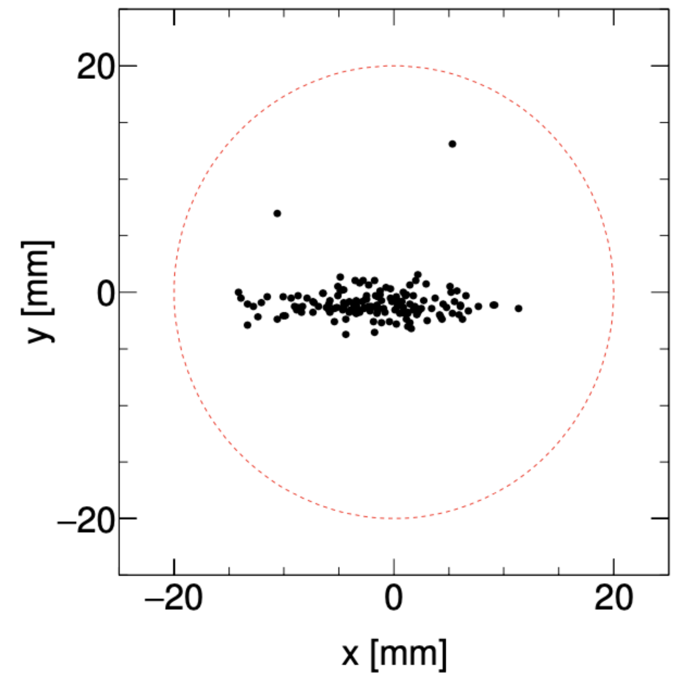
Profile of incident surface muon

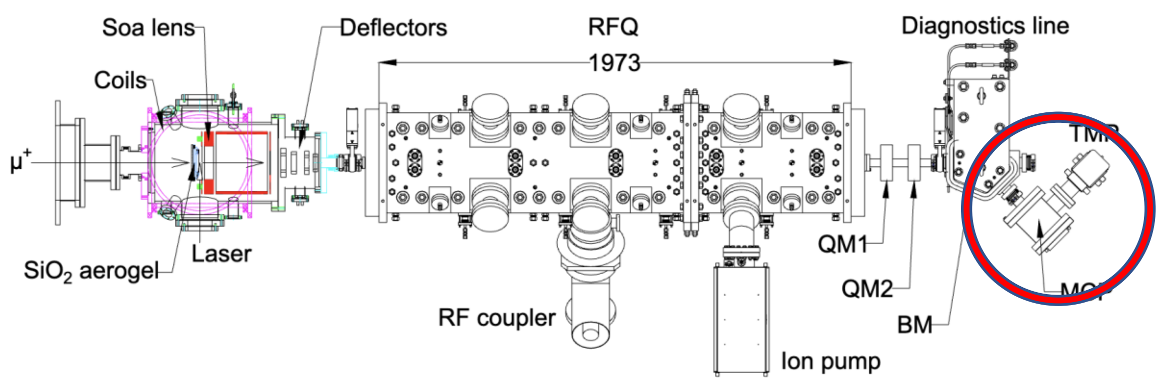




Muon beam profile measurement

- 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





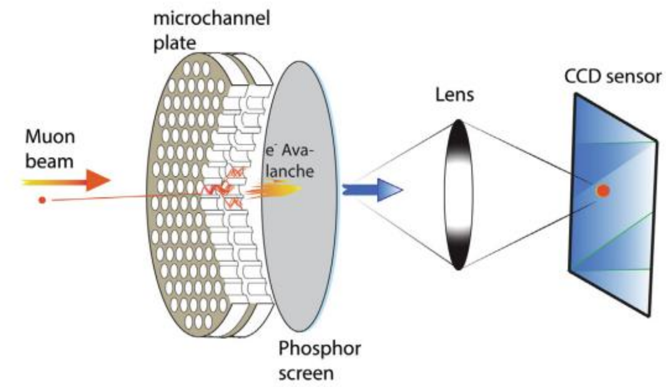


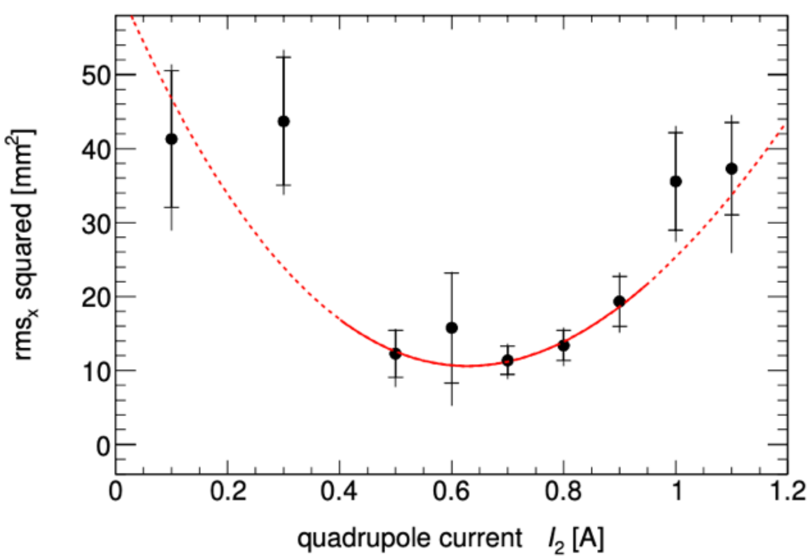
Fig. 1. A schematic view of the MCP based BPM.

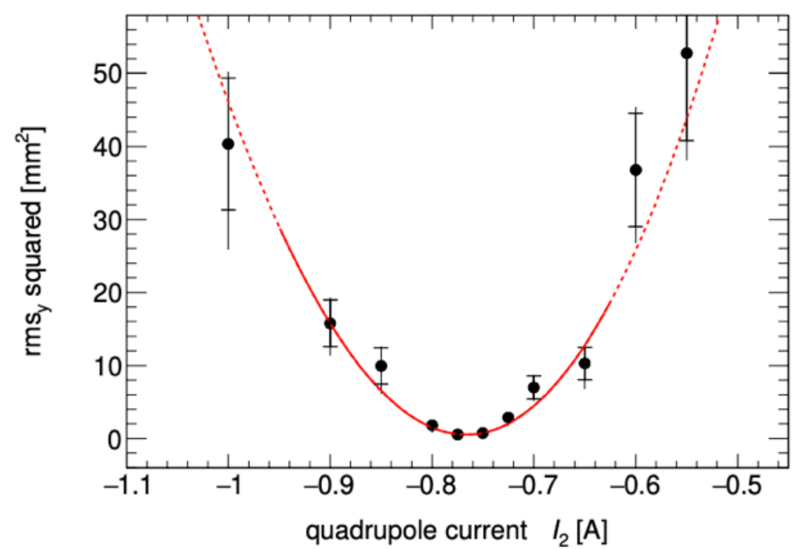
Emittance measurement

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

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

arXiv:2410.11367





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