Alternative Muon Cooling at J-PARC

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International Muon Collider Collaboration: Demonstrator Workshop

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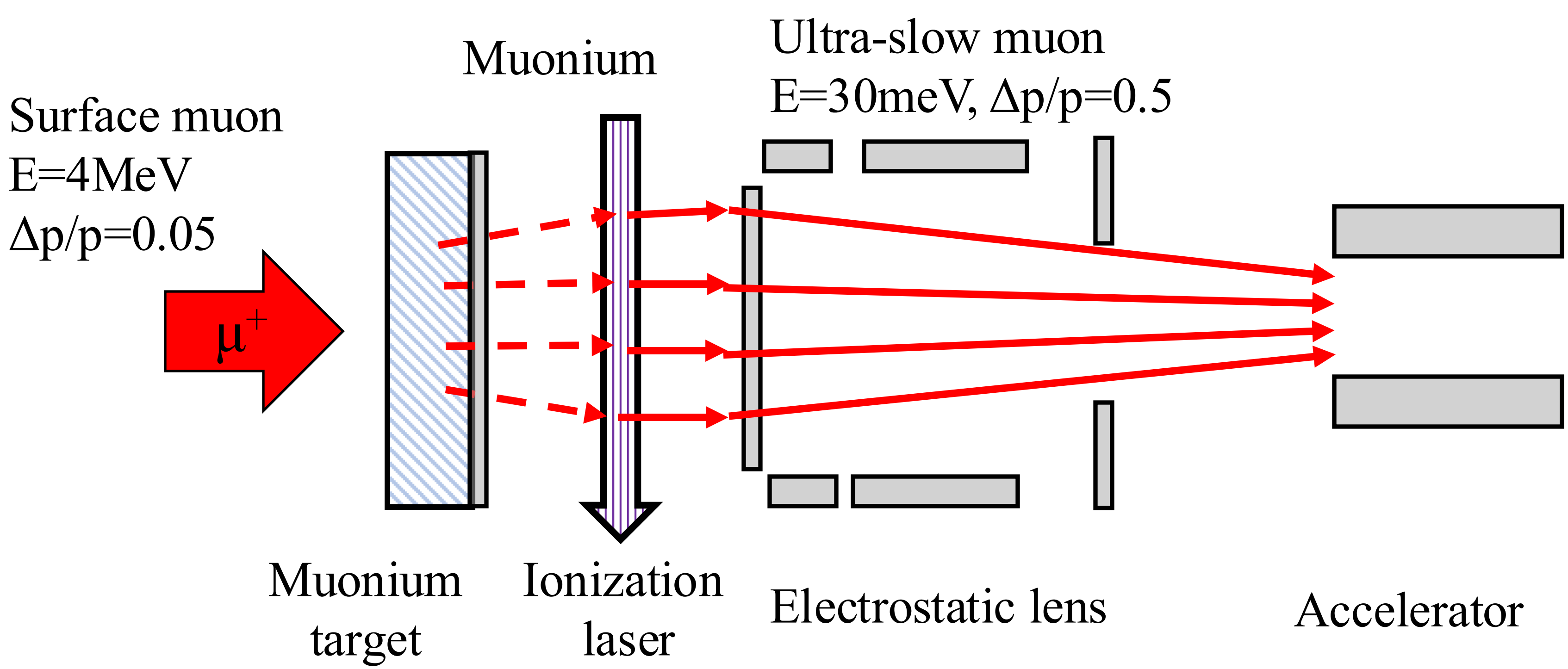
The Muon cooling at J-PARC

✓ ***Thermal μ^+ source by laser ionization of thermal muonium (μ^+e^-)***

✓ ***Ultra-slow muon (USM)***

Surface μ → Mu formation → Emission of thermal Mu
→ Laser ionization of Mu (USM) → Extracted by electrostatic lens



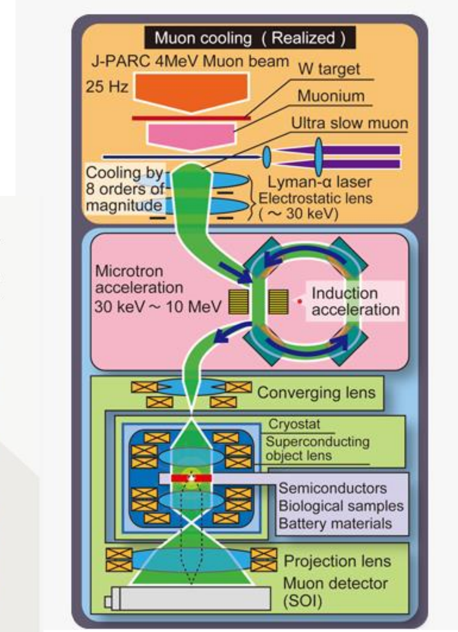
Specification of USM

- ✓ **Normalized transverse RMS emittance : ~0.3 π mm mrad.**
  - ×1/1000 times smaller emittance
- ✓ **Energy: 30 meV**
- ✓ **Polarization: ×1/2 smaller**
  - Hyperfine splitting of muonium (4GHz)
- ✓ **Efficiency: >10^{-3}/surface μ^+**
  - Depends on laser energy, Mu target and initial μ beam
- ✓ **Short pulse duration. FWHM ~ 2 ns**
  - Determined by laser pulse. No CW or high-rep operation.
  - Longitudinal cooling: Δt=2ns & ΔE <100eV (determined by extraction)
- ✓ **Simple extraction**
  - Electrostatic immersion lens for initial transport
- ✓ **Positive muon only**

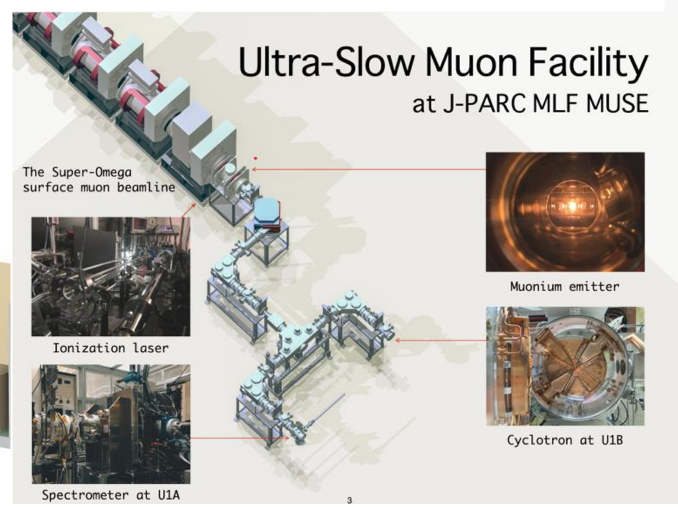
Proposed Applications

- USM = short pulse & low energy muon source
- Applications…
  - Muon g-2/EDM experiment: 212MeV acc.
  - muSR: O(10)keV
  - Transmission muon microscope: MeV
  - (Muonium spectroscopy)
  - $\mu^+ \mu^+$collider ???: recent one

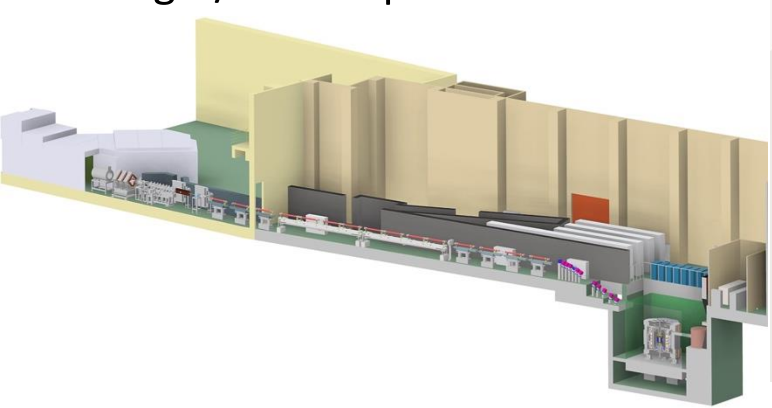
Transmission Muon Microscope



J-PARC MLF U-line (USM facility)



Muon g-2/EDM experiment



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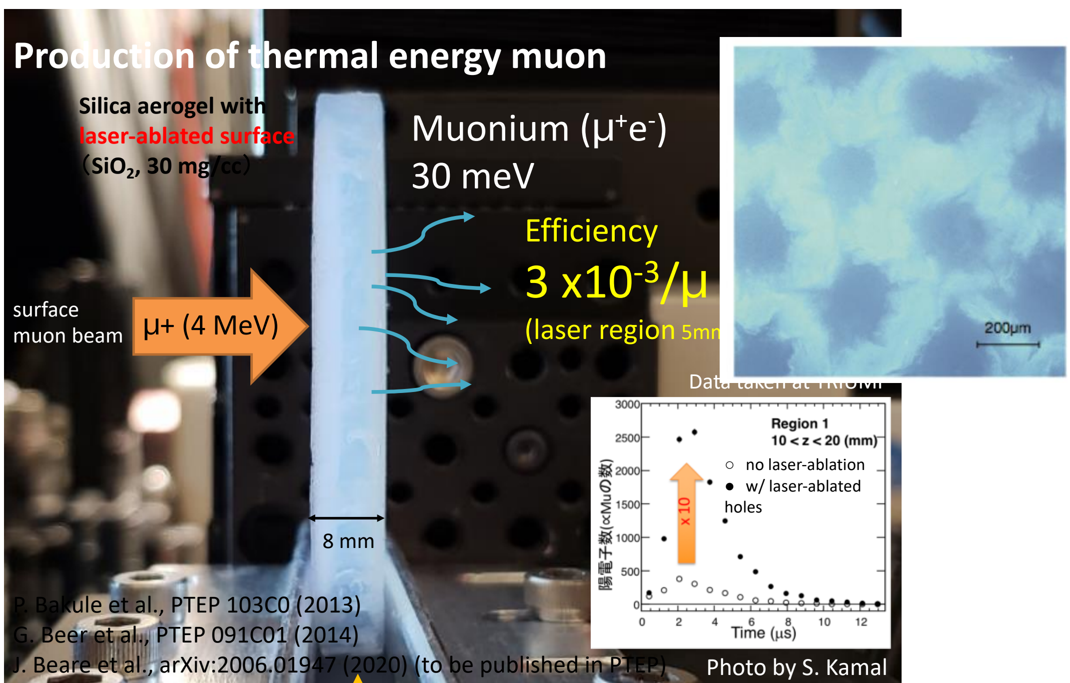
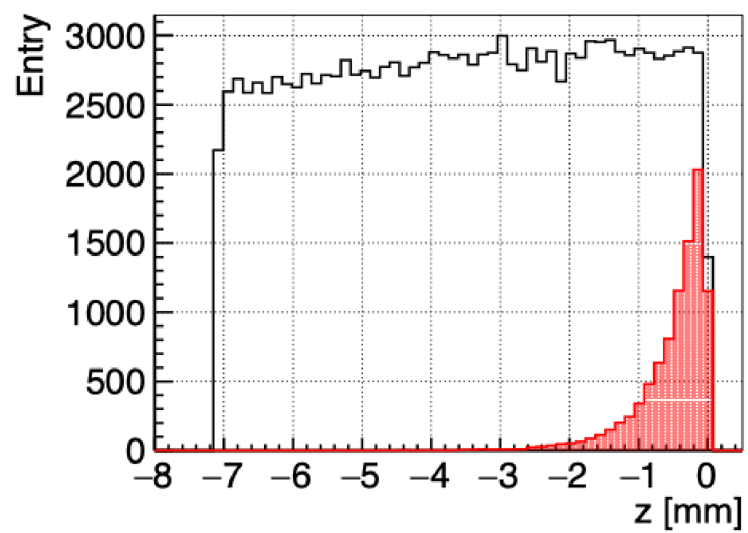
High efficiency muonium target

- A laser ablated aerogel target
  - Operation room temperature
  - Holes at surface to increase emission area→ **×10 emission !!**
- Modeling of diffusion using random walk inside a target.
  - Muonium stops near the surface is emitted to vacuum
    - Mu in the laser region/incoming muon beam: 0.3%



Stopped muon vs **Emitted (6%)**

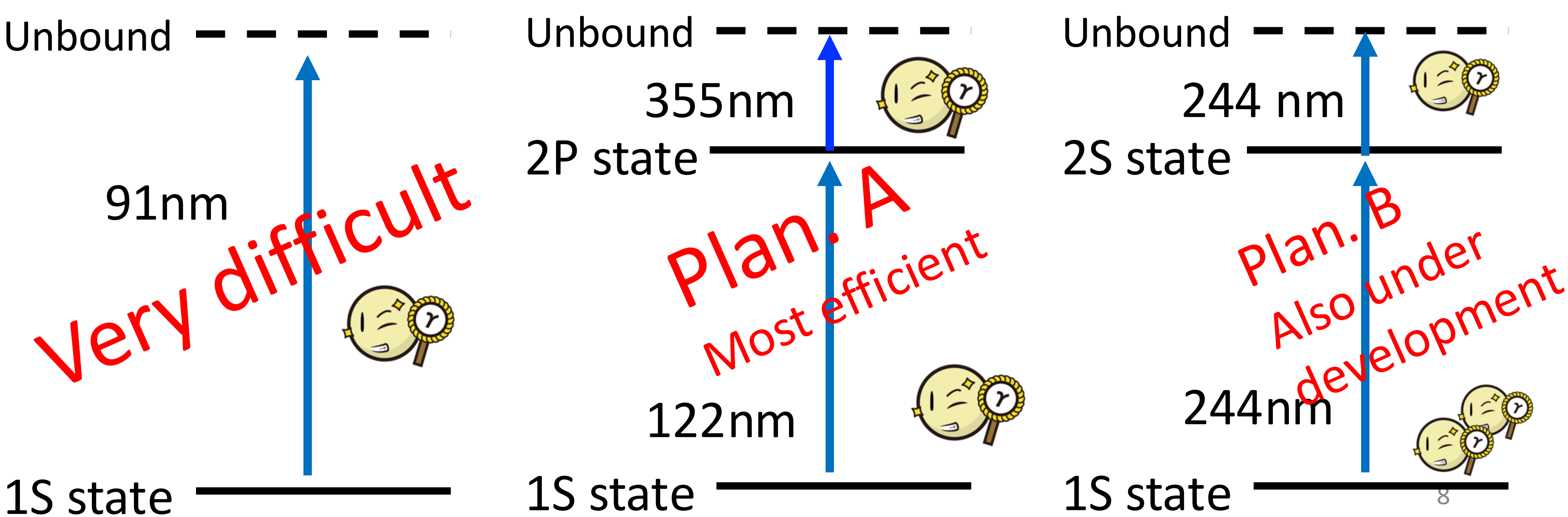


Resonant multi-photon ionization

- Goal: ionize more than 10% of total emitted Mu.

✓ **Ionization of Mu directly from 1S is very difficult = 91nm.**

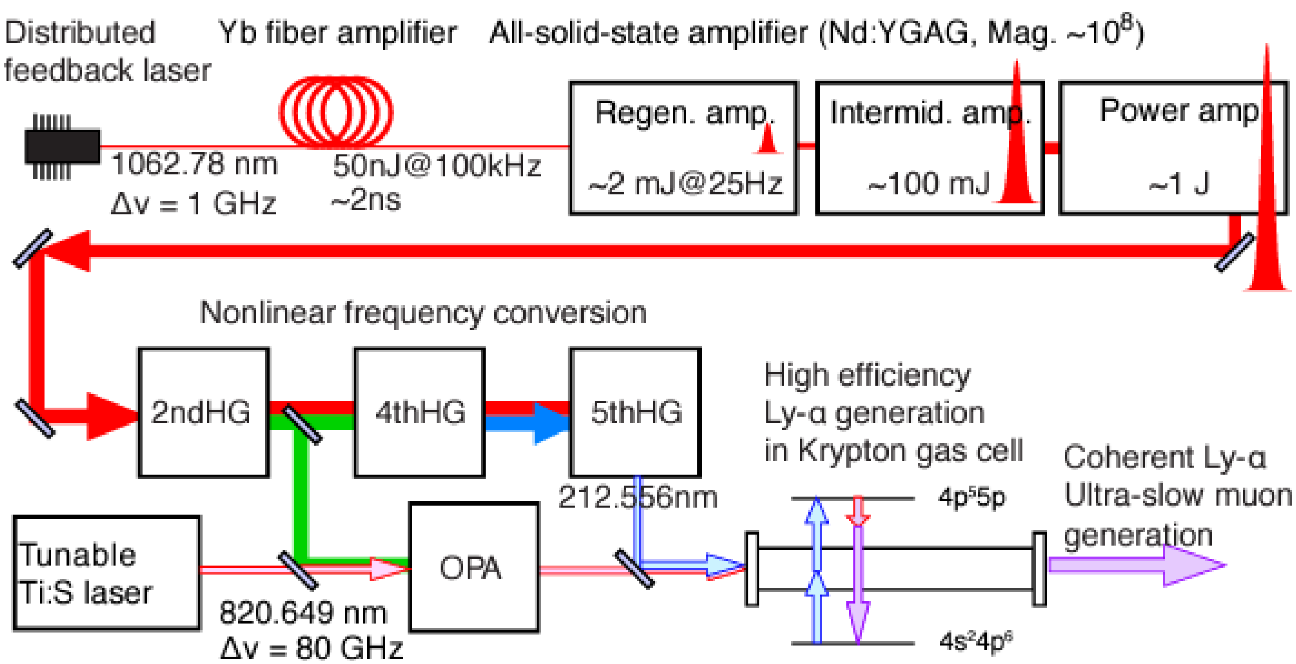
- **Mu is excited to its higher energy state, then it is ionized.**
  - ✓Excitation process requires less laser density = efficient process
  - ✓Ionization process requires high laser intensity, but we can use longer wavelength laser for ionization from excited state = easier.

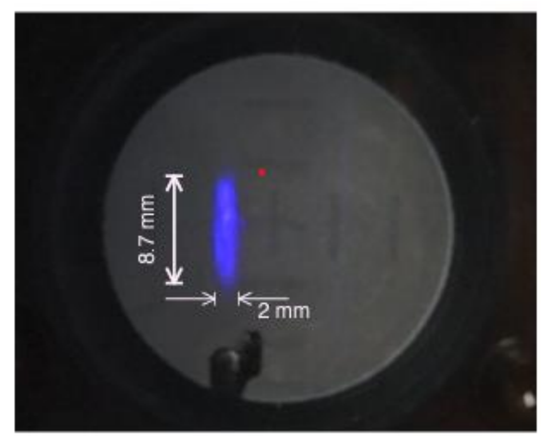


Solid state VUV light source

- Key technology is VUV light source at λ=122nm: challenging
  - Large Mu emission volume → high power is required.
  - **Goal: 122nm, 100μJ, 2ns, 80GHz, 25Hz rep, spot size 2cm^2**
- More than ~10μJ can be produced now. World record!!

  ⇔ 121nm laser for laser cooling of anti-H: ~ 10 nJ



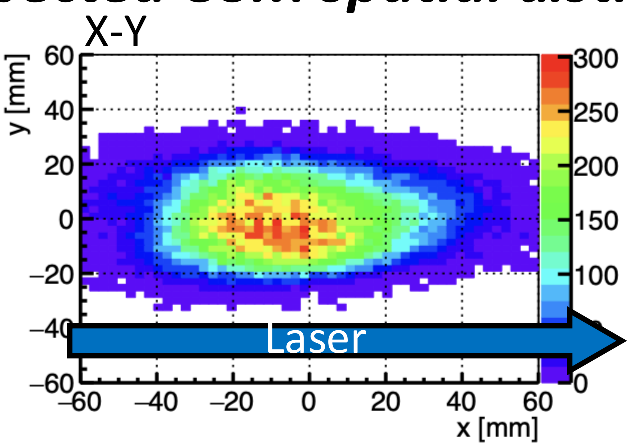


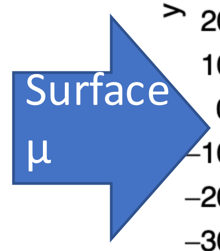
Y. Oishi et al, 2023 J. Phys.: Conf. Ser. 2462 012026

Expected performance at MLF H-line

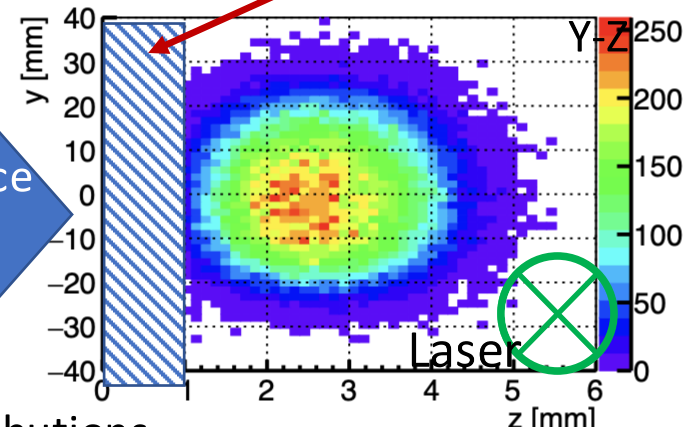
- MLF H-line: muon beamline for g-2 exp. at J-PARC
- USM: **~ 10^5 μ^+/s** ($100\mu J$ @122nm+300mJ @355nm)
  - Efficiency: ~ 1×10^{-3} / surface μ
  - Pulse duration: 2ns

Expected USM spatial distribution



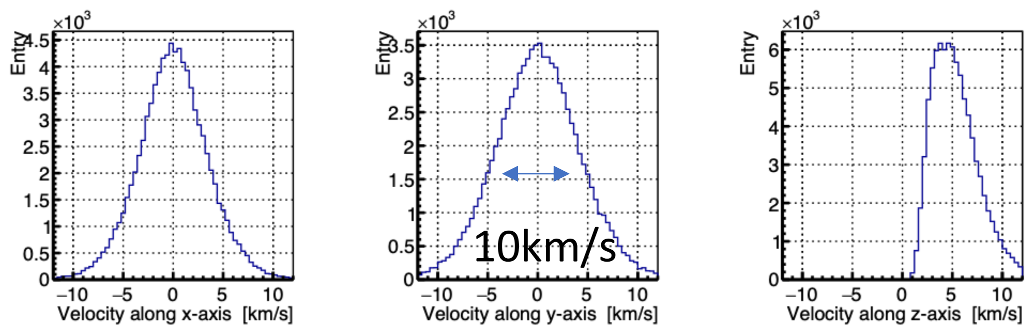


Mesh electrode (surface of aerogel at z=0)



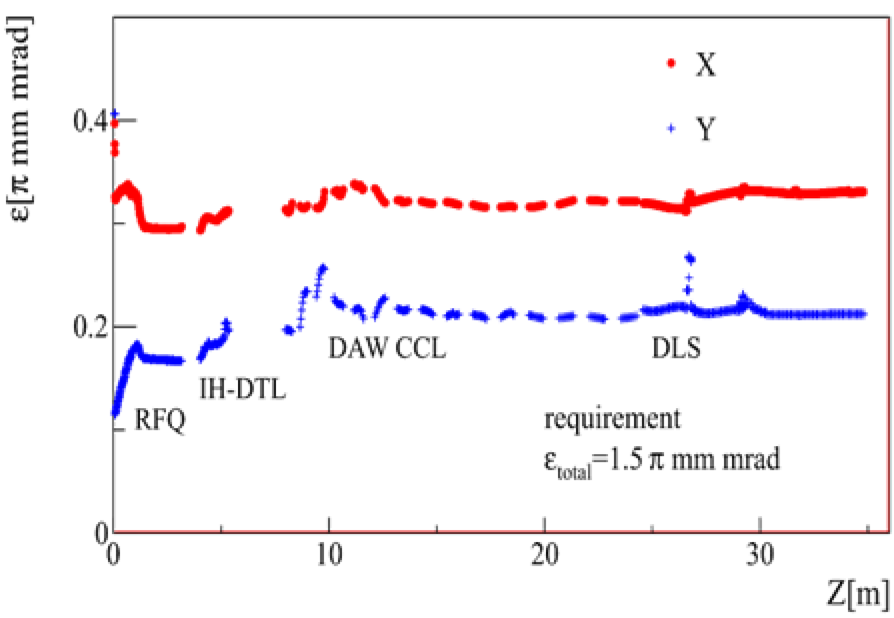
Velocity distributions

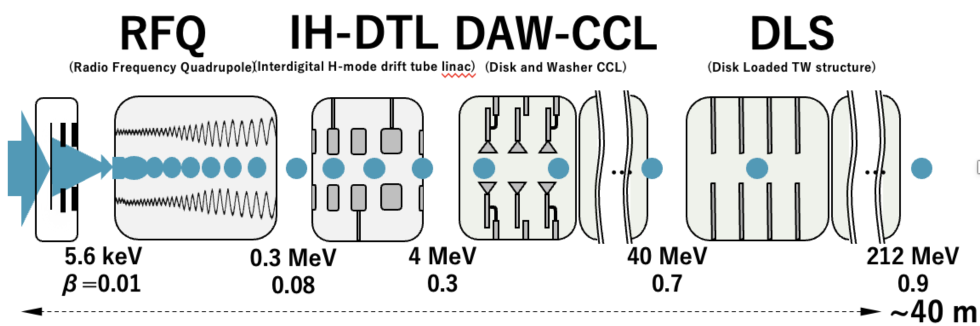
Large beam size
But very slow



Expected Emittance after acceleration

- USM: extracted by static E-field, then accelerated by a muon Linac
- Simulation emittance growth from 30meV to 212MeV
  - One of the smallest emittance μ^+ beam is possible
  - Longitudinal emittance is also small: ~0.1 mm





Muon Linac for muon g-2 experiment.
→ Under preparation. Ready by FY2029

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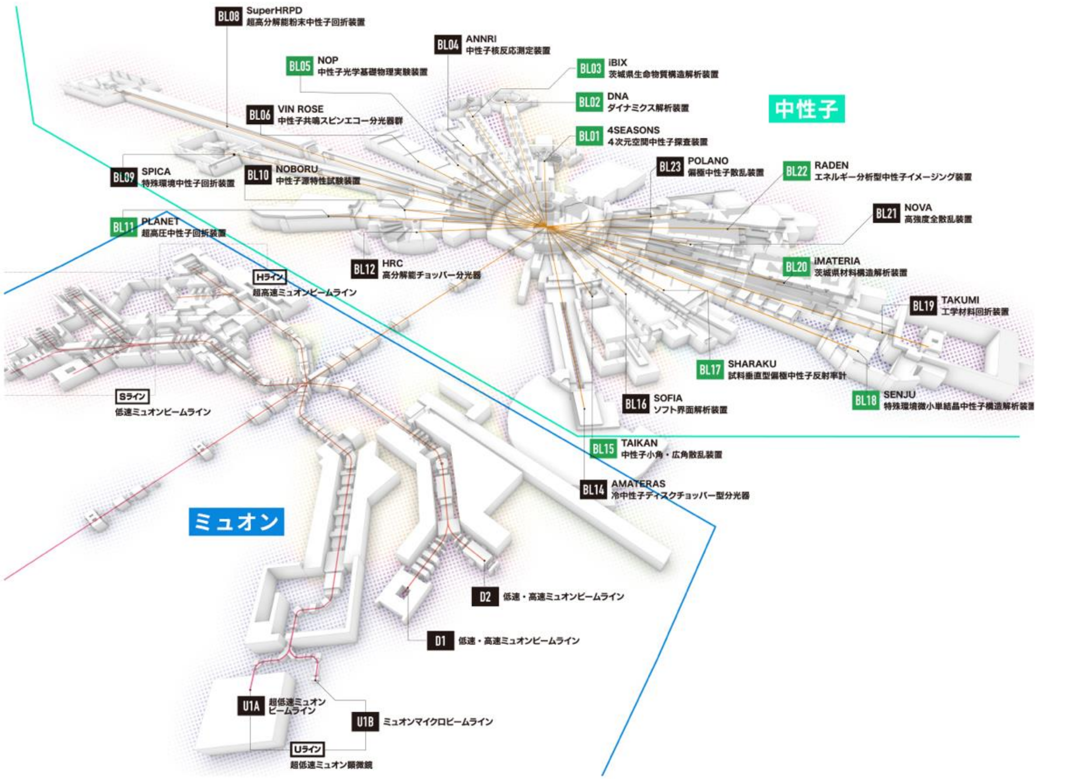
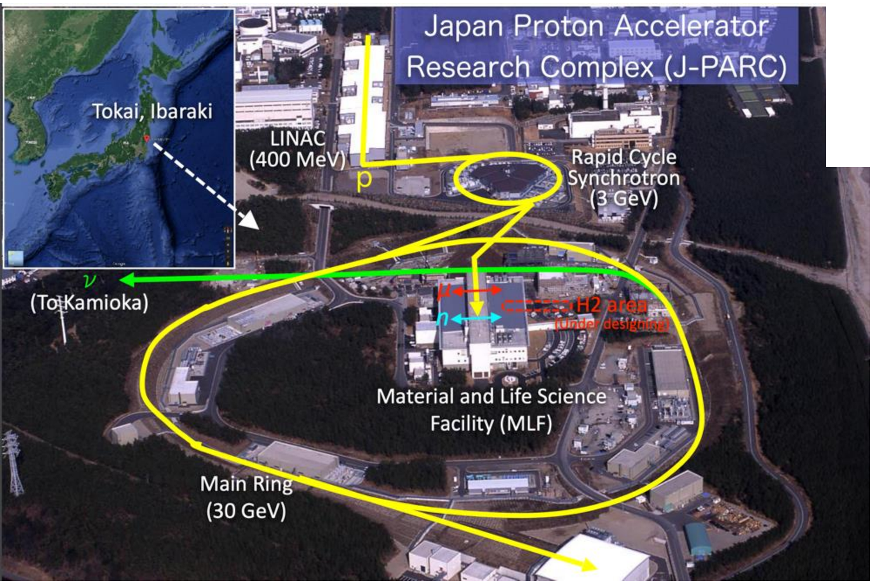
- Introduction
- Key technologies and expected performance
- Current status of muon cooling experiments
- Future prospect

J-PARC MLF

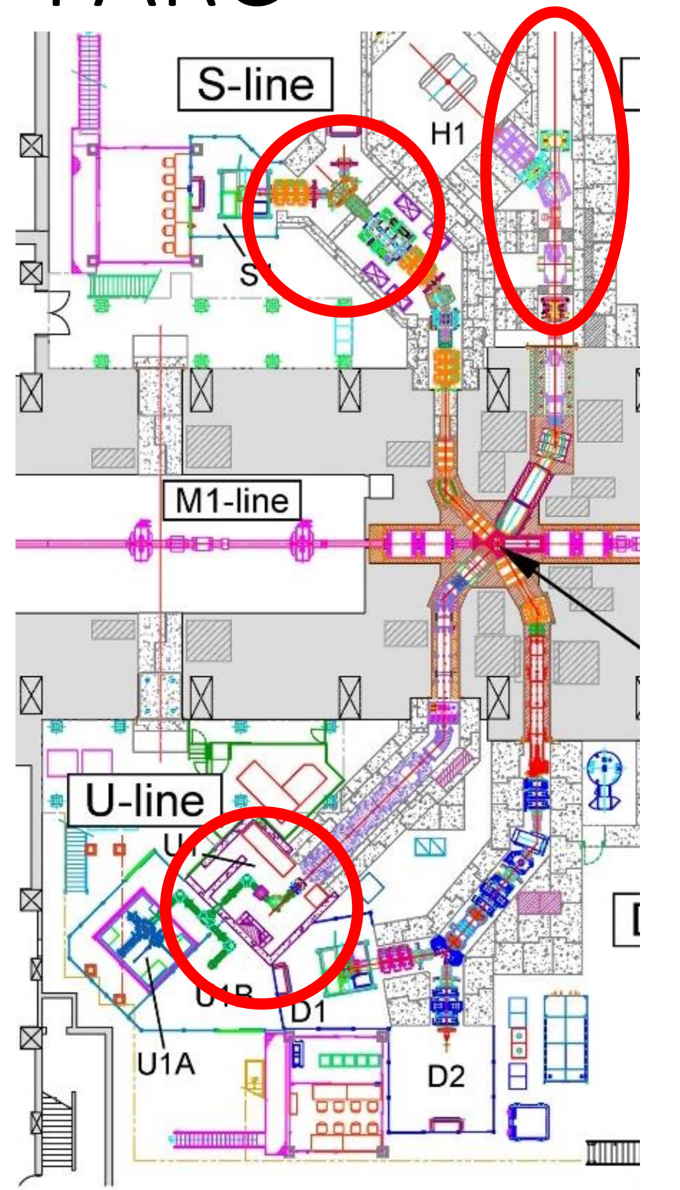
- Material life science facility
- 3GeV, 1MW, 25Hz proton beam
  - 10% for muon
  - 4 muon beamlines
  - 8 experimental areas





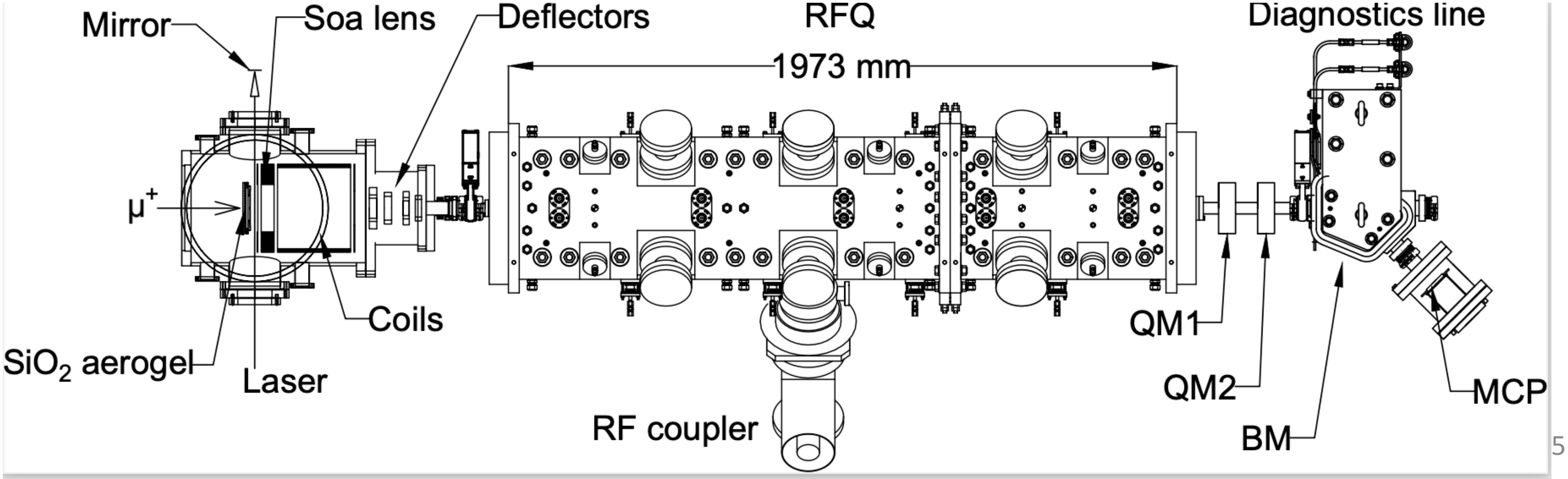
Demonstrations of muon cooling at J-PARC

- A lot of cooling demonstration & beyond
- S-line
  - Cooling & rf-acceleration demonstration.
  - Muonium spectroscopy
- U-line: U for ultra-slow
  - For Material science w/ cooled μ^+
  - USM acceleration with cyclotron
- H-line
  - Under preparation for g-2/EDM exp.
  - High intensity surface μ beam + laser + muon linac



Demonstration @ MLF S-line

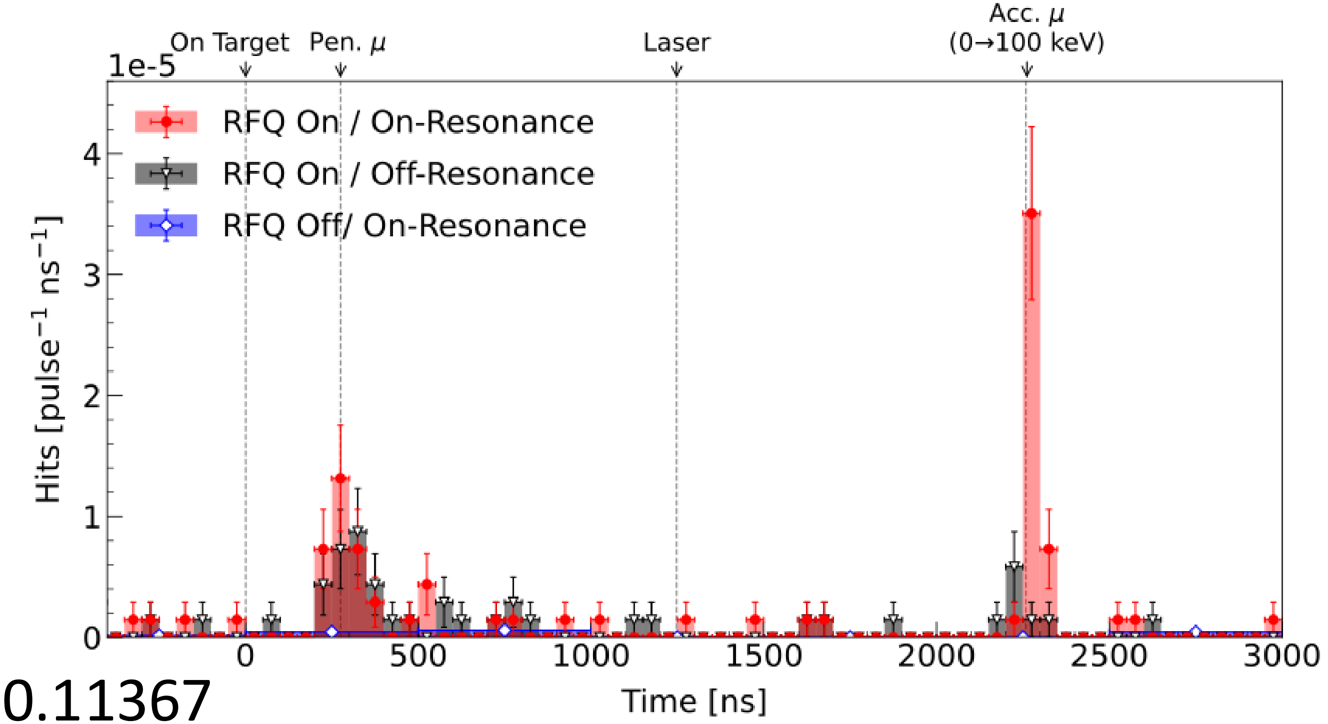
- **Muon cooling & RF acceleration**
  - Cooling → Extraction by E-field → RFQ
  - 3MeV→30meV→5.7keV→100keV
- **Collaborating with Mu 1S-2S spectroscopy experiment**
  - 244nm pulsed laser by Okayama univ.
  - Laser for spectroscopy→Very low ionization eff ($\sim10^{-5}$). Enough for demonstration.



World first muon acceleration !!

- Cooled muon rf-acceleration experiment during April 2024
  - Clear peak only when laser on-resonance & RFQ ON
    - TOF agrees with the expectation.
    - Intensity: 2 × 10^{-3} μ/pulse

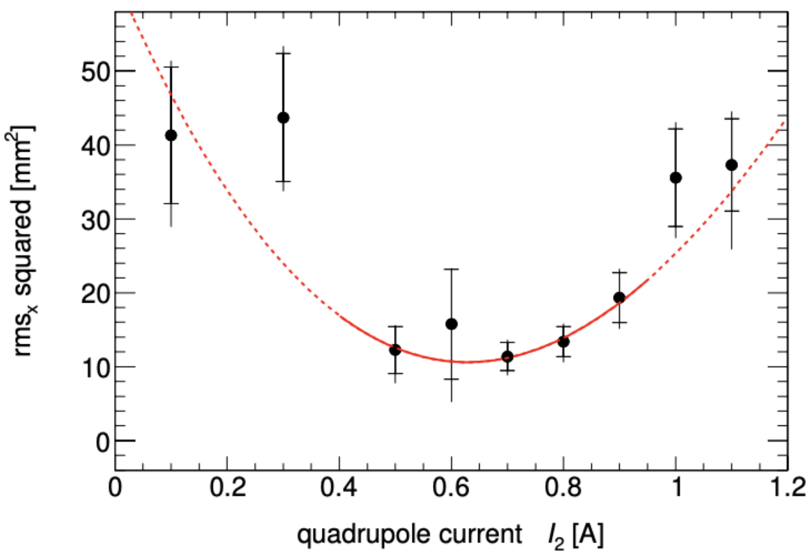
MCP signal at the beam diagnostic line after the RFQ

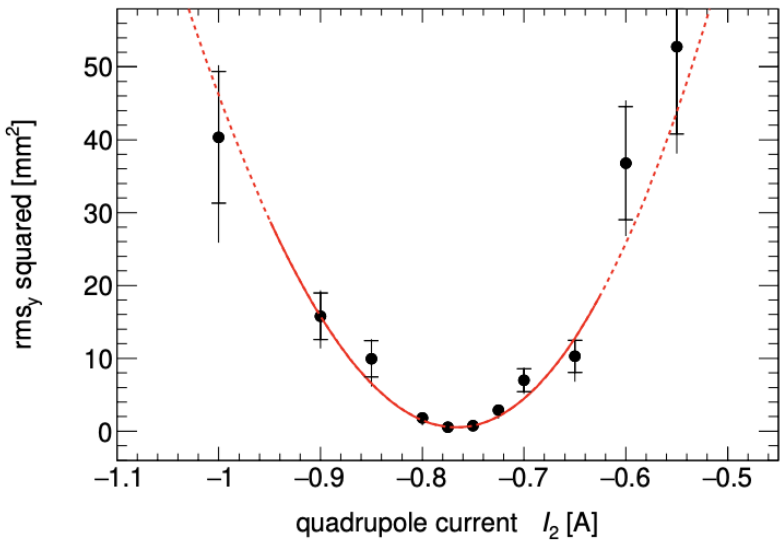


arxiv:2410.11367

Emittance evaluation

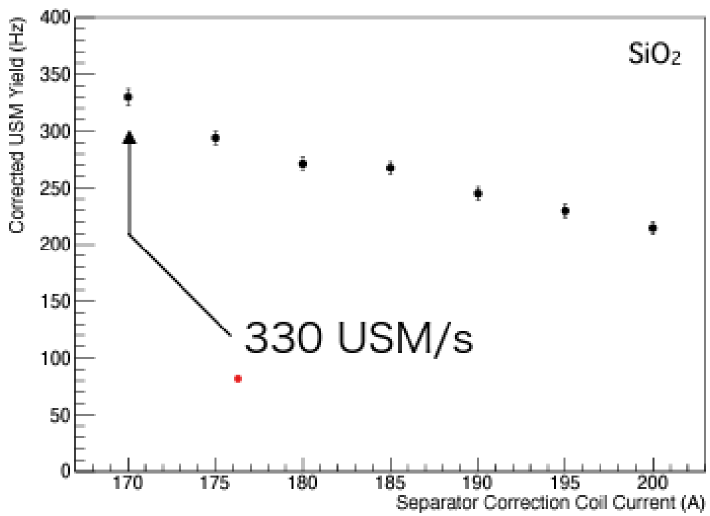
- ✓ Q-scan measurement for transverse emittance evaluation
  - Quadrupole strength vs beam size
- ✓ Normalized rms transverse emittance
  - **Horizonal: $0.85 \pm 0.25\ ^{+0.22}_{-0.13}$ π mm mrad**
  - **Vertical: $0.32 \pm 0.03\ ^{+0.05}_{-0.02}$ π mm mrad**
- ✓ > 100 times reduction of normalized RMS emittance !!



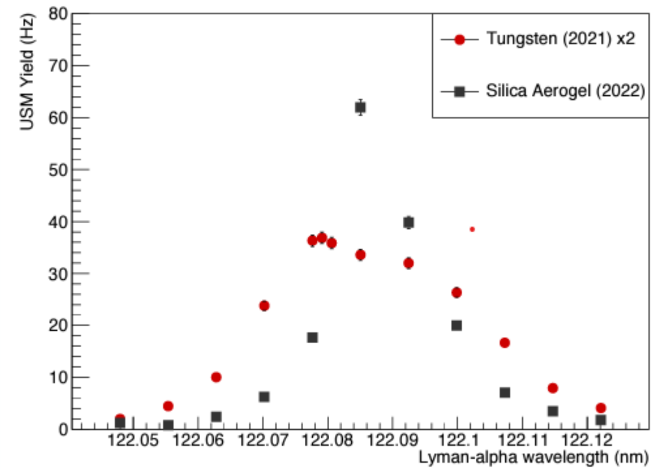


Cooling demonstration @ MLF U-line

- SiO2 target + Lasers for 1S-2P-unbound in FY 2022
  - **2.5μJ** @122-nm and **7mJ** @355-nm.
  - Extracted at 30keV by E-field→ detection by a MCP: 330 USM/s
- Recent U-line: R&D towards cooled muon μSR
  - Study of low energy muon transport
  - Laser upgrade in parallel.



Flux: 330 USM/s.
Surface muon optimization



VUV wavelength dependence

Comparison of doppler width of different temperature target

Report in the Muon Advisory Committee 2022

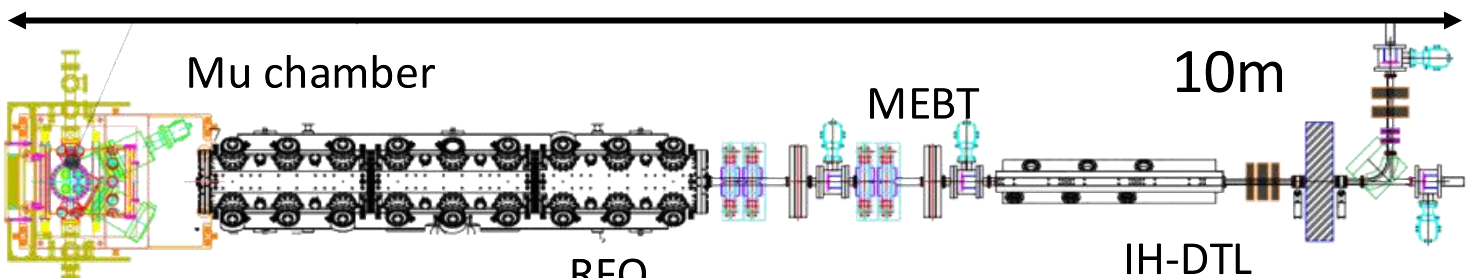
Next step: Muon cooling at H-line

✓Preparation underway for muon g-2/EDM exp. including..

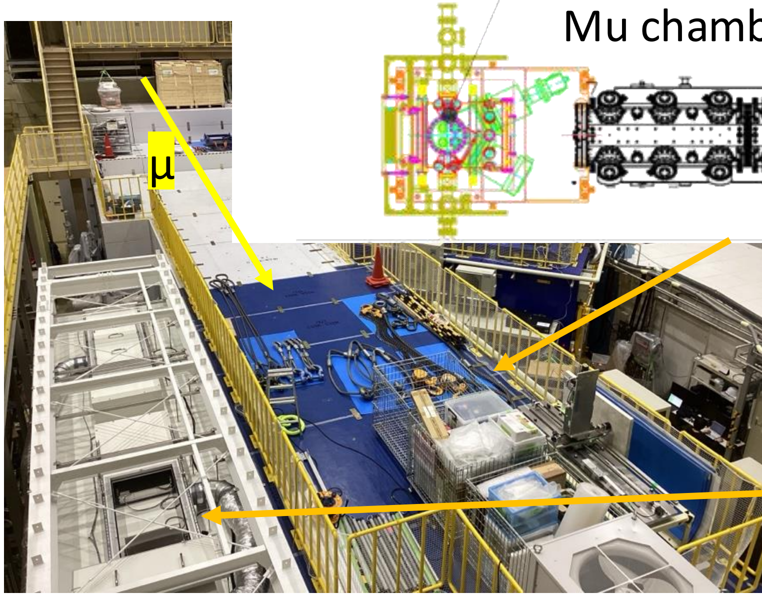
1. Surface μ : > 10^8 μ/s (10^6 μ/s at S2 area) in this FY
2. New laser: FY2025 → Energy upgrade by FY2027
3. Accelerators: 340keV RFQ in FY2026 → 4MeV acc.

➢ Next mid-term milestone: 1000 μ^+/s, 340keV, early FY 2026

- Beyond demonstration stage. Looking for ideas to “use” the beam.
- Final goal: >10^5 μ/s & 212MeV by FY 2029



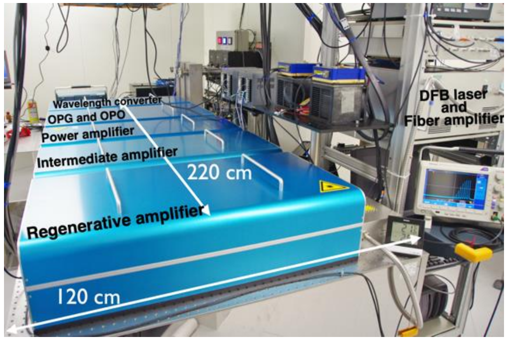
Inside H2: cavities are ready (not installed)

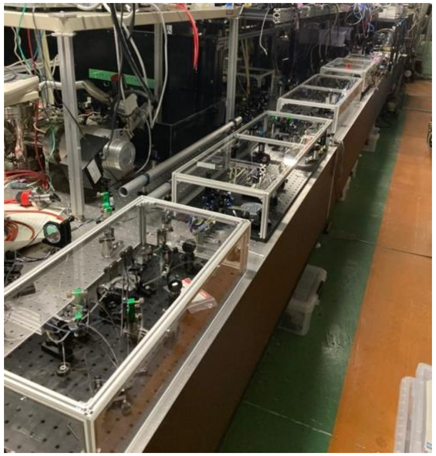


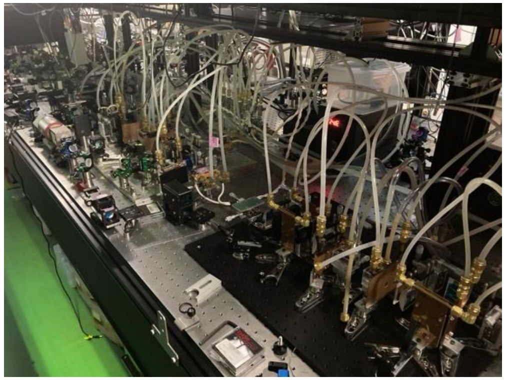
New laser room under preparation
(now I am preparing for optics to assemble the laser…)

Upgrade of lasers

- Lasers are essential to increase the efficiency
  - Three lasers for two ionization scheme
- 122nm: 1S→2P
  - Development of Nd:YSAG amp for 1062.78nm
    - Necessary, but worse crystal quality
  - Issue of optics degradation: evaluation of MgF_2, LiF
  - Current: >10μJ → Goal: 100μJ w/ new amp & long cell
- 244nm: 1S→2S→unbound
  - 30mJ at 5Hz achieved→ Goal: 60mJ, 25Hz
  - Should be narrow linewidth→linewidth improvement
  - Cf: laser for acc. Demonstration: 1mJ, 25Hz
- 355nm: 2P→unbound
  - Sharing the same system with 244nm laser
  - 10ns, 1.7J, 5Hz @1064nm now→ goal: 3ns, >1J, 25Hz
  - Thermal issue, common for such high energy laser







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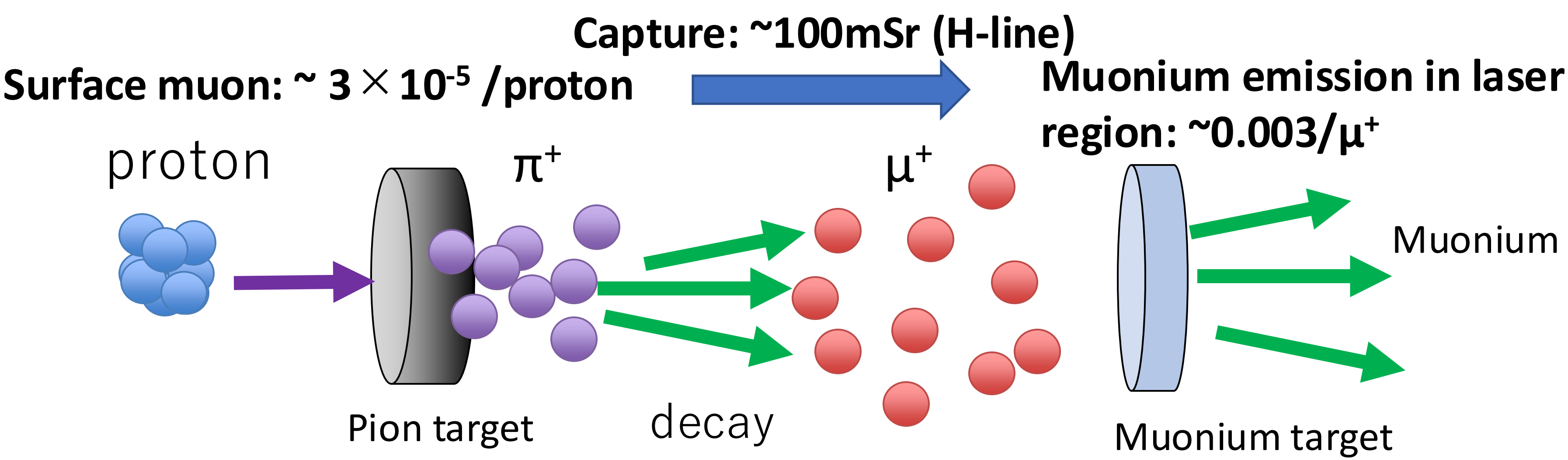
Towards higher intensity…

- Ultra-slow muon: **very low emittance !!** But **intensity is low** ($<10^6$ /s)
  - ✓ Challenge is improvement of cooling eff. = cooled μ^+/proton
- We can use ① π stopped at surface of π target & ② μ^+ stopped near the surface of Mu target
  - Even if ionization eff. & capture every surface muon are 100%, cooling efficiency could be order of 10^{-7}/proton.



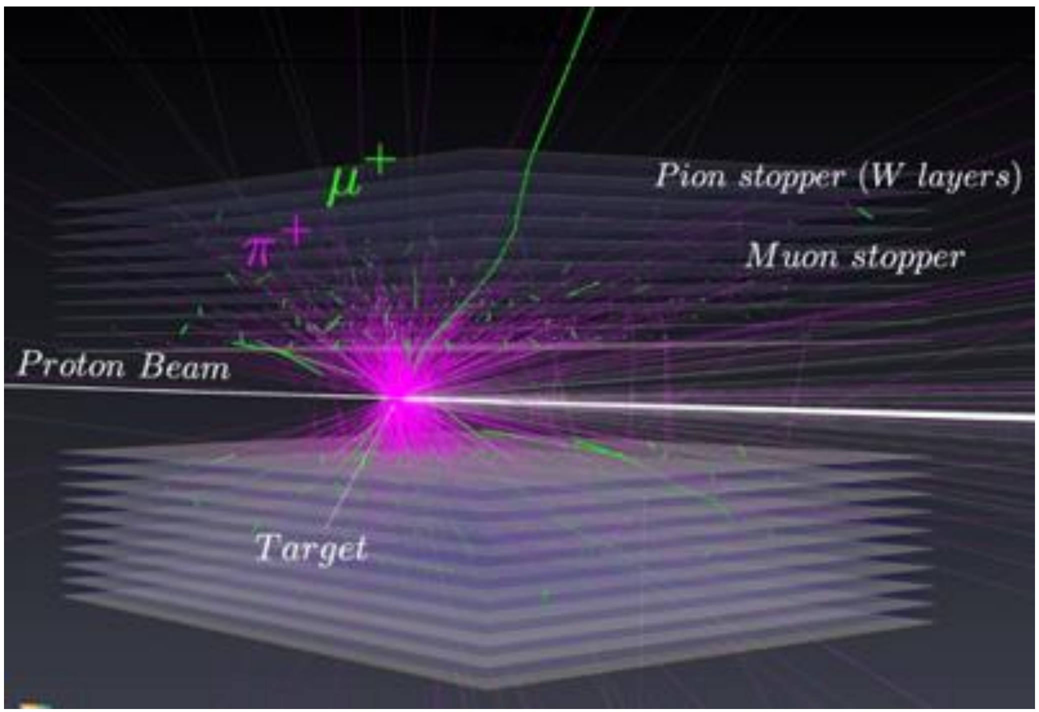
Multi-layered production target??

- We are discussing how to increase the "surface" of each target.

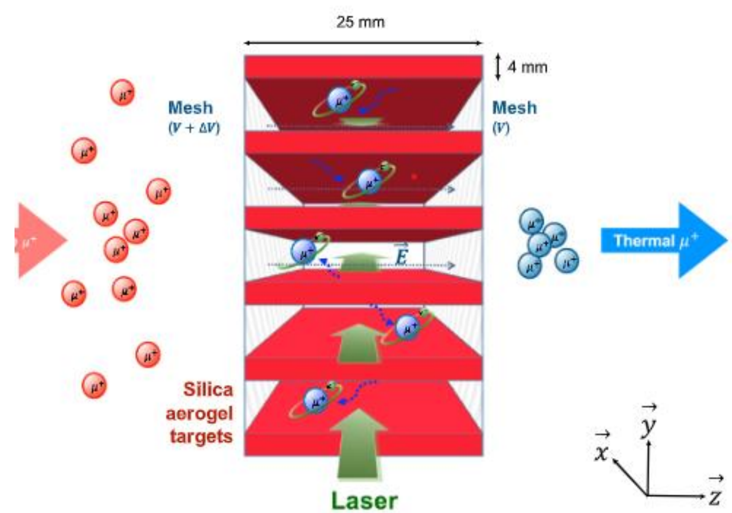
➢ One of such proposals: Installation of many thin π/Mu targets to stop π & Mu as much as possible at the surface of one of targets?

  - Recent proposal of $\mu^+\mu^+$ or μ^+e^- collider

Just conceptual stage… Need detailed (a lot of) simulaitons



Compact version for g-2/EDM
Multi target for Mu production
→ ×5 more USM

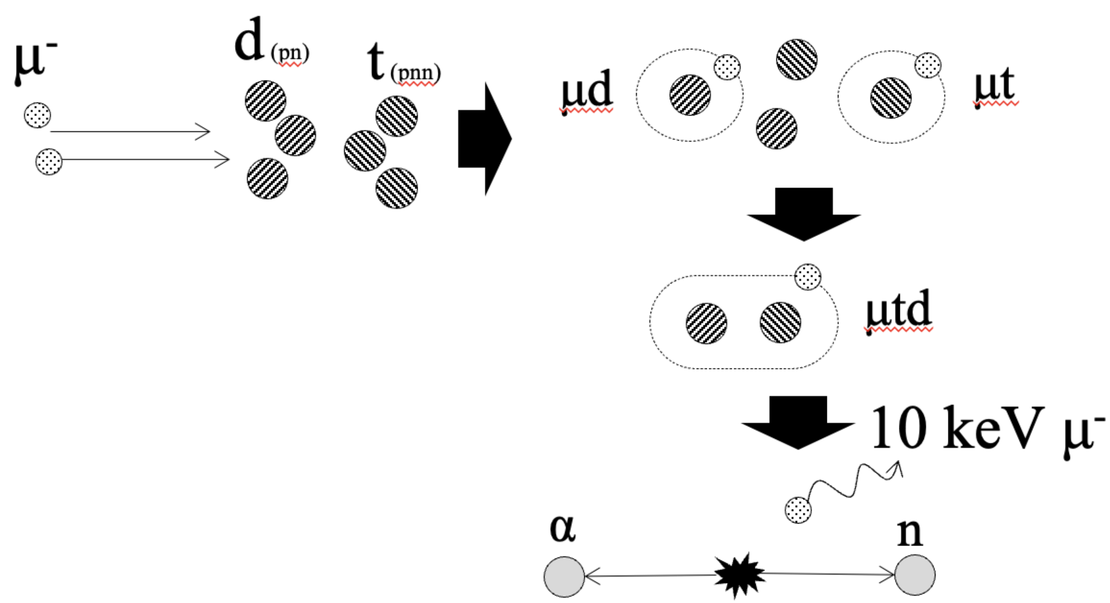


Cooling of μ⁻ ?

- Obviously, this scheme can not be used for μ⁻ cooling
  - No anti-muonium target…
  - Photo-ionization of muonic atom is challenging. Need dedicated super-intense X-ray facility. (I was told it is not a major issue for collider scale projects…)
- Idea towards ultra-slow negative muon is under discussion at J-PARC

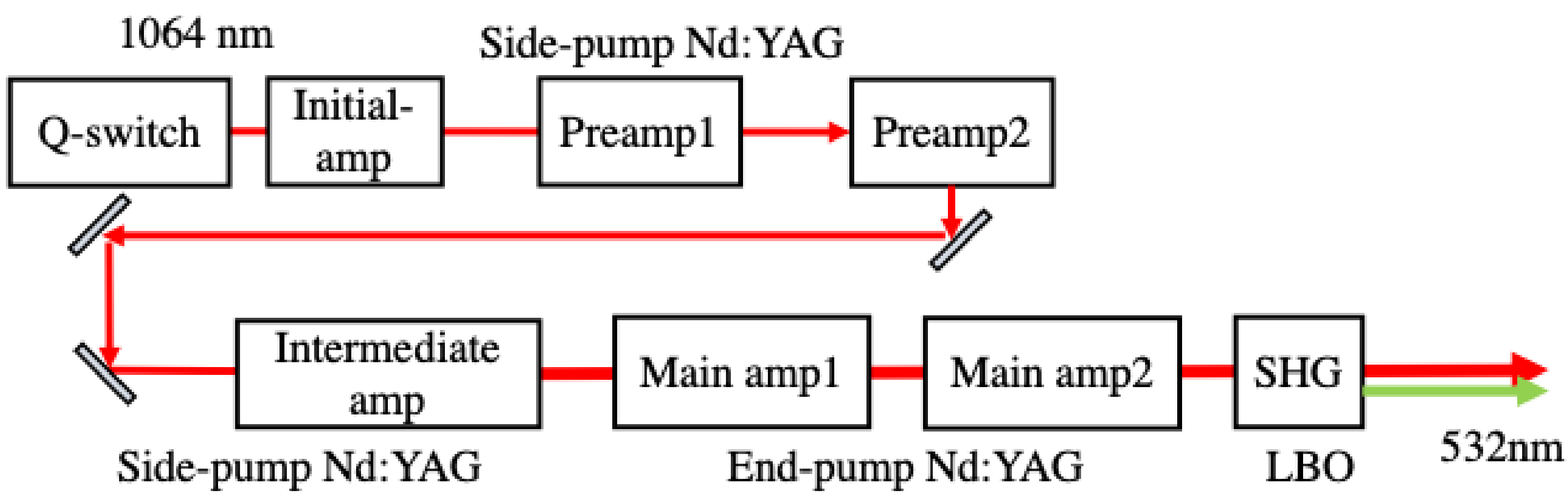
✓ μCF: one of such ideas. Long history of proposal, but very difficult

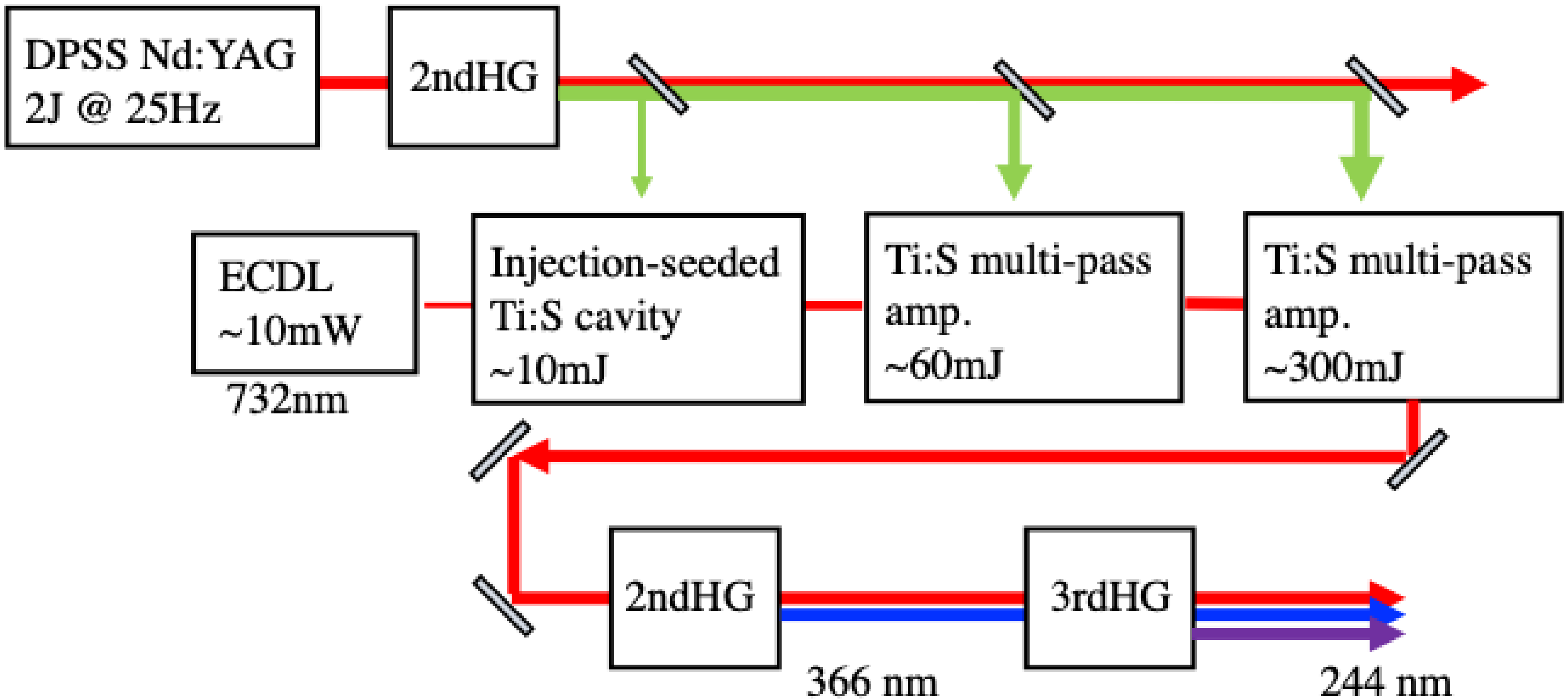
~100 μ⁻/s at J-PARC ?



Summary

- Muon cooling with a high efficiency muonium target and high energy lasers at J-PARC: Ultra-slow muon (USM)
- Demonstration of ultra-slow muon generation with a laser ablated aerogel target and lasers are ongoing.
- **We finally succeeded to accelerate cooled muons !!**
  - Now we have the beam!!
  - Any interesting R&D?
- Development of more intense laser towards >10^5 Hz
- New idea for more intense USM has been proposed. Interesting future plans.


1064 nm
Side-pump Nd:YAG
Q-switch
Initial-amp
Preamp1
Preamp2
Intermediate amp
Main amp1
Main amp2
SHG
Side-pump Nd:YAG
End-pump Nd:YAG
LBO
532nm


DPSS Nd:YAG
2J @ 25Hz
2ndHG
ECDL
~10mW
732nm
Injection-seeded
Ti:S cavity
~10mJ
Ti:S multi-pass
amp.
~60mJ
Ti:S multi-pass
amp.
~300mJ
2ndHG
3rdHG
366 nm
244 nm