Search for muon EDM at J-PARC

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On behalf of the J-PARC muon g-2/EDM collaboration

Outline

- EDM of muon
- Experimental method
- Current status of J-PARC muon g-2/EDM experiment
- Schedule & summary

EDM of muon

- Muon: lepton, the second-generation. (106MeV, τ=2.2μs)
- Muon EDM: CP violation of the second generation charged lepton

➢ Less stringent experimental limit compared to other particles

  - Short lifetime, no E-field enhancement, etc

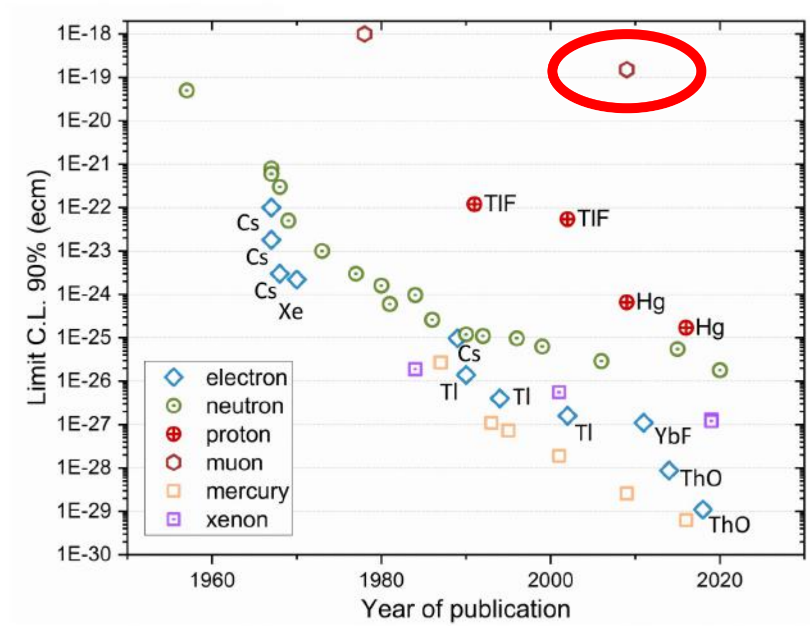
Experimental limit: (BNL)

- **$|d| < 1.8 \times 10^{-19}$ e・cm (90% C.L.)**

Indirect limit from electron EDM

- **$|d| < 2 \times 10^{-20}$ e・cm**
  - Assuming muon EDM is the only source of electron EDM
  - Phys. Rev. Lett. 128, 131803

History of direct limit of EDM (arxiv: 2102.08838)



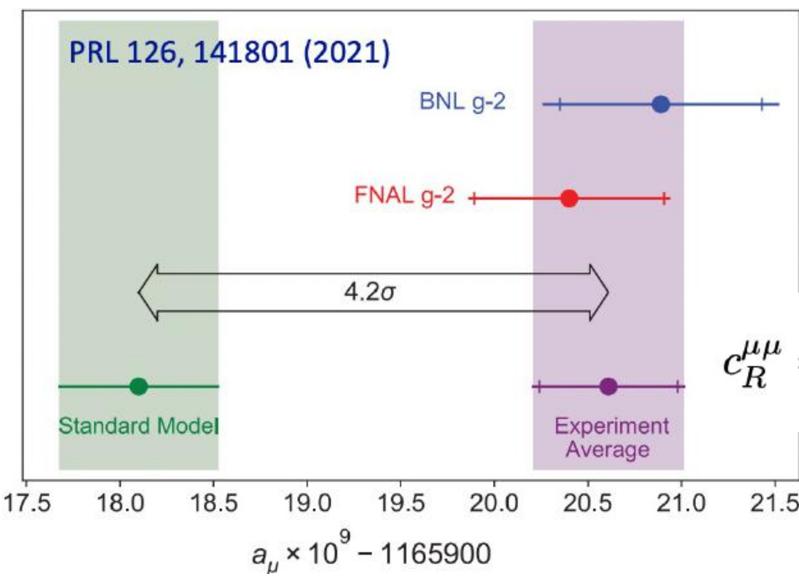
Motivation: muon g-2 anomaly

- Muon g-2: 4.2 σ discrepancy between the measured value and the prediction by the SM.

✓ EDM and g-2 are induced by the same dipole operator.

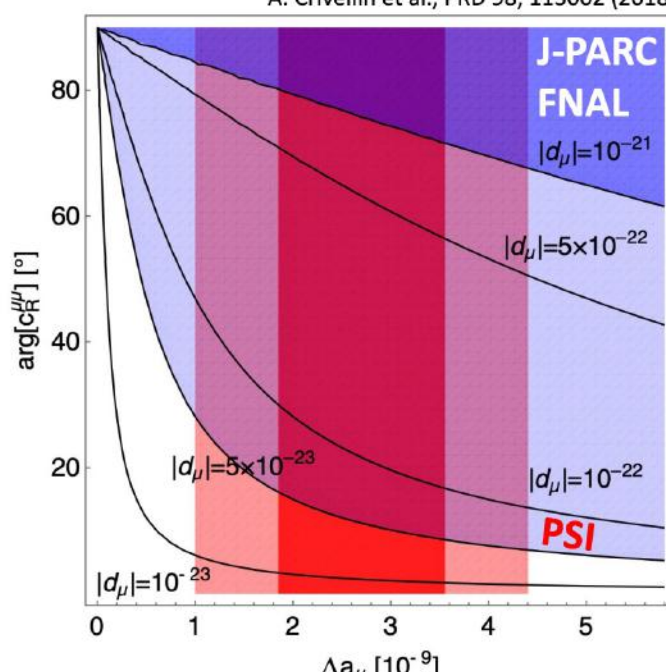
  - g-2: real part ↔ EDM: imaginary part

- We can naively expect large muon EDM unless the complex phase is very small.



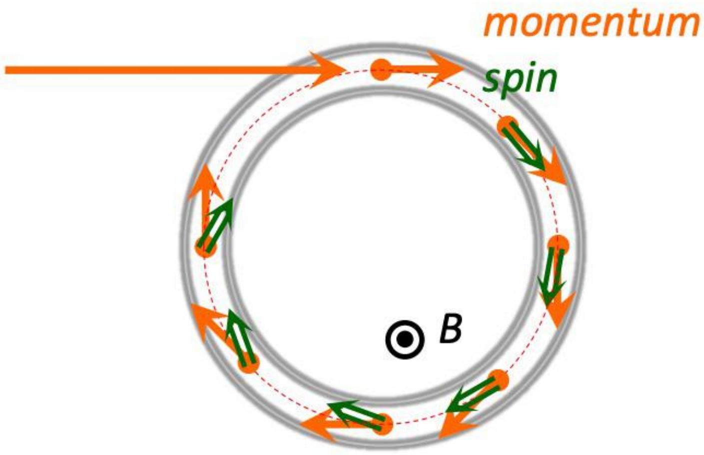
$$c_R^{\mu\mu} = -\frac{e}{4m_\mu} a_\mu - i\frac{1}{2} d_\mu$$

A. Crivellin et al., PRD 98, 113002 (2018



Experimental method of muon EDM (and g-2) measurement

1. Store a polarized muon beam inside uniform B-field
2. Spin precession by EDM (and g-2 depending on the detail of the setup)
3. Measure the direction of muon spin from decay e^+
4. Extract the precession frequency



(spin precession induced by g-2)

- In the rest frame of μ^+, decay e^+ is preferentially emitted in the direction of the μ spin.

Experimental method of muon EDM measurement

- **β~1 !!** → Both B and E-field induce EDM (and g-2)
- Conventional μ⁺ beam has large emittance: Focusing E-field for storage
  - **Magic gamma (γ~30) is used to simplify the formula**.

✓ Our idea: **low emittance μ⁺ beam for storage without E-field.**

➢ Clear separation of EDM and g-2 signal -> simultaneous measurement.

g-2 term and EDM term are orthogonal to each other

Cancellation by magic gamma approach (γ~30)

$$\vec{\omega} = \vec{\omega}_a + \vec{\omega}_\eta$$

$$= -\frac{e}{m}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta} \times \vec{E}}{c} + \frac{\eta}{2}\left(\vec{\beta} \times \vec{B} + \frac{\vec{E}}{c}\right)\right]$$

Vanish with no E-field

Our new approach: Low emittance muon beam

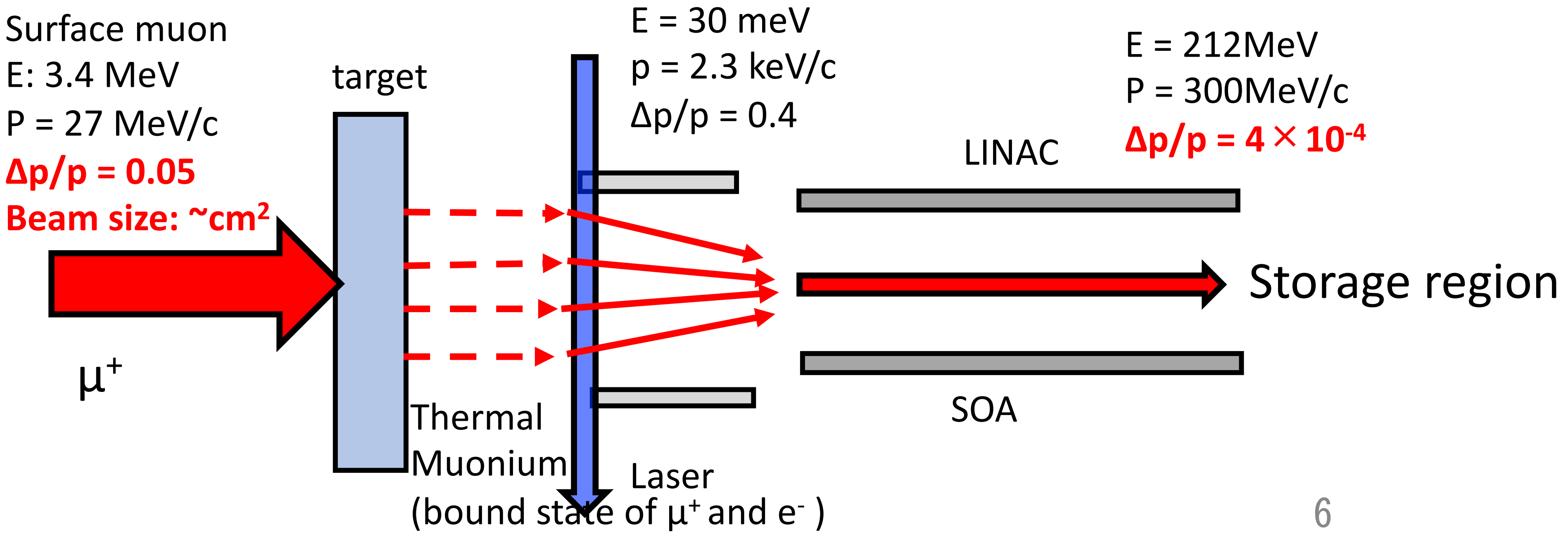
- Conventional μ^+ beam from decay of π has large emittance

➢ ***Cooling of muon***

 ➢ ***Ultra-slow muon (USM): laser ionization of thermal Muonium from the target***

 ➢ Drawback is **decrease of spin polarization** by spin change w/ e^-

➢ ***Re-acceleration of USM → Low emittance muon beam !!***



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➢ ***Re-acceleration of USM → Low emitt***

Sur

E: 3

P =

Δp/

ion

SOA

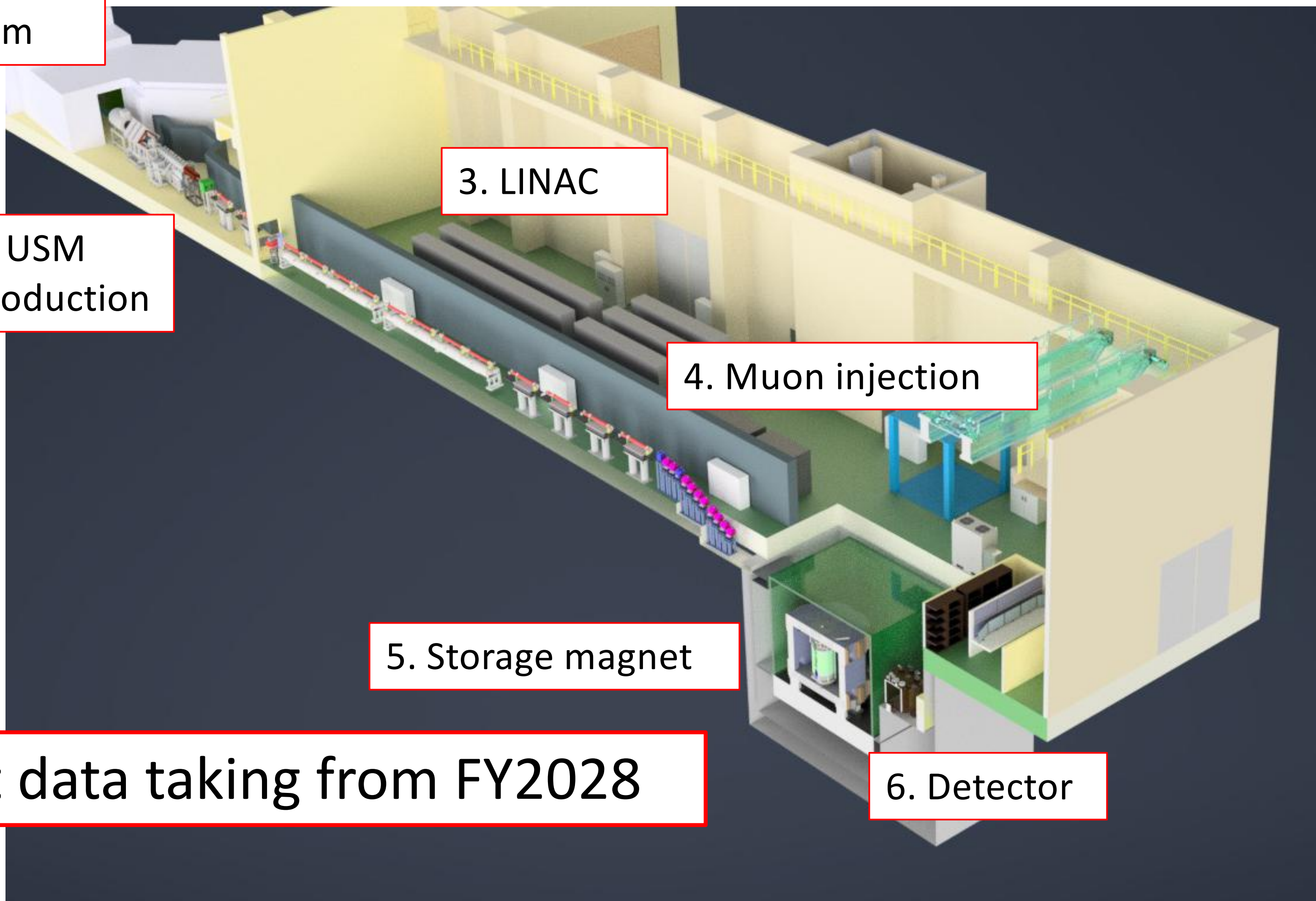
Muonium

Laser

(bound state of μ^+ and e^-)

New muon g-2/EDM experiment
@ J-PARC
Also featuring
compact storage magnet, full tracking detector

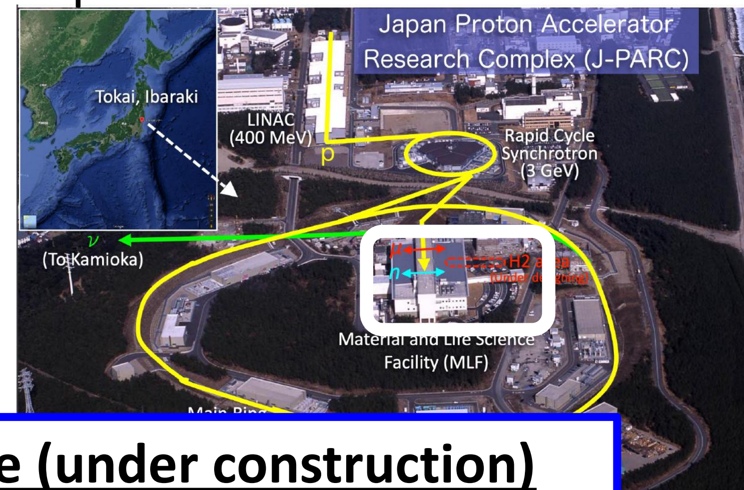
Muon g-2/EDM experiment at J-PARC

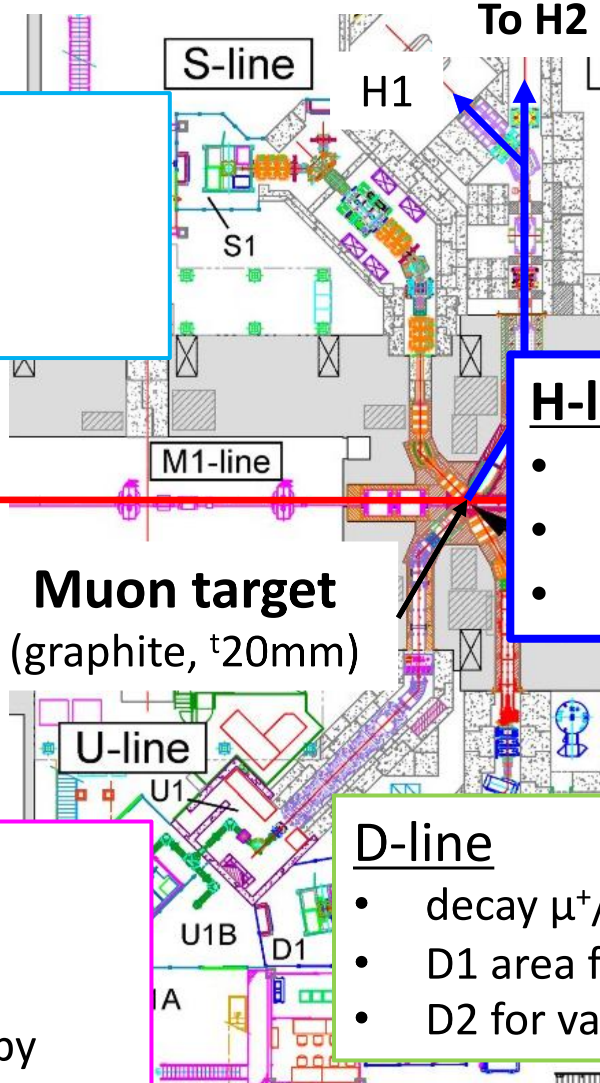


Start data taking from FY2028

J-PARC muon facility (MUSE)

- MUSE (MUon Science Establishment): Intense pulsed muon beam





S-line
- surface μ^+
- S1 for μSR
- S2 for Mu 1S-2S

3GeV proton from RCS

2e15 /s @1MW

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

H-line (under construction)
- **surface μ^+**, cloud μ^+/μ^-, e^-
- H1 for DeeMe & MuSEUM
- H2 for g-2/EDM & TμM

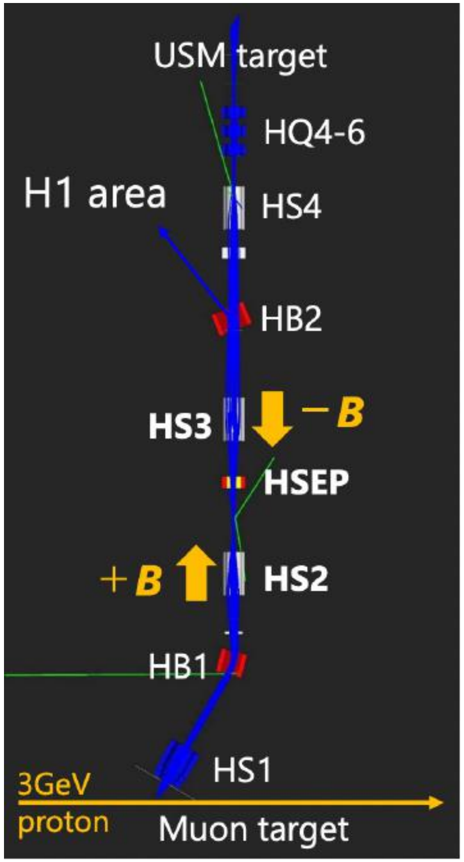
U-line
- ultra slow μ^+
- U1A for μSR
- U1B for μ microscopy

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

H-line optics

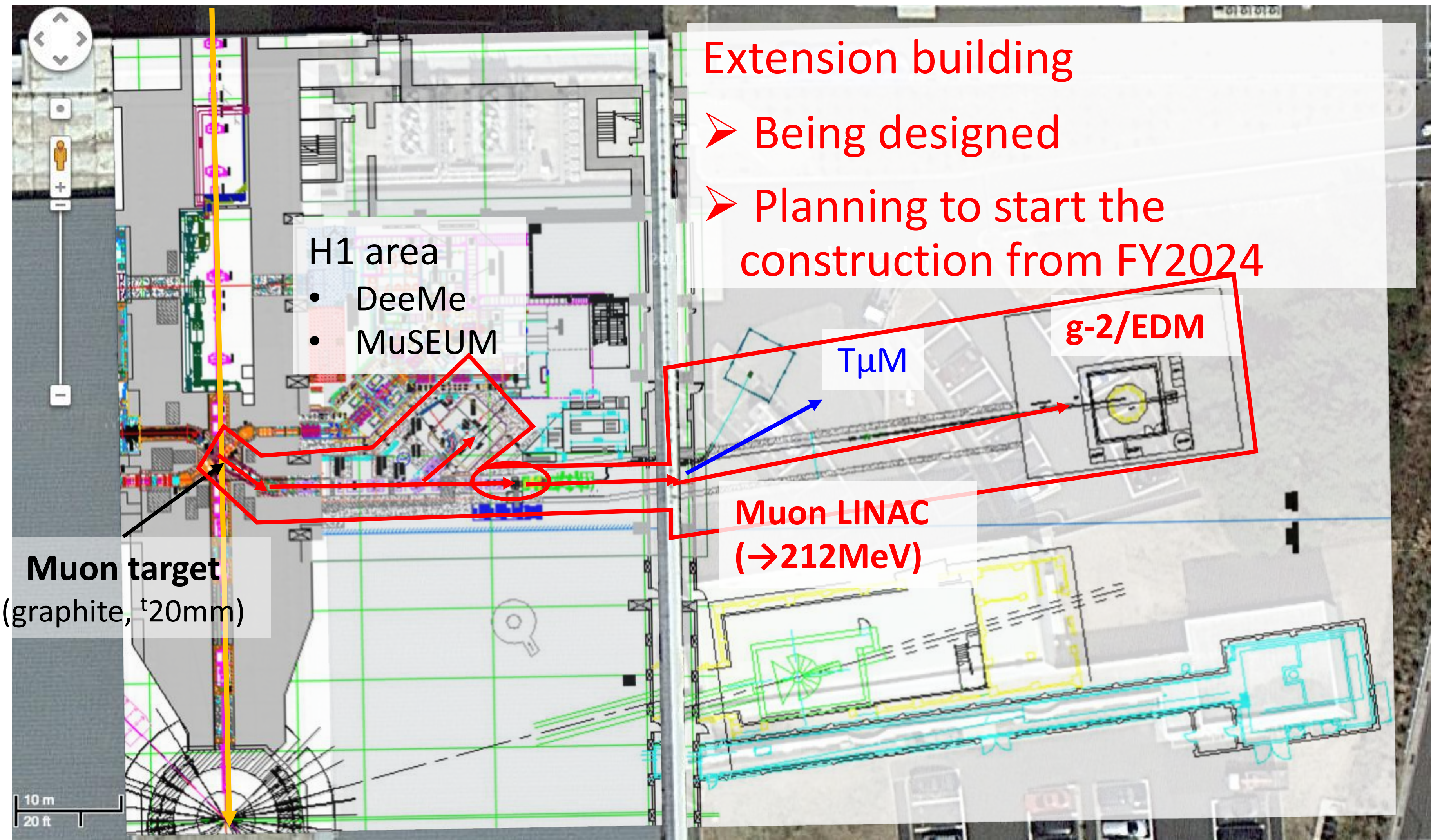
1. H-Line

- **High intensity** surface muon beam
  - From decay of π @ Graphite target
  - 100% polarized, Δp/p ~ 5%
  - **Pulsed, 4MeV, 10^8 μ^+/s, 25Hz**
- Beam to H1 area from 15th Jan 2022.
- First beam to H2 (g-2/EDM) in next FY

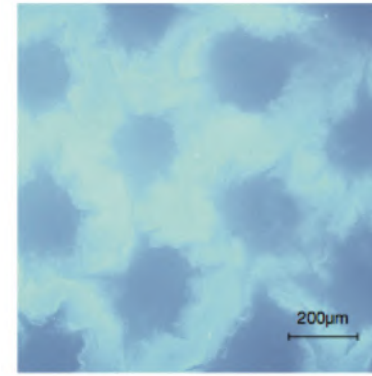


1. Extension building

- A new extension building will be constructed. (now there is parking lot)



2. Muonium target

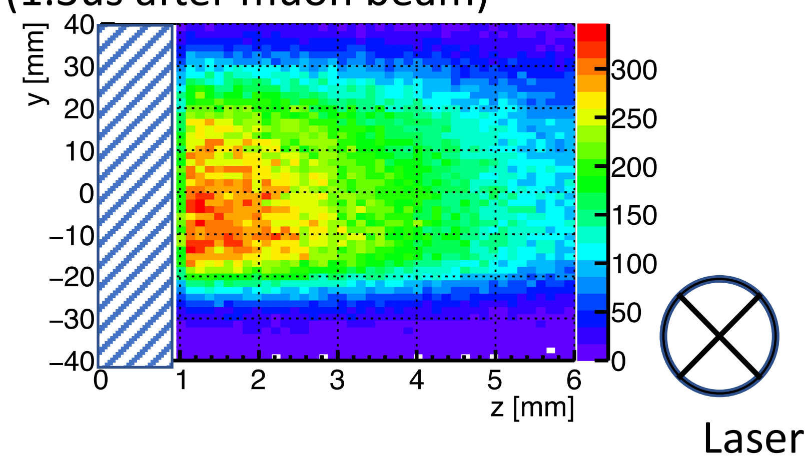


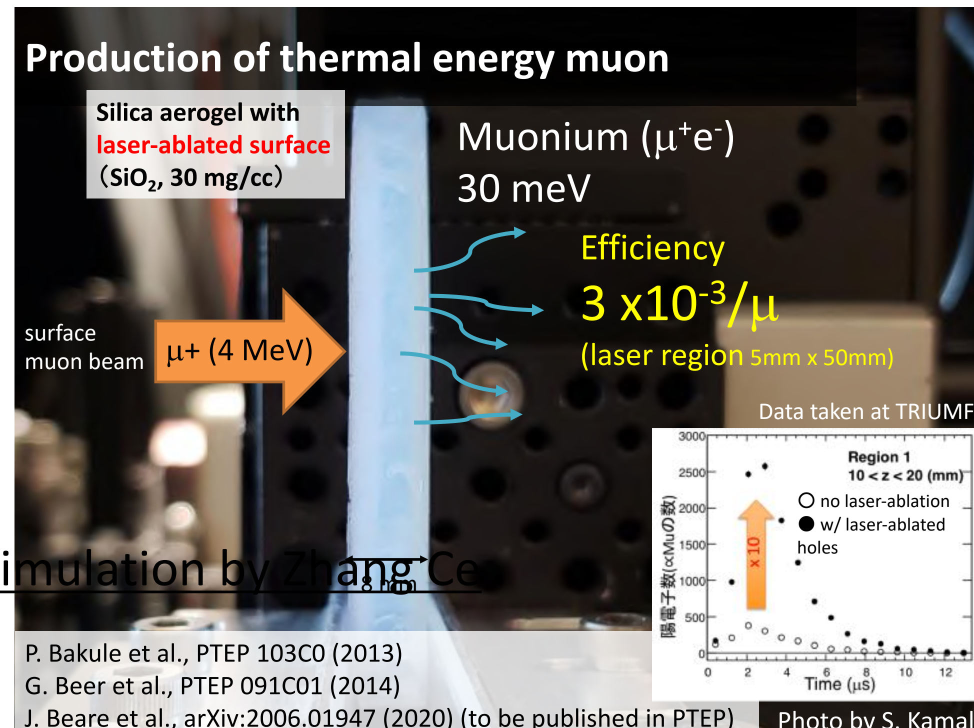
- Laser ablated aerogel target
  - Surface muon stops inside the target
  - Muonium (Mu) is formed, thermalize and diffuses.
  - Finally, emitted to vacuum (T=300K ~ 7mm/μs)

➢ Efficiency: $3 \times 10^{-3}/\mu$

- Spin exchange between μ^+ & e^-
  → spin pol. of μ^+ becomes 50%

Expected emission profile at H-line
(1.3us after muon beam)

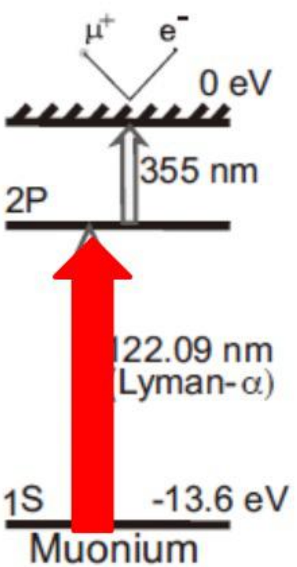


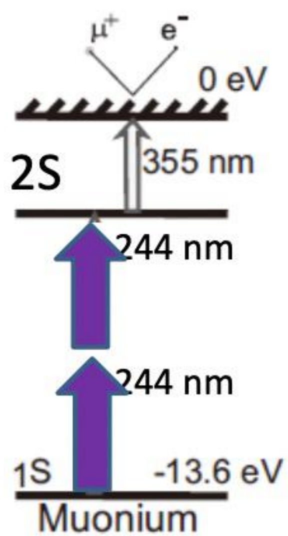


Simulation by Zhang Ce

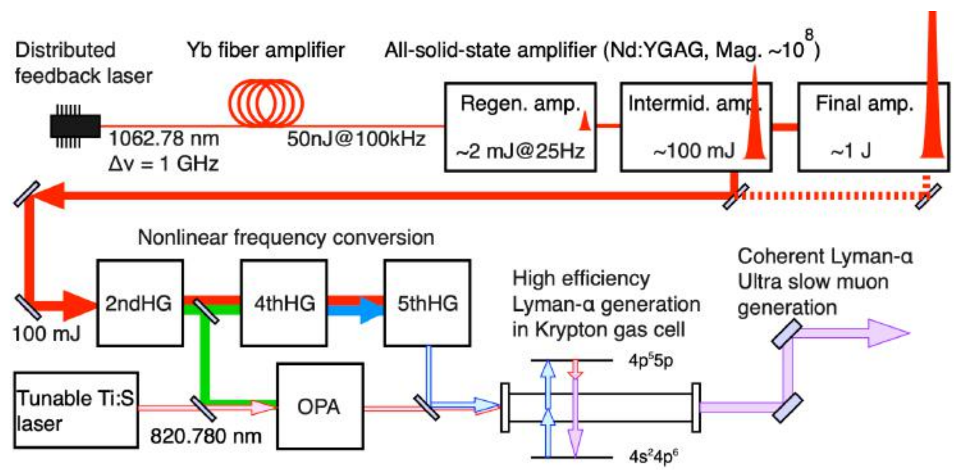
2. Laser ionization of muonium

- Two possible schemes for laser ionization
  - 1S state → 2P state (122nm) → unbound state (355nm): Plan A
  - 1S state → 2S state (244nm) → unbound state (244nm): Plan B
- Large Mu emission area → Development of **strong VUV laser**
  - ➢ PlanA: Goal: **E=100μJ**, Δt=2ns, Δν=80GHz @ 122nm
  - ✓ 5μJ @ Mu region is under operation (world record!)





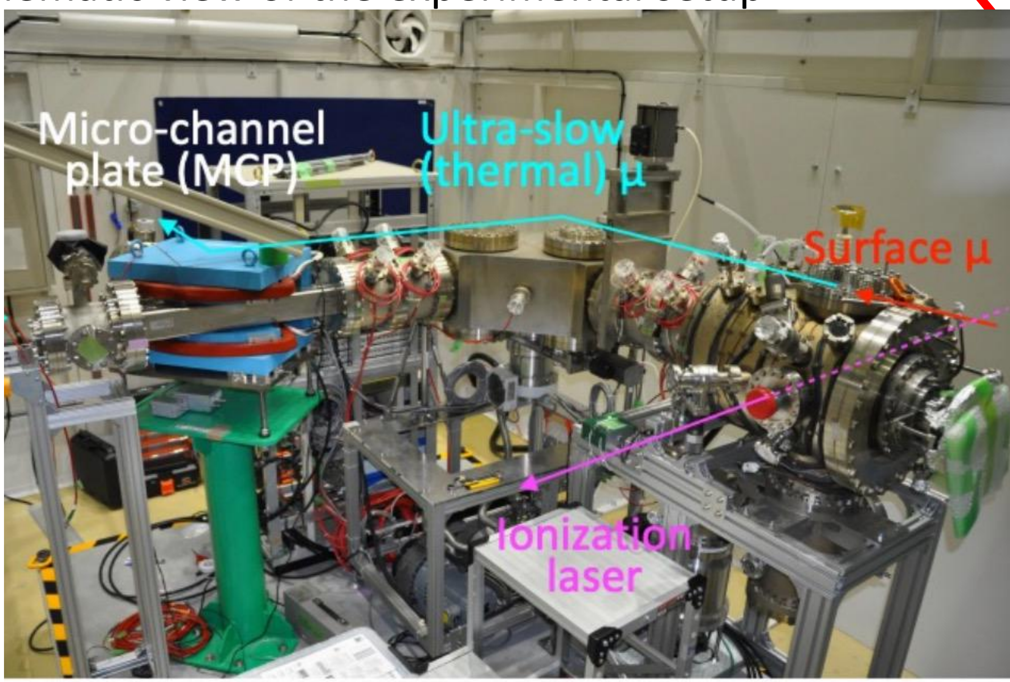
All solid-state VUV laser system for 122nm

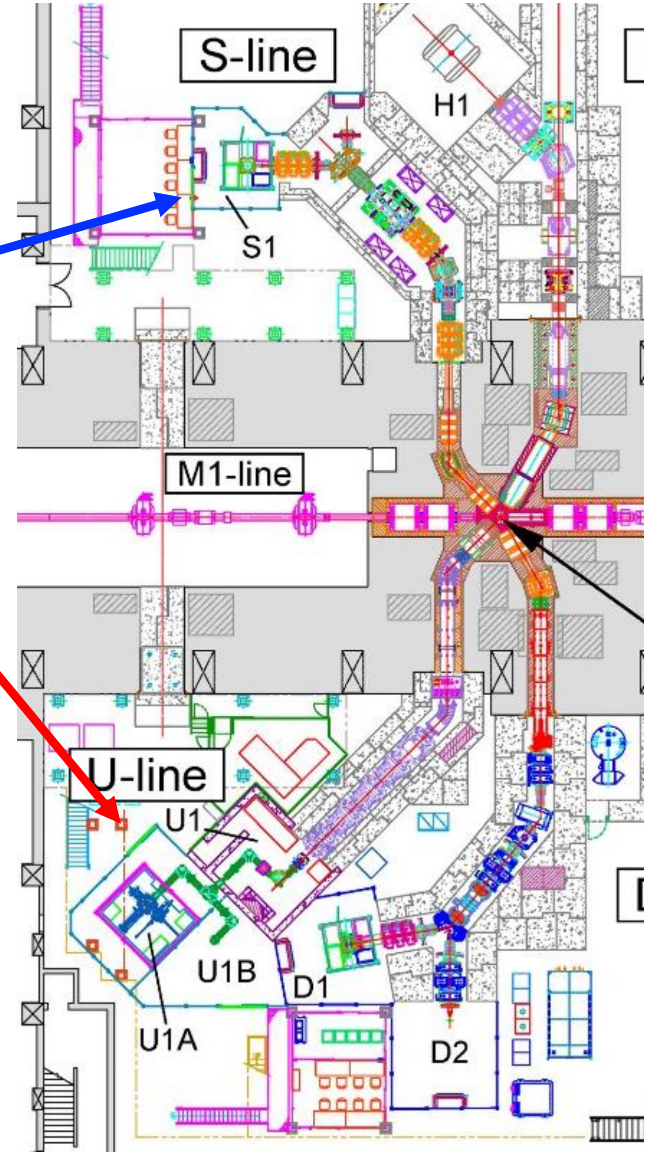


Demonstration of USM generation

- Laser ablated SiO_2 target + laser
- **Succeeded to observe USM signal in 2022 !!**
  - ✓ 1S→2P→unbound scheme: U-line
  - ✓ 1S→2S→unbound scheme: S-line
    - With Mu spectroscopy experiment

Schematic view of the experimental setup





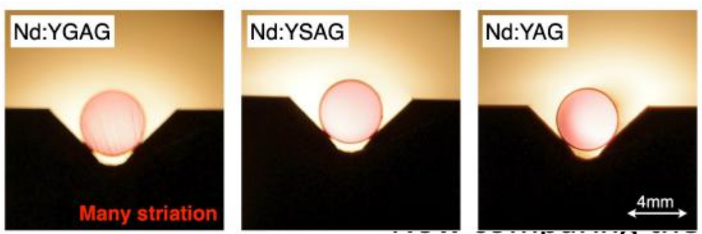
R&D for higher pulse energy

- Required pulse energy for high ionization efficiency
  - 100μJ @122nm for 1S→2P→unbound scheme
  - 60mJ @244 nm for 1S→2S→unbound scheme

<u>More than 10 times improvement is required</u>

Development of 122nm laser

- Study of recently developed crystals. (quality vs size)
- Better FWM efficiency

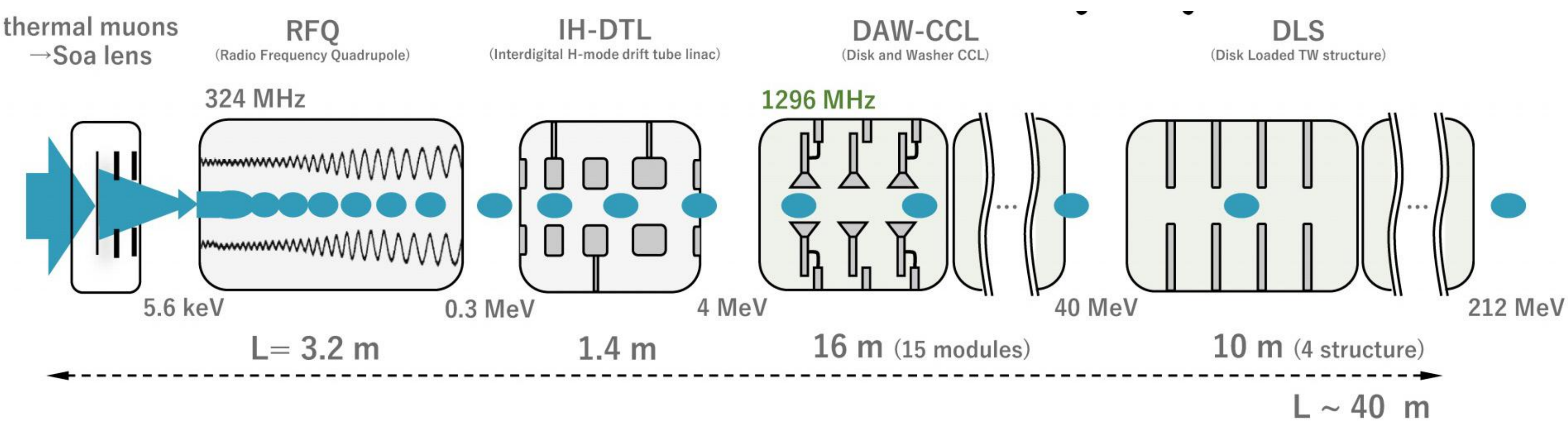


Development of 244nm laser

- Laser for spectroscopy by Okayama group
- Development of high energy laser for Ti:S @KEK.

3. Muon Linac

- USM is extracted by E-field → Acceleration using Linac
  - From 30meV to 200 MeV
- Dedicated design for muon acceleration
  - Mass, velocity
- 4 steps depending on β.
- L = 40m in total



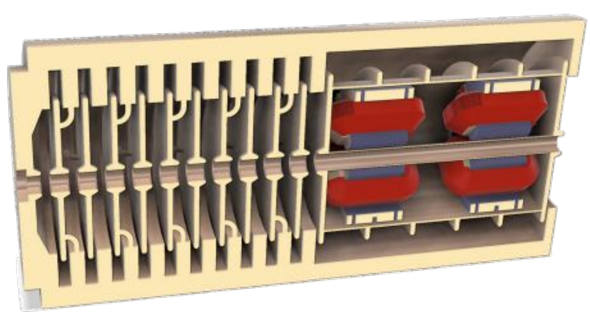
Current status of Linac

- RFQ: Use J-PARC RFQ-II originally designed to accelerate H−
- IH-DTL: High power test of proto-type (PRAB 25 (2022) 110101) → Fabrication of production version is completed
- DAW: 1^{st} tank is being fabricated.
- DLS: Design for 1^{st} structure is finished→ Proto-type in FY2022

➢ Development of beam monitors & end-to-end simulation of LINAC

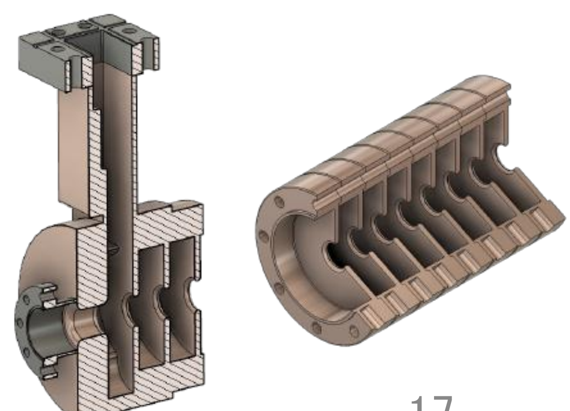
IH-DTL

1^{st} tank of DAQ (14 tanks in total)



DAW tank (11 cell)

DLS:
Coupler and regular cell



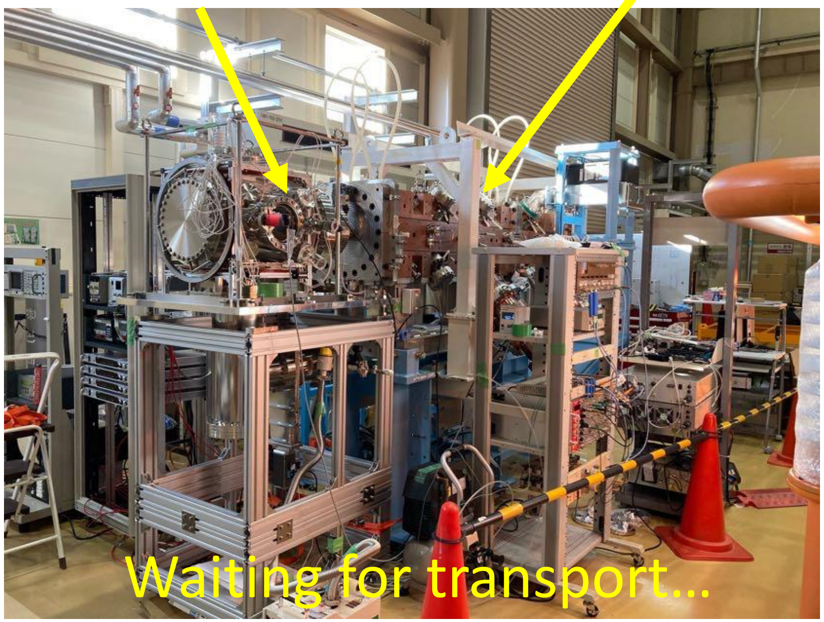
Demonstration of USM acceleration

- World first acceleration of μ^+ in Mu^- using RFQ in 2017 by our group

➢ **Demonstration of acceleration of USM using an RFQ in next FY**
  - **30meV → 80keV**

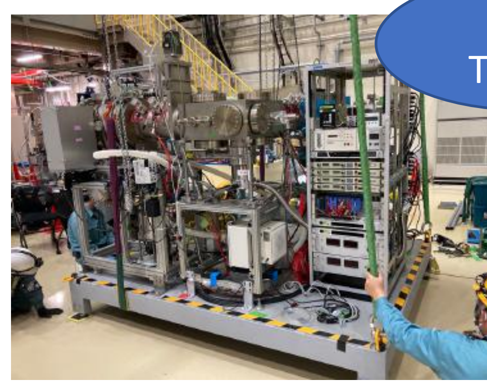
USM chamber

RFQ



✓ Study of USM at MLF S-line **now!**
  - R&D before acceleration
  - Collaboration with Mu spectroscopy experiment

Pictures of last week



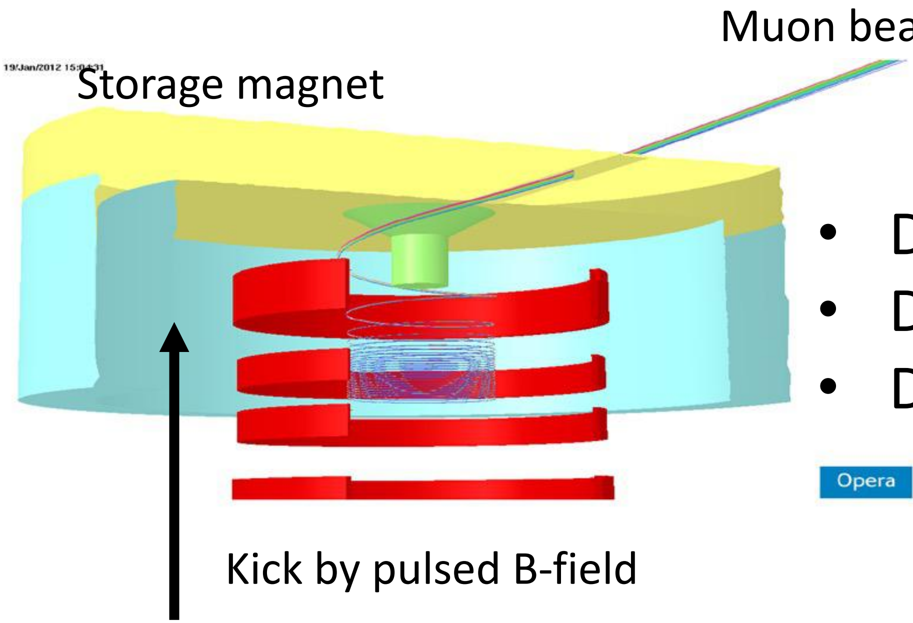
4. Injection

- Compact storage region for better B-field uniformity

➢ Conventional 2D injection of beam to storage region is impossible

✓ Instead, μ^+ is spirally injected to storage region **(3D)**

- **Kicking the muon beam <u>vertically</u> by pulsed B-field for storage with good injection efficiency**

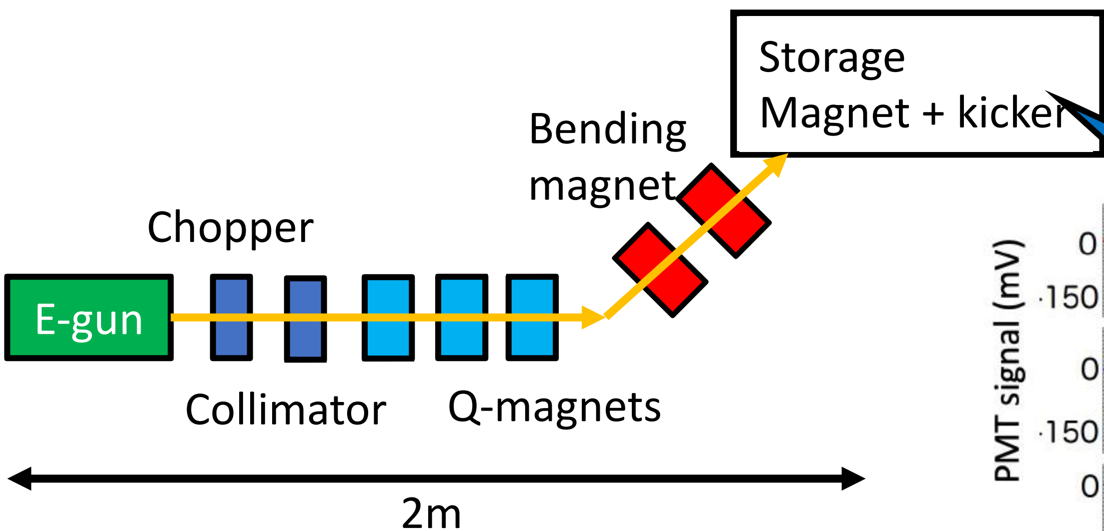


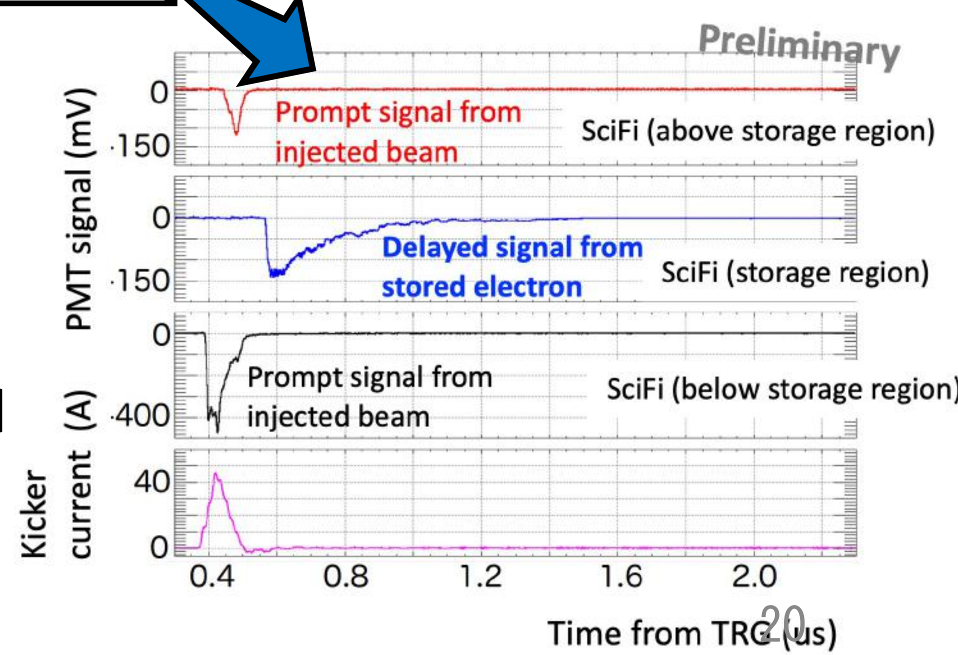
- Design of beam transport
- Design of the kicker
- Discussion of beam monitor

Ongoing

Demonstration of the injection scheme with e^-

- R&D with e^- beam in parallel with the design for muon injection.
  - Proof of principle (E=80keV, B=80mT, R=0.12m)
  - Study of the beam tuning and monitors dedicated to the scheme





- First signal of stored e^- is observed
- ➢ R&D for better understanding of the stored beam (monitors etc)

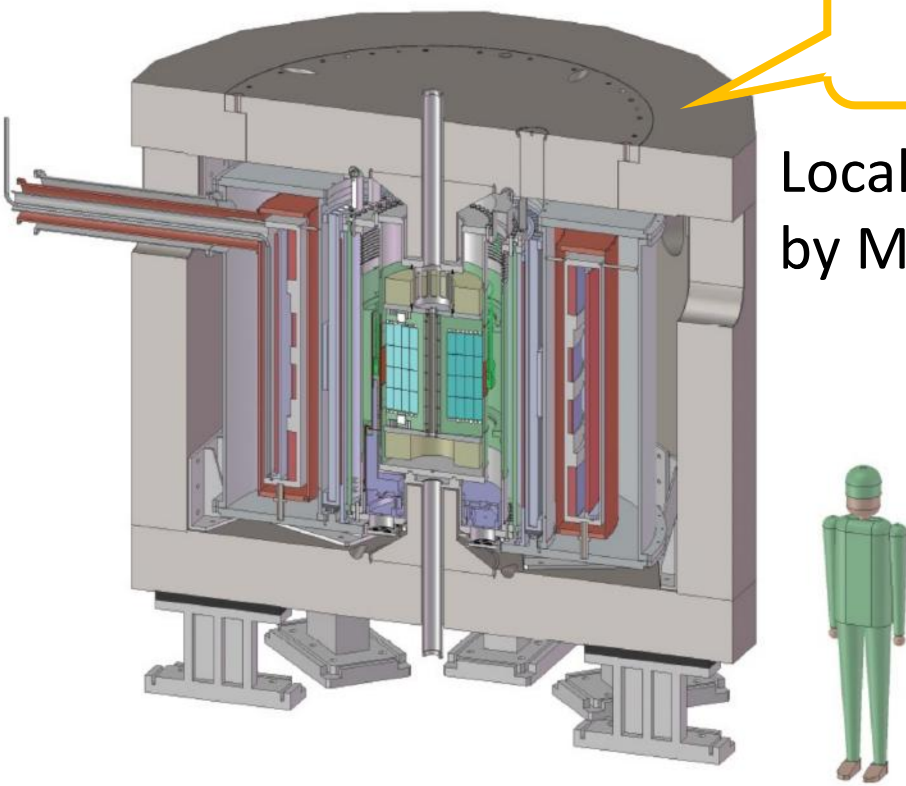
5. Storage magnet

✓ A compact superconducting magnet based on MRI technology

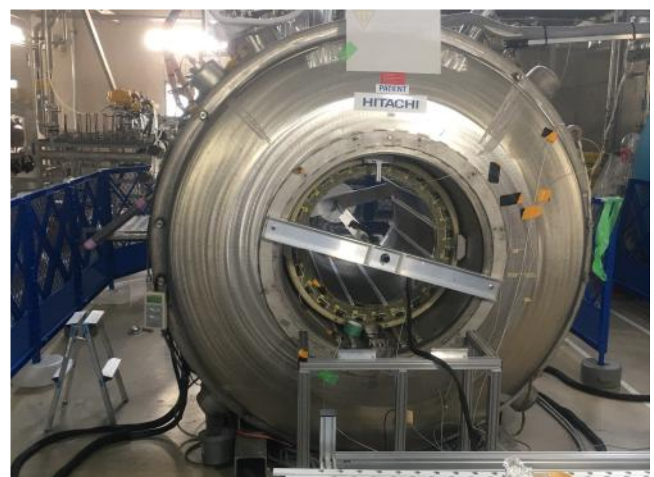
- **B=3T, ϕ = 66cm:** Good uniformity is expected (**ΔB (local) < 0.2 ppm**)

➢ **Design and simulations to evaluate the expected uniformity for production from FY2025**

Uniform B-field (3T) and
Weak focusing magnetic field



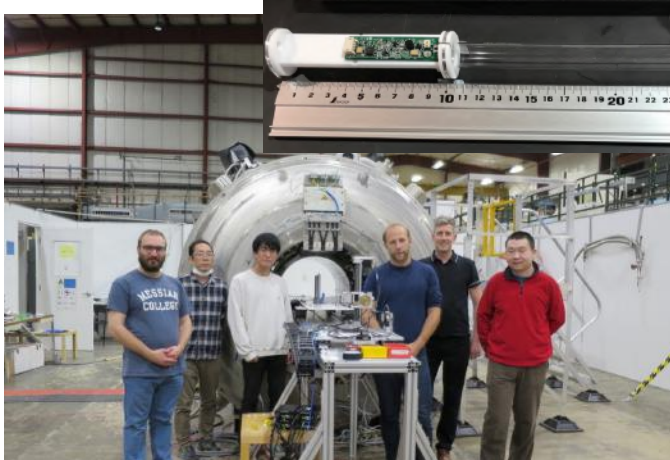
Local uniformity of 1ppm is established by MUSEUM magnet (1.7T, Mu HFS)



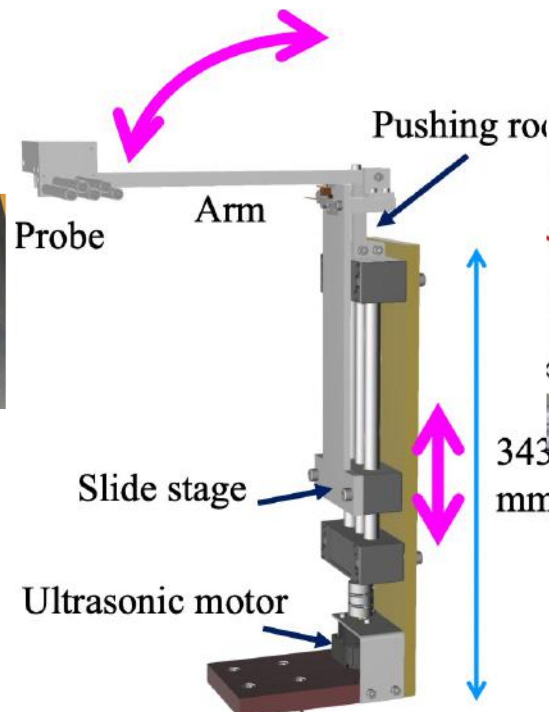
NMR probes

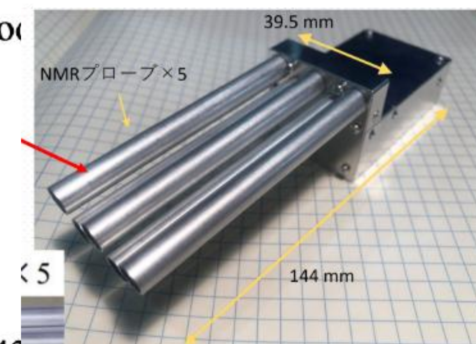
- High precision water NMR probes are developed for B-field monitor
  - Standard probe: for calibration of other probes
  - Field mapping probes and their moving stage
  - Fixed probe: time variation

Standard probe:
JP-US cross calibration at 3T
(Nov, 2022)
→Analysis



Mapping probe and its moving stage

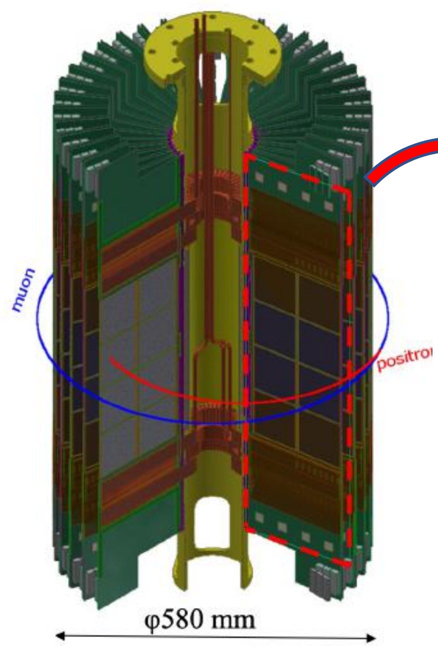




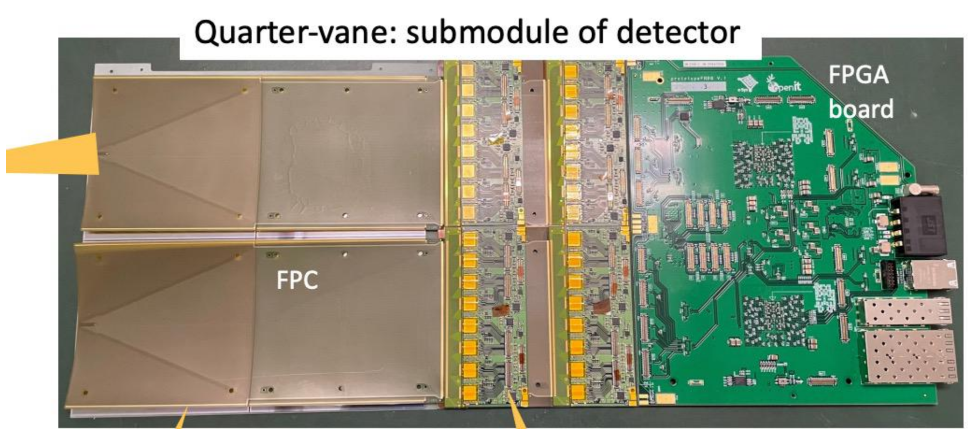
Prototype in 2022

6. Positron tracking detector

- Positron tracking detector for decay e^+ is required.
  - Detection of e^+ (100MeV < E < 300MeV), reconstruction of decay time and energy, and stability over rate change (1.4MHz ~ 14kHz)
- **New Silicon strip detector is being developed**
  - **Major components are in or completed the mass-productions.**

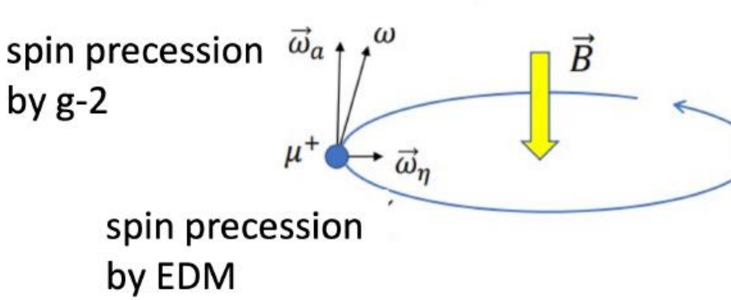


Total 40-vanes.
One vane is consisted with four quarter vanes

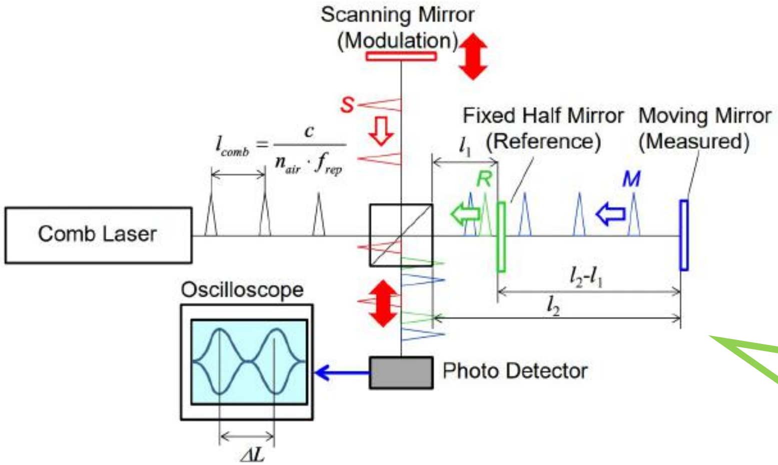


Sensor alignment

- Alignment between detector and B-field direction is essential for EDM
  - Tilt of the detectors→ g-2 signal becomes fake-EDM signal
- Goal: 1μm precision
  - Assembly procedure is being studied
  - Assembly precision of ~2um is already achieved



- Detector position monitor using an optical comb is being developed



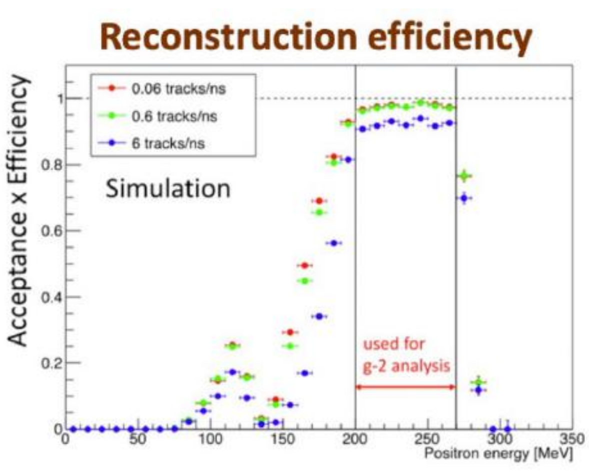
Detect the position of detectors from the interferometer signal

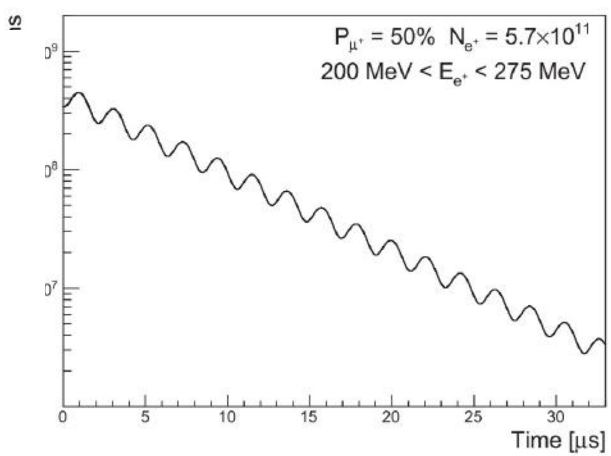
Analysis and expected signal

- g-2/EDM signal are extracted from e$^+$ energy and decay time →
  - # of high energy e$^+$ event in laboratory frame depends on the relative angle between spin and momentum
- g-2: in-plane precession signal ($\overrightarrow{\omega} \propto \vec{B}$)
- **EDM: out-of-plane precession (up-down asymmetry)** ($\overrightarrow{\omega} \perp \vec{B}$)

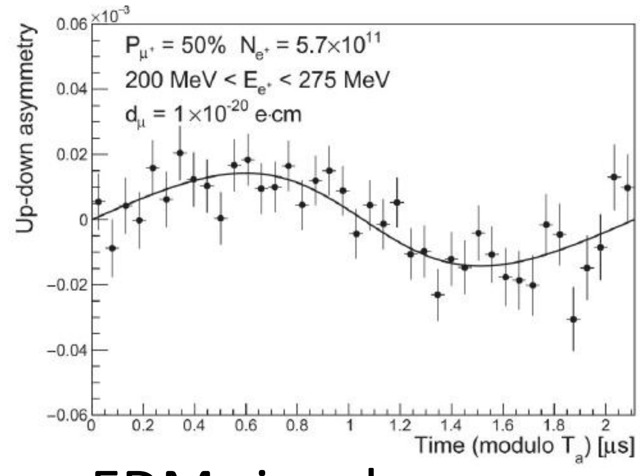
Expected signal (simulation)

Higher energy e+ event vs time





g-2 signal



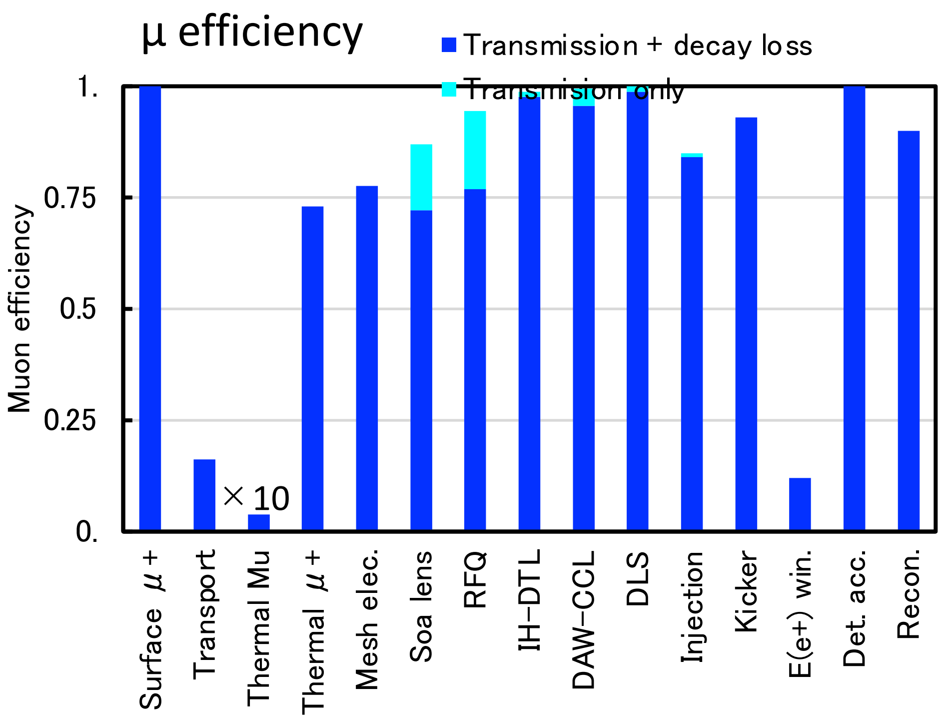
EDM signal

Expected sensitivity

- Overall efficiency: **1.3 × 10^{-5} /μ & Spin polarization is 50%**

➢ 2.2 × 10^{7} sec data taking → $\Delta d_\mu = 1.5 \times 10^{-21}$ e cm

✓ ***100 times better sensitivity than the current direct limit***



$$\Delta d_\mu = \frac{e\hbar}{4mc} \cdot \frac{\pi a_\mu}{A\beta} \cdot \frac{1}{P\sqrt{N_0}} = (3.94 \times 10^{-16}\ \mathrm{e \cdot cm}) \cdot \frac{1}{P\sqrt{N_0}}$$

Systematic uncertainty

- Major systematic uncertainties are
  - Misalignment of the detector: assumed rotation angle is <3.6 μrad
  - Residual axial E-field: should be less than < 1V/cm
    - High sensitivity E-field monitor is required for evaluation of E_z.
  - Radial B field: Very small at the storage plane

Uncertainty source	EDM 10^{-21} [e·cm]	Remarks on this experiment
Detector misalignment	0.36	Estimate based on laser alignment monitor system. Corresponds to ϕ-axis rotation of 3.6 μrad.
Axial E field	0.001	$E_z = 1$ mV/cm is assumed.
Radial B field	0.00001	$E_z = 1$ mV/cm causes a shift of z position and it becomes $B_r \sim 3.5 \times 10^{-10}$ T.
Total	0.36	

➢ Spin of μ^+ in Mu can be flipped easily → Spin reversed μ^+ beam → powerful tool for systematic uncertainty test

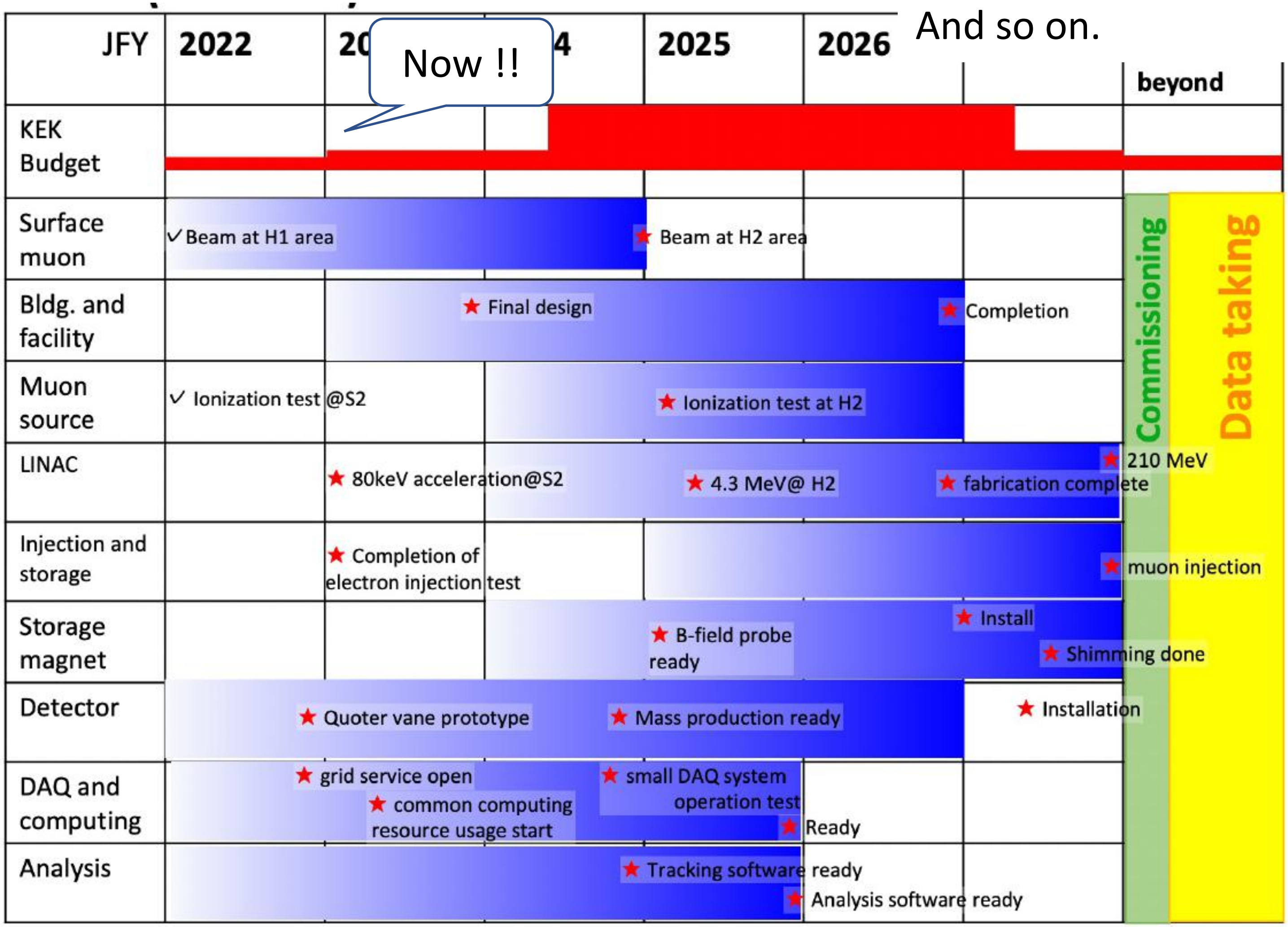
Schedule

Milestones in FY2023:

- 80keV acceleration test
- Final design of Bldg.
- Completion of electron injection

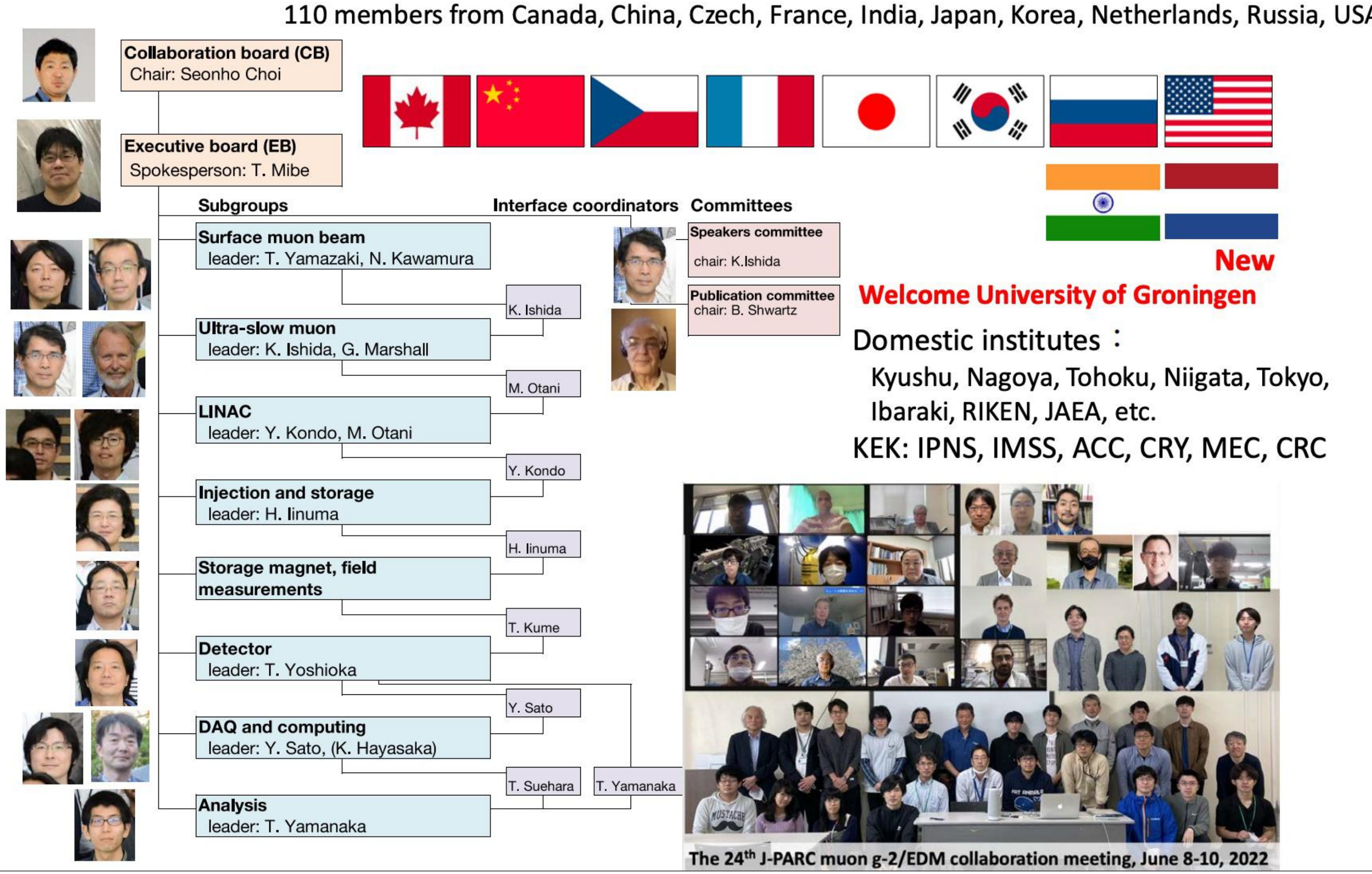
And so on.

- Data taking from FY2028



Collaboration

- 110 members from Canada, China, Czech France, India, Japan, Korea, Netherlands, Russia, USA



Summary

- J-PARC muon g-2/EDM experiment intends to measure the muon g-2 and EDM with a new experimental approach.

➢ New experimental approach
  - Low emittance muon beam with no strong focusing by E-field
  - MRI-type storage ring with high uniform B-field
  - Full-tracking silicon strip detector

- The development and construction is in progress to start data taking in FY2028.

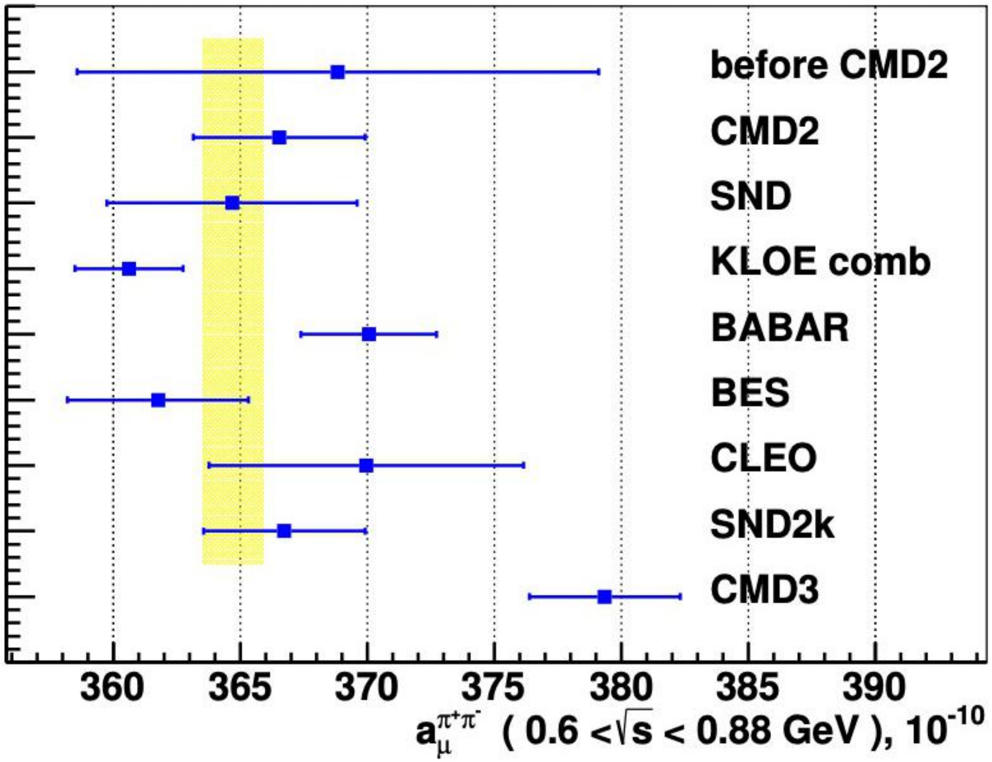
✓ Intend to reach $\Delta d = 1.5 \times 10^{-21}$ e cm

100 times better sensitivity

ばっくあっぷ

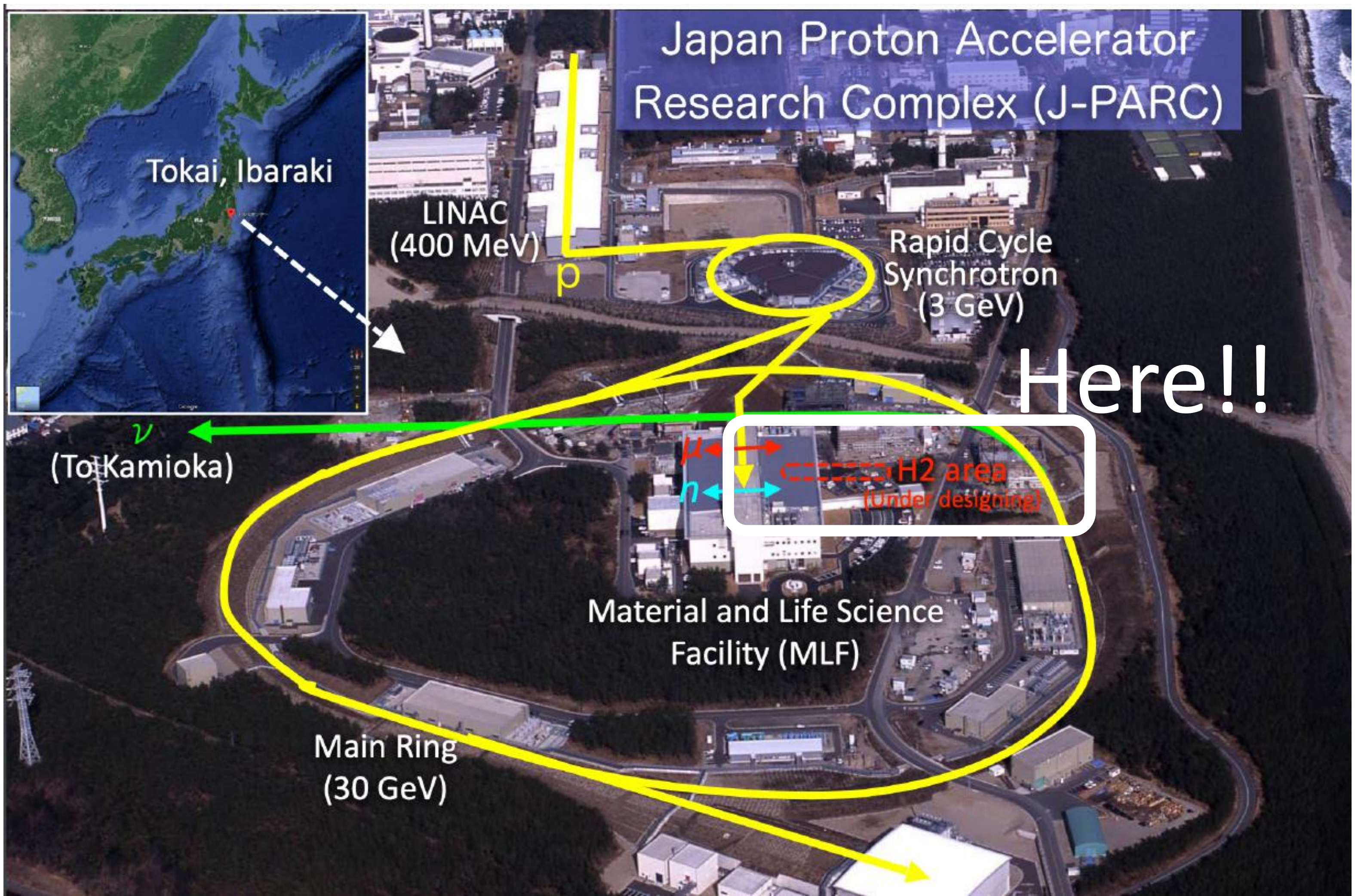
CMD-3 result

- **In case** there is someone who is also interested in g-2…
  - CMD3 result agrees with lattice calculation, disagrees with previous results
- We need more input from the experiments.
  - Belle II result in the future (?)



arXiv:2302.08834

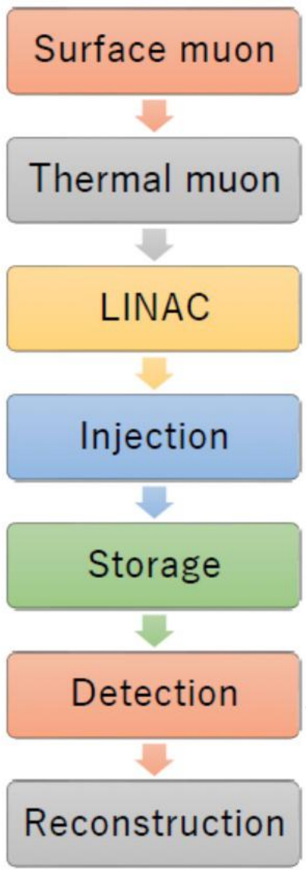
Japan Proton Accelerator Research Complex (J-PARC)



End-to-end simulation

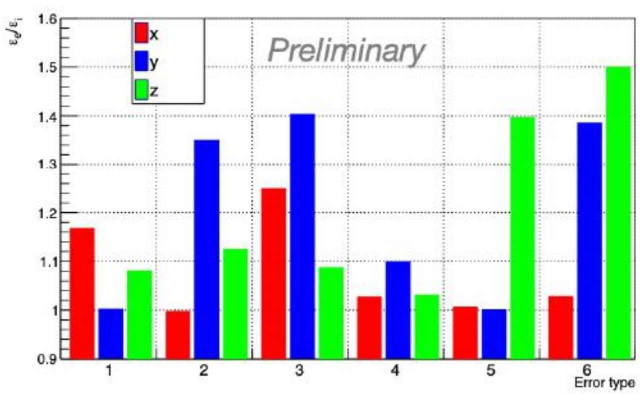
- End-to-end simulation is underway
    - For realistic simulation samples and for further analysis study

Simulation flow



➢ Recent activities

- **Error study of LINAC** to identify the possible sources of increase of emittance (GPT-spin)
- **Development of software framework** to handle detector simulation and track reconstruction (g2esoft)



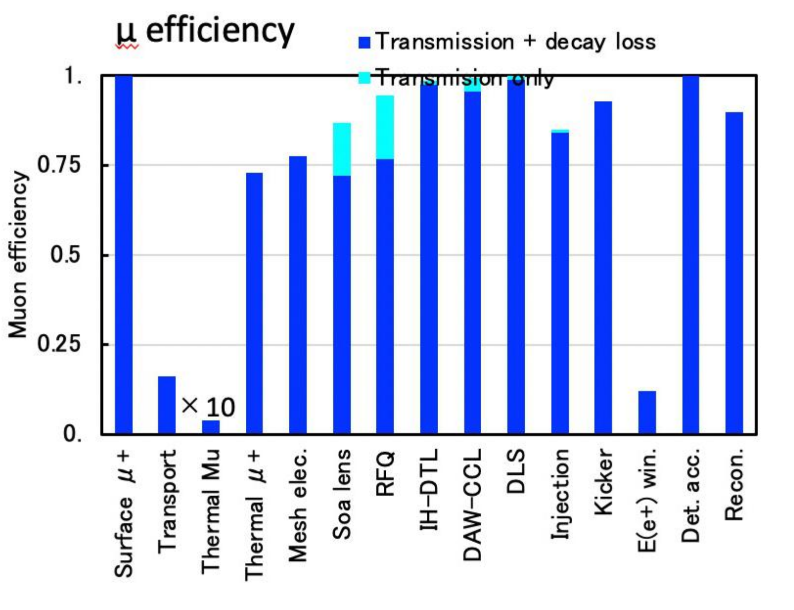
E.g., evaluation of emittance increase due to various error source

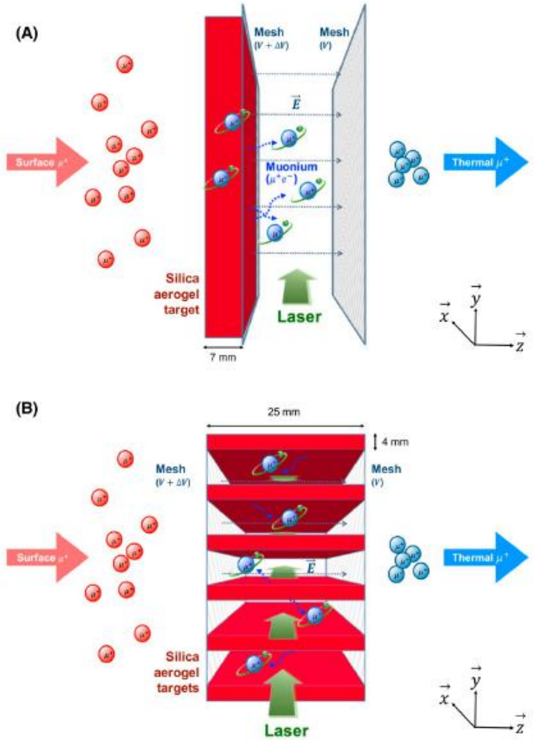
➢ Aiming to prepare 20M samples in FY2023 and study their properties

Ideas for higher sensitivity

- You can find that thermal Mu part has relatively low efficiency.
  - Room for higher sensitivity

➢ Proposal to increase the thermal Mu efficiency with a multi-layered target. → × 3.5 time more Mu emission from the target





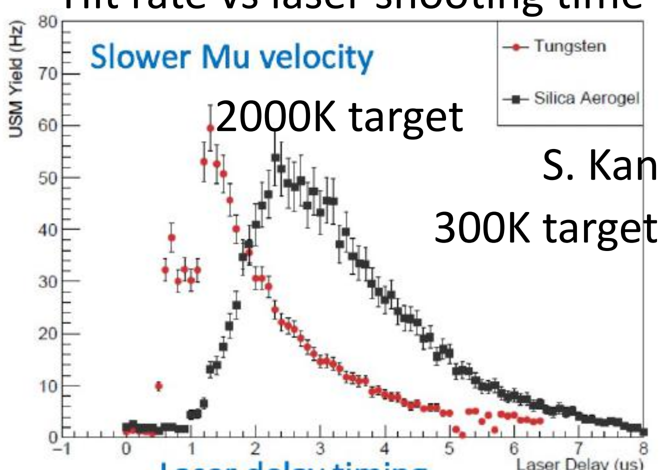
Demonstration of USM generation

- Demonstration of USM generation with aerogel target in FY2022.
  - ✓ 1S→2P→unbound scheme: MLF U-line
  - ✓ 1S→2S→unbound scheme: MLF S-line
    - collaboration with Mu spectroscopy experiment

USM is extracted by E-field → detected by a MCP

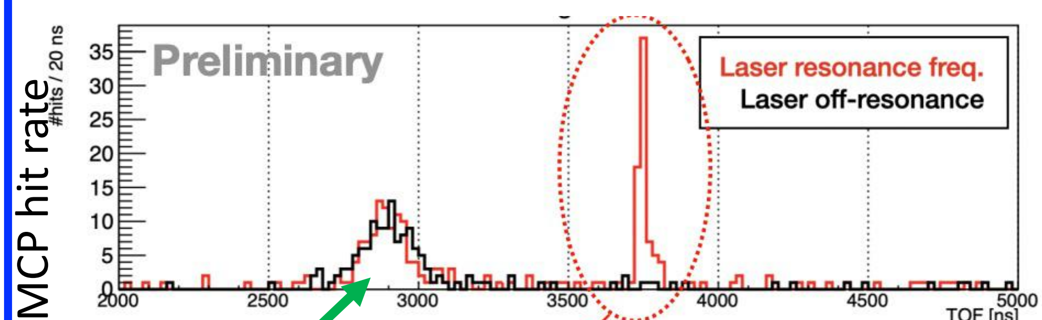
1S->2P->unbound scheme

Hit rate vs laser shooting time



1S->2S->unbound scheme

Timing spectrum (hit vs time after trigger)



Time from DAQ trigger

Signal by a muon penetrating the target

Comparison of experiments

Prog. Theor. Exp. Phys. **2019**, 053C02 (2019)

<table>
<tr><th></th><th>BNL-E821</th><th>Fermilab-E989</th><th>Our experiment</th></tr>
<tr><td>Muon momentum</td><td colspan="2">3.09 GeV/c</td><td>300 MeV/c</td></tr>
<tr><td>Lorentz γ</td><td colspan="2">29.3</td><td>3</td></tr>
<tr><td>Polarization</td><td colspan="2">100%</td><td>50%</td></tr>
<tr><td>Storage field</td><td colspan="2">$B = 1.45$ T</td><td>$B = 3.0$ T</td></tr>
<tr><td>Focusing field</td><td colspan="2">Electric quadrupole</td><td>Very weak magnetic</td></tr>
<tr><td>Cyclotron period</td><td colspan="2">149 ns</td><td>7.4 ns</td></tr>
<tr><td>Spin precession period</td><td colspan="2">4.37 μs</td><td>2.11 μs</td></tr>
<tr><td>Number of detected e^+</td><td>5.0×10^9</td><td>1.6×10^{11}</td><td>5.7×10^{11}</td></tr>
<tr><td>Number of detected e^-</td><td>3.6×10^9</td><td>–</td><td>–</td></tr>
<tr><td>a_μ precision (stat.)</td><td>460 ppb</td><td>100 ppb</td><td>450 ppb</td></tr>
<tr><td>(syst.)</td><td>280 ppb</td><td>100 ppb</td><td><70 ppb</td></tr>
<tr><td>EDM precision (stat.)</td><td>$0.2\times10^{-19}\ e\cdot\mathrm{cm}$</td><td>–</td><td>$1.5\times10^{-21}\ e\cdot\mathrm{cm}$</td></tr>
<tr><td>(syst.)</td><td>$0.9\times10^{-19}\ e\cdot\mathrm{cm}$</td><td>–</td><td>$0.36\times10^{-21}\ e\cdot\mathrm{cm}$</td></tr>
<tr><td></td><td>**Completed**</td><td>**Running**</td><td>**In preparation**
Full approval by the lab (March, 2019)</td></tr>
</table>

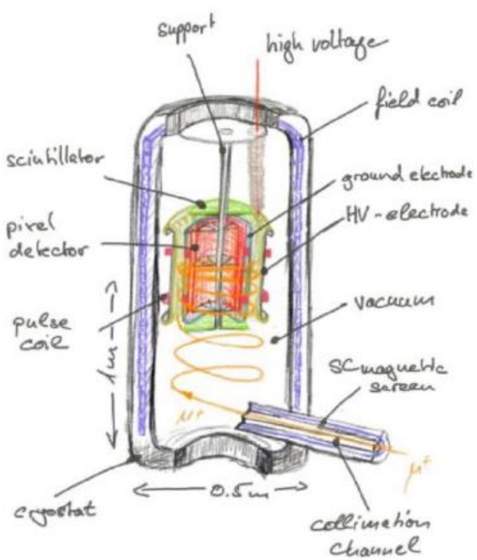
Muon EDM @ PSI

- Experiment using "frozen spin" technic focusing on EDM
- g-2 term is completely canceled by E-field

$$\vec{\omega} = \vec{\omega}_a + \vec{\omega}_\eta$$

$$= -\frac{e}{m}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta} \times \vec{E}}{c} + \frac{\eta}{2}\left(\vec{\beta} \times \vec{B} + \frac{\vec{E}}{c}\right)\right]$$

Demonstration of frozen spin technique



Phase I

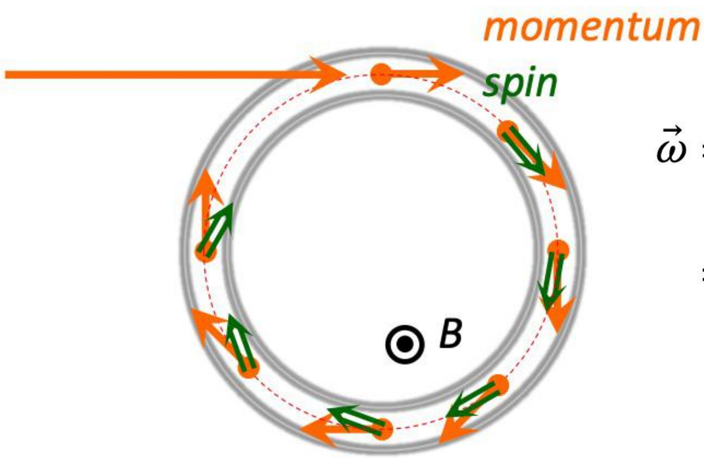
$\sigma(d_\mu)_{\mathrm{I}} = 3 \times 10^{-21}$

Phase II

$\sigma(d_\mu)_{\mathrm{II}} = 6 \times 10^{-23}$

Experimental method of muon EDM measurement

1. Store a polarized muon beam inside uniform B-field
2. Spin precession by EDM (and g-2 depending on the detail of the setup)
3. Measure the direction of muon spin from decay e^+
4. Measure precession frequency



(spin precession induced by g-2)

EDM term

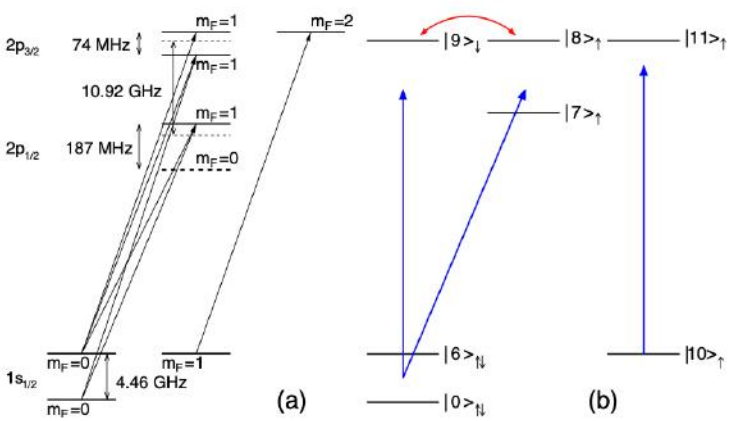
$$\vec{\omega} = \vec{\omega}_a + \vec{\omega}_\eta$$

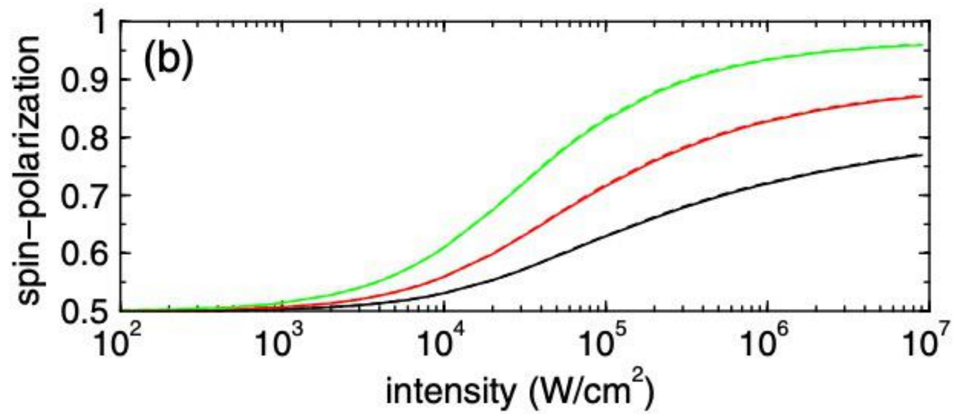
$$= -\frac{e}{m}\left[\boxed{a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta}\times\vec{E}}{c}} + \boxed{\frac{\eta}{2}\left(\vec{\beta}\times\vec{B} + \frac{\vec{E}}{c}\right)}\right]$$

g-2 term

Spin re-polarization

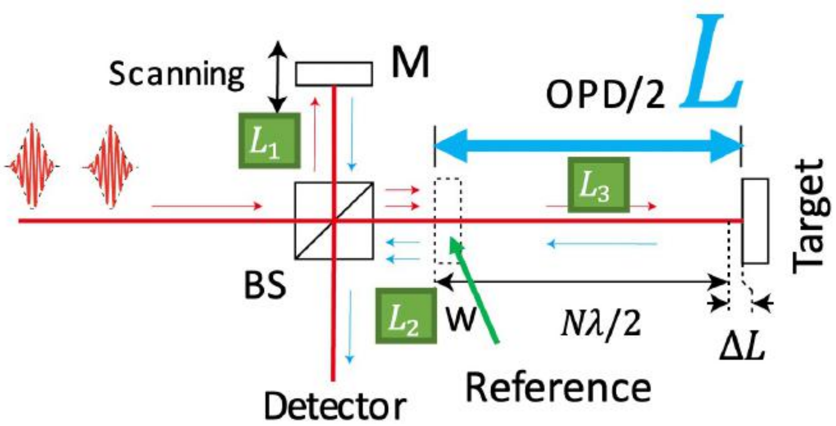
- Optical pumping of μ^+ in muonium is theoretically possible
  - We need intense, circular polarization 122nm pulse train.

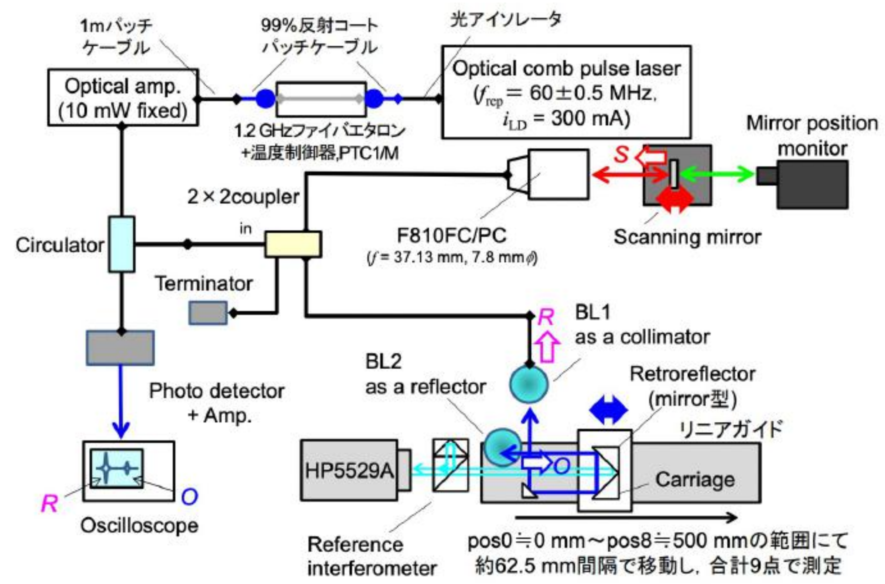




Alignment monitor

- Sensor position monitor which can be used under strong magnetic field.
- Comb + fiber +Interferometer
- Required sensitivity: O(1) μm





Previous muon EDM experiment

Electronics for DAQ

- Development of
  - Timing Control Board
  - Backend board (AMANEQ)
  - FPGA-based Readout Board (FRBS)

✓ Distribution test of clock and signal was succeeded.

✓ Evaluation of timing stability is underway