Muon g-2/EDM experiment at J-PARC

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

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Liverpool, 2024/11/13

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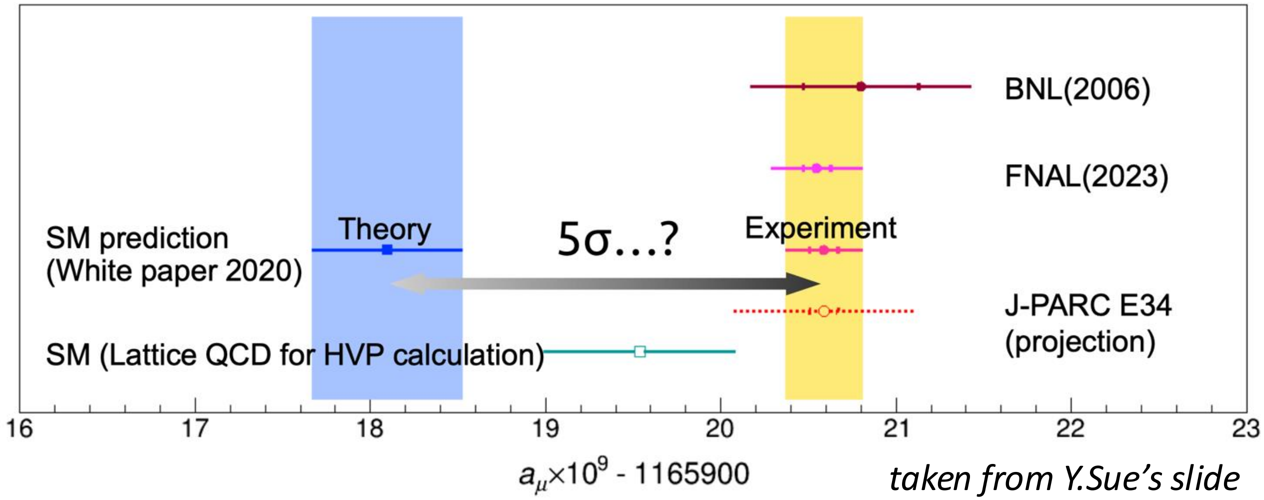
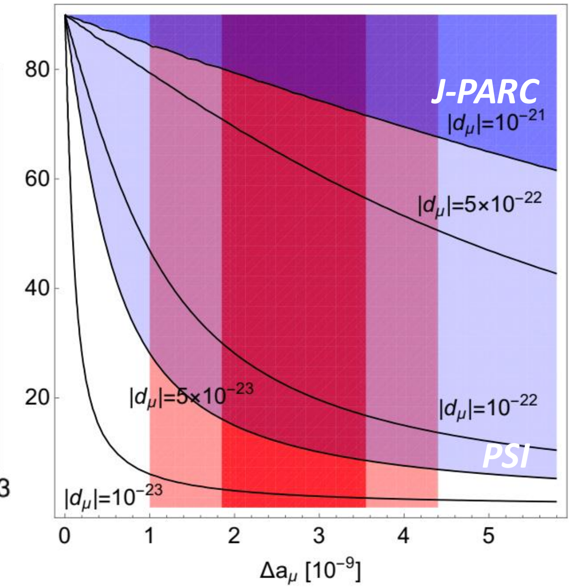
Physics motivation of muon g-2/EDM measurement

1. Muon anomalous magnetic moment (g-2)
   - 5 σ tension b/w measurement(BNL & FNAL) & prediction from SM (WP).
   - This may be contribution from physics beyond the SM.
     - However, lattice QCD calculation on HVP contribution is not consistent with the dispersive approach.
   - From the experimentalist side, independent measurement from FNAL is desirable.
2. Muon electric dipole moment (EDM)
   - EDM and g-2 can be induced by the same new physics.
   - Upper limit given by BNL: $1.8 \times 10^{-19}\ \mathrm{e \cdot cm}$ (95% C.L.)



taken from Y.Sue's slide



How to measure muon g-2/EDM precisely

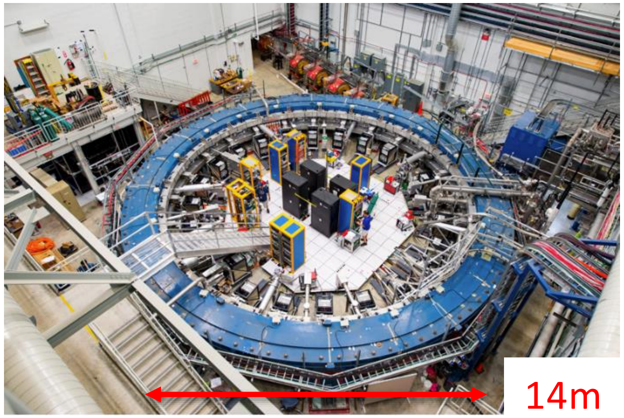
- Muon g-2/EDM can be measured from spin precession of muon in a uniform B-field.
  - time dependent spin information reconstructed from decay positron energy/momentum.

$$\vec{\omega}_a + \vec{\omega}_\eta = -\frac{\mathrm{e}}{m_\mu}\left[\underbrace{a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta}\times\vec{E}}{c}}_{\text{g-2}} + \underbrace{\frac{\eta}{2}\left(\vec{\beta}\times\vec{B} + \frac{\vec{E}}{c}\right)}_{\text{EDM}}\right]$$

BNL/ FNAL experiment

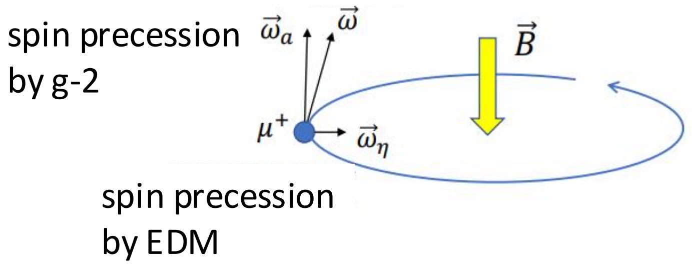
$$\vec{\omega}_a + \vec{\omega}_\eta = -\frac{\mathrm{e}}{m_\mu}\left[a_\mu \vec{B} - \underbrace{\left(a_\mu - \frac{1}{\gamma^2 - 1}\right)}_{=0}\frac{\vec{\beta}\times\vec{E}}{c} + \frac{\eta}{2}\left(\vec{\beta}\times\vec{B} + \frac{\vec{E}}{c}\right)\right]$$

- Magic gamma approach to cancel out 2nd term.
  - p = 3.1 GeV/c
  - muon orbit: ϕ = 14 m at B = 1.45 T.
- Strong focusing by electric field.



How to measure muon g-2/EDM precisely

J-PARC experiment



- Measurement at $\vec{E}$ = 0.
  - Muons will be stored by weak focusing B-field
  - This requires low emittance muon beam & dedicated beam injection scheme.

$$\vec{\omega}_a + \vec{\omega}_\eta = -\frac{\mathrm{e}}{m_\mu}\left[\underbrace{a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\overbrace{\frac{\vec{\beta}\times\vec{E}}{c}}^{=0}}_{\text{g-2}} + \underbrace{\frac{\eta}{2}\left(\vec{\beta}\times\vec{B} + \overbrace{\frac{\vec{E}}{c}}^{=0}\right)}_{\text{EDM}}\right]$$

- Measurement at lower muon momentum becomes possible.
  → **More compact storage region with better uniformity of B-field**.
  - p = 0.3 GeV/c, ϕ = 0.66m at B = 3 T

- This leads to the
  1. **independent measurement of muon g-2**
     to validate BNL/FNAL result at **different systematic uncertainty**.
  2. clear separation of g-2 and EDM signal.

How to measure muon g-2/EDM precisely

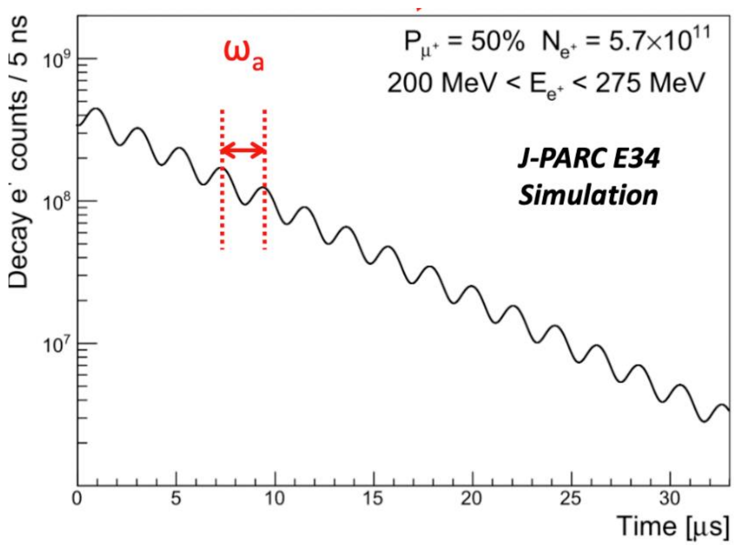
J-PARC experiment

- Measurement at $\vec{E} = 0$.
  - Storage by weak focusing B-field
  - Utilize low emittance muon beam.

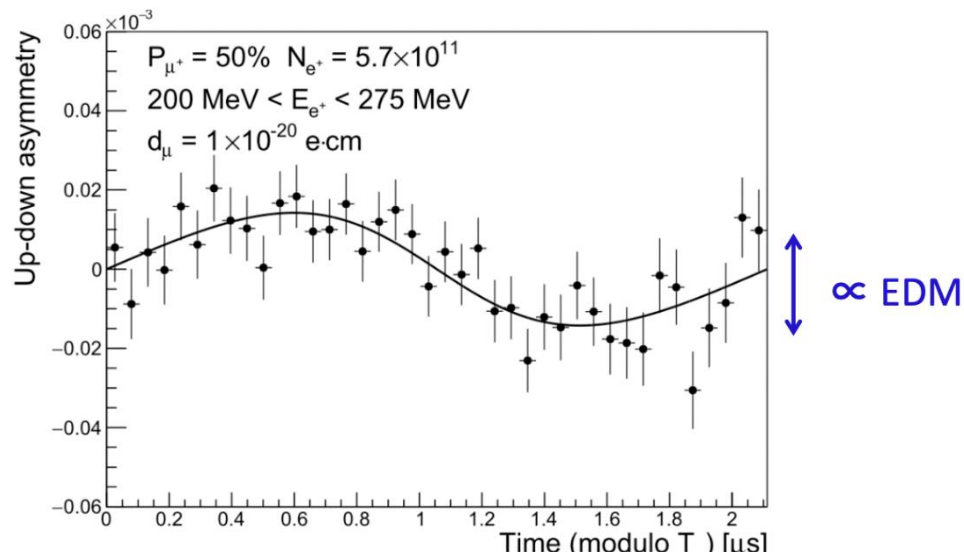
$$\vec{\omega}_a + \vec{\omega}_\eta = -\frac{e}{m_\mu}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\overbrace{\frac{\vec{\beta}\times\vec{E}}{c}}^{=0} + \frac{\eta}{2}\left(\vec{\beta}\times\vec{B} + \overbrace{\frac{\vec{E}}{c}}^{=0}\right)\right]$$

g-2 EDM

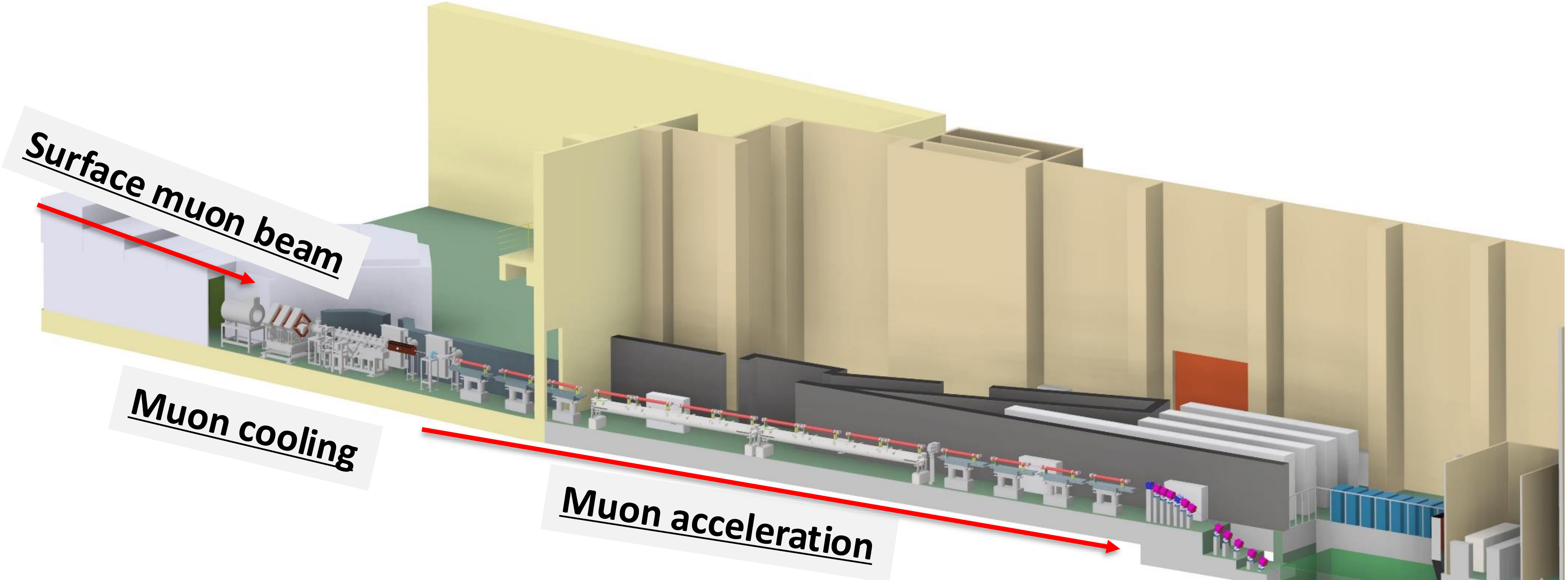
Number of detected positron (p: 200-275 MeV)

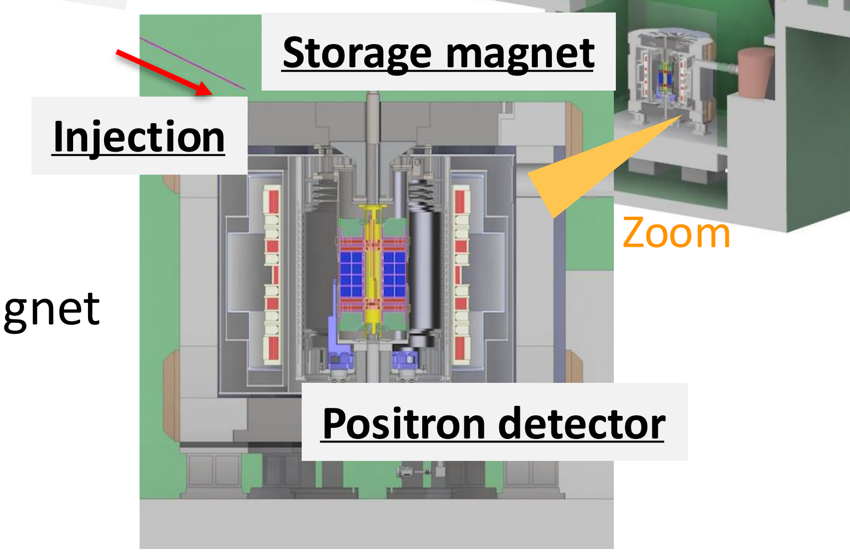


Up-down asymmetry of detected positron



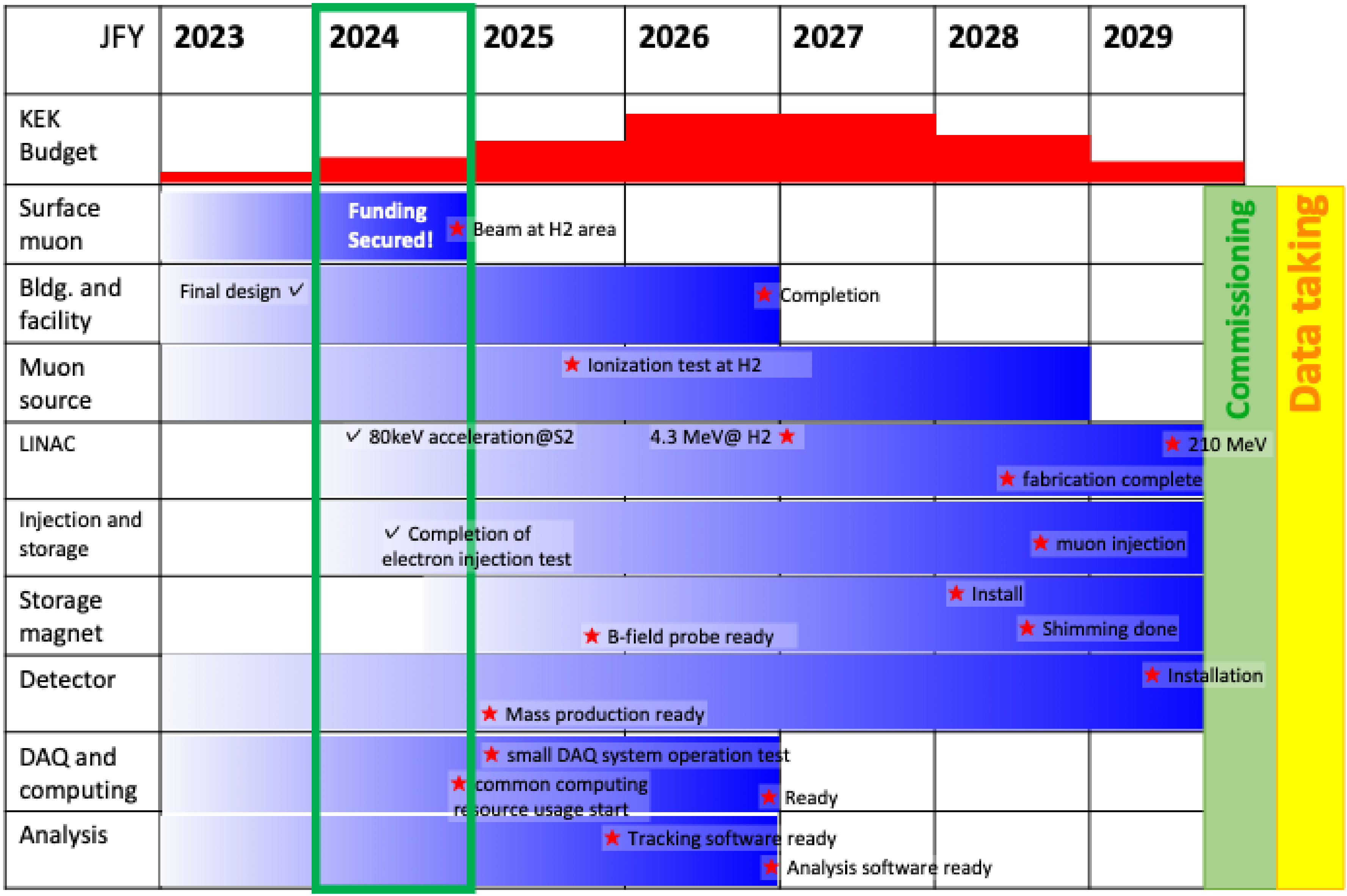
Experimental setup overview





1. High intensity muon beam from MLF
2. Low emittance beam
   by muon cooling & reacceleration.
3. Dedicated beam injection scheme.
4. Quite uniform B-field by MRI-like magnet
5. Compact detector
   with high hit rate tolerances

Schedule


JFY
2023
2024
2025
2026
2027
2028
2029
KEK Budget
Surface muon
Funding Secured!
Beam at H2 area
Bldg. and facility
Final design ✓
Completion
Muon source
Ionization test at H2
LINAC
✓ 80keV acceleration@S2
4.3 MeV@ H2
210 MeV
fabrication complete
Injection and storage
✓ Completion of electron injection test
muon injection
Storage magnet
Install
Shimming done
B-field probe ready
Detector
Installation
Mass production ready
DAQ and computing
small DAQ system operation test
common computing resource usage start
Ready
Analysis
Tracking software ready
Analysis software ready
Commissioning
Data taking

Expected sensitivity

- Total efficiency of muon will be 1.3×10^{-5}.

Subsystem	Efficiency	Subsystem	Efficiency
H-line acceptance and transmission	0.16	DAW decay	0.96
Mu emission	0.0034	DLS transmission	1.00
Laser ionization	0.73	DLS decay	0.99
Metal mesh	0.78	Injection transmission	0.85
Initial acceleration transmission and decay	0.72	Injection decay	0.99
RFQ transmission	0.95	Kicker decay	0.93
RFQ decay	0.81	e^+ energy window	0.12
IH transmission	0.99	Detector acceptance of e^+	1.00
IH decay	0.99	Reconstruction efficiency	0.90
DAW transmission	1.00		

Muon g-2

- Statistical uncertainty: 450 ppb (2 years of data taking)
  - Uncertainty comparable to BNL can be reached
  - Possibility of further improvement under discussion
- Systematic uncertainty: less than 70 ppb.

Anomalous spin precession (ω_a)		Magnetic field (ω_p)	
Source	Estimation (ppb)	Source	Estimation (ppb)
Timing shift	< 36	Absolute calibration	25
Pitch effect	13	Calibration of mapping probe	20
Electric field	10	Position of mapping probe	45
Delayed positrons	0.8	Field decay	< 10
Diffential decay	1.5	Eddy current from kicker	0.1
Quadratic sum	< 40	Quadratic sum	56

Muon EDM

- Statistical uncertainty: $1.5 \times 10^{-21}\ \mathrm{e \cdot cm}$
  - 2 orders of magnitude improvement from upper limit.
- Systematic uncertainty: $0.4 \times 10^{-21}\ \mathrm{e \cdot cm}$
  - mainly from detector mis-alignment

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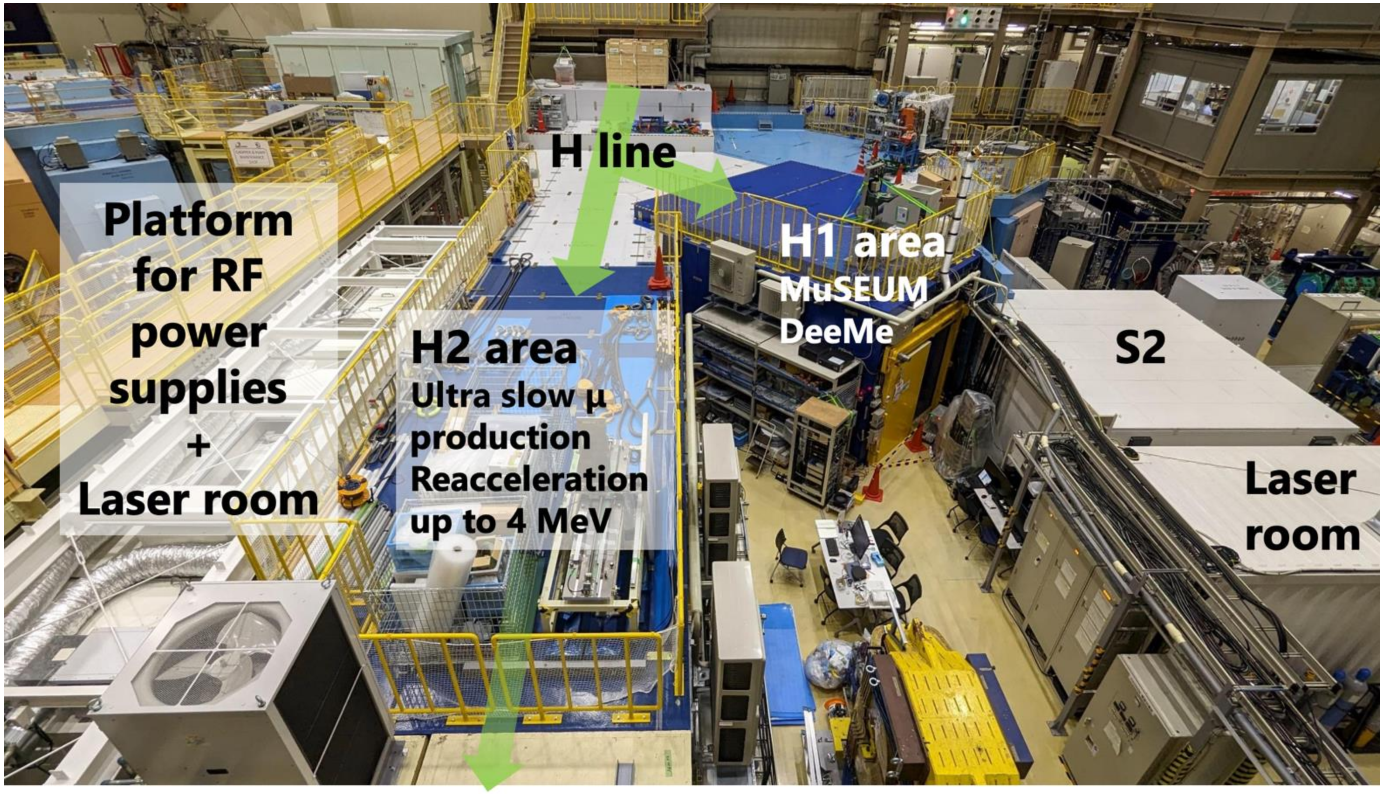
Surface μ⁺ beam at MLF

- MLF H2 beam line.
  - Surface μ^+ beam: 4MeV with 25Hz rep.
  - Beam rate : 1.2×10^8 muons/s is expected at the Mu production target.
  - H2 area was constructed inside the existing MLF bldg.
- A new extension building and beam line: waiting for the budget approval.

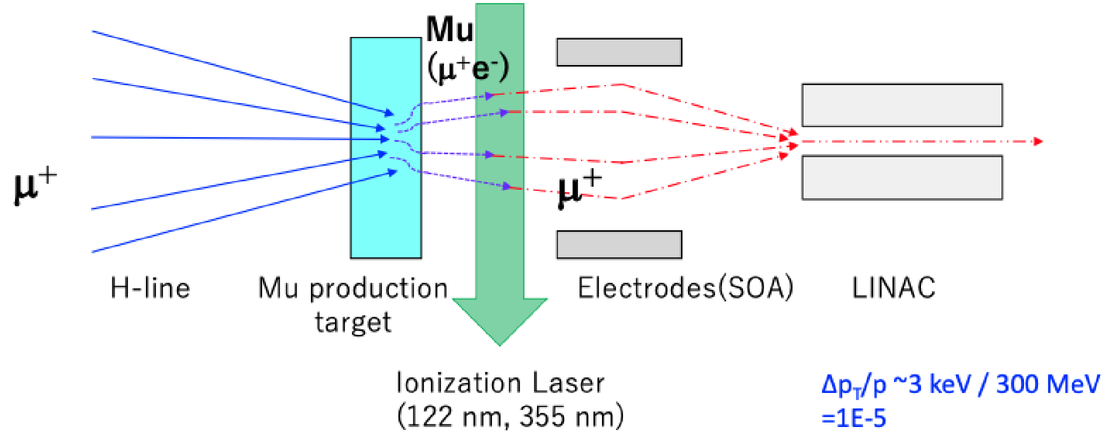


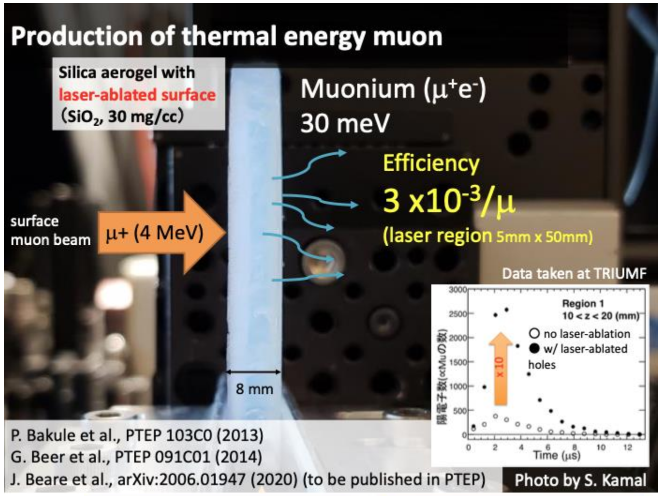
Future extension to accelerate up to 212 MeV
For muon g-2/EDM and transmission muon microscope

Muon cooling

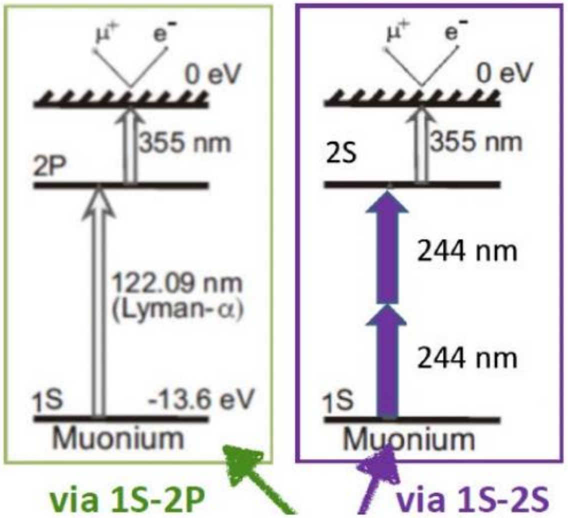
- **Low emittance muon beam will be realized by reacceleration of thermal muon.**
  - Silica aerogel target : Surface muons stopped, and thermal muoniums emitted.
  - Laser ablated aerogel to increase the efficiency.

	surface muon	thermal muon	accelerated muon
E	3.4 MeV	30 meV	212 MeV
p	27 MeV/c	2.3 keV/c	300 MeV/c
$\Delta p/p$	0.05	0.4	4×10^{-4}



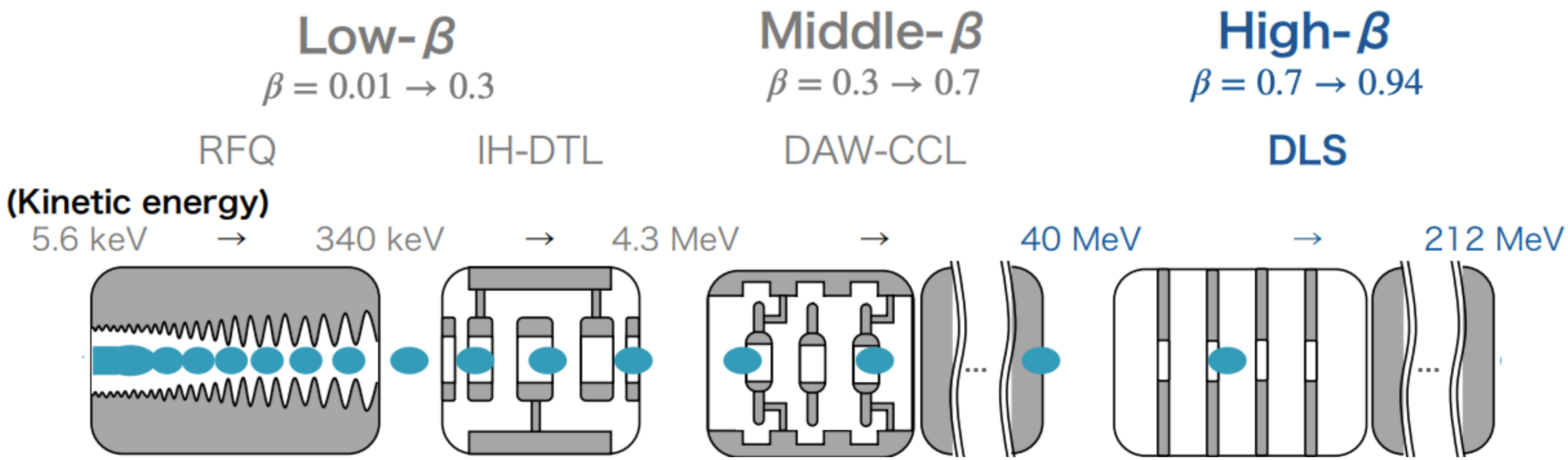


- Thermal muonium ionization by laser.
  - Two scheme under consideration.
  - 1S-2P excitation by 122nm
    or 1S-2S excitation by 244nm



Muon acceleration

- Muon reacceleration to 300MeV/c by muon LINAC.
  - Series of 4 types of cavities depending on the muon β of each stage.

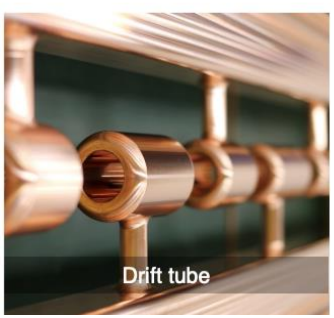


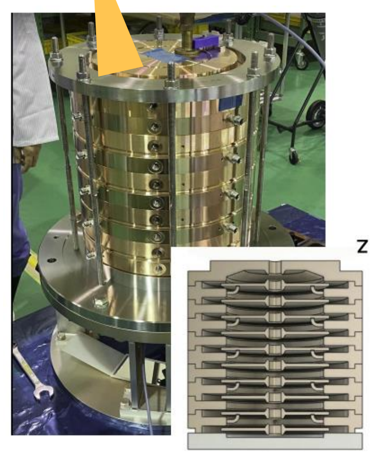
Acceleration test with thermal μ planned.

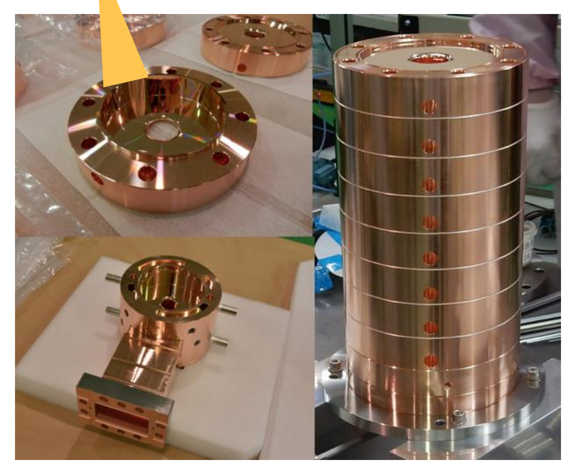
Fabrication completed. High power test on going

Prototype fabricated and tested

Prototype fabricated and tested

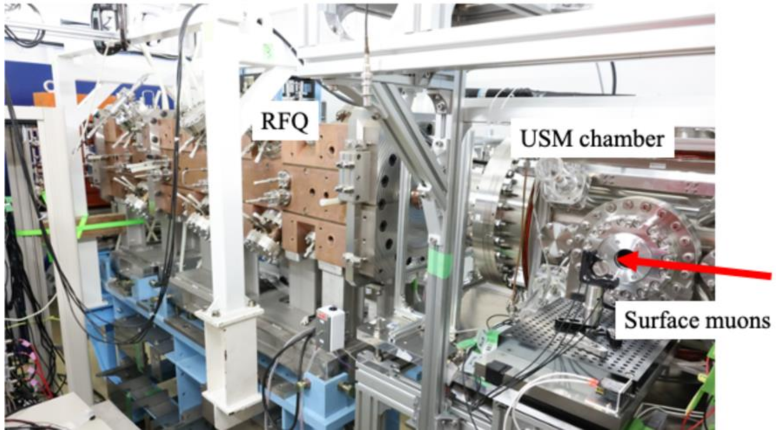


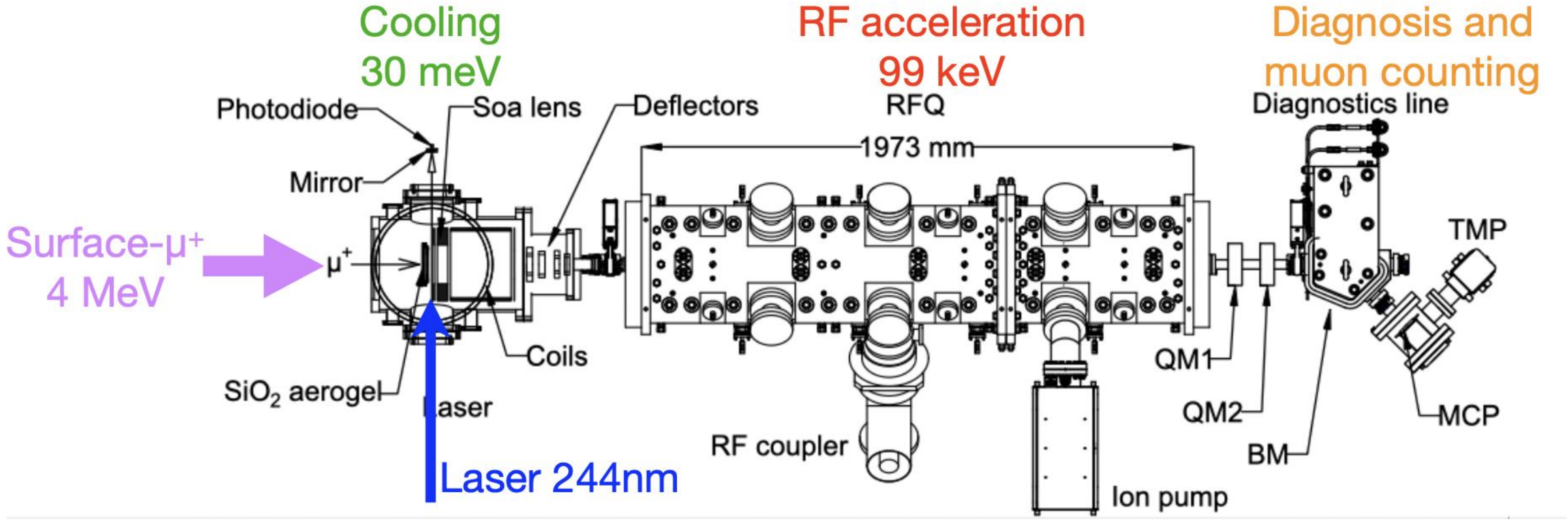




Muon acceleration test

- Ultraslow muon production and acceleration was tested in 2024 spring.
  - held at MLF S2 line
  - 244 nm Ionization laser to utilize 1S-2S (not 1S-2P) transition
  - This test includes Mu ionization, SOA chamber, and acceleration up to 90keV.

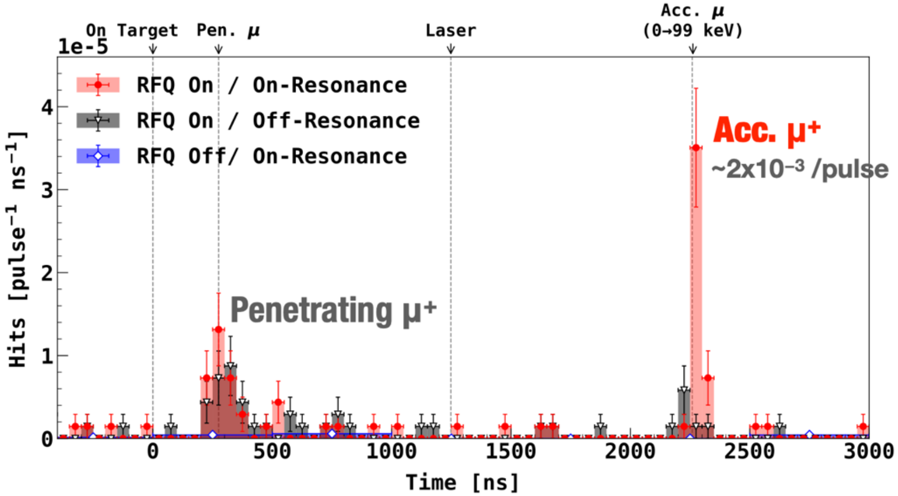




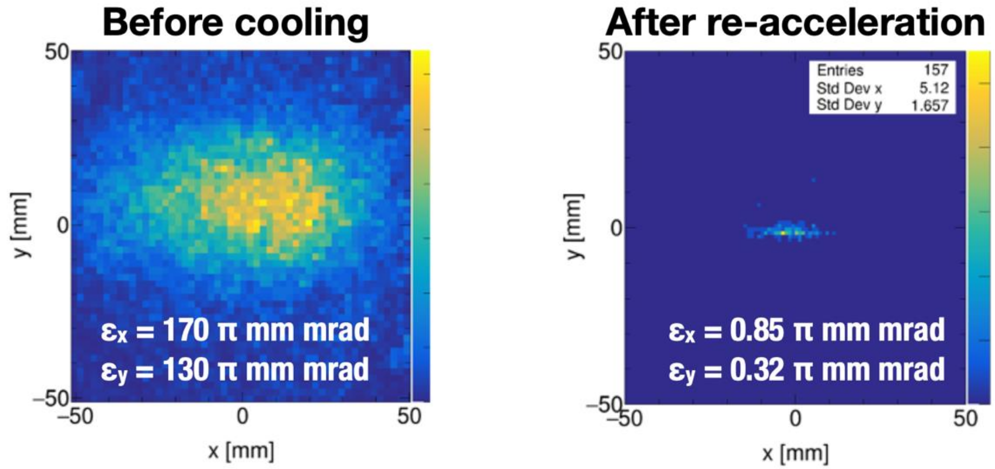
Demonstration of muon reacceleration

- Muon re-acceleration is demonstrated.

Time between and laser irradiation hits in MCP



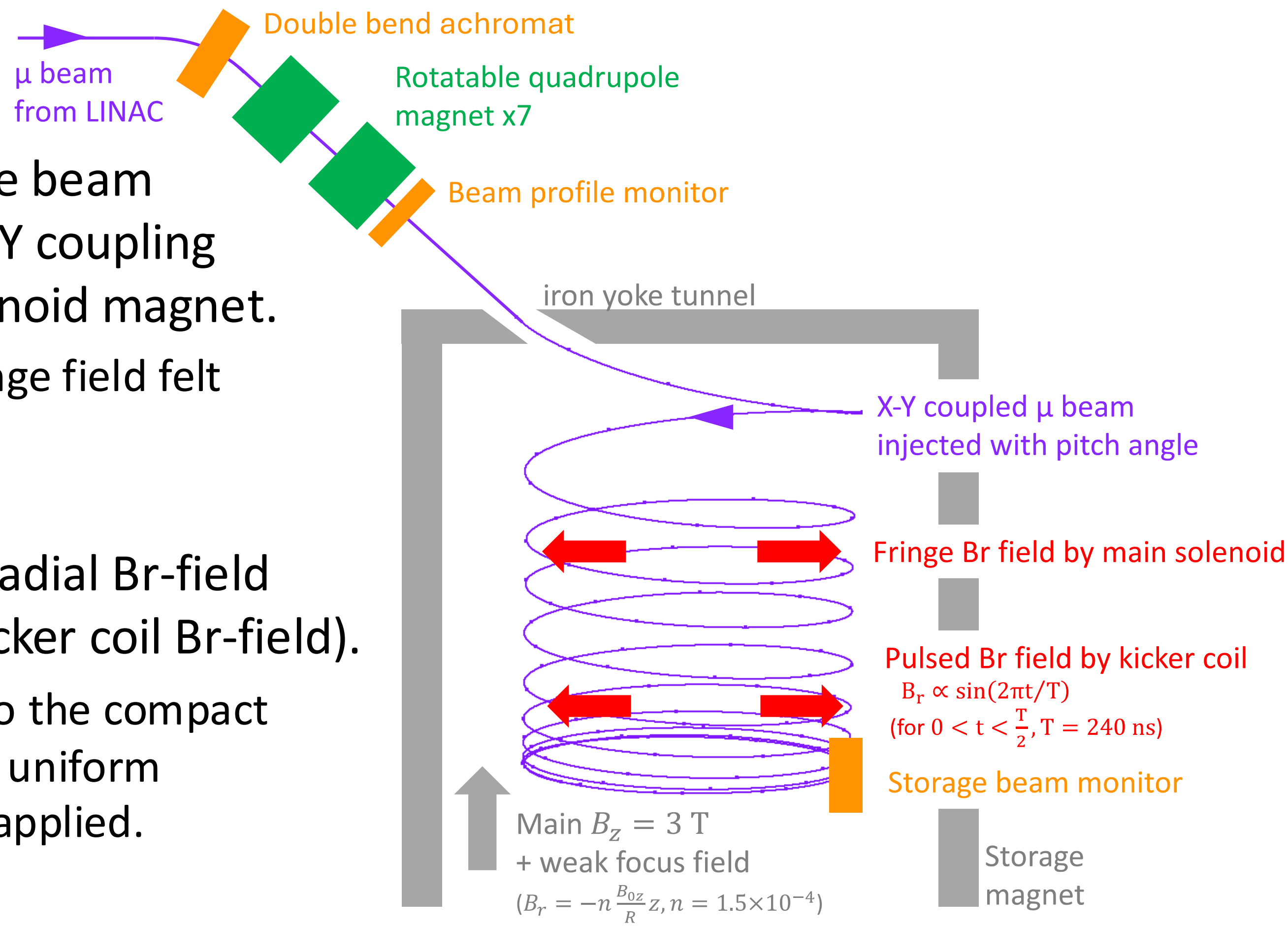
- Reduction of emittance by muon cooling is demonstrated.



Reduction of O(10^{-3}) from the surface muon beam

Three-dimensional spiral beam injection

- Low emittance muon beam (300MeV, 0.3π mm-mrad) will be injected into compact storage orbit (Bz=3.0T, R=33.3cm), and stored without electric focusing with good injection efficiency.



<u>Key points</u>

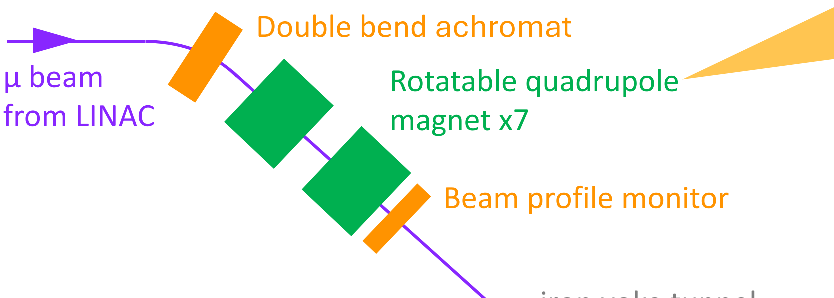
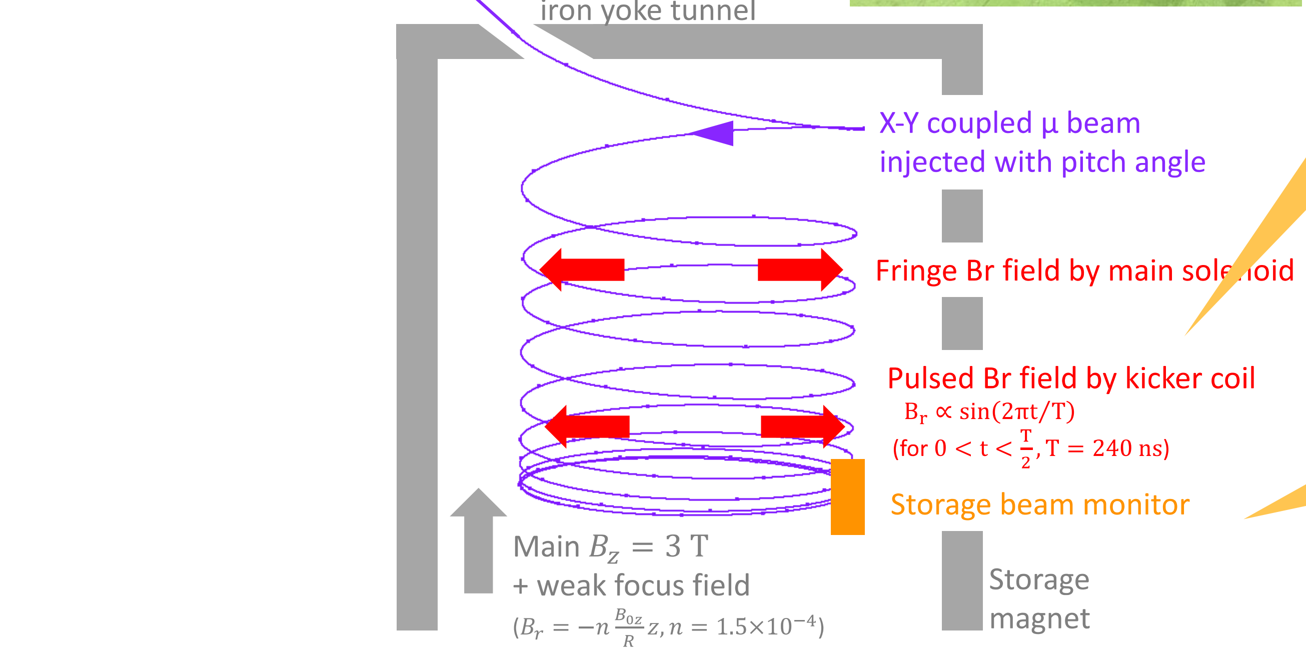
1. Inject low emittance beam with appropriate X-Y coupling is injected into solenoid magnet.
   - to compensate fringe field felt by each muon

2. Apply appropriate radial Br-field (Fringe Br-field + kicker coil Br-field).
   - to guide muons to the compact region where the uniform magnetic field is applied.

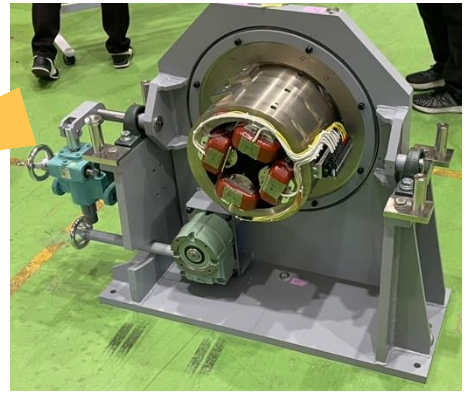
3. Store muon beam by weak focusing.

Three-dimensional spiral beam injection

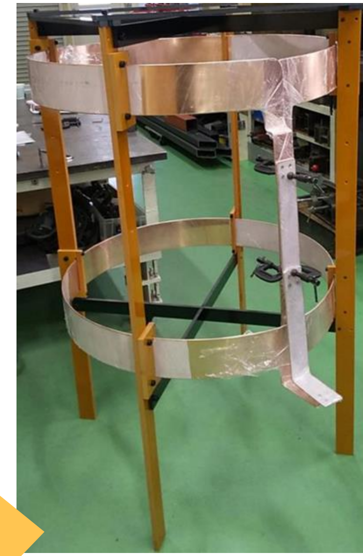
- Design and prototyping of each devices is ongoing.

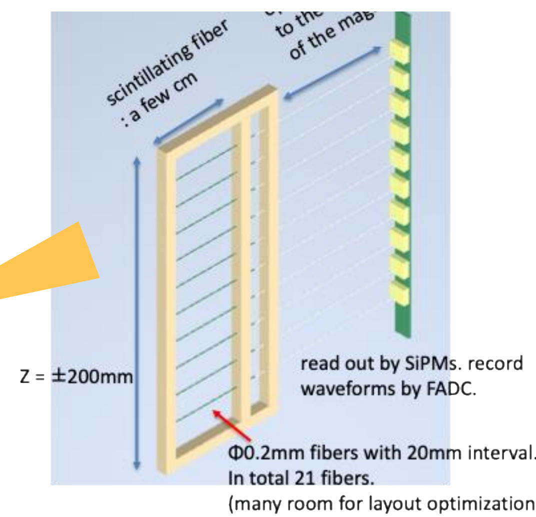
Rotatable QM prototype



Kicker coil prototype

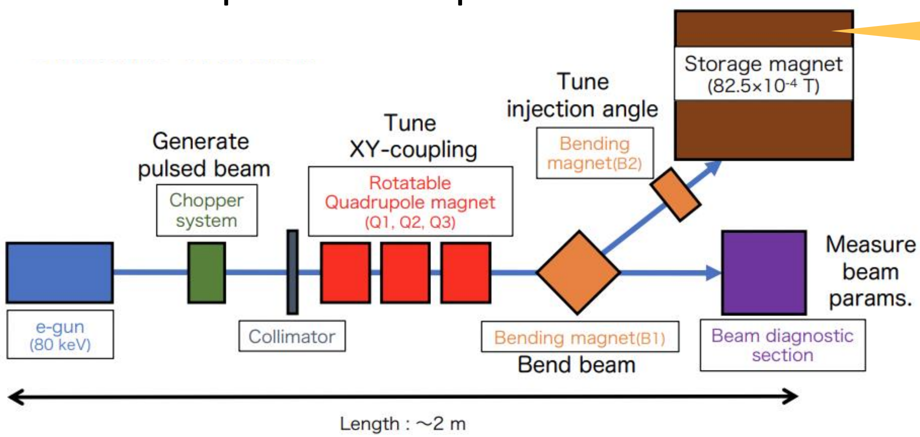


Storage beam monitor

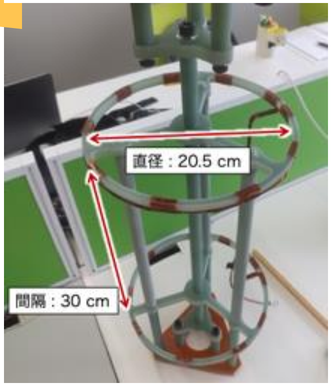


Demonstration of beam injection scheme

- Demonstration of beam injection scheme has been performed.
  - It uses electron beam, but on the same concept as real experiment.

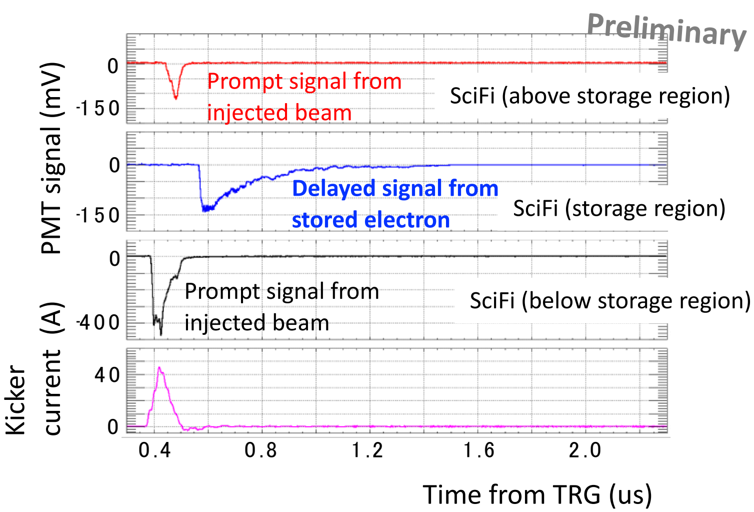


Kicker coil inside solenoid magnet

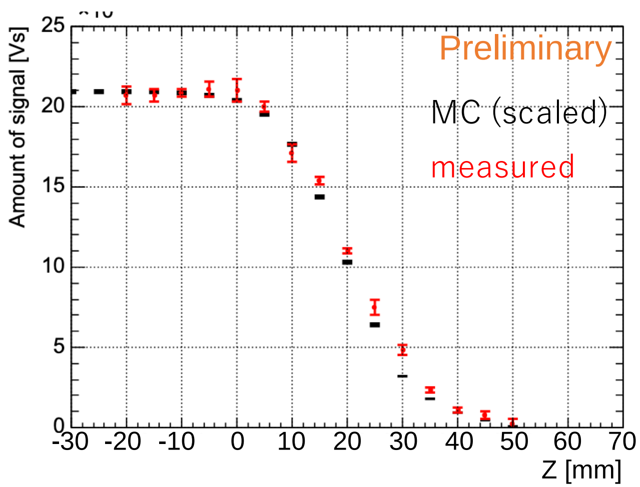


- Signal from stored electron beam is successfully observed.

Timing spectrum from beam monitors



Vertical distribution of stored beam (cumulative)

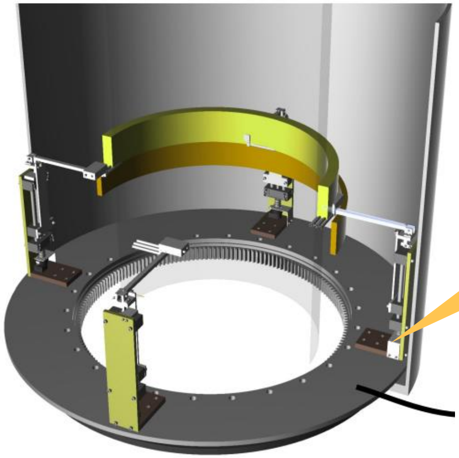


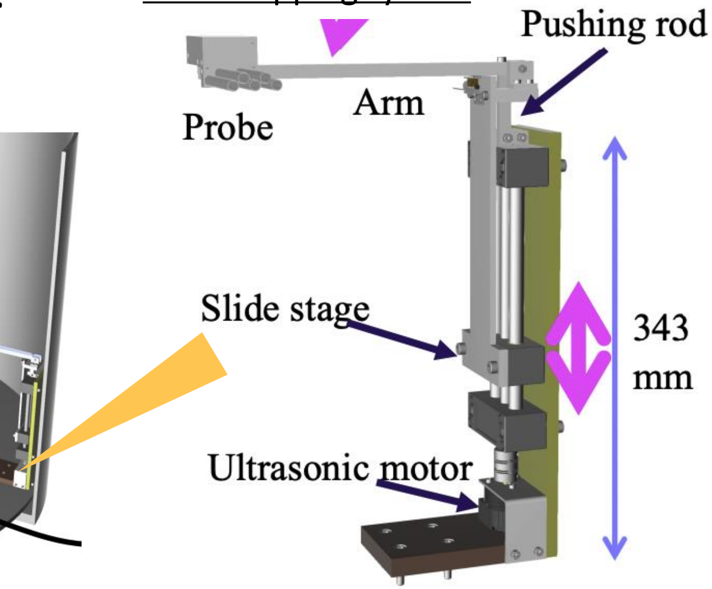
Storage magnet

- Highly uniform (0.1ppm) magnetic field will be achieved by shimming.
  - Compact solenoid magnet based on MRI magnet technology.
  - B-field measurement by a high precision NMR probe
- Local uniformity of 1ppm is already demonstrated by the MuSEUM experiment magnet.
- Field mapping system under design.
  - B-field meas. in the muon storage region.
  - Theta motion + z motion.

Superconducting magnet for MuSEUM experiment.

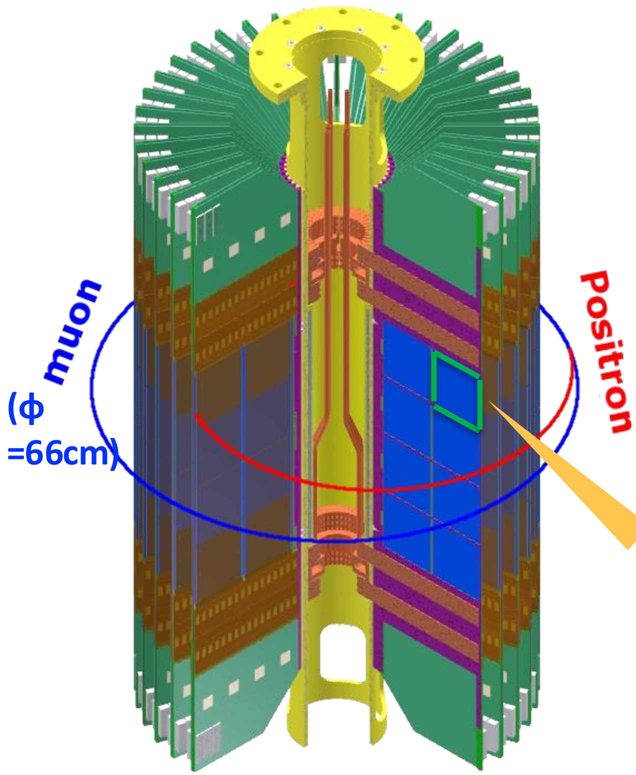
Field mapping system



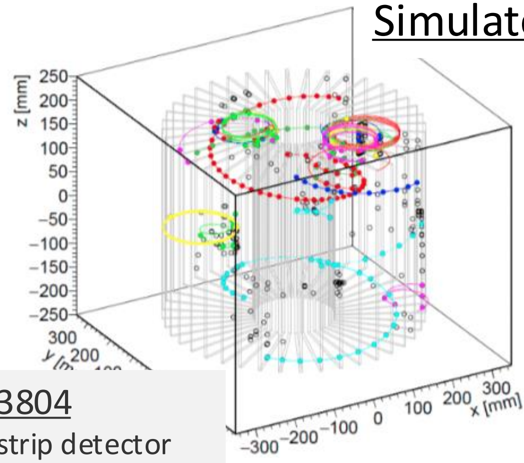


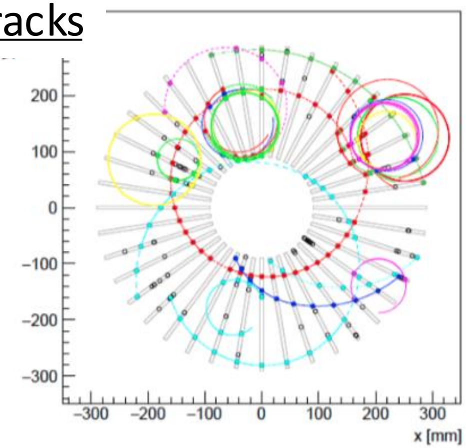
Positron tracker

- Silicon detector for momentum measurement of decay positrons.
  - High hit rate capability (6 tracks/ns) and stability over rate changes (1.4 MHz ❼10 kHz)
  - Silicon strip sensor: Hamamatsu S13804, 190um pitch.
  - High efficiency for positron in the analysis window (p=200-270 MeV/c).



Simulated tracks

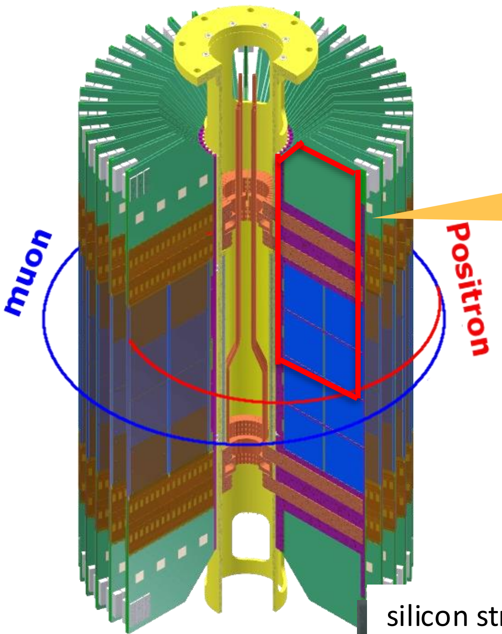




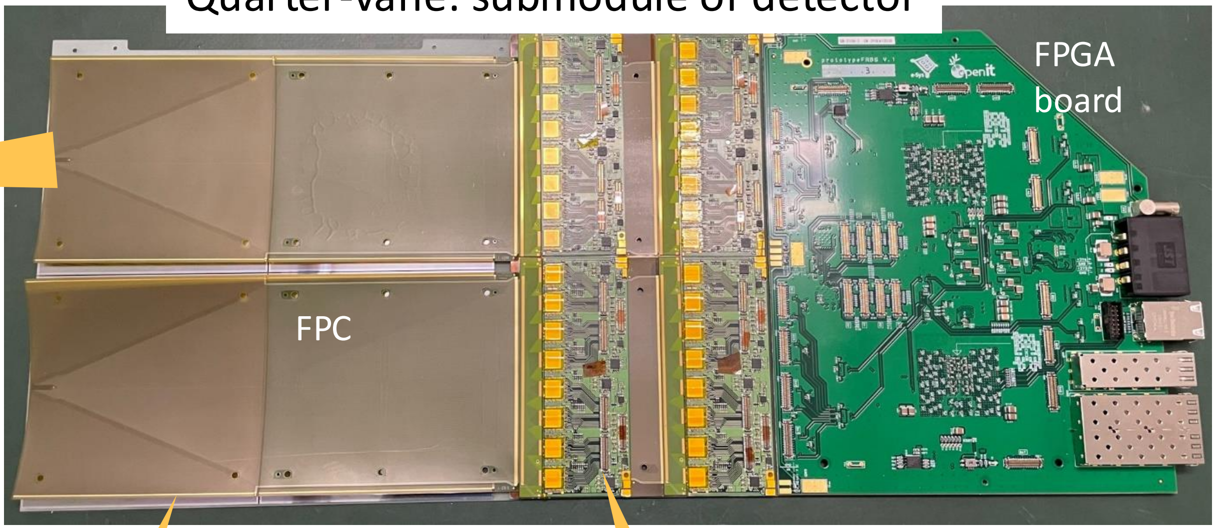
HPK S13804
- silicon strip detector
- size: 100 x 100mm^2, 190um strip

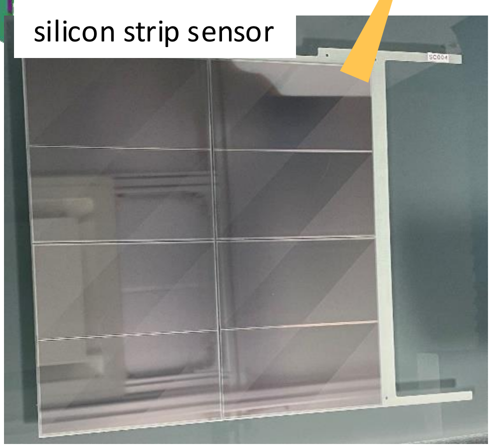
Positron tracker

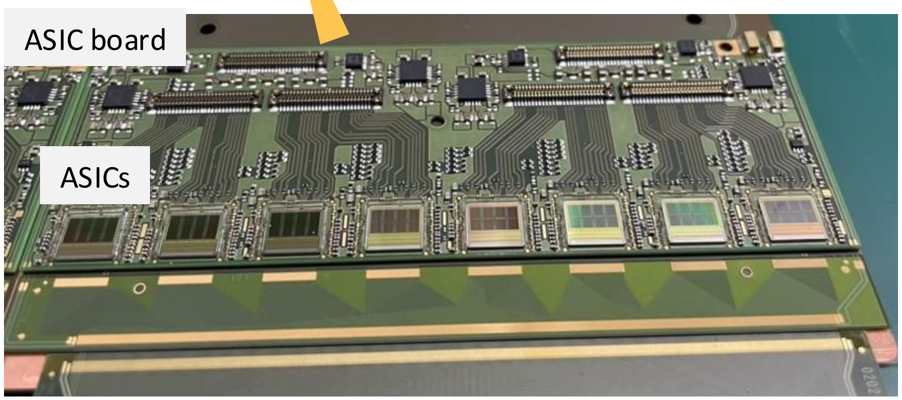
- Major components are in or completed the mass-productions.
- Assembly procedure is under R&D.
- A quarter-vane prototype is under its operation test.



Quarter-vane: submodule of detector

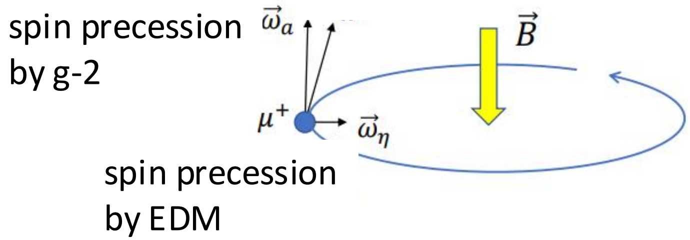






Sensor alignment for EDM measurement

- Precise alignment between detector and B-field is essential for muon EDM measurement.
  - If rotated each other, "g-2 component" of spin precession comes into "EDM component".



$$\vec{\omega}_a + \vec{\omega}_\eta = -\frac{e}{m}\left[\underbrace{\frac{g-2}{2}\vec{B}}_{\text{g-2}} + \underbrace{\frac{\eta}{2}\vec{\beta}\times\vec{B}}_{\text{EDM}}\right]$$

- Goal of sensor alignment is 10 μrad (~ 1um) precision.
  -> Sensor position/rotation/deformation should be monitored during DAQ.
  - This will be achieved by a combination of several methods.

<u>Track-based alignment</u>

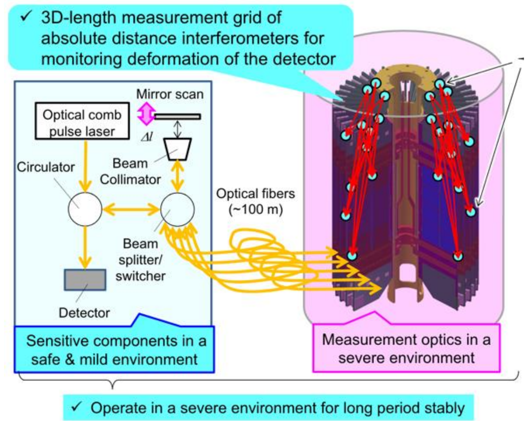
- Sensor position reconstructed by minimization of positron track fitting in physic data.

Minimize χ^2 in the positron track fitting.

$$\chi^2 = \sum_{track}\sum_{point}\frac{(x_{meas} - x_{fit})^2}{\sigma^2}$$

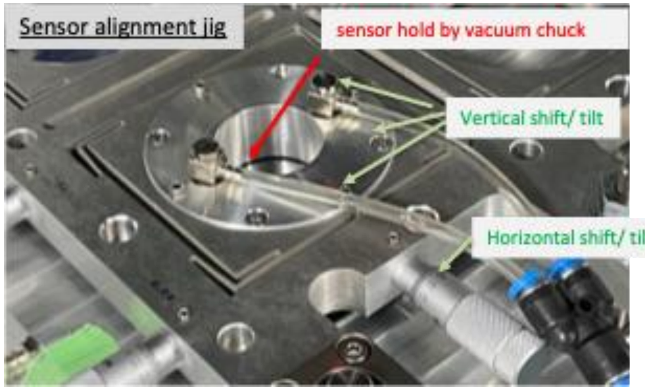
<u>Laser-based alignment monitor</u>

- Interferometer with optical comb laser.
- Monitor distance between fixed points.



<u>Precise detector assembly</u>

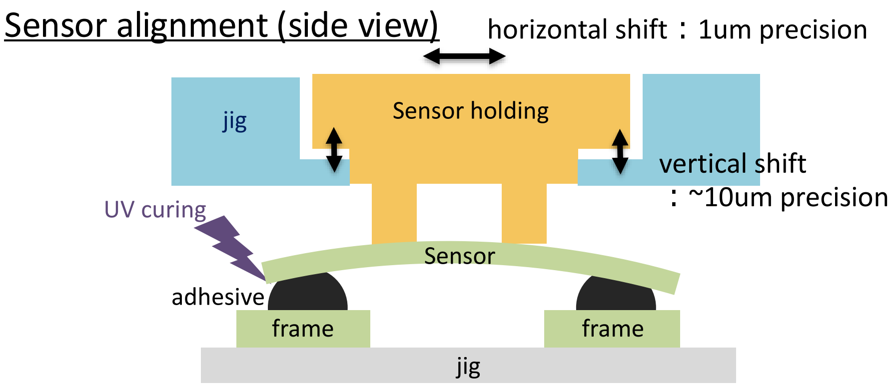
- Sensor position measurement by CMM & laser tracker.
- Position alignment by dedicated jig.

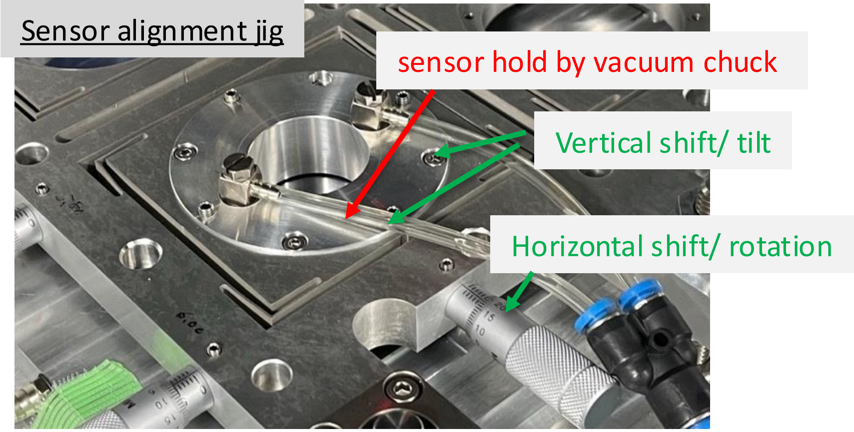


Sensor alignment for EDM measurement

- Silicon sensors are glued on GFRP frame. Gluing procedure with an alignment of O(1) um precision is under development.

- CMM (3D coordinate measuring machine) in temperature control room
  - sensor position & shape measurement by 1um precision
  - temperature is kept to 20 ± 1 deg. , to avoid thermal expansion.
- Sensor positioning by a dedicated jig.
  - Horizontal shift (1um step) & Vertical shift (~10 um step)
  - Gluing by a UV curing adhesive.





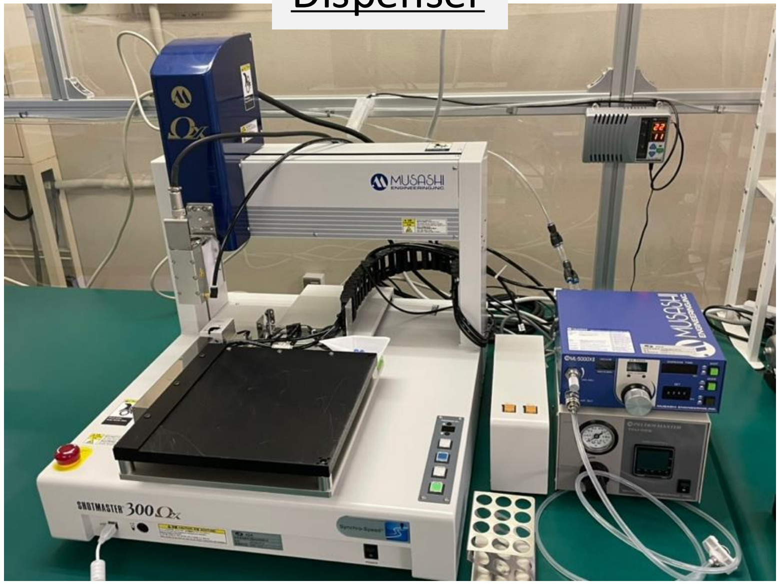
Positron tracker assembly

- We plan to assemble positron tracker in Japan from 2026.
  - at Kyushu Univ, KEK, (likely) J-PARC.

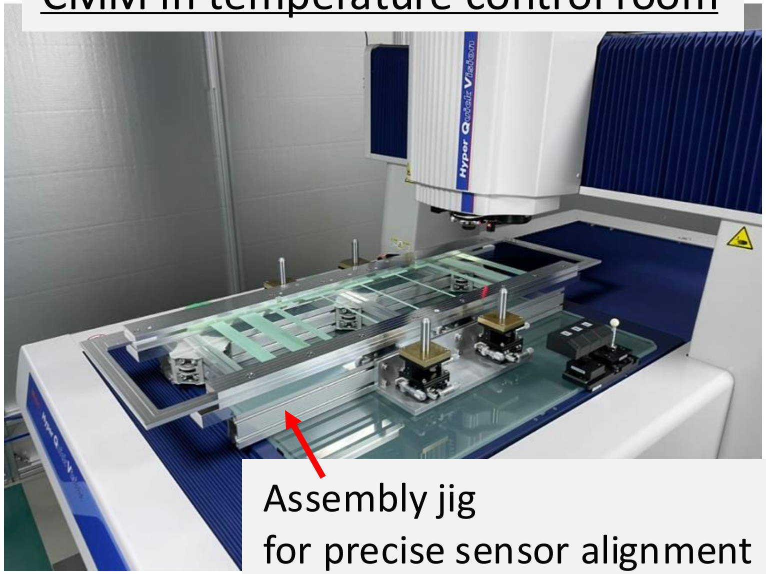
- We are preparing a lab for this.
  - Assembly of silicon tracker still seems rather complicated, and we are welcome for collaborations.

Wire bonder

Dispenser



CMM in temperature control room



Assembly jig
for precise sensor alignment

Table of contents

Very preliminary

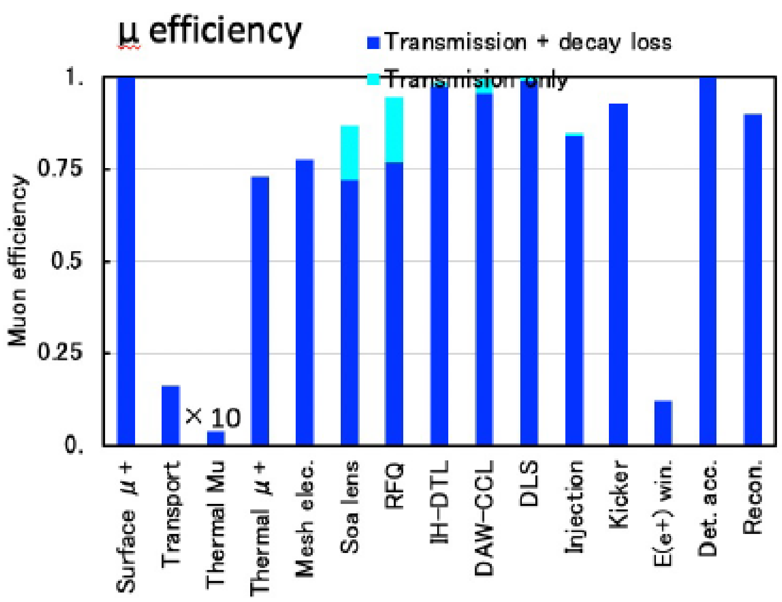
- Statistical uncertainty is comparable to BNL (450ppb).
  Can we improve it to FNAL level (100ppb) ?

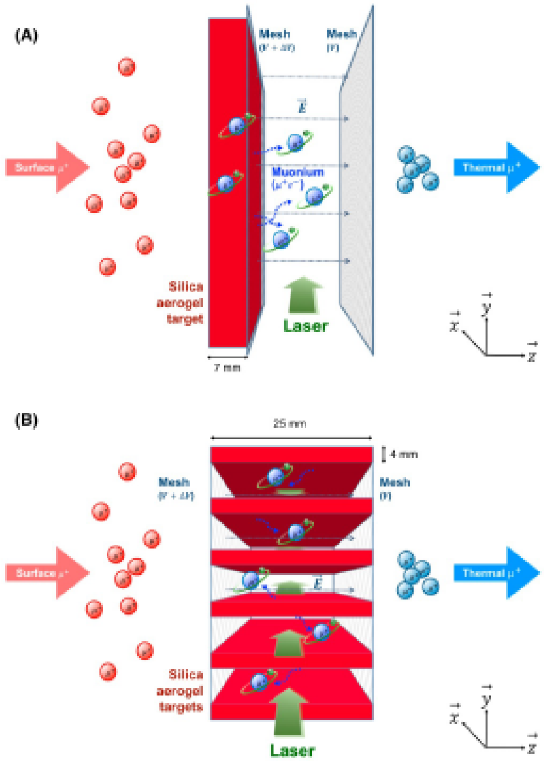
Possible idea for improvement No.1

Very preliminary

- 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



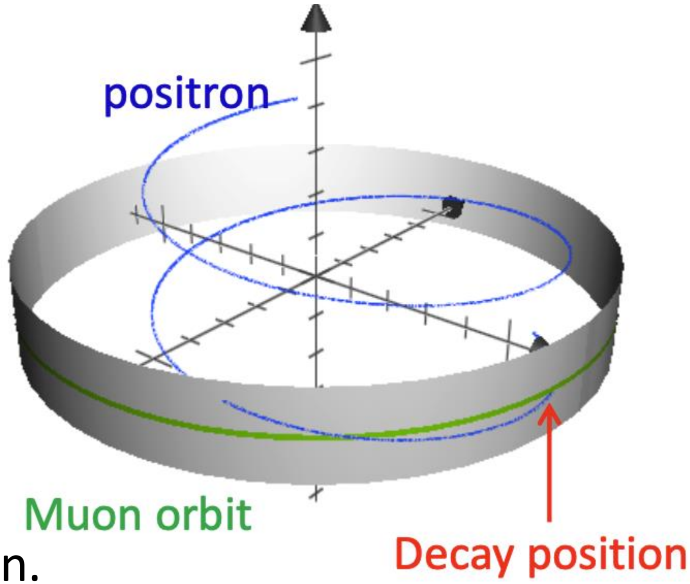


Possible idea for improvement No.2

Very preliminary

- Since we are using tracker instead of calorimeter for positron detection, reconstruction of positron emission angle at muon rest frame may be possible.
- This enables us to include low momentum positrons for g-2/EDM analysis.
  - Factor ~2 improvement is expected for g-2/EDM statistical uncertainty.

- To realize this, we need
  1. Detection of low momentum positrons.
     - Increase number of silicon sensors
  2. Better performance of positron track-back.
     - Reduced and/or well understanding of detector material budget.
  3. Further precise muon beam injection
     - to uniquely identify muon decay vertex from positron track and stored muon orbit.



- This seems to be an interesting possibility, but there is still a long way to go for its realization.

Possible idea for improvement No.3

- Increasing muon momentum, storage magnetic field will reduce statistical uncertainty.
  - $\frac{\delta\omega_a}{\omega_a} = \frac{1}{\omega_a \gamma \tau_0}\sqrt{\frac{2}{NA^2}}$, $\omega_a = a\frac{qB}{m}$
  - If we modify our design as 300MeV->600MeV, 3T -> 6T,
    then statistical uncertainty will be ~100 ppm.

- This option could be realized, but it needs R&D to judge it.
  - Acceleration to 600MeV
    : Can be possible, but R&D needed to keep it inside the original building design.
  - B field to 6T
    : Can be possible, but iron return yoke may become too heavy.
  - Beam injection
    : Injection becomes easier by reduced geometrical beam emittance, but it becomes more difficult by larger fringe field, and relatively less pulsed field.
    It is hard to judge which affects a lot.

Summary

- Muon g-2/EDM experiment at J-PARC aims to perform an an independent measurement of muon g-2/EDM.
  This will be realized by utilizing low emittance muon beam stored in a compact region with a uniform B-field only by weak focusing magnetic field.

- We aim to start commissioning from JFY 2029.
  After 2 years of data taking,
  - muon g-2 measurement at 450ppb (stat.) and 70ppb (syst.)
    : statistics comparable to BNL, completely different source of systematics
  - muon EDM sensitivity at $1.5 \times 10^{-21}\ \mathrm{e} \cdot \mathrm{cm}$ (stat.)
    : 2 orders of magnitude improvement.

- All the key technology of this experiment (surface muon, muon cooling, reacceleration, injection, uniform B-field, positron tracker) are getting ready for realization.

- Possible ways to improve statistical uncertainty is also under consideration.

BACKUP

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

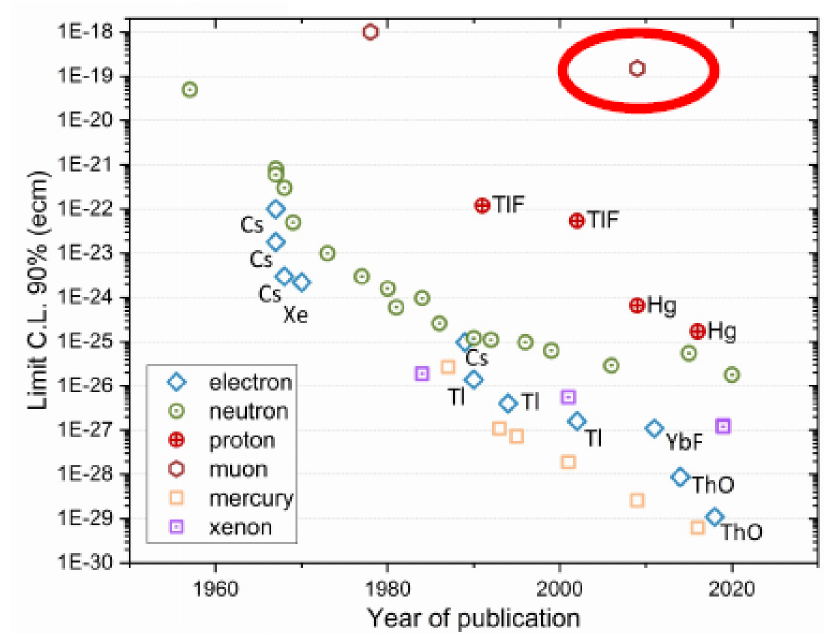
Experimental limit: (BNL)

- **$|d| < 1.8 \times 10^{-19}$ 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)

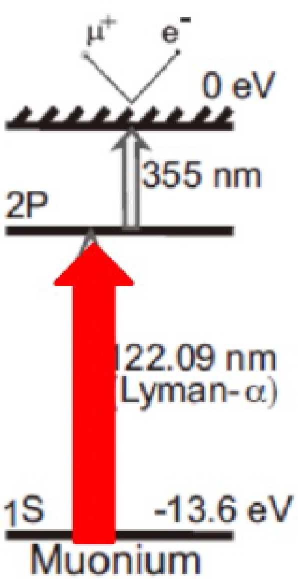


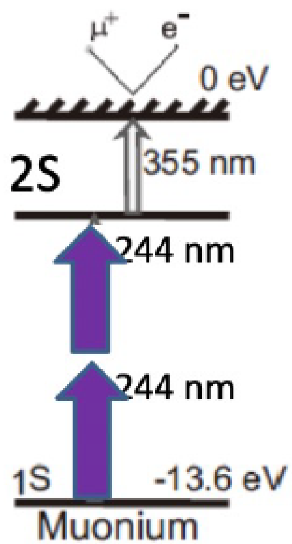
Extension building

- A new extension building will be constructed.
  - Construction of extension bldg. is also ready, and waiting for the budget approval.

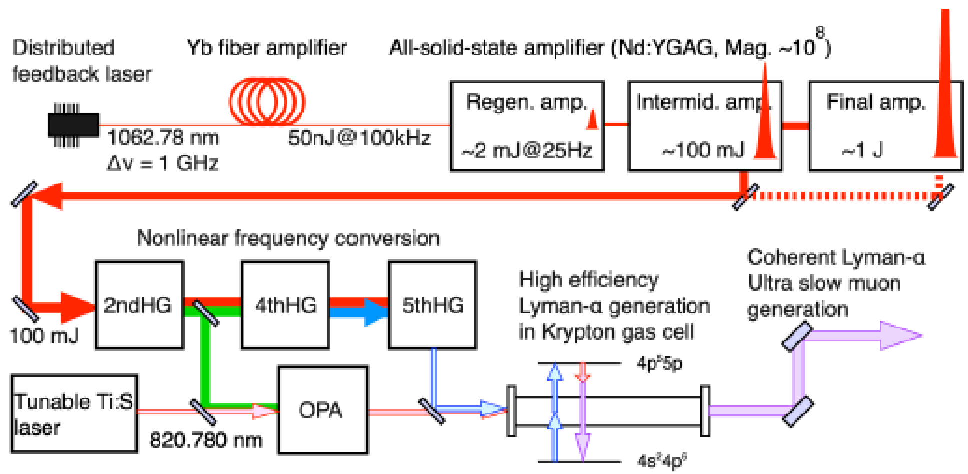
2. Laser ionization of muonium

- 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



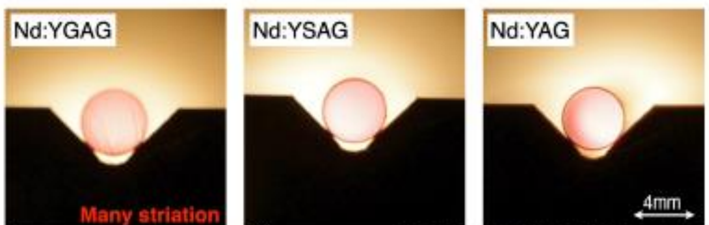
R&D for higher pulse energy

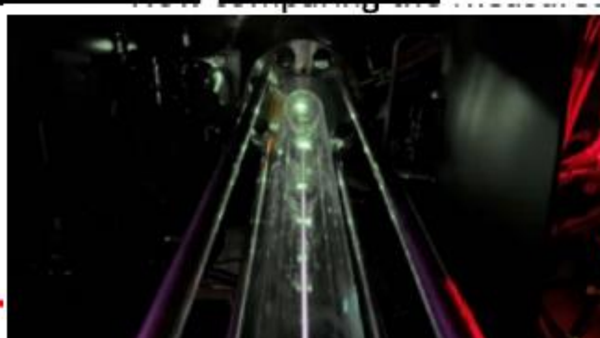
- Required pulse energy for high ionization efficiency
  - 100μJ @122nm for 1S→2P→unbound scheme
  - 60mJ @244 nm for 1S→2S→unbound scheme

More than 10 times improvement is required

Development of 122nm laser

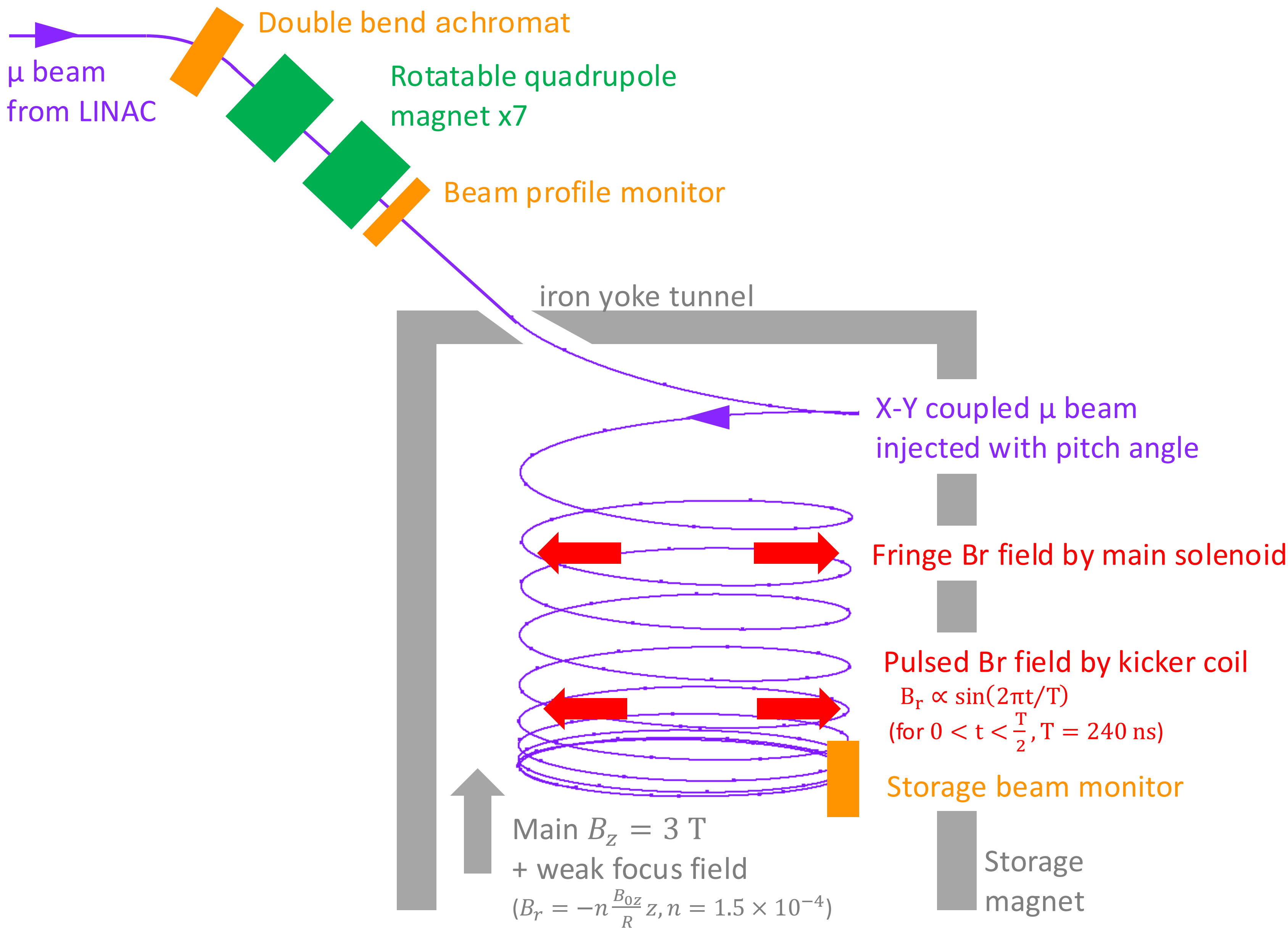
- Study of recently developed crystals. (quality vs size)
- Better FWM efficiency





Development of 244nm laser

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

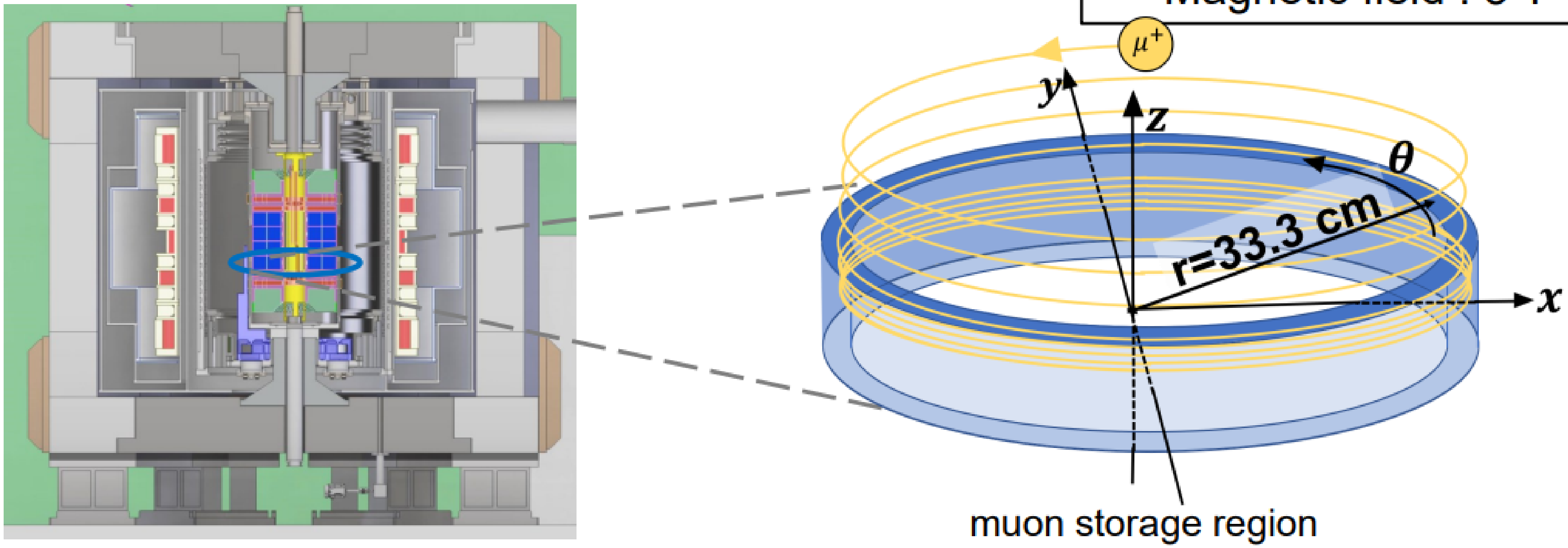


Double bend achromat
μ beam
from LINAC
Rotatable quadrupole
magnet x7
Beam profile monitor
iron yoke tunnel
X-Y coupled μ beam
injected with pitch angle
Fringe Br field by main solenoid
Pulsed Br field by kicker coil
$B_r \propto \sin(2\pi t/T)$
(for $0 < t < \frac{T}{2}$, $T = 240$ ns)
Storage beam monitor
Main $B_z = 3$ T
+ weak focus field
$(B_r = -n\frac{B_{0z}}{R}z, n = 1.5 \times 10^{-4})$
Storage
magnet

Muon storage region at J-PARC

Requirement:
Uniformity (azimuthal average) : 0.2 $\mathrm{ppm}_{p\text{-}p}$
peak-to-peak↑

Specification
- Region size:
  - Radius: 33.3±1.5 cm
  - Height: 0±5 cm
- Magnetic field : 3 T

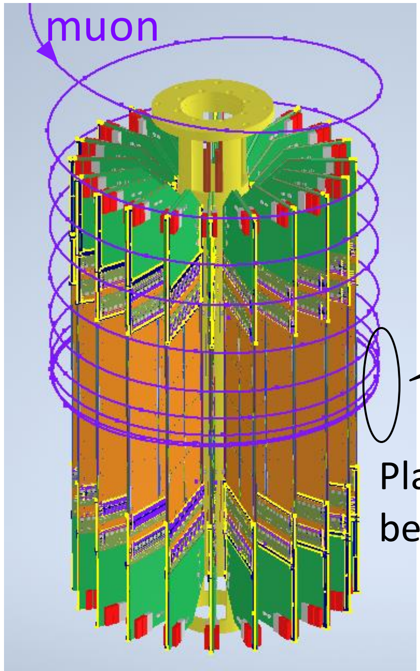


muon storage magnet

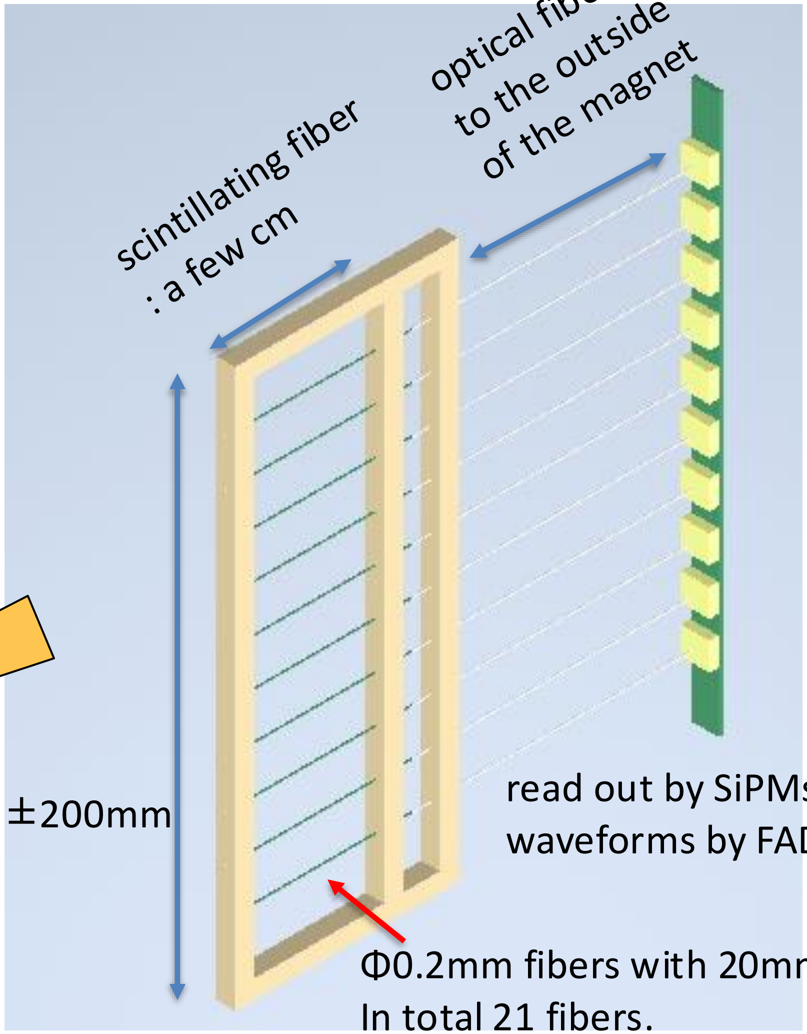
muon storage region

Storage beam monitor

- Beam profile monitor installed on storage orbit.
- Beam profile monitor made by thin scintillating fibers (ϕ=0.2mm) read out by SiPMs.
- **Low mass detector with low occupancy (1%).**
  - to prevent multiple scattering
- Prototype is being tested in injection test bench.



Placed on beam storage orbit

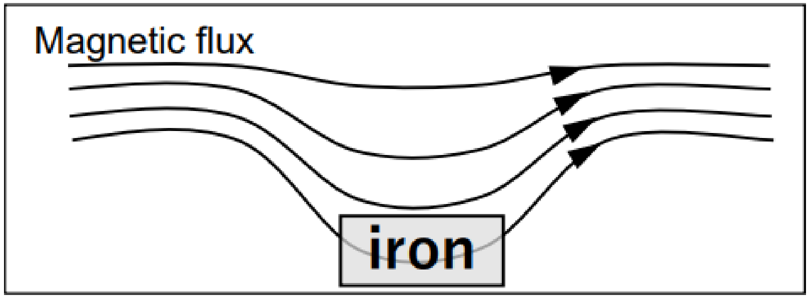


Passive shimming

Passive : put iron shim pockets

Principle:
put iron piece
→ passively magnetize to saturation
→ compensate B_z

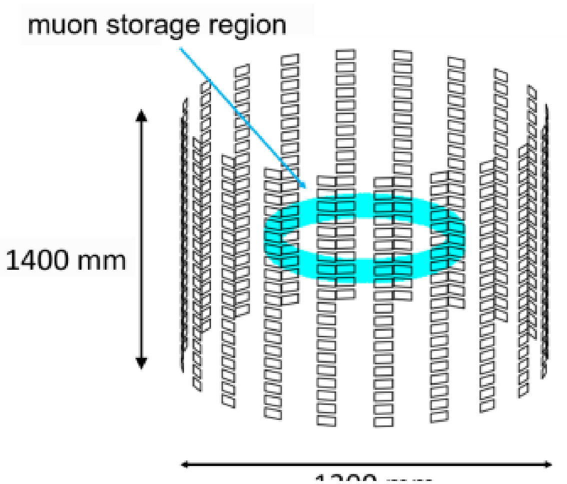
illustration indicating field tuning with iron piece



magnetic field at $\vec{r}$ by iron piece positioned at $\vec{r}'$ in 3 T

$$\vec{B}(\vec{r}) = -B_s \frac{v}{4\pi|\vec{r}-\vec{r}'|^3}\left(\vec{e}_z - \frac{3\vec{e}_z\cdot(\vec{r}-\vec{r}')}{|\vec{r}-\vec{r}'|}\frac{\vec{r}-\vec{r}'}{|\vec{r}-\vec{r}'|}\right)$$

B_s: saturated magnetic flux density of iron ≃ 2.15 T v: iron volume

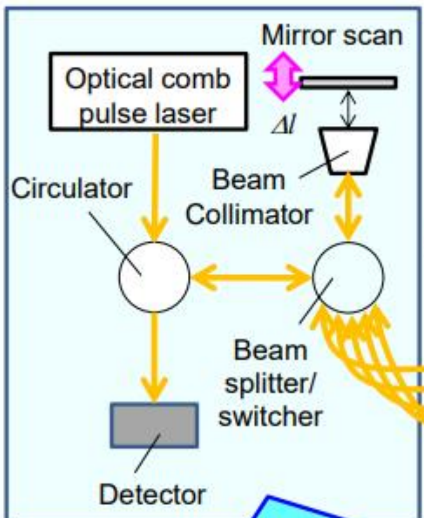


←Our passive shimming system

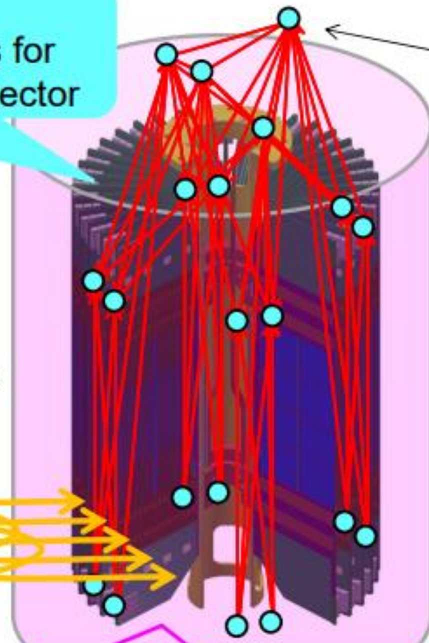
- for coarse shimming: 20 × 20 pockets (max : 77 cm³/pocket)
- for fine shimming : 20 × 20 pockets (max : 4 cm³/pocket)←not used in this study

【Goal】3D-length measurement grid consists of optical fiber introduced interferometers

✓ 3D-length measurement grid of absolute distance interferometers for monitoring deformation of the detector

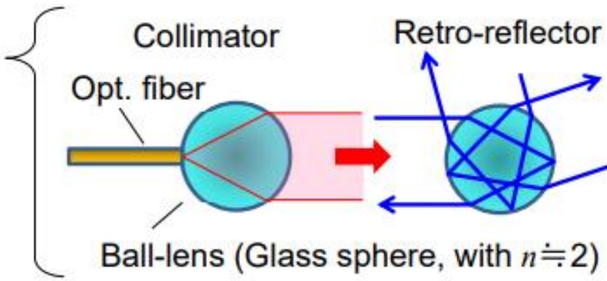


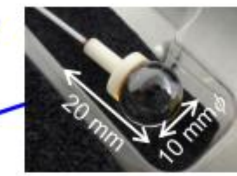
Sensitive components in a safe & mild environment

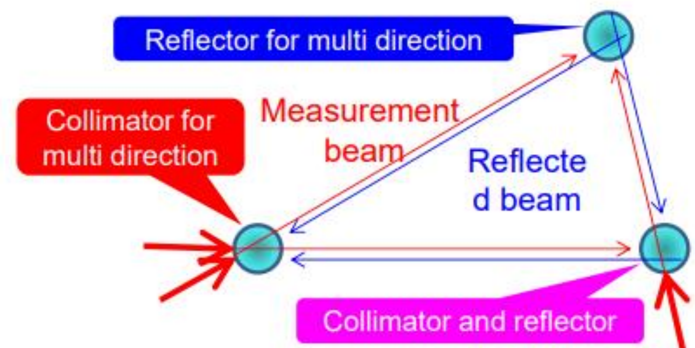


Measurement optics in a severe environment

✓ Operate in a severe environment for long period stably



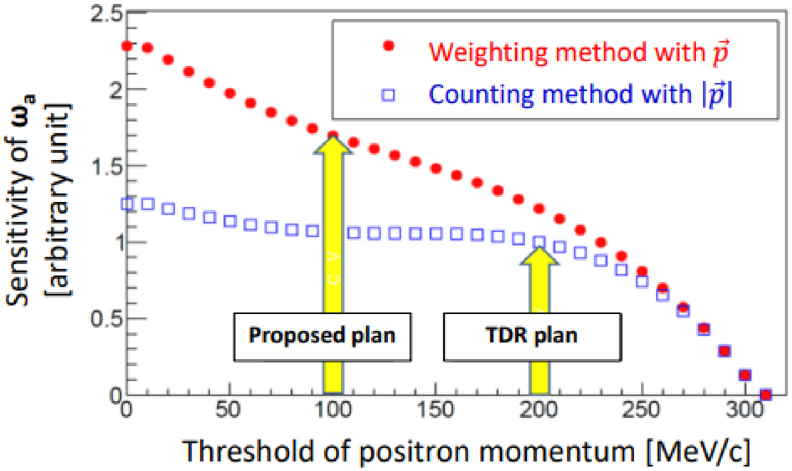


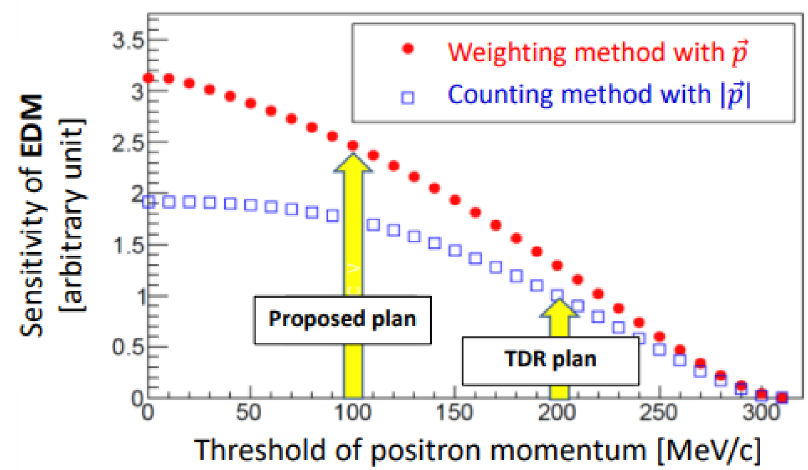


- ✓ Combine multi functions for the optical system of the measurement grid
- ✓ Make the system Small, Stable, Accurate, and Robust with lower cost

Further Sensitivity Improvement of ω_a and EDM

- If we additionally use low momentum positrons with full-information of tracks, the sensitivities of ω_a and EDM are further improved.





- We assume perfect reconstruction efficiency and no uncertainty on positron emission angle.
- Sensitivity is increased by x1.7 (ω_a) and x2.5 (EDM) by combining low momentum positrons(p_{e+} > 100 MeV/c) with full-information of tracks.