Status of g-2/EDM experiment at J-PARC

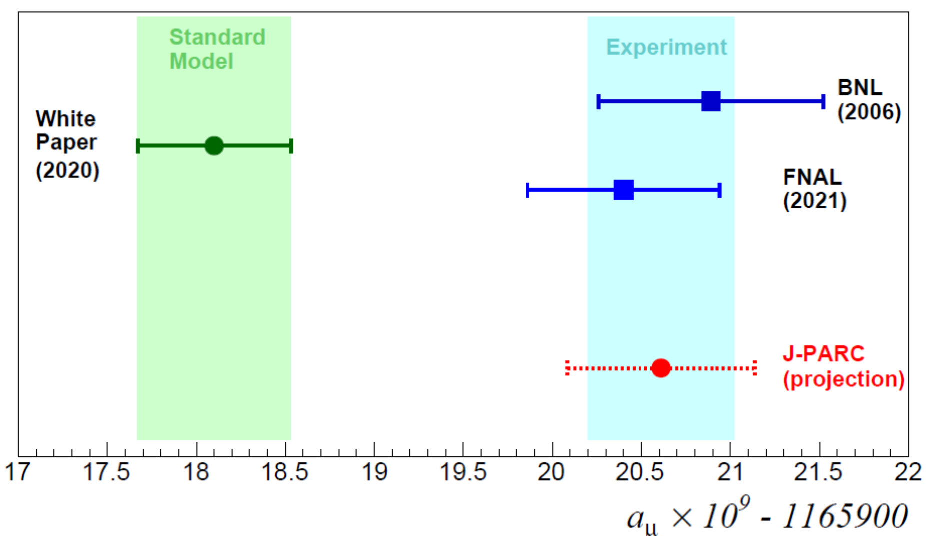
S.Ogawa (Kyushu Univ.)
on behalf of the J-PARC muon g-2/EDM collaboration

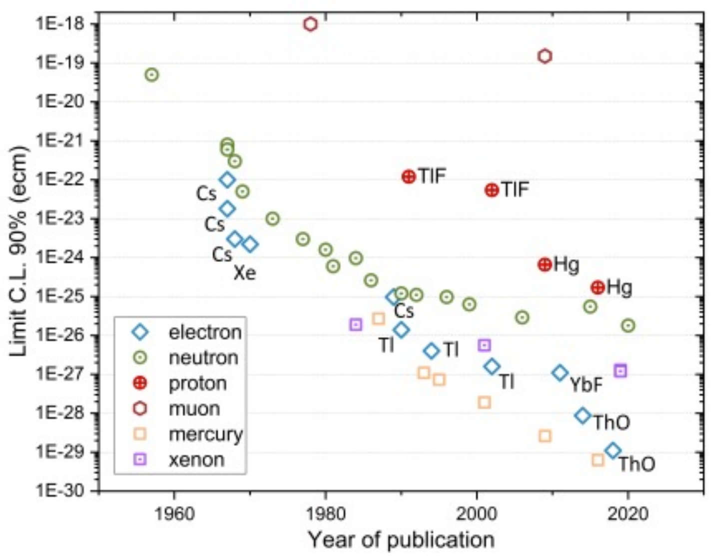
@FCCP 2022

Muon g-2 / EDM

- Muon anomalous magnetic moment (g-2)
  - 4.2 σ tension b/w measurement & prediction
  - Measurement: 116592061(41) × 10- 11(350 ppb)
  - SM prediction: 116591810(43) × 10- 11(370 ppb)
  - Can be a contribution from new physics.

- Muon EDM
  - Upper limit given by BNL: $1.8 \times 10^{-19}\ \mathrm{e \cdot cm}$ (95% C.L.)
  - Indicates CP violation in lepton sector.





Muon g-2/EDM measurement

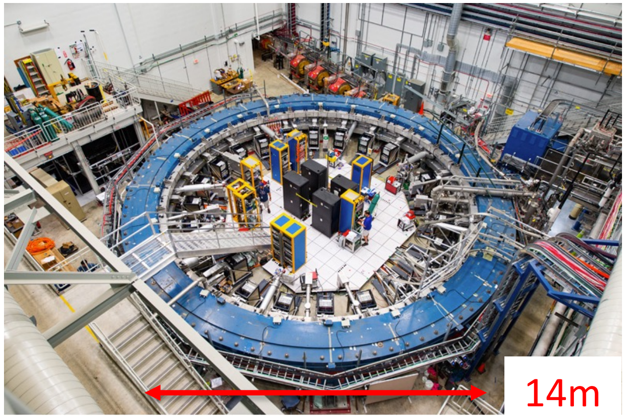
- Muon g-2/EDM can be measured from spin precession of muon in a uniform B-field.
  - time dependent spin information reconstructed from decay positron energy/momentum.

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

<u>BNL/ FNAL experiment</u>

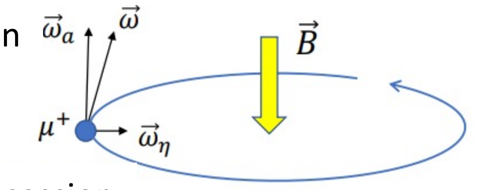
$$\vec{\omega}_a + \vec{\omega}_\eta = -\frac{e}{m_\mu}\left[a_\mu \vec{B} - \underbrace{\left(a_\mu - \frac{1}{\gamma^2-1}\right)}_{=0}\frac{\vec{\beta}\times\vec{E}}{c} + \frac{\eta}{2}\left(\vec{\beta}\times\vec{B} + \frac{\vec{E}}{c}\right)\right]$$

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



Muon g-2/EDM measurement

J-PARC experiment



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

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

- 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

- Independent measurement of muon g-2
  to validate BNL/FNAL result at different systematic uncertainty.
- Clear separation of g-2 and EDM signal.

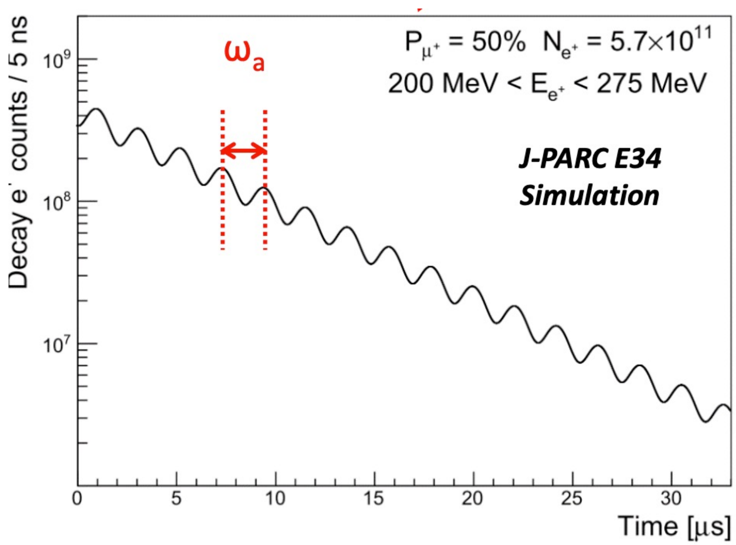
Muon g-2/EDM measurement

J-PARC experiment

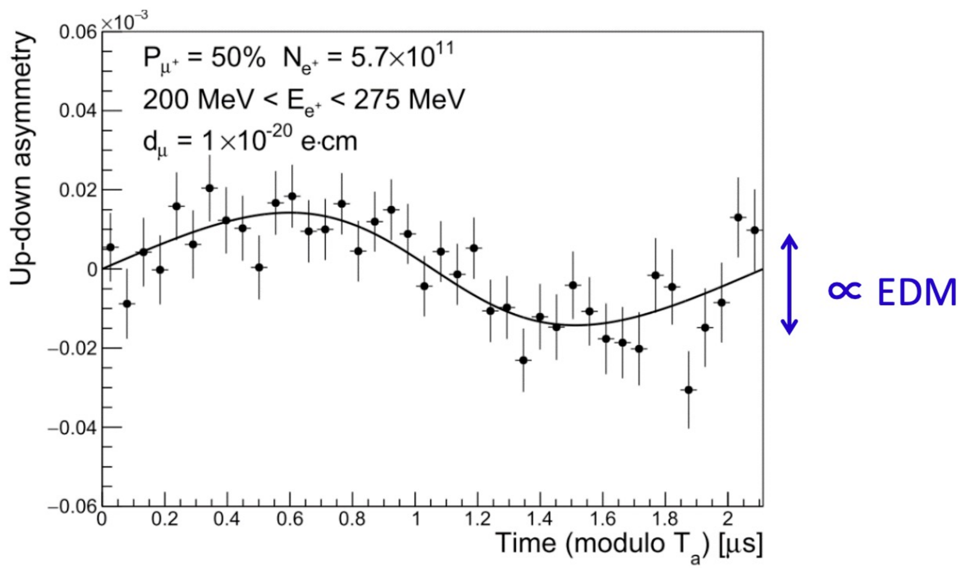
- Measurement at $\vec{E} = 0$.
  - Storage by weak focusing B-field
  - Utilize low emittance muon beam.

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

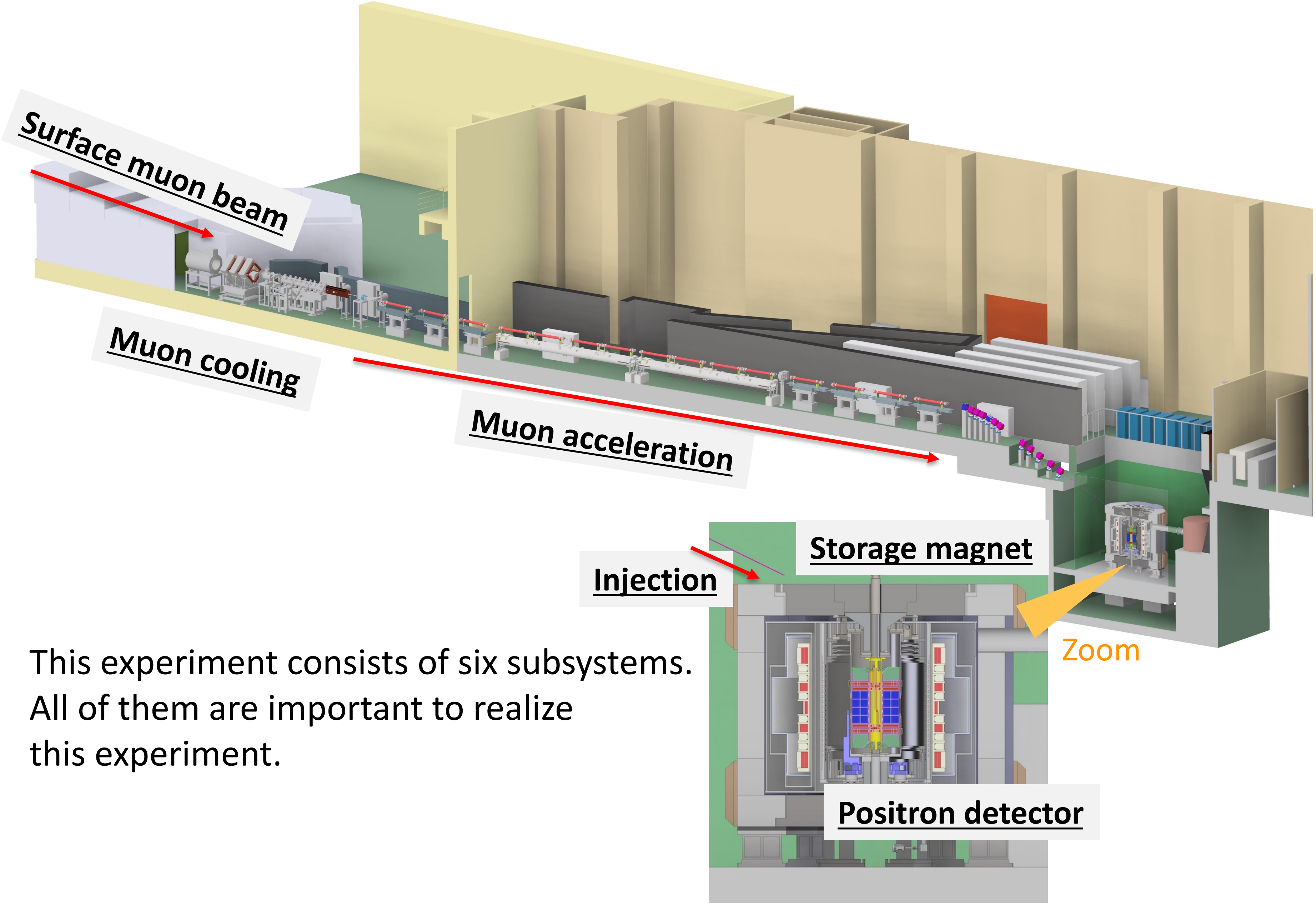
Number of detected positron (p: 200-275 MeV)



Up-down asymmetry of detected positron



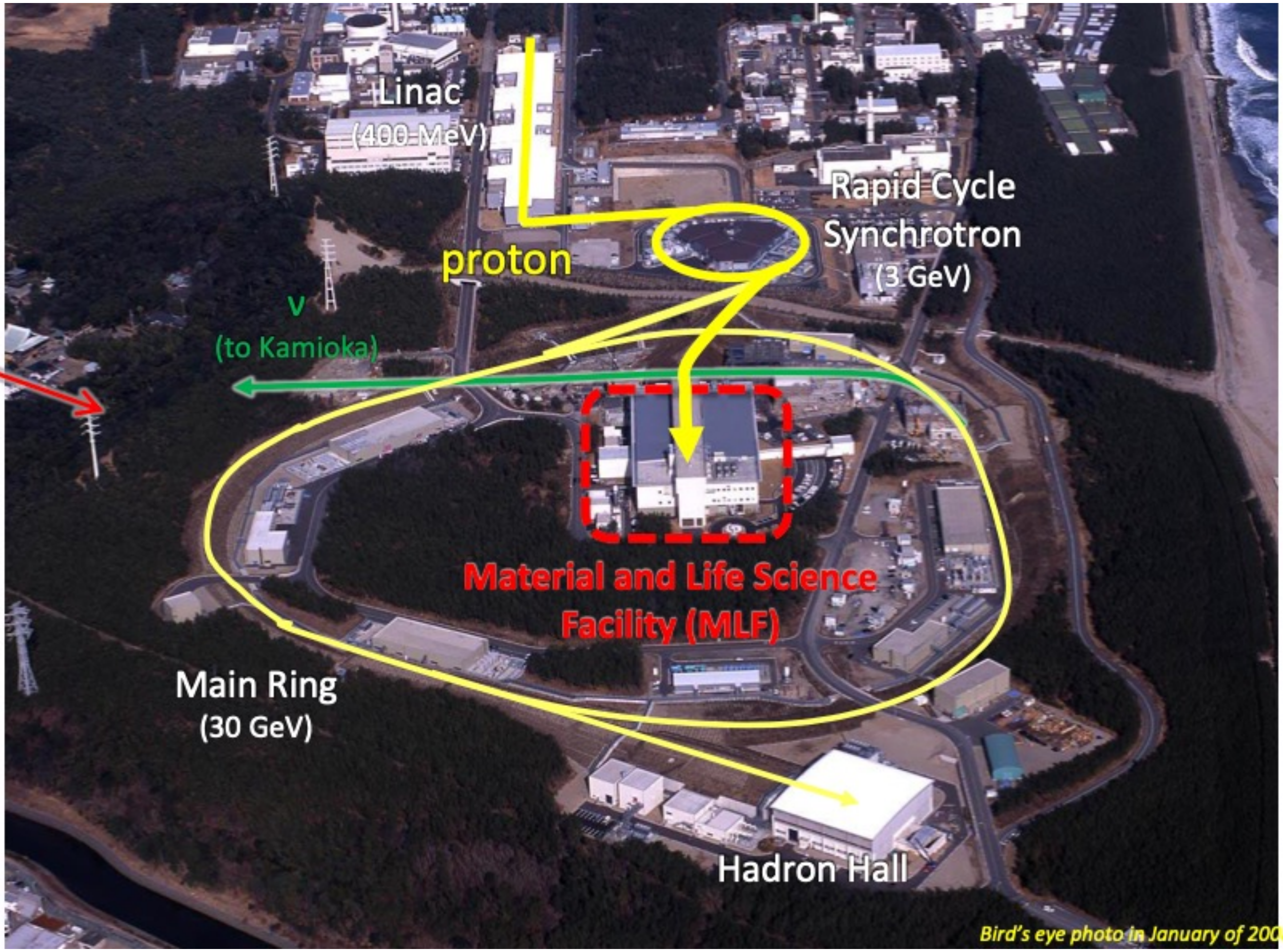
Muon g-2/EDM experiment at J-PARC



This experiment consists of six subsystems.
All of them are important to realize
this experiment.

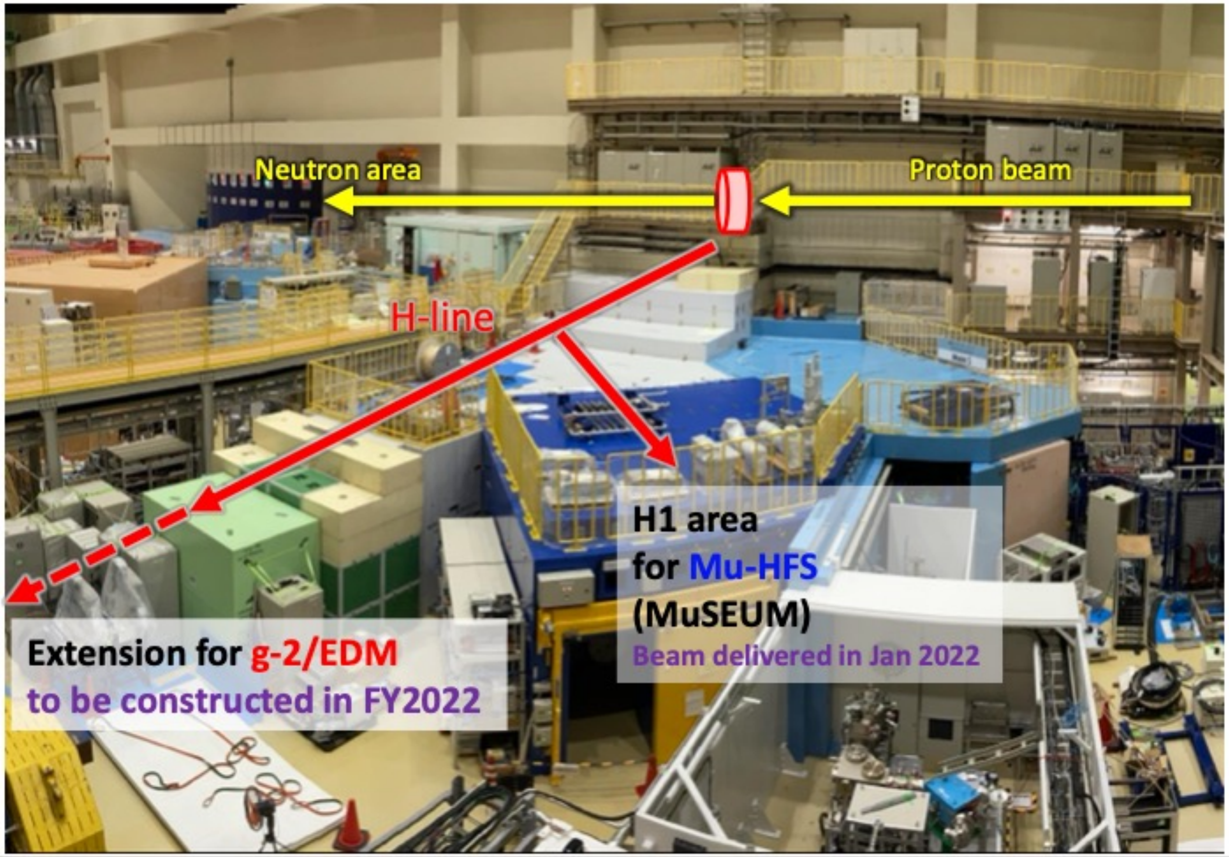
J-PARC MLF

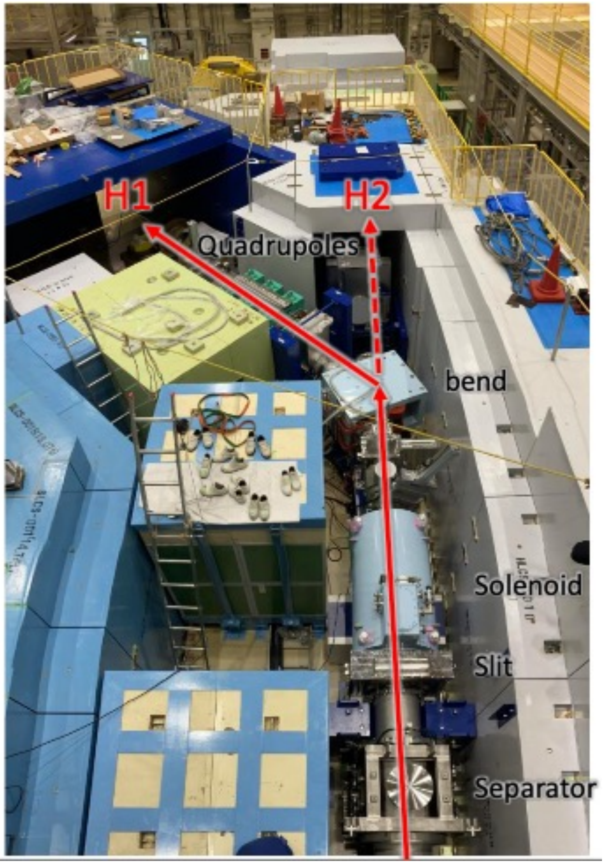

Ibaraki, Japan


Linac
(400 MeV)
Rapid Cycle
Synchrotron
(3 GeV)
proton
ν
(to Kamioka)
Material and Life Science
Facility (MLF)
Main Ring
(30 GeV)
Hadron Hall
Bird's eye photo in January of 2008

Surface μ⁺ beam

- MLF H2 beam line.
  - Surface μ^+ beam: 4MeV, 10^8 μ+/s with 25Hz rep
  - Beam line extension inside the (existing) MLF bldg. in this fiscal year.
  - Construction of extension bldg. is also ready.

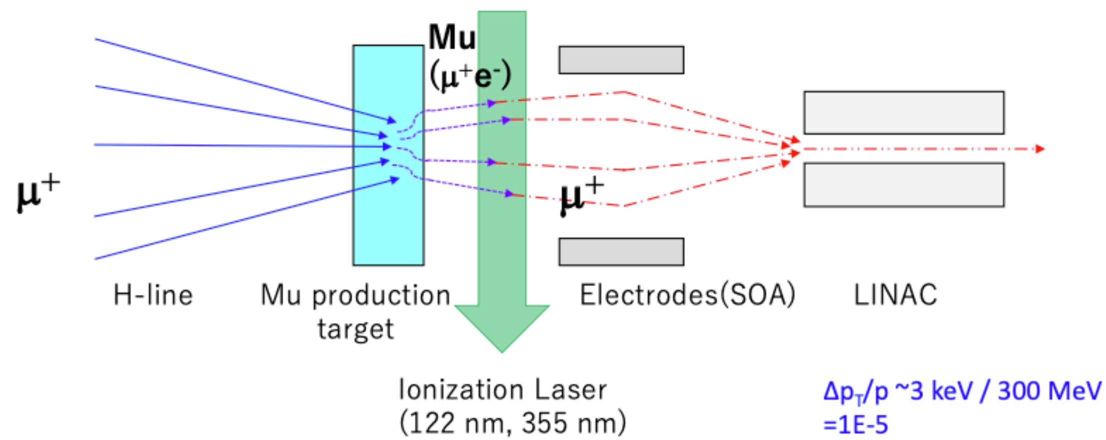


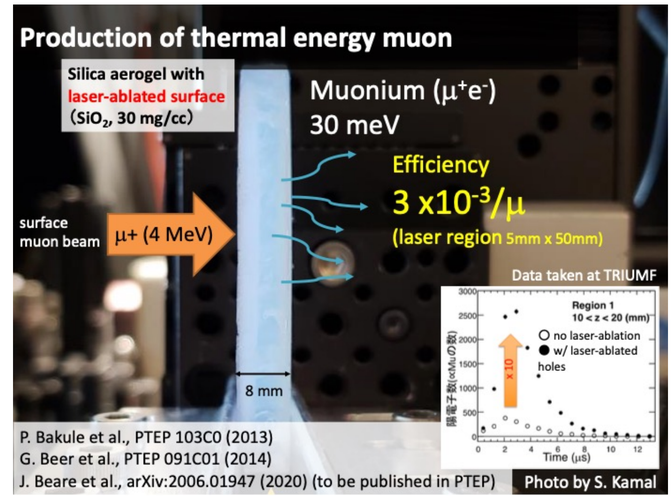


Muon cooling

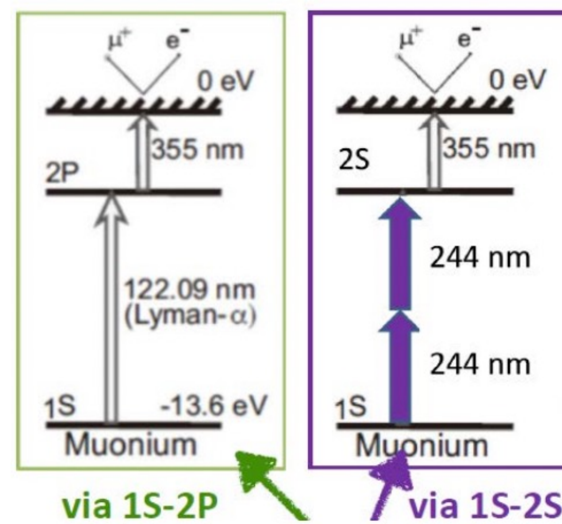
- Low emittance muon beam by reacceleration of thermal muon.
  - Silica aerogel target : Surface muons stopped, and thermal muoniums emitted.
  - Laser ablated aerogel to increase the efficiency.

	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}



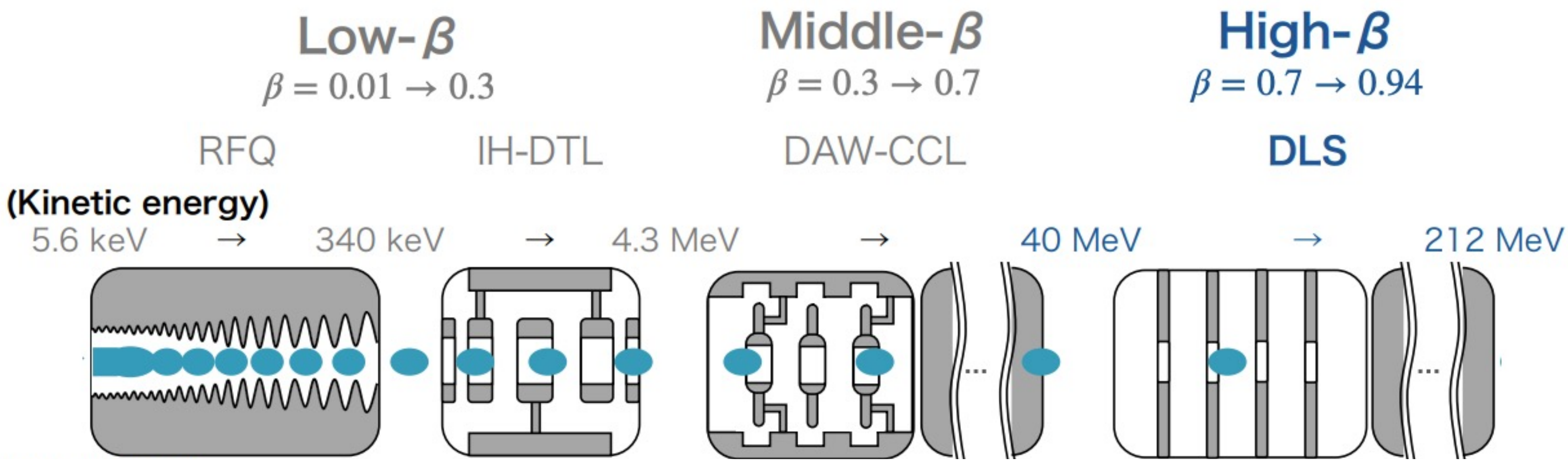


- Thermal muonium ionization by laser.
  - Two scheme under consideration.
  - 1S-2P excitation by 122nm
    or 1S-2S excitation by 244nm



Muon acceleration

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

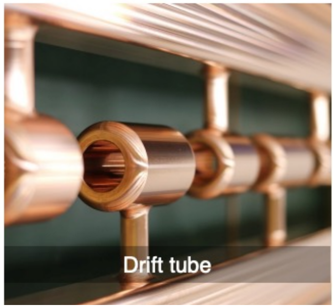


Acceleration test with thermal μ planned in 2023

Fabrication completed

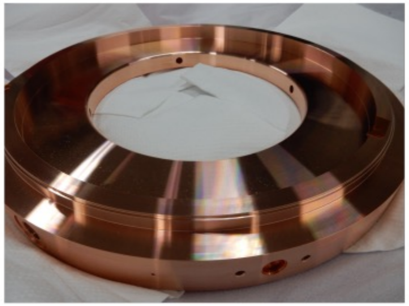
1st tank under fabrication

Prototype fabrication in JFY2022



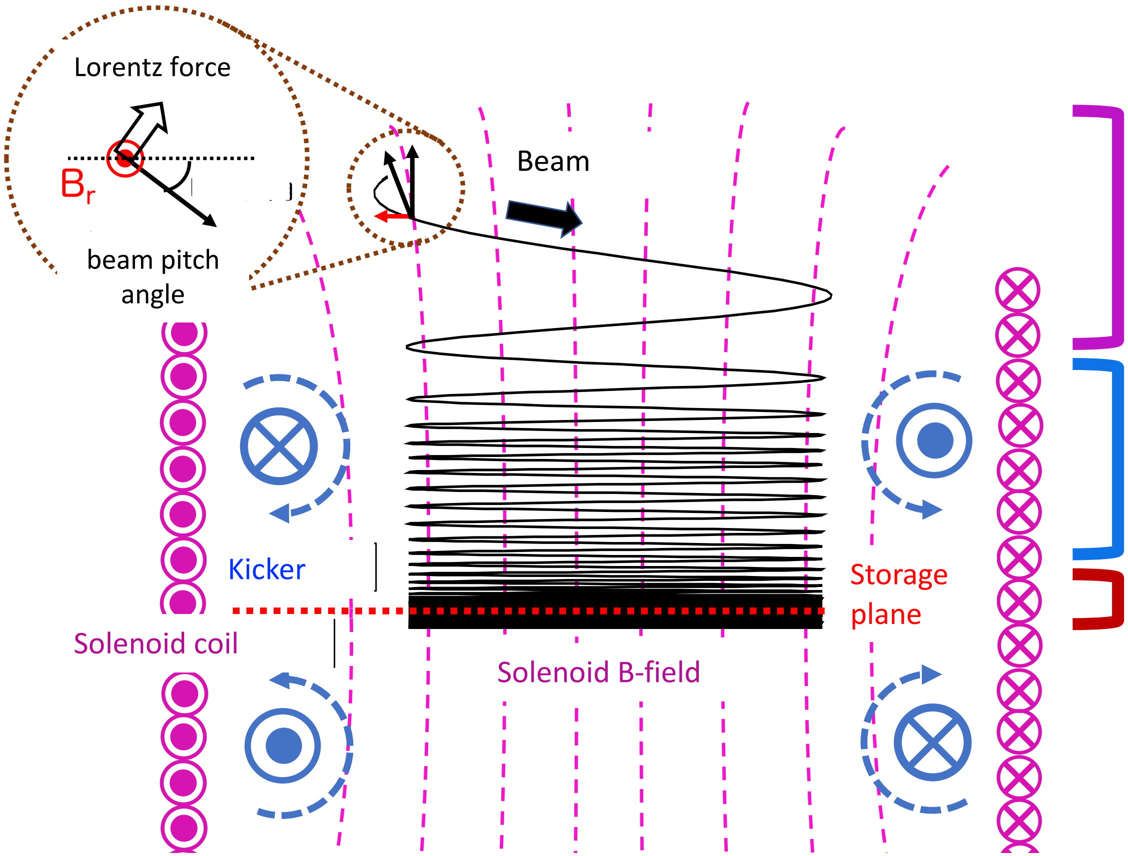
Washer 1,2 (×2)

Disk1



Muon beam injection

- 3D spiral injection scheme is adopted for muon beam injection into the storage region.
  - Key: Tuning of beam parameter & kicker coil design.
  - Expected injection efficiency: ~ 85%.



① injection region :
Fringe B-field of solenoid
- Reduces beam pitch angle by Br

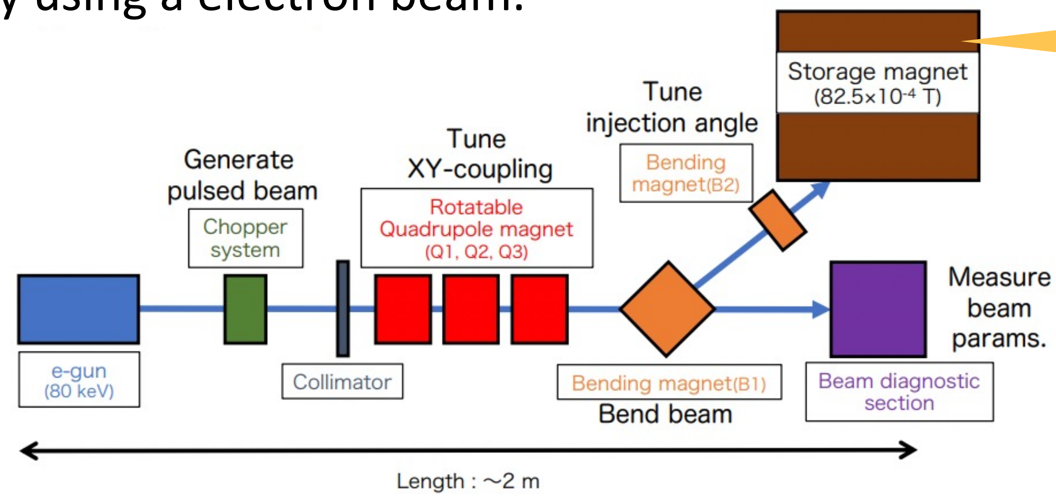
② Kick region :
Pulsed B-field by kicker coil.
- Vertical kick of beam by Br

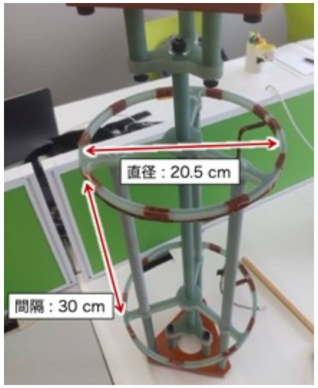
③ Storage region :
Weak-focusing B-field
- Beam storage with betatron oscillation

Muon beam injection

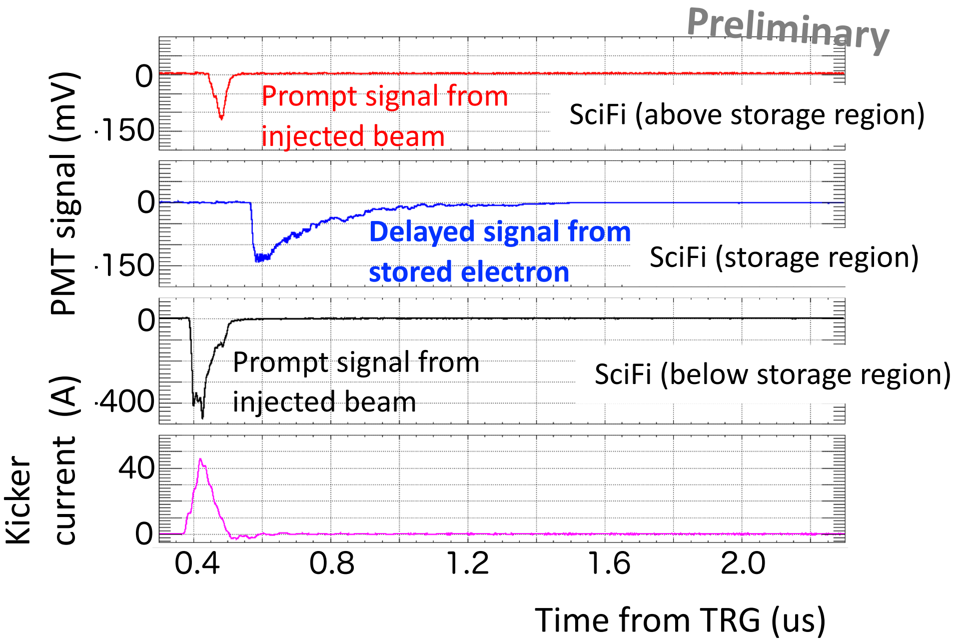
- Demonstration of 3D spiral injection scheme is ongoing in a test setup by using a electron beam.

Kicker coil inside solenoid magnet



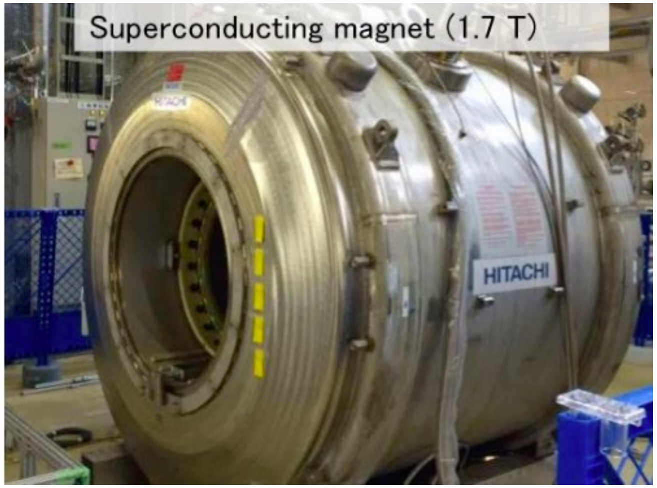


- Signal from stored electron beam is successfully observed.



Storage magnet

- Highly uniform magnetic field will be achieved by shimming.
  - Compact solenoid magnet based on MRI magnet technology.
  - B-field measurement by a high precision NMR probe



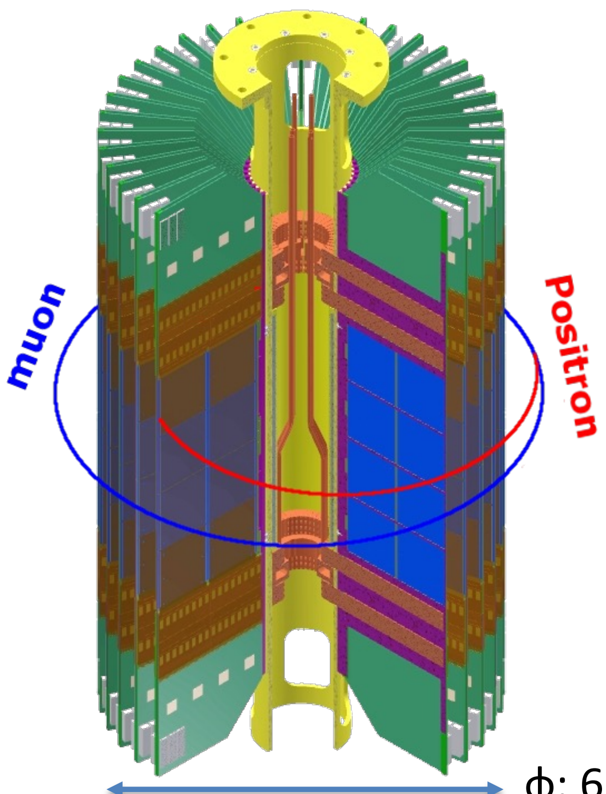
- Local uniformity of 1ppm is already demonstrated by the MuSEUM magnet.

- Field mapping system under design.
  - B-field meas. in the muon storage region.
  - Theta motion + z motion.

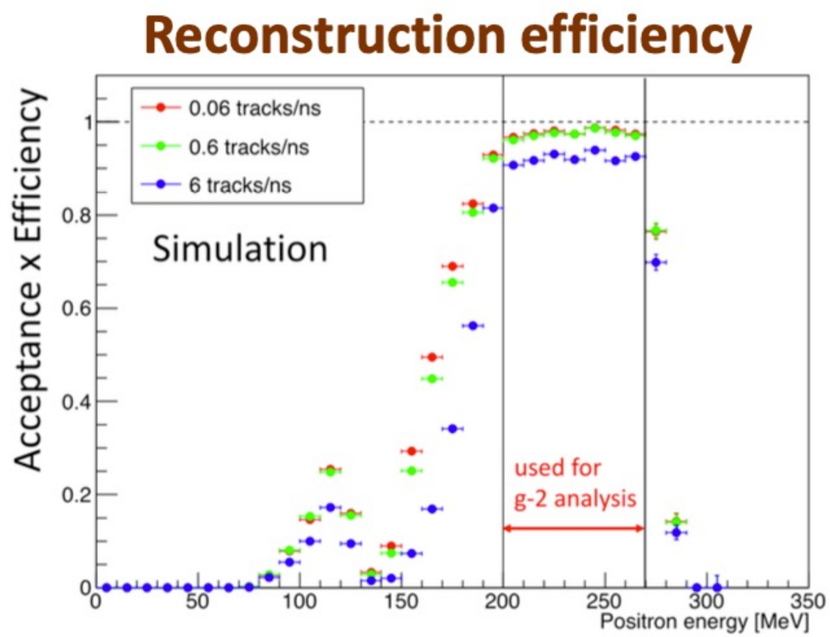
Field mapping system (CAD)

Positron Detector

- Silicon detector for momentum measurement of decay positrons.
  - Silicon strip sensor: Hamamatsu S13804, 190um pitch.
  - High hit rate capability (6 tracks/ns)
    and stability over rate changes (1.4 MHz→10 kHz)
  - High efficiency for positron in the analysis window (p=200-270 MeV/c).

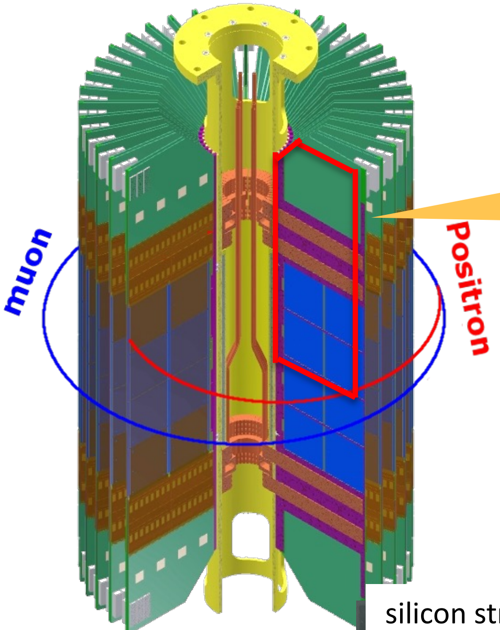


ϕ: 66 cm

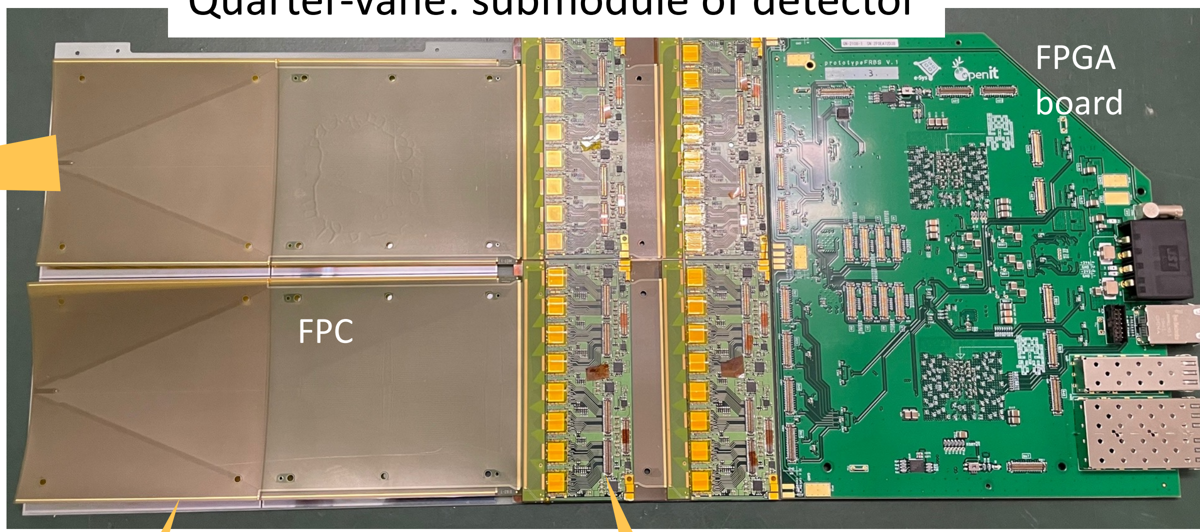


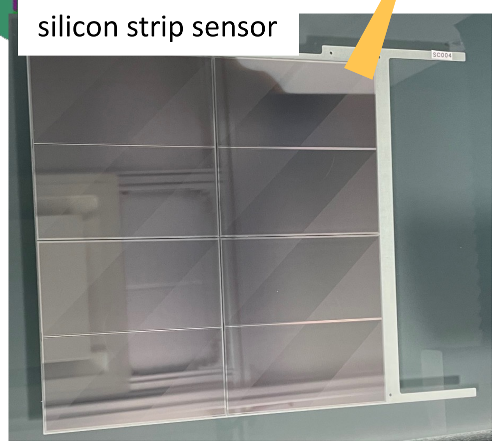
Positron detector

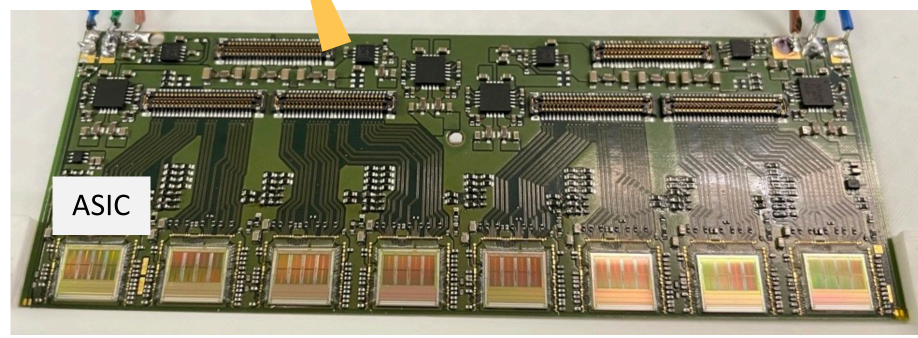
- Major components are in or completed the mass-productions.
- Assembly procedure is under R&D.



Quarter-vane: submodule of detector

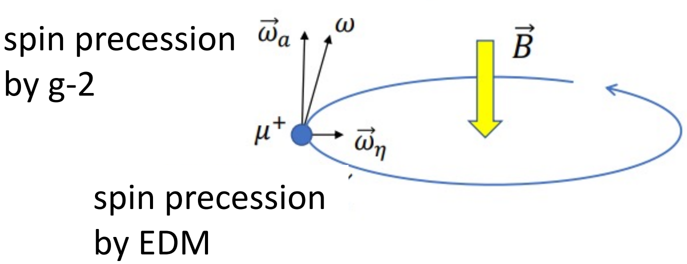


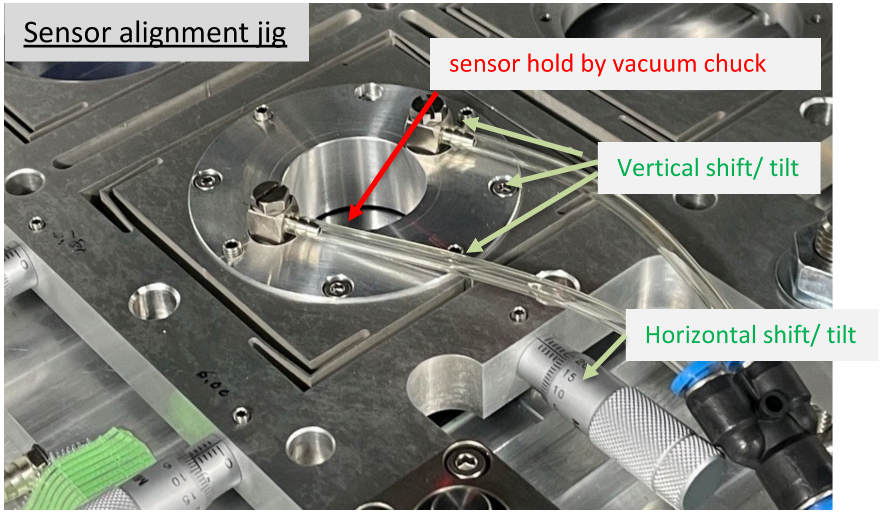


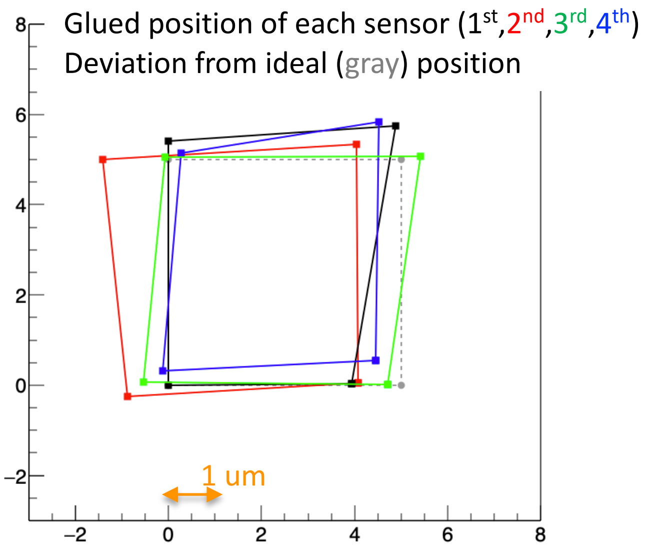


Sensor alignment

- 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”.
- Goal of sensor alignment: 1um precision.
  - Assembly procedure under development.
    - sensor alignment jig under test
    - sensor position/shape measurement by coordinate measuring machine.
  - Precision of ~ 2um already achieved (near to the goal).

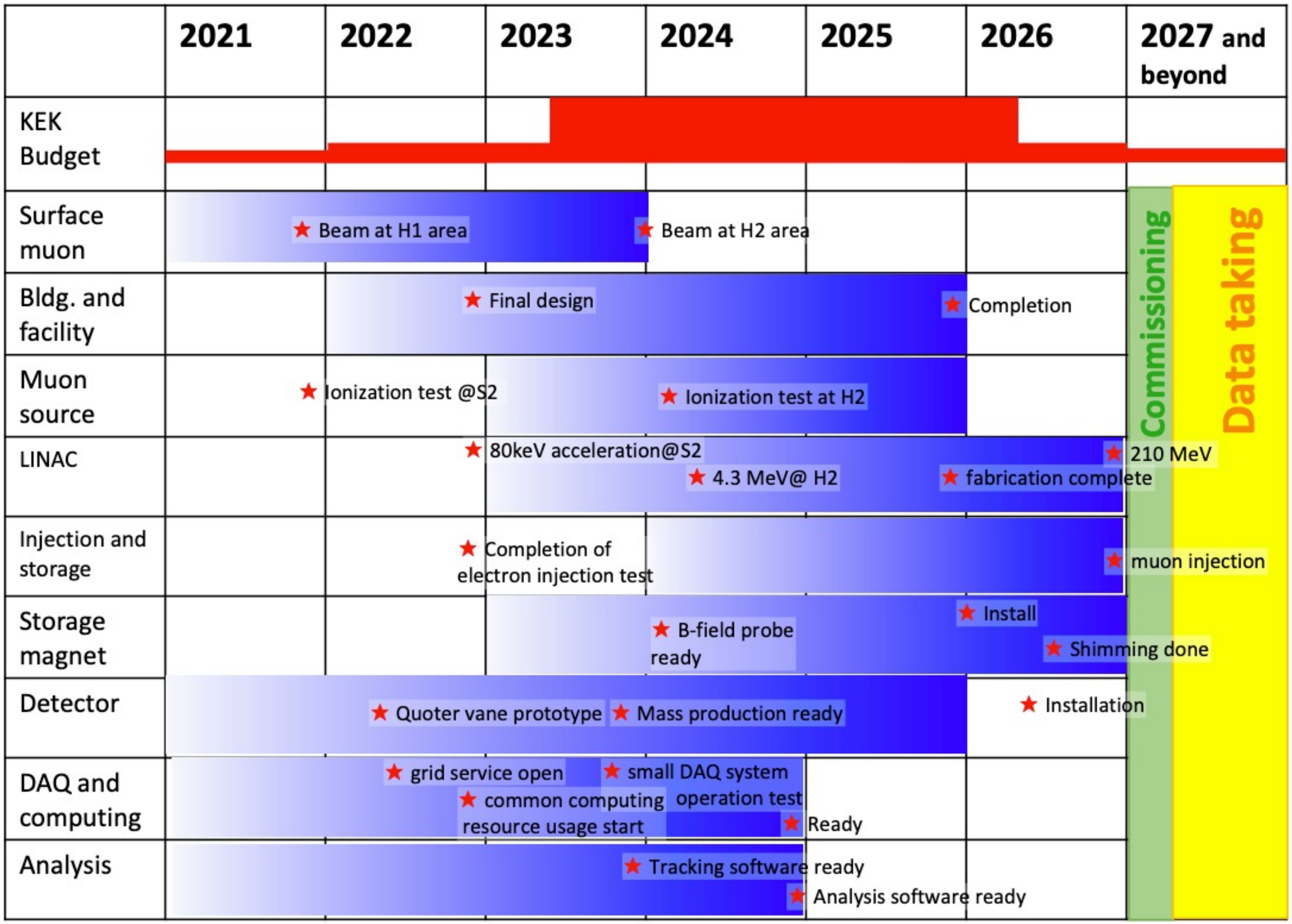






Schedule

Physics data taking expected from JFY 2027.



Expected sensitivity

- Total efficiency of muon will be 1.3×10^{-4}.

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
- 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: 1.5×10^{-21} e $\cdot$ cm
- Systematic uncertainty: 0.4×10^{-21} e $\cdot$ cm
  - mainly from detector mis-alignment

Summary

- Muon g-2/EDM experiment at J-PARC aims to measure muon g-2/EDM by utilizing
  - Low emittance muon beam stored by weak focusing magnetic field.
  - Compact storage magnet with low momentum muon.
- This will be an independent measurement from BNL/FNAL at different systematics.

- All subsystem of this experiment are getting ready for realization.
  - Some of them are already in “construction phase”.

- Expected data taking from JFY 2027.
- After 2 years of data taking,
  - muon g-2 measurement at 450ppb(stat.) : comparable to BNL.
  - muon EDM sensitivity at $1.5 \times 10^{-21}\ \mathrm{e} \cdot \mathrm{cm}$ (stat.): 2 orders of magnitude improvement.