J-PARC muon g-2/EDM experiment

Yutaro Sato

Niigata University

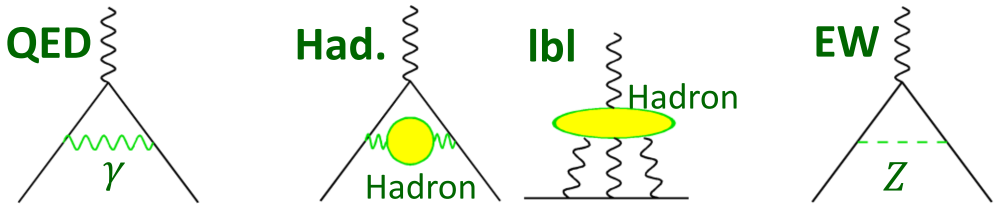
On behalf of the J-PARC muon g-2/EDM collaboration

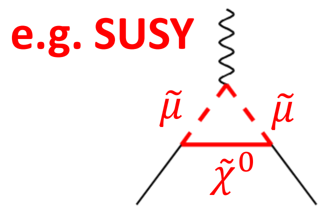
Aug. 30th 2022 CIPANP2022

Muon g-2 and EDM

Muon anomalous magnetic moment (a_μ, g-2)

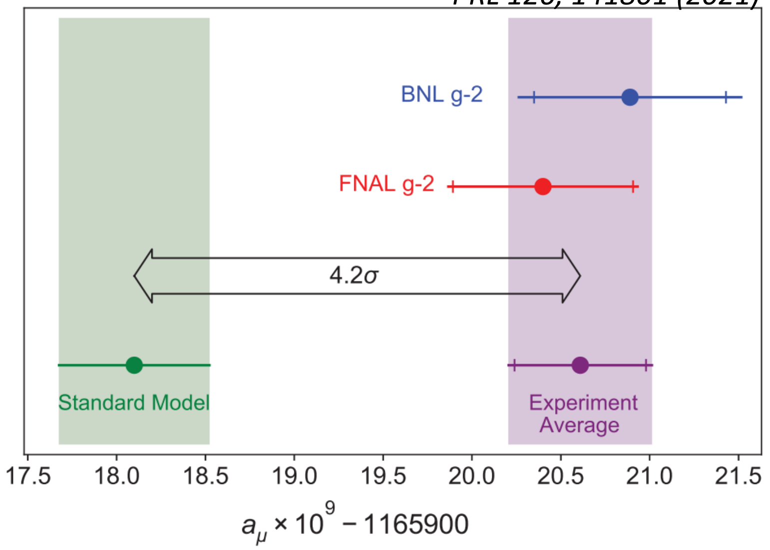
- Deviation of g-factor from the prediction of Dirac equation for fermions.
  - $a_\mu = \frac{g-2}{2} = a_\mu(QED) + a_\mu(had) + a_\mu(weak) + a_\mu(New\ Physics)$





- 4.2σ deviation between the SM prediction and measurements
  - σ_{SM} : 0.37 ppm [white paper]
  - σ_{exp} : 0.35 ppm [BNL+FNAL]

PRL 126, 141801 (2021)



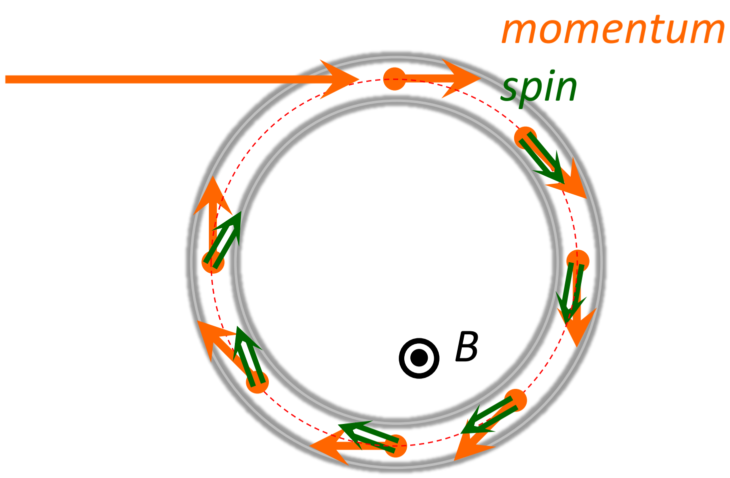
Electric Dipole Moment (EDM)

- If non-zero EDM exists, it means T-violation. → CP-violation
- Exp. upper. limit : $d < 1.8 \times 10^{-19} e \cdot \mathrm{cm}$ (95% C. L.) by BNL E821.

→ A new experiment to measure muon g-2 and EDM at J-PARC

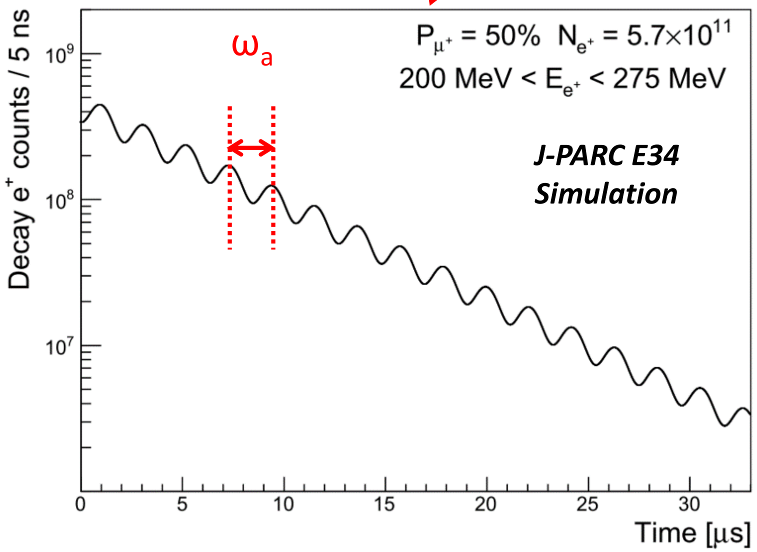
Experimental Approaches

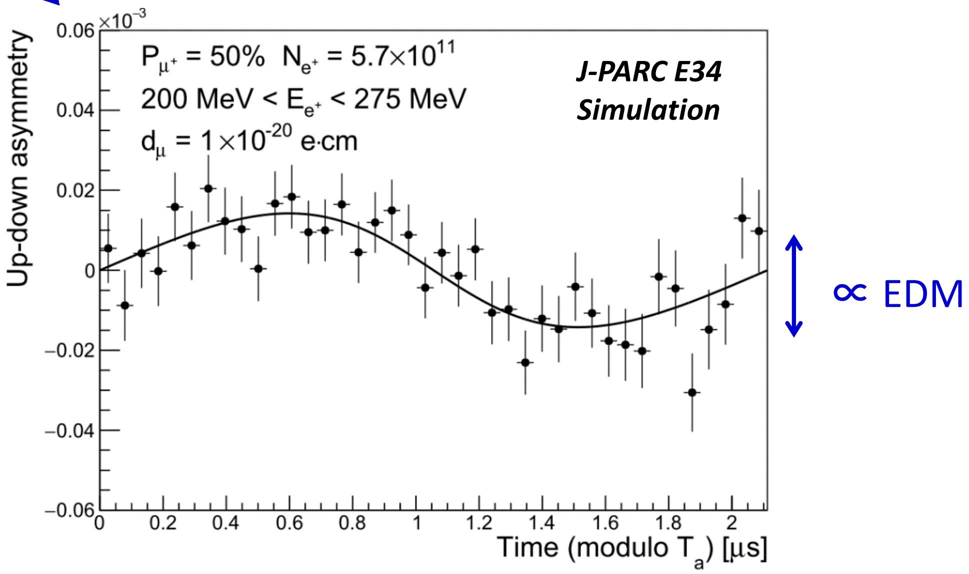
- In uniform B-field, muon spin rotates ahead of momentum due to g-2 ≠ 0.



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

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





Experimental Approaches (BNL, FNAL)

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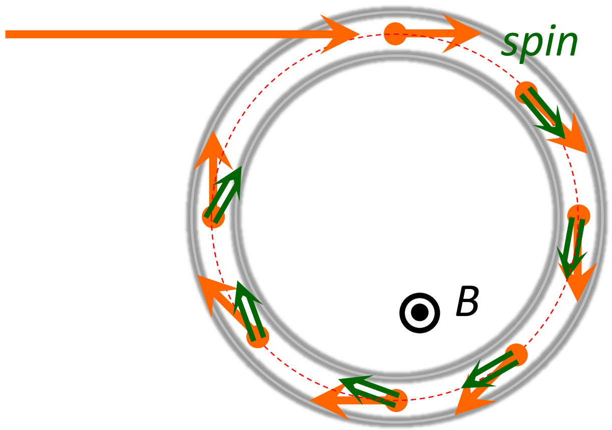

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g-2 term

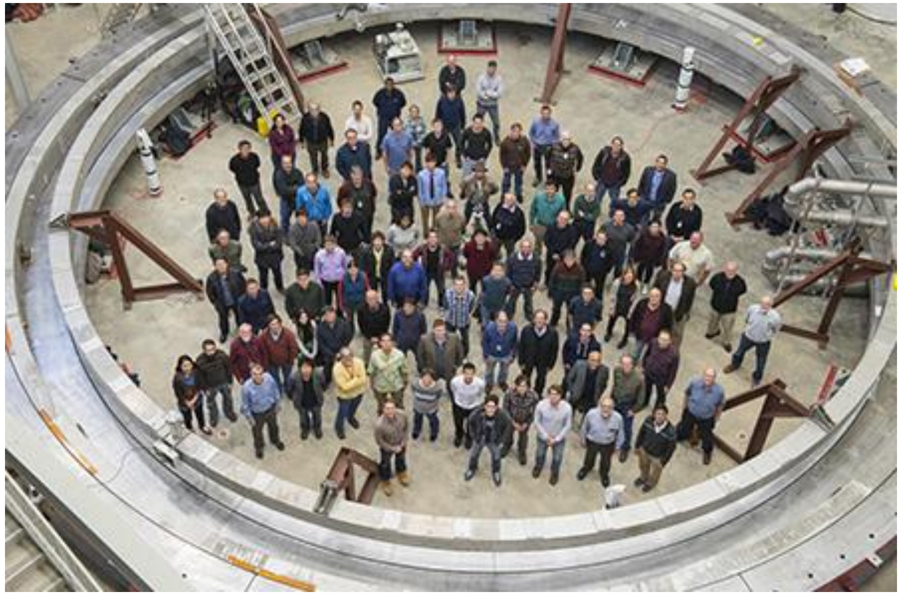
EDM term

BNL E821 & FNAL E989

- Magic momentum

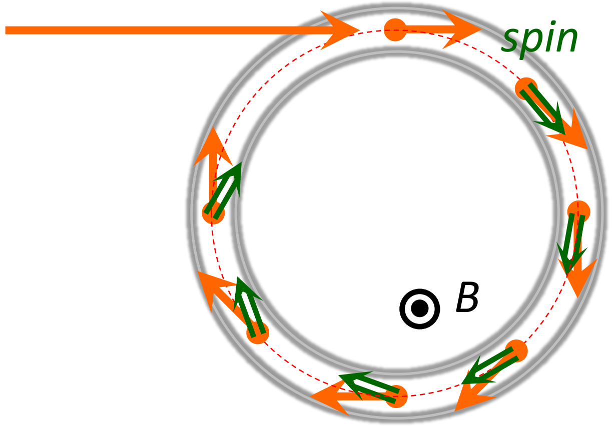
  $\gamma = 29.3 \ (p = 3.1 \ \mathrm{GeV}/c)$
- Weak electric focusing.

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



Experimental Approaches (J-PARC)

- In uniform B-field, muon spin rotates ahead of momentum due to g-2 ≠ 0.



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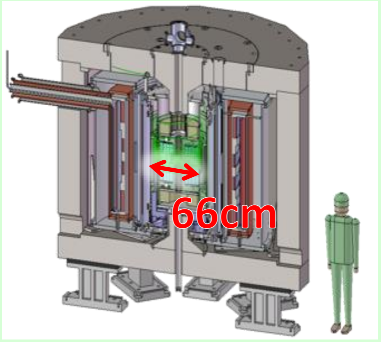
$$\vec{\omega} = -\frac{e}{m_\mu}\left[a_\mu \vec{B} + \frac{\eta}{2}\left(\vec{\beta} \times \vec{B} + \frac{\vec{E}}{c}\right)\right]$$

J-PARC E34

- No electric field
- Very weak magnetic focusing

$$\vec{\omega} = -\frac{e}{m_\mu}\left[a_\mu \vec{B} + \frac{\eta}{2}\left(\vec{\beta} \times \vec{B}\right)\right]$$

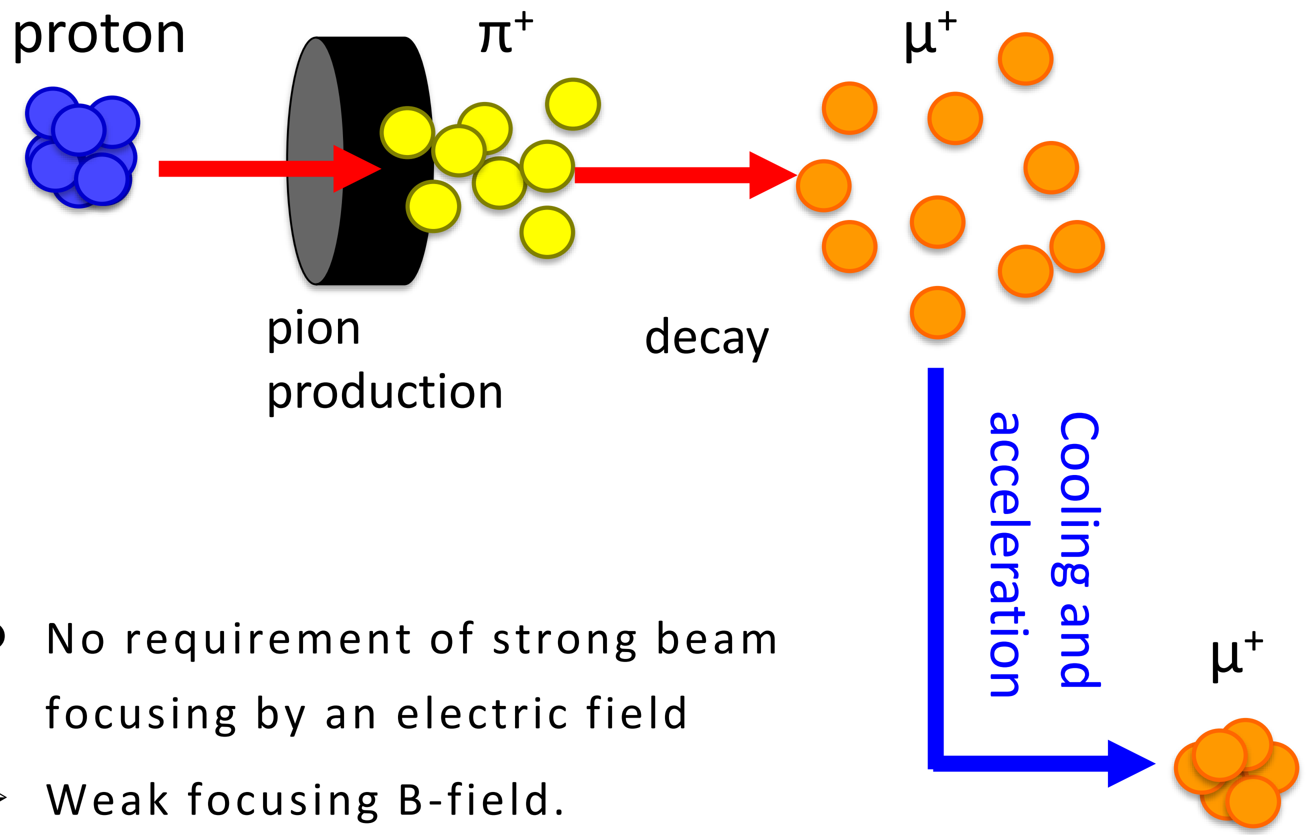


$p = 300$ MeV/c

→ **Different systematic uncertainty.**

→ **Clear separation of $\vec{\omega}_a$ and $\vec{\omega}_\eta$.**

Reaccelerated thermal muon beam



Conventional muon beam

Emittance ~ 1000π mm・mrad

Strong focusing with electric field
Muon loss
Pion background

Reaccelerated thermal muon beam

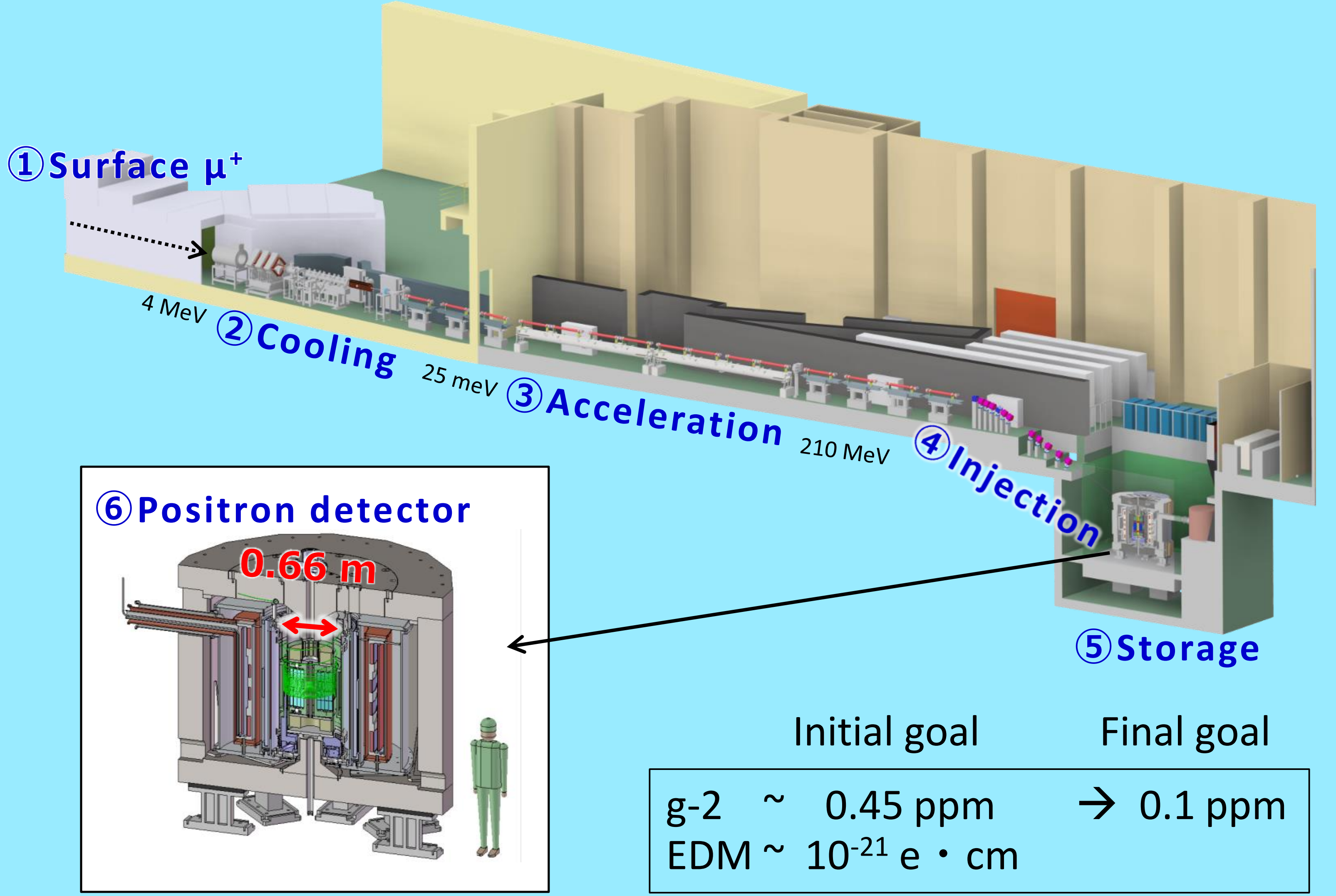
Emittance ~ 1π mm・mrad

Free from any of the above

- No requirement of strong beam focusing by an electric field
  - ➢ Weak focusing B-field.
- Free from magic momentum of 3.094 GeV/c
  - ➢ Lower momentum beam of 300 MeV/c
    - Compact storage ring with excellent uniformity (Δ~0.1 ppm)
    - Full tracking detector for decay positron

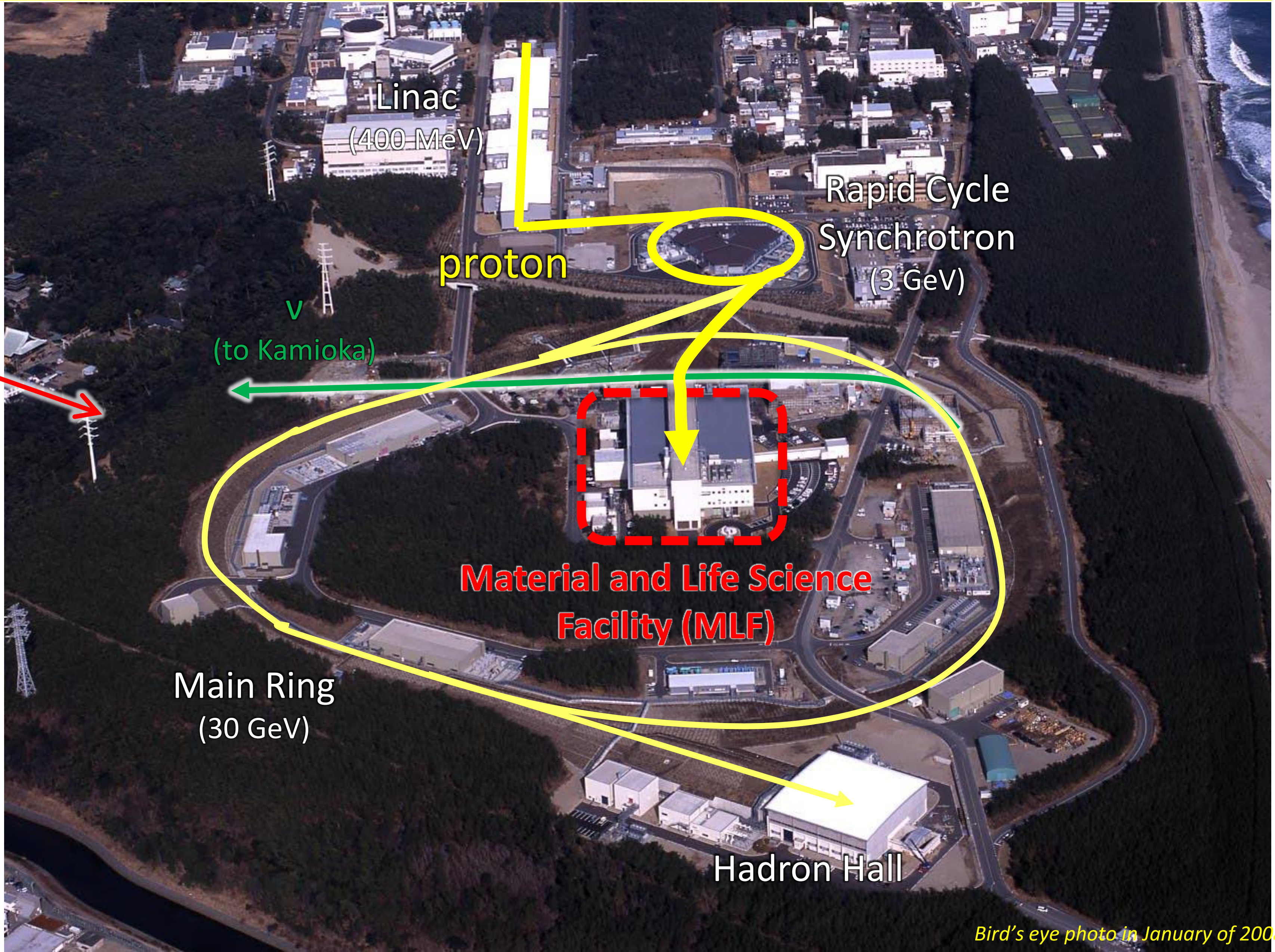
J-PARC muon g-2/EDM Experiment

① Muon Beam Line and experimental area
② Thermal muon
③ Muon linac
④ Injection
⑤ Storage
⑥ Detector



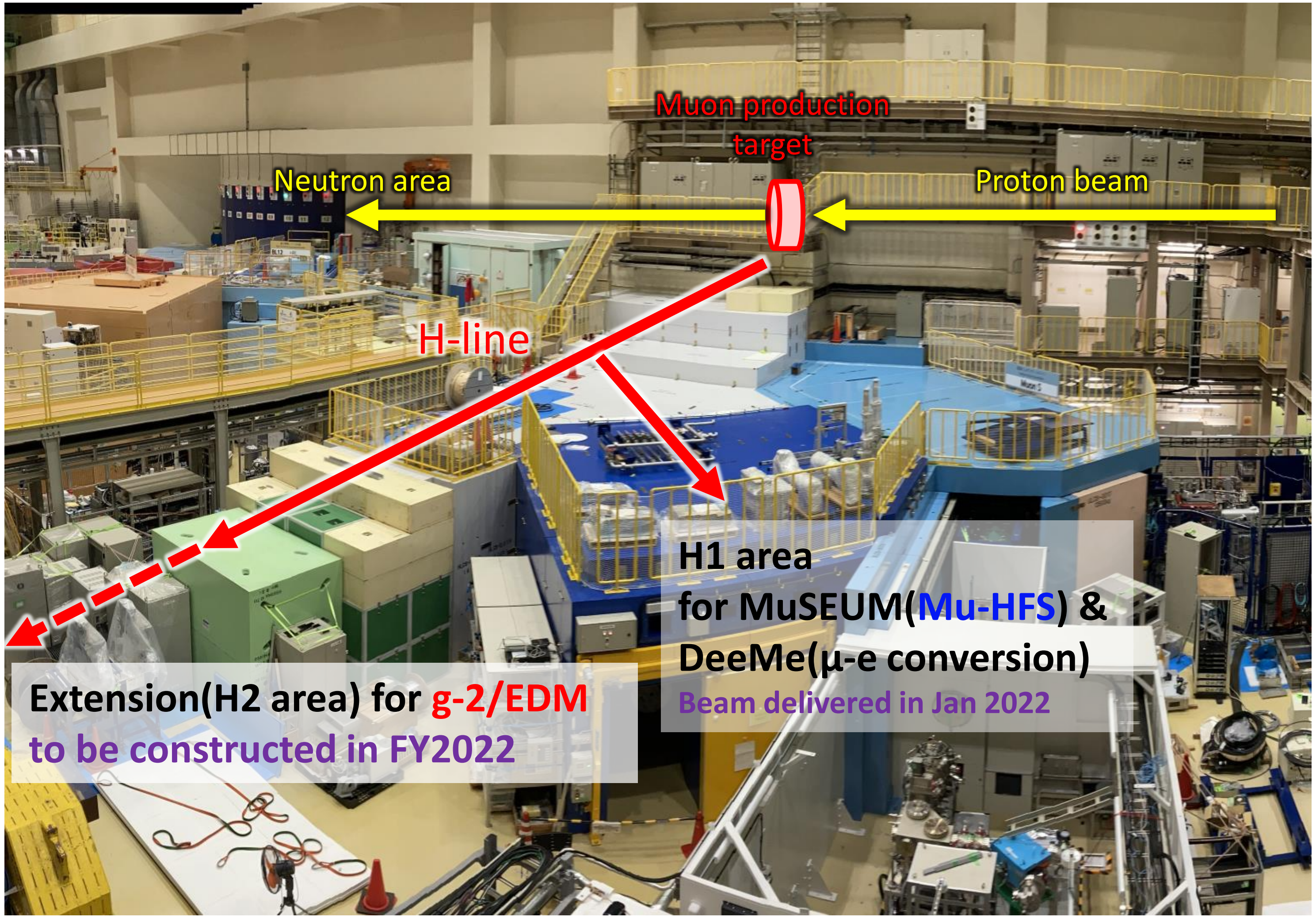
	Initial goal		Final goal
g-2	~ 0.45 ppm	→	0.1 ppm
EDM	~ 10^{-21} e・cm		

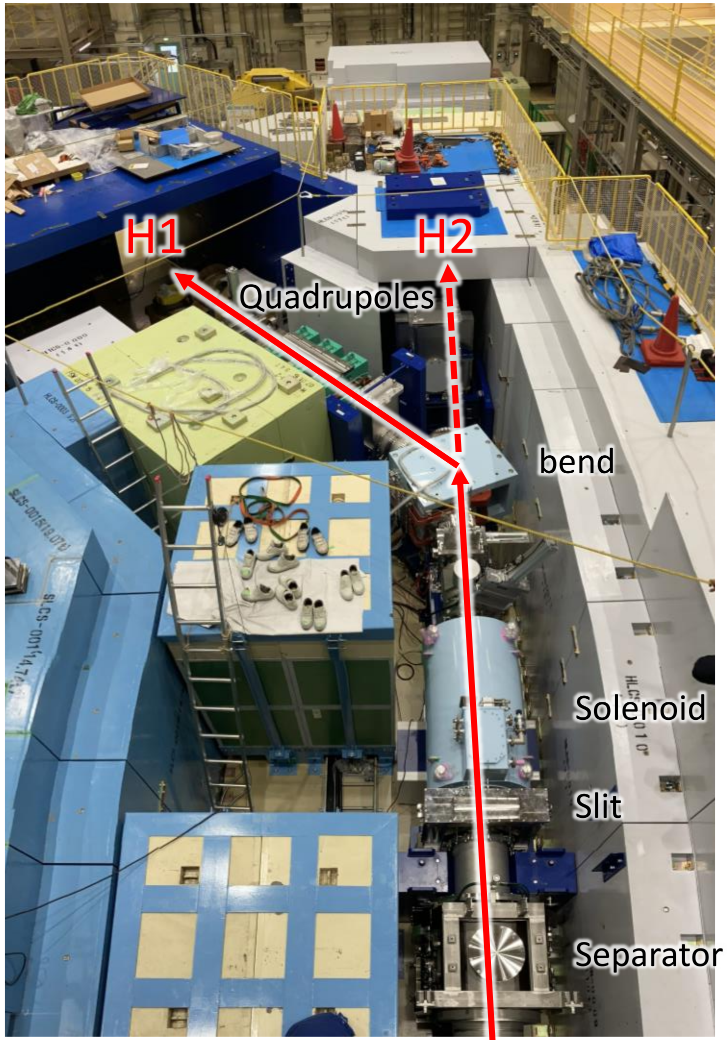
J-PARC Proton Accelerator Research Complex (J-PARC)



① Muon Beam Line and Experimental Area

- Construction of H-line up to H1 area has been finished.
- The first beam of H-line was detected on Jan. 15, 2022.



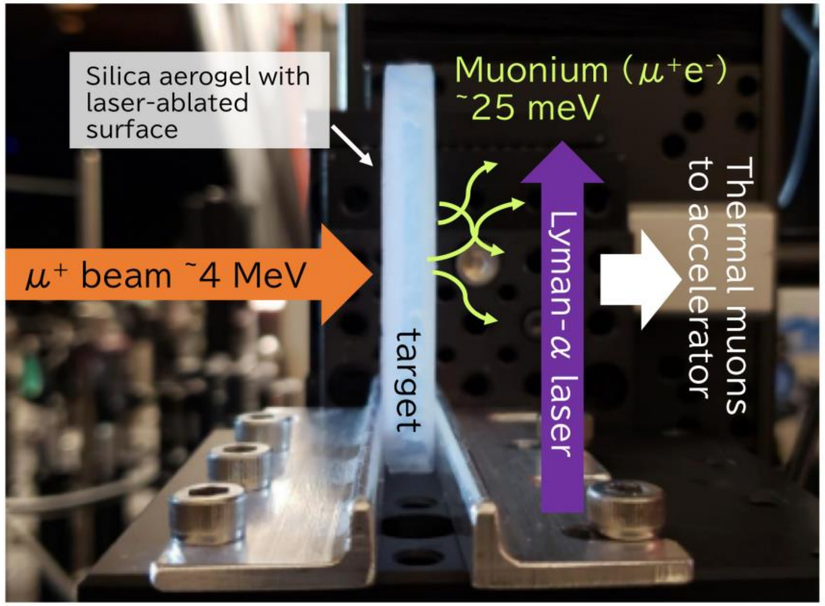


① Muon Beam Line and Experimental Area

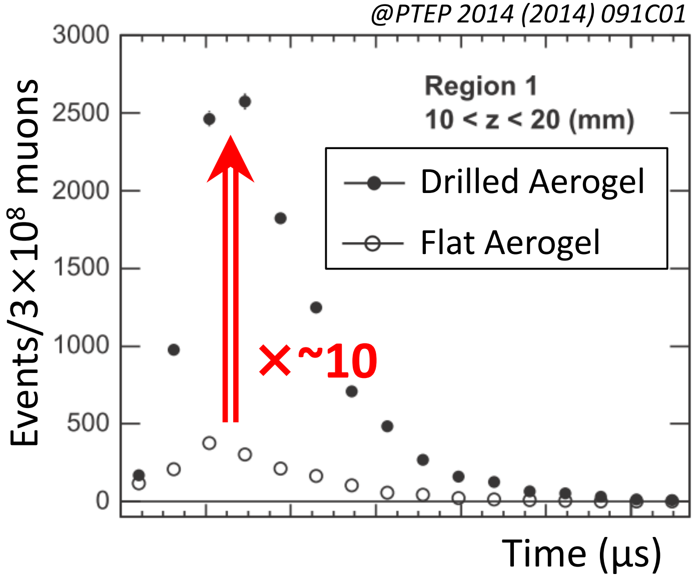
- The extension building (H2) is being ready for construction.

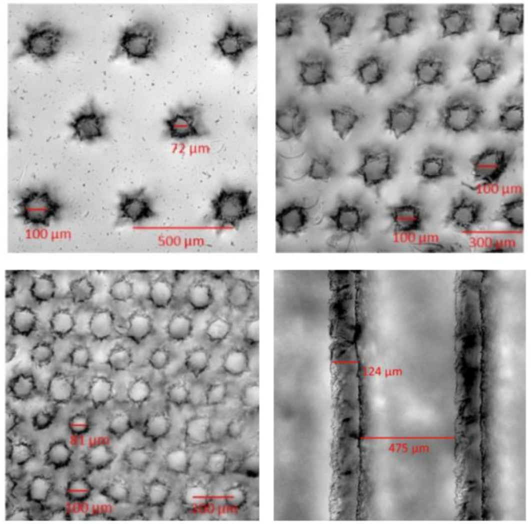
② Thermal Muon Production

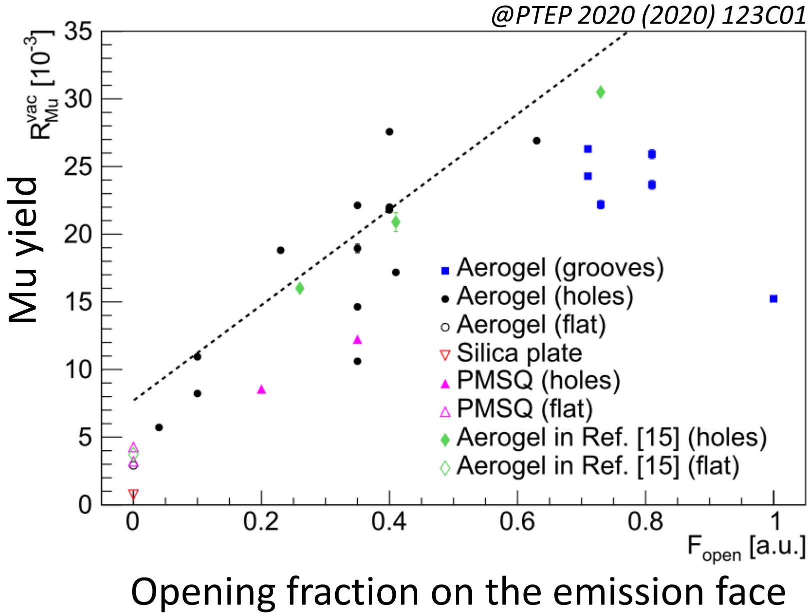
- **Surface muon (27 MeV/c) is stopped at an target and muonium (μ^+e^-) is emitted.**
- A muonium is ionized by laser and thermal muon beam (25 meV/c) is produced.



- **Muonium production target : Laser ablated Silica aerogel**
  - ×10 more muonium emission rate compared to flat silica aerogel.
  - Various laser-ablated structures and aerogel materials were studied.







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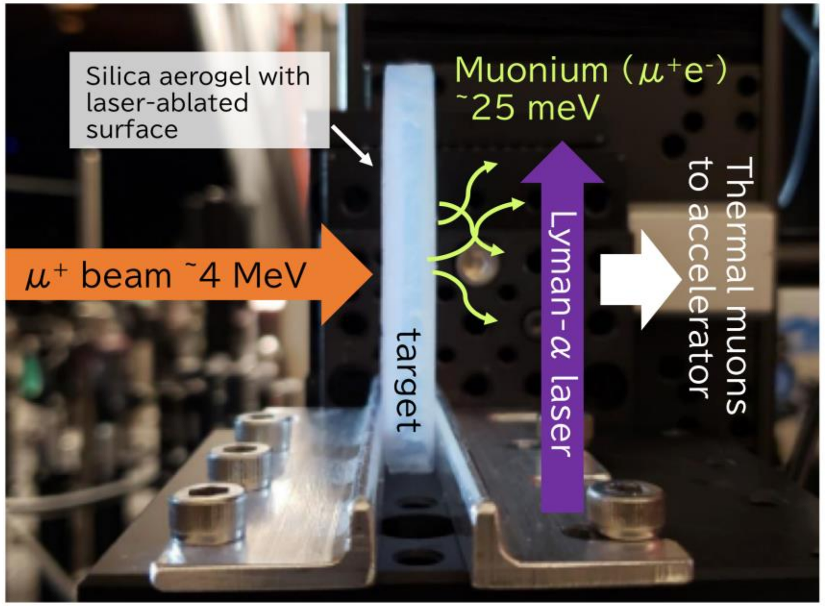
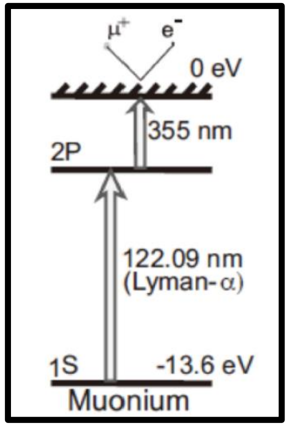
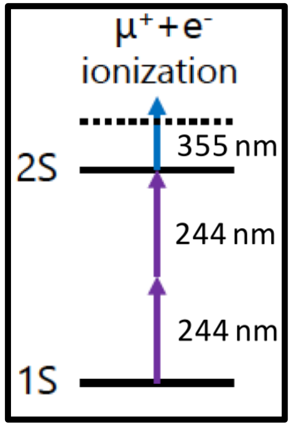


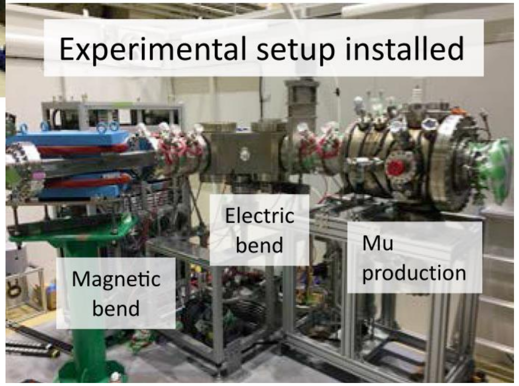
Laser-resonant ionization methods

- **Original plan : an intense 122 nm (Lyman-α) laser**
  - Efficient single photon excitation
  - Challenging 100 μJ Lyman-α laser development

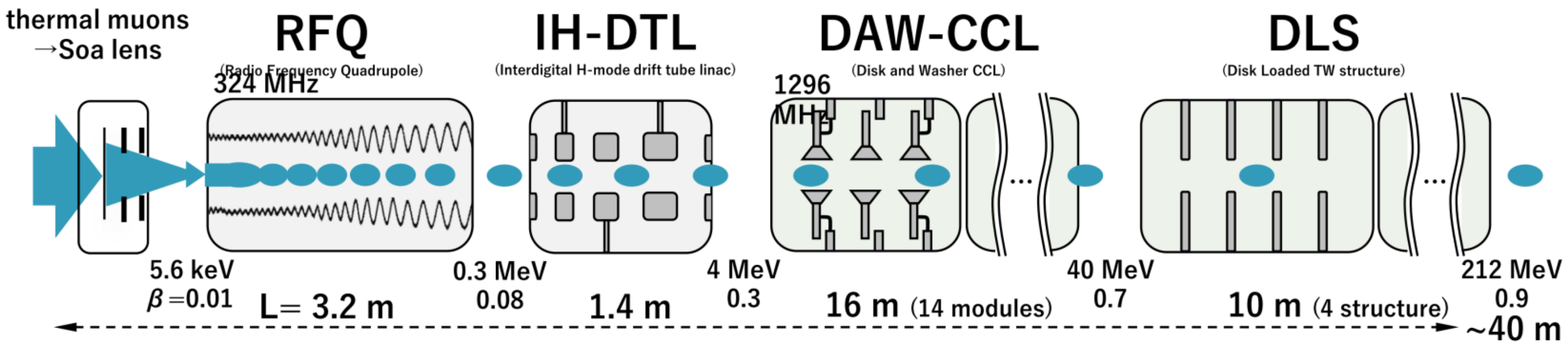


- **Plan B : ionization scheme with 244 nm laser**
  - Established laser technology
  - Collaboration with the muonium1S-2S spectroscopy measurement experiment

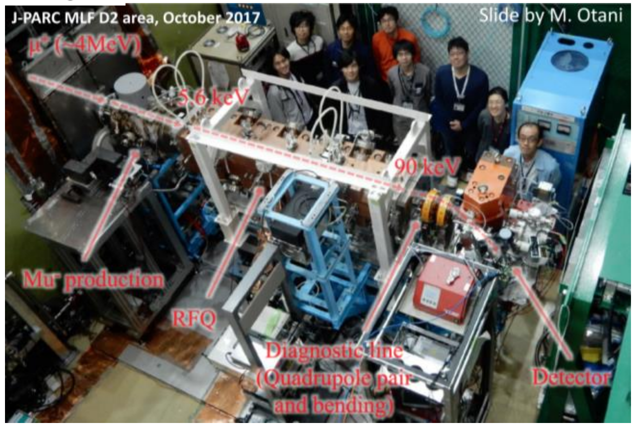




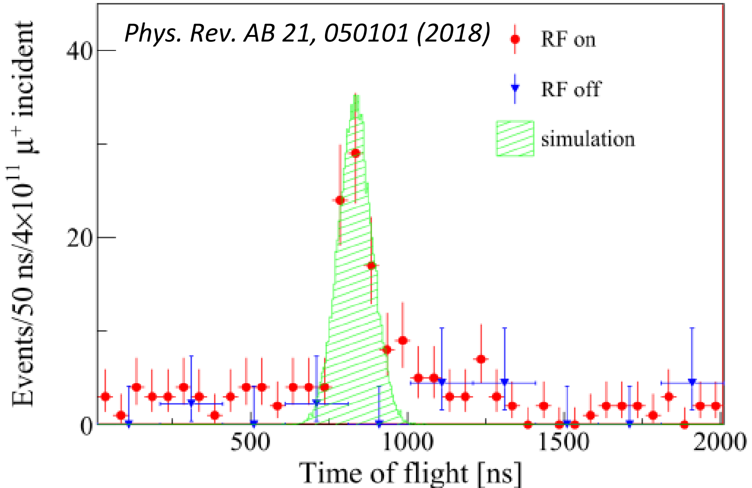
③ Muon Acceleration



World 1st acceleration of muons by RFQ



- Thermal muons are reaccelerated up to 300 MeV/c by **muon LINAC**.
  - Fast acceleration to avoid muon decay loss
  - No emittance growth.
- Different cavity to realize fast re-acceleration through wide β region.
- **World's 1st acceleration of μ in Mu^- (= $\mu^+e^-e^-$) in 2018 by RFQ**
  - Acceleration of thermal μ is planned in 2023 by RFQ



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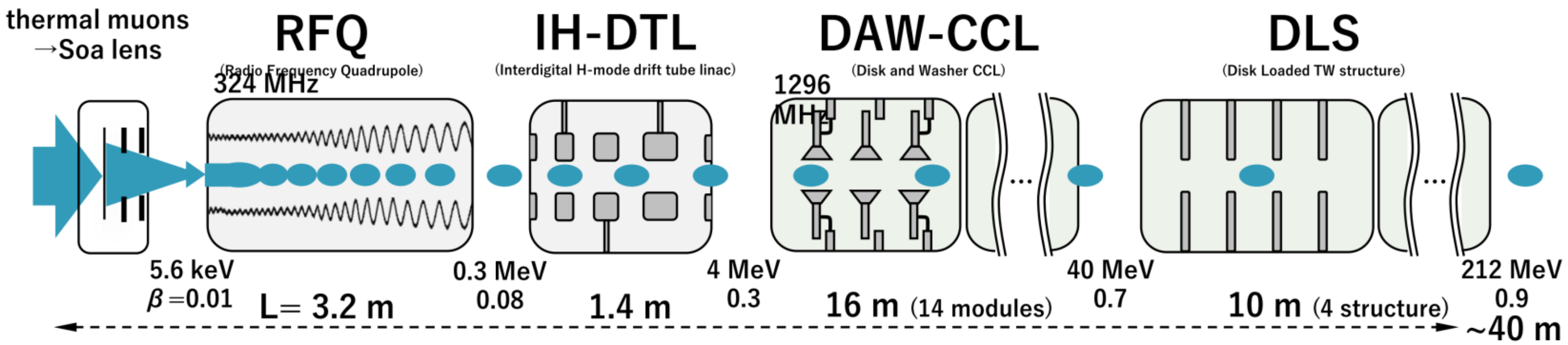
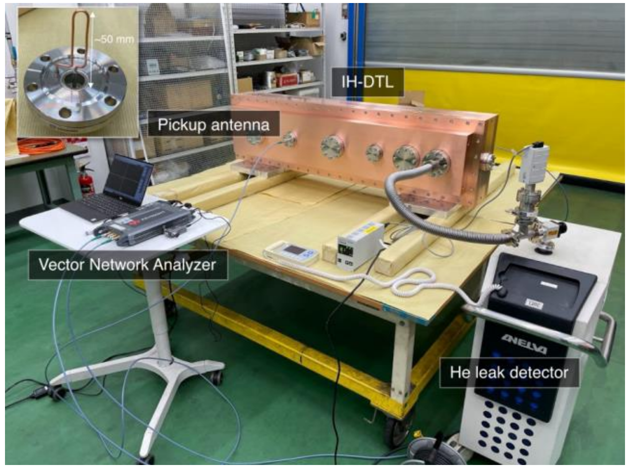


- The rest of acceleration cavities are designed

  and their performances are being evaluated with prototypes.
  - IH-DTL : Fabrication of real-type was completed.
  - DAW-CCL : 1st tank is being fabricated.
  - DLS : prototypes will be fabricated FY2022
- R&Ds for beam monitor system is also ongoing.
  - *Phys. Rev. Accel. Beams, 23,022804(2020)*

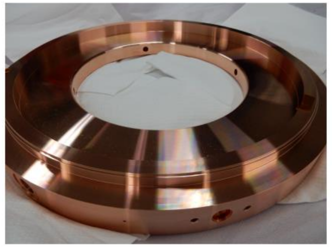
IH-DTL (real-type)



1st tank of DAW-CCL

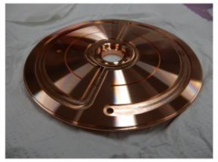
Washer 1,2 (×2)

Disk1



Stem with washer

Cooling channel

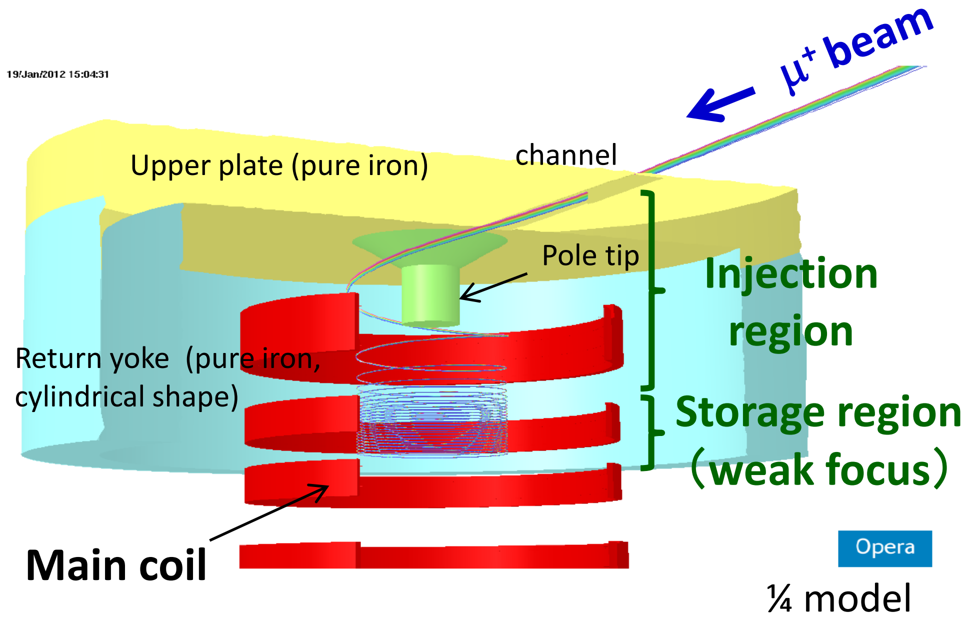


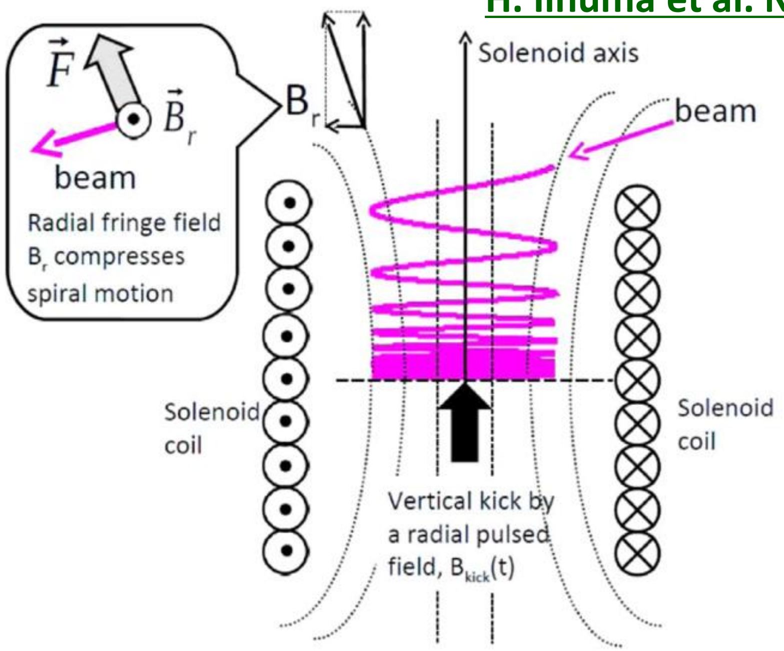
Stem with disk

④ 3D-Spiral Beam Injection

- For injection of muon beam into compact storage ring,
  3D-spiral injection scheme has been invented.
  - Smooth connection between **injection** and **storage regions.**
  - **Pulsed magnetic kicker** to guide muon beam into stable orbit.
  - **Weak-focusing magnetic field** to control muon beam within a few cm.

H. Iinuma et al. NIMA 832 (2016) 51



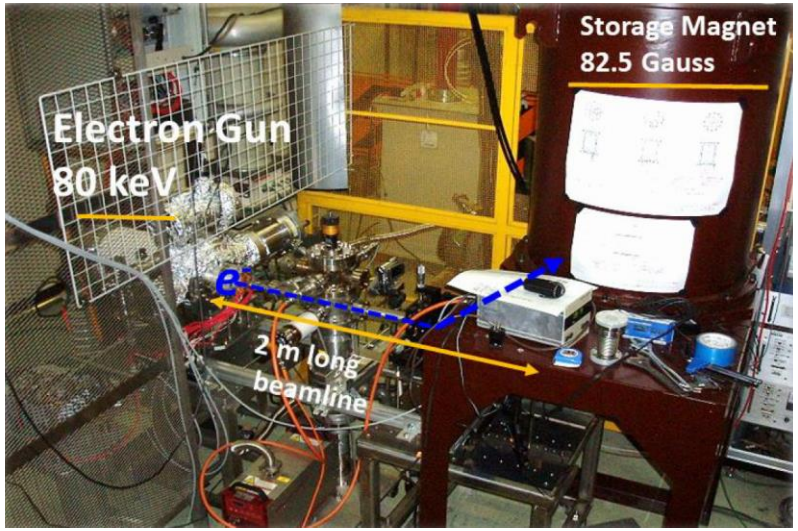


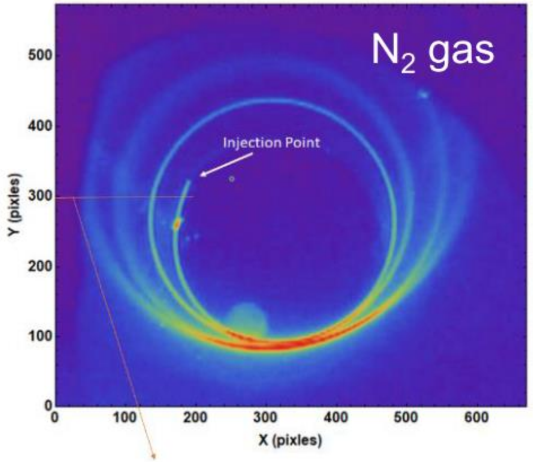
➢ **Higher injection efficiency : ~85%** ⇔ 3-5% @BNL E821 [PRD73 072003 (2006)]

④ 3D-Spiral Beam Injection

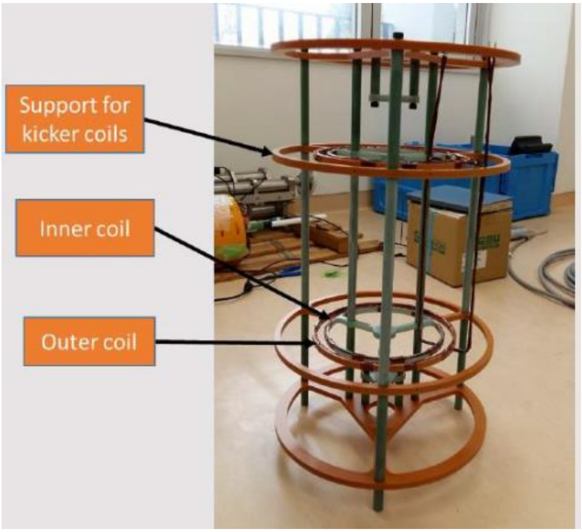
- Demonstration experiment of the injection scheme with low momentum electron beam is progressing well.
  - Visualize 3D spiral beam trajectory with CCD camera.
- Prototypes of kicker was fabricated and will be demonstrated.

Demonstration experiment setup



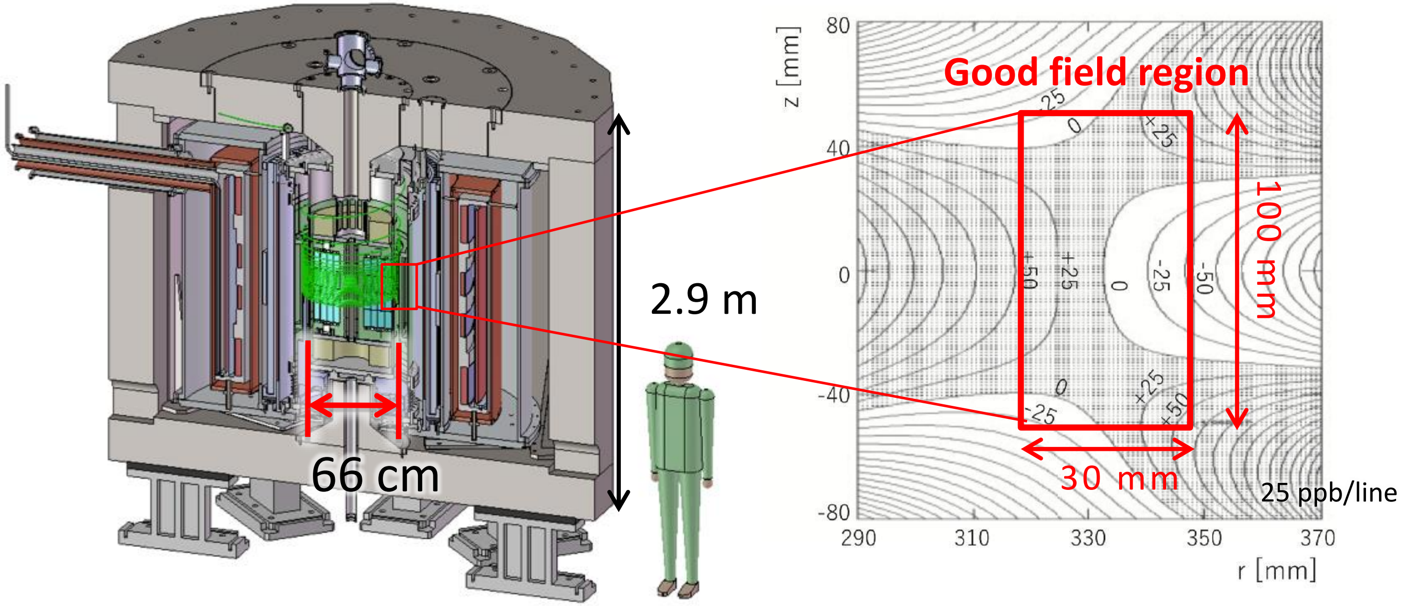


Prototypes of kicker



⑤ Muon Storage Magnet

- 3T MRI-type superconducting solenoid magnet is used to store a muon beam.

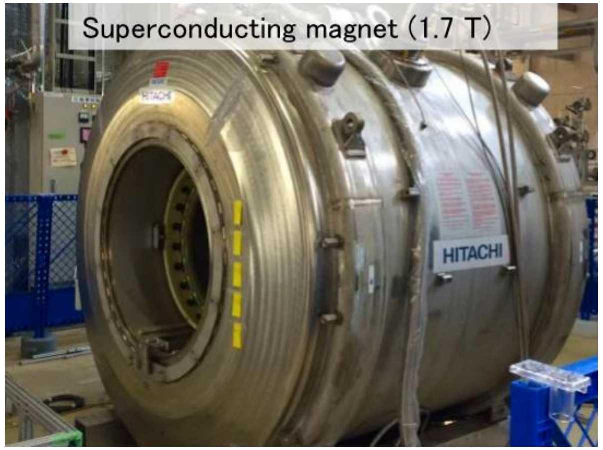


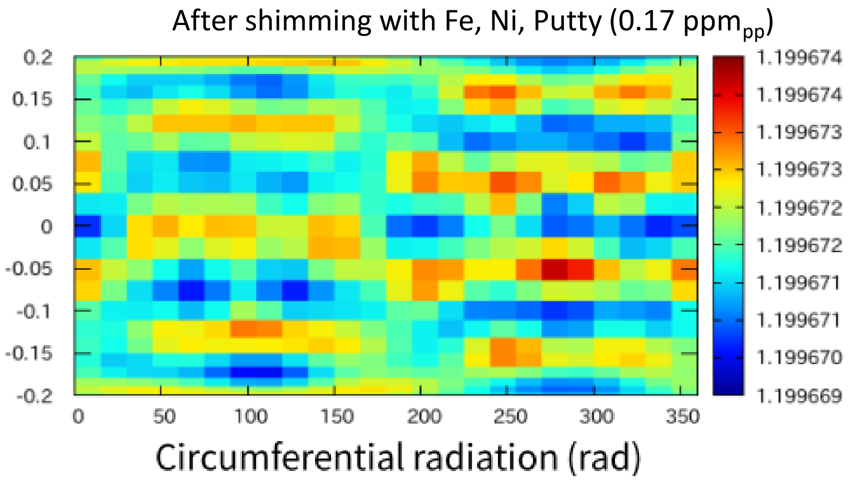
M. Abe et. Al., Nuclear Inst. and Methods in Physics Research A890, 51 (2018)

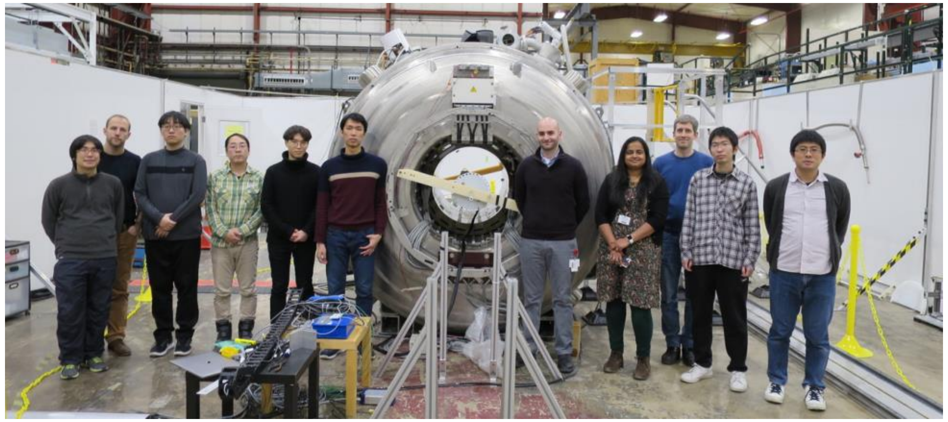
⑤ Muon Storage Magnet

- High uniformity of the magnetic field is achieved by **shimming**.
  - Local uniformity of 1 ppm was confirmed with the magnet used in the MuSEUM experiment.
- **High precision NMR probes** are used for field measurement.
  - Cross-calibration is underway in a joint research project between Japan and the US.
  - An accuracy of 15 ppb has been achieved.

Cross-calibration of FNAL and J-PARC field probes



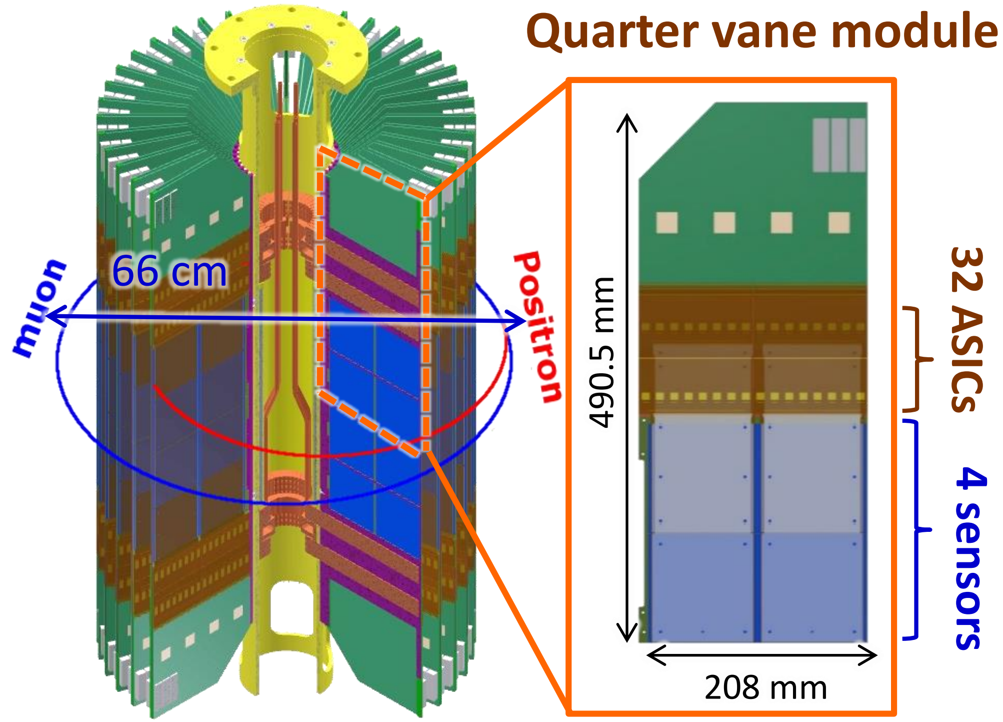




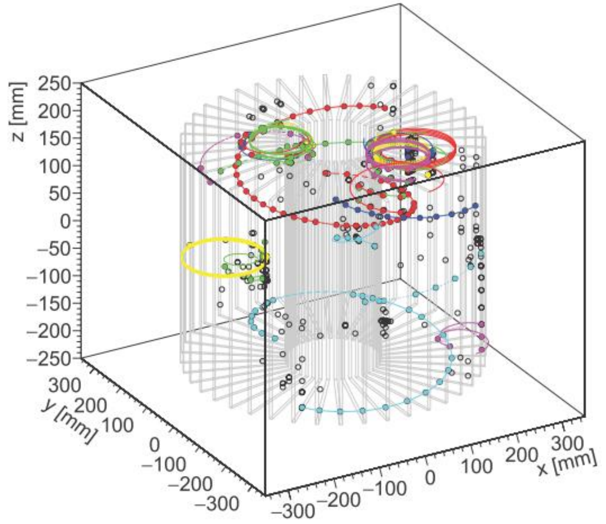
⑥ Positron Detector

- Positron tracks are measured by **Silicon-strip detector**.
  - Positrons with a momentum of 100-300 MeV/c
  - High hit rate capability (6 tracks/ns)
    and stability over early to late rate changes (1.4 MHz → 10 kHz)
  - Design optimized for pulsed beam.

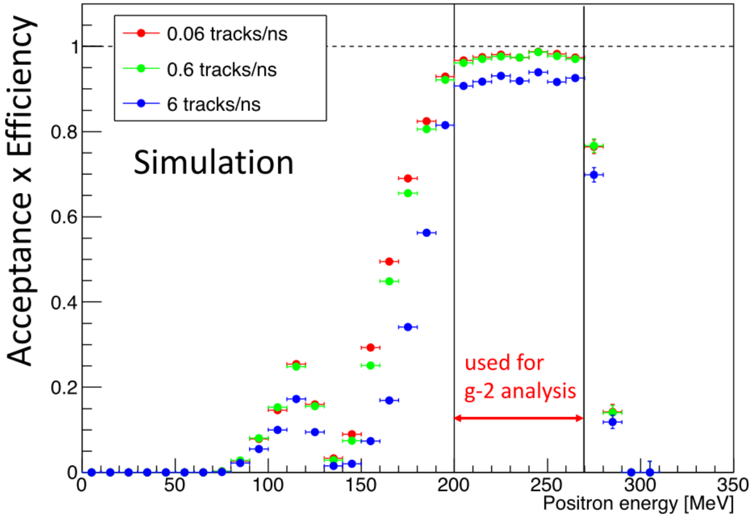
Quarter vane module



Event display with 25 muons

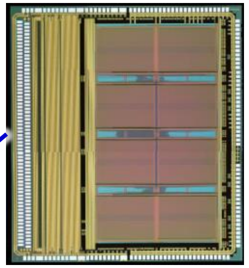


Reconstruction efficiency



⑥ Positron Detector

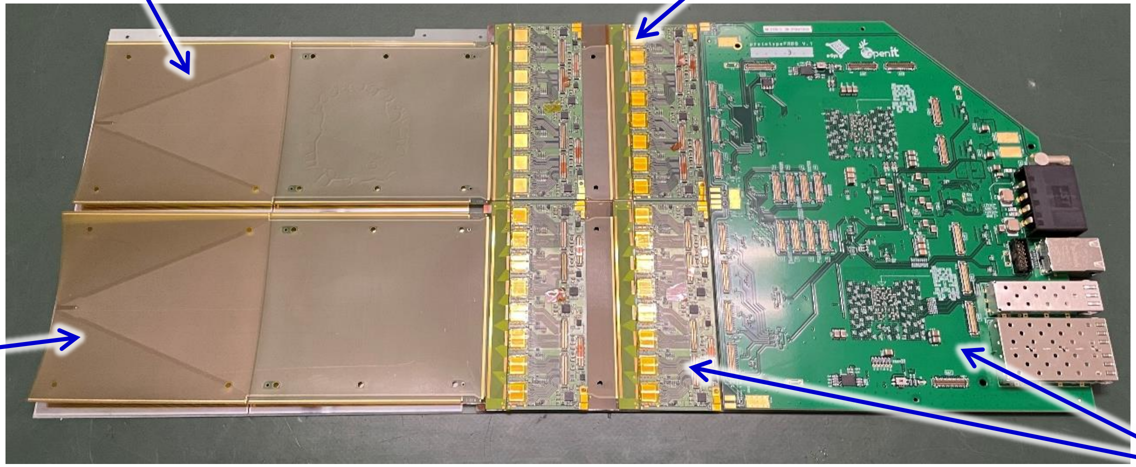
- Major components are in or completed the mass-productions.
- Prototype module is being assembled.



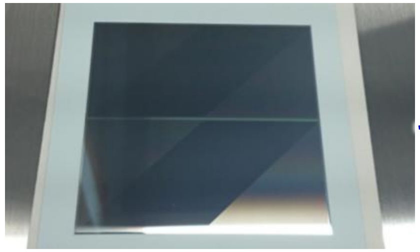
Readout ASIC (SliT)
- Silterra 180-nm CMOS process
- Binary output with sampling interval of 5 ns
- Mass-production : done

IEEE TNS 67, 2089 (2020)

Flexible printed circuit boards
- Made by Fujikura Ltd.
- Mass-production : done



Quarter vane module



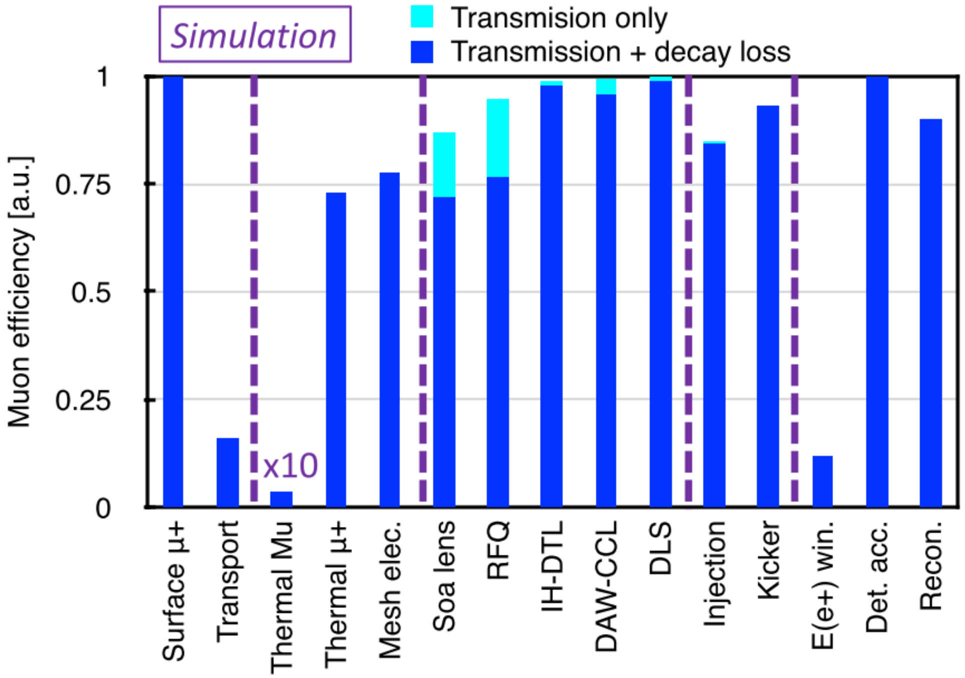
Silicon-strip sensor
- Made by Hamamatsu Photonics K.K., S13804
- Strip pitch : 190 μm
- Mass-production : ongoing

Rigid printed circuit boards
- Prototypes were fabricated and being tested.

Statistics Estimation

Prog. Theor. Exp. Phys. 2019, 053C02

- Overall efficiency : 1.3×10^{-5}
- Assuming 2.2×10^{7} sec (~255 days) of data taking, total number of reconstructed e^{+} is 5.7×10^{11}.



Expected uncertainties

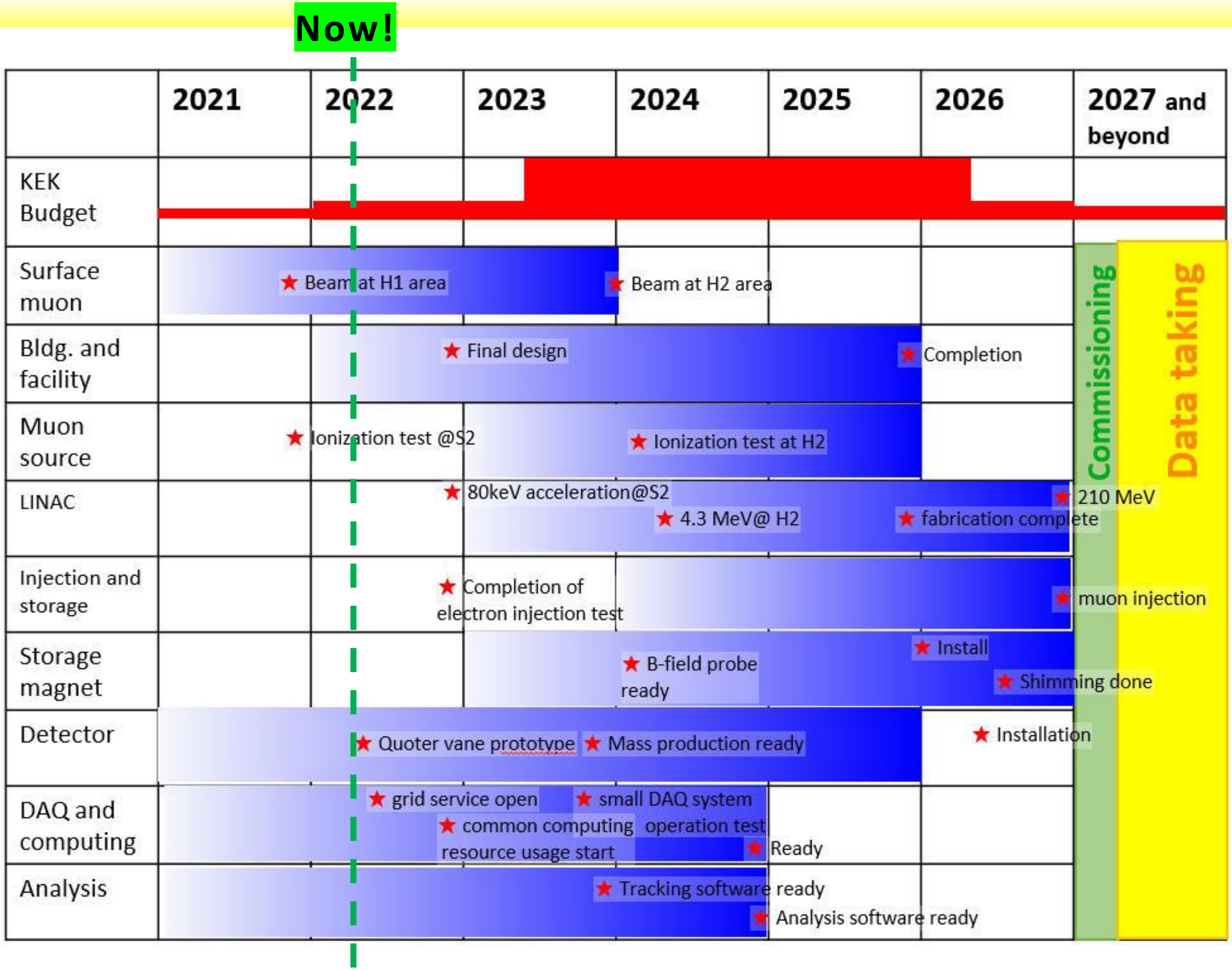
	Stat.	Syst.
δa_{μ} [ppb]	450	<70
δ EDM [10^{-21} e・cm]	1.5	0.36

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

➢ **2-year running will reach the BNL precision of a_{μ}.**

➢ **Systematic uncertainties will be much smaller than the statistical ones.**

Schedule



Reach the BNL precision in ~2-year running

J-PARC Muon g-2/EDM Collaboration

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

Collaboration board (CB)
Chair: Seonho Choi

Executive board (EB)
Spokesperson: T. Mibe

Subgroups

- **Surface muon beam** — leader: T. Yamazaki, N. Kawamura
- **Ultra-slow muon** — leader: K. Ishida, G. Marshall
- **LINAC** — leader: Y. Kondo, M. Otani
- **Injection and storage** — leader: H. Iinuma
- **Storage magnet, field measurements**
- **Detector** — leader: T. Yoshioka
- **DAQ and computing** — leader: Y. Sato, (K. Hayasaka)
- **Analysis** — leader: T. Yamanaka

Interface coordinators

K. Ishida, M. Otani, Y. Kondo, H. Iinuma, T. Kume, Y. Sato, T. Suehara, T. Yamanaka

Committees

Speakers committee
chair: K.Ishida

Publication committee
chair: B. Shwartz

New
Welcome University of Groningen

Domestic institutes:
Kyushu, Nagoya, Tohoku, Niigata, Tokyo, Ibaraki, RIKEN, JAEA, etc.
KEK: IPNS, IMSS, ACC, CRY, MEC, CRC

The 24th J-PARC muon g-2/EDM collaboration meeting, June 8-10, 2022

Summary

- **J-PARC muon g-2/EDM experiment** aims to measure muon g-2 and EDM with a method different from BNL/FNAL experiment.
  - Low emittance muon beam with no strong focusing.
  - MRI-type storage ring with a good injection efficiency and high uniformity of local B-field.
  - Full-tracking detector with large acceptance
- The experiment is getting ready for realization.
  - Construction of new muon beam line "H-line"
  - R&Ds of the subsystem is going well.
- Expecting data taking from FY2027.