Status and prospect of the J-PARC muon g-2/EDM experiment

Kazuhito Suzuki

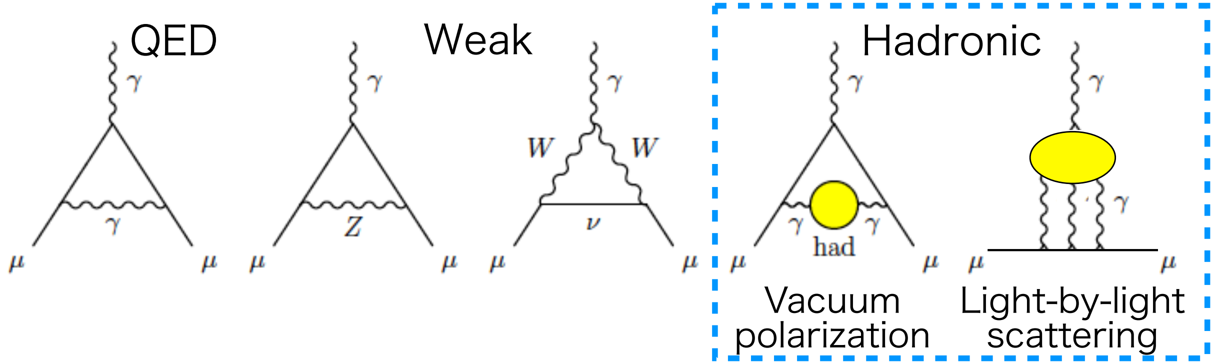
Kobayashi-Maskawa Institute, Nagoya University

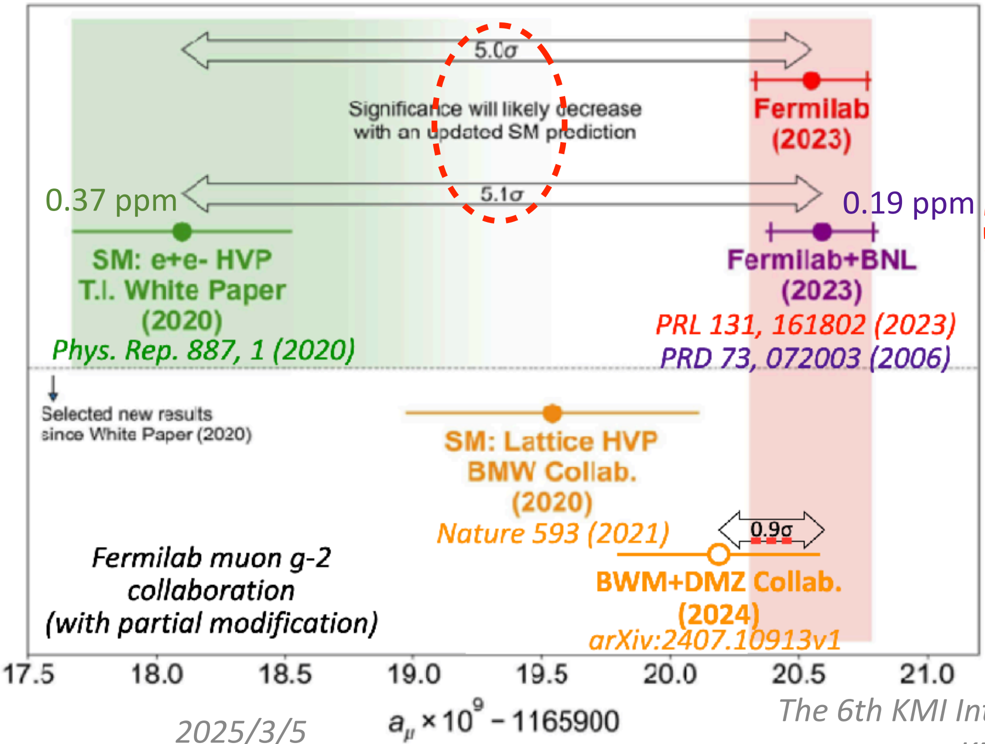
On behalf of the J-PARC muon g-2/EDM collaboration

Muon g-2 and EDM

Magnetic dipole moment anomaly (a_μ)

$$a_\mu = \frac{g-2}{2} \qquad \vec{\mu} = g\left(\frac{e}{2m}\right)\vec{s},$$





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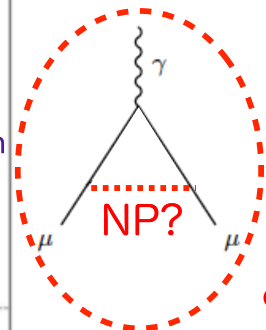

Electric dipole moment (EDM, d_μ)

$$\vec{d} = \eta\left(\frac{e}{2mc}\right)\vec{s}.$$

T-violating $d_\mu \neq 0$
→ CP-violation in the lepton sector
→ New Physics.

	Standard model	Experimental searches
$\lvert d_\mu \rvert$ [ecm]	O(10^{-42}) [1]	< 1.8×10^{-19} (95% C.L.) [2] < 1.9×10^{-20} (ThO) [3] < 8.9×10^{-21} (HfF) [4]

[1] Mass-ratio deduction to d_e of M. Pospelov and A. Ritz, PRD 89, 056006 (2014); [2] BNL E821, PRD 80, 052008 (2009); [3] Y. Ema et al., PRL 128, 131803 (2022); [4] Y. Ema, High Energy News, Vol. 42, No. 2 (2023).

- *Good probes for new physics.*

Muon g-2 and EDM

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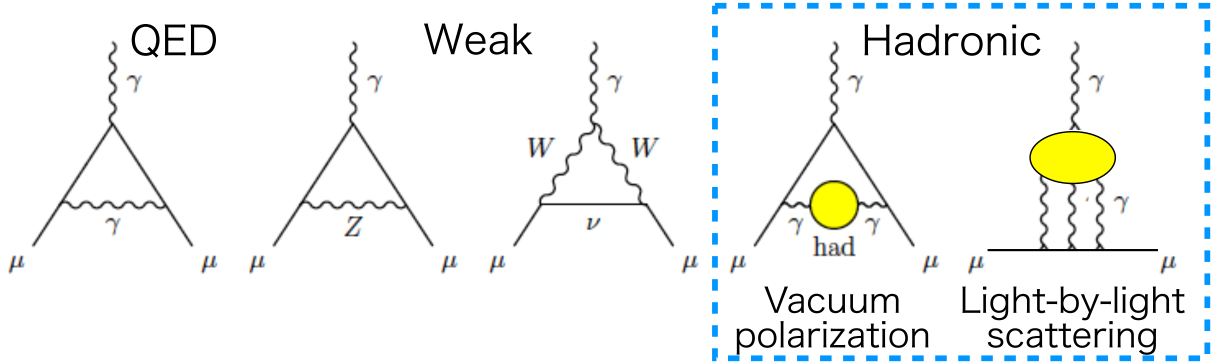

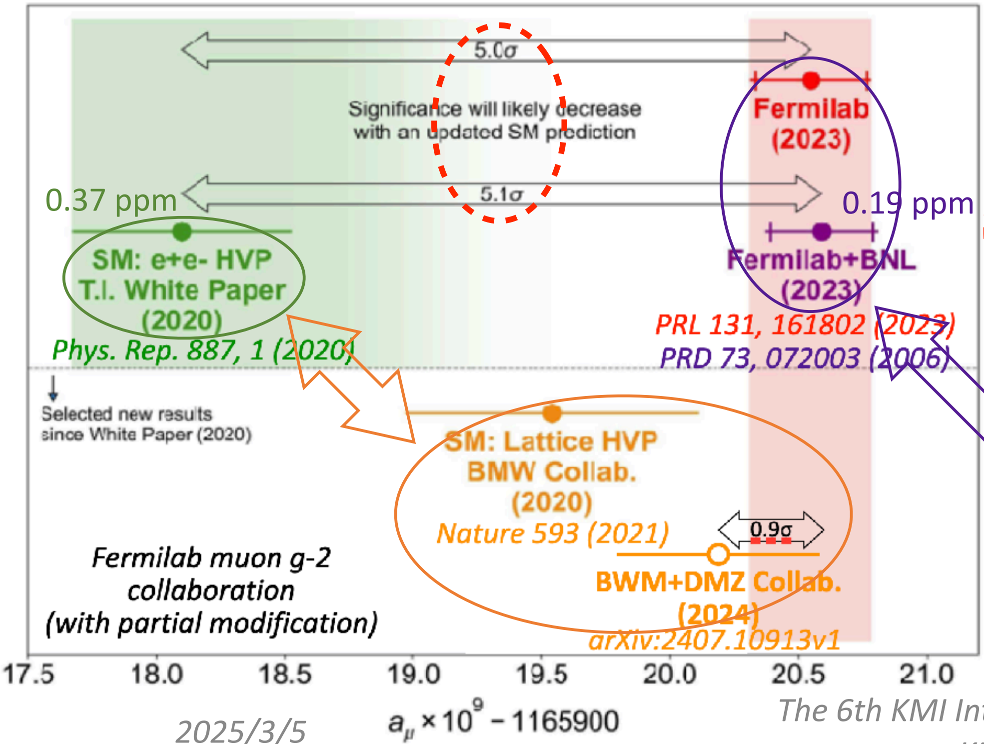

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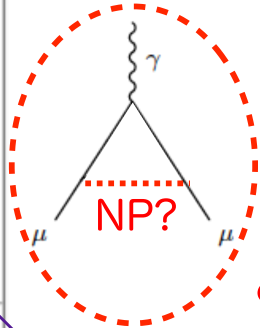
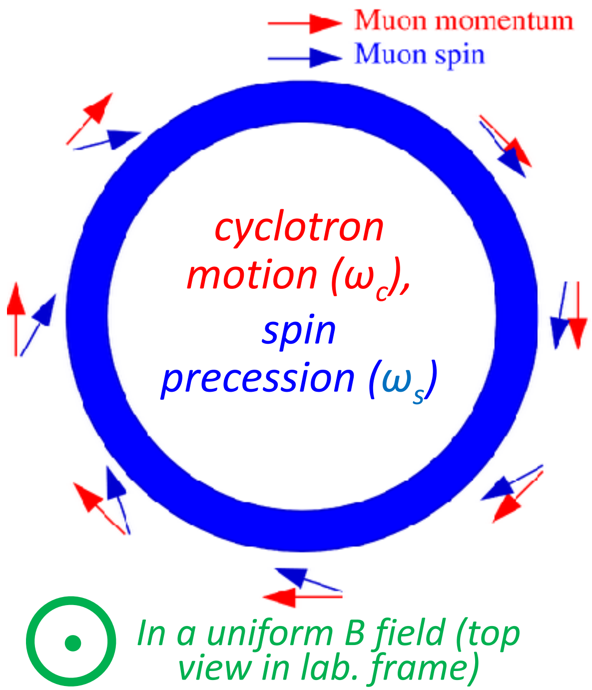


- *Good probes for new physics.*
- *Testing with various approaches enhances our understanding of a_μ.*

J-PARC muon g-2/EDM exp.

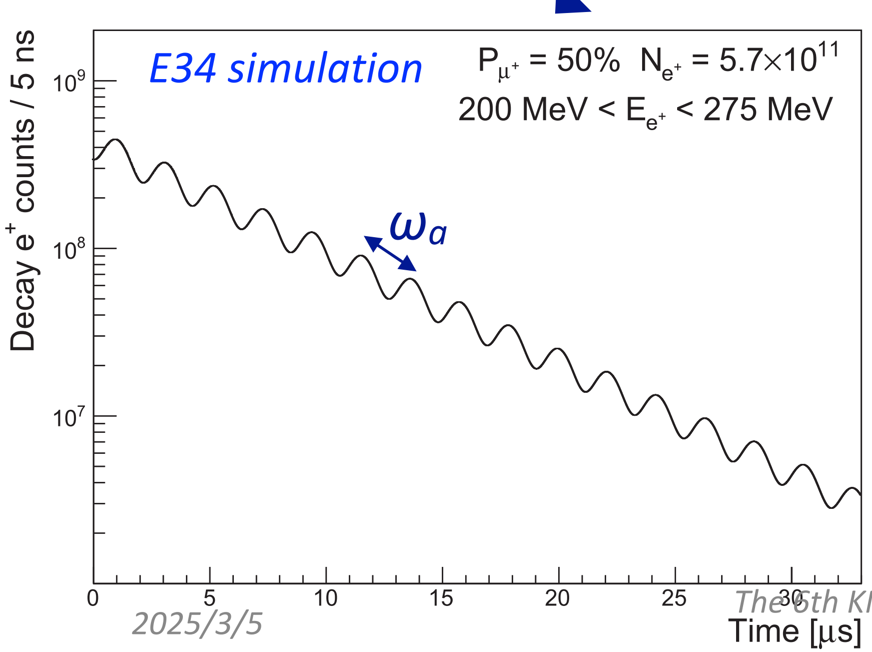
Experimental principle

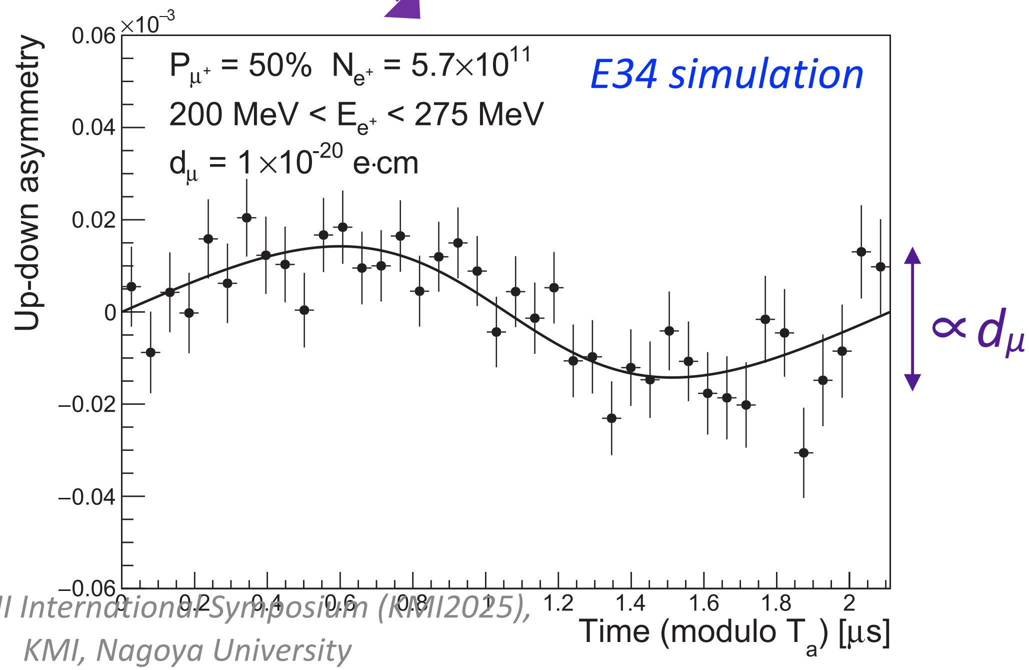
- *Muon storage in a uniform magnetic field*
  - *Horizontal "beat" frequency (a_μ),*
  - *Vertical oscillation amplitude (d_μ),*
  - *Using decay positron tracking and B-field meas.*



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

ω_a $(= \omega_s - \omega_c)$ ω_η

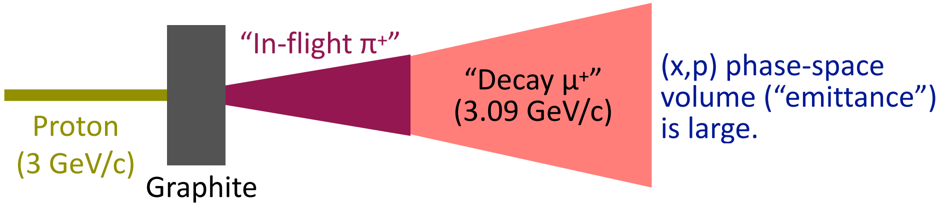




Experimental approach

BNL/Fermilab experiments

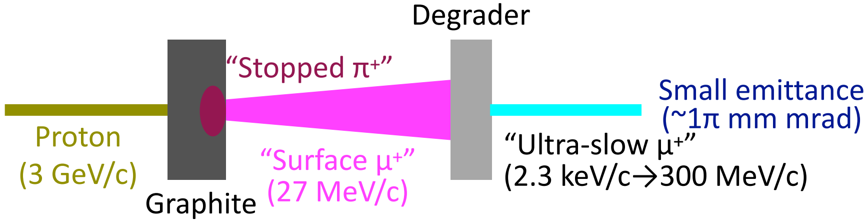
- Conventional muon beam



→ Strong E-focusing & "magic γ"

J-PARC experiment

- Small-emittance muon beam



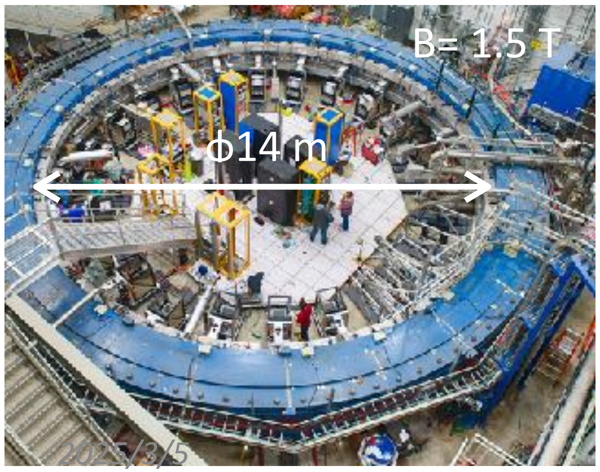
→ Weak B-focusing & any γ

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

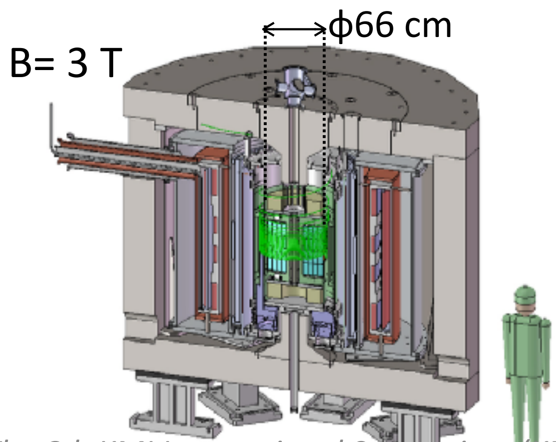
⇨ $$-\frac{e}{m}\left[a_\mu \vec{B} + \frac{\eta}{2}\left(\vec{\beta}\times\vec{B} + \frac{\vec{E}}{c}\right)\right]$$

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

→ Large storage ring



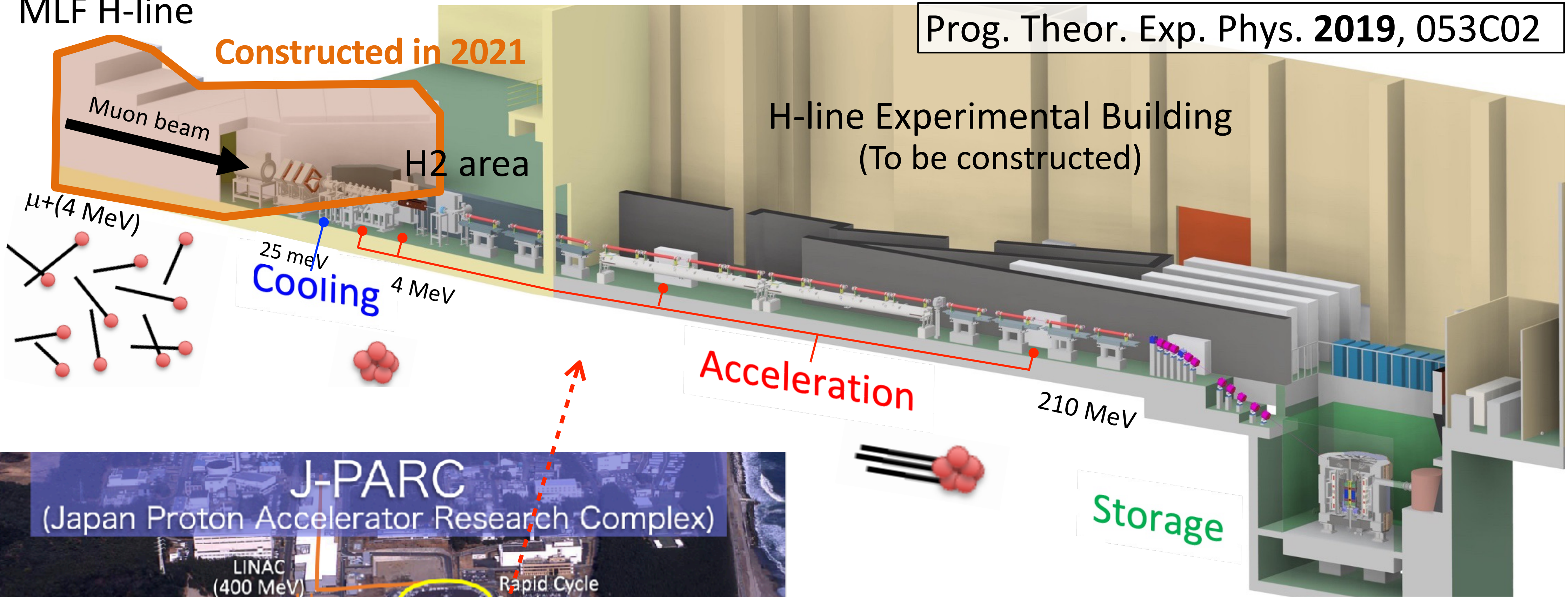
→ Compact storage magnet

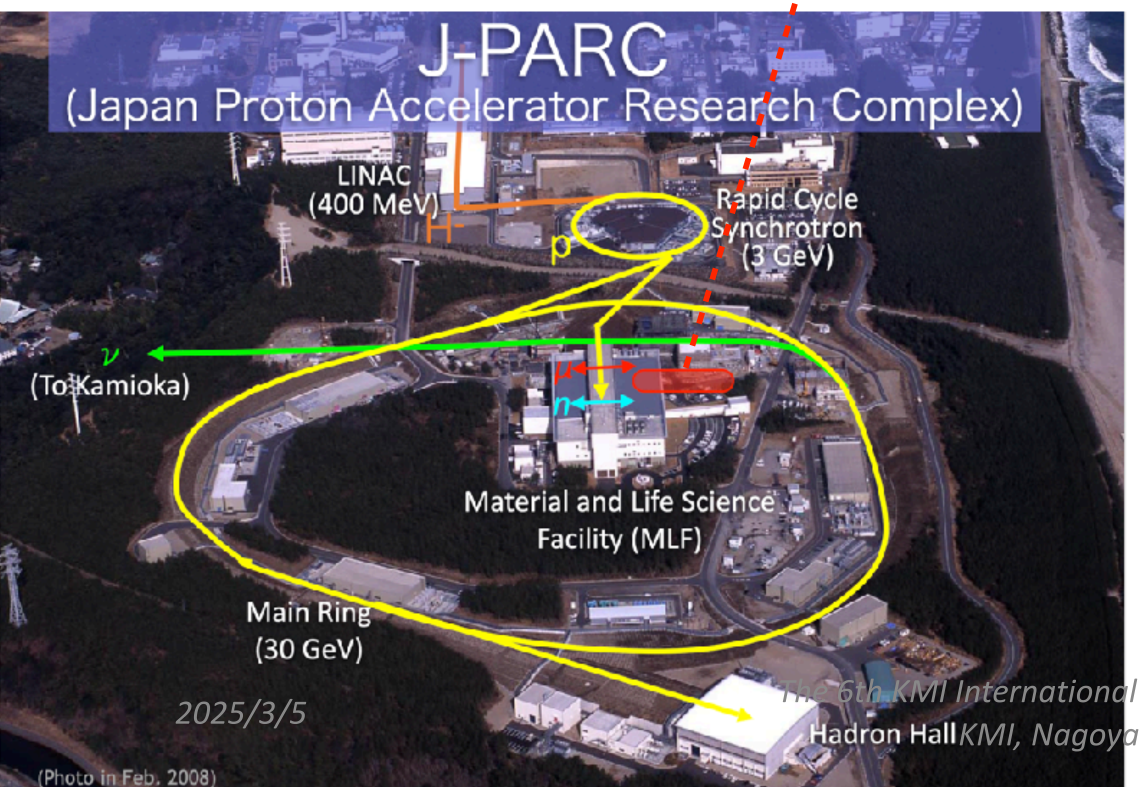


- Existing MRI technology with an excellent local uniformity,
- High injection efficiency,
- Full-tracking capability with large acceptance,
- a_μ and d_μ simultaneous meas.

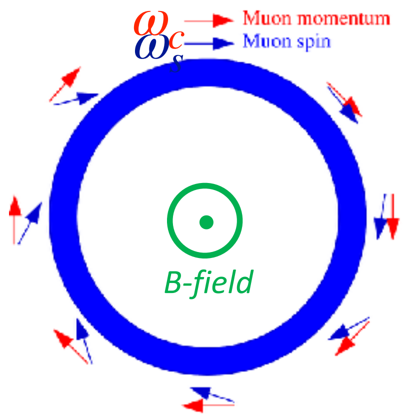
J-PARC muon g-2/EDM experiment

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



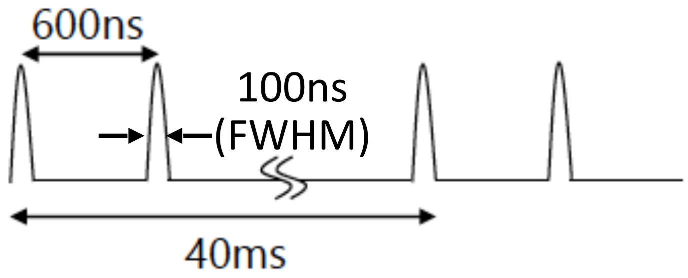


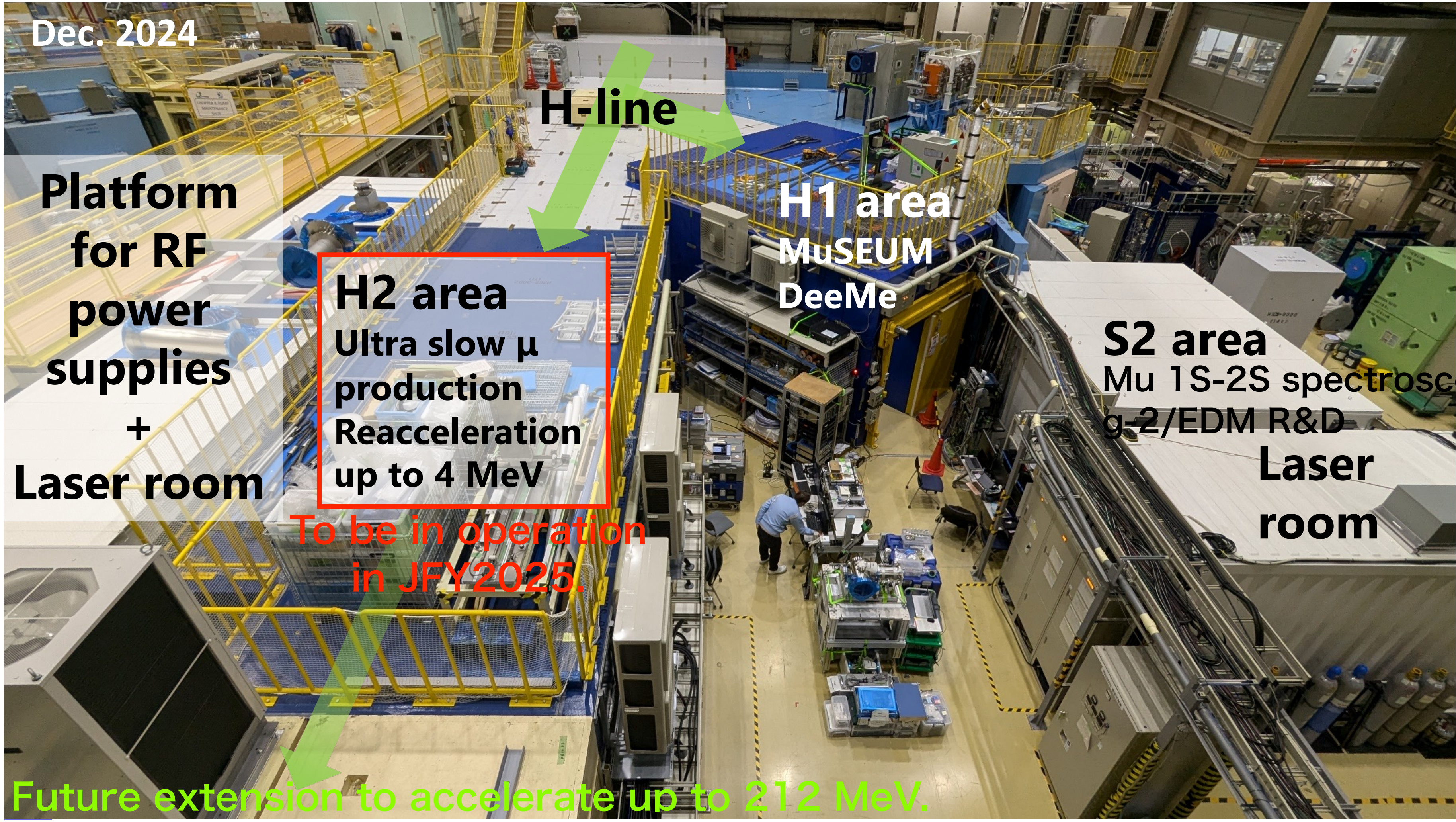
Aims to launch the experiment in JFY2030.



Muon beam line & experimental area

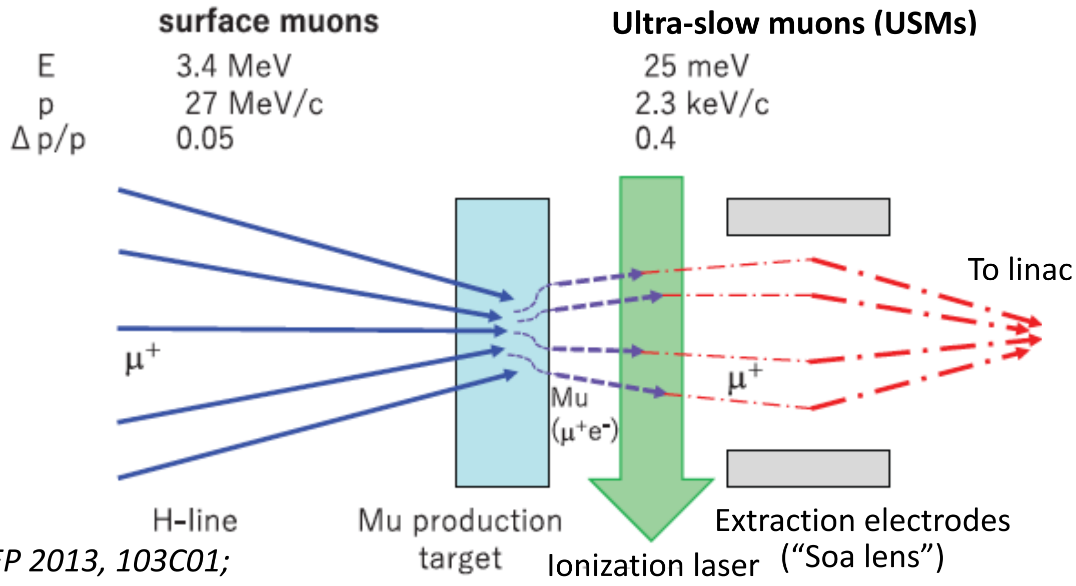
- *MLF H2 area*
  - *Double-pulsed surface muons (25 Hz),*
  - *Design intensity: ~10^8 μ^+/s.*





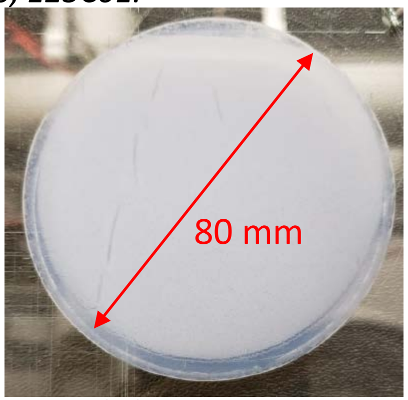
Cooling: ultra-slow muon source

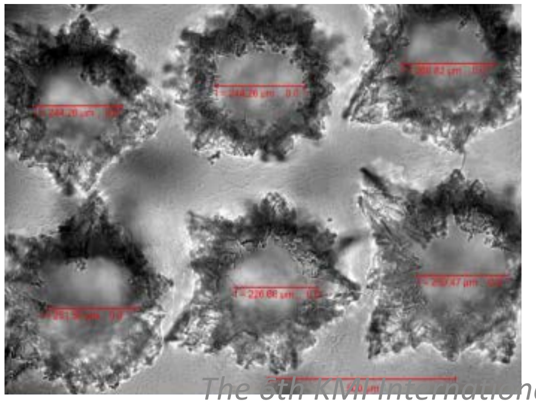
- *Generation of the "ultra-slow muons" (USMs)*
  - *Cooling the surface muons to the thermal energy at room temperature,*
  - *Using thermal muonium (μ^+e^-, Mu) and laser-resonant ionization.*



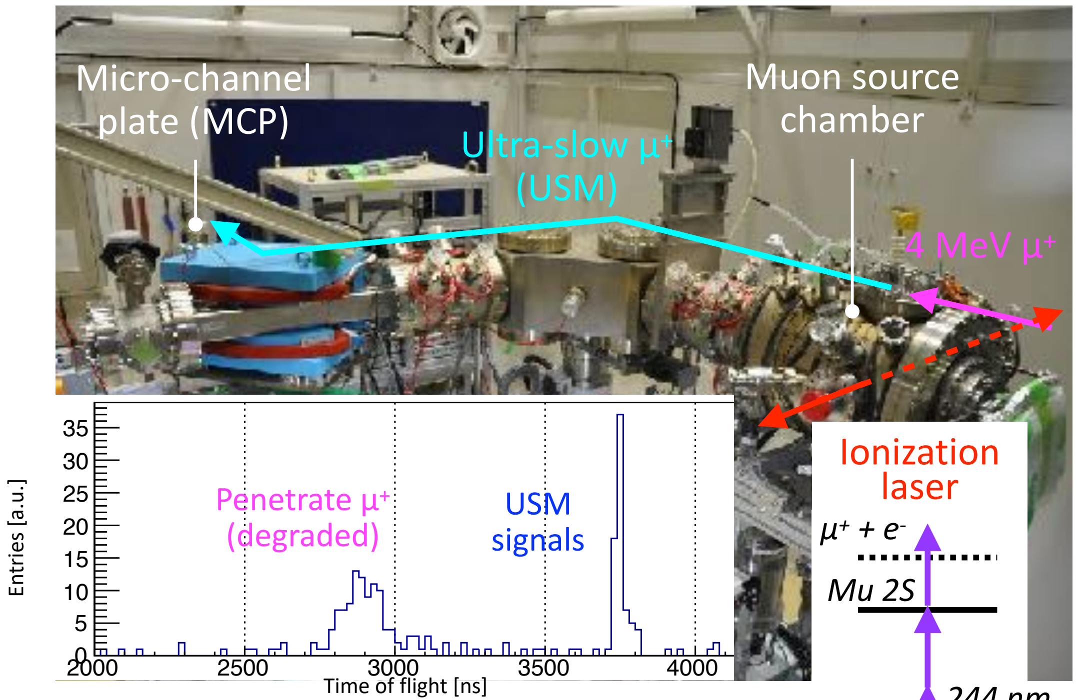
PTEP 2013, 103C01;
PTEP 2014, 091C01;
PTEP 2020, 123C01.

Laser-ablated silica aerogel





USM generation in Mu 1S-2S laser spectroscopy

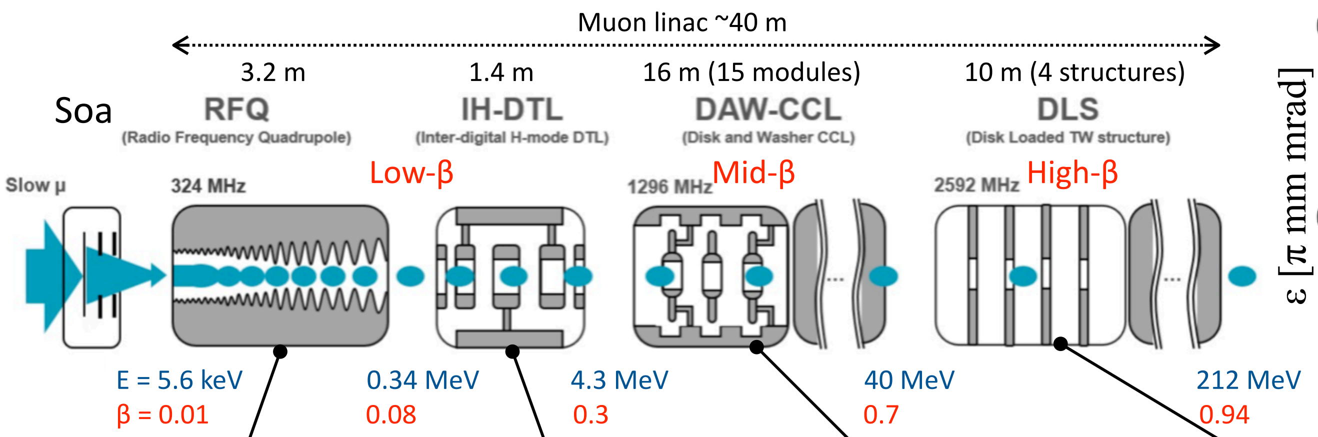


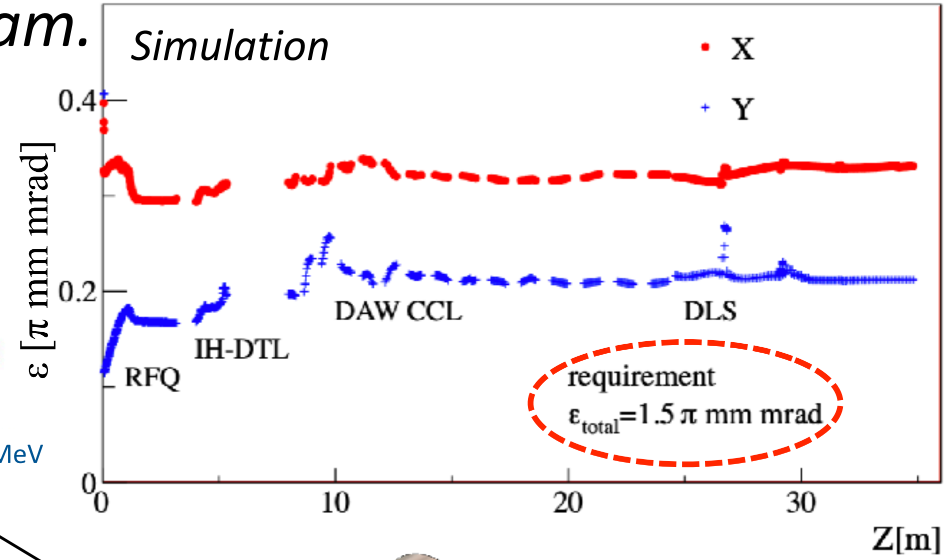
Developed by Okayama Univ.

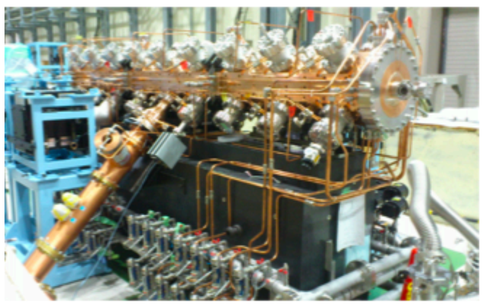
- *Successfully generated the USMs.*
  - *Ready to use for the acceleration.*
- *Further developments for stable operation and higher yield.*

Acceleration: muon linac

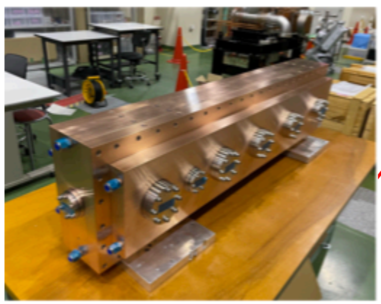
- *Acceleration of the USMs suppressing the emittance growth*
  - *4-stage linac, from the p-like acceleration to the e-like one.*
  - *Leading to the small-emittance muon beam.*

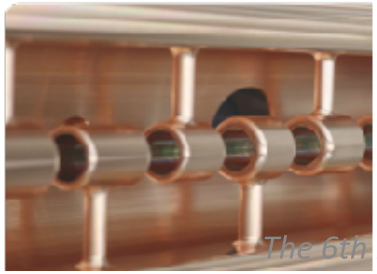






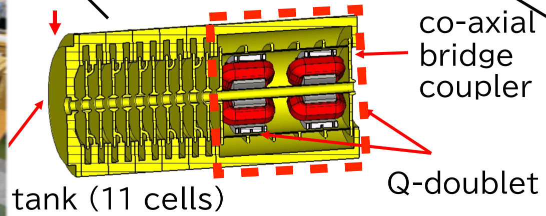
Ready for acceleration

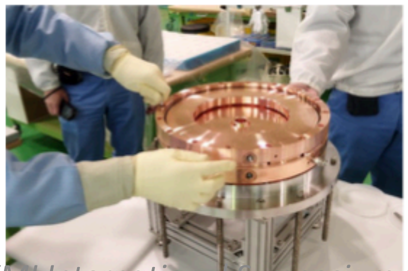


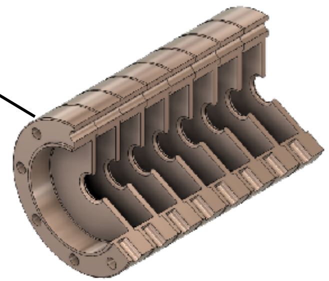


Cavity is ready for acceleration.

See A. Kondo's poster.





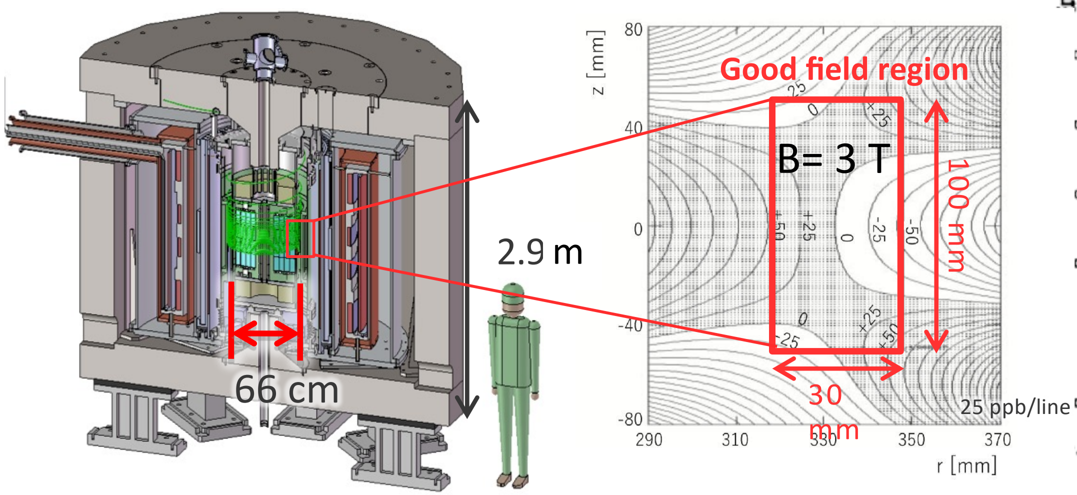


DAW-tank and DLS-cell prototypes were tested.
→ Production.

Designing and prototyping of remaining components are on-going.

Storage: magnet & injection scheme

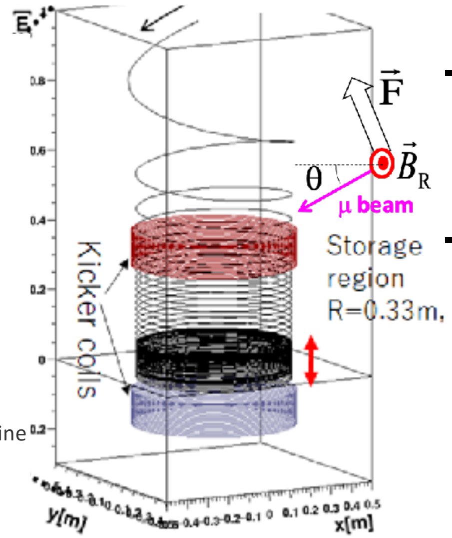
- *A compact storage magnet*



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

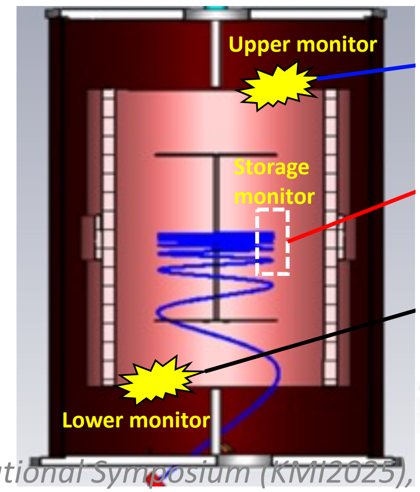
- *MRI-type superconducting solenoid (B= 3 T),*
- *Local B-field uniformity < 0.1 ppm,*
- *Weak B-focusing: n-index~ (1.5±0.5)x10^{-4}.*
- *Developments of the shimming technique and field monitoring system are in progress.*

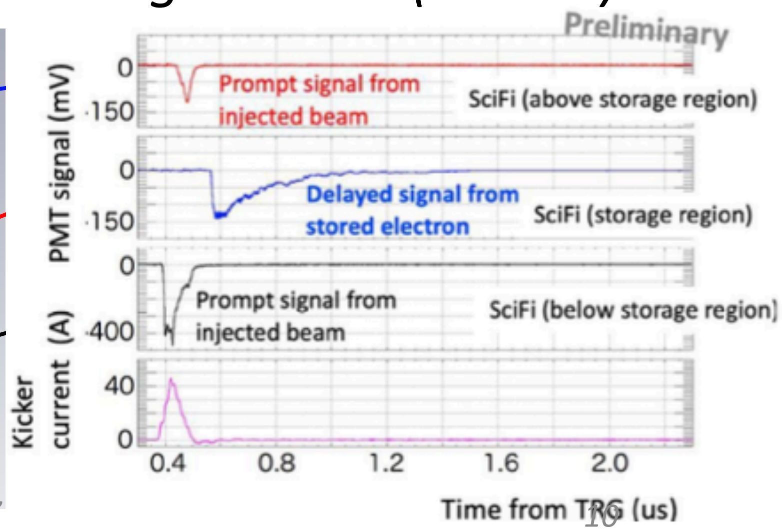
- *3D spiral injection with vertical kicks*



NIM A832 (2016), 51-62.

- *To inject into the small orbit with high efficiency.*
- *Extensive studies are on-going for*
  - *Injection parameters,*
  - *Kicker bench tests.*
- *The injection scheme has been successfully demonstrated using e$^-$ beam (80 keV).*

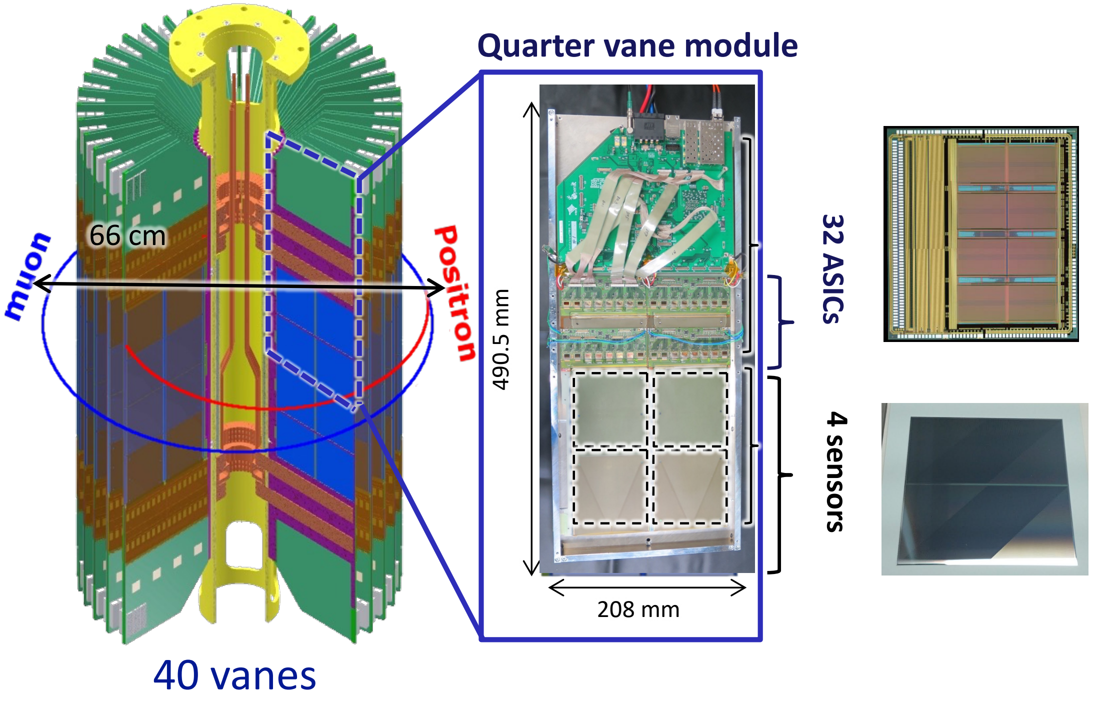




H. Iinuma et al., PASJ2022 FROB05

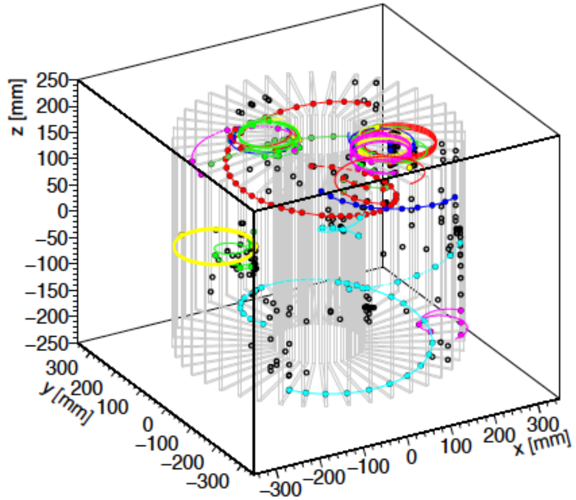
Storage: positron tracking detector

- *Radially arranged silicon strip sensors*

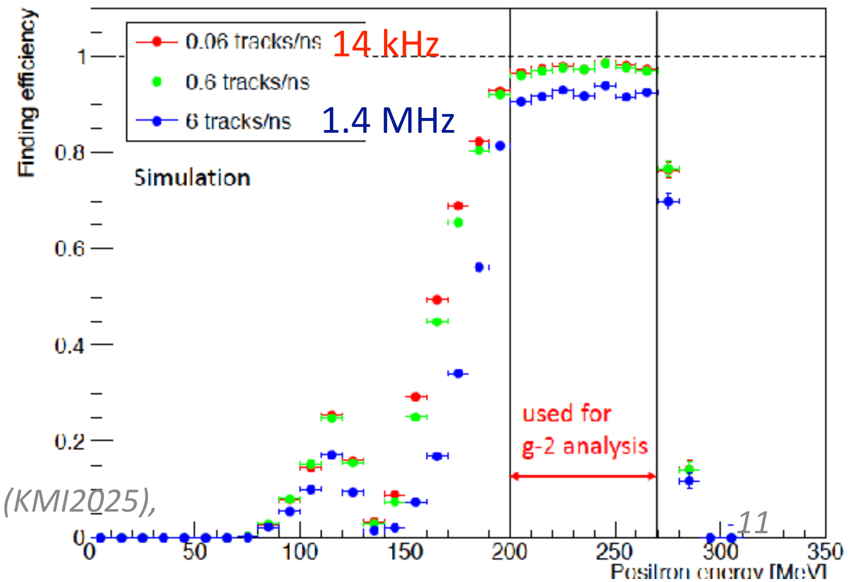


  - *Most of the components are in or completed the mass production.*
  - *Quarter vane prototypes are being tested under the experimental conditions.*
    - ▸ *Static B-field, pulsed kicker B-field, cooling test.*

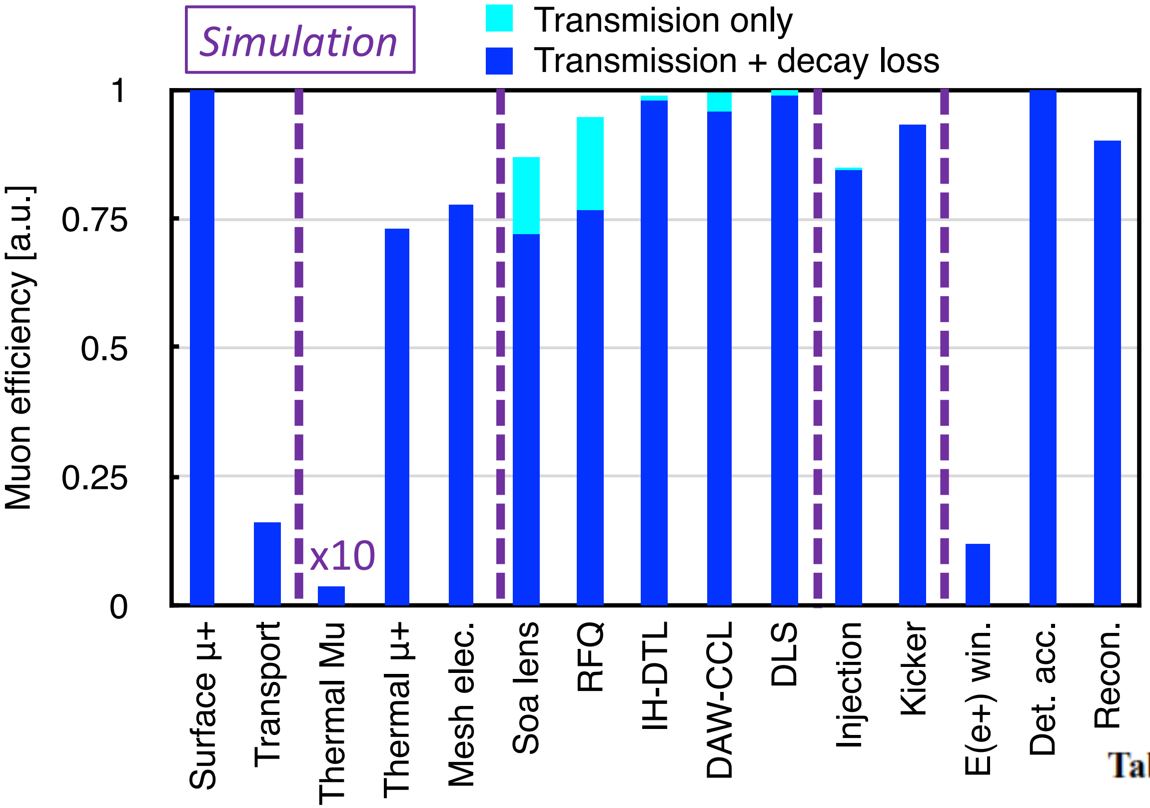
  - *Reconstruct the e⁺ momentum vector from tracking.*



  - *Performance stability over the rate change is required.*



Expected sensitivities



- *Overall μ^+ efficiency: 1.3×10^{-5}.*
- *~2-year running will reach the BNL precision of a_μ assuming*
  - *2.2×10^7 s data taking time,*
  - *1 MW proton beam,*
    - *5.7×10^{11} e^+'s for analysis,*
  - *50% μ^+-polarization.*

Expected uncertainties

	Stat.	Syst.
δa_μ [ppb]	450	< 70
δEDM [10^{-21} e・cm]	1.5	0.36

Table 6. Estimated systmatic uncertainties on a_μ.

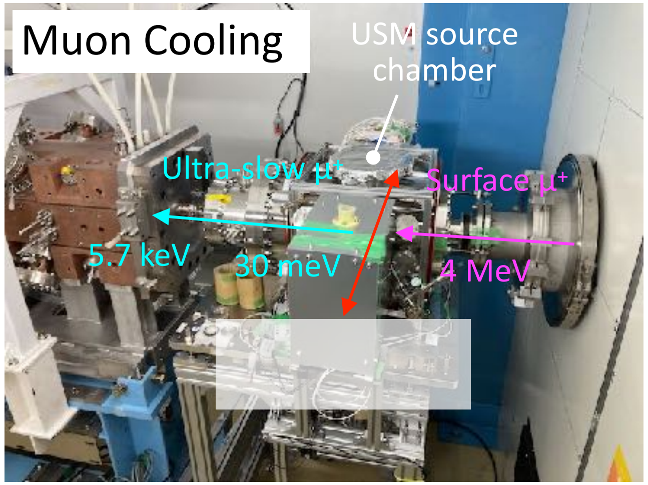
Anomalous spin precession (ω_a)		Magnetic field (ω_p)	
Source	Estimation (ppb)	Source	Estimation (ppb)
Timing shift	< 36	Absolute calibration	25
Pitch effect	13	Calibration of mapping probe	20
Electric field	10	Position of mapping probe	45
Delayed positrons	0.8	Field decay	< 10
Diffential decay	1.5	Eddy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

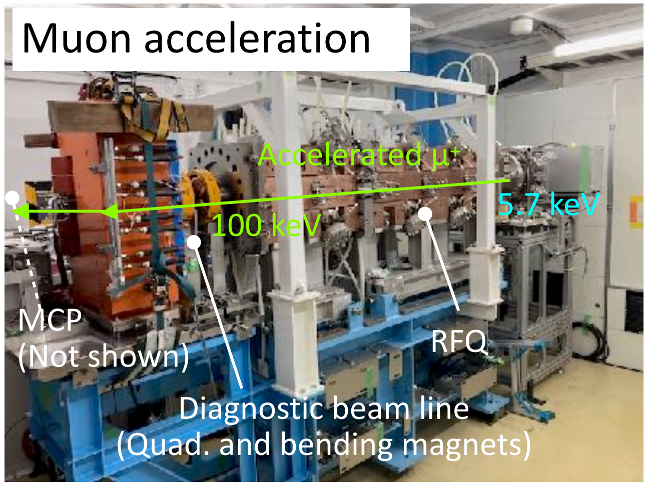
Systematic uncertainties will be much smaller than the statistical ones.

Achievement in JFY2024

- ***Muon RF-acceleration***
  - *For the first time in the world,*
  - *From 5.7 keV to 100 keV.*

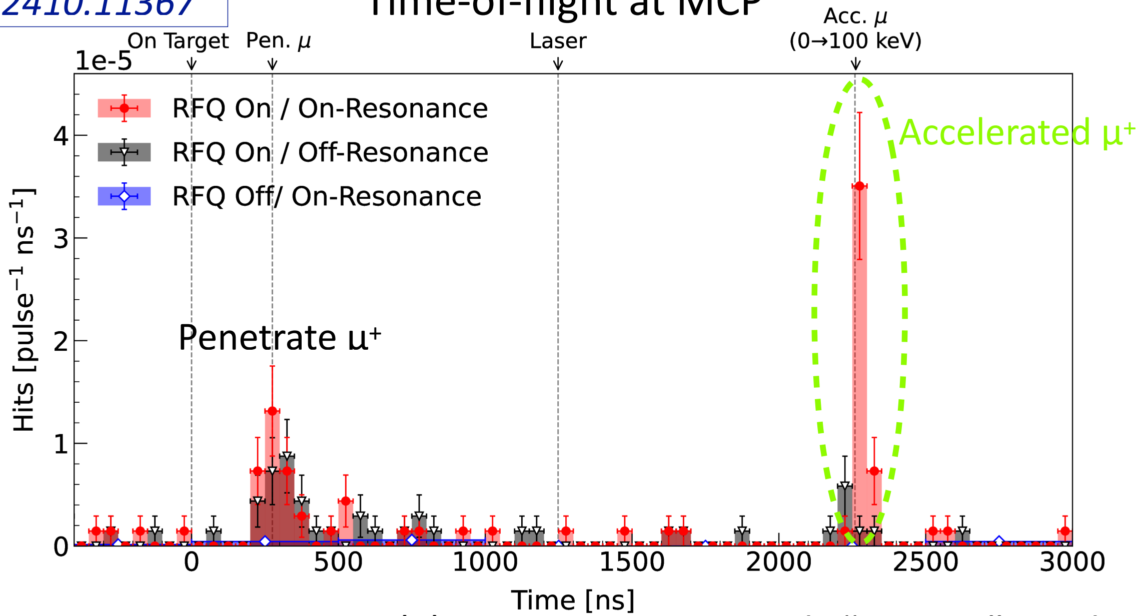
MLF S2 area (April 2024)



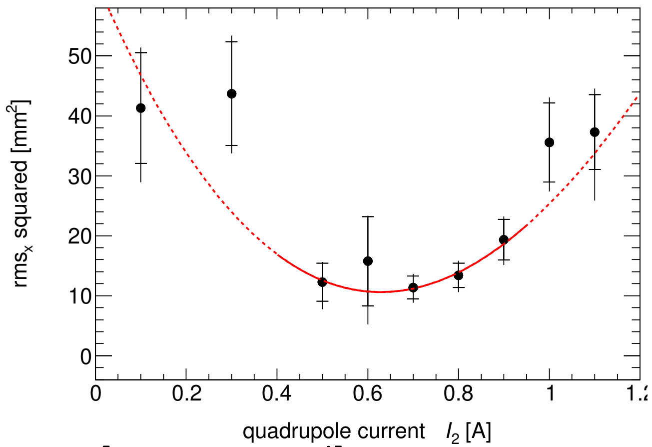


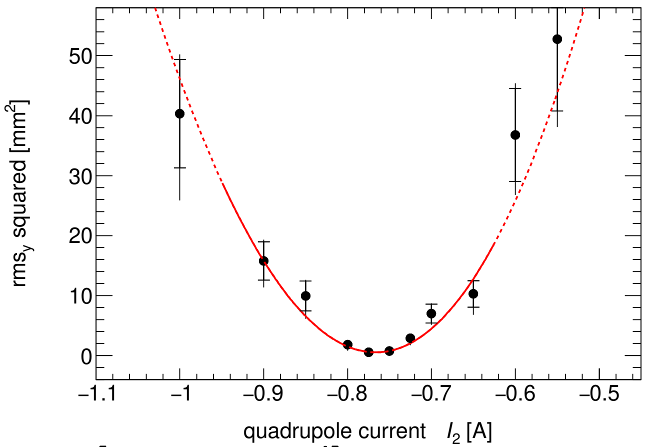
arXiv: 2410.11367

Time-of-flight at MCP



Transverse emittance (ε) measurements with “Q-scan” method

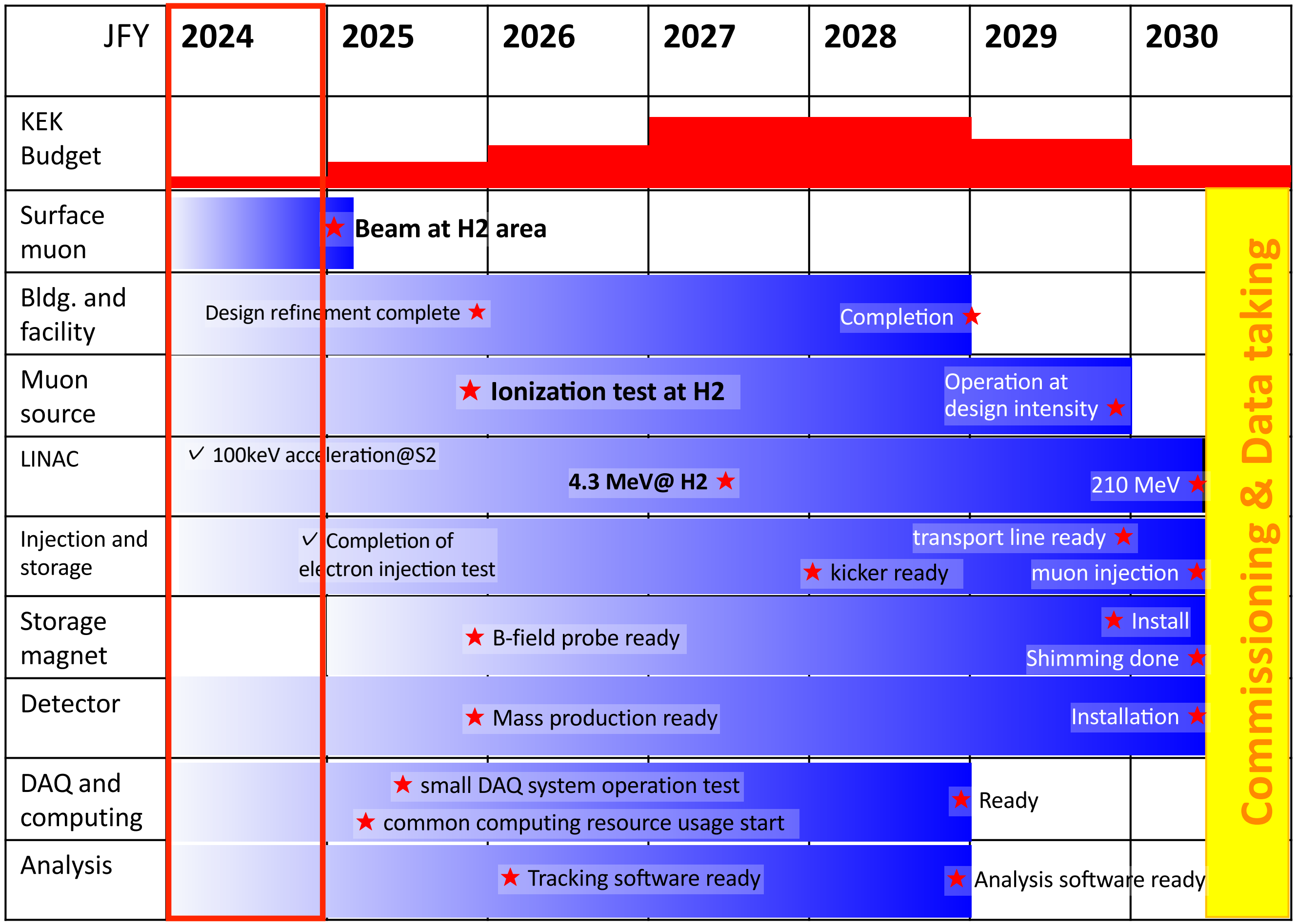




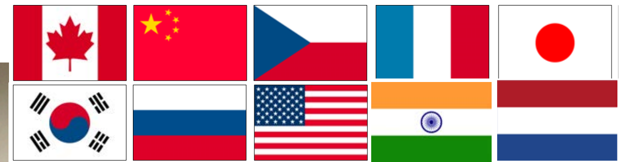
ε_x [π mm・mrad]
$= 0.85 \pm 0.25$ (stat.) $^{+0.22}_{-0.13}$ (syst.)
x 1/200
was 170 (before cooling, simulation).

ε_y [π mm・mrad]
$= 0.32 \pm 0.03$ (stat.) $^{+0.05}_{-0.02}$ (syst.)
x 1/400
was 130 (before cooling, simulation).

Intended schedule & collaboration



- *Various milestones are set in each JFY.*
  - *Developments and implementations,*
  - *Demonstrations for the upstream sections,*
  - *Overall commissioning is planned to begin in JFY2030.*
- *> 100 collaborators push forward the experiment.*
  - *From 10 countries,*
  - *Still growing.*

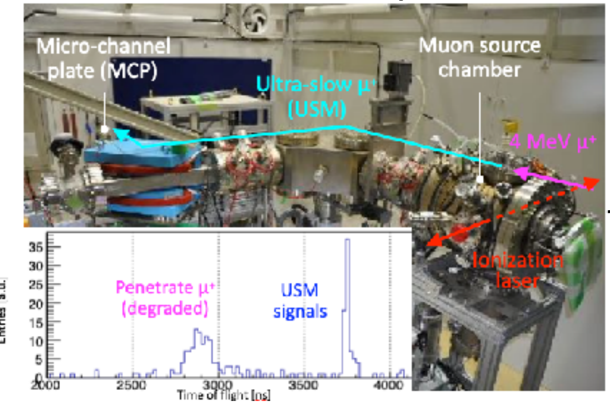


KMI contributions in 2023-2024 (1)

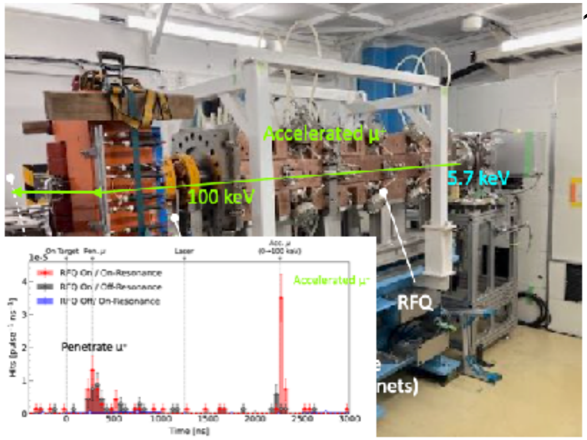
Prog. Theor. Exp. Phys. **2019**, 053C02

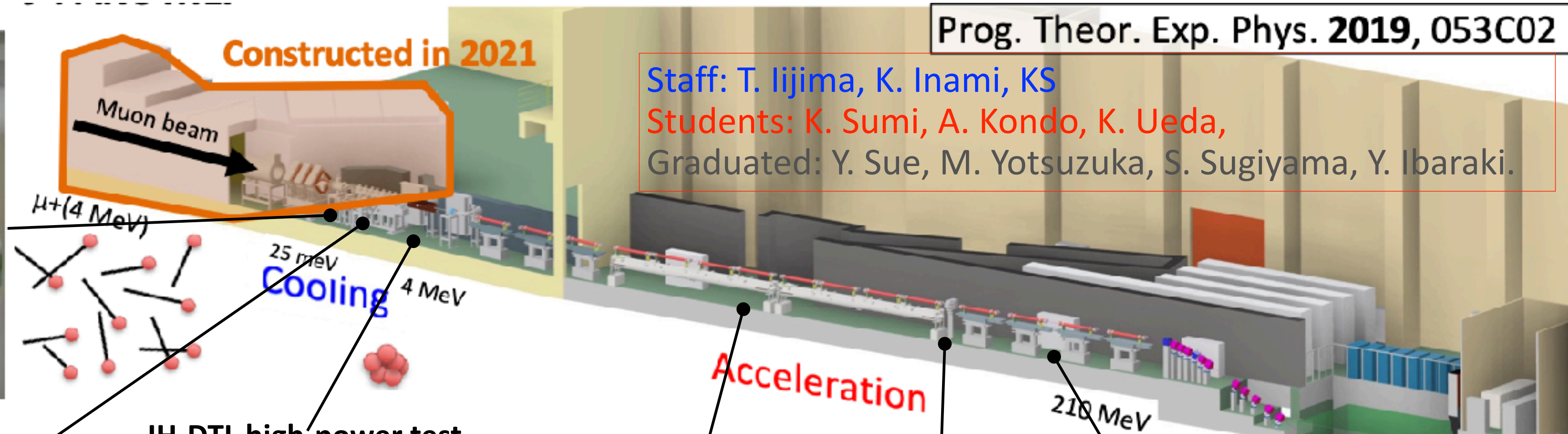
Staff: T. Iijima, K. Inami, KS
Students: K. Sumi, A. Kondo, K. Ueda,
Graduated: Y. Sue, M. Yotsuzuka, S. Sugiyama, Y. Ibaraki.

USM source development

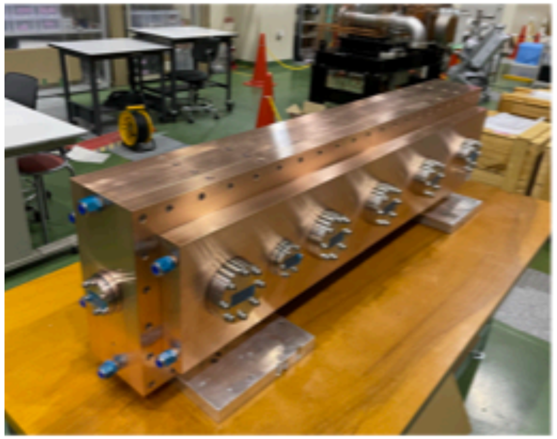


USM acceleration

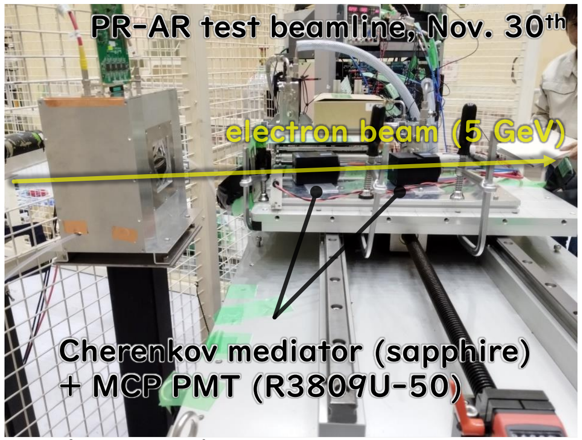




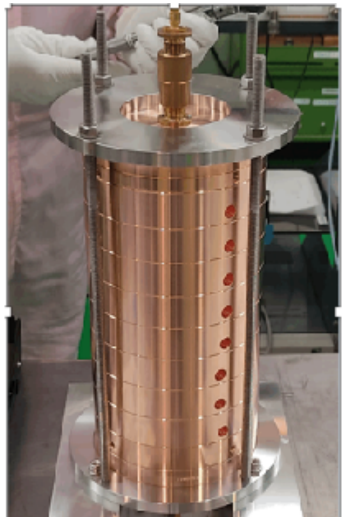
IH-DTL high-power test



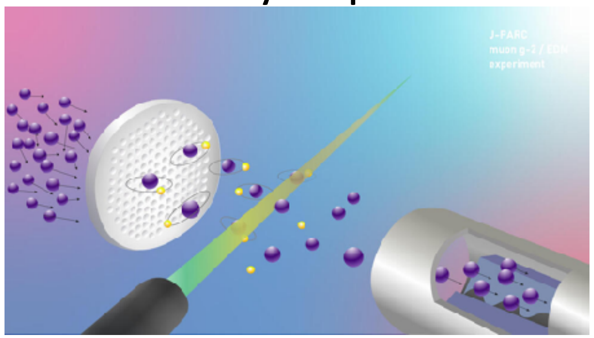
Bunch width monitor development



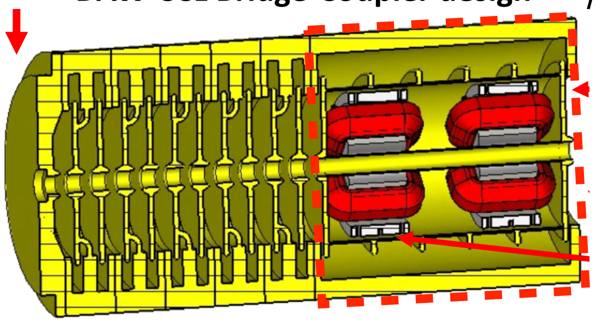
DLS development



Schematic by KMI promotion

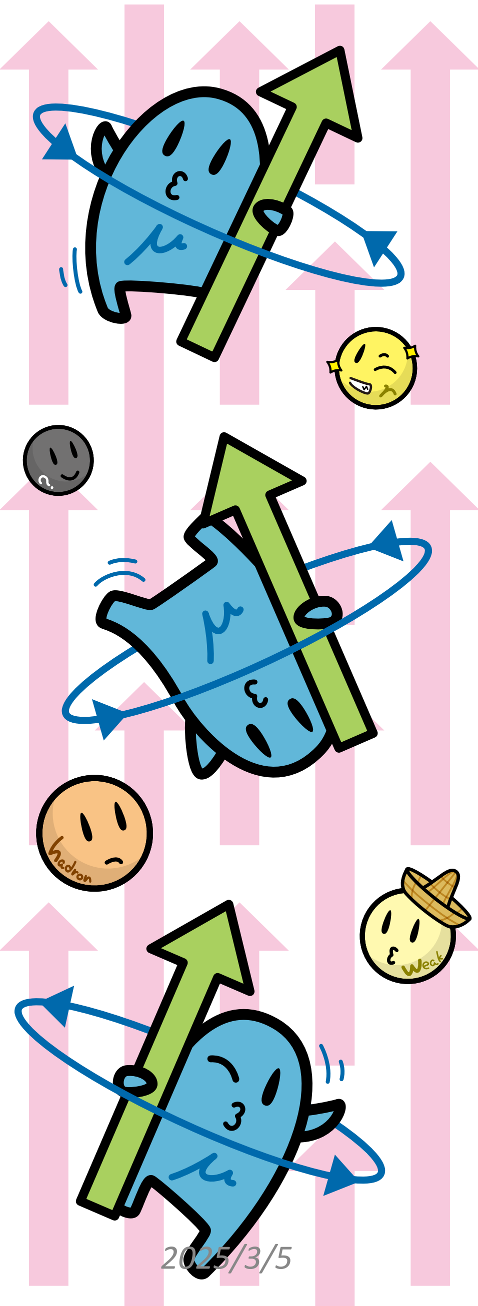


DAW-CCL Bridge-Coupler design



KMI contributions in 2023-2024 (2)

- *Hosted an international school and a collaboration meeting.*



Simon Eidelman School on

Muon Dipole Moments and Hadronic Effects

supported by Wilhelm and Else Heraeus Foundation

Sep 2nd-6th 2024
KMI, Nagoya University, Japan

Web ■ https://indico.kmi.nagoya-u.ac.jp/event/8/
contact ■ muonschool24_contact@hepl.phys.nagoya-u.ac.jp

Topics & Lecturer

Muon magnetic moment: Experiment
Anna Driutti (Pisa)
Muon magnetic moment: Theory
Martin Hoferichter (Bern)
Data input to hadronic vacuum polarization
Zhiqing Zhang (IJCLab)
Lattice QCD: Hadronic vacuum polarization
Aida El-Khadra (UIUC)
Lattice QCD: Light-by-light
Harvey Meyer (Mainz)
Hadronic light-by-light: Phenomenology
Franziska Hagelstein (Mainz)
Hadronic light-by-light: Data input
Andrzej Kupsc (NCBJ/Uppsala)
New physics contributions
Kei Yamamoto (Hiroshima Tech)
Detector technology
Paula Collins (CERN)
Accelerator technology
Mika Masuzawa (KEK)
Precision measurements
Xing Fan (Northwestern)
Monte Carlo generators
Yannick Ulrich (Bern)

Scientific organizers

Gilberto Colangelo (Bern), Achim Denig (Maintz), Toru Iijima (Nagoya, Chair), Kenji Inami (Nagoya), Jim Libby (Indian Inst. Tech. Madras), Tsutomu Mibe (KEK), Boris Shwartz (BINP)

Local organizers

Seiso Fukumura (Niigata), Toru Iijima (Nagoya), Kenji Inami (Nagoya), Masato Kimura (KEK), Tsutomu Mibe (KEK), Yuki Sue (Nagoya), Kazumichi Sumi (Nagoya), Kazuhito Suzuki (Nagoya)

Kobayashi-Maskawa Institute for the Origin of Particles and the Universe
FlaP Flavor Physics International Research Center
科研費 KAKENHI 22K21347, 22K21347, 22K21350
WILHELM UND ELSE HERAEUS-STIFTUNG

14 lecturers & 63 on-site participants from 20 countries.

The 29th muon g-2/EDM collaboration meeting
11 Dec 2024, 09:00 → 13 Dec 2024, 21:30 Asia/Tokyo
ES635 (ES Building, Higashiyama Campus, Nagoya university)

47 on-site participants.

Summary

- *The J-PARC muon g-2/EDM experiment aims to measure a_μ and search for d_μ with high sensitivities using the small-emittance muon beam.*
  - *Very different from the BNL/Fermilab approach,*
  - *Will enhance our experimental understanding of a_μ.*
- *The experiment is progressing well to launch the experiment in JFY2030.*
  - *Cooling and world's first acceleration of muons have been demonstrated successfully.*
  - *The development and implementation of the experimental instruments and facility construction are progressing well.*
- *KMI significantly contributes to the experiment as well as to the community.*
  - *Young researchers are the driving force.*