Muon g–2/EDM in the Post FNAL Era

Masato Kimura (IPNS, KEK)
on behalf of the J-PARC muon g–2/EDM collaboration

29 Sep 2025 | Flavor Changing and Conserving Processes @ Anacapri

Dipole Moment

$$H = -\vec{\mu} \cdot \vec{B} - \vec{d} \cdot \vec{E}$$

Magnetic Dipole Moment

$$\vec{\mu} = g\frac{q}{2m}\vec{s}$$

$$a_\mu = \frac{g-2}{2} = a_\mu^{\mathrm{QED}} + a_\mu^{\mathrm{EW}} + a_\mu^{\mathrm{had}} + a_\mu^{\mathrm{BSM}}$$

Electric Dipole Moment

$$\vec{d} = \eta\frac{q}{2m}\vec{s}$$

$d_\mu \neq 0$ →
CPV in the lepton sector

	$\vec{E}$	$\vec{B}$	$\vec{\mu}$ or $\vec{d}$
P	-	+	+
C	-	-	-
T	+	-	-

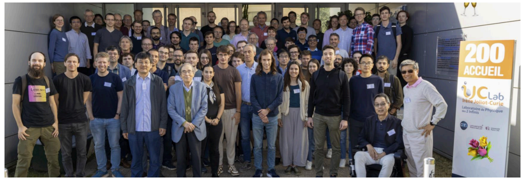
Good probes for new physics

Status of Muon g−2

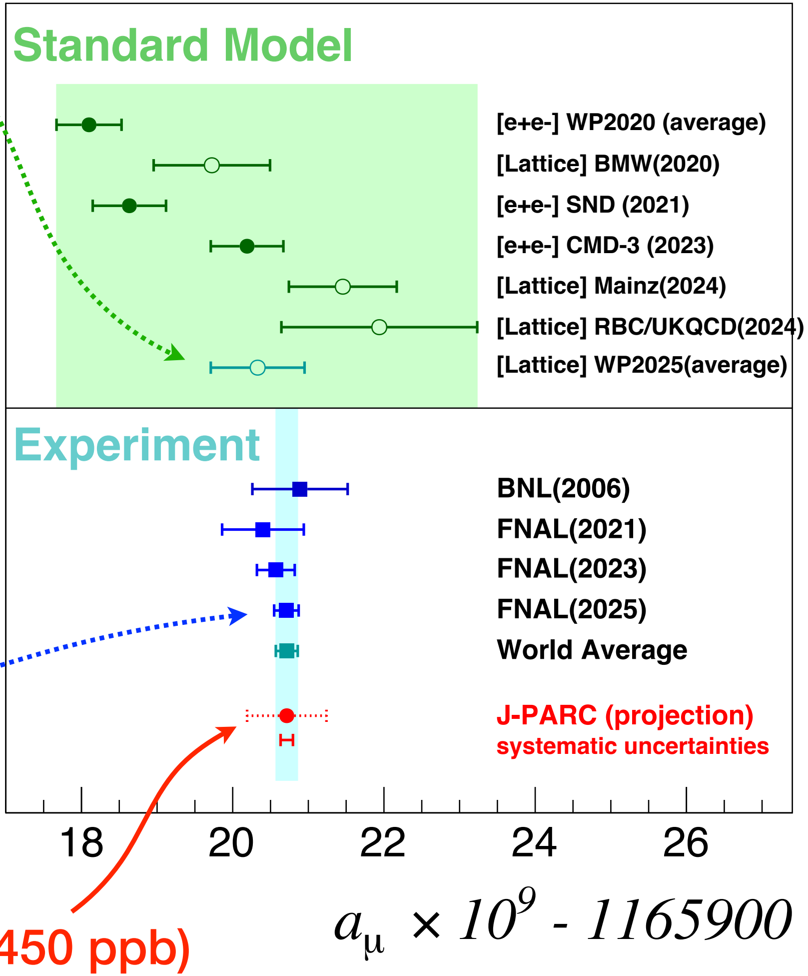
WP: Physics Reports 1143, 1-158
FNAL: Phys.Rev.Lett. 135, 101802

- **2nd edition of the "White paper" on May 28th**
  - "CMD-3 has increased the tensions among data-driven dispersive evaluations to a level that makes it impossible to combine the results in a meaningful way"
  - "lattice-QCD calculations of HVP have matured considerably. … enables consolidate averages."
  - "Theory need to be improved by a factor of four to match the experimental precision."

8th theory initiative workshop few weeks ago at Paris, moving forward to next steps
https://indico.ijclab.in2p3.fr/event/11652

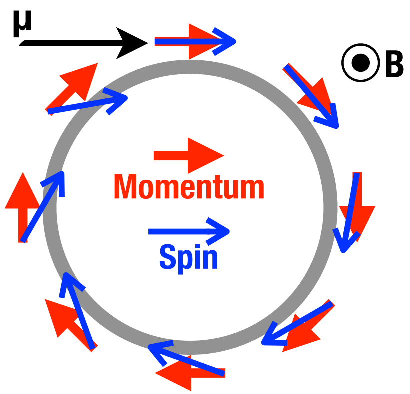


- **The final result of FNAL E989 on June 3rd**
  - Beautiful result with 127 ppb precision, consistent with the previous results



The only experiment to independently measure g−2 (450 ppb)

Experimental Principle

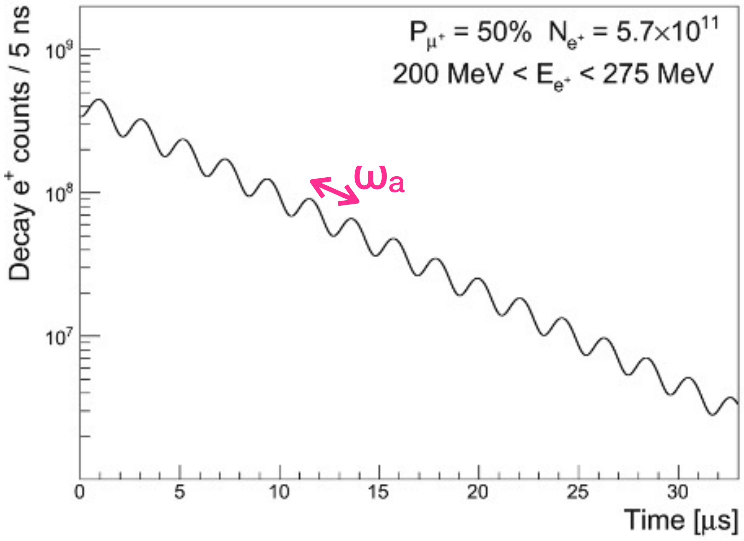


- The spin precession vector w.r.t. cyclotron motion under an EM field:

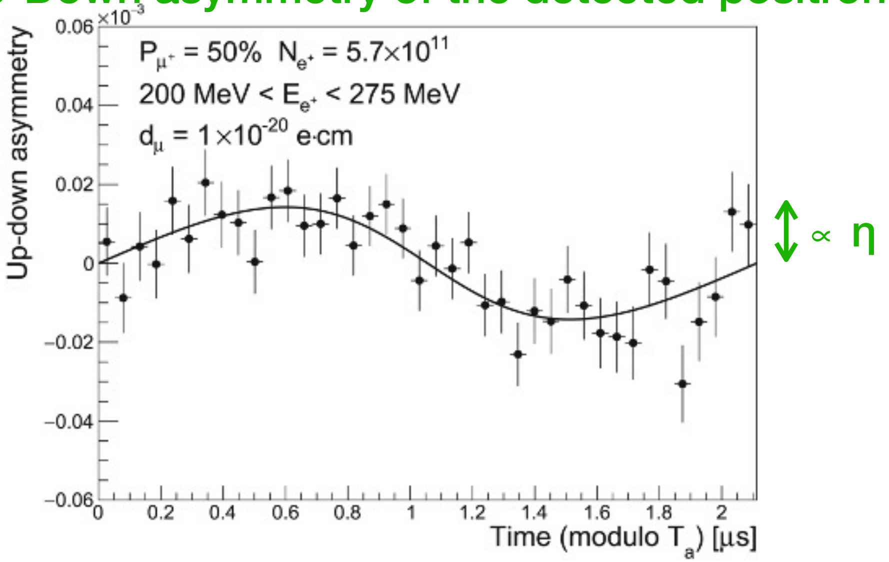
$$\overrightarrow{\omega_a} + \overrightarrow{\omega_\eta} = -\frac{e}{m_\mu}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta}\times\vec{E}}{c} + \frac{\eta}{2}\left(\vec{\beta}\times\vec{B} + \frac{\vec{E}}{c}\right)\right]$$

g–2 precession | EDM precession

Number of the detected positron



Up-Down asymmetry of the detected positron



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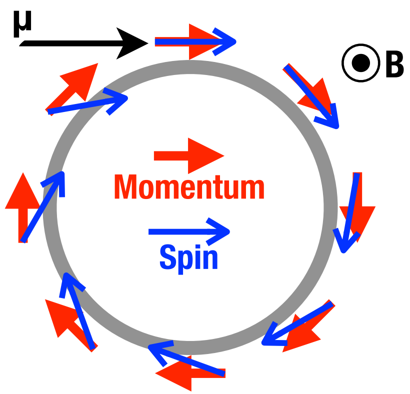
$\left(a_\mu - \frac{1}{\gamma^2-1}\right) \rightarrow 0$; $\vec{E} \rightarrow 0$

g−2 precession: $a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta}\times\vec{E}}{c}$

EDM precession: $\frac{\eta}{2}\left(\vec{\beta}\times\vec{B} + \frac{\vec{E}}{c}\right)$

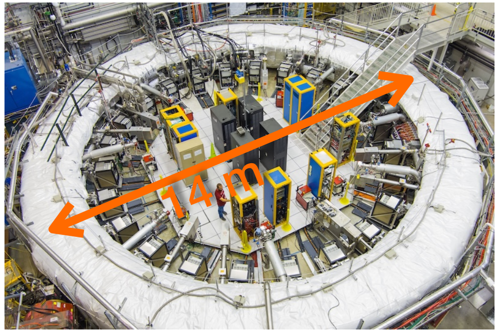


- Two different experimental approaches..

BNL and FNAL

- Electric focusing to store muons on the orbit
- "Magic gamma"

$$\rightarrow a_\mu - \frac{1}{\gamma^2 - 1} = 0$$



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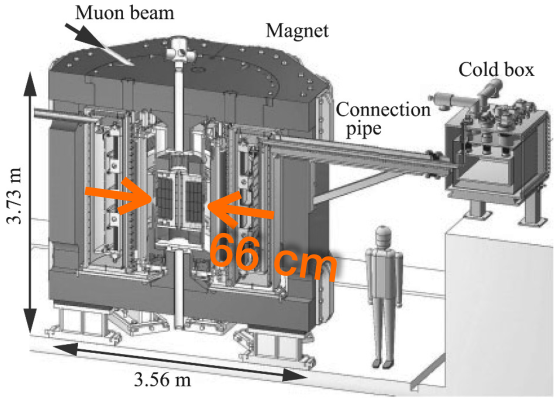
J-PARC (This talk)

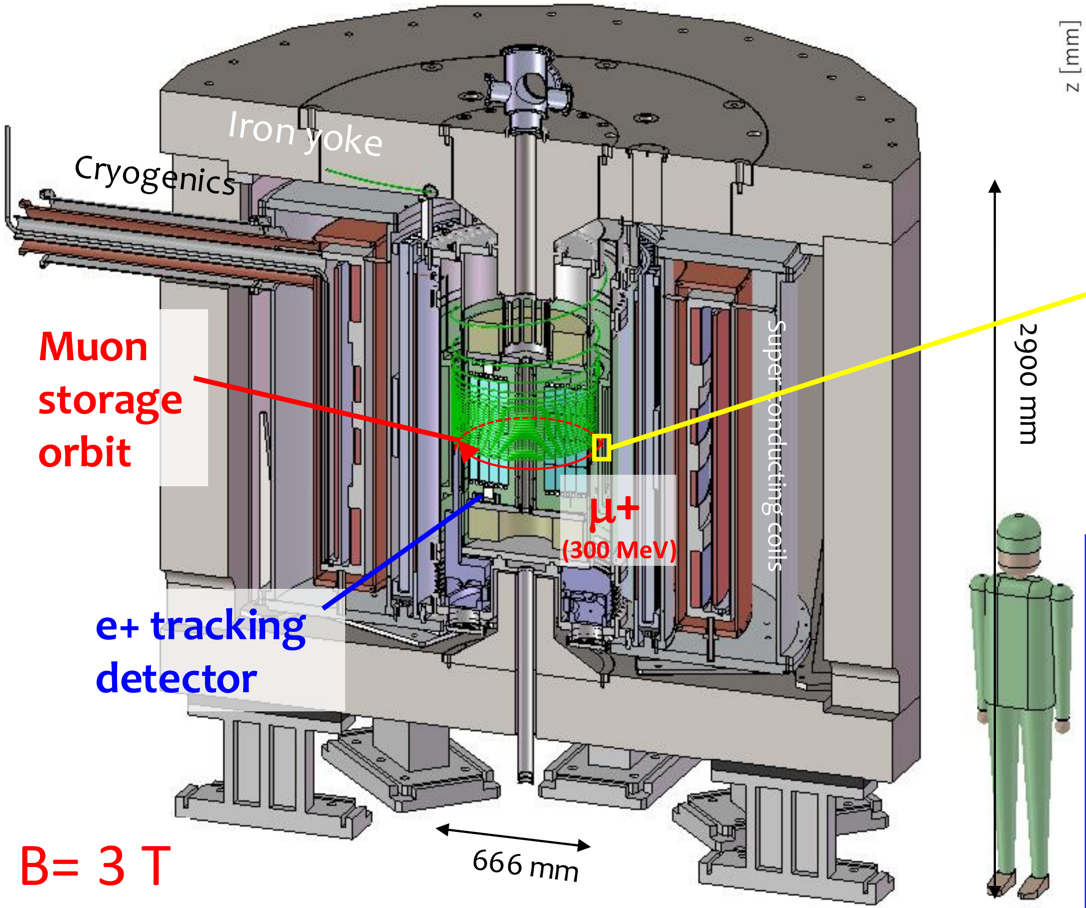
PTEP2019 053C02

- **No electric field**
- Weak magnetic focusing to store
- Free from magic gamma



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

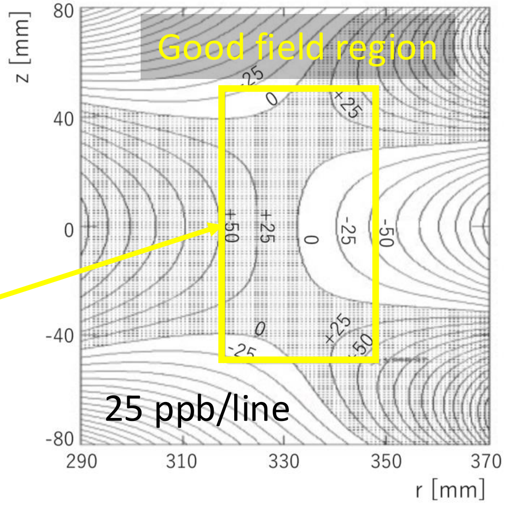
The Storage Ring



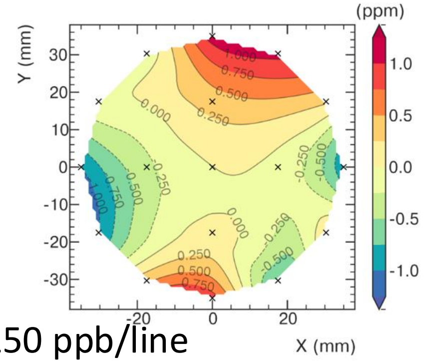
B= 3 T

M. Abe et. al., NIM A 890, 51 (2018)

Calculated average field uniformity



FNAL Run 1 PRA 103, 042208 (2021)



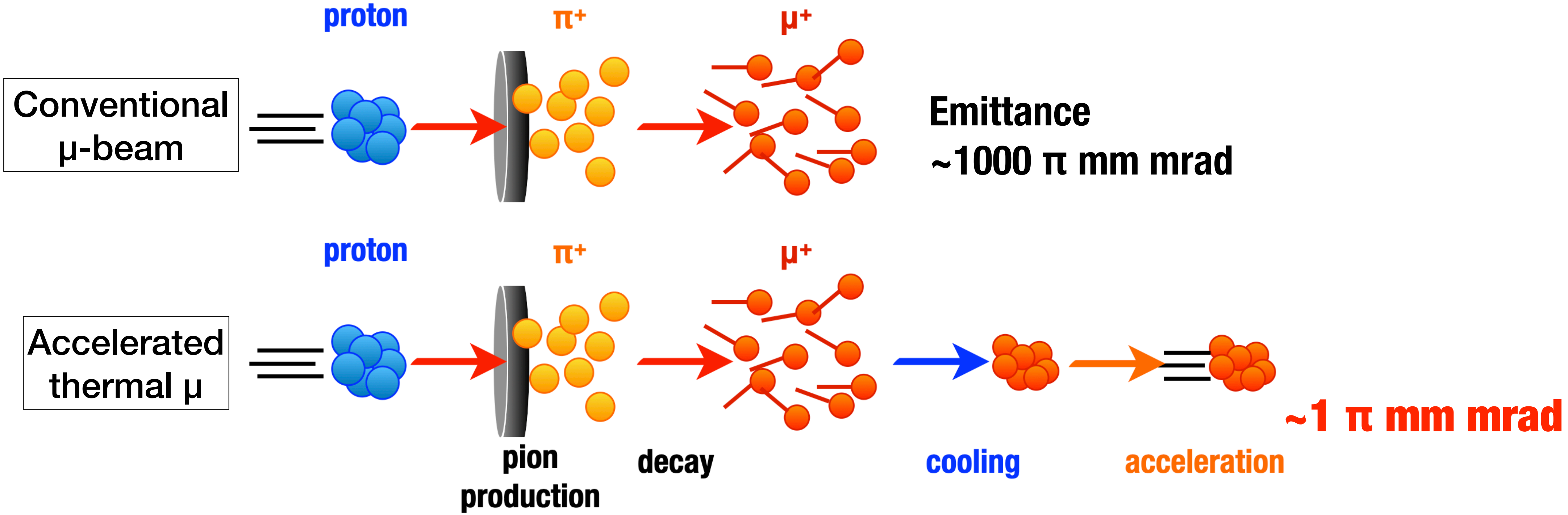
250 ppb/line

Comparison of g−2 Experiments

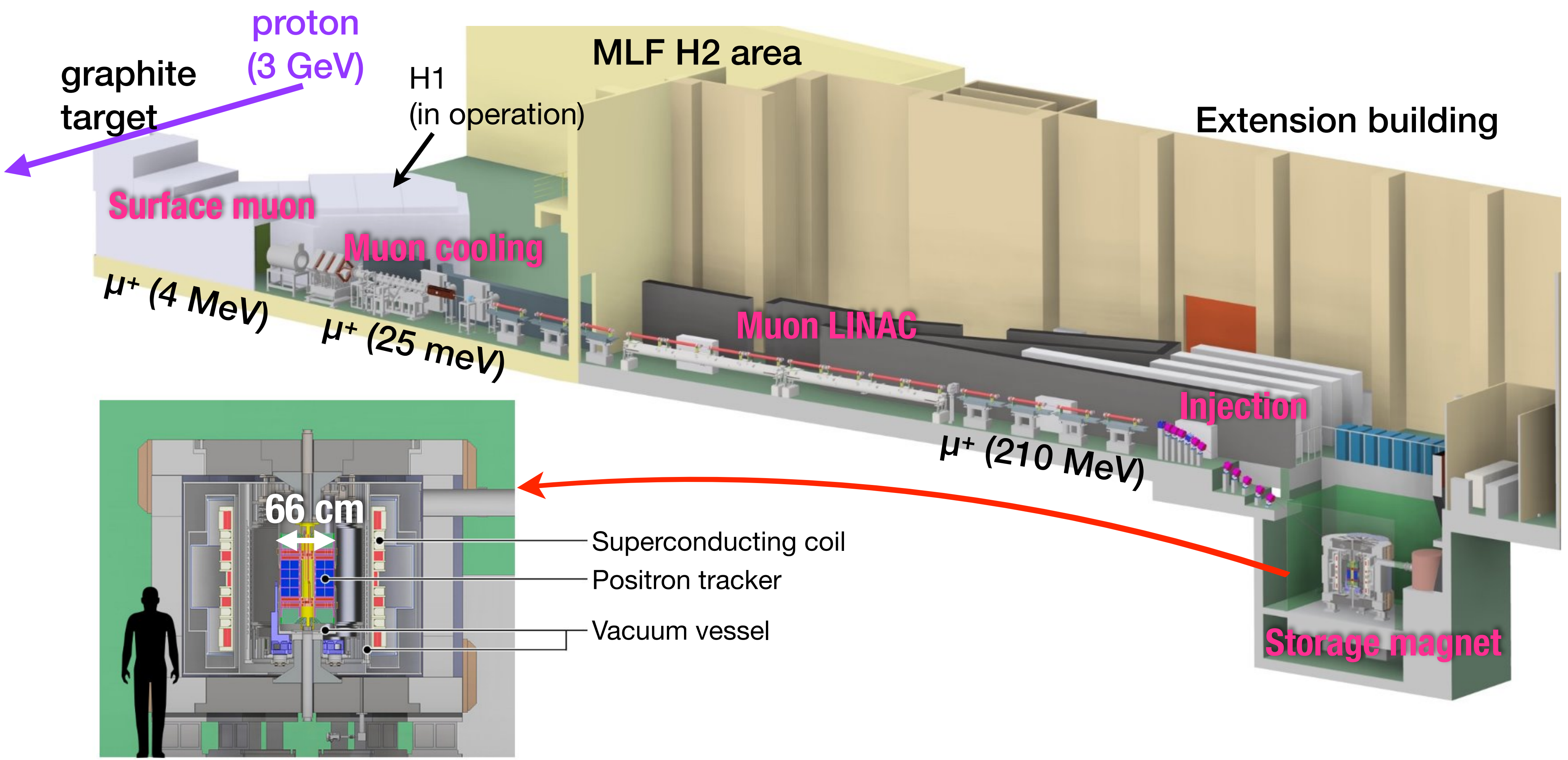
	BNL-E821	FNAL-E989	J-PARC-E34
Muon momentum	3.09 GeV/c		300 MeV/c
Lorentz γ	29.3		3
Polarization	100%		50%
Storage field	$B = 1.45$ T		$B = 3.0$ T
Focusing field	Electric quadrupole		Very weak magnetic
Cyclotron period	149 ns		7.4 ns
Spin precession period	4.37 μs		2.11 μs
Number of detected e^+	5.0×10^9	1.6×10^{11}	5.7×10^{11}
Number of detected e^-	3.6×10^9	–	–
a_μ precision (stat.)	460 ppb	~~100 ppb~~ 98 ppb	450 ppb
(syst.)	280 ppb	~~100 ppb~~ 78 ppb	<70 ppb
EDM precision (stat.)	0.2×10^{-19} $e \cdot$ cm	–	1.5×10^{-21} $e \cdot$ cm
(syst.)	0.9×10^{-19} $e \cdot$ cm	–	0.36×10^{-21} $e \cdot$ cm

Key Technique: Reaccelerated Thermal Muon Beam

- Beam storage w/o electric field requires low emittance beam
- Increase the phase space density by cooling and reaccelerating the conventional muon beam



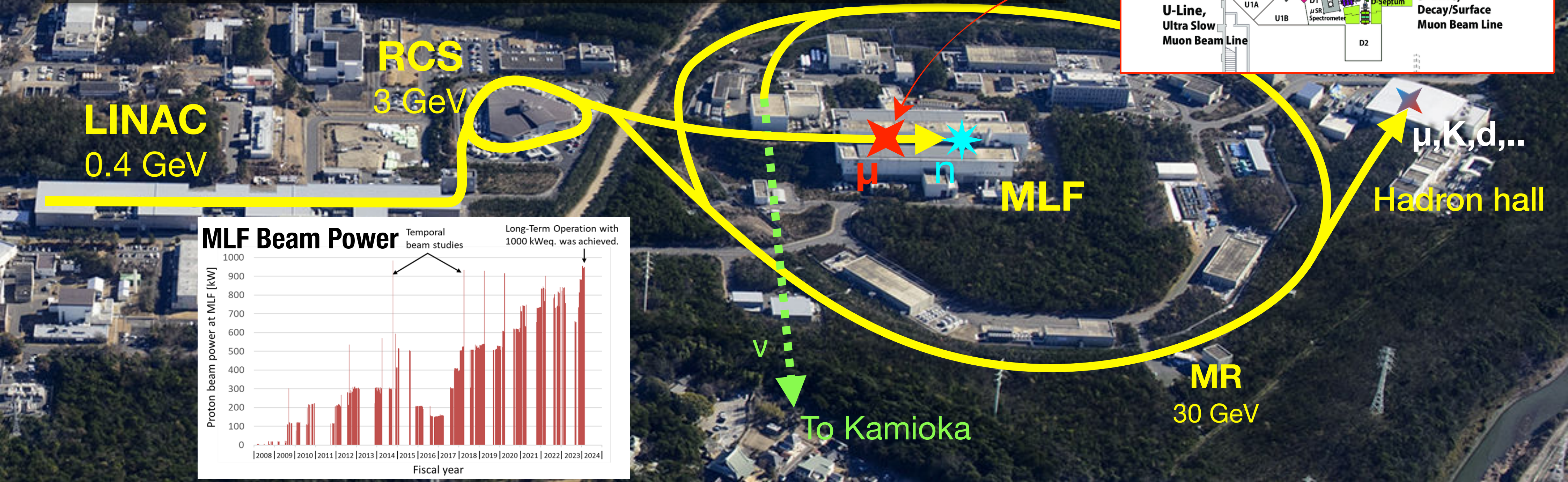
Overview of J-PARC E34

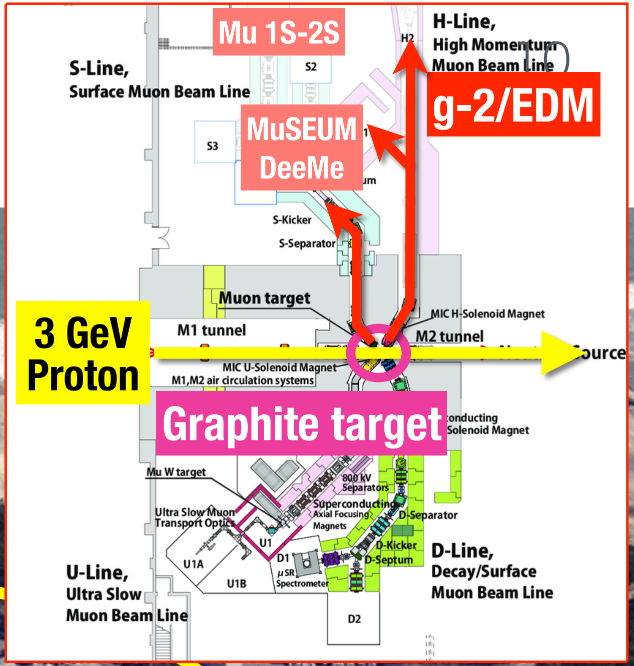


J-PARC/Muon Facility

Pacific ocean

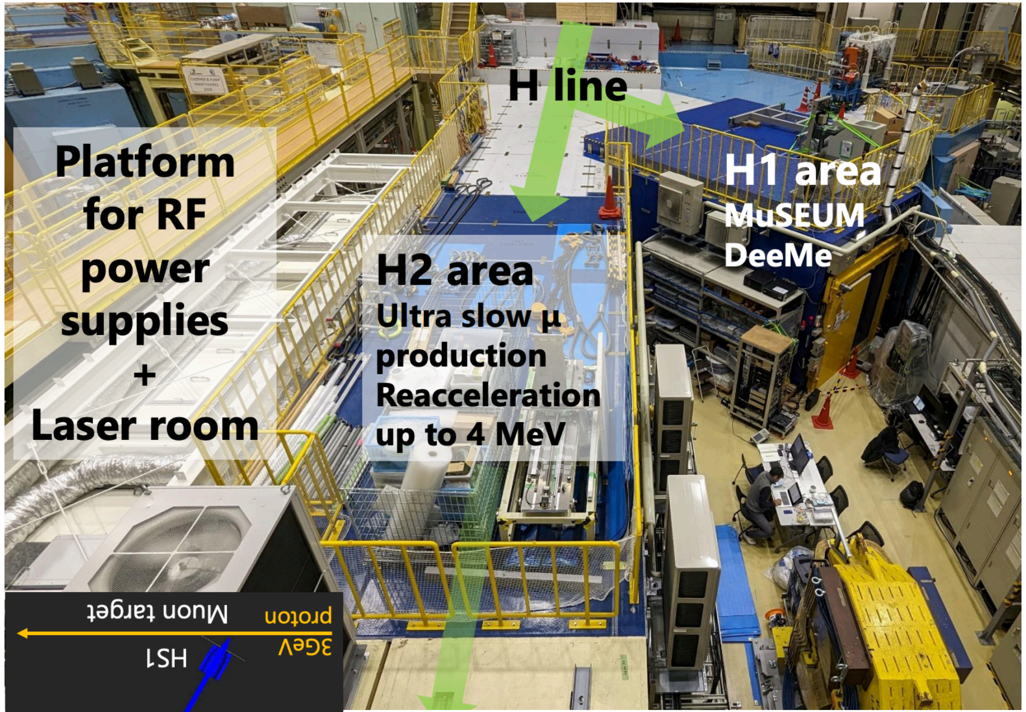
- 3 GeV proton from RCS hits the graphite target to produce muons in MLF (Material and Life science experimental Facility)
- **1 MW stable operation** of RCS/MLF was established so that world's highest intensity pulsed muon beam is in use

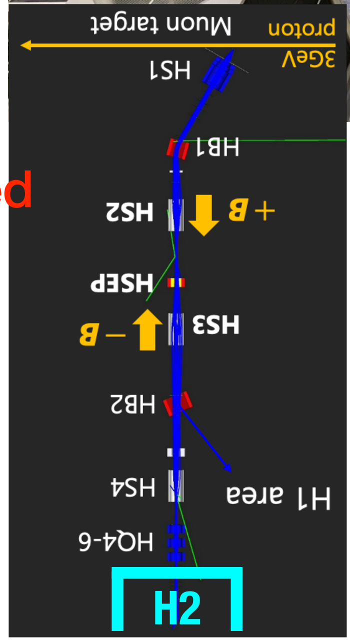


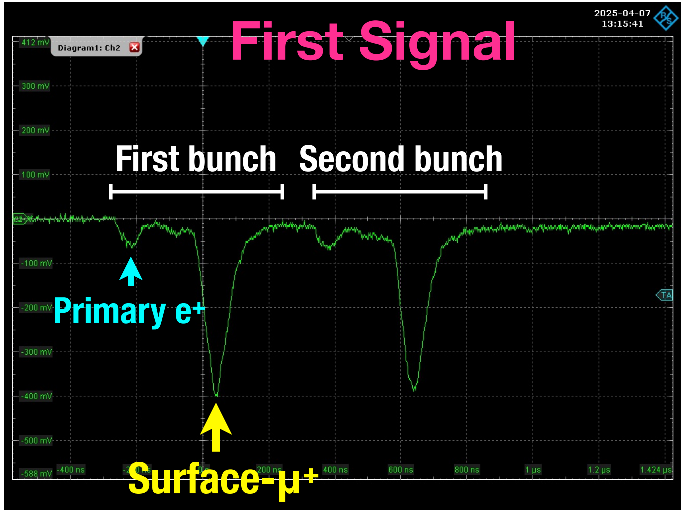


Experimental Area -"H2"-

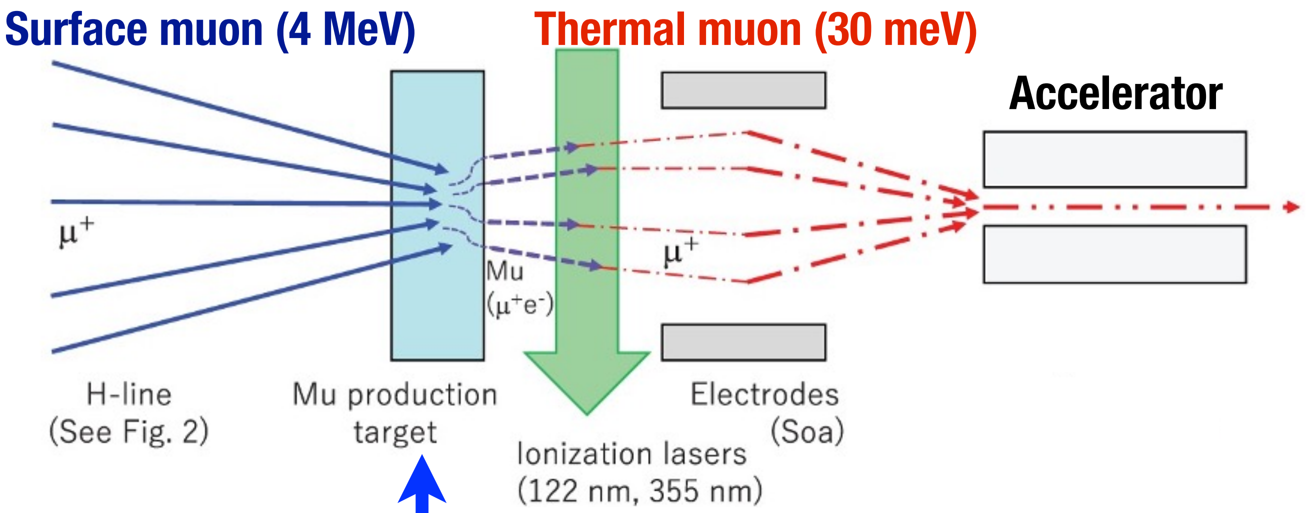
- Designed to deliver a surface μ⁺ of **10^8 /sec** with the 25 Hz repetition rate
- **First surface μ⁺ beam in April 2025**
  - Commissioning of the surface beamline is ongoing
- **Construction of the area for the acceleration up to 4 MeV was completed**
- Infrastructures are being built to be ready for the acceleration
  - Clean room for the laser,
  - Power supplies for the accelerator,
  - ..



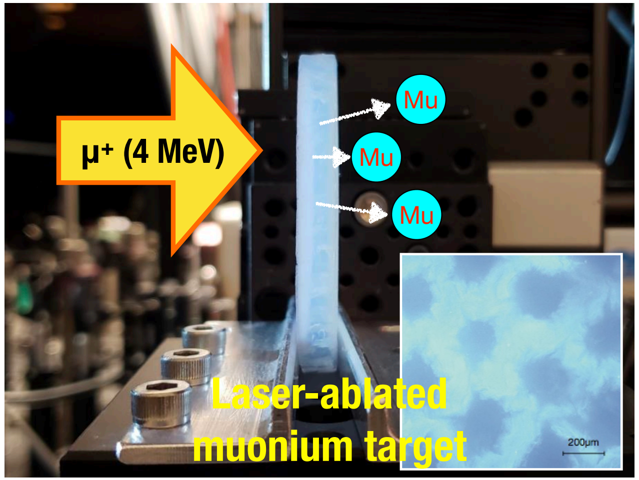




Muon Cooling



1. Stop the surface muon by silica aerogel target
2. Diffuse out into vacuum in a form of muonium (μ^+e^-)
3. Laser ionization to produce thermal muon
4. Focus it to the LINAC by a static field ("Soa lens")

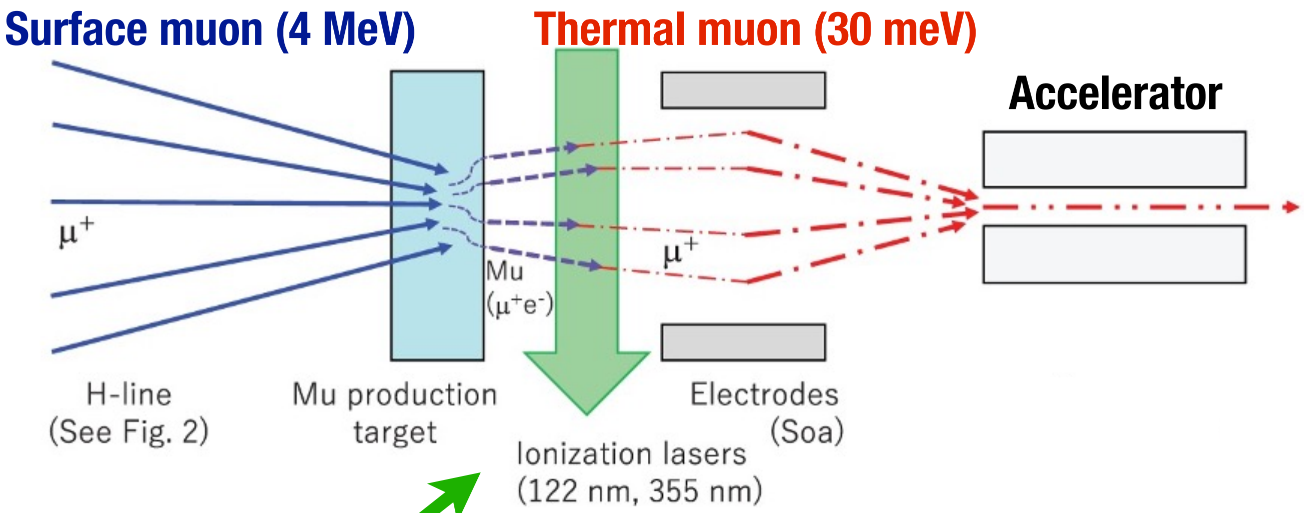


Silica aerogel target

- Laser-ablation to enhance the Mu emission probability
- Typical efficiency is..
  - Surface muon stopping efficiency ~50%, times
  - Muonium formation efficiency ~50%, times
  - Vacuum emission efficiency ~10%

PTEP2013 103C01, PTEP2014 091C01, PTEP2020 123C01

Muon Cooling



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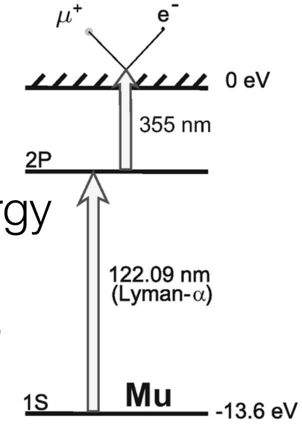
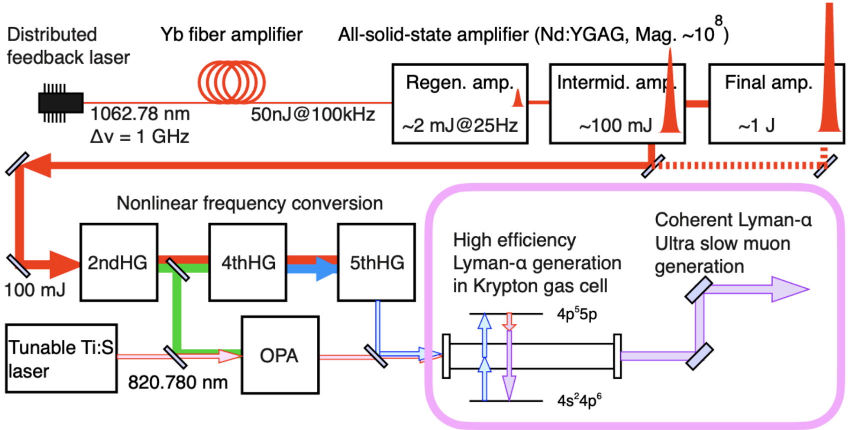
Ionization laser

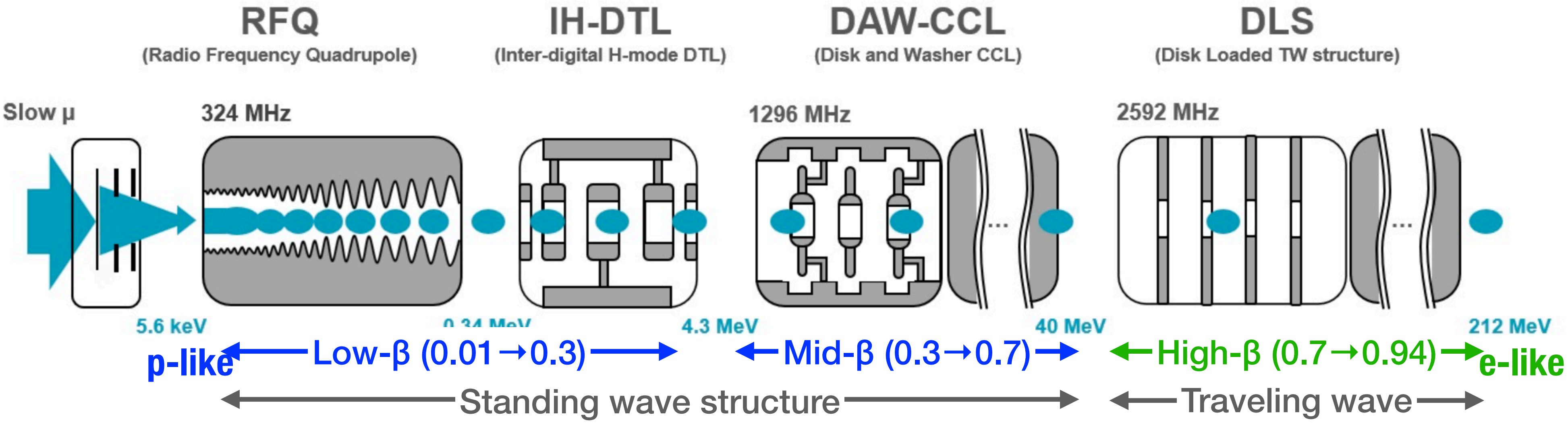
- 122 nm and 355 nm lasers for the 1S-2P transition
- Staged upgrading plan toward a high-energy (100 μJ for 122 / 100 mJ for 355) laser; First light without the final amplifier in 2025
- Installation to the H2 area has just started

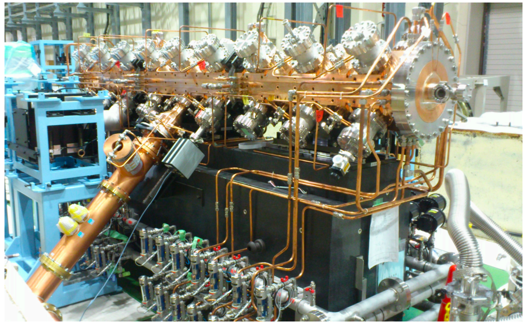




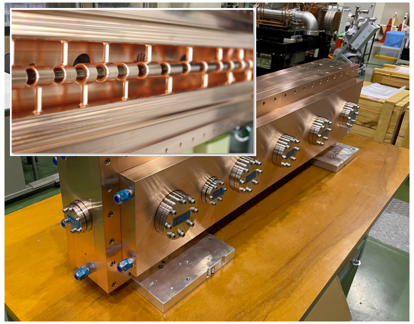
Accelerator

- Ultraslow muon acceleration up to 212 MeV by a dedicated liner accelerator
- Four steps acceleration depending on β. Total length 40 m

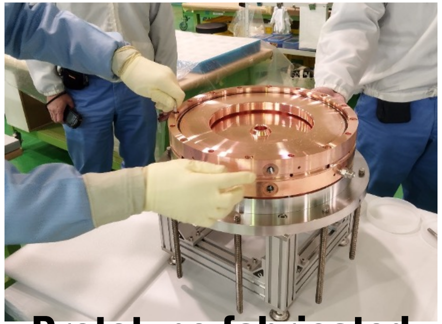




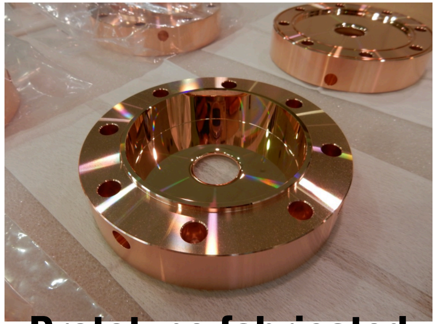
μ acceleration test



Fabrication completed



Prototype fabricated and tested



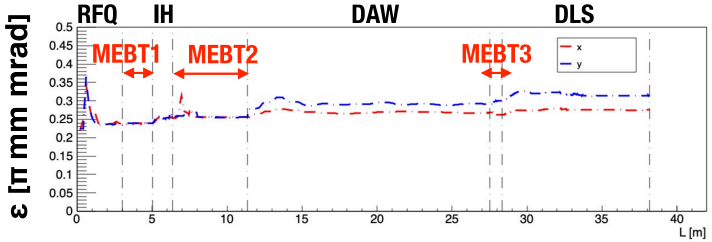
Prototype fabricated and tested

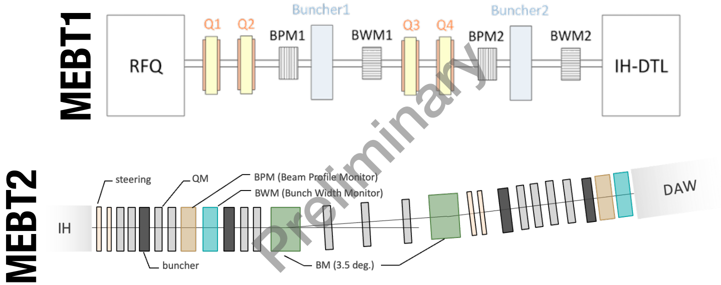
Accelerator System

- Many adjuncts are necessary to construct a new accelerator
- Design, development, fabrication, and test of each components are ongoing

Ex) Beam diagnostic/transport line

- Careful design to fit limited space without emittance growth



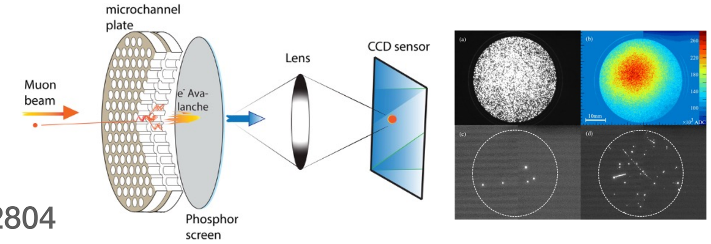


Ex) Beam monitors

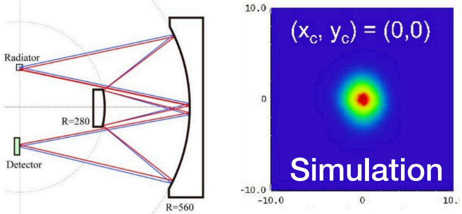
- Impossible to directly use beam monitors operated in proton/electron accelerators due to different energy, intensity, and background
- Several monitors are under development to be used in different place

MCP-based monitors for low-energy muon

NIM A899 22-27, PRAB 23 022804



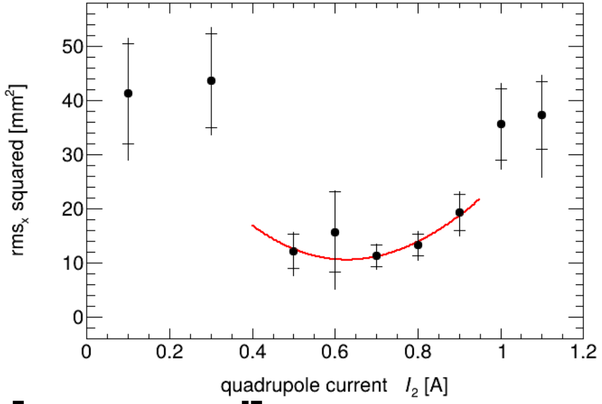
Cherenkov detection for the downstream section

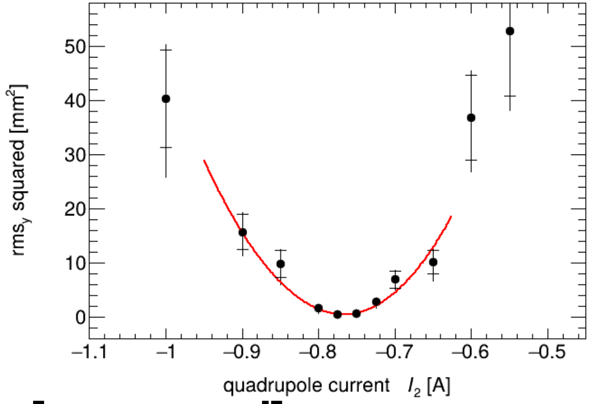


Demonstration of Cooling/Accelerating

- Ultraslow muon production and its acceleration in May 2024 to demonstrate the novel muon beam
  - Already available facilities/instruments were used instead of the real one
- The world's first low emittance muon beam of 100 keV was achieved!

Emittance measurement by Q-scan





ε_x [π mm mrad] $= 0.85 \pm 0.25(\text{stat})\ {}^{+0.12}_{-0.02}(\text{syst})$

x 1/200

ε_y [π mm mrad] $= 0.32 \pm 0.03(\text{stat}) \pm 0.02(\text{syst})$

x 1/400

of the surface-μ beam

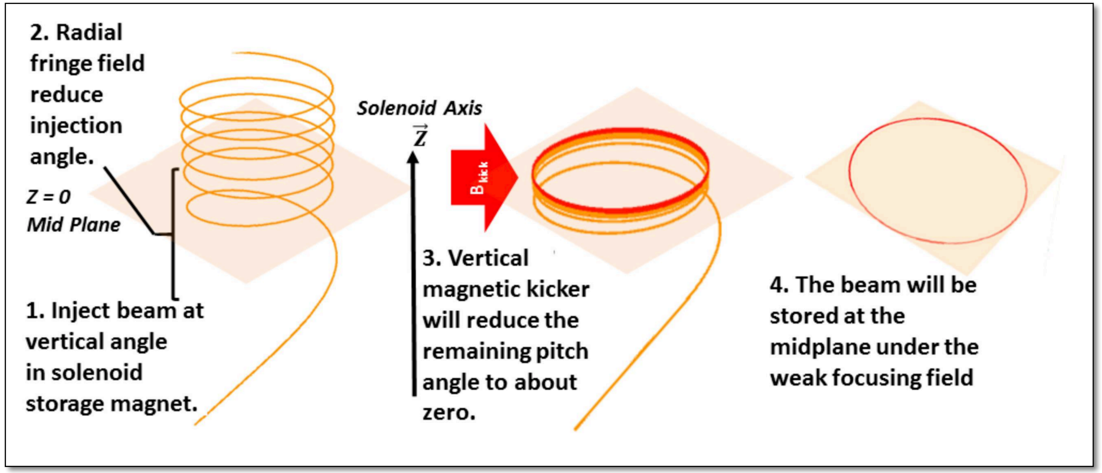
Published in PRL134, 245001

See detail for another talk later

Beam Injection

NIM A832, 51-62

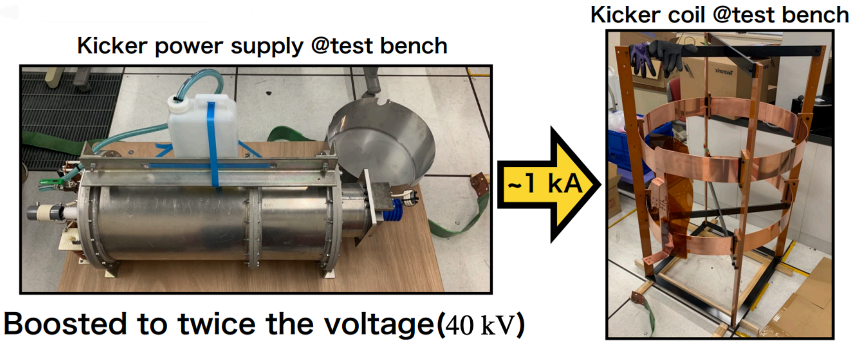
- A **new concept of three dimensional spiral injection scheme** for injection into the storage magnet
  - Allows an injection of muon to the small orbit
- A framework to systematically design the scheme has been developed



See details for IPAC'25 WEPM029, WEPM055

- Several works are ongoing for the proof-of-principle

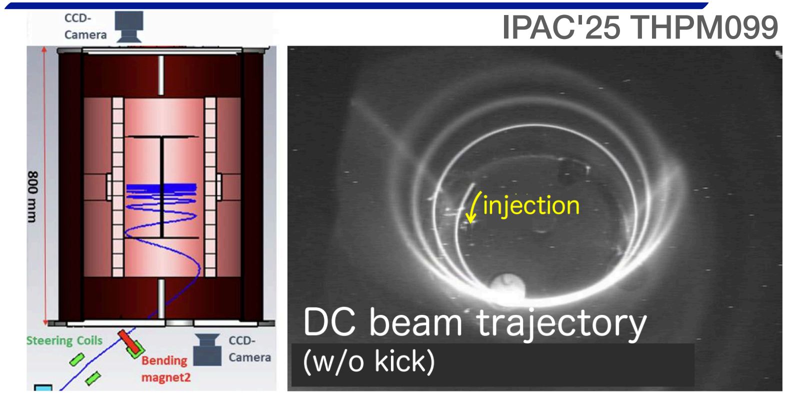
Prototype of the kicker coil



Boosted to twice the voltage(40 kV)

Test with an electron beam

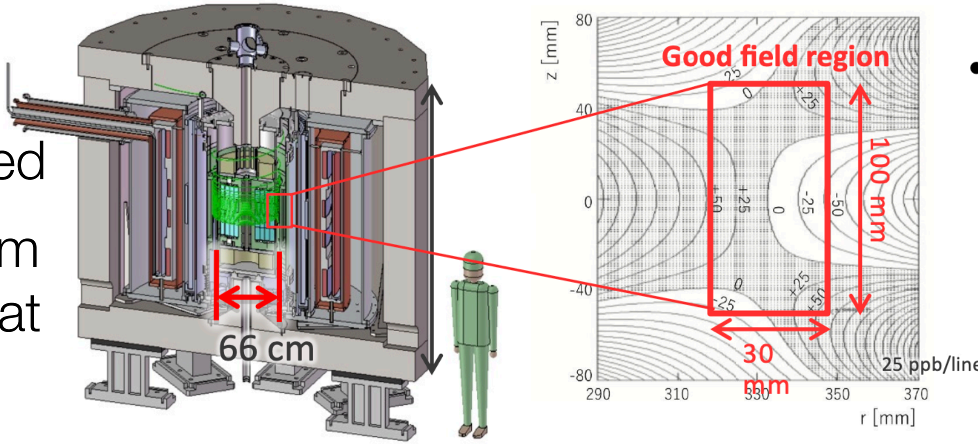
IPAC'25 THPM099



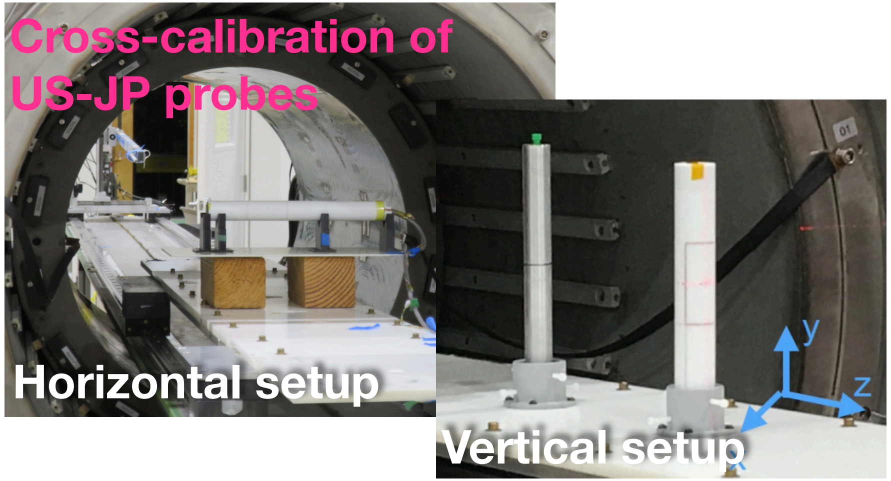
DC beam trajectory (w/o kick)

Storage Magnet

NIM A890, 51-63

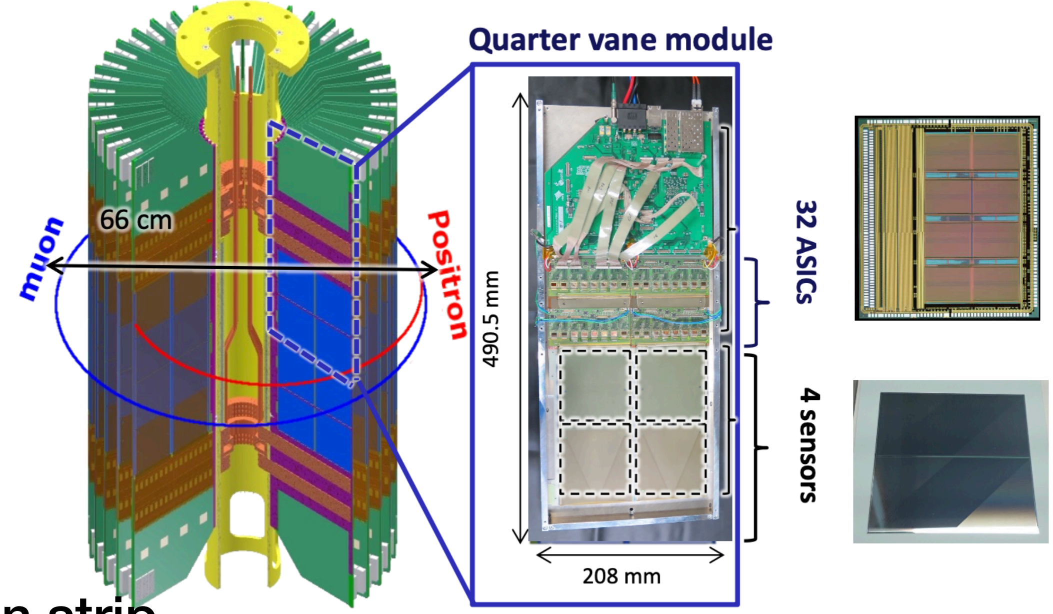


- A compact MRI-type superconducting magnet
  - **Local non-uniformity of <0.1 ppm** is expected
- Shimming studies in collaboration with Muonium hyperfine spectroscopy experiment (MuSEUM at H1 area) have confirmed 1 ppm uniformity
- NMR probe and the field mapping system under development

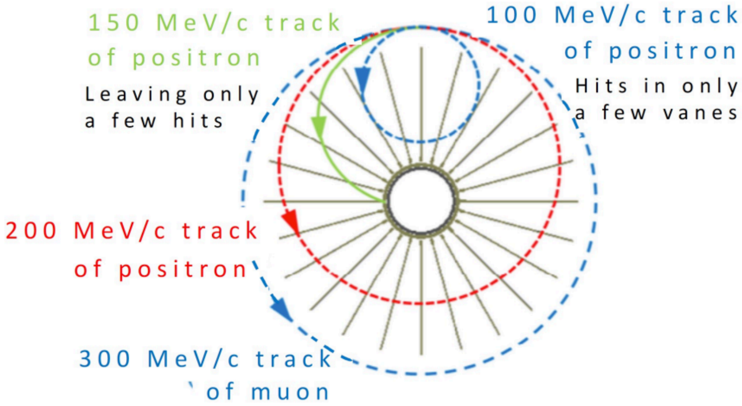


Positron Tracking Detector

- The positron detector is required to..
  - Detect e+ in around 100-300 MeV,
  - Reconstruct the momentum vector,
  - Operate stably over the rate change of 14k-1.4M Hz, and
  - Operate under the 3 T field

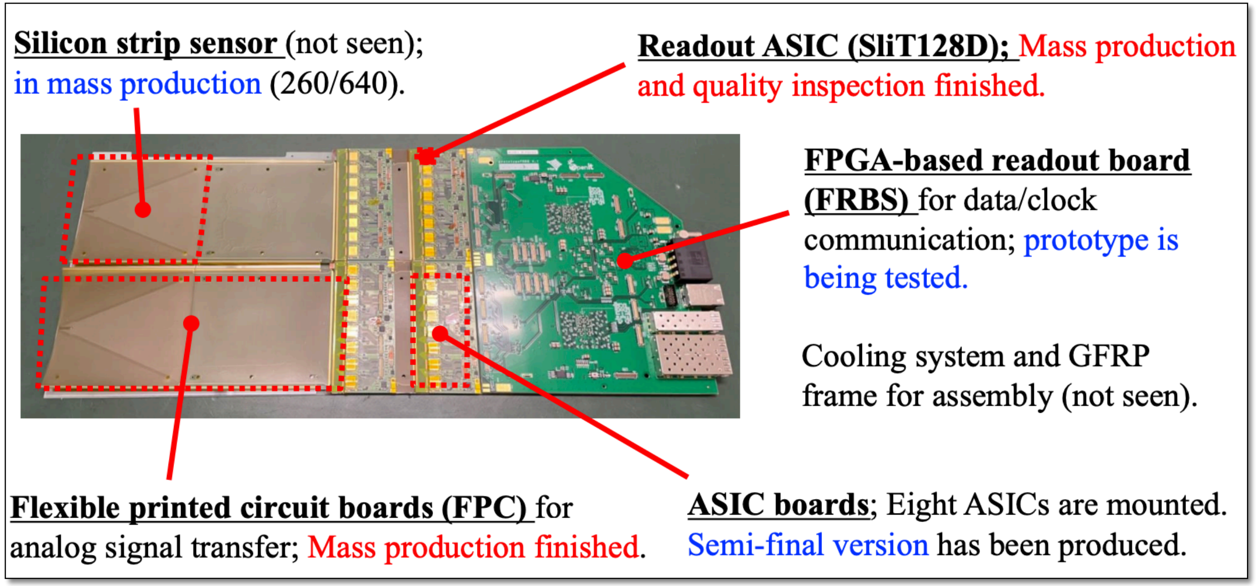


- **A new orthogonally arranged silicon strip sensor** is under development
  - Total 40 vanes, with the fiducial area of r200 x h400 mm^2
  - Track reconstruction efficiency >90% in our analysis window of 200-275 MeV

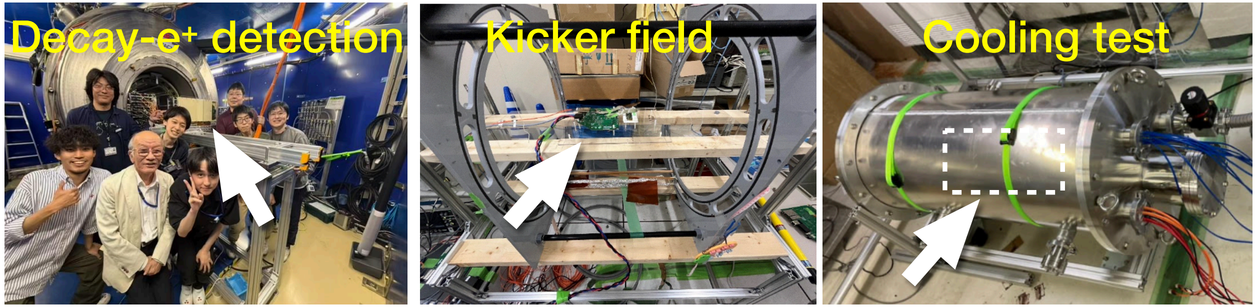


Positron Tracking Detector

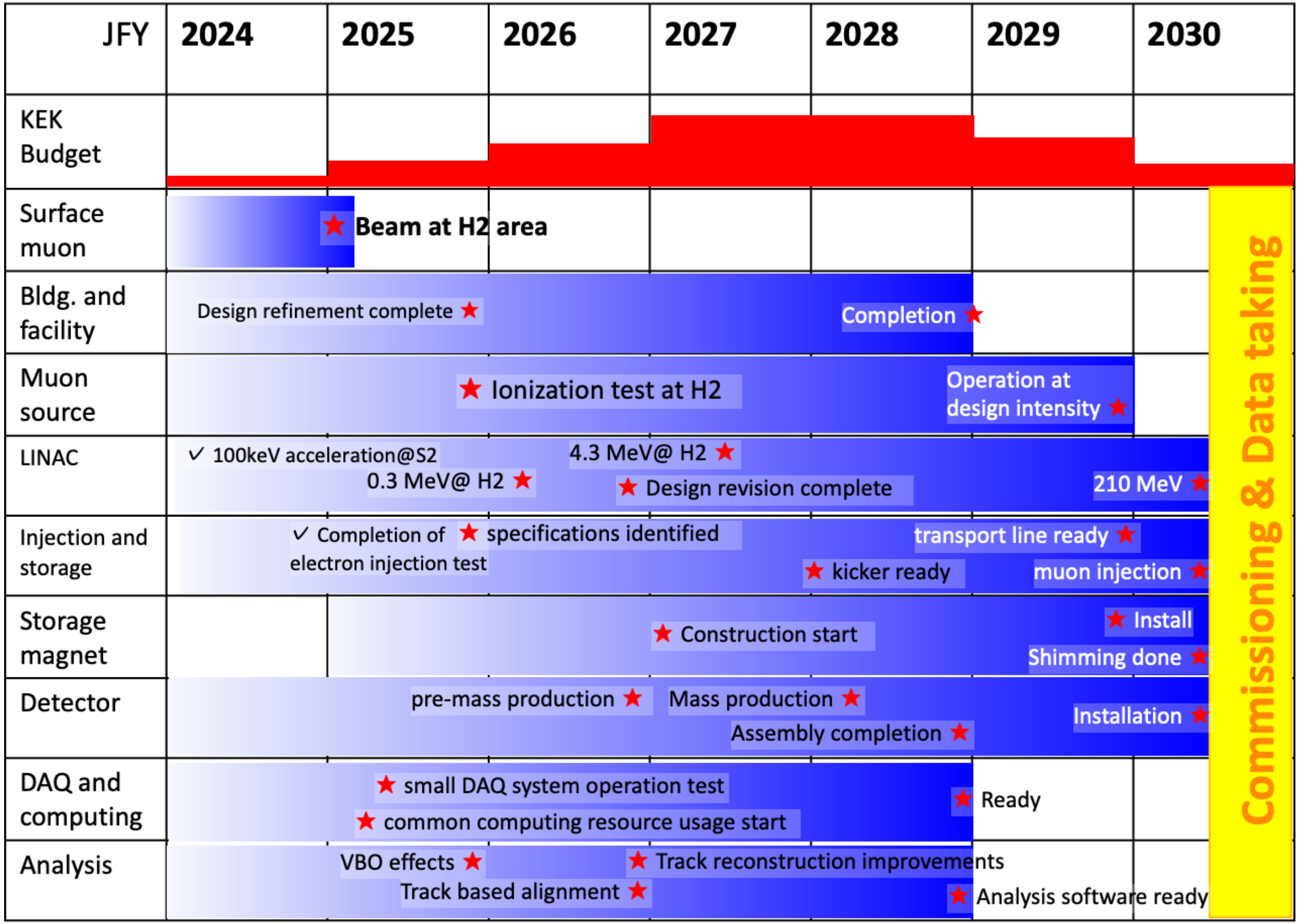
- **Major components are in or completed mass production**
- Assembly and alignment procedures are under R&D
  - Rather important for the EDM search
  - ~1 μm for the sensor alignment and 10 μrad rotation and 200 μrad tilt for the vane alignment are required
- "Quarter-vane" prototypes are fabricated and being tested in various conditions



Quarter-vane operation tests



Experiment Schedule



History

- 2009 Proposal
- 2015 TDR
- 2016 IPNS focused review
- 2016 SAC (priority #3)
- 2019 KEK-IPNS stage-2, KEK-IMSS stage-2
- 2024 MEXT funding (partial construction)
- 2025 MEXT funding (partial construction)

Towards Higher Sensitivity

$$\frac{\delta\omega_a}{\omega_a} = \frac{1}{\omega_a \gamma \tau P}\sqrt{\frac{2}{NA^2}}$$

$$\omega_a = a_\mu \frac{eB}{m}$$

valuable	definition	value
ω_a	anomalous spin precession frequency, $a_\mu \cdot (eB/m)$	$2\pi/2\ \mu s$
B	magnetic field strength	3 T
γ	Lorentz gamma factor, E/m	3
p	momentum of muon	300 MeV/c
τ	muon lifetime at rest	2.2 μs
P	muon polarization	50%
N	number of detected decay positron	6×10^{11}
A	average analyzing power of positron	0.42

Current precision goal: 450 ppb

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Higher sensitivity can be realized by

1. Higher polarization (P)
2. Higher momentum (γ)
3. Stronger magnetic field (B)

Being studied by the collaboration to be compatible to the precision of the theory prediction even in future

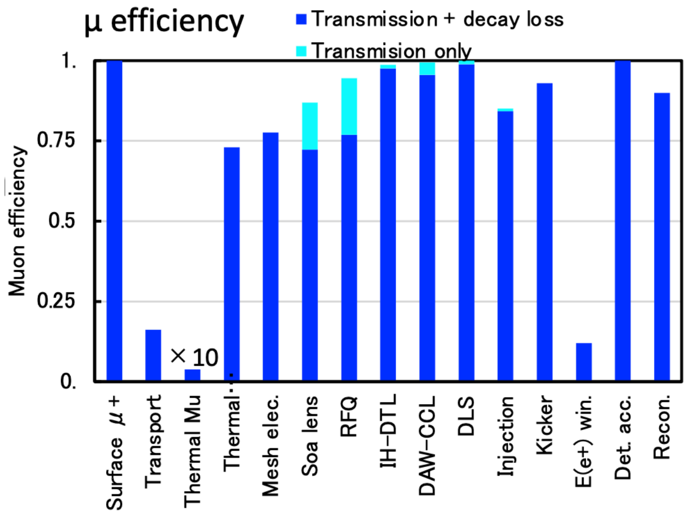
Summary

- New measurement of muon g–2/EDM utilizing **a low-emittance muon beam** stored in **a compact region**
  - **Complementary systematic sensitivities** to the BNL/FNAL measurements
- **Many new and key technologies getting ready for realization**
- Expected commissioning and data taking in 2030
- 2 years data taking for **450 ppb (stat.)** ⊕ **70 ppb (syst.)** precision for g–2 and **1.5×10^{-21} e cm** sensitivity for EDM

Backup

Expected Sensitivity

Total efficiency of μ^+ per initial production
$= 1.3 \times 10^{-5}$ (with polarization of 50%)



g−2 sensitivity

- Statistical uncertainty = 450 ppb (2-years data taking with 1 MW proton beam)
  - Compatible to the BNL final result
- Systematic uncertainty less than 70 ppb

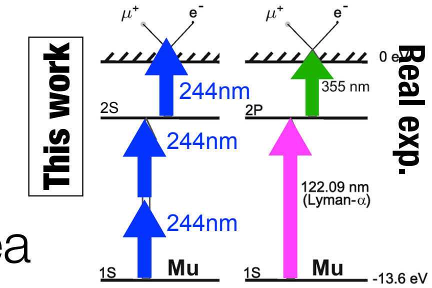
EDM sensitivity

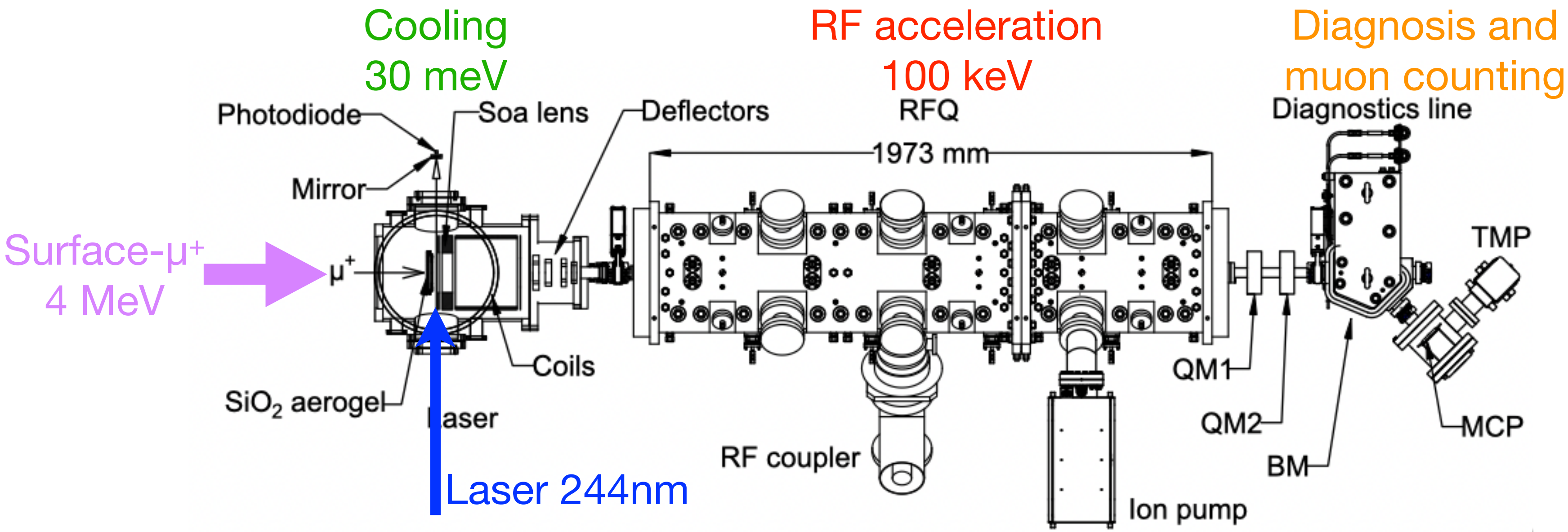
- Statistical uncertainty = 1.5×10^{-21} e cm
- Systematic uncertainty = 0.4×10^{-21} e cm

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

Demonstration of Cooling/Reaccelerating

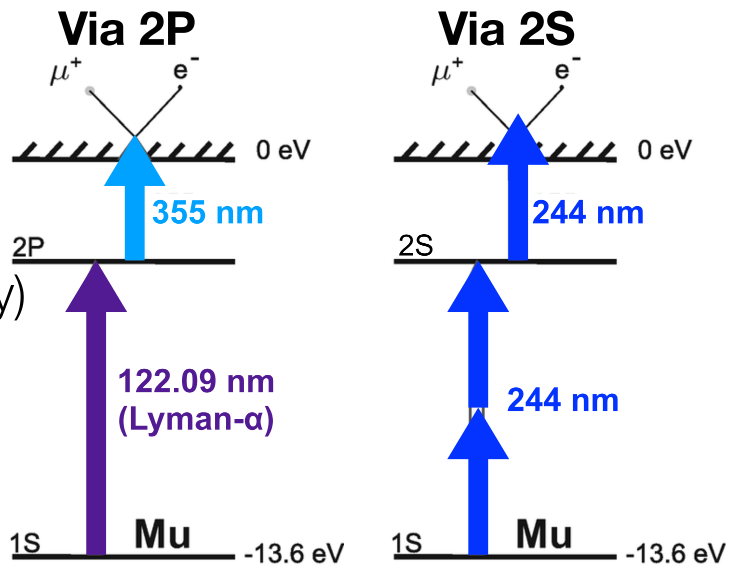
- Ultraslow muon production and its acceleration during Mar.-Apr. '24 beam time
- **Currently available facilities/instruments were used** instead of the real ones
  - S2 area (surface muon line) instead of the H2 area
  - 244 nm Ionization laser to utilize 1S-2S (not 1S-2P) transition
  - Prototype RFQ (shorter version), limited by the experimental area





Laser

- Irradiate pulsed laser to the diffused muonium
- Unbound the muonium through an intermediate step (Impossible to directory unbound the 13.6 eV (=91 nm) energy)
- Choose solid laser technique as a high-intensity, high-stability, and long lifetime light source
- Goal: 100 μJ for Ly-α, 300 mJ for 355 nm



J-PARC MLF	U-line	S2-area	H2-area
Scheme	1S→2P	1S→2S	1S→2P (backup: 1S→2S)
Status	Long-term operated with Ly-α=10 μJ Upgrading to 20 μJ	Lead by Okayam-U (Mu 1S2S spectroscopy) Used at the first μ^+-acc. test	Under construction First light planned in 2025
Achieved USM rate after transportation	330 Hz	>0.1 Hz	Final goal: 10^5 Hz