J-PARC Muon *g*-2/EDM

Worksnop on Muon Physics at the Intensity and Precision Frontiers

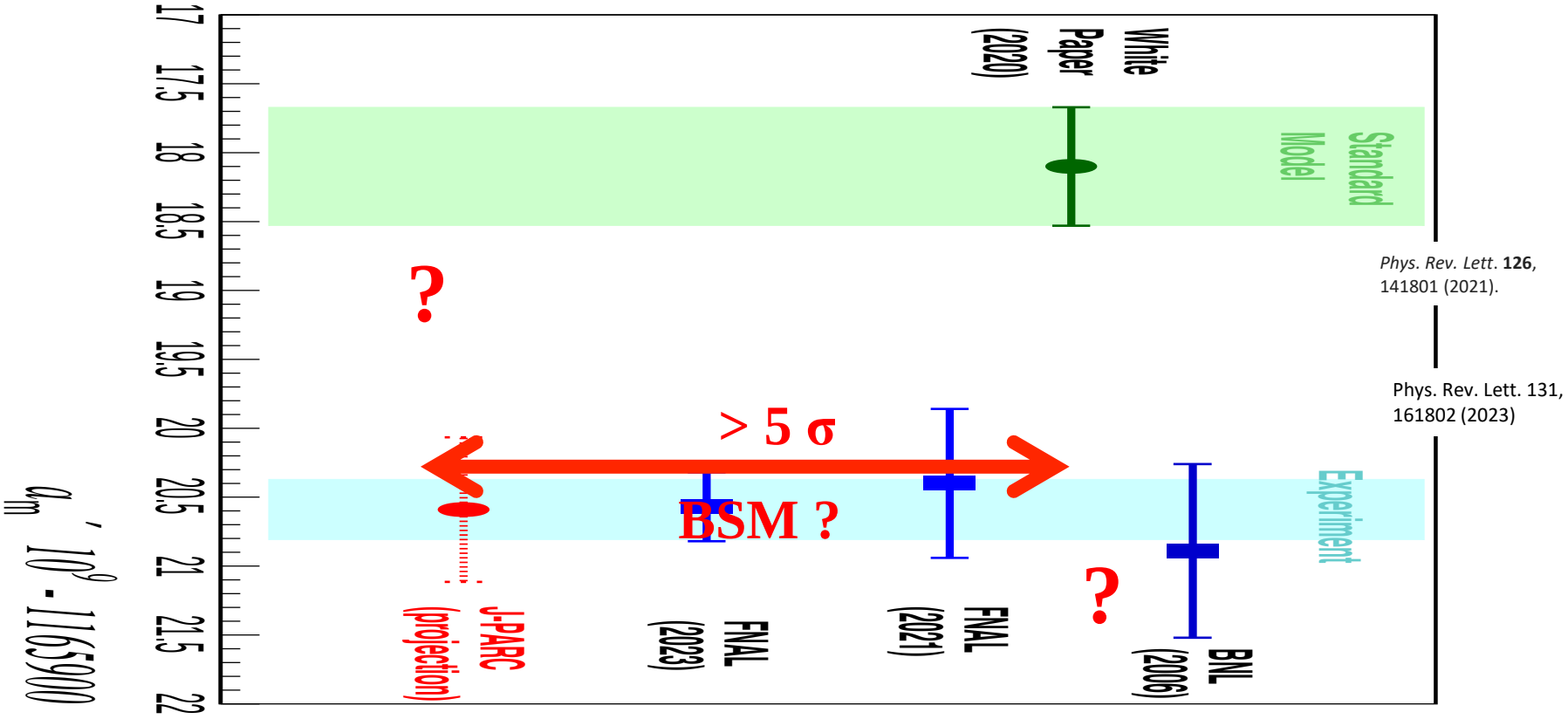
2024/04/20

Kyushu University (九州大学)

Tamaki Yoshioka (吉岡 瑞樹)

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

Present Status of Muon g-2



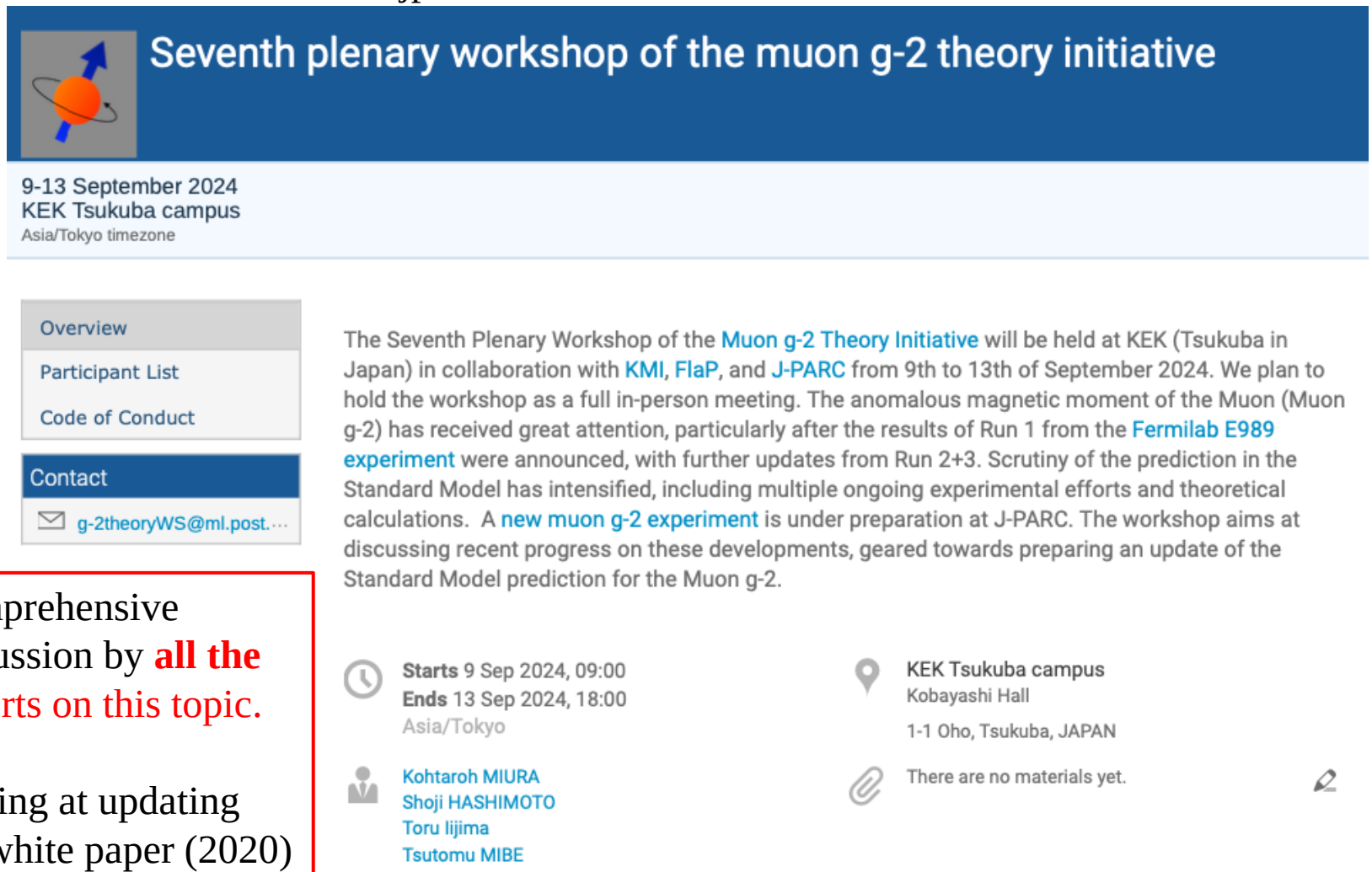
Phys. Rev. Lett. **126**, 141801 (2021).

Phys. Rev. Lett. 131, 161802 (2023)

1. New Physics?
2. SM calculation is wrong?
3. Systematics of experiments?

Muon g-2 Theory Initiative Workshop at KEK

https://conference-indico.kek.jp/event/257/



Comprehensive discussion by **all the** experts on this topic.

Aiming at updating the white paper (2020)

Experimental Principle

- 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.

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

g-2 precession

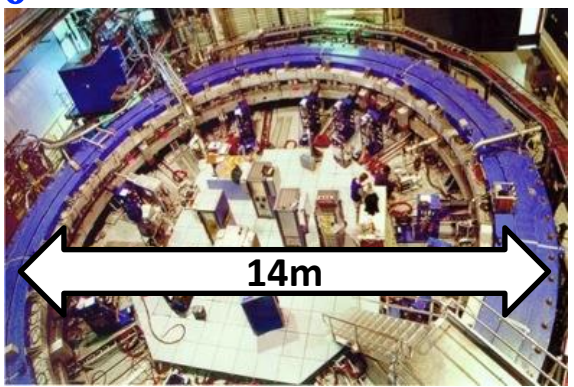
EDM precession

- **BNL/FNAL experiment**

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

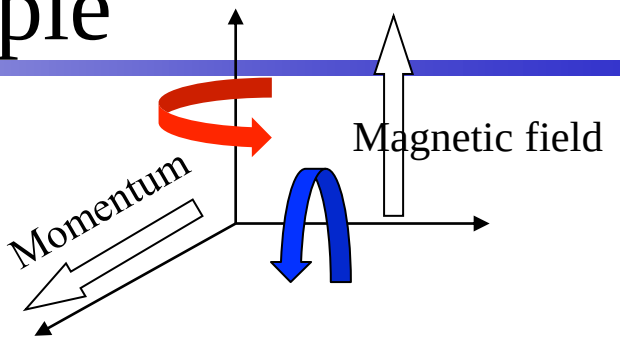
= 0

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



Experimental Principle

- **J-PARC Experiment**
  - Measurement at E = 0.
    - Muons will be stored by weak focusing B-field.
    - This requires low emittance muon beam and dedicated beam injection scheme.



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

$= 0$ $= 0$

  - Measurement at lower muon momentum becomes possible.

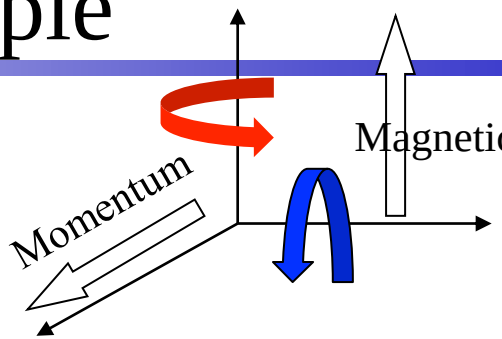
→ More compact storage region with better uniformity of B-field.

- P = 0.3 GeV/c, φ = 0.66 m at B = 3 T

  - This leads to the
    - Independent measurement of g-2 to confirm BNL/FNAL result at different systematic uncertainty.
    - Clear separation of g-2 and EDM signal.

Experimental Principle

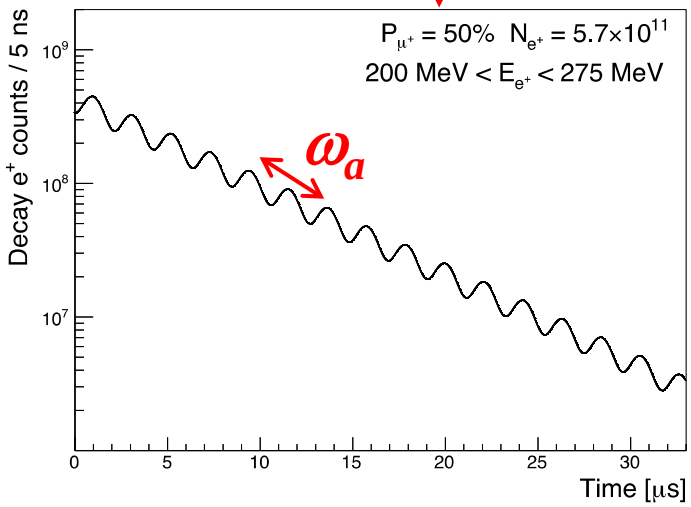
- **J-PARC Experiment**
  - Measurement at E = 0.
    - Muons will be stored by weak focusing B-field.
    - This requires low emittance muon beam and dedicated beam injection scheme.



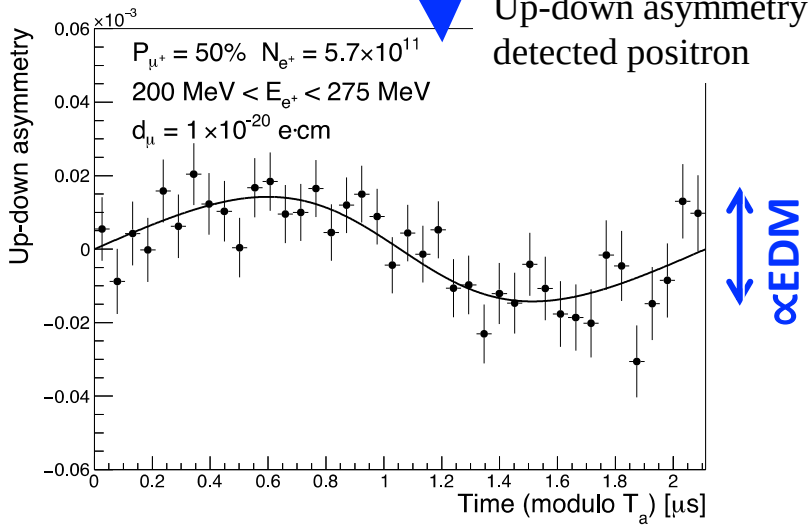
$$\vec{\omega}_a + \vec{\omega}_\eta = -\frac{e}{m}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta} \times \vec{E}}{c} + \frac{\eta}{2}\left(\vec{\beta} \times \vec{B} + \frac{\vec{E}}{c}\right)\right]$$

$= 0$ $= 0$

Number of detected positron



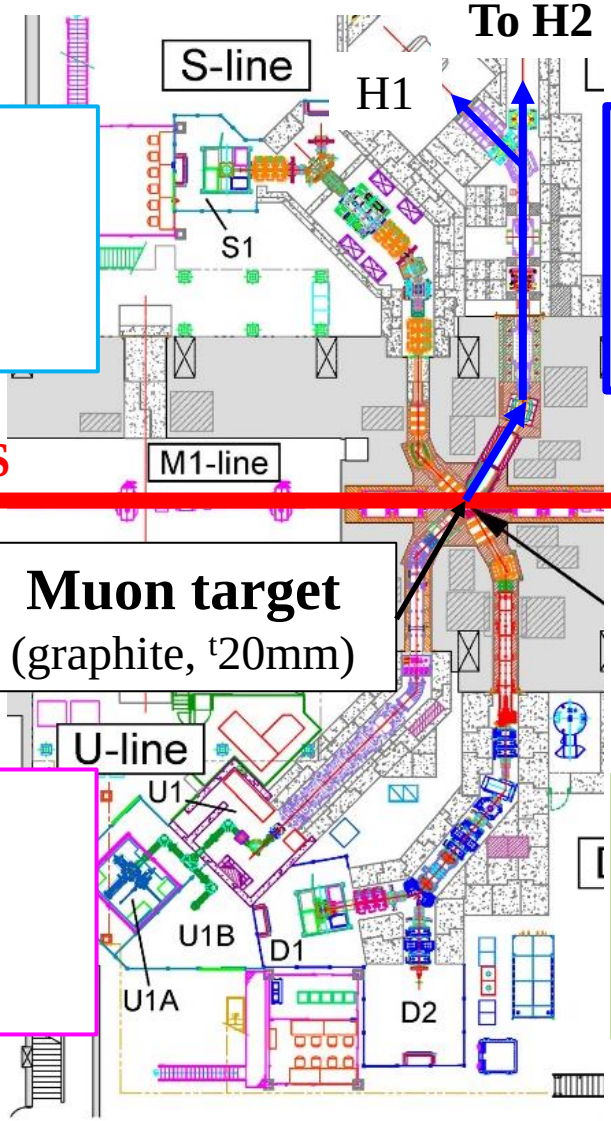
Up-down asymmetry of detected positron



Bird's eye photo in Feb. 2008

J-PARC Muon Facility in MLF

- **MUSE (Muon Science Establishment) in the MLF**



S-line
- surface μ^+
- S1 for μSR
- S2 for Mu 1S-2S

H-line
- **surface μ^+**, cloud μ^+/μ^-, e^-
- H1 for DeeMe & MuSEUM
- H2 for g-2/EDM & TμM

3GeV proton from RCS

2e15 /s @1MW

Muon target
(graphite, t20mm)

(Neutron target)

U-line
- ultra slow μ^+
- U1A for nm-μSR
- U1B for μ microscopy

D-line
- decay μ^+/μ^-, surface μ^+
- D1 area for μSR
- D2 for variety of science

J-PARC Muon g-2/EDM Experiment

J-PARC MLF H-line

Constructed in FY2021

Muon beam

μ^+ (4 MeV)

cooling

energy reduction by 10^8

μ^+ (25 meV)

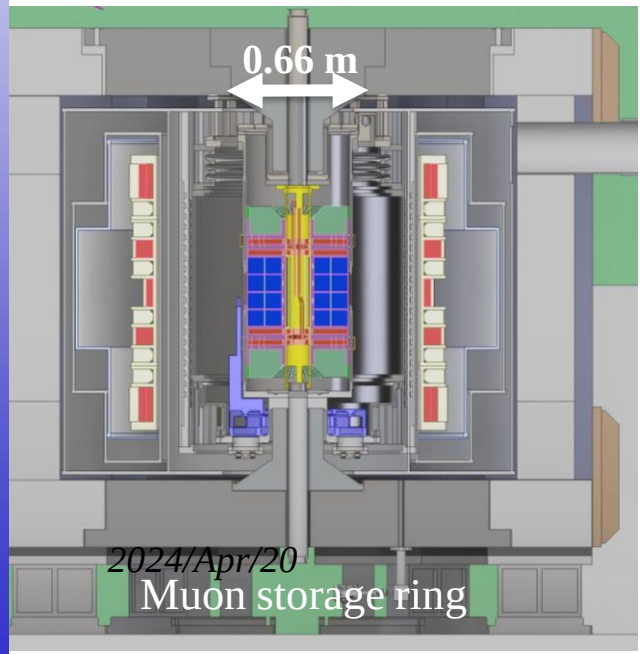
acceleration

acceleration by 10^{10}

μ^+ (210 MeV)

Injection

storage

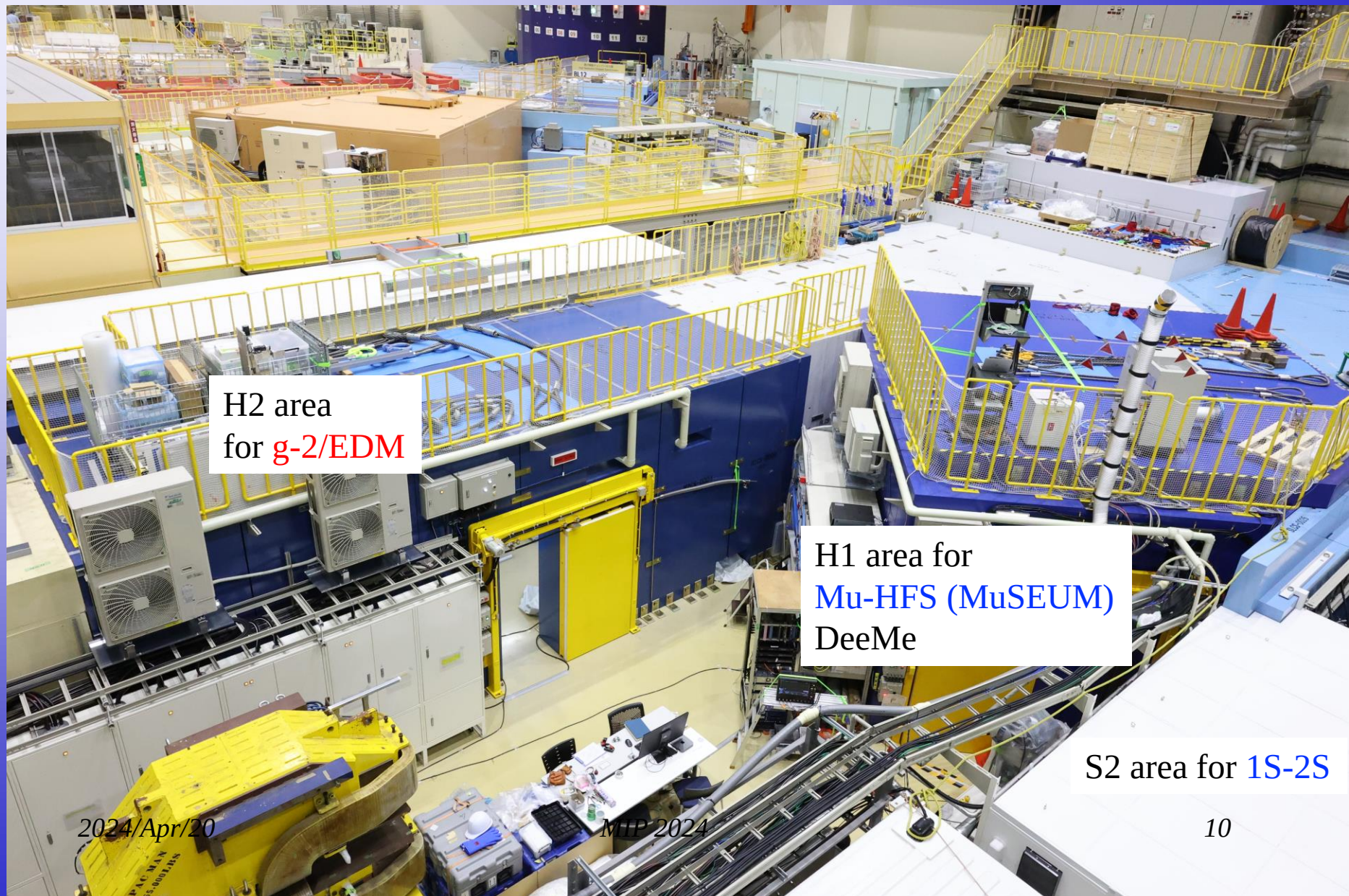


Measurement of g-2 and EDM with a compact storage magnet (1/20 of previous exp.) with new muon beam by cooling and acceleration.

- Construction of facility has been started in 2022
- Aiming for data taking from 2028

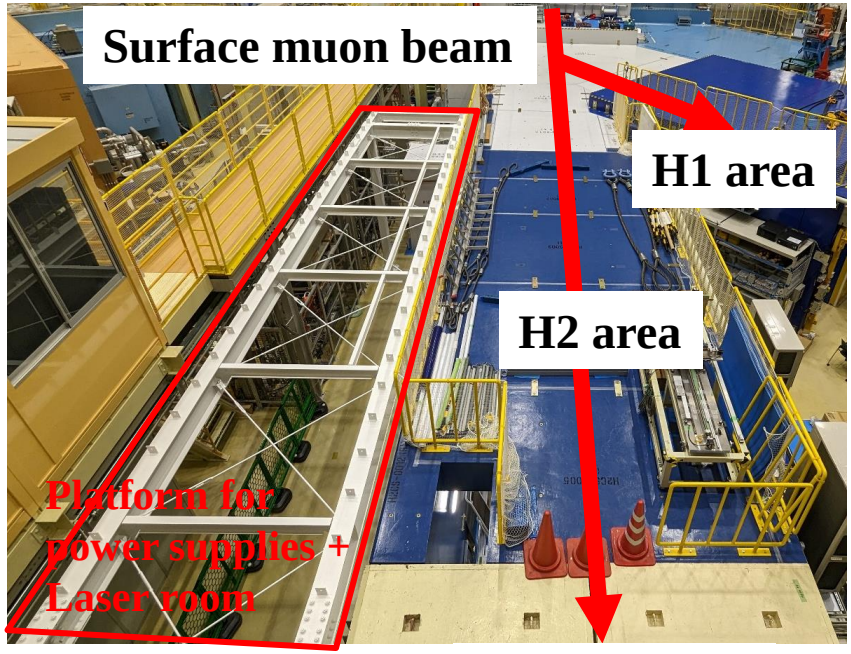
Experimental Area

As of Apr. 2024

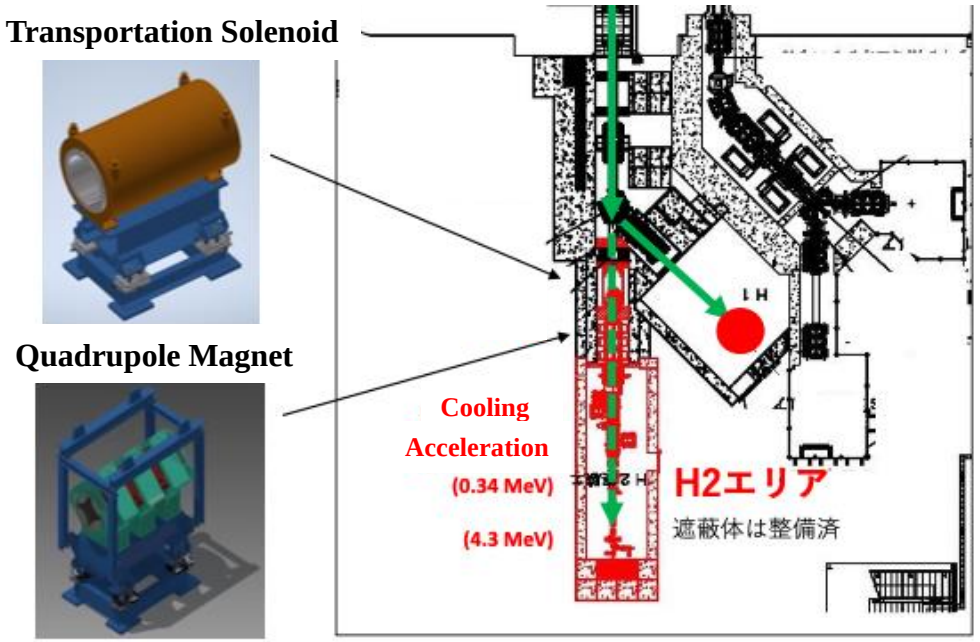


Surface μ^+ beam at MLF

- MLF H2 beamline
  - Surface μ^+ beam: 4 MeV, 10^8 /s w/ 25 Hz rep.
  - Beam rate: 1.2 $\times 10^8$ muons/s is expected at the Mu production target.
- Beamline extension to H2 area is planned for FY2024 (Budget secured !).
- Acceleration test up to 4 MeV is planned for FY2025 (Budget secured !).



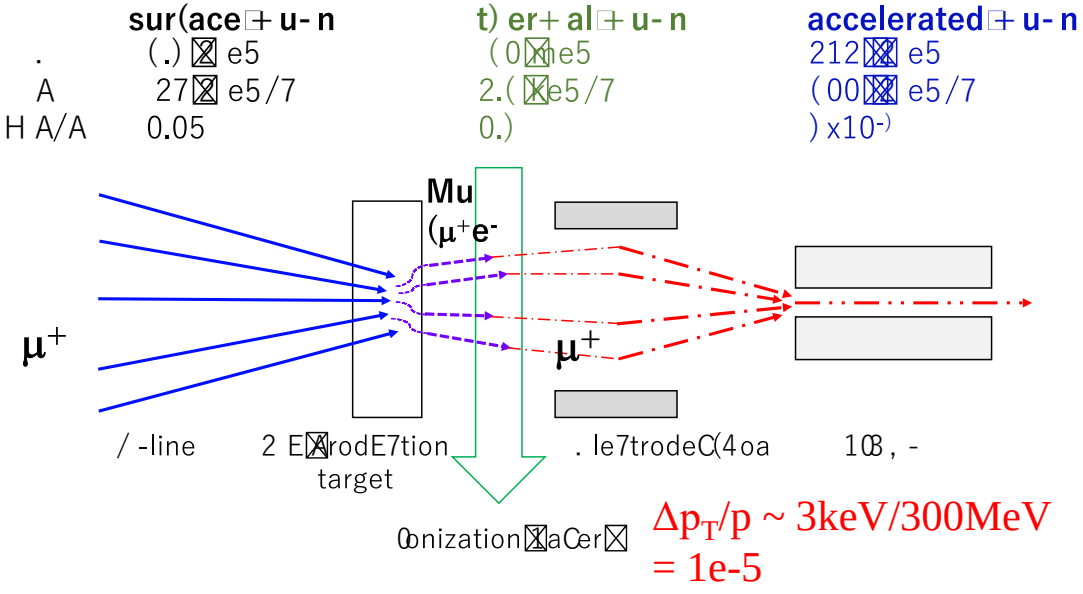
To g-2/EDM



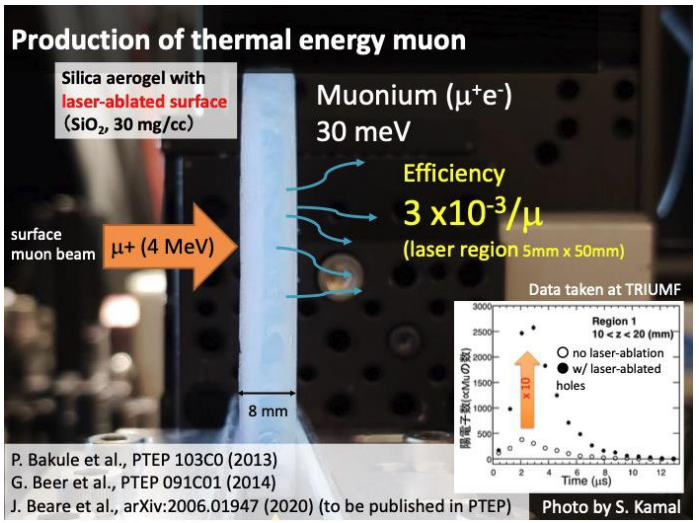
Extension Building

Muon Cooling

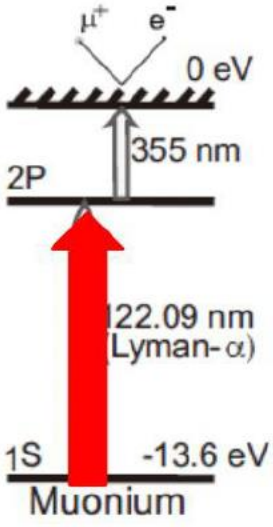
- Low emittance muon beam by reacceleration of thermal muon.
  - ✓ **Silica aerogel target**: Surface muons stopped, and thermal muoniums emitted.
  - ✓ Laser ablated aerogel to increase the efficiency.

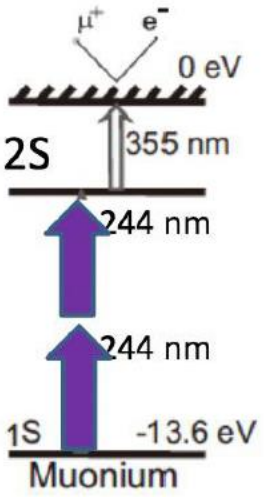


$\Delta p_T/p \sim 3\text{keV}/300\text{MeV} = 1\text{e-}5$



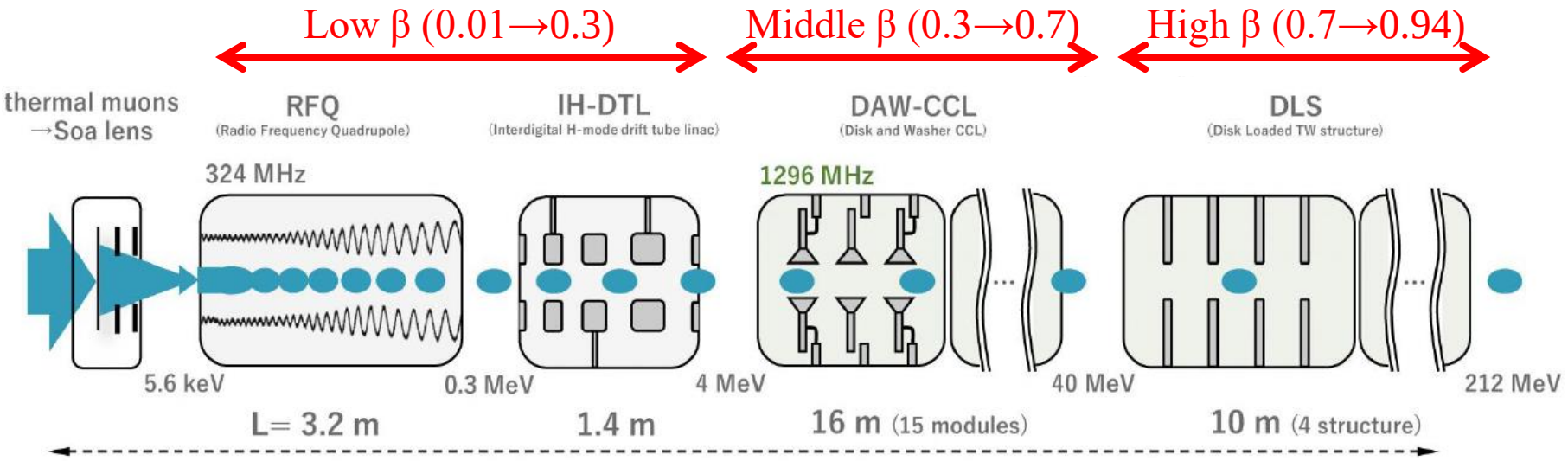
- Thermal muonium ionization by laser
  - ✓ Two scheme under consideration.
  - ✓ 1S-2P excitation by 122 nm
  - or 1S-2S excitation by 244 nm.





Muon Acceleration

- Muon acceleration to 300 MeV/*c* by dedicated muon LINAC.
- 4 steps acceleration depending on β. L = 40 m in total.

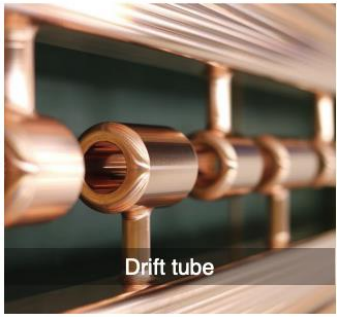


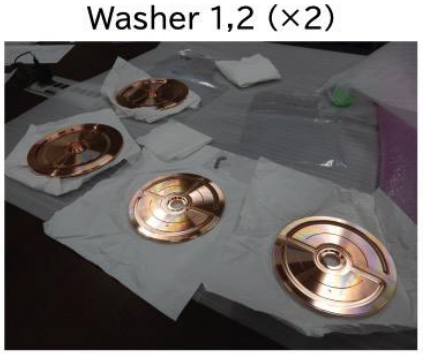
Acceleration test w/ thermal μ is on-going.

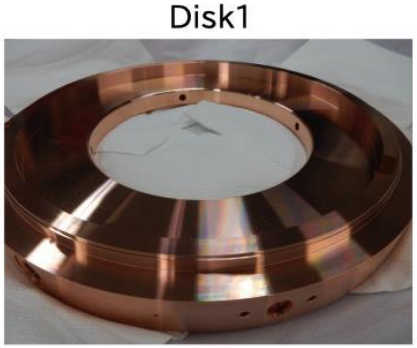
Fabrication completed

1st tank fabricated

Prototype fabricated and tested.

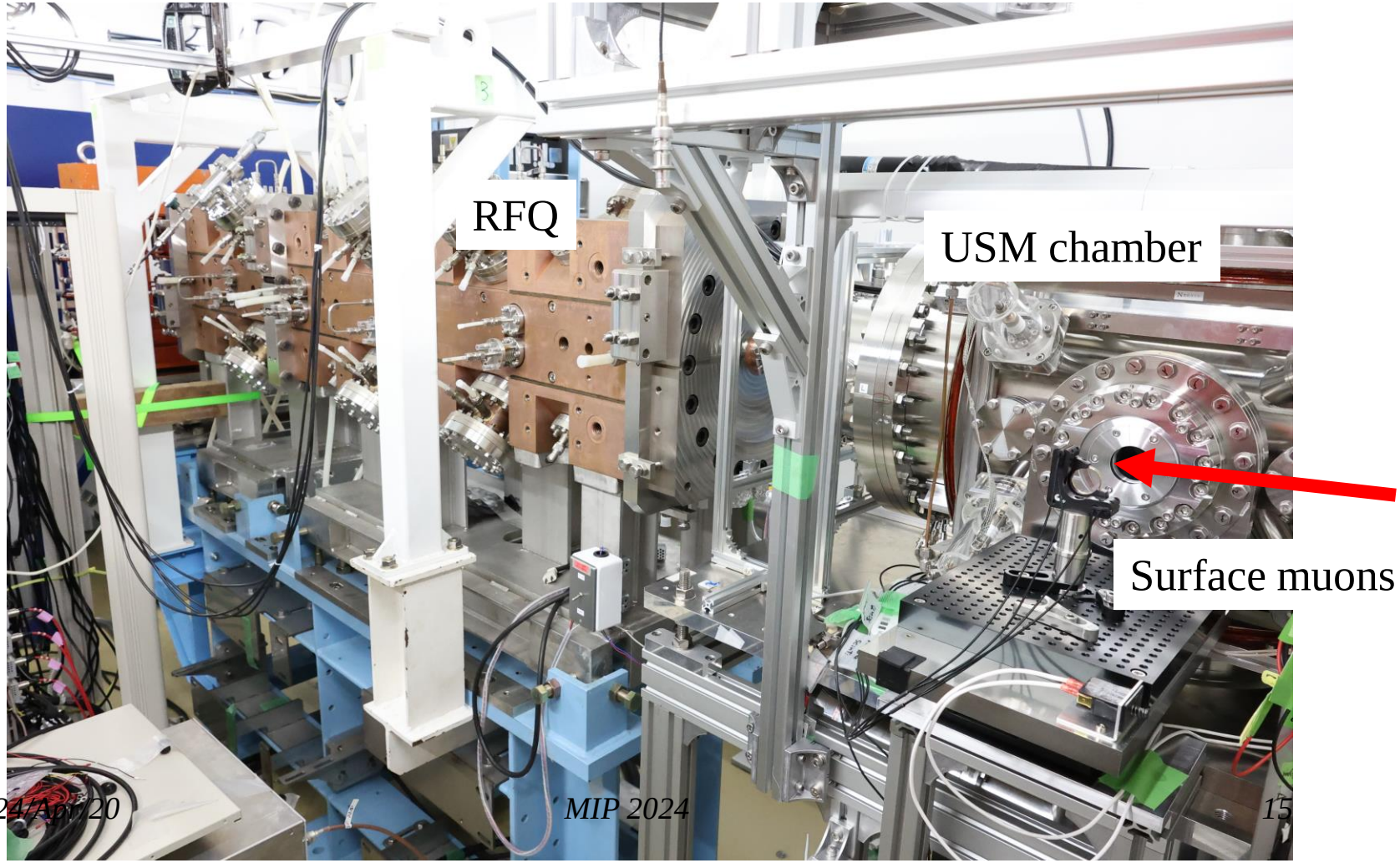






Demonstration of Muon Cooling/Acceleration

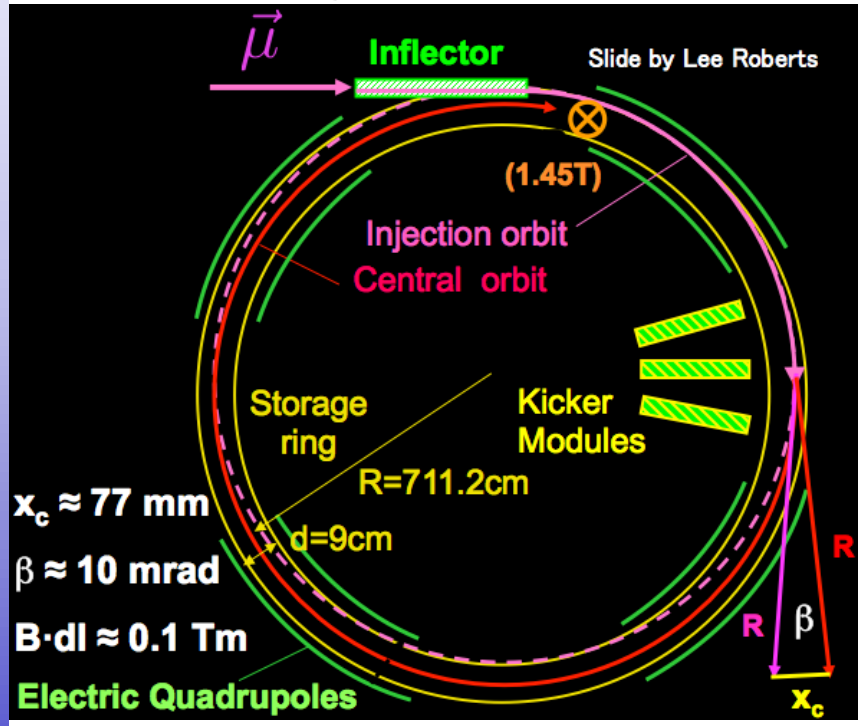
- Ultra Slow Muon (USM) production using “real” USM chamber has been tested.
- Demonstration of acceleration to 90 keV of μ^+ using RFQ is currently on-going.



Muon Beam Injection

- 3D spiral injection scheme is adopted for muon injection into the storage magnet.

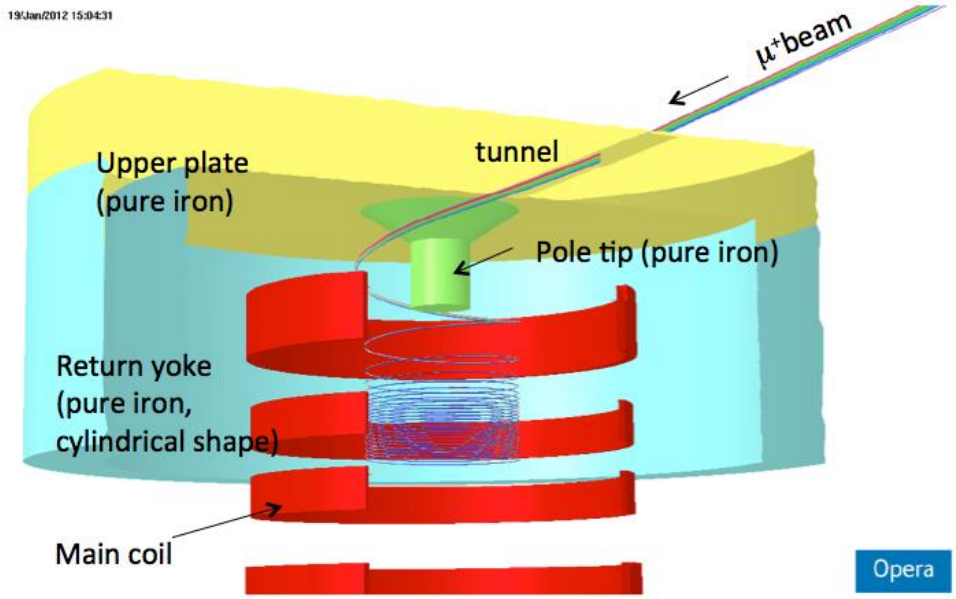
Horizontal injection



Injection efficiency : 3-5%(*)

(*) PRD73,072003 (2006)

3D spiral injection (J-PARC E34)



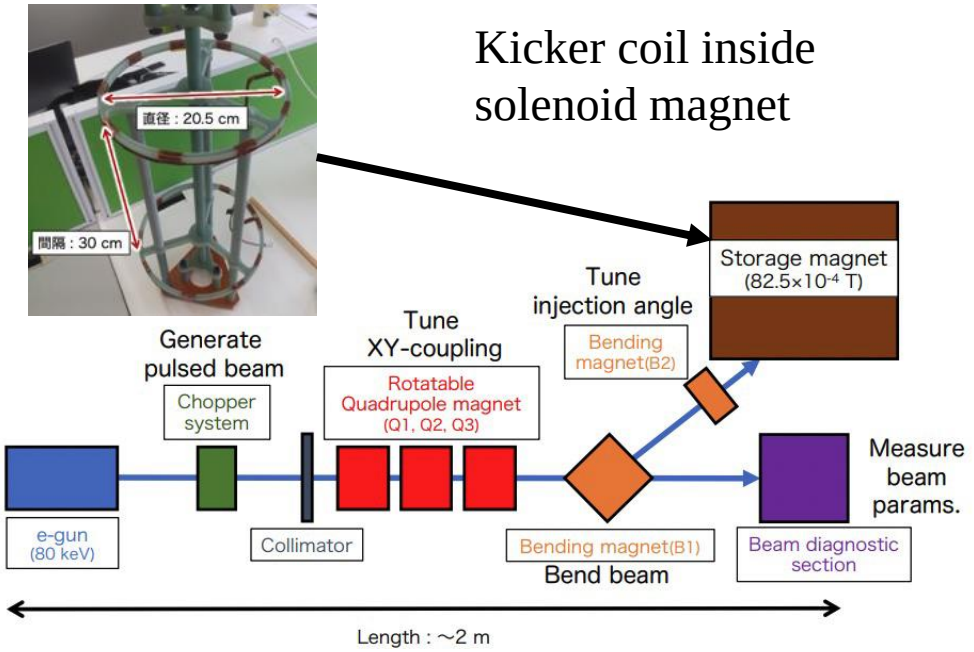
Injection efficiency : ~85%

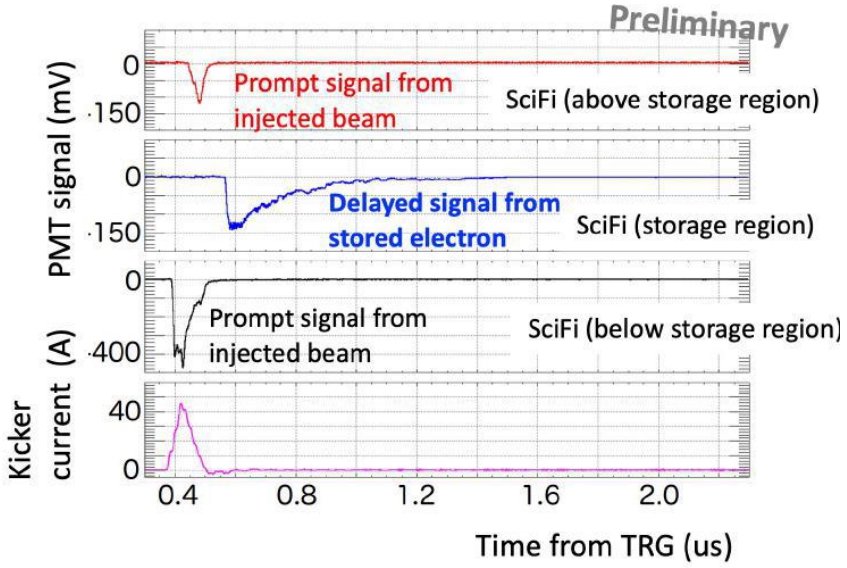
H. Iinuma et. al., NIM A 832, 51-62 (2016)

Demonstration of Spiral Injection

- Demonstration of 3D spiral injection scheme is on-going in a test setup by using an electron beam.
  - E = 80 keV, B = 80 mT, R = 0.12m

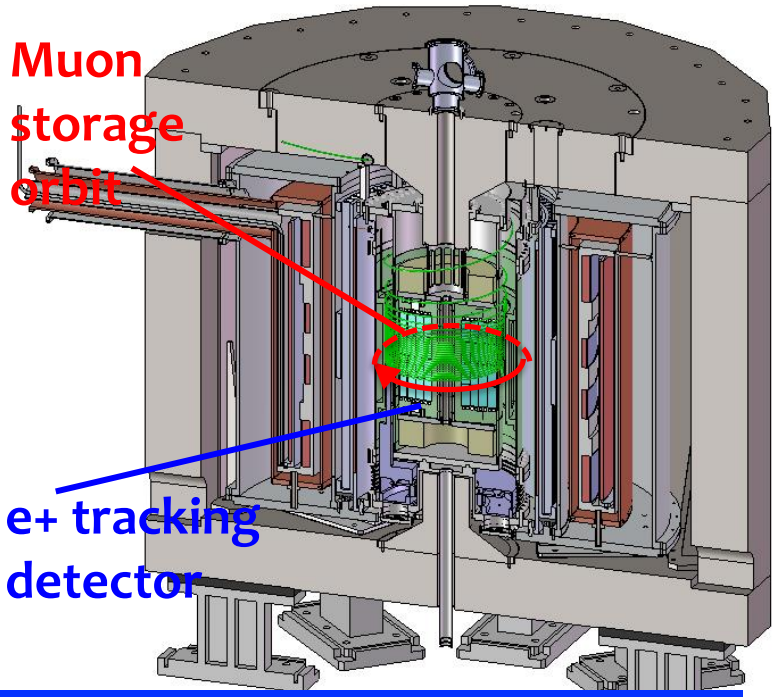
- First signal from stored electron beam is successfully observed.





Storage Magnet

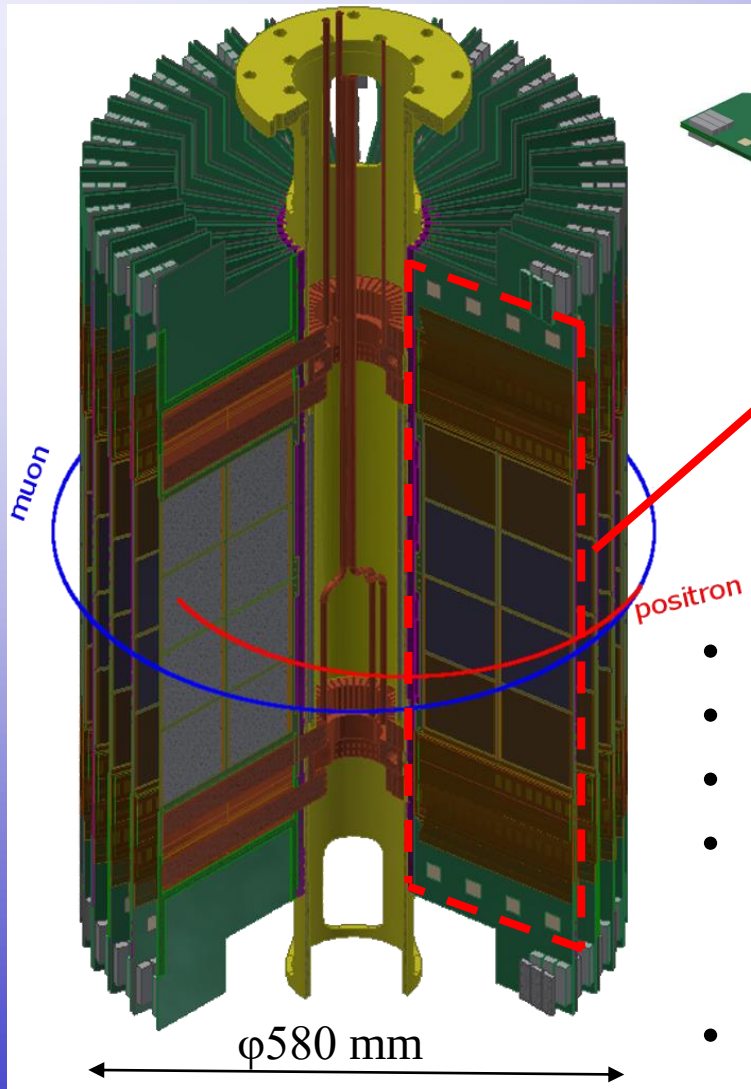
- A compact superconducting magnet based on MRI technology.
  - B = 3 T, φ = 66 cm: Good local uniformity is expected (ΔB < 0.2 ppm)
- Local uniformity of 1 ppm is already demonstrated by the MUSEUM magnet.



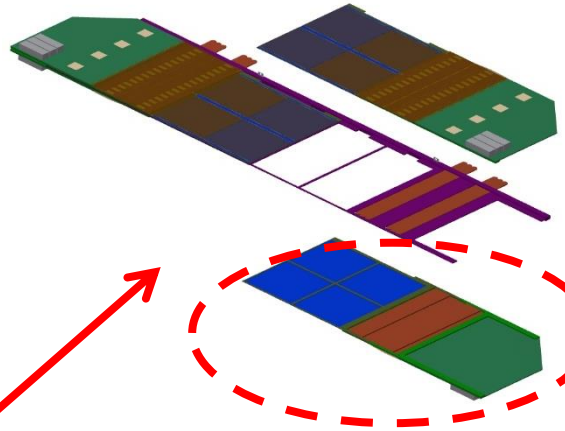
M. Abe et. al., NIM A 890, 51 (2018)

Superconducting magnet (1.7T)

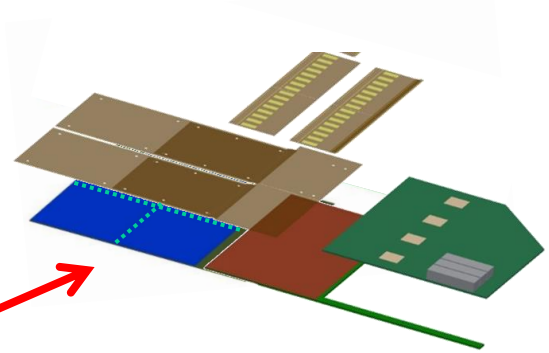
Positron Tracking Detector



Vane structure



Quarter vane structure



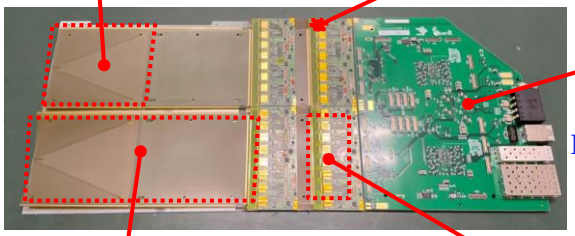
- Number of vane: 40
- Fiducial volume: 200mm (radial) x 400mm (axial)
- One vane consists of four quarter vanes.
- Two-dimensional hit position is reconstructed from orthogonally arranged silicon strip sensor (190 μm pitch & 5 cm strip length).
- Readout ASIC w/ 5nsec sampling rate.

Positron Tracking Detector

- Production of detector components are on track.

Silicon strip sensor (not seen); in mass production (260/640).

Readout ASIC (SliT128D); Mass production finished and quality inspection is on-going.

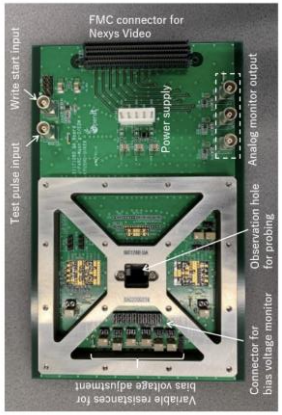


FPGA-based readout board (FRBS) for data/clock communication; prototype is being tested.
MS thesis (Okamura, Niigata U)
Cooling system and GFRP frame for assembly (not seen).

Flexible printed circuit boards (FPC) for analog signal transfer; Mass production finished.

ASIC boards; Eight ASICs are mounted. Semi-final version has been produced.

- Quality inspection of ASIC has completed.

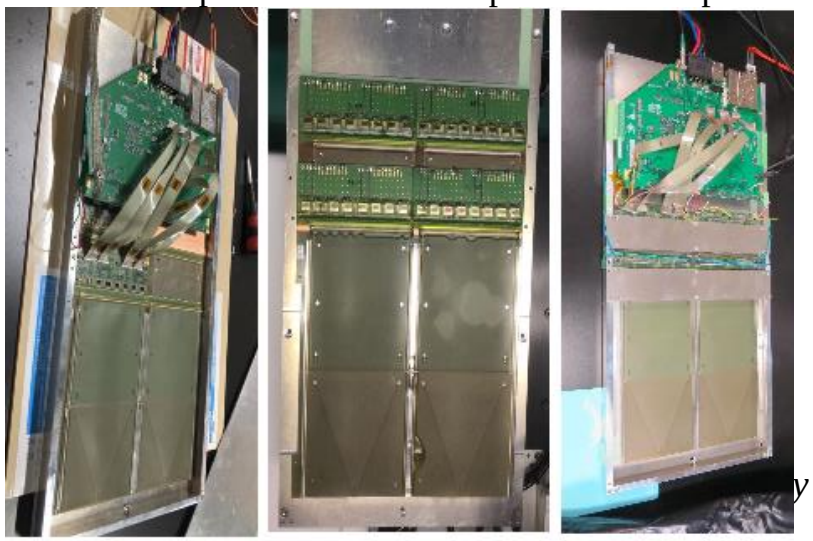


Defect	Number
Appearance defects	3
Abnormal power supply current	23
Slow control failure	4
Defective channels	291
High time walk channels	560
Abnormal analog waveforms	21
No defect	4833
Total	5735

Submitted to NIM (arXiv:2401.11920)

- Three types of quarter vane prototypes were produced and tested.

Electronical proto. Mechanical proto. Noise proto.



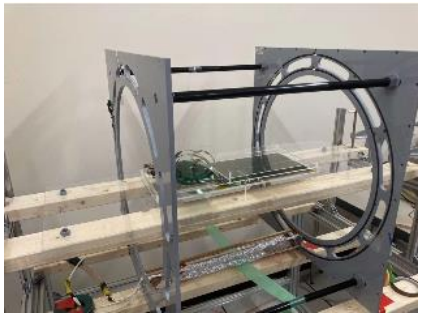
MS thesis (Umebayashi, Kyushu U)

- Operation tests under magnetic field and kicker field were carried out/in preparation.

magnetic field

Operation test will be next month.

kicker field



Visible effects was observed.

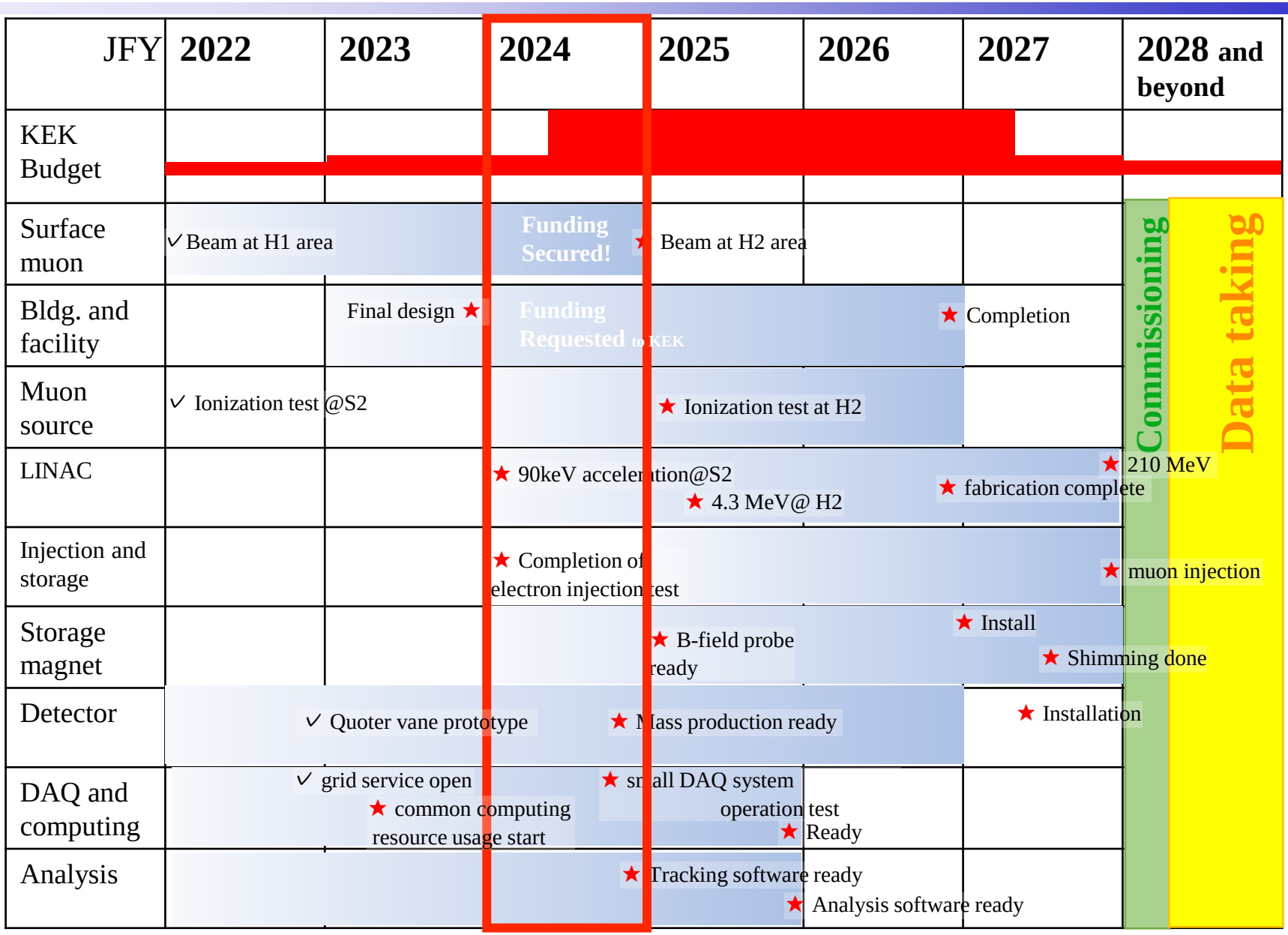
Expected Sensitivity

- Total efficiency of muon: 1.3×10^{-5}.
- Muon g-2
  - Statistical uncertainty: 450 ppb (2 year of data taking)
    - ✓ Comparable to BNL.
  - Systematic uncertainty: less than 70 ppb.
- Muon EDM
  - Statistical uncertainty: 1.5×10^{-21} e·cm.
  - Systematic uncertainty: 0.4×10^{-21} e·cm.
    - ✓ Mainly from detector mis-alignment

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		

Anomalous spin presession (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

Schedule and Milestones



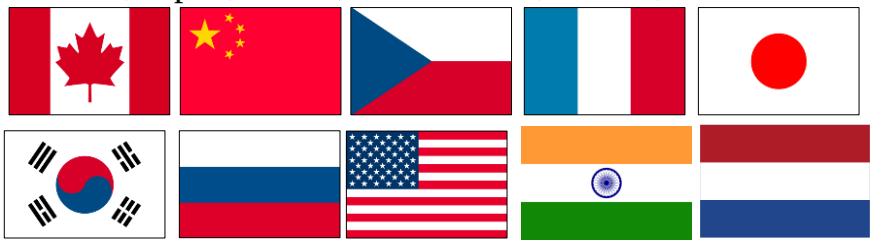
The Collaboration

Collaboration Board (CB)
Chair : Tamaki Yoshioka

Executive board (EB)
Spokesperson: T. Mibe

SJTU newly joined
Liang Li, Bingzhi Li
Welcome !!

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



Subgroups

Surface muon beam
leader: T. Yamazaki, N. Kawamura

Ultra-slow muon
leader: K. Ishida

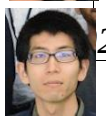
LINAC
leader: M. Otani

Injection and storage
leader: H. Iinuma

Storage magnet, field measurements
leader: K. Sasaki

Detector
leader: T. Yoshioka

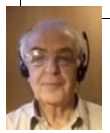
DAQ and computing
leader: Y. Sato



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, **Y. Sato**

Publication committee
chair: B. Shwartz

Working groups

physics analysis
T. Yamanaka, S. Ogawa

Domestic institutes：
Kyushu, Nagoya, Tohoku, Niigata, Toyama C, Tokyo, Ibaraki, RIKEN, JAEA, etc.

KEK: IPNS, IMSS, ACC, CRY, MEC, CRC

The 28th collaboration meeting at Niigata University, Dec. 13-15, 2023

Summary

- Muon g-2/EDM experiments at J-PARC aims to measure muon g-2/EDM by utilizing
  - Low emittance muon beam stored in a compact region with a uniform B-field only by weak focusing magnetic field.
- This will be an independent measurement from BNL/FNAL at different systematics.
- Most of the key technology of this experiment are getting ready for realization. Expected data taking from JFY2028.
- After 2 years data taking,
  - Muon g-2 measurement at 450 ppb (stat.), 70 ppb (syst.): statistics comparable to BNL, completely different source of systematics
  - Muon EDM sensitivity at 1.5×10^{-21} e･cm (stat.)

Your participation is very welcome !!