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J-PARC

Muon g-2/EDM Experiment at J-PARC

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for the J-PARC E34 Collaboration

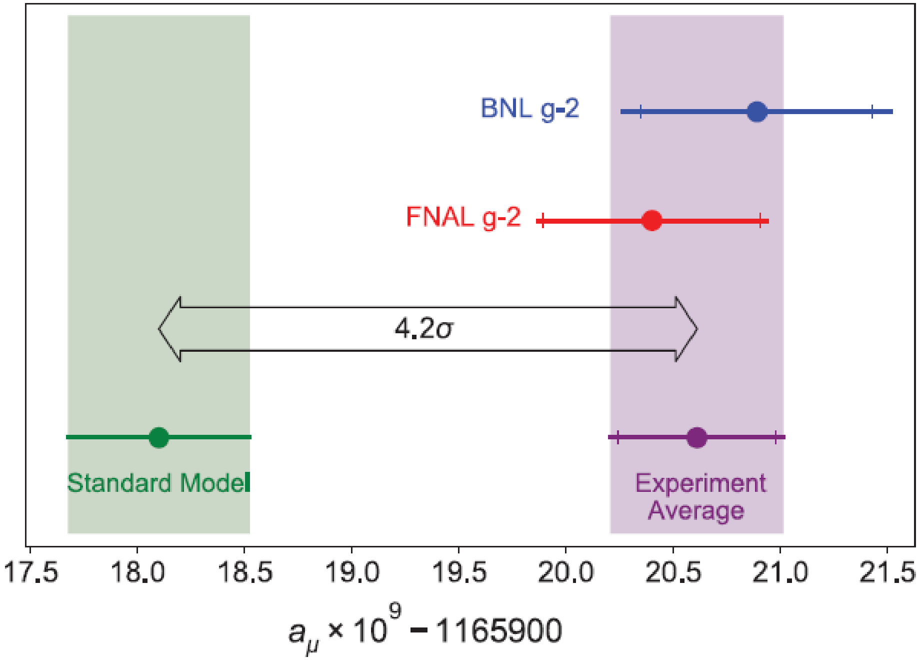
Outline of Slides

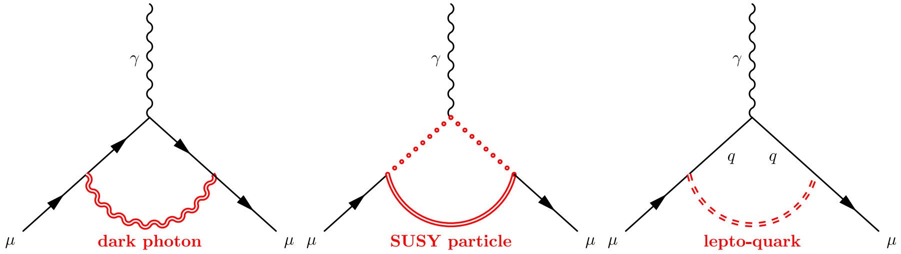
- Overview of the J-PARC muon g-2/EDM experiment
- Status of the experimental components
- Statistical and systematic uncertainties on a_μ
- Recent updates and schedule of the experiment

Muon g-2 and EDM

- Anomalous magnetic moment (g-2) of muon
  - Calculated in 0.37 ppm precision for muon in the SM (Phys. Rep. 887 (2020) 1–166)
  - The best experimental precision is 0.46 ppm by the FNAL E989 Experiment.
  - The experimental average value deviates from the SM prediction by 4.2 σ.
  - Can new physics explain this discrepancy?
- Electric dipole moment (EDM) of muon
  - If non-zero EDM exists, it means T violation.
  - Current experimental limit for muon is $|d_\mu| < 1.8 \times 10^{-19}$ e・cm by the BNL E821 experiment.
    - Phys. Rev. D **80**, 052008 (2009)
  - The SM expectation of muon EDM is ~2×10^{-38} e・cm.
  - New physics predicts much larger EDM.
- **A new experiment to measure muon g-2 and EDM is under preparation at J-PARC.**

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





BSM contributions to the muon g-2

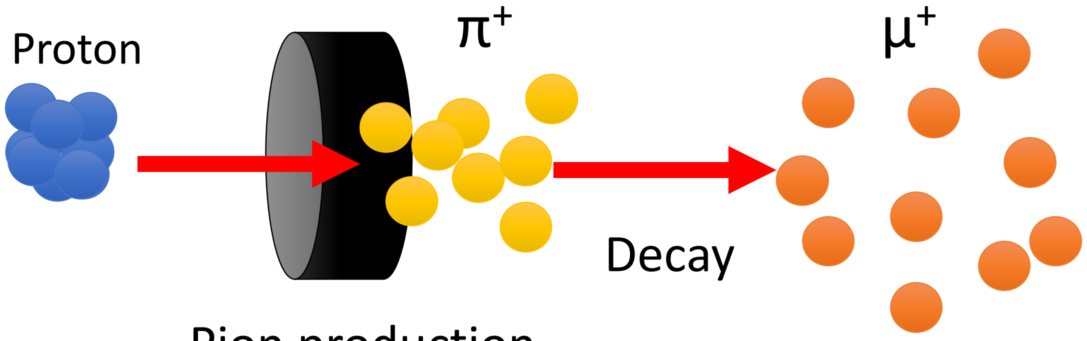
Muon g-2 Measurement

- The spin precession vector (with respect to cyclotron motion) in the electromagnetic field can be written as follows.

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

- In the BNL and FNAL experiments, to use a beam focusing electric field, the muon momentum is chosen to satisfy $\boxed{a_\mu - \frac{1}{\gamma^2 - 1} = 0}$ to make $\vec{\omega} = -\frac{e}{m} a_\mu \vec{B}$.
  - It corresponds to *p*=3.094 GeV/c and is called as the magic momentum.
- In the J-PARC experiment, the electric field itself is eliminated, $\boxed{\vec{E} = 0}$.
  - **Use of a reaccelerated thermal muon beam is a key of this method.**

Reaccelerated Thermal Muon Beam



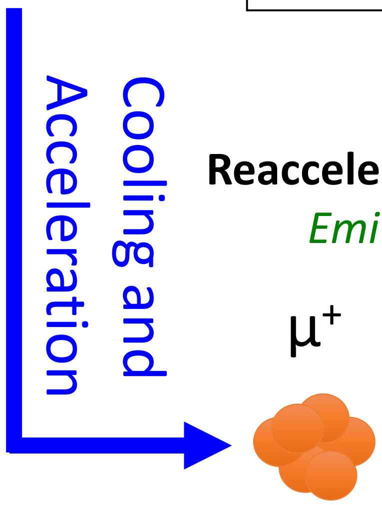
Conventional muon beam

Emittance ~1000π mm ･mrad

Strong focusing with electric field
Muon loss
Pion background

Reaccelerated thermal muon beam

- No requirement of strong beam focusing by an electric field.
  → Gradient magnetic field for beam focusing
- Free from magic momentum of 3.094 GeV/c
  → Lower momentum beam of 300 MeV/c
  - Compact storage region with highly uniform magnetic field.
  - Full tracking detector for decay positrons



Reaccelerated thermal muon beam

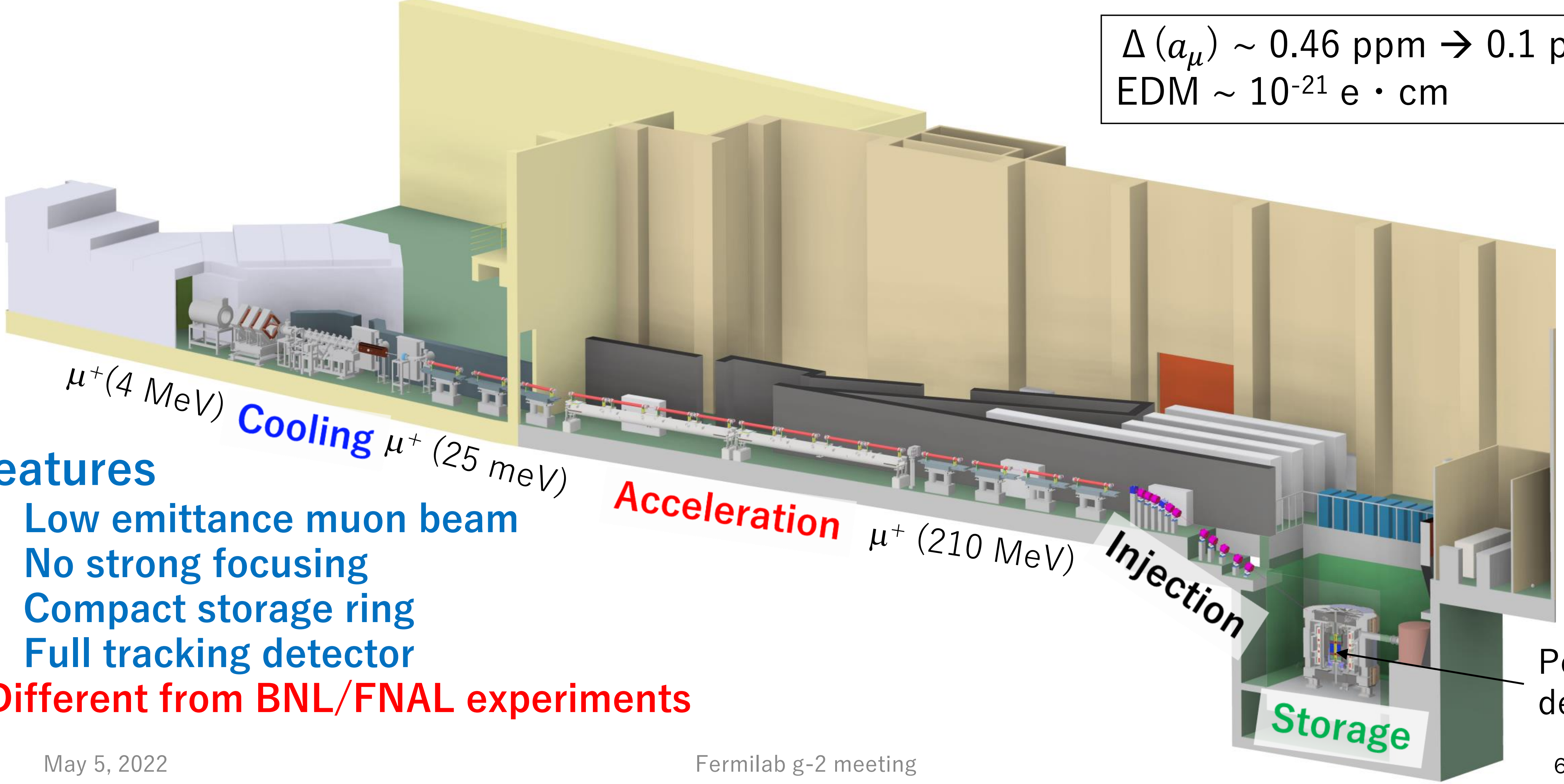
Emittance ~1π mm ･mrad

Free from any of the above

J-PARC E34 Experiment

Initial goal **Final goal**

$\Delta(a_\mu) \sim 0.46$ ppm → 0.1 ppm
EDM ~ 10^{-21} e・cm



Features

- Low emittance muon beam
- No strong focusing
- Compact storage ring
- Full tracking detector

Different from BNL/FNAL experiments

Comparison of Experiment Parameters

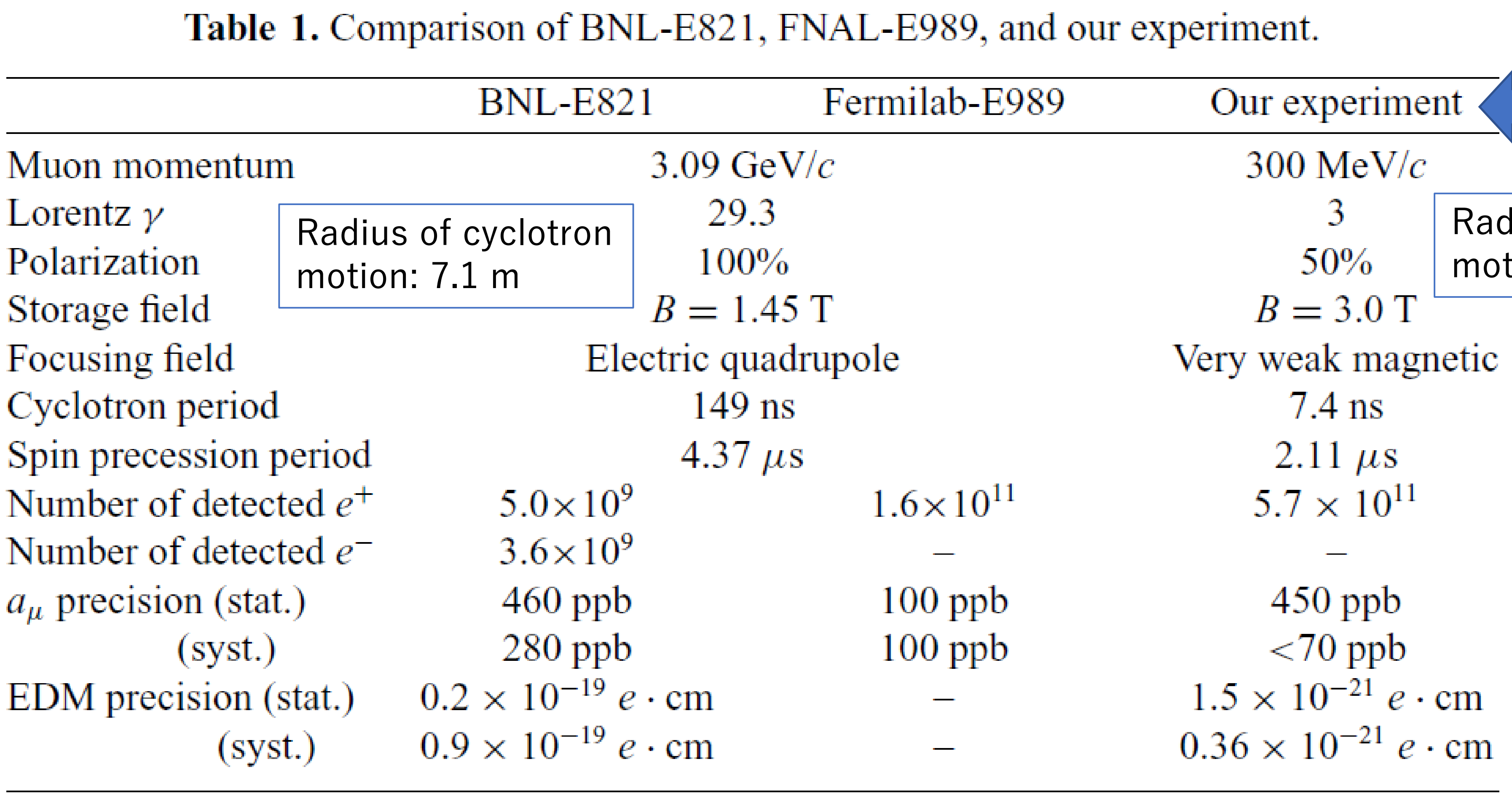


Table 1. Comparison of BNL-E821, FNAL-E989, and our experiment.

	BNL-E821	Fermilab-E989	Our experiment
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	450 ppb
(syst.)	280 ppb	100 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

J-PARC E34

Radius of cyclotron motion: 7.1 m

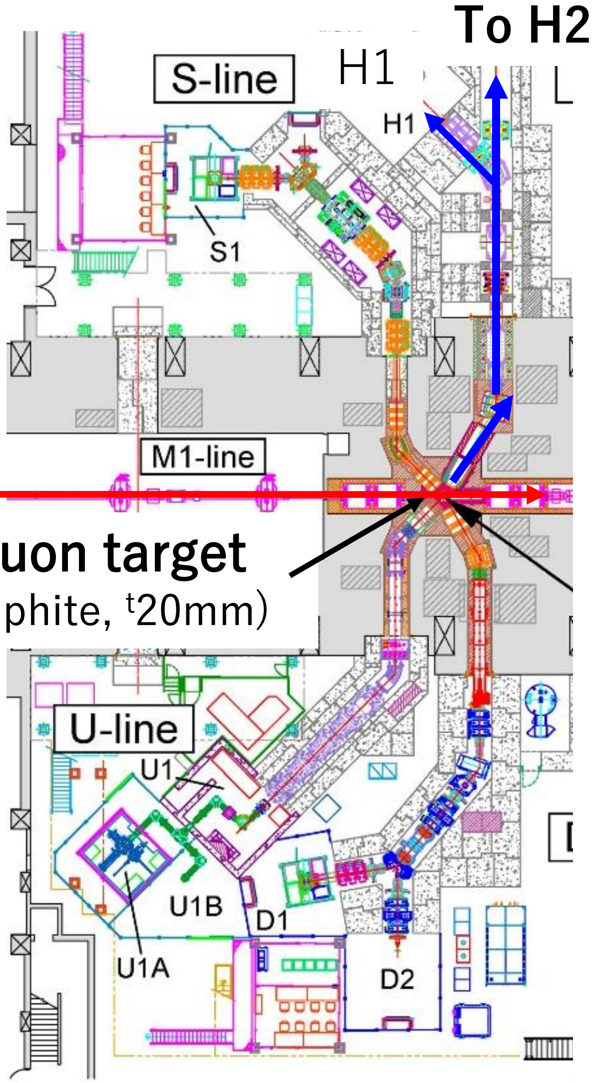
Radius of cyclotron motion: 333 mm

PTEP 2019 (2019), 053C02

J-PARC Facility

Located at Ibaraki prefecture in Japan

Muon Facility at J-PARC



S-line

- surface μ^+
- dedicated to μSR
- S1 area is available
- S2 is under construction
- S3/S4 are planned

3 GeV proton from RCS

2×10^{15} /s @1MW

Muon target
(graphite, ^{t}20mm)

U-line

- ultra slow μ^+
- U1A for nm-μSR
- U1B for μ microscopy
- under commissioning

H-line

- **surface μ^+ (>10^8 μ^+/s),** decay μ^+/μ^-, e^-
- **for high intensity & long beamtime** experiments
- H1 for DeeMe & MuSEUM
- **H2** for **g-2/EDM** & transmission muon microscopy
- **under construction**

D-line

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

H-line Construction

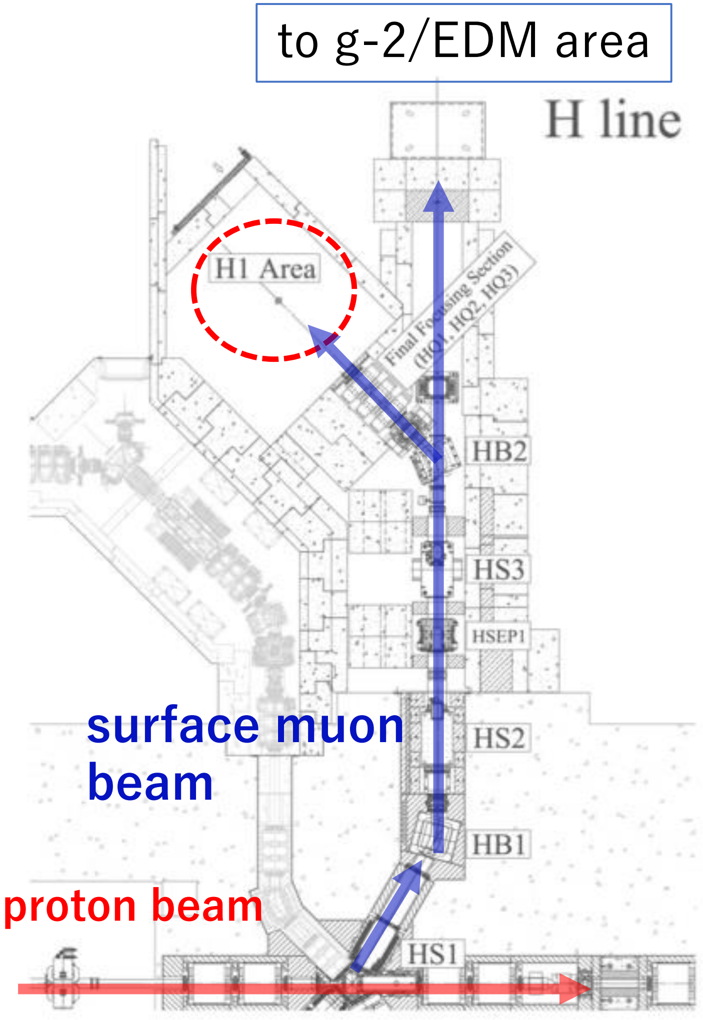
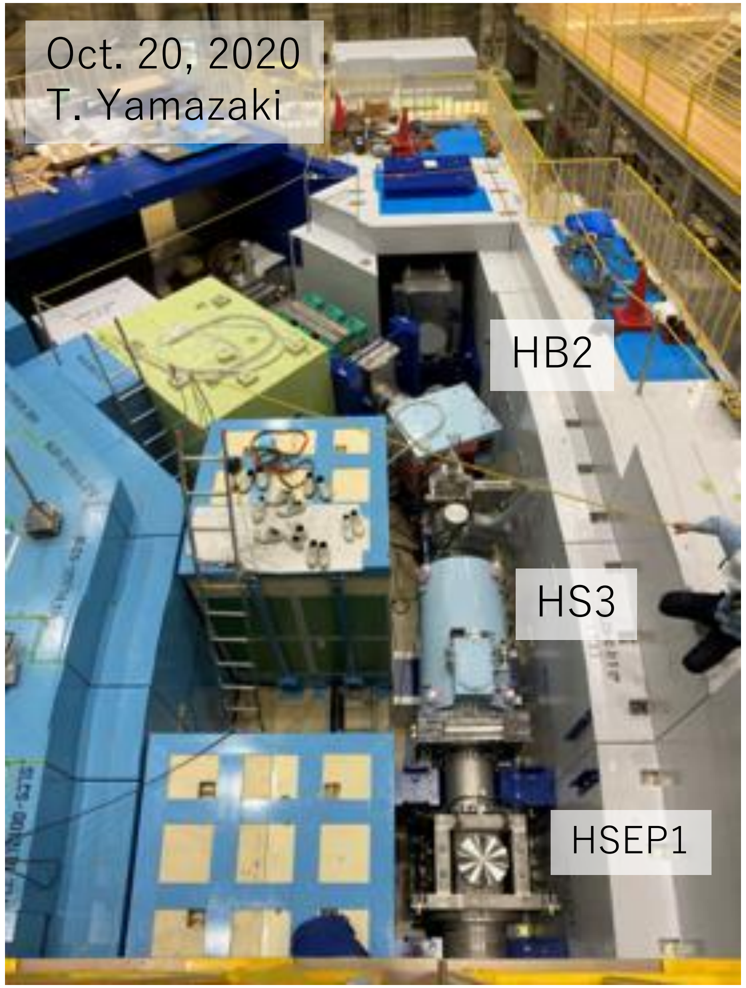
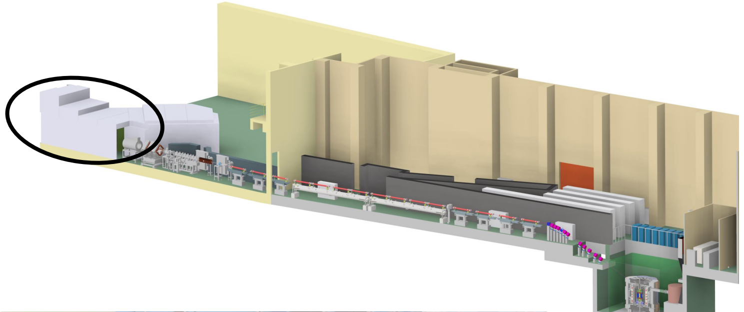
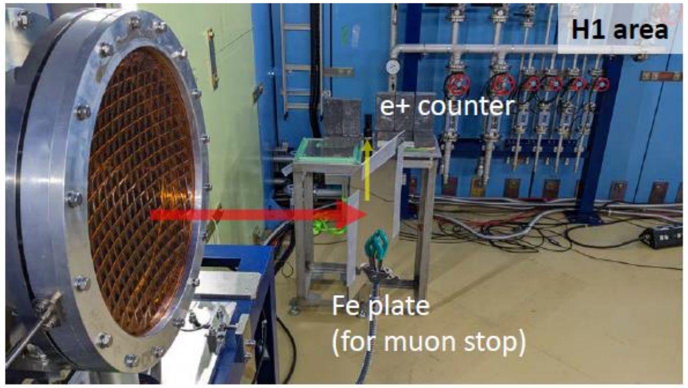


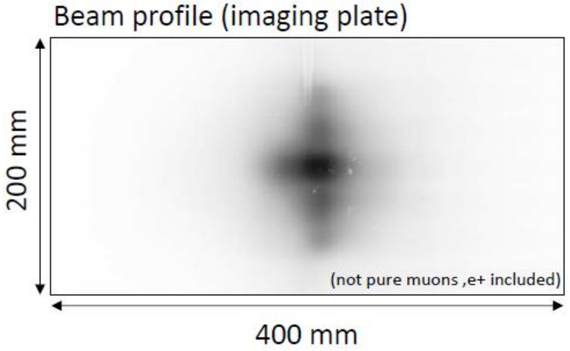
Fig. 2. The H-line layout.





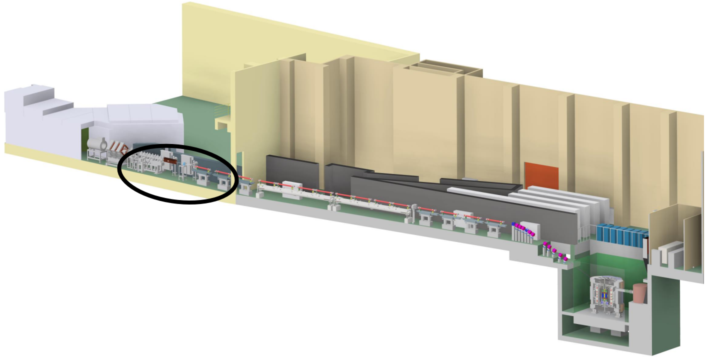


Muon beam profile monitor at H1 area and the detected beam profile.

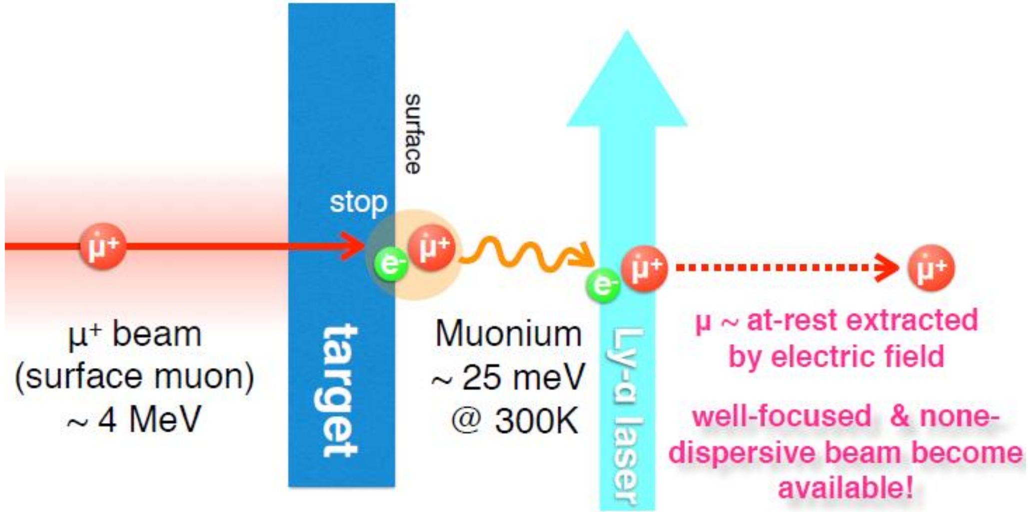

Beam profile (imaging plate)

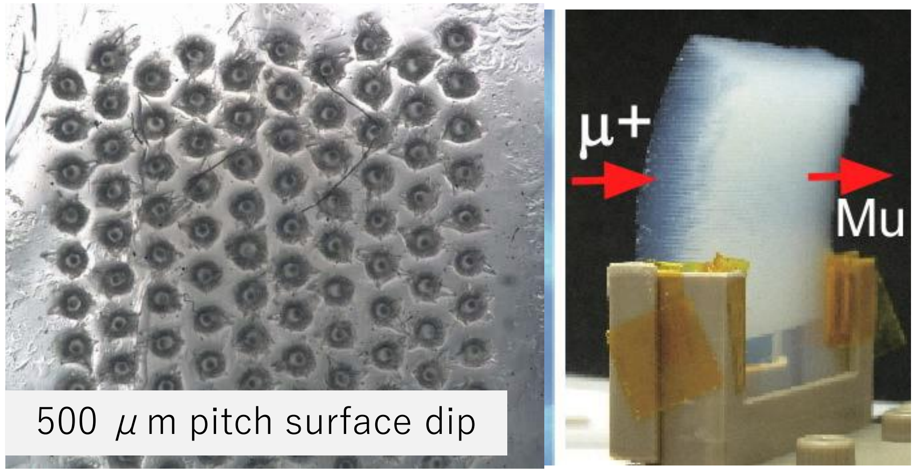
- Construction of H-line up to H1 area has been finished.
- The first beam of H-line was detected on Jan. 15, 2022.

Thermal Muon Beam



- Surface muon beam from the H-line will be used as the source.
  - Monochromatic and ~100% polarized beam
- Muon beam is stopped at an agerogel target and muonium (bound state of e^- and μ^+) is produced.
  - Laser-ablated silica aerogel is used for muonium production target.
  - Various laser-ablated structures and aerogel materials were studied (PTEP2020, 123C01).
- An electron is stripped from a muonium by laser and thermal muon beam is produced.

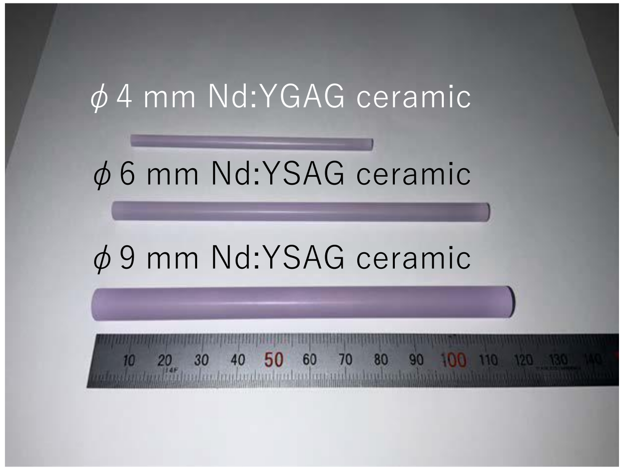




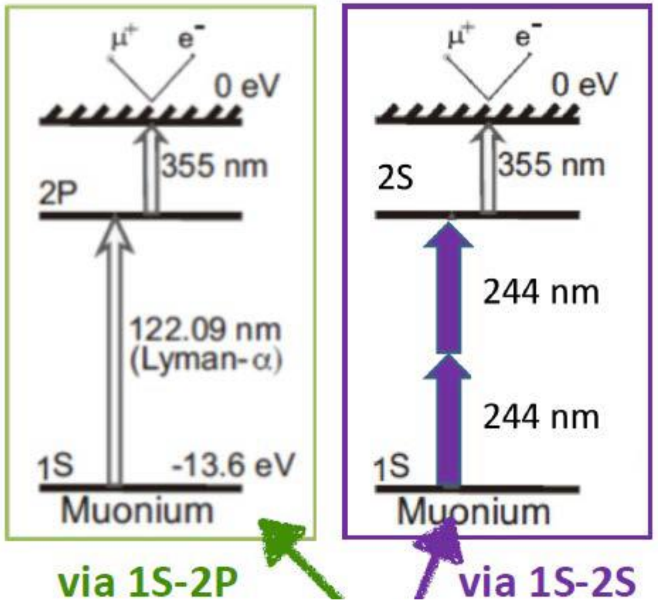
laser-ablated silica aerogel

Muonium Ionization

- In the original plan, an intense Lyman-α laser is used to ionize muonium.
  - To achieve the design goal of 100 μJ power laser, larger crystal is produced and tested in J-PARC MLF U-line.

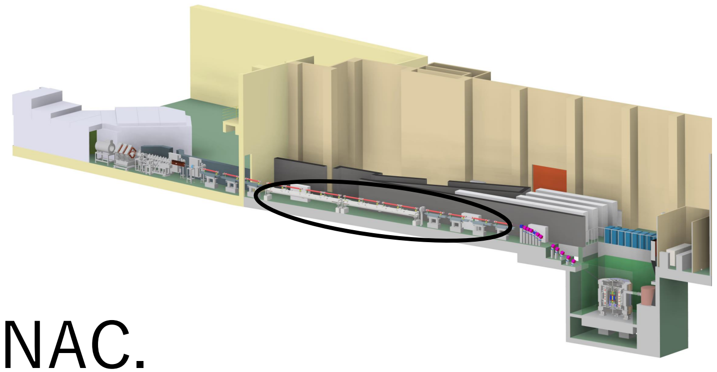


- As an alternative method, ionization scheme with 244 nm laser is being developed collaborating with the muonium 1S-2S spectroscopy measurement experiment.

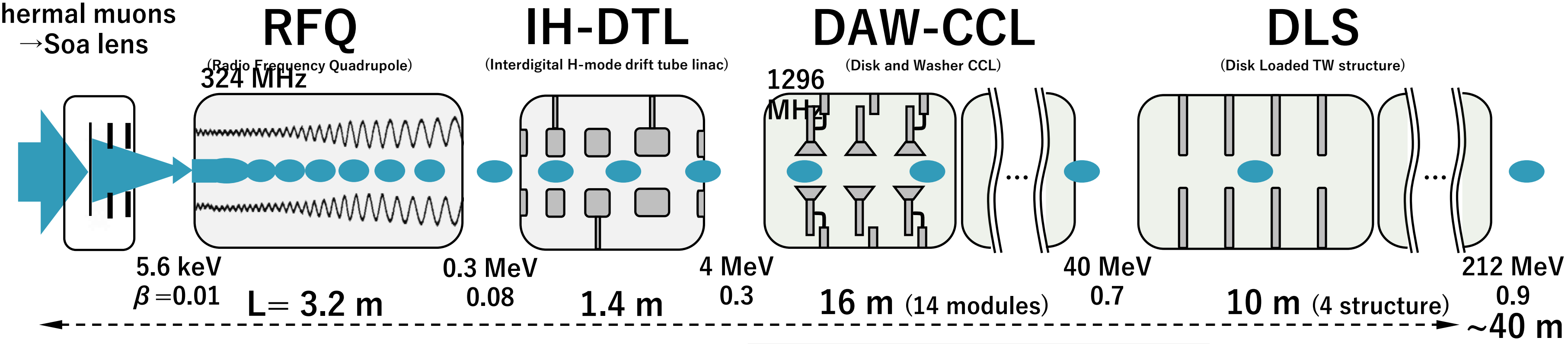


Slow muon beam line constructed for Mu 1S-2S experiment

Muon Acceleration



- Thermal muon beam is accelerated to 300 MeV/c in a LINAC.



thermal muons
→Soa lens

RFQ
(Radio Frequency Quadrupole)
324 MHz

IH-DTL
(Interdigital H-mode drift tube linac)

DAW-CCL
(Disk and Washer CCL)
1296 MHz

DLS
(Disk Loaded TW structure)

5.6 keV
β=0.01

L= 3.2 m

0.3 MeV
0.08

1.4 m

4 MeV
0.3

16 m (14 modules)

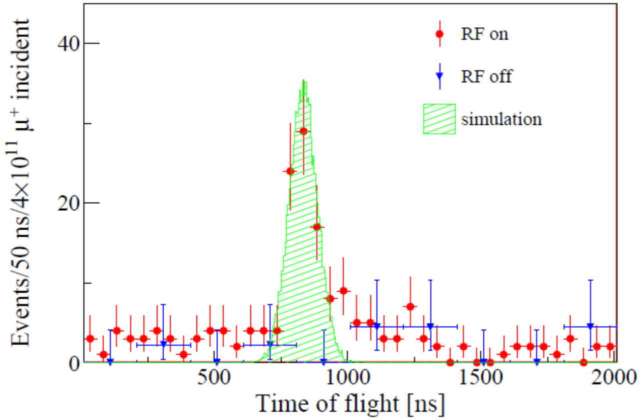
40 MeV
0.7

10 m (4 structure)

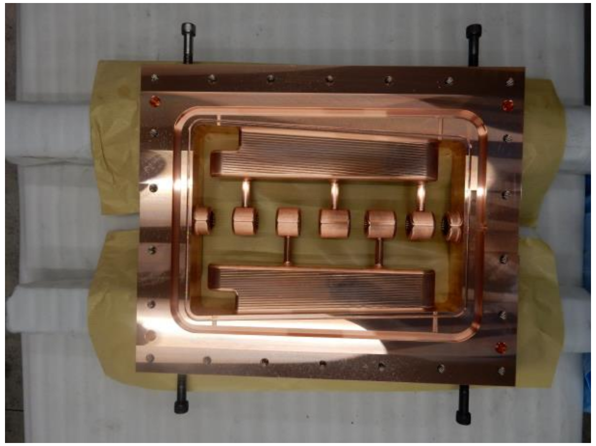
212 MeV
0.9

~40 m

- Acceleration of muon (to be precise Mu$^-$) with RFQ has been succeeded already.
- The rest of acceleration cavities are also designed and their performances are being evaluated with prototypes.

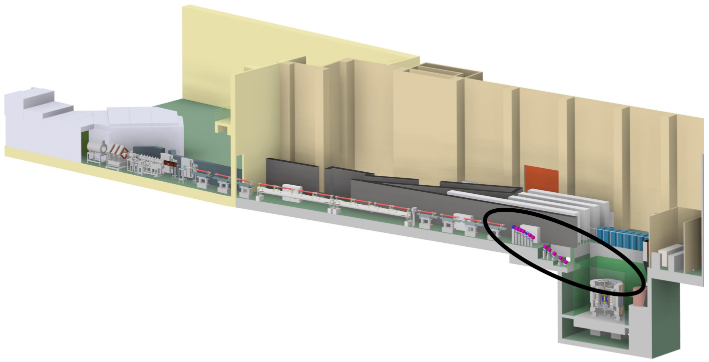


Signal indicating the arrival of Mu- when RF was on ([Phys. Rev. Accel. Beams **21**, 050101 (2018)](https://doi.org/10.1103/PhysRevAccelBeams.21.050101))

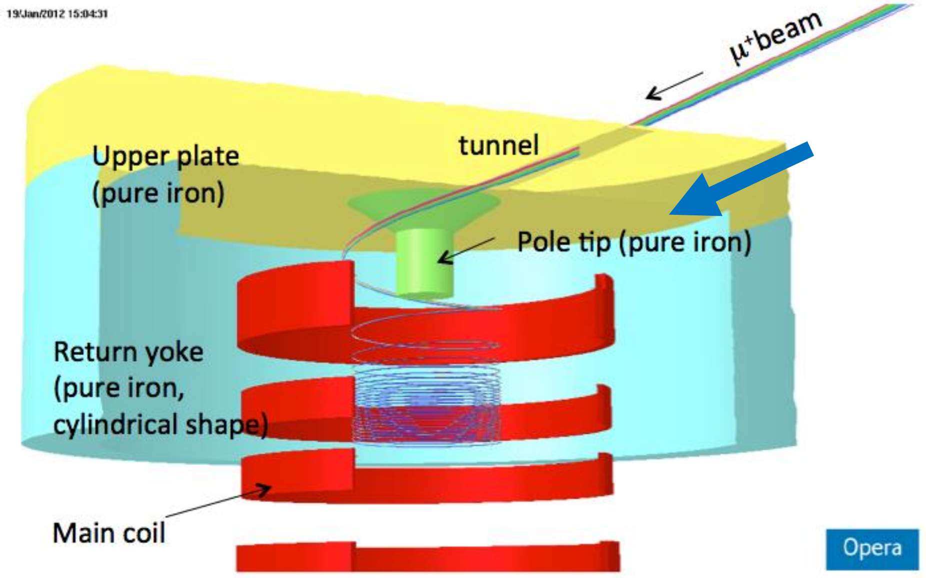


Prototype of IH-DTL

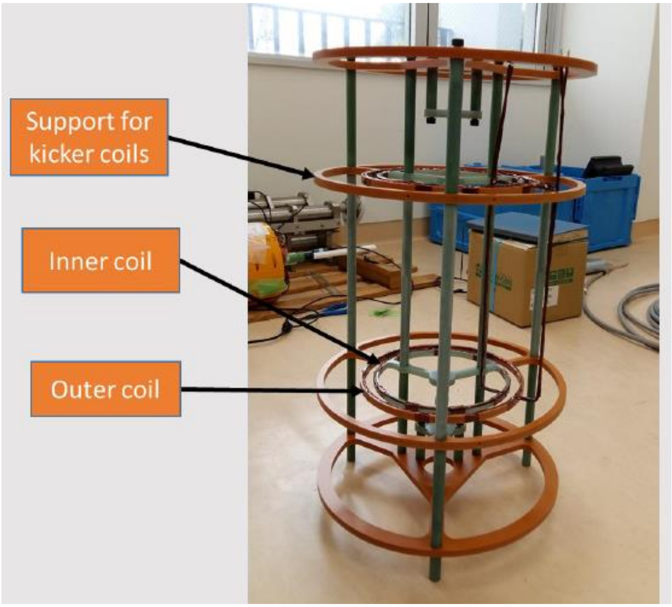
3D Spiral Injection



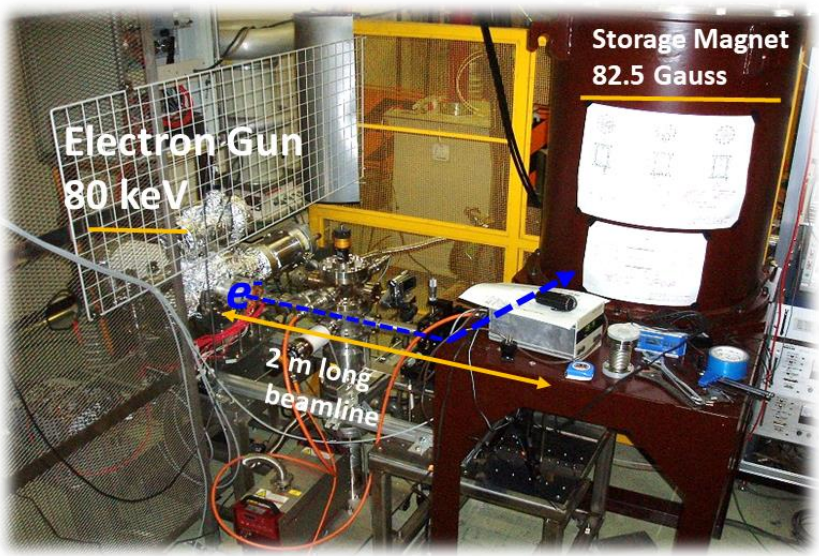
- To inject the 300 MeV/c muon beam into 66 cm-diameter storage ring, 3D spiral injection scheme was developed.
- Prototypes of kicker were fabricated, and the injection scheme is validated using low momentum electron beam.



3D spiral Injection orbit

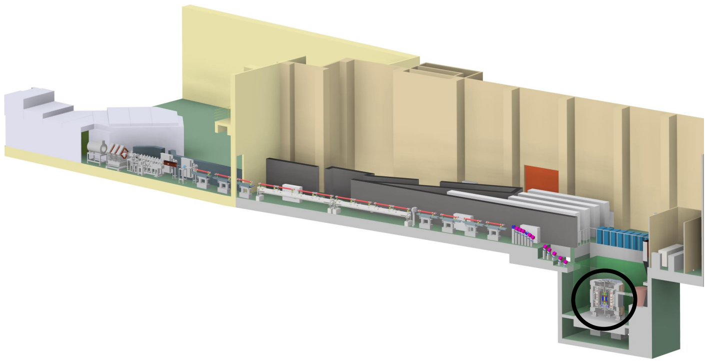


Prototype of kicker coils

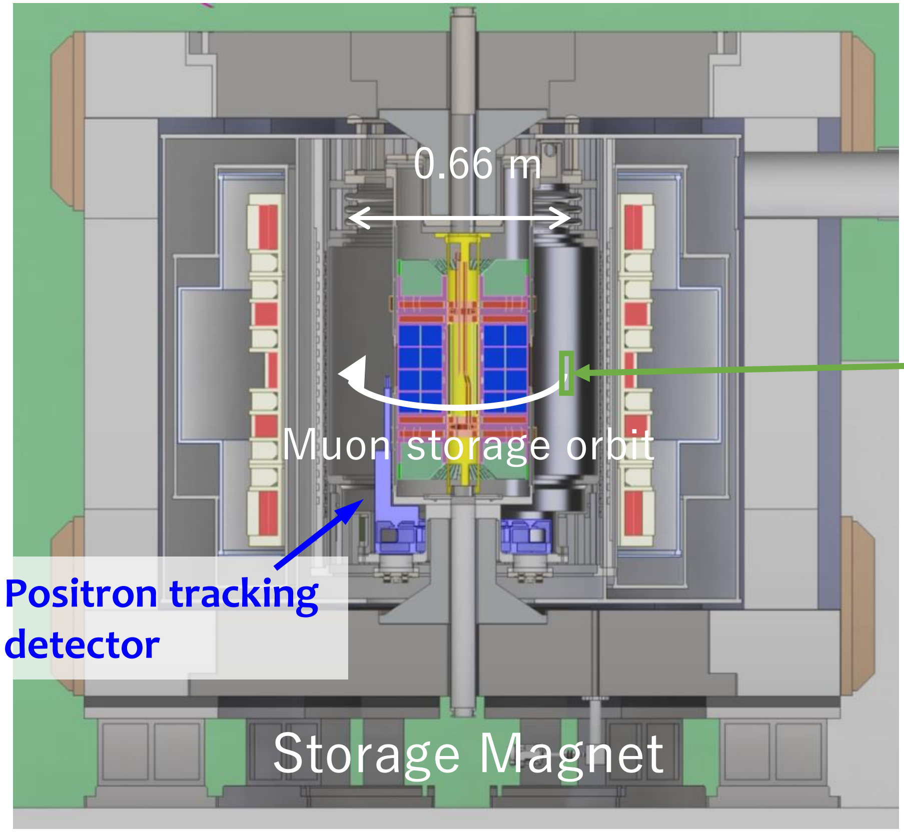


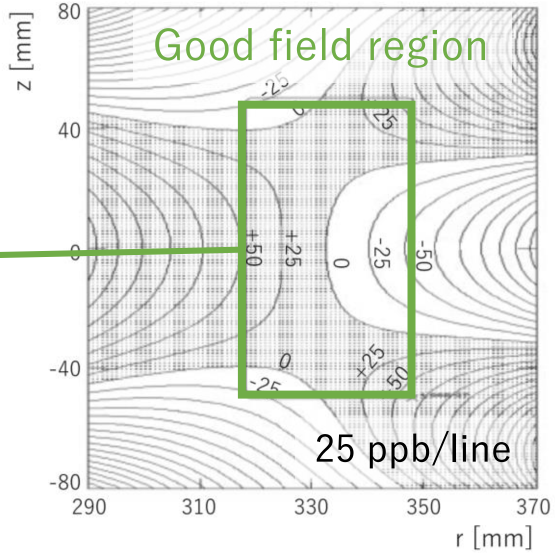
Spiral injection test equipment using electron beam

Storage Magnet



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





Designed main field uniformity

- In good storage volume, field uniformity is better than 100 ppb.

- Weak focusing magnetic field is also applied to in the storage region.

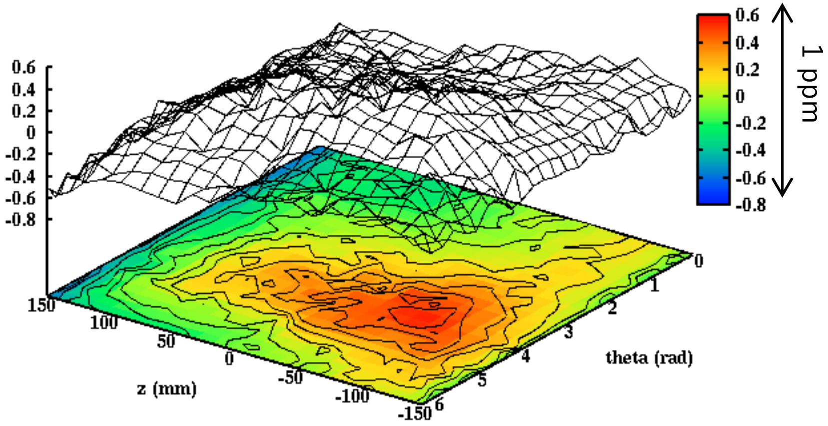
$$B_r = -n\frac{B_{0z}}{R}z,$$

$$B_z = B_{0z} - n\frac{B_{0z}}{R}(r-R) + n\frac{B_{0z}}{2R^2}z^2,$$

Magnetic Field Measurement

- High uniformity of the magnetic field is achieved by shimming.
  - Local uniformity of 1 ppm was confirmed with the magnet used in the MuSEUM (muonium hyperfine structure measurement) experiment.
- High precision NMR probes are used for field measurement.
  - The standard probe was cross-calibrated between J-PARC g-2 and FNAL g-2 at Argonne National Laboratory (ANL) since 2017.
  - In 2017 cross-calibration, ~7 ppb agreement was obtained with 15 ppb uncertainties.

MRI magnet for MuSEUM experiment

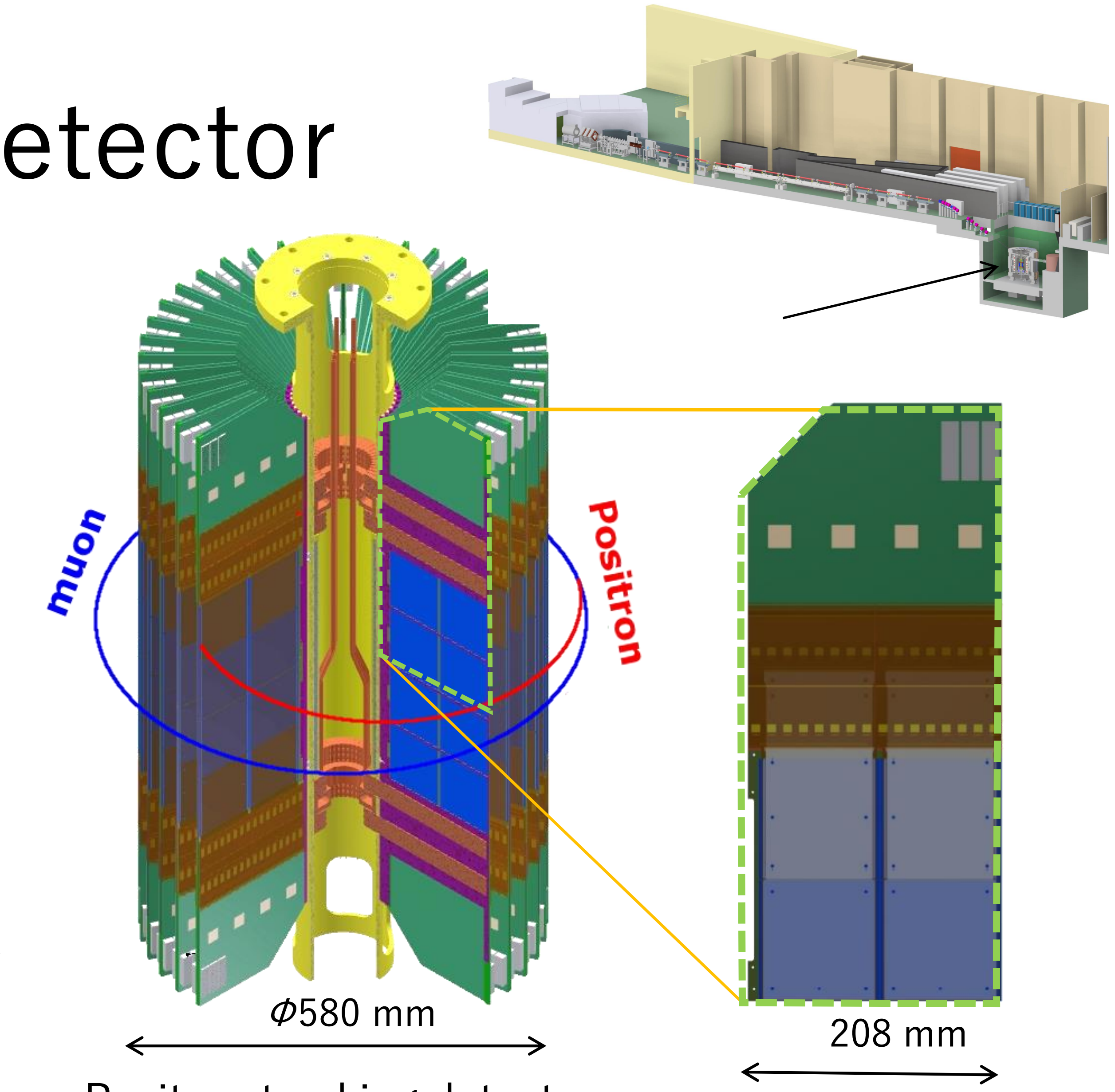


Magnetic field after shimming

Cross calibration at ANL in January 2019

Positron Tracking Detector

- Positrons from decay of stored muon beam are detected by the detector consisting of silicon strip sensors installed in the storage magnet.
    - Positron tracks are reconstructed from hits in radially arranged detector modules called “vanes” and 40 vanes will be used.
    - Each vane has silicon strip sensors in both sides with their strip directions orthogonal each other and 2D positions are reconstructed.
- The detector is required to operate in the highest muon decay rate of 6 tracks/ns.
    - To cope with this situation, 190 μm pitch silicon strip sensor signals are readout by 5 ns sampling rate.



Positron tracking detector

¼ Vane

Detector Components

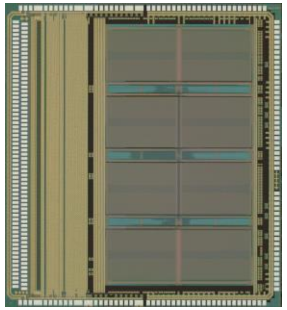
- Mass production of detector components are ongoing.
- Assembly procedures are being developed.

Flexible printed circuit boards

Specification
Fujikura Ltd.
Min. line/space: 35/35 μm (Sensor FPC) 15/12.5 μm (Pitch adapter)
1024 lines/layer

Specification
Hamamatsu Photonics K.K. S13804
98.77×98.77 mm size
190 μm pitch strip
512×2 strip

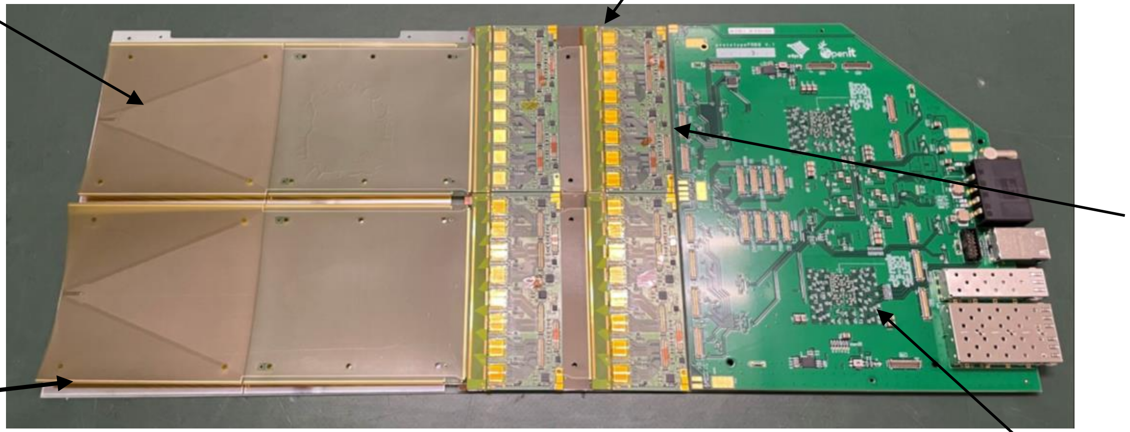
Silicon strip sensor



Specifications
>4 MIP range
1600 e^- ENC@30 pF
128 ch/chip
8096 memory buffer/ch
5 ns sampling

Readout ASIC (SliT) IEEE TNS. 67, (2020) 2089-2095

- Mass production finished.



¼ vane (before assembly)

ASIC boards

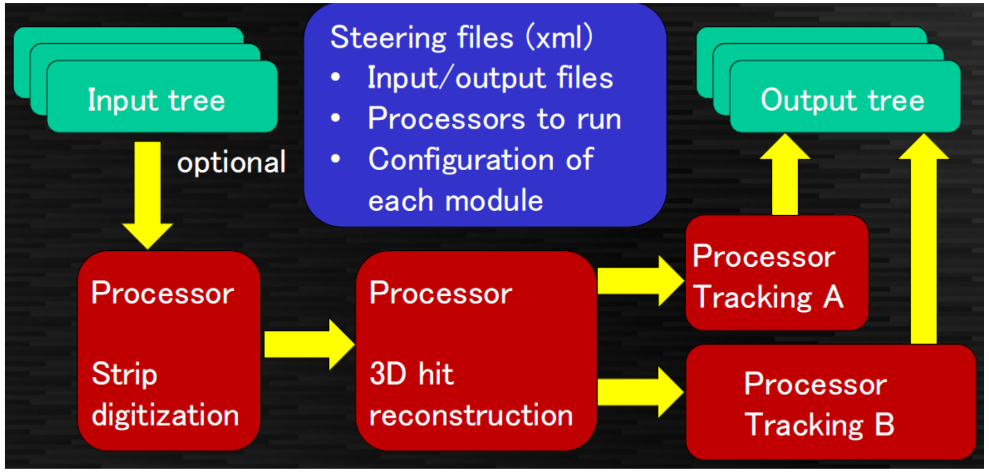
- Semi-final version has been produced.

FPBA-based readout board

- Prototype version is being tested.

Track Reconstruction

- To manage detector simulation and track reconstruction, a new software framework was developed (named “g2esoft”).
- Track reconstruction algorithm operating in high track density is being implemented in this software framework.



Input tree

optional

Steering files (xml)
- Input/output files
- Processors to run
- Configuration of each module

Output tree

Processor

Strip digitization

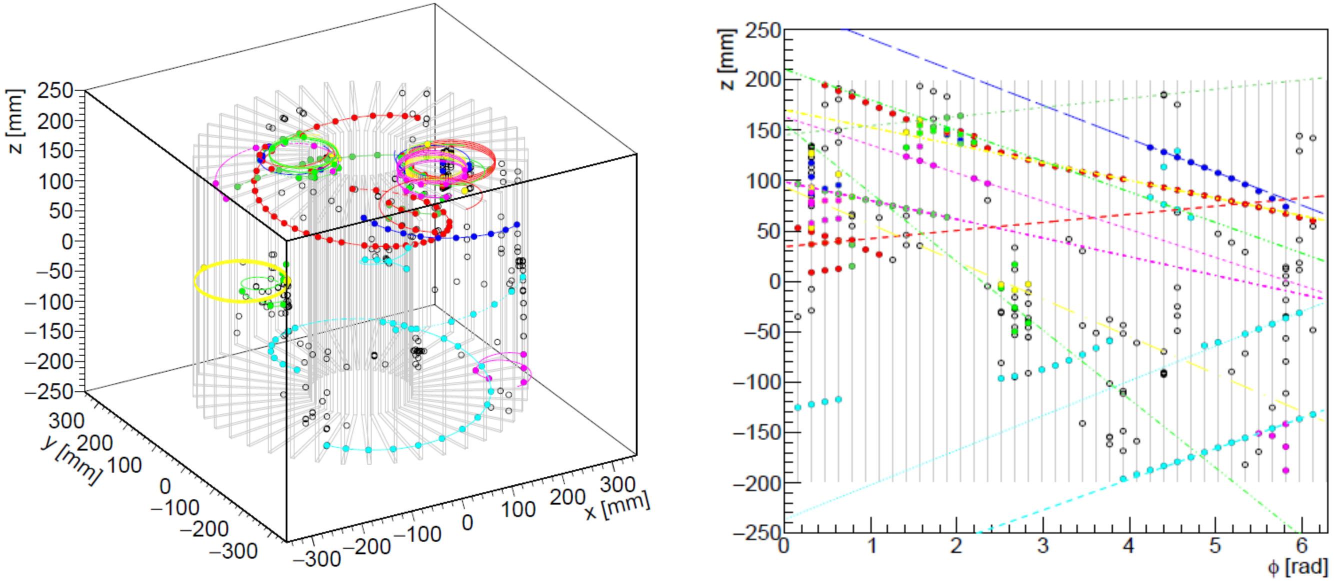
Processor

3D hit reconstruction

Processor Tracking A

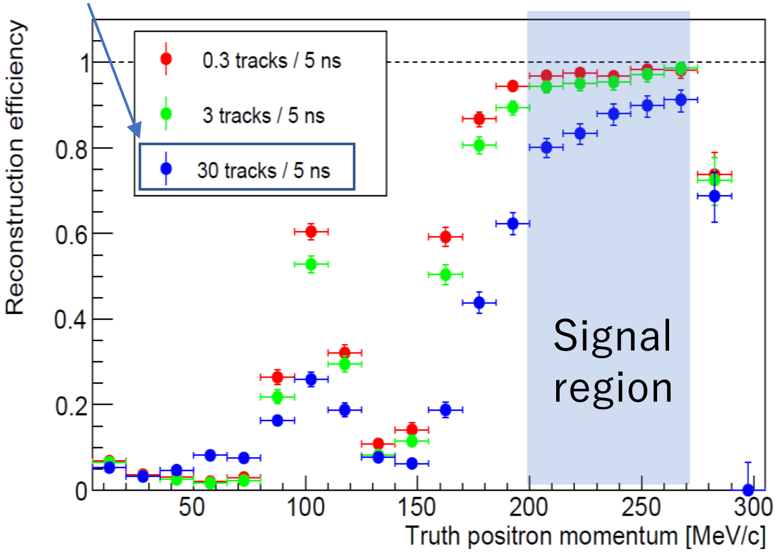
Processor Tracking B

Concept of g2esoft



Simulated positron hits and reconstructed tracks with 25 positrons

Expected highest pile-up condition



Track reconstruction efficiency using the current algorithm

Extraction of a_μ

- The anomalous magnetic moment (a_μ) is extracted from the following formula.

$$a_\mu = \frac{R}{\lambda - R}$$

where, $R = \frac{\omega_a}{\omega_p}$,

- ω_a : spin precession angular frequency of muon in the storage ring
- ω_p : Larmor precession angular frequency of a free proton in the storage ring

and $\lambda = \frac{\mu_\mu}{\mu_p}$ is the muon-to-proton magnetic moment ratio.

- The precision of the direct measurement by muonium spectroscopy is 120 ppb.
- The MuSEUM experiment at J-PARC is expected to improve this precision.

Statistics Estimation

- The expected initial muon rate at 1 MW proton beam is ~2×10^9/sec.
- Cumulative efficiency from the initial muon production target to the detected positrons is 1.3×10^{-5}.
- Then, the total number of the detected positrons at 2×10^7 sec run (~230 days) is 5.7×10^{11}.

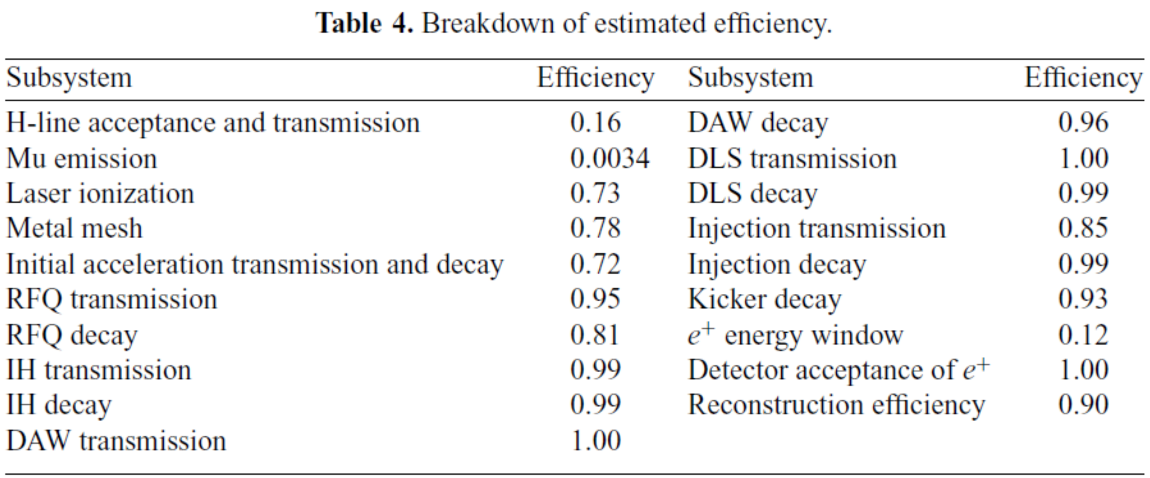


Table 4. Breakdown of estimated efficiency.

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		

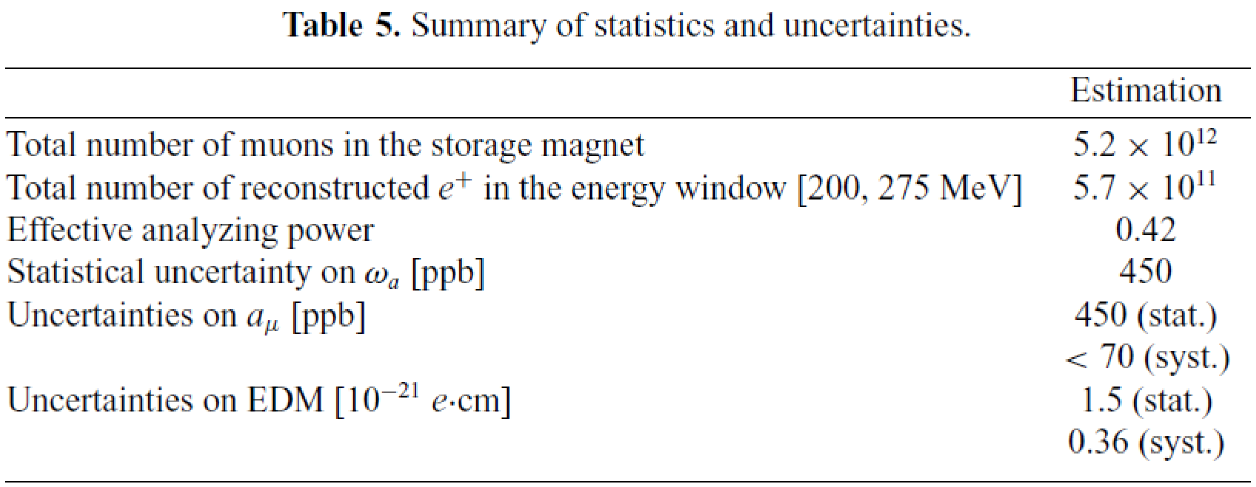


Table 5. Summary of statistics and uncertainties.

	Estimation
Total number of muons in the storage magnet	5.2×10^{12}
Total number of reconstructed e^+ in the energy window [200, 275 MeV]	5.7×10^{11}
Effective analyzing power	0.42
Statistical uncertainty on ω_a [ppb]	450
Uncertainties on a_μ [ppb]	450 (stat.)
	$<$ 70 (syst.)
Uncertainties on EDM [10^{-21} $e\cdot$cm]	1.5 (stat.)
	0.36 (syst.)

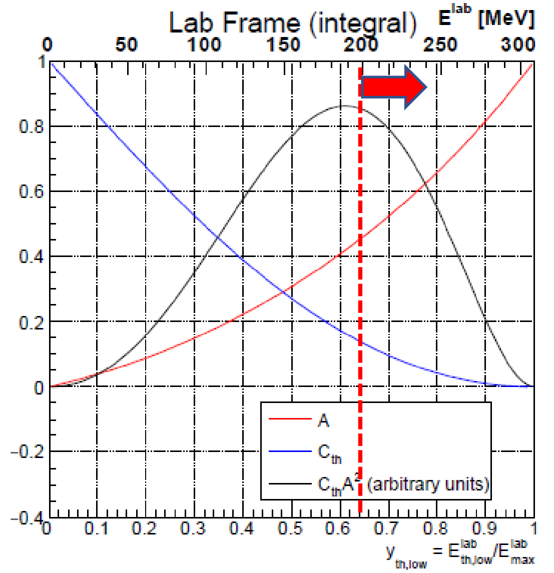
PTEP 2019 (2019), 053C02

Statistical Uncertainty of a_μ

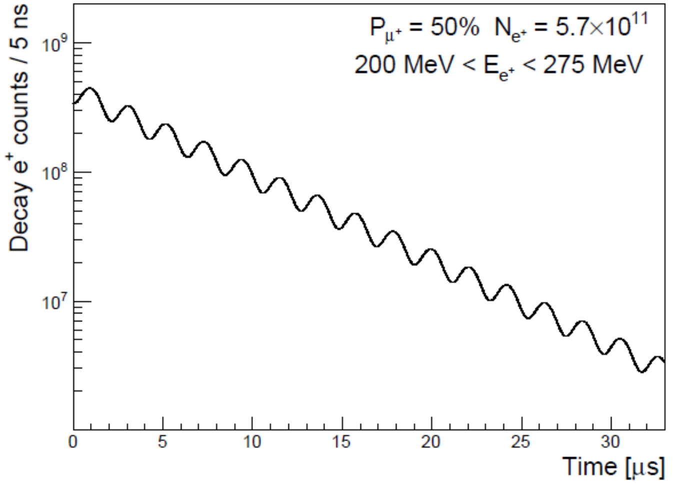
- The momentum range of the decay positions is determined to be [200,275] MeV/c from the detector acceptance and to maximize the analyzing power.
- The statistical uncertainty on a_μ (or ω_a, to be precise) is estimated to be 0.45 ppm from the following five-parameter-function fit to a toy wiggle plot

$$N(t) = N_0 e^{-t/\gamma\tau}[1 + A\cos(\omega_a t + \varphi)].$$

- The toy MC fit result is consistent with the analytical estimation of the statistical uncertainty on ω_a of $\frac{\Delta\omega_a}{\omega_a} = \frac{\sqrt{2}}{\gamma\tau A\sqrt{N}\omega_a}$ where, N is the total number of detected positrons.



Analyzing power as a function of the momentum threshold



Toy simulation of a time spectrum of the number of decay positrons

Systematic Uncertainties of a_μ

- Major sources of systematic uncertainties of ω_{a} and ω_{p} which consist a_μ will be explained in this slides.

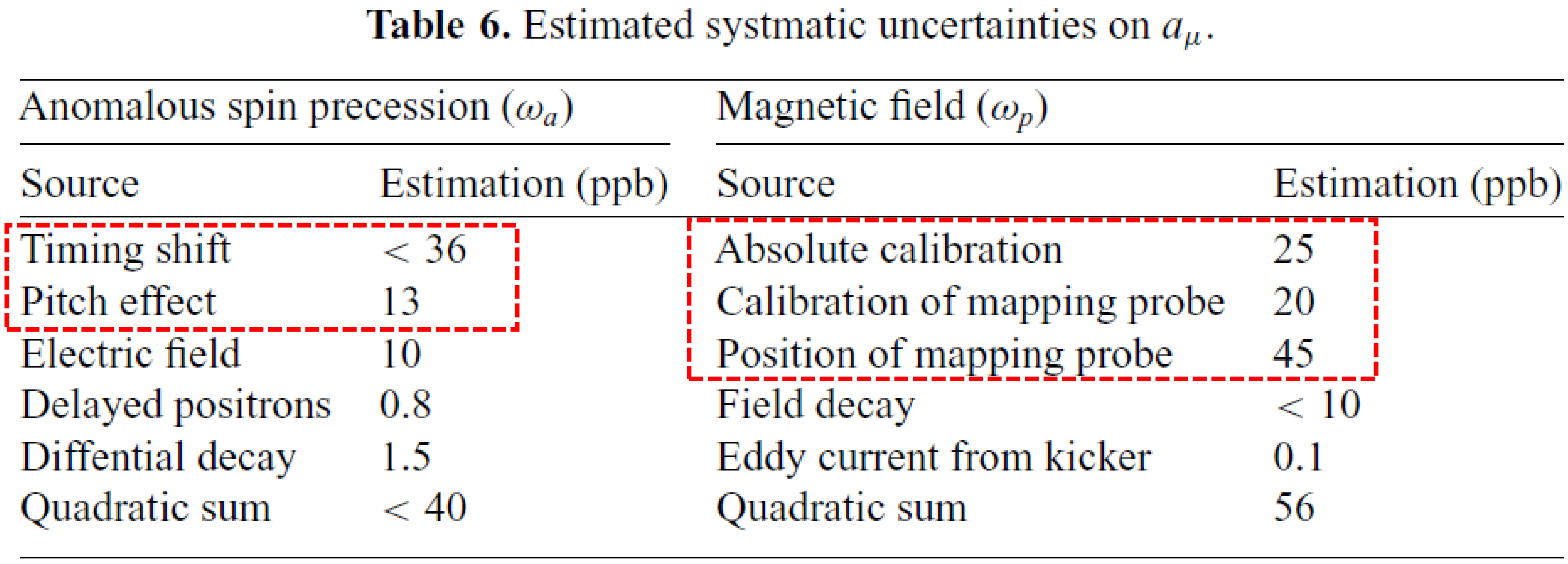


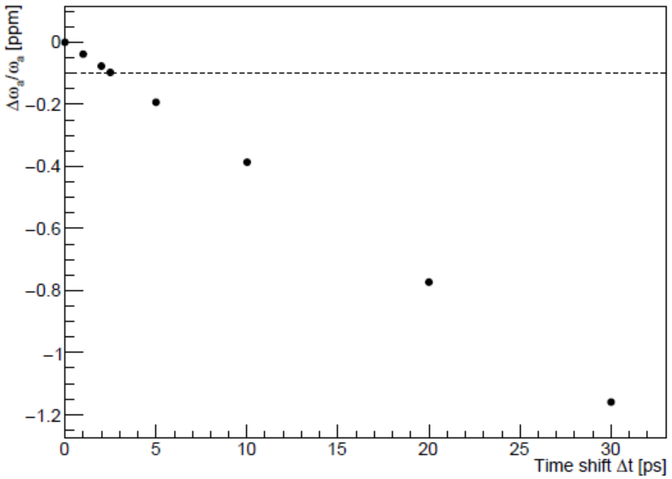
Table 6. Estimated systmatic uncertainties on a_μ.

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

PTEP 2019 (2019), 053C02

Early-to-late Effect

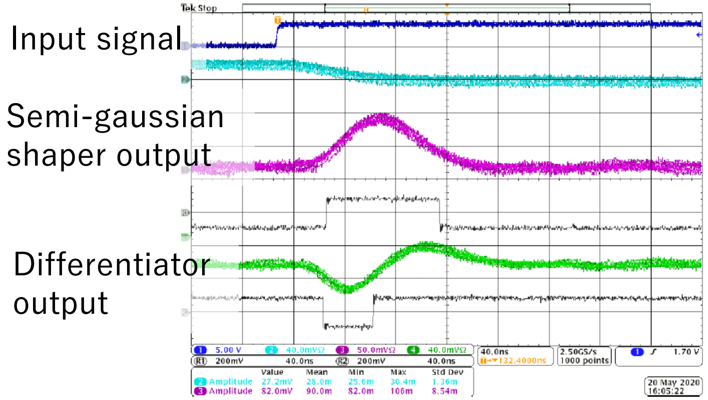
- Since the rate of decay positrons changes by a factor of 150 within our data taking period (~30 μs), detector performance changes as a function of time.
  - Performance like track reconstruction efficiency has only a small dependence on the rate of decay positrons (and this dependence can be evaluated from real data), systematic uncertainty on ω_a can be constrained to a negligibly level.
- However, if the muon decay time measurement is affected by the rate change, only a small shift leads to a large uncertainty on ω_a measurement.
  - Timing shift of 2.5 ps during 30 μs data taking period will be 0.1 ppm uncertainty on ω_a.
  - Even with a tracking detector, pile-up of signals in single detector strip can cause a timing shift.



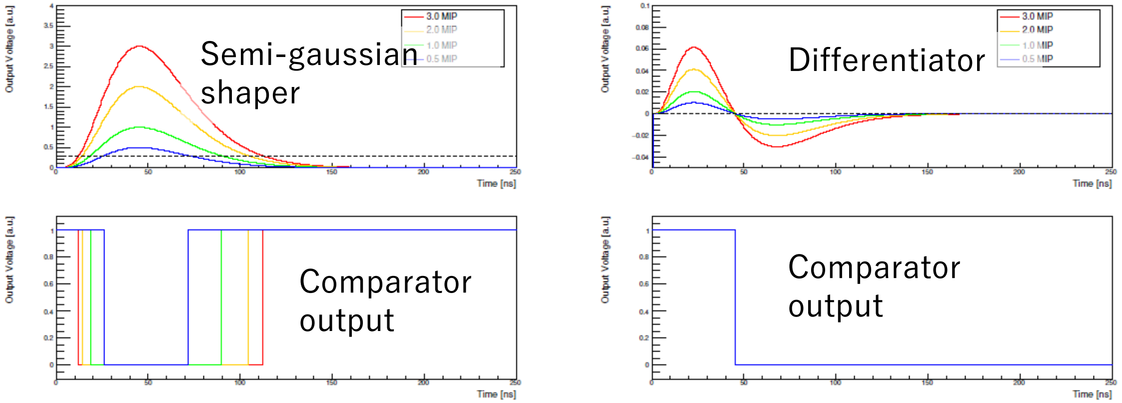
Systematic uncertainty on ω_a as a function of the shift of the muon decay time measurement

Pile-up Effect on Readout ASIC

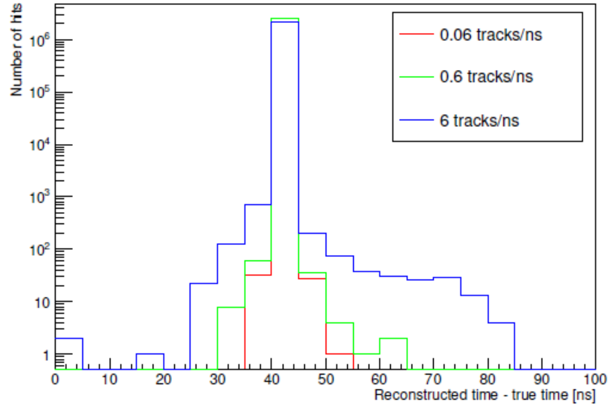
- To suppress such an effect, we implemented a differentiator into the readout ASIC circuit for the positron detector.
  - Hit timing of the differentiator output has a small dependence on the input charge (<1 ns between 0.5-3 MIP input)→ less affected by pile-up signals
- Systematic uncertainty on ω_a due to signal pile-up is estimated by using detector simulation with readout ASIC waveform emulation and is estimated to be less than 36 ppb.



Output waveform of readout ASIC (IEEE TNS. 67, (2020) 2089-2095)



Simulation of readout ASIC waveform with different input charge



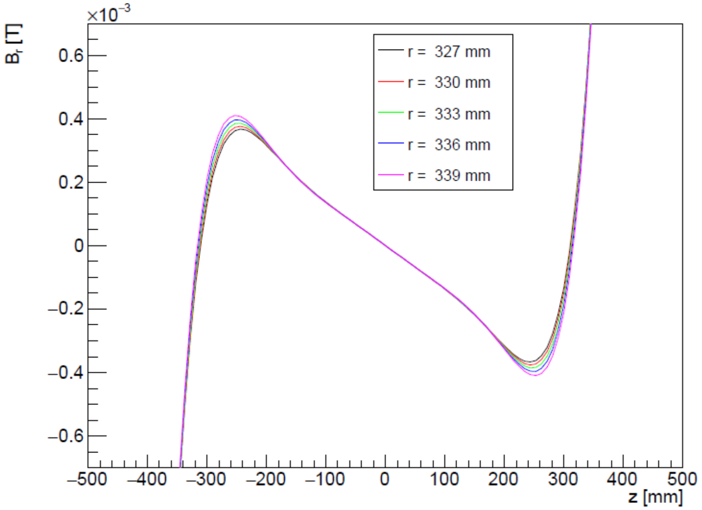
Time shift of hit timing for different pile-up conditions

Pitch Effect

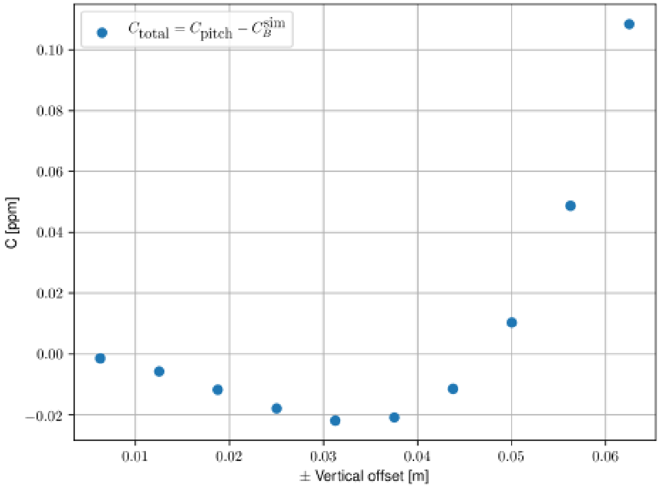
- For a muon beam in a focusing field, betatron oscillation need to be considered when calculating the spin precession frequency and it is rewritten as

$$\vec{\omega} = -\frac{e}{m}\left[a_\mu \vec{B} - a_\mu \left(\frac{\gamma}{\gamma+1}\right)(\vec{\beta}\cdot\vec{B})\vec{\beta}\right].$$

  - Because of this, what we measure is shifted from the true ω_a value (so-called a pitch effect).
- Correction factor for this effect is estimated from the precise muon tracking program.
  - Correction factor exceeds 100 ppb at |z|>60 mm but correction accuracy is estimated to be 13 ppb combining with measured muon beam distribution.



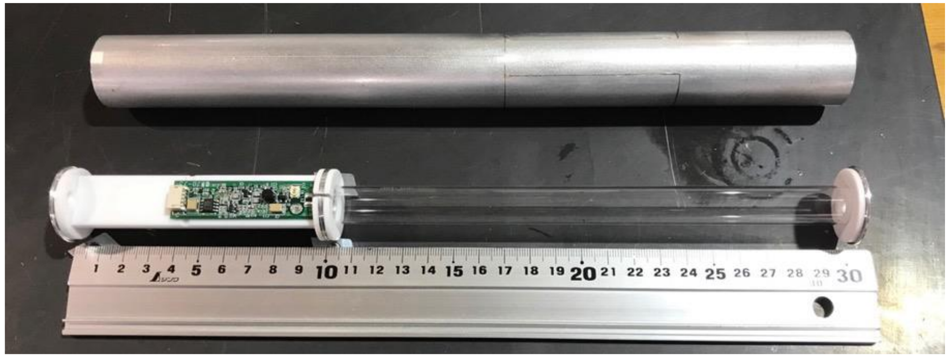
Radial magnetic field for vertical beam focusing



Correction factor for pitch-effect as a function of the vertical position

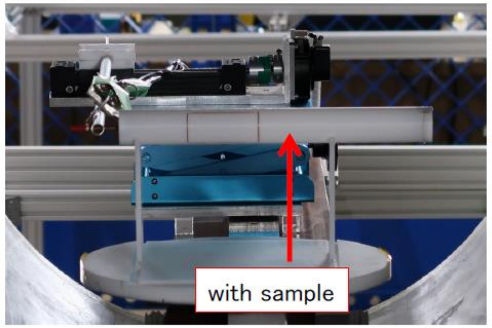
Absolute Calibration of NMR probe

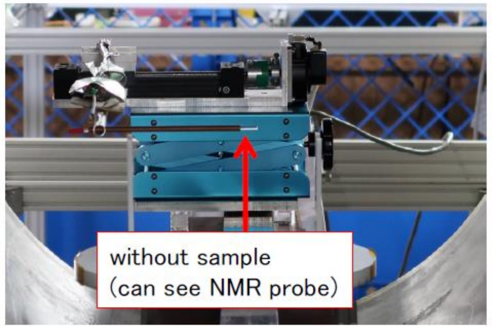
- Intrinsic resolution of the standard NMR probe is estimated to be 18 ppb.
- Temperature control precision of 0.1 degree lead to another 10 ppb uncertainty.
- Uncertainties on diamagnetic field shielding effect (2.5 ppb) and material effect (9 ppb)
- The total uncertainty of the absolute calibration of the standard NMR probe is estimated to be 25 ppb.



Standard NMR probe

Measure NMR frequency difference between in the cases with sample and without sample

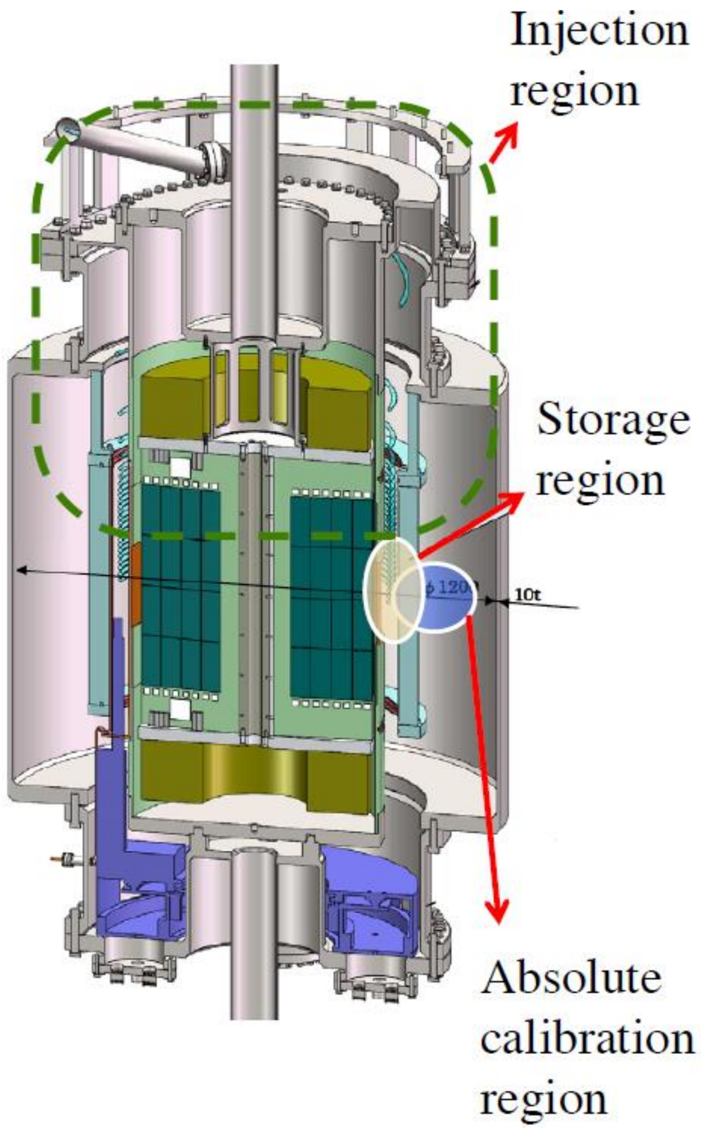




Material effect measurement

Calibration of Trolley Probe and Field Mapping Accuracy

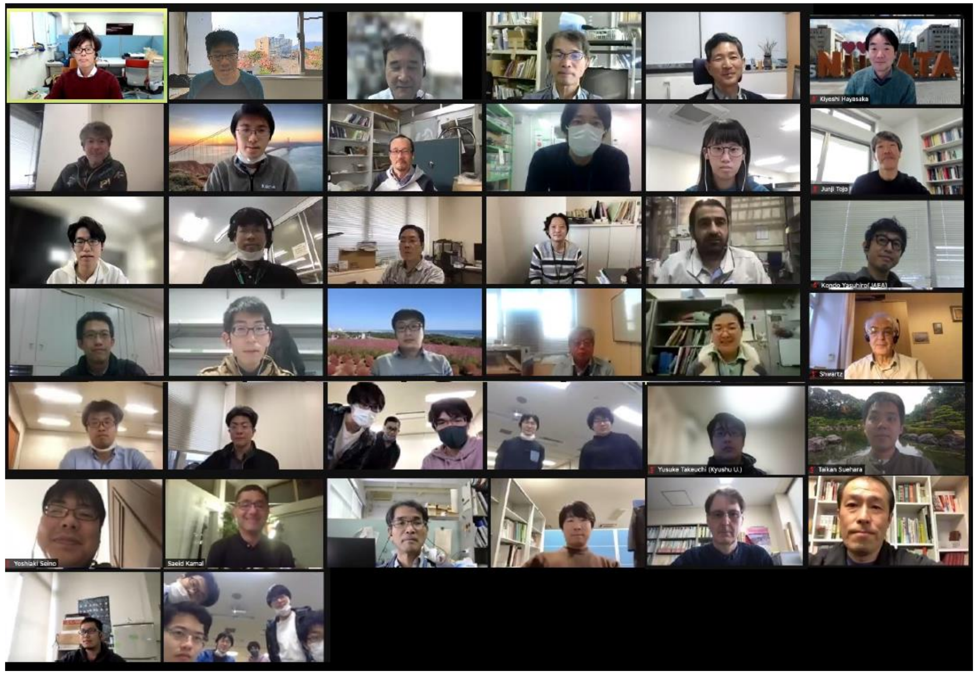
- Trolley probe measures the magnetic field in good field region.
- There is a field gradient 0.2 ppm/mm at a radius of 400 mm, where the trolley probe and the standard probe will be calibrated.
    - Position accuracy will be 0.1 mm → 20 ppb for trolley probe calibration.
- Gradients of magnetic field for weak focusing are 450 ppb/mm (radial) and 6 ppb/mm (vertical)
    - 0.1 mm Position accuracy → 45 ppb for field mapping
    - The average magnetic field will be evaluated by weighting muon beam distribution estimated by the positron detector measurement to the measured field map.



Recent Experiment Status

- Now the collaboration consists of 110 members from Canada, China, Czech, France, India, Japan, Korea, Russia, USA
  - Domestic institutes：Kyushu, Nagoya, Tohoku, Niigata, Tokyo, Ibaraki, RIKEN, JAEA, etc. KEK: IPNS, IMSS, ACC, CRY, MEC, CRC

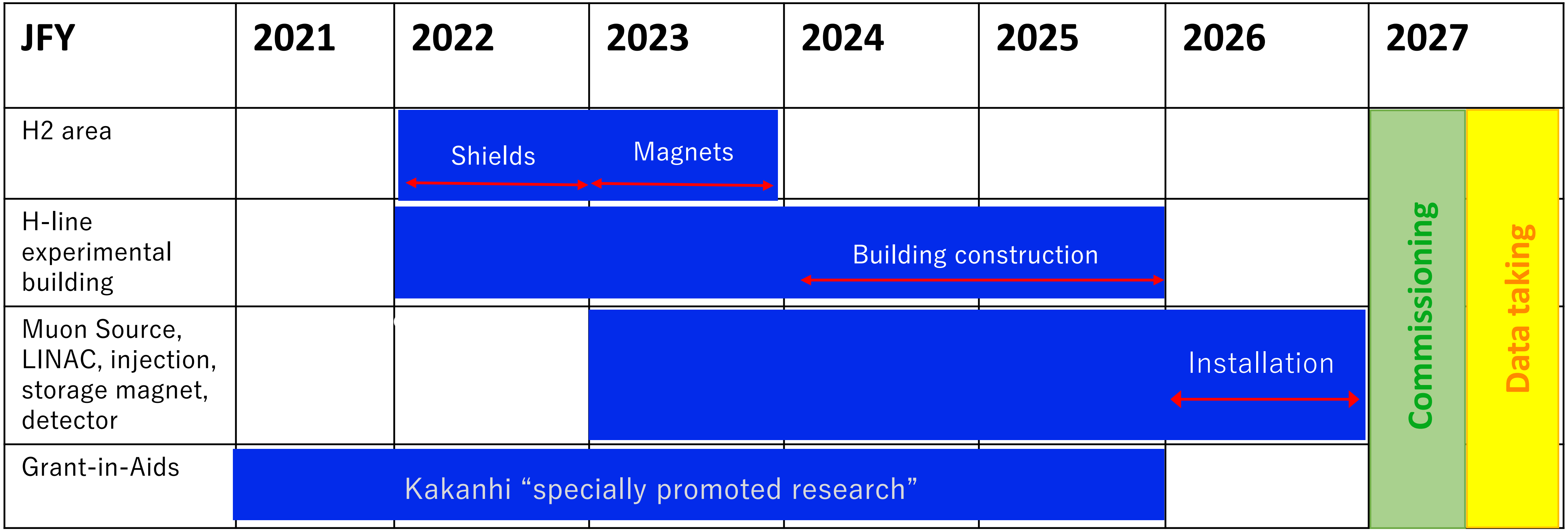
Date	Events
Dec. 2017	Responses and revised TDR were submitted to review committee.
Mar. 2019	KEK-SAC endorsed the E34 for the near-term priority.
May 2019	Summary paper of TDR was published (PTEP 2019 (2019), 053C02)
July 2020	Funded by KEKENHI “Specially Promoted Research” by JSPS
Jun. 2021	KEK requested a funding to Japanese government (MEXT), then MEXT requested to MOF.



23rd Collaboration Meeting in Dec. 2021@Online/J-PARC

Schedule

- Construction of experimental components is ongoing aiming at the start of the experiment in 2027 JFY.



JFY	2021	2022	2023	2024	2025	2026	2027
H2 area		Shields	Magnets				Commissioning Data taking
H-line experimental building				Building construction			
Muon Source, LINAC, injection, storage magnet, detector						Installation	
Grant-in-Aids		Kakanhi “specially promoted research”					

Summary

- In the J-PARC E34 experiment, measurement of muon g-2 and EDM is planned with a method different from BNL/FNAL experiments.
  - Use of reaccelerated thermal muon beam enables muon beam focusing without an electric field.
  - Use of lower momentum muon beam enables the compact storage region with highly uniform magnetic field.
  - The tracking detector for decay positrons reduces pile-up of signals and is able to measure the momentum direction of positrons.
- Construction of the beam line has been started and the first beam was detected in 2022.
- Preparation of the experiment is ongoing aiming at the start of the data taking in 2027 JFY.