Muon g-2/EDM Experiment at J-PARC

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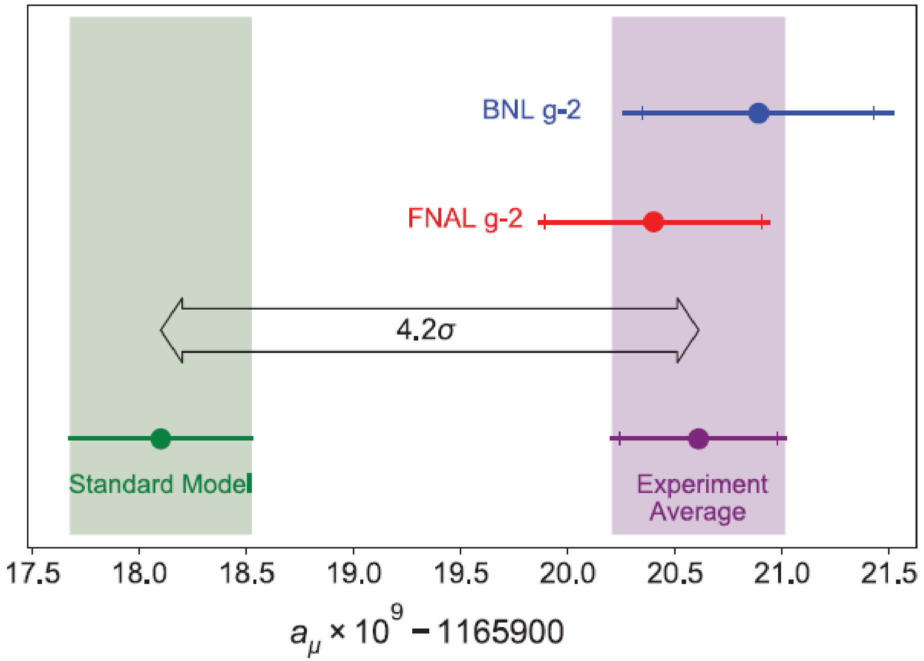
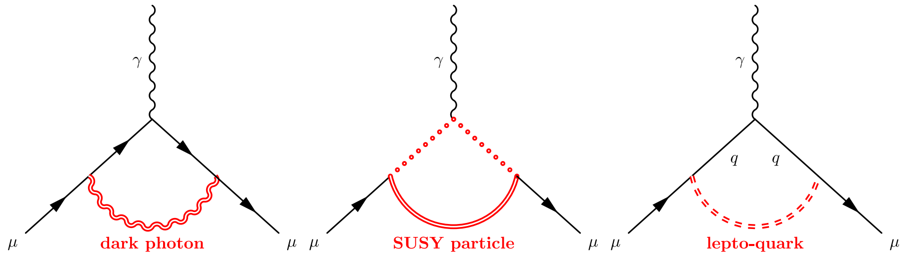
for the J-PARC E34 Collaboration

Muon g-2 and EDM

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



- **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 $\sim 2 \times 10^{-38}$ e・cm.
  - New physics predicts much larger EDM.



BSM contributions to the muon g-2

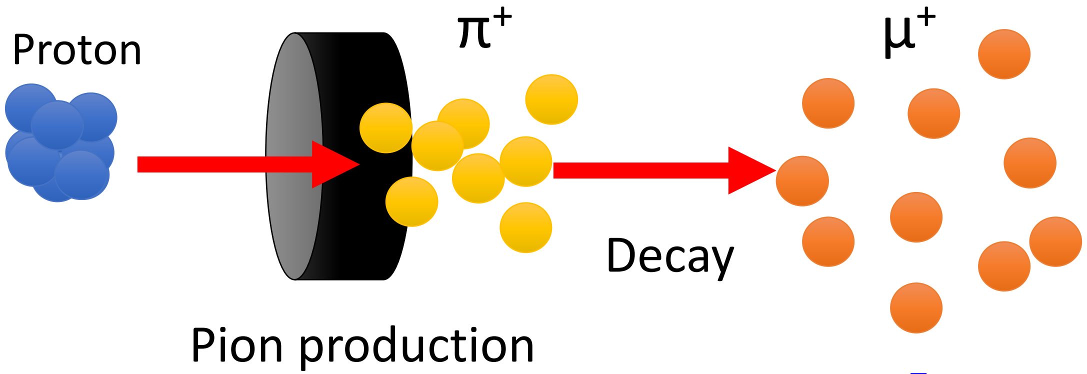
Electric Field Contribution to Muon g-2 Measurement

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

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

- In the BNL and FNAL experiments, to use a beam focusing electric field, the muon momentum is chosen to satisfy $\boxed{a_\mu - \frac{1}{\gamma^2-1} = 0}$.
  - 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



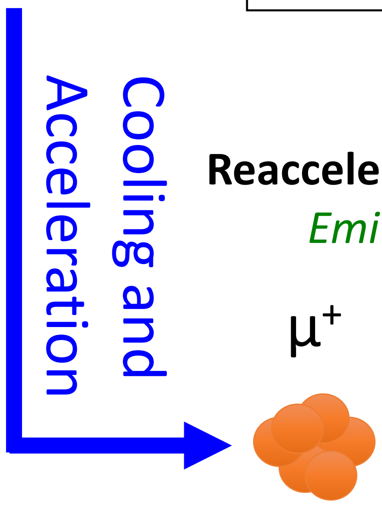
Conventional muon beam

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

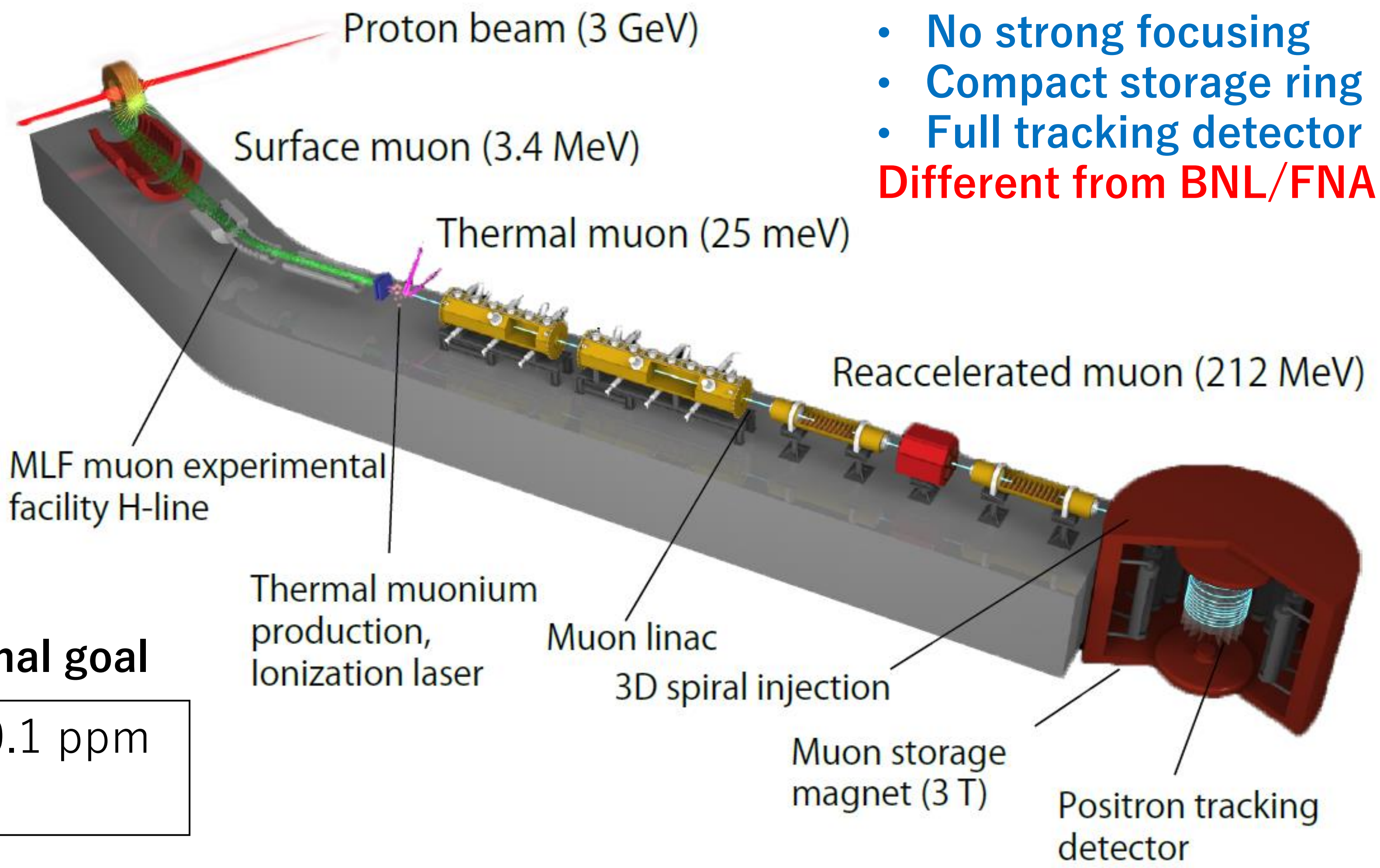


Reaccelerated thermal muon beam

Emittance ~1π mm ･mrad

Free from any of the above

J-PARC E34 Experiment



Features

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

Different from BNL/FNAL experiments

Initial goal **Final goal**

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

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.)	$0.2 \times 10^{-19}\ e \cdot$ cm	–	$1.5 \times 10^{-21}\ e \cdot$ cm
(syst.)	$0.9 \times 10^{-19}\ e \cdot$ cm	–	$0.36 \times 10^{-21}\ e \cdot$ cm

J-PARC E34

Radius of cyclotron motion: 7.1 m

Radius of cyclotron motion: 333 mm

PTEP 2019 (2019), 053C02

J-PARC Facility

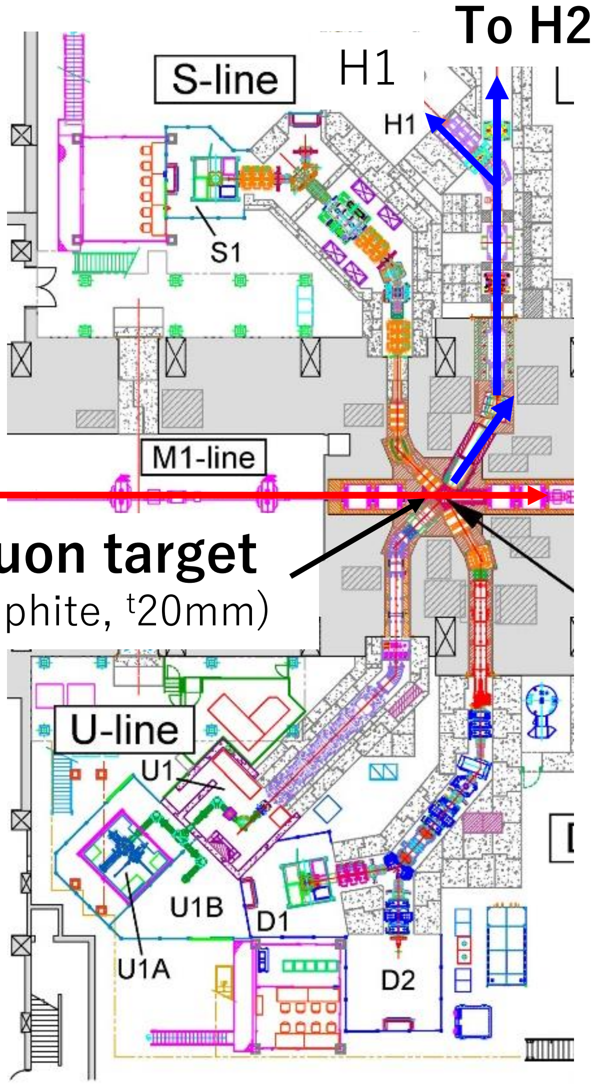
Located at Ibaraki prefecture in Japan

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



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

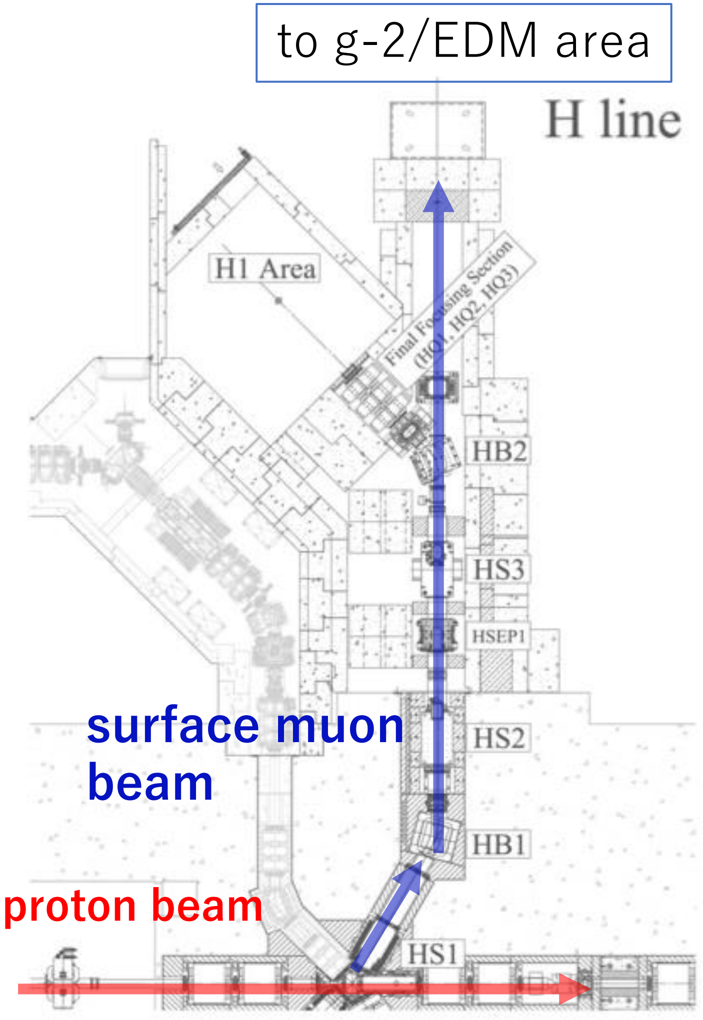
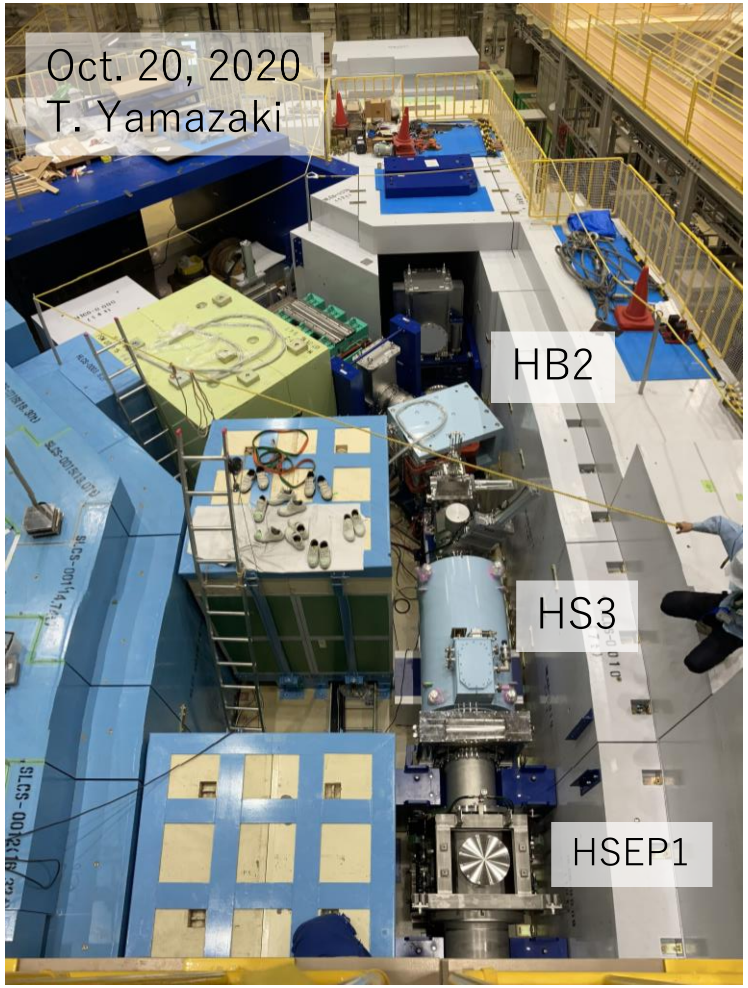
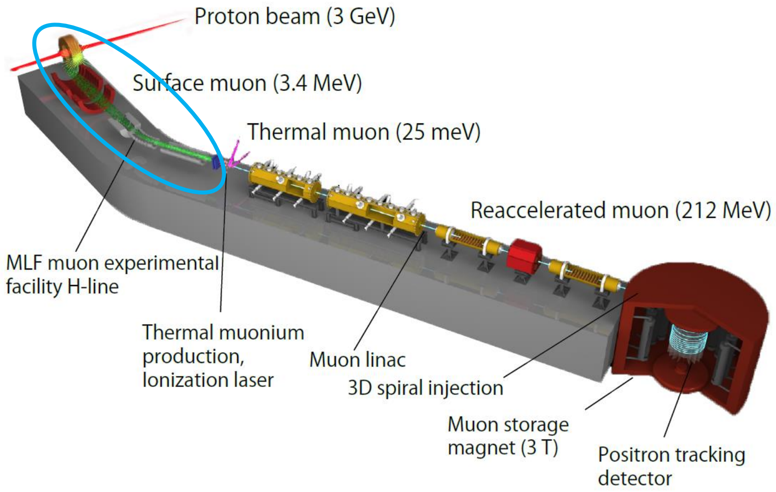


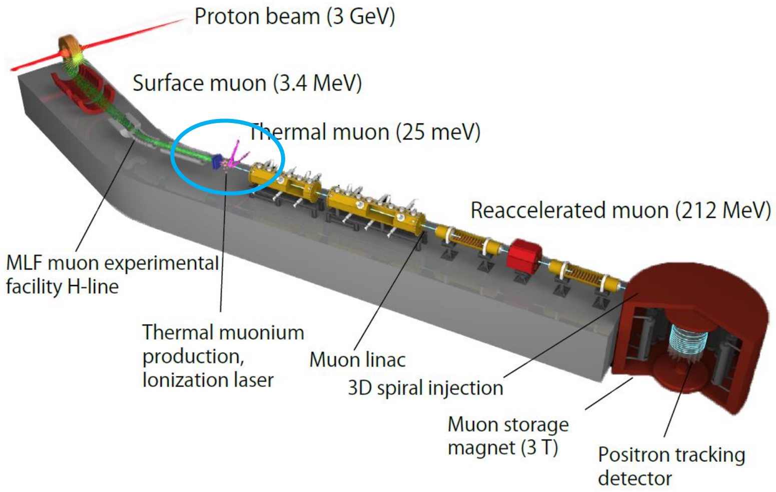
Fig. 2. The H-line layout.





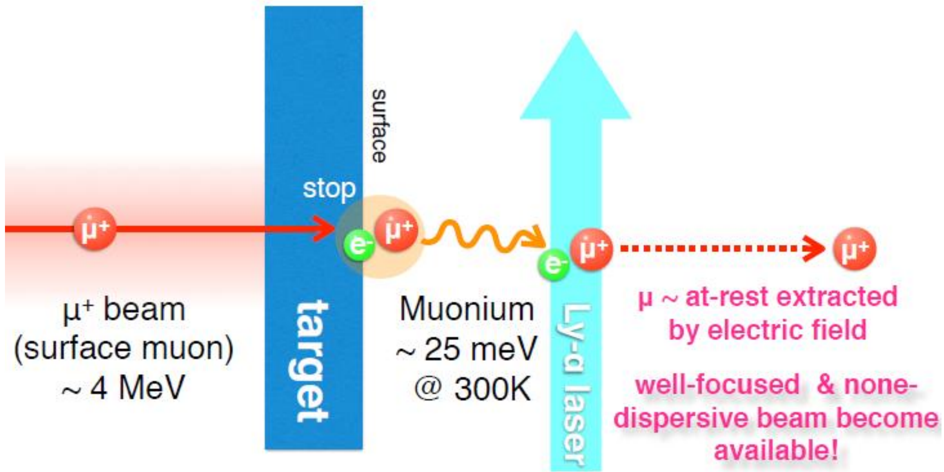
- Construction of H-line already started.
- The minimum construction of the upstream part of H-line (H1 area) has finished and it is ready to start beam commissioning.

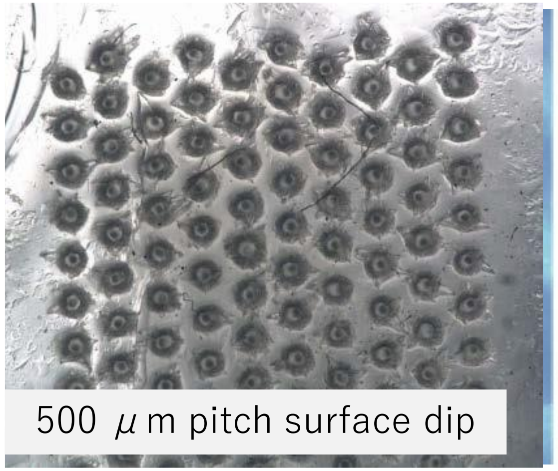
Thermal Muon Beam

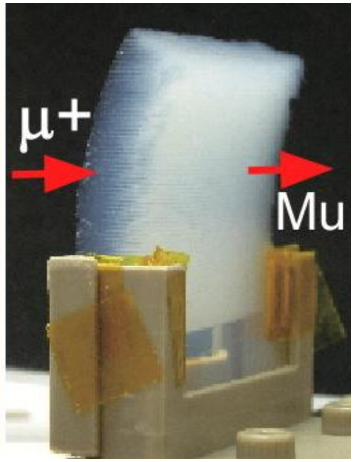


- Surface muon beam from the H-line is used as the source.
  - Monochromatic and ~100% polarized beam
- Muon beam is stopped at a target and muonium (bound state of e^- and μ^+) is produced.
  - Laser-ablated silica aerogel is used for muonium production target.
- An electron is stripped from a muonium by laser and thermal muon beam is produced.

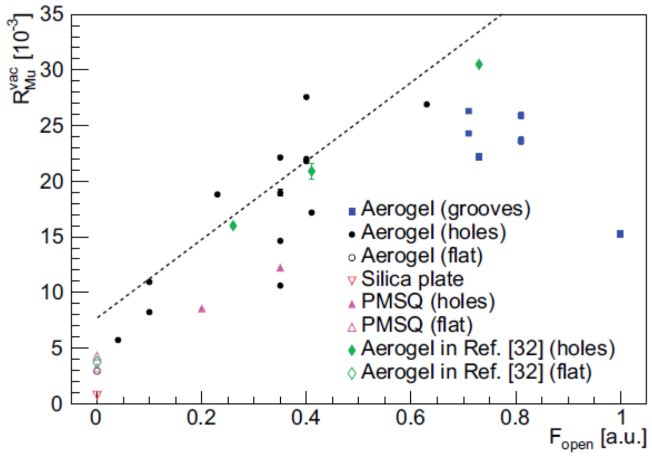
Various laser-ablated structures and aerogel materials were studied.







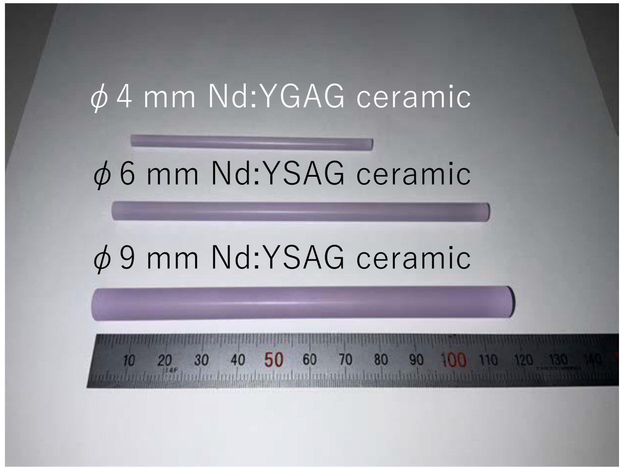
laser-ablated silica aerogel



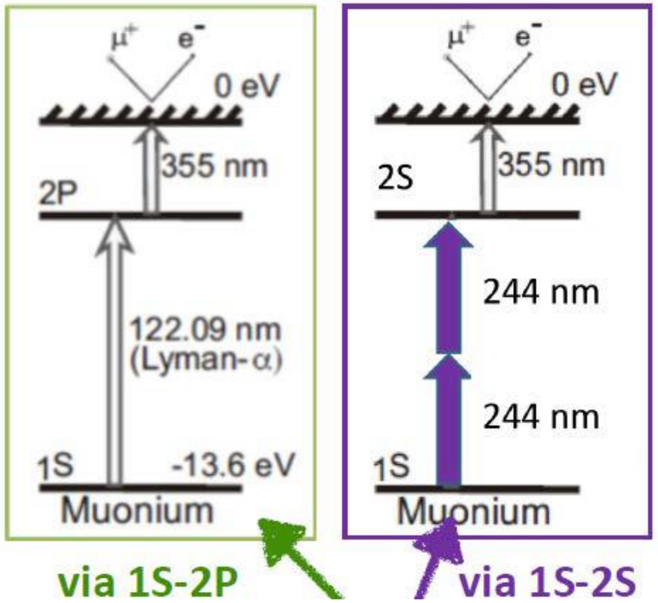
PTEP2020, 123C01

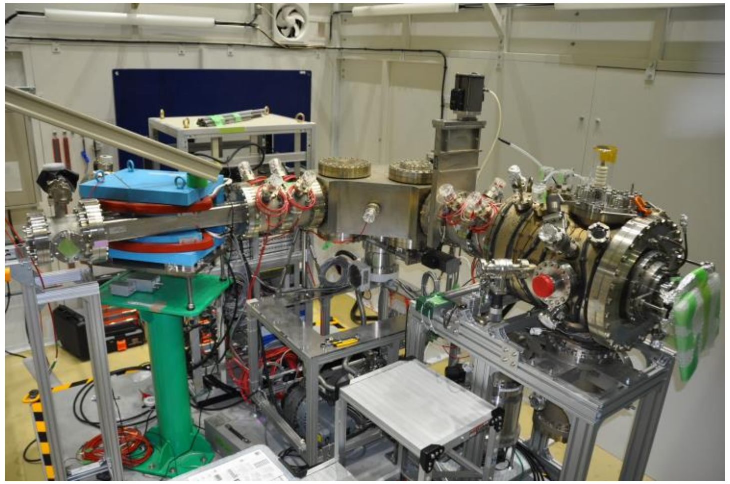
Muonium Ionization

- 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.



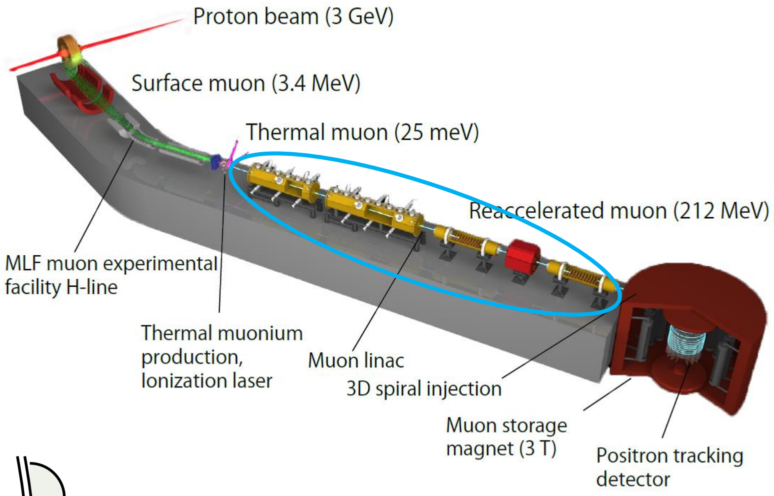
- As an alternative method, ionization scheme with 244 nm laser is being developed collaborating with the muonium 1S-2S spectroscopy measurement experiment.

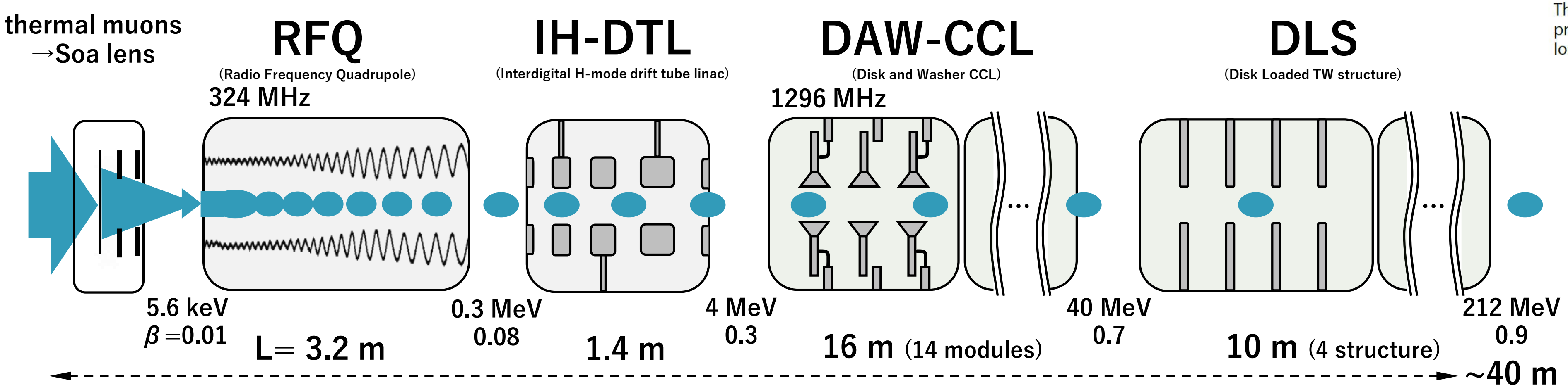




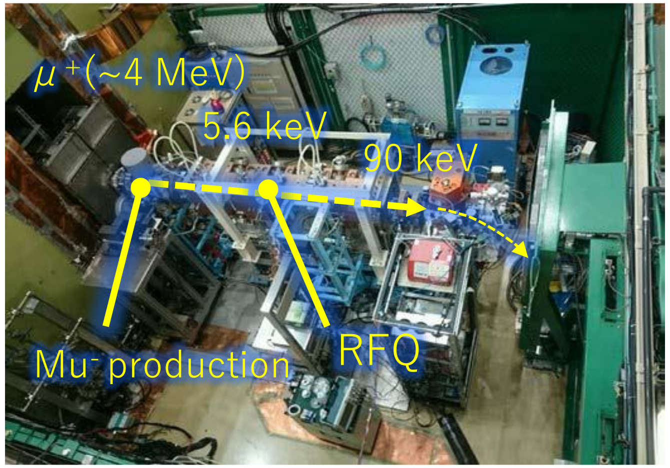
Slow muon beam line constructed for Mu 1S-2S experiment

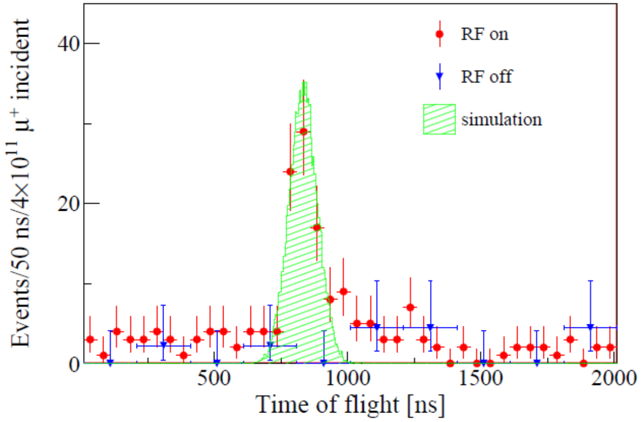
Muon Acceleration





- Thermal muon beam is accelerated to p=300 MeV/c in LINAC.
- Acceleration of muon (to be precise Mu^-) with RFQ has been succeeded already.

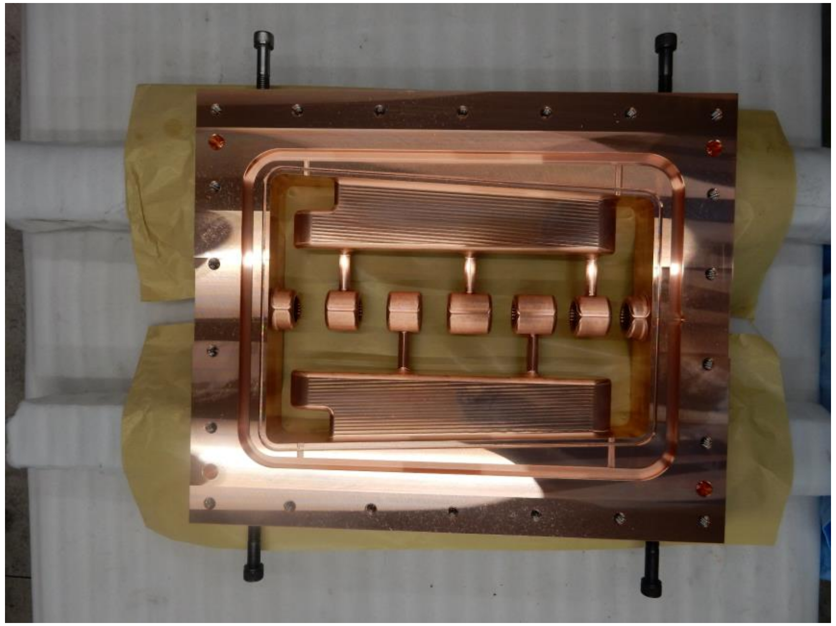




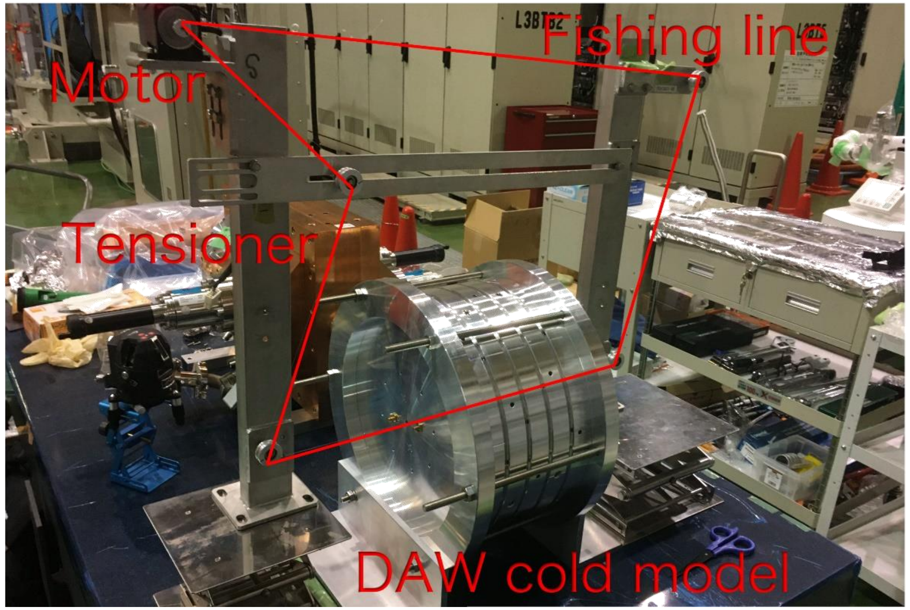
Signal indicating the arrival of Mu- when RF was on (Phys. Rev. Accel. Beams **21**, 050101 (2018))

Muon Acceleration (2)

- Next parts of acceleration cavities were designed.
- Their prototypes were produced, and performance evaluation were almost finished.
- Actual cavities of upstream part (IH-DTL and 1st tank of DAW-CCL) were started to be produced.



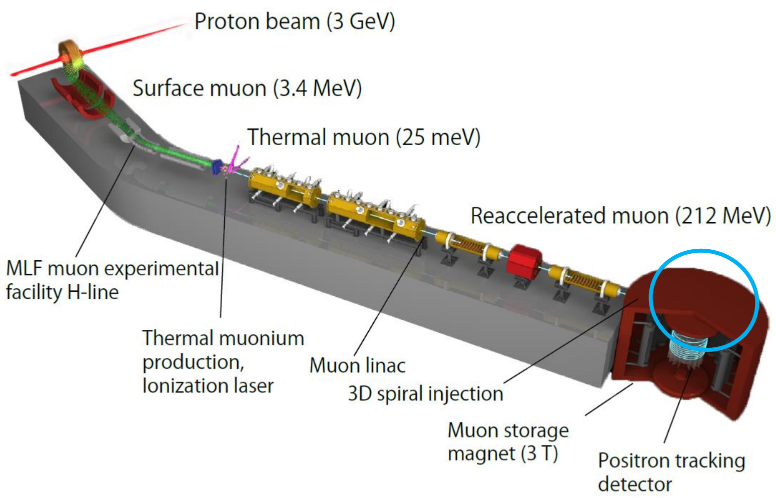
Prototype of IH-DTL

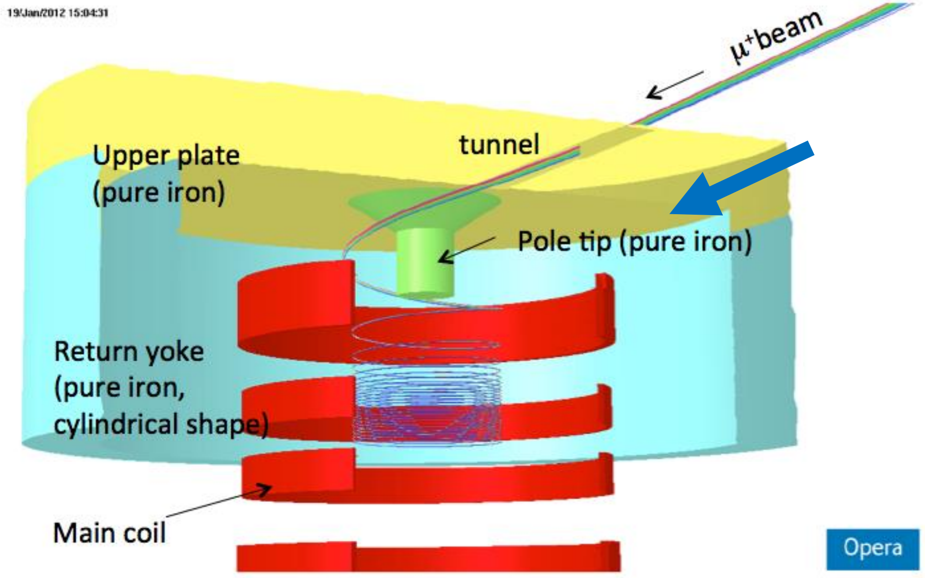


Cold model of DAW

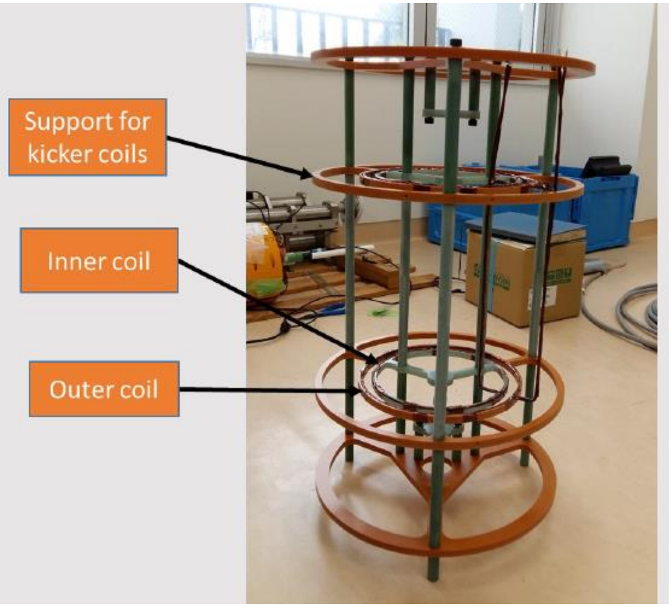
3D Spiral Injection

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

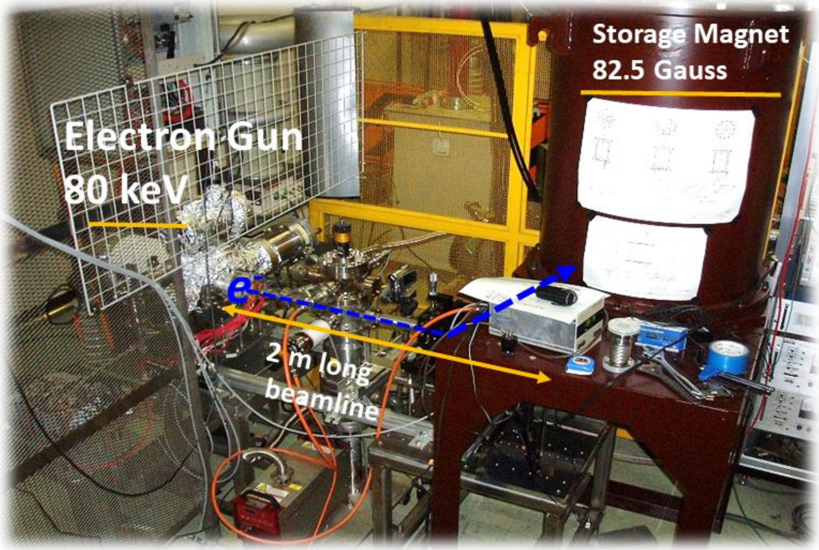




3D spiral Injection orbit

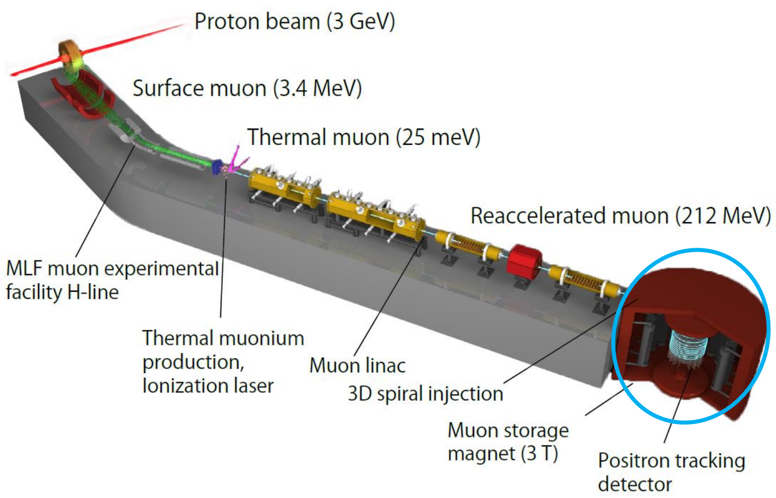


Prototype of kicker coils



Spiral injection test equipment using electron beam

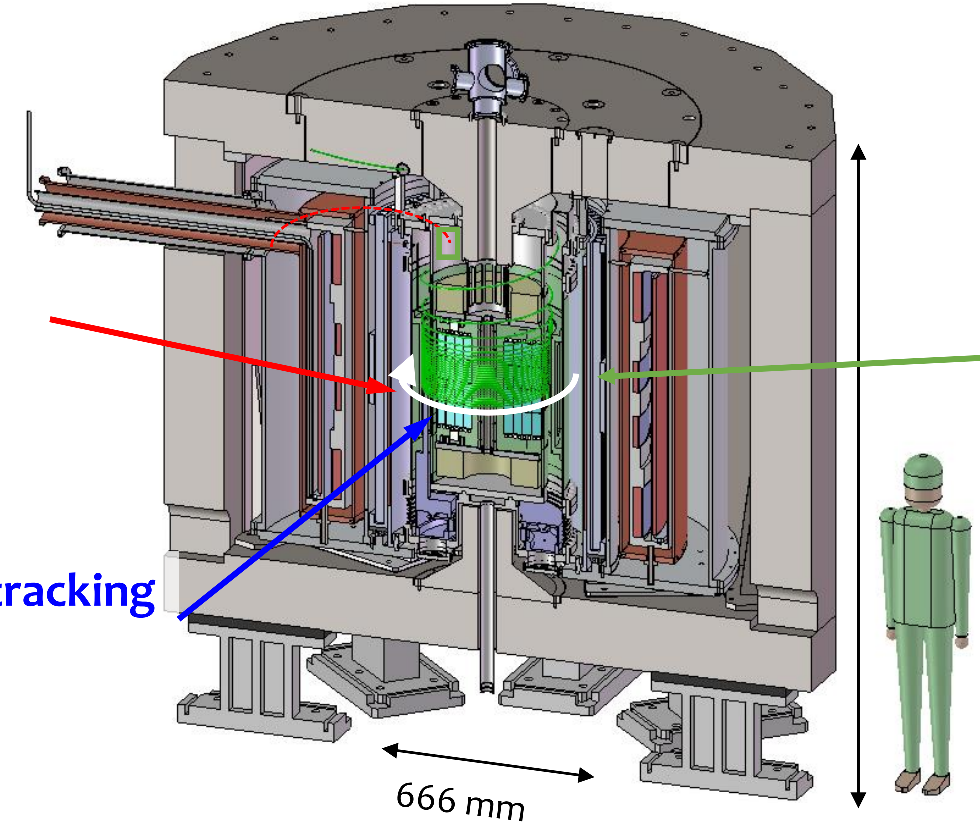
Storage Magnet

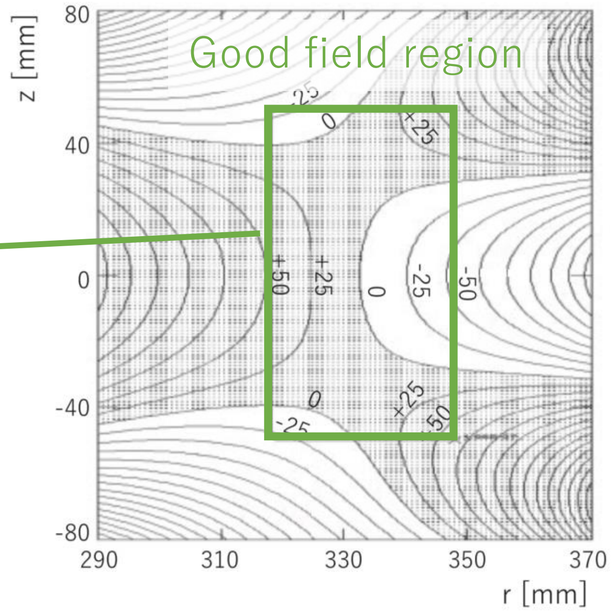


- 3 T MRI-type solenoid magnet will be used to store a muon beam.
- Weak focusing magnetic field is also applied to keep muon beam size..

Muon storage orbit

Positron tracking detector



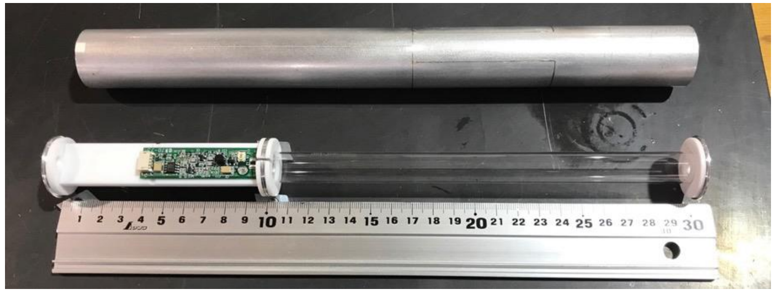


25 ppb/line

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

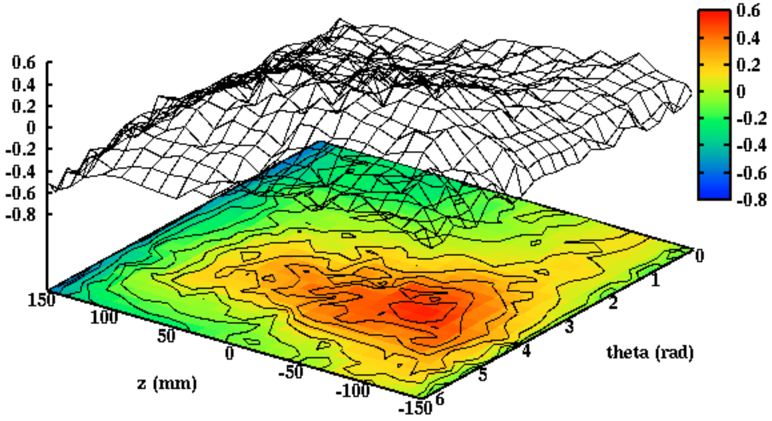
Magnetic Field Measurement

- 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, ~7 ppb agreement was obtained with 15 ppb uncertainties.



Standard NMR probe

MRI magnet for MuSEUM experiment

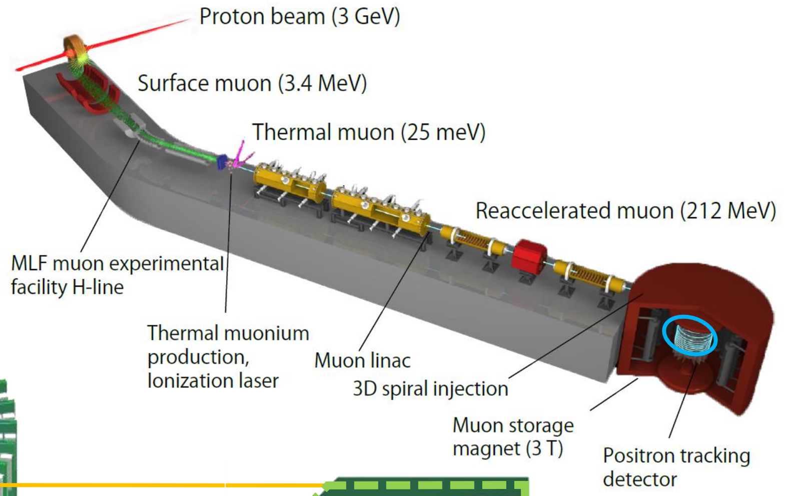


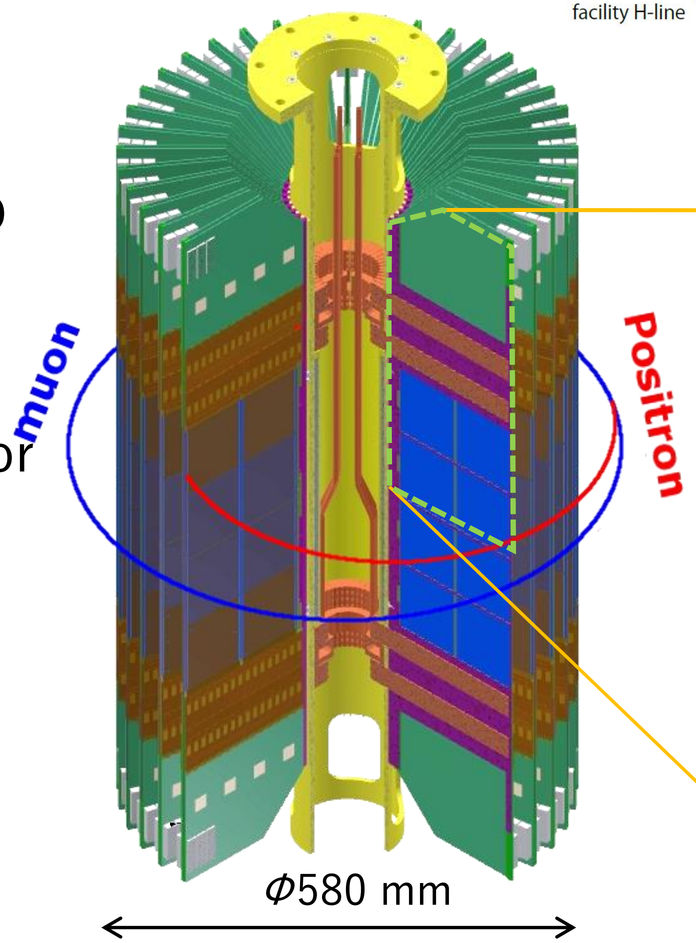
Magnetic field after shimming

Cross calibration at ANL in January 2019

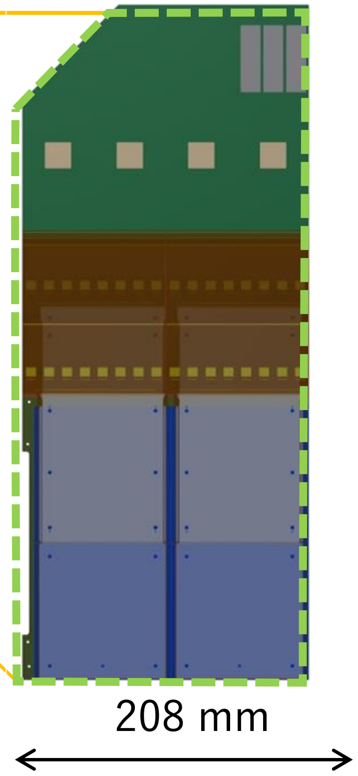
Positron Tracking Detector

- 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”.
    - There will be 40 vanes in total.
- Each vane has silicon strip sensors in both sides with their strip directions orthogonal each other.





Positron tracking detector

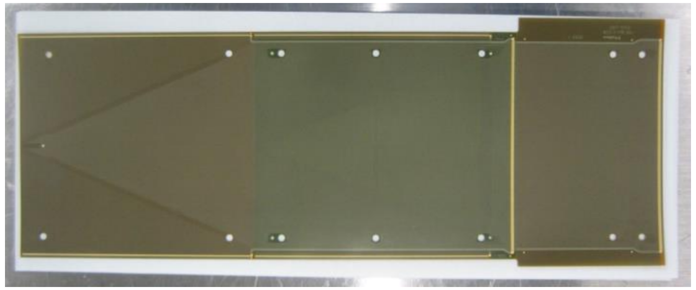


¼ Vane

Detector Components

Mass production of detector components are ongoing.

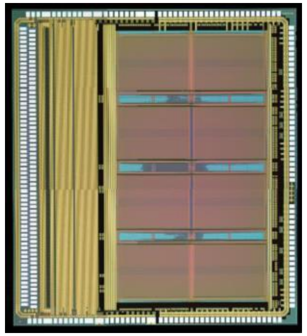
272 mm



Sensor FPC　　Pitch adapter

Flexible printed circuit boards

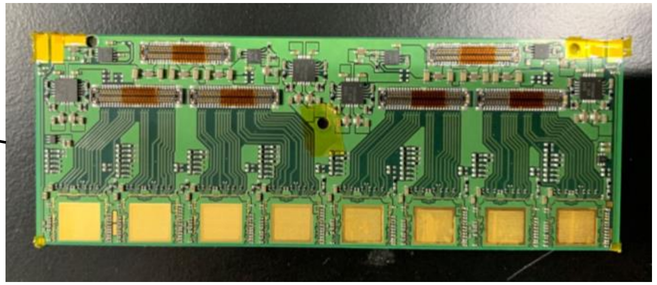
Specification
Fujikura Ltd.
Min. line/space: 35/35 μm (Sensor FPC) 15/12.5 μm (Pitch adapter)
1024 lines/layer



Readout ASIC

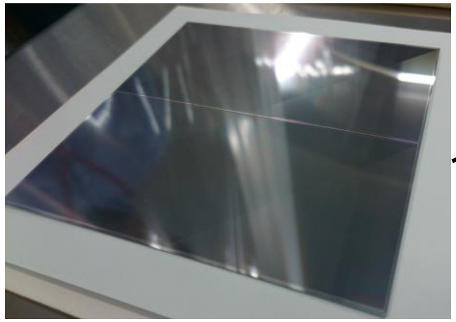
IEEE TNS. 67, (2020) 2089-2095

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

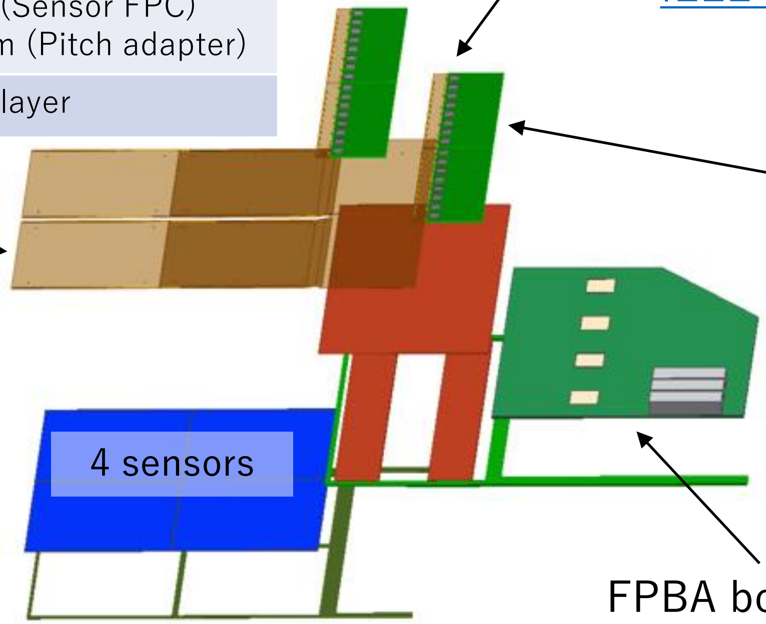


ASIC boards (almost final version)

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



Silicon strip sensor

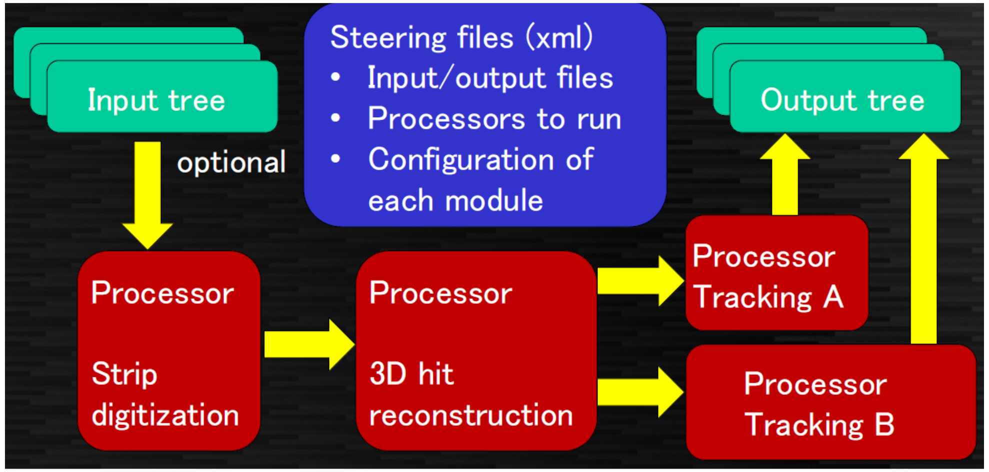


¼ vane structure

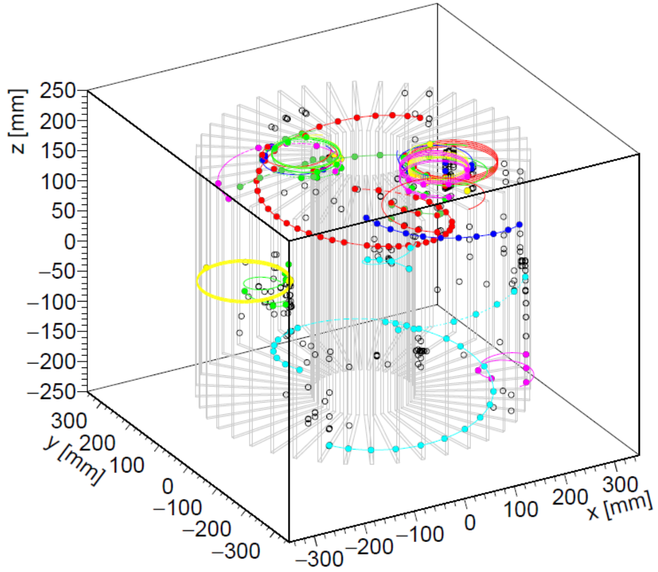
FPBA board
- Prototype version is being produced.

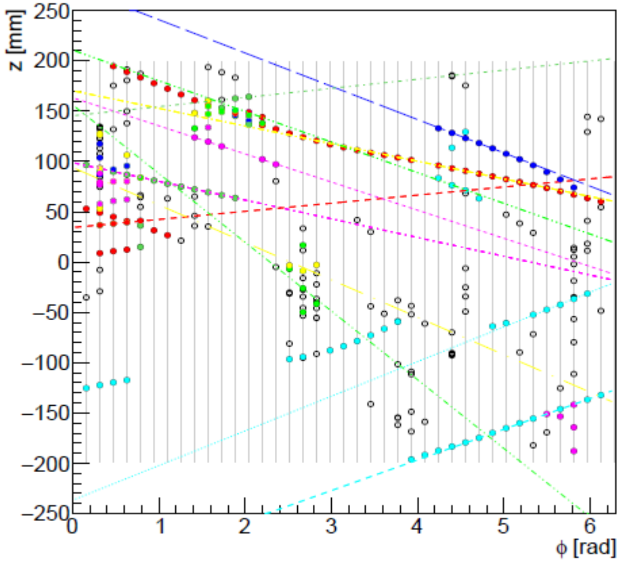
Track Reconstruction

- 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.



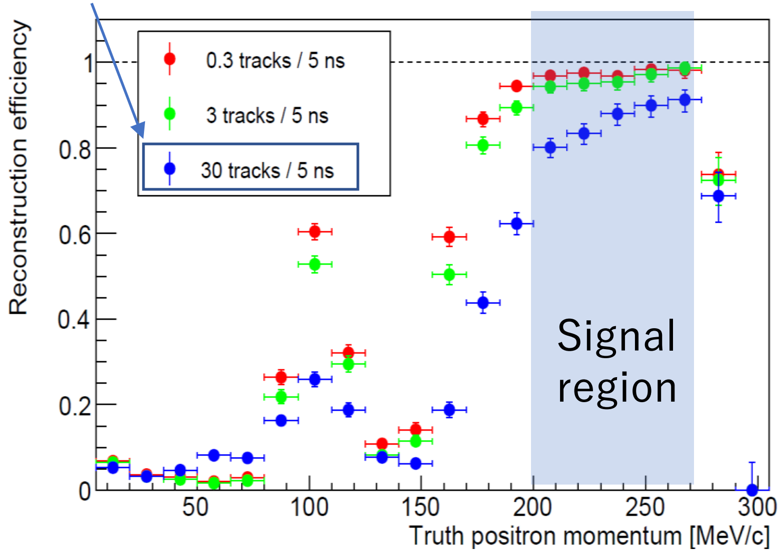
Concept of g2esoft





Simulated positron hits and reconstructed tracks with 25 positrons

Expected highest pile-up condition



Track reconstruction efficiency using the current algorithm

EDM Measurement

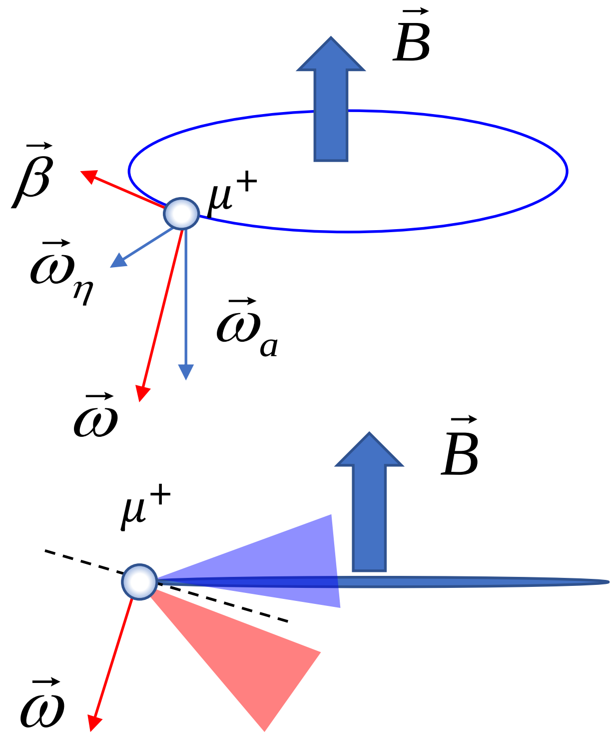
- If there is a contribution from the EDM to the muon spin precession, the combined angular velocity vector with respect to the momentum direction is obtained as

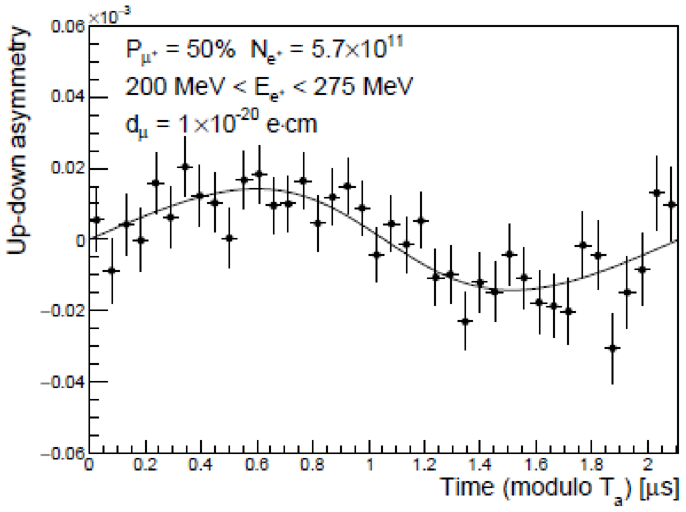
$$\vec{\omega} = \vec{\omega}_a + \vec{\omega}_\eta = \underbrace{-a\frac{q}{m}\vec{B}}_{\text{g-2}} \underbrace{-\eta\frac{q}{2m}(\vec{\beta}\times\vec{B})}_{\text{EDM}}.$$

  - ω_η/ω_a (with d_μ=10^{-21} e・cm) is about 10^{-5}
  → Too small to see a ω_η contribution (~10^{-10}) in $|\omega|$
  - But the tilt of angular velocity vector is visible (~10^{-5} rad).

$$\tan\delta = \frac{\omega_\eta}{\omega_a} = \frac{\eta\beta}{2a}.$$

- The tilt of the angular velocity vector is observed as an asymmetry between up-going and down-going decay positrons.
  - In practice, the up-down asymmetry as a function of time will be used to extract an EDM value.

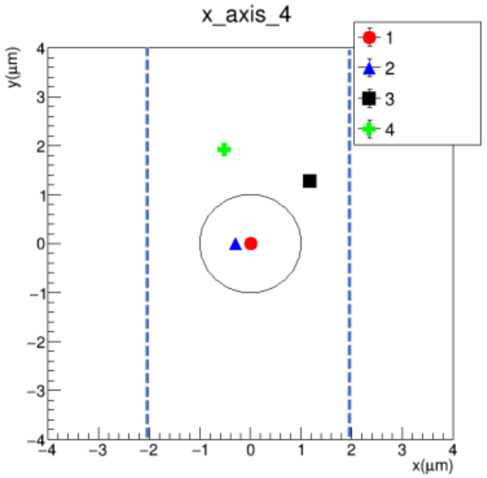




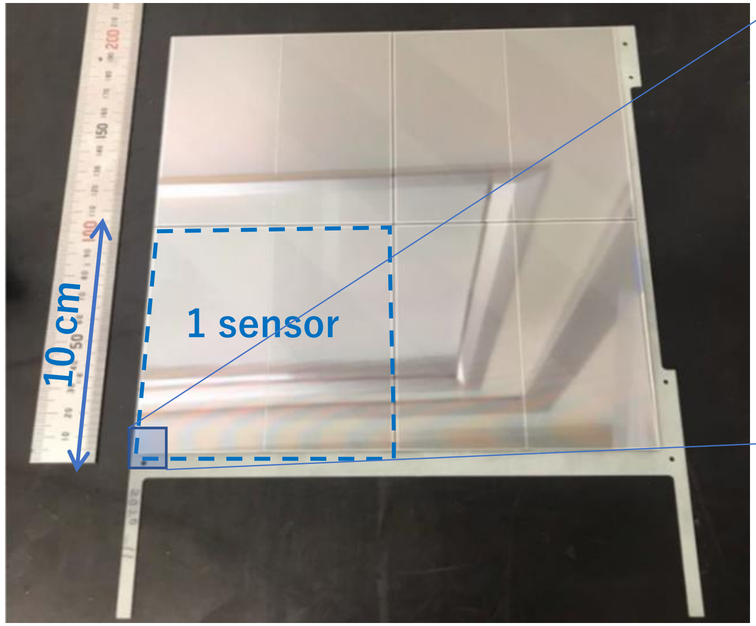
Detector Alignment

- To achieve 10^{-21} e・cm sensitivity of the EDM, sensors on the detector need to be positioned in the precision better than 1 μm.
- Detector assembly aiming at the accuracy of 1 μm in sensor plane is being developed.
  - Sensor assembly with the position deviation less than 3 μm was achieved so far.
- A way to measure sensor positions using positron tracks is also being developed.

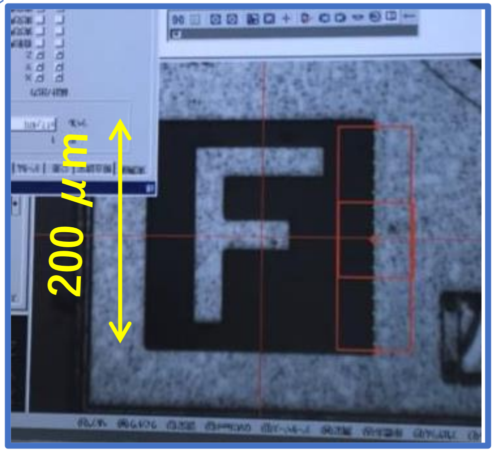
Sensor assembly using a coordinate measuring machine (CMM)



Example of the deviation from the target position after sensor gluing



4 sensors glued on frame



Sensor position is aligned measuring positions of marks on each corner of sensors with a CMM.

Experiment Status

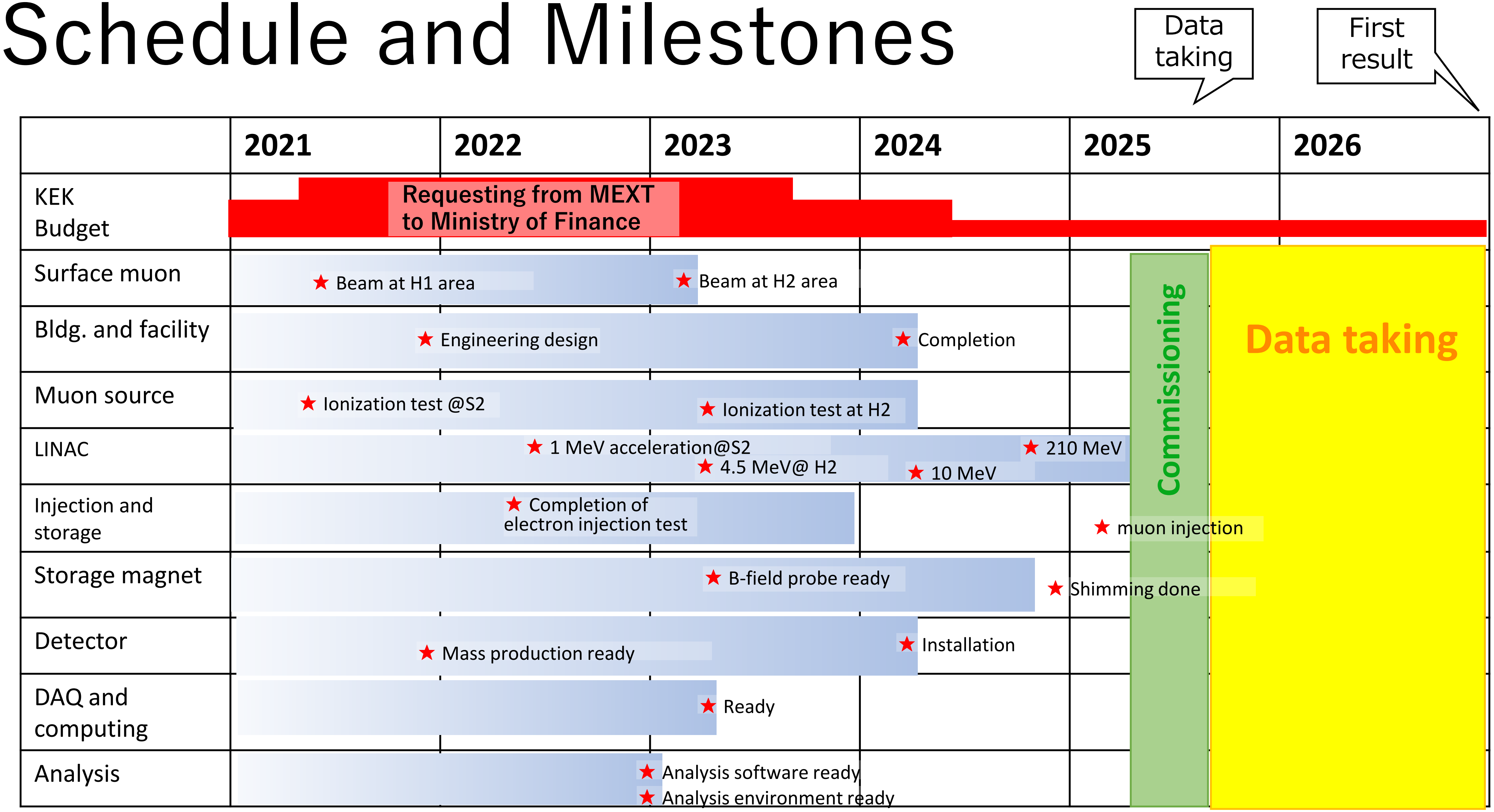
- A revised TDR was submitted to review committee in December 2017.
- Summary paper of the TDR was published by PTEP in 2019
  - [PTEP 2019 (2019), 053C02]
- KEK-SAC endorsed the experiment for the near-term priority in 2019.
- KEK prepared for a function request to Japanese government (MEXT) in 2020.
- The experiment was funded by Specially Promoted Research by JSPS from 2020.

116 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

19th Collaboration Meeting in Dec. 2019@J-PARC

Schedule and Milestones



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, which is required for the EDM measurement.
- Construction of the beam line has been started and other components of the experiment also move to the construction phase.
- Funding status is getting better and the start of the data taking is scheduled in 2025.

Backup

End-to-End Simulation

- Efficiency of muon beam at each step is estimated using the latest simulations and measurements.
  - Cumulative efficiency is 1.3×10^{-5}

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		

Statistics Estimation

Estimated statistics at 1 MW proton beam and 2×10^7 s run (~230 days)

	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.)