KYUSHU UNIVERSITY

Activities on J-PARC Muon g-2/EDM Experiment at Kyushu University

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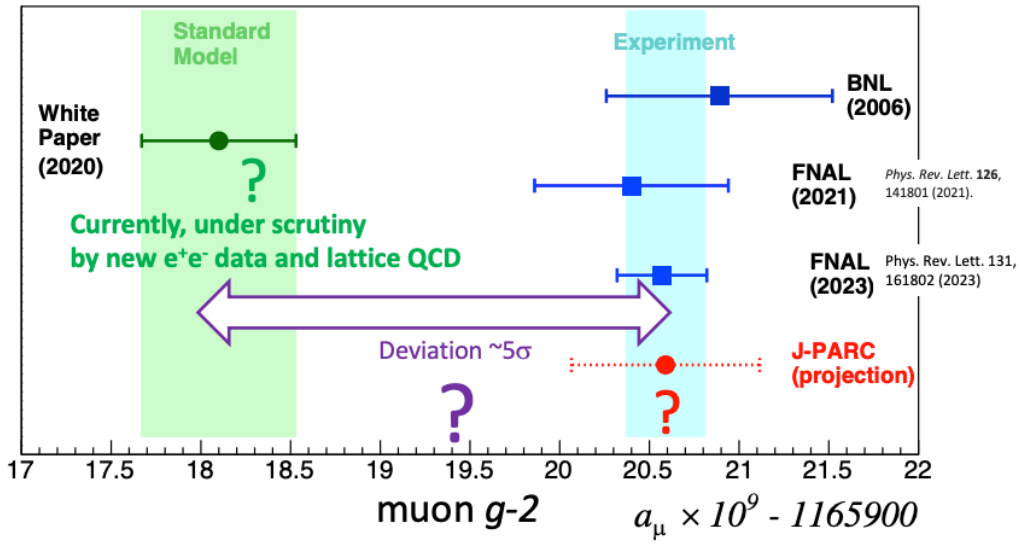
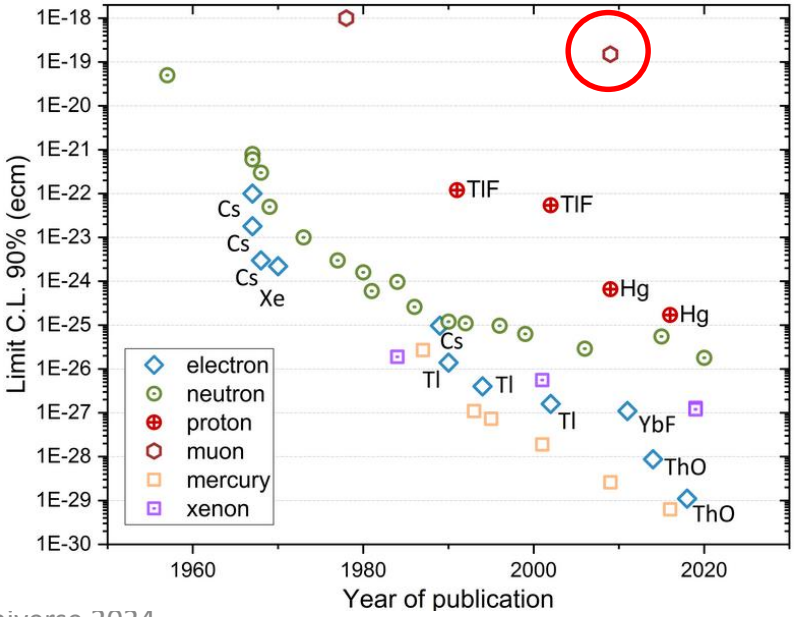
Muon g-2 and EDM

- Muon anomalous magnetic moment (g-2)
  - The latest result was published from FNAL E989 in 2023 and it was consistent with the previous result and the BNL experiment.
    - Phys. Rev. Lett. **131**, 161802 (2023)
    - The final result of FNAL E989 is expected in 2025.
  - The difference between the combined experimental value and the SM value exceed 5σ.
    - Muon g-2 theory initiative workshop was held at KEK in last year and it was agreed to updated the SM value in 2025.
- Muon electric dipole moment (EDM)
  - Existence of EDM for elementary particles indicates CP violation.
  - The experimental bound: $|d_\mu| < 1.8 \times 10^{-19}$ e・cm
    - BNL E821：PRD 80, 052008 (2009)

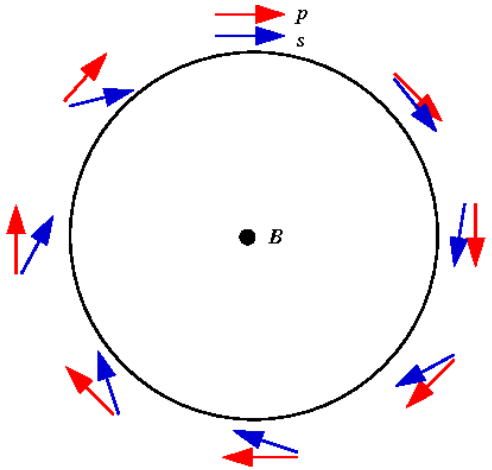




Experimental Approaches

Spin precession vector with respect to cyclotron motion in EM field

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



Spin precession in cyclotron motion

BNL/FNAL approach

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

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

Magic momentum of 3.094 GeV/c is used.

J-PARC approach

$$\vec{E} = 0$$

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

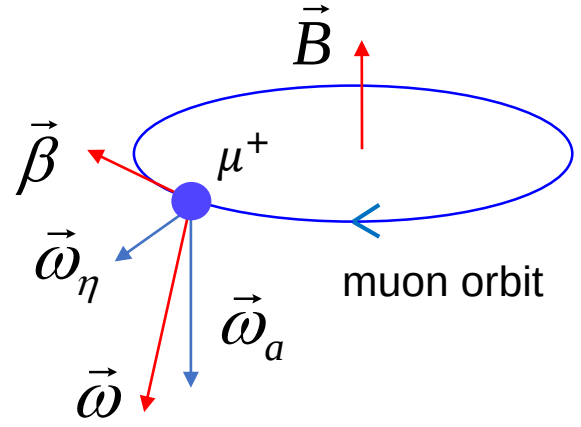
Reaccelerated thermal muon beam is a key of this method.

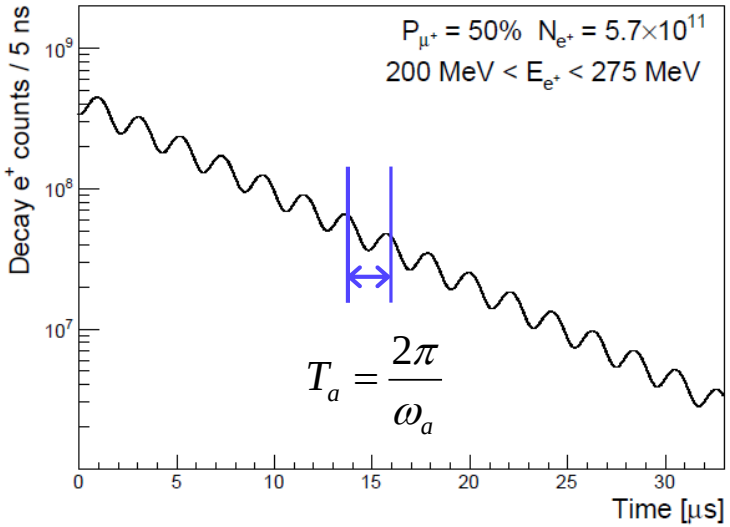
Measurement Principle

- Once electric field contribution is eliminated, g-2 and EDM can be obtained from the time spectrum of the number positrons from muon decay.

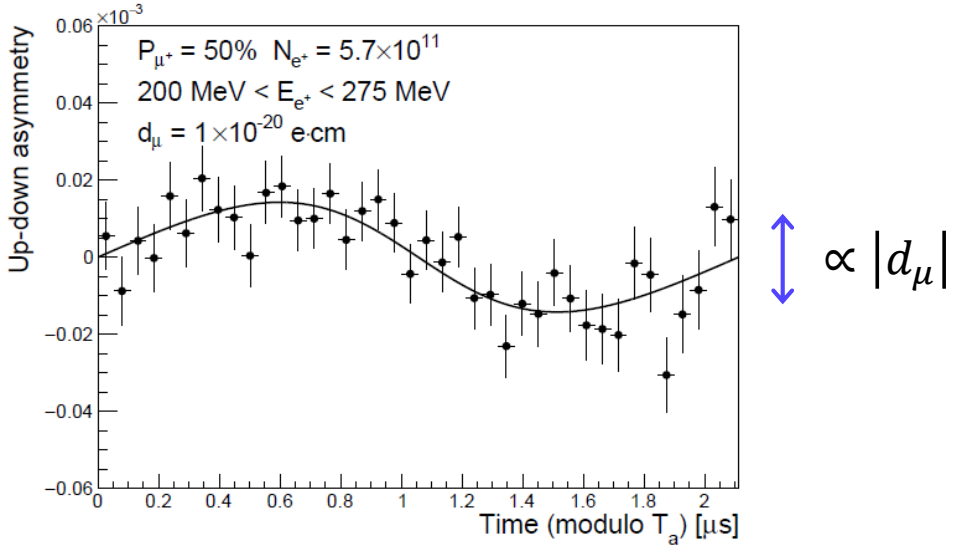
$$\vec{\omega} = \vec{\omega}_a + \vec{\omega}_\eta = -\frac{e}{m}\left[a_\mu \vec{B} + \frac{\eta}{2}\left(\vec{\beta} \times \vec{B}\right)\right]$$

g-2 EDM



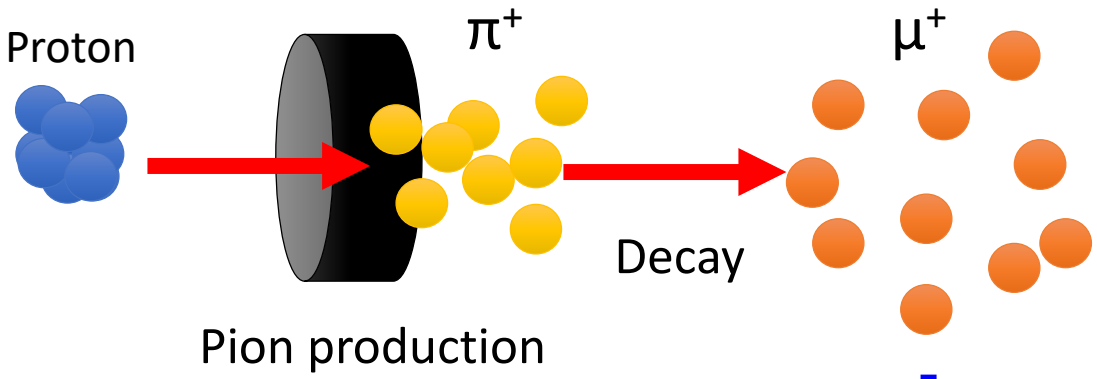


Time spectrum of the number of positrons from muon decay



Up-down asymmetry of positrons from muon decay

Reaccelerated Thermal Muon Beam



Conventional muon beam

Emittance ~1000π mm ·mrad

Strong focusing with electric field
Muon loss
Pion background

Cooling and Acceleration

Reaccelerated thermal muon beam

Emittance ~1π mm ·mrad

μ^+

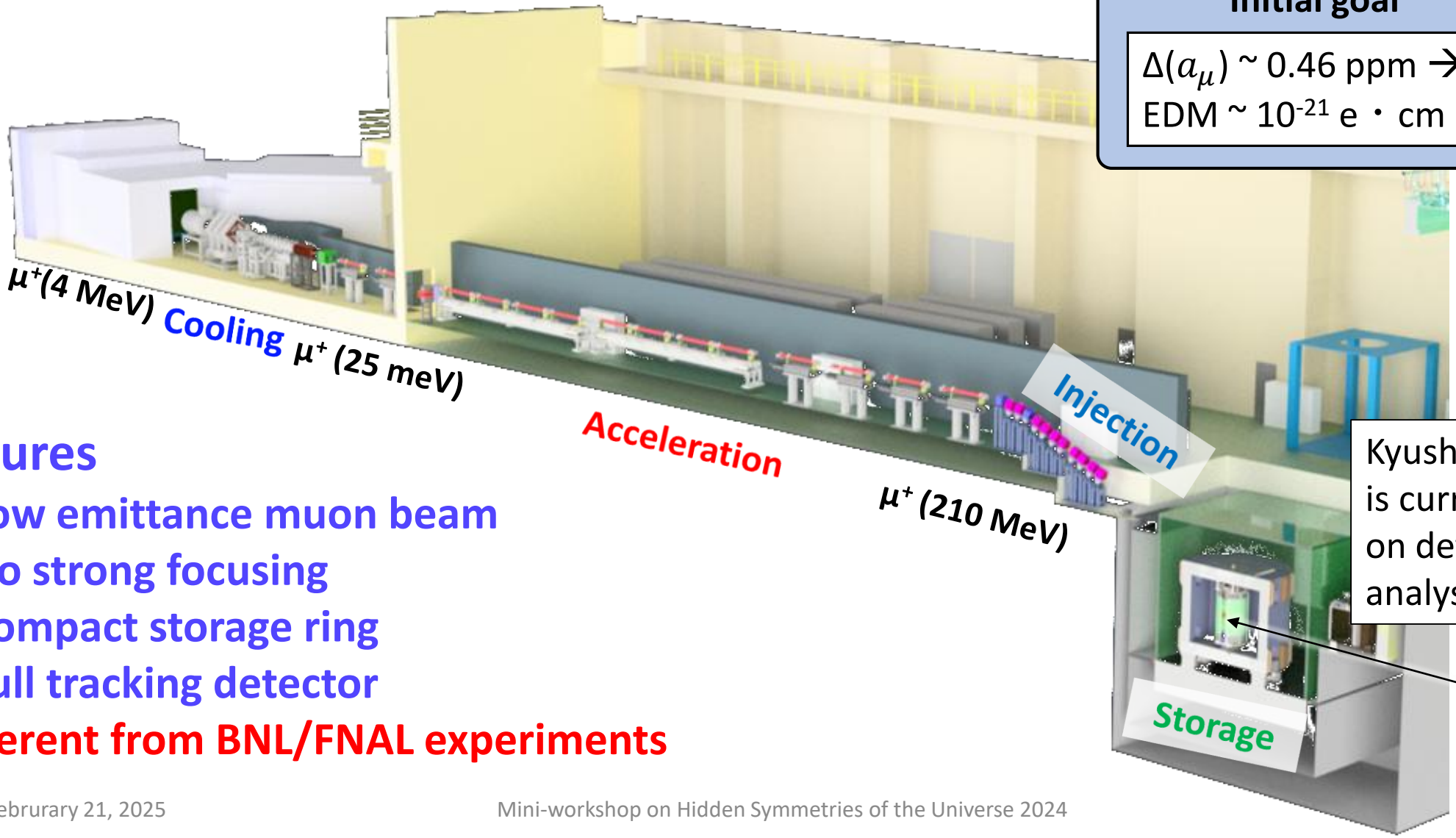
Free from any of the above

Reaccelerated thermal muon beam

- Strong beam focusing by an electric field is not needed.
  → **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**

J-PARC E34 Experiment

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



Kyushu University is currently working on detector and analysis software.

Positron detector

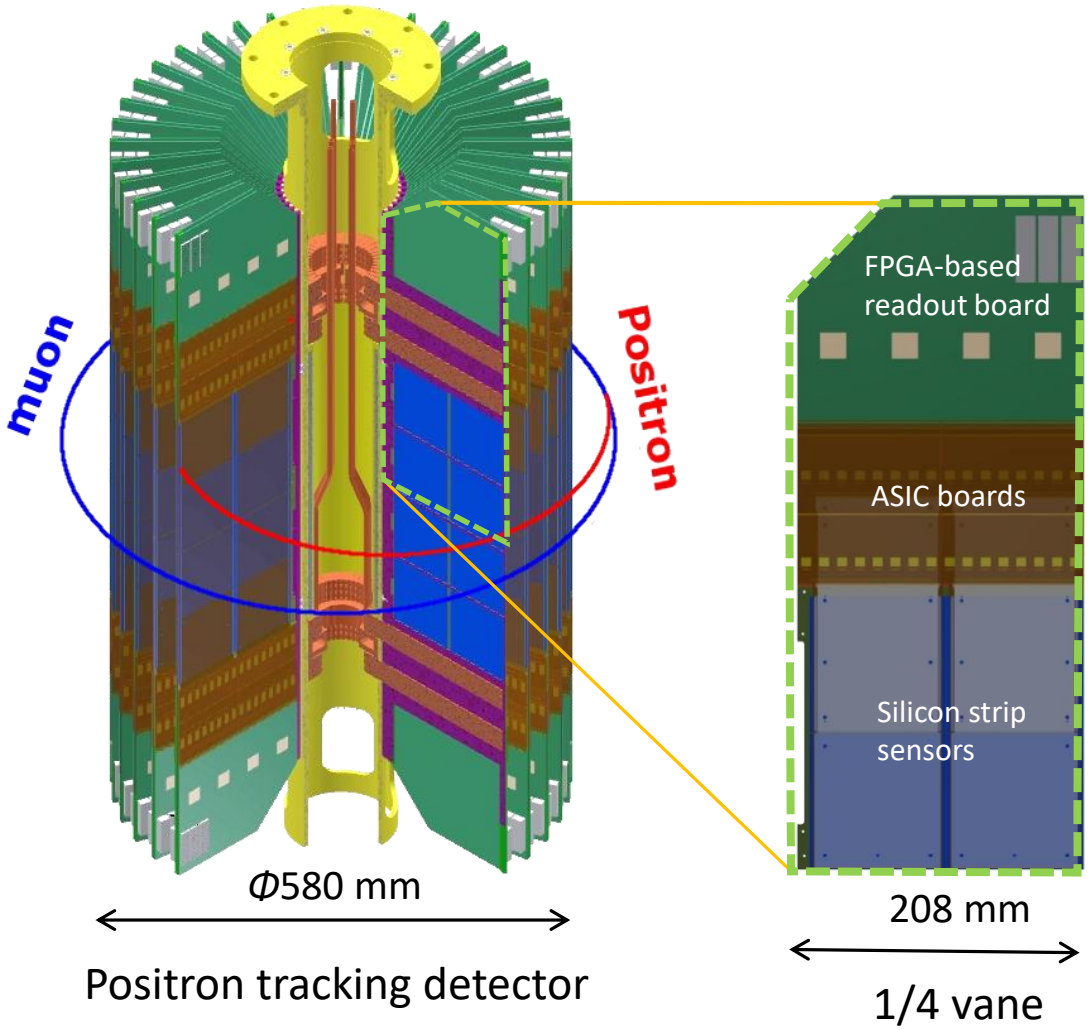
Features

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

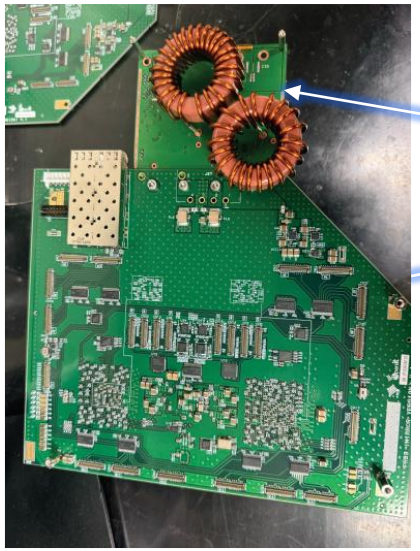
Different from BNL/FNAL experiments

Positron Tracking Detector

- Positrons from decay of stored muon beam are detected by the detector consisting of silicon strip sensors.
  - Positron tracks are reconstructed from hits in radially arranged detector modules (vanes).
  - Sensors with orthogonal strip direction in both sides of a vane
- The detector is required to operate in the highest muon decay rate of 6 tracks/ns.
  - 190 μm pitch silicon strip sensor
  - 5 ns sampling rate in readout ASIC

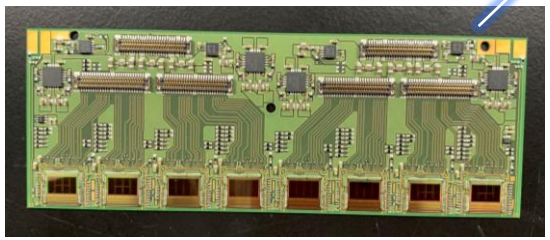


Detector Components

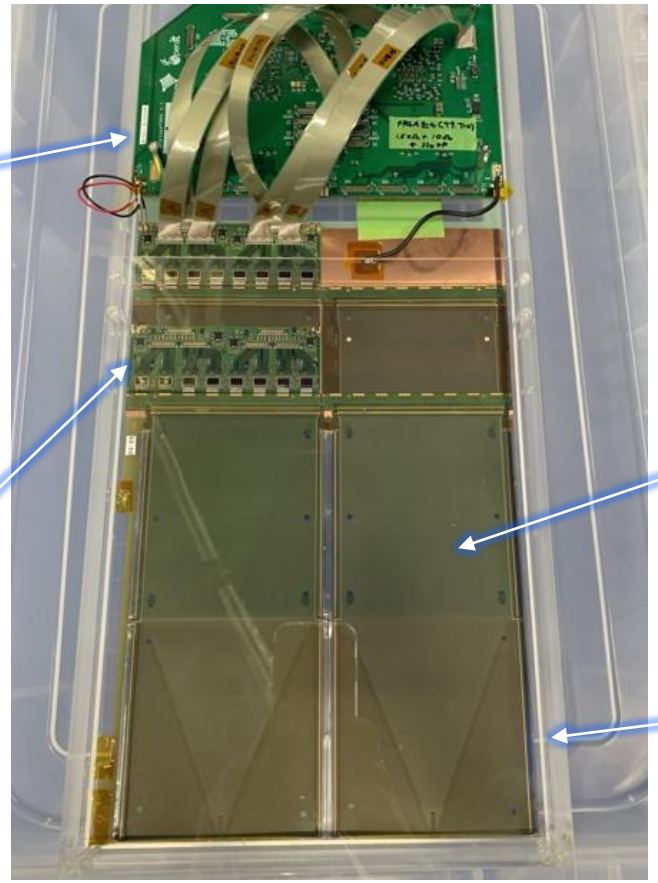


DC-DC convertor:
Prototype is tested

FPGA-based readout board:
Prototype is being tested.

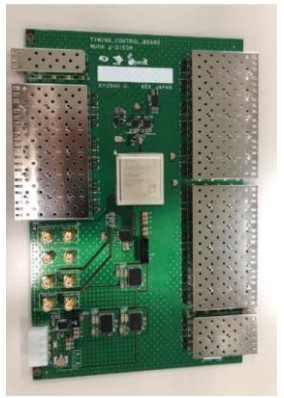


ASIC board: Mass production started



Prototype of 1/4 vane

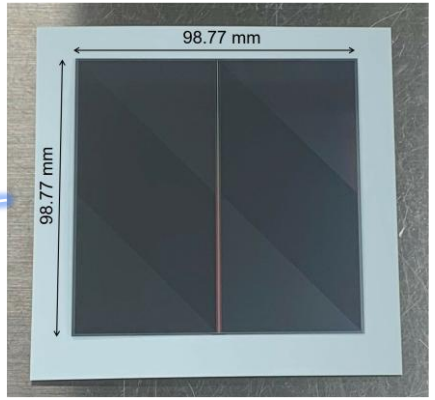
AMANEQ board



Timing control board

Backend boards：Completed

Flexible printed circuit board:
Mass production finished



Hamamatsu
Photonics
S13804

Silicon strip sensor: In mass production

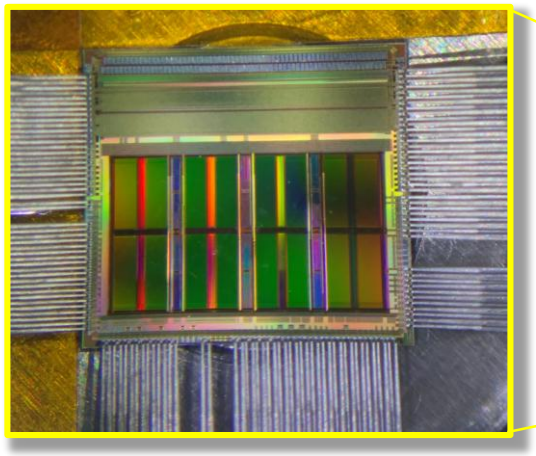
Facility at Kyushu University

- The laboratory has various apparatus required for semiconductor detector development.
- Various studies and fabrication work have been conducted using them.

Inspection of ASIC

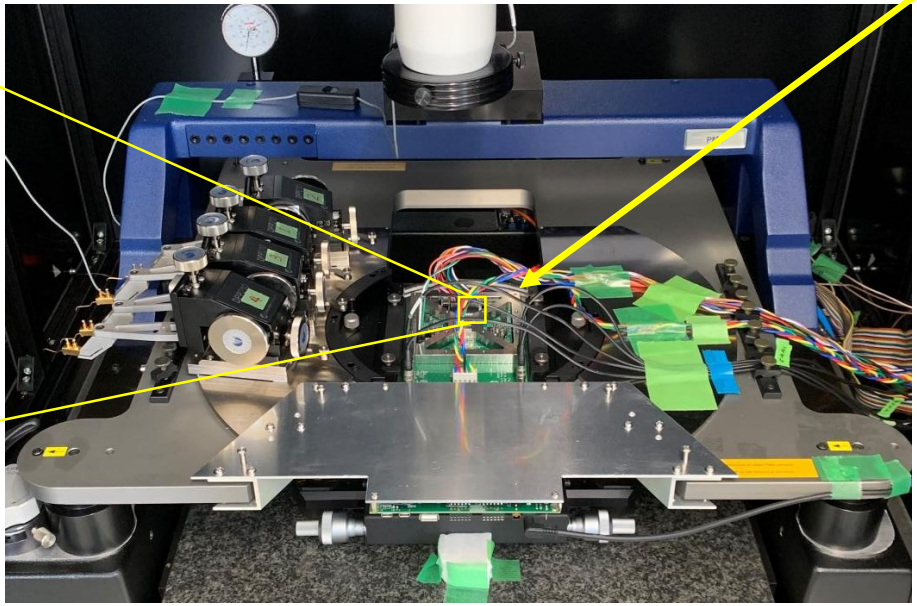
- Inspection of readout ASICs was performed at Kyushu University.
  - A probe card was installed to a probe station and bare chips were probed to survey its performance.
- Inspection process was established and ~5700 chips were inspected in two years.

Probe card for readout ASIC



ASIC probing

Inspection



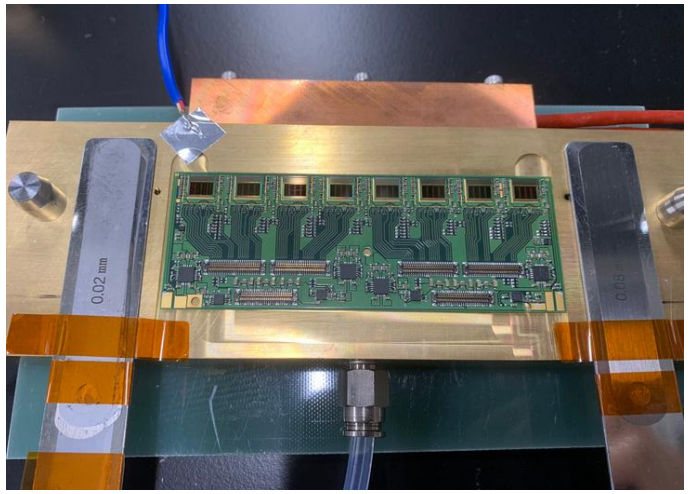
Probe station with probe card installation

Probe station and measuring devices

ASIC Implementation on Circuit Board

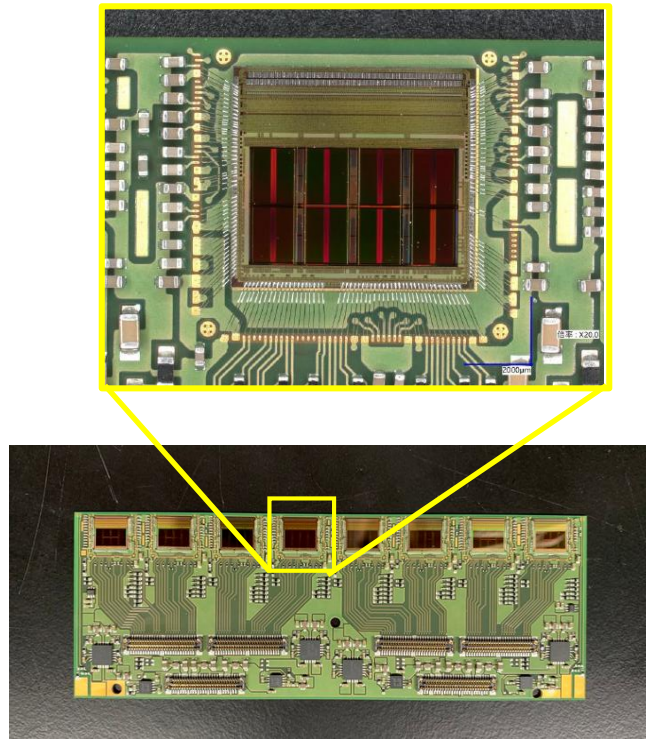
- ASICs after inspection are implemented on a circuit board.
  - They are mounted using an assembling jig.
  - Then, wire-bonding is performed.

Glue dispense on circuit board



Circuit board on assembling jig

Wire bonding operation

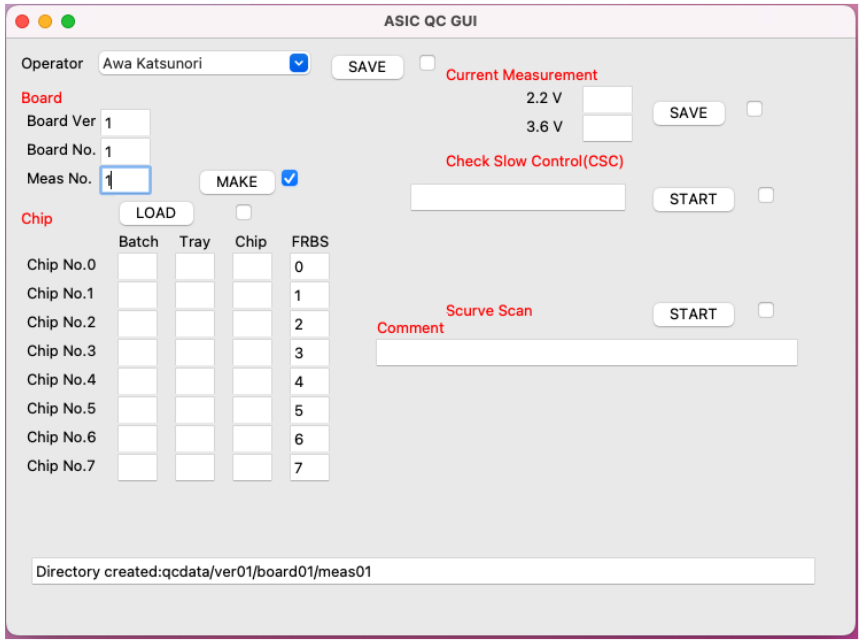


ASICs after wire bonding

ASIC Board Inspection

- Circuit boards after ASIC implementation are being tested.
- Currently, mass-inspection system is being developed at Kyushu University.

ASIC board operation test

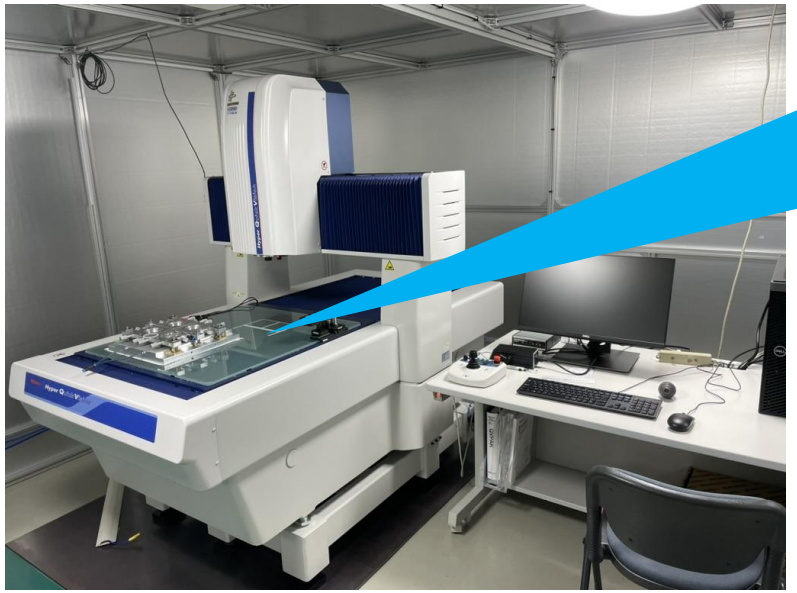


GUI for ASIC board inspection

Detector Assembly

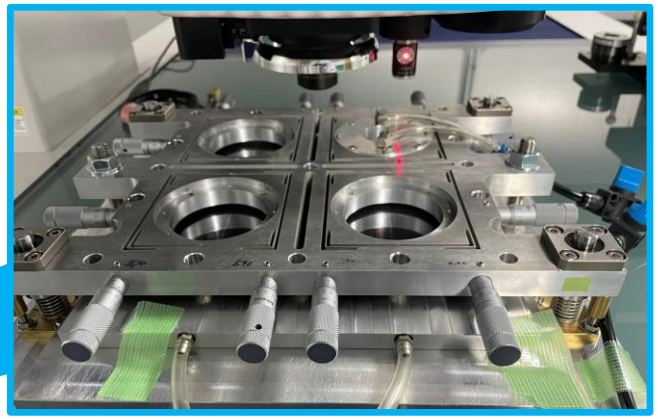
- Currently further detector assembly is performed at KEK.
- Students at Kyushu University are also working on the development of assembling jigs and processes.

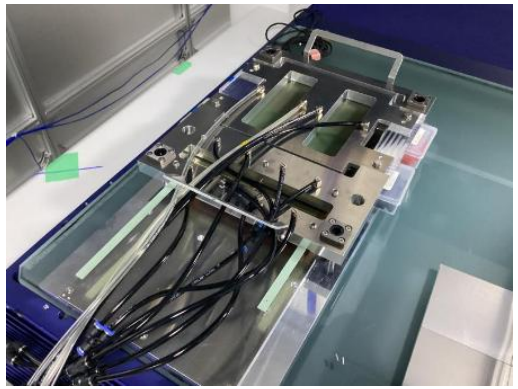
Detector assembly room at KEK



3D coordinate measuring machine at KEK

Sensor assembling jig

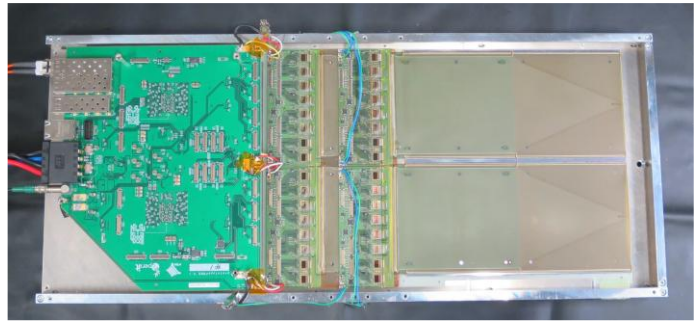




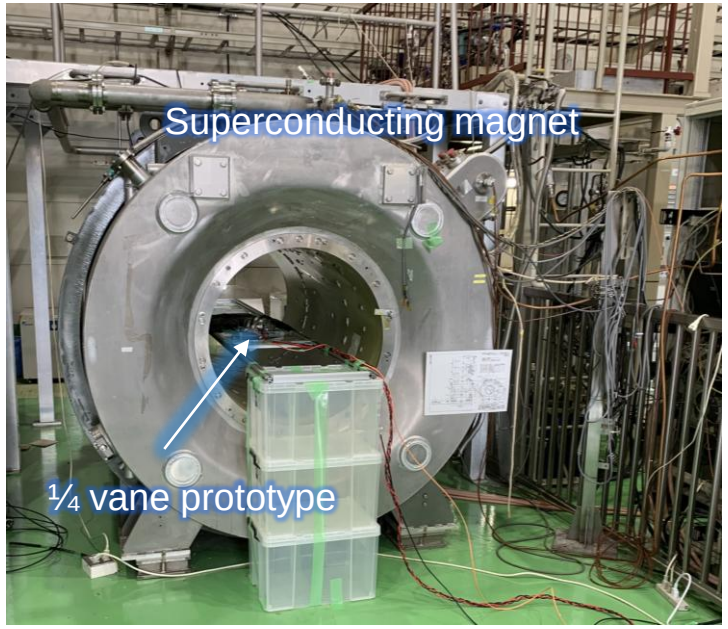
Assembling jig for readout boards

Operation Tests of Detector Module

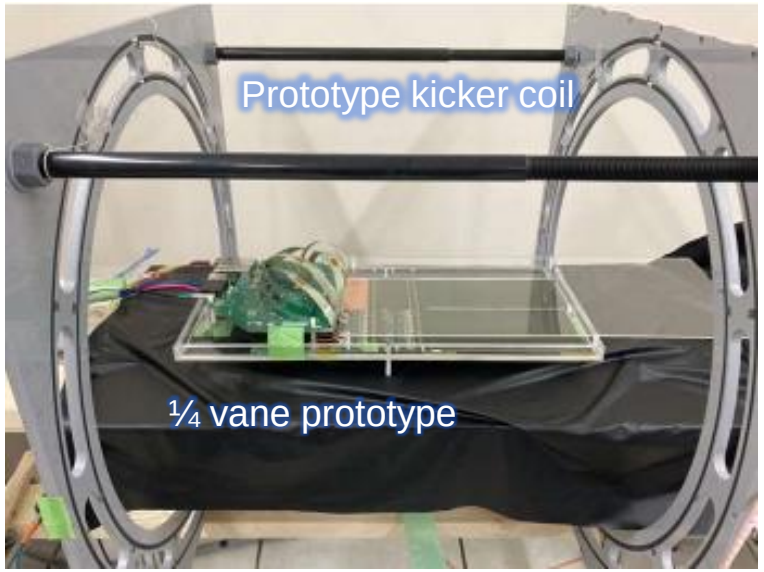
- Several prototype modules were produced.
- Operation tests were performed in various conditions using prototype detector modules.



¼ vane prototype



Operation test in high magnetic field at KEK

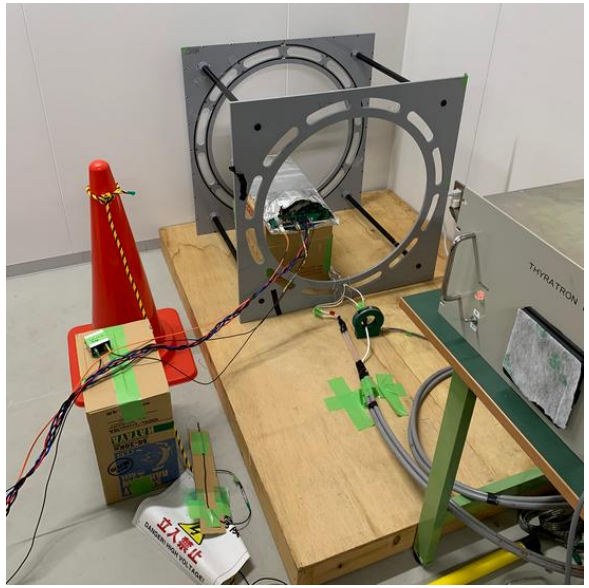


Operation test in kicker magnetic field at Tokai

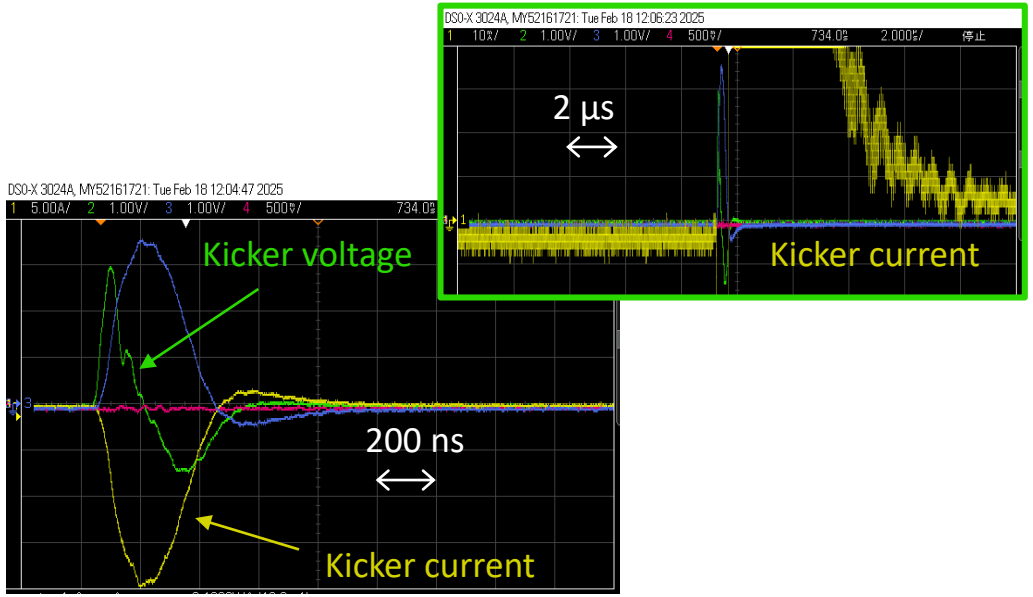
Operation test in vacuum at KEK

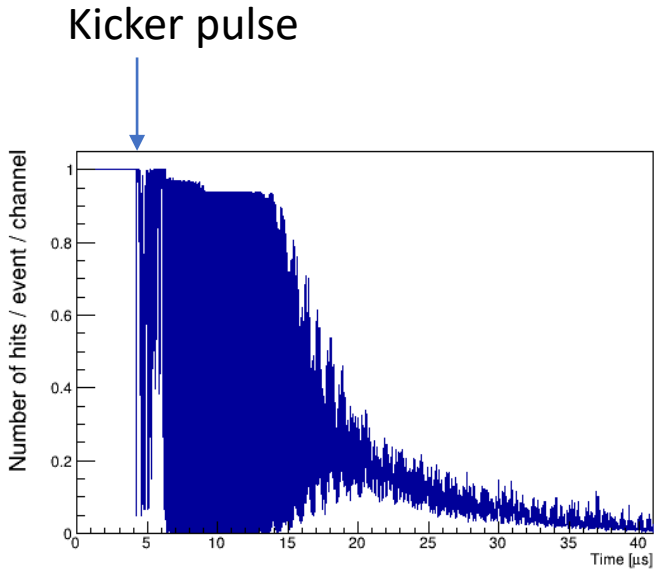
Operation Test in Kicker Magnetic Field

- There is an issue in an operation in kicker magnetic field.
  - High frequency current flowing the kicker coil causes large noise in detector.
- To investigate and solve this issue, a prototype kicker system was moved to Kyushu University and further test is conducted.



Operation test at Kyushu University

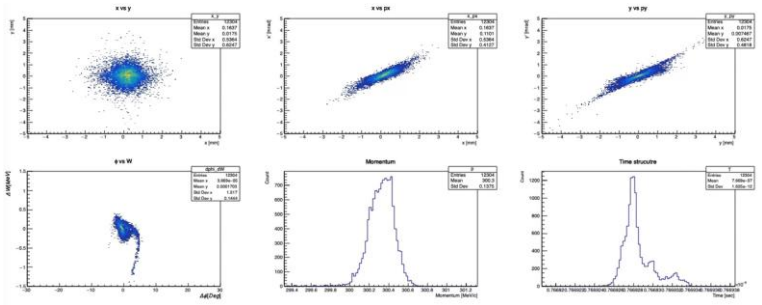


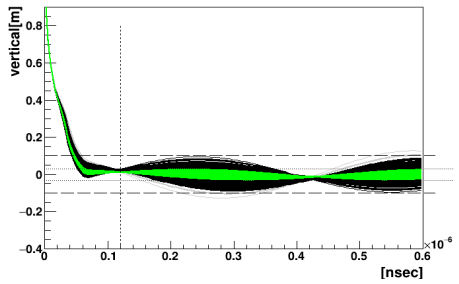


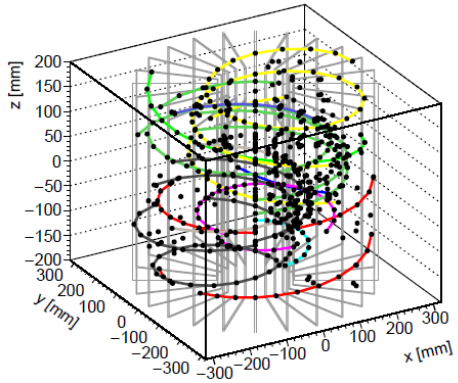
Detector hit data

Software and Computing

- Software framework (g2esoft) was developed to manage detector simulation and track reconstruction.
- End-to-end simulation which starts from the muon beam from H-line to the detection in the storage magnet has been conducted.
- To support computing requirements at the actual experiment, Grid and CernVM File System (CVMFS) servers are set up at KEK Computing Center.



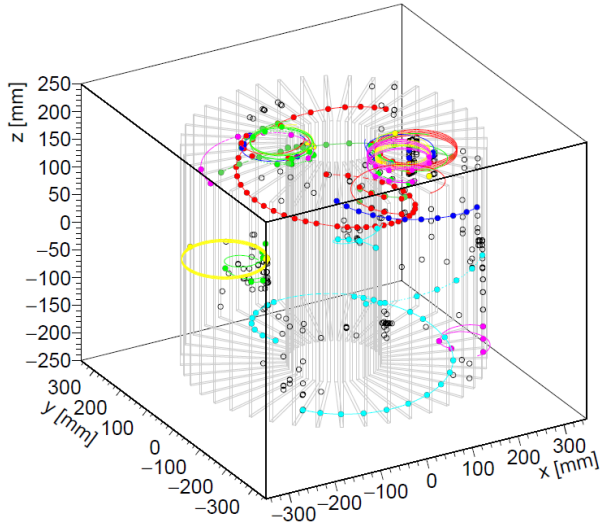




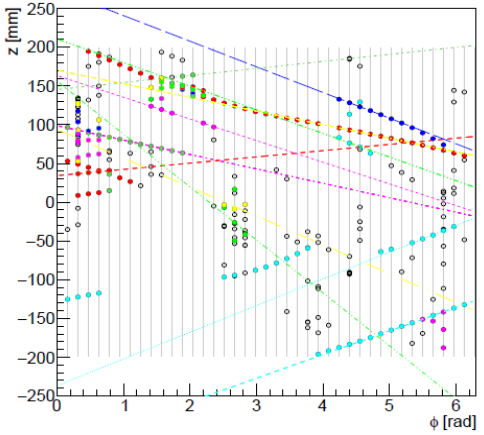
Surface muon → **Thermal muon** → **Acceleration** → **Transport & Injection** → **Storage** → **Detection** → **Reconstruction**

Track Reconstruction

- One of the challenges in software is track reconstruction speed.
  - At the actual experiment, ~3 × 10^4 signal tracks/s will be detected.
- High speed track reconstruction algorithm based on Hough transform in z-ϕ plane has been developed.
  - A factor of improvement in reconstruction speed is desired to process data at the same rate as the data taking using ~1000 CPUs.

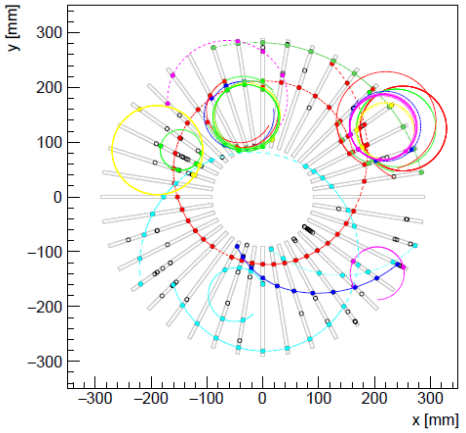


Event display of detector (corresponding to ~one time window)



Projection to z-ϕ plane

- High momentum tracks leave hits on a straight line.



Top view of the detector

Experiment Status

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

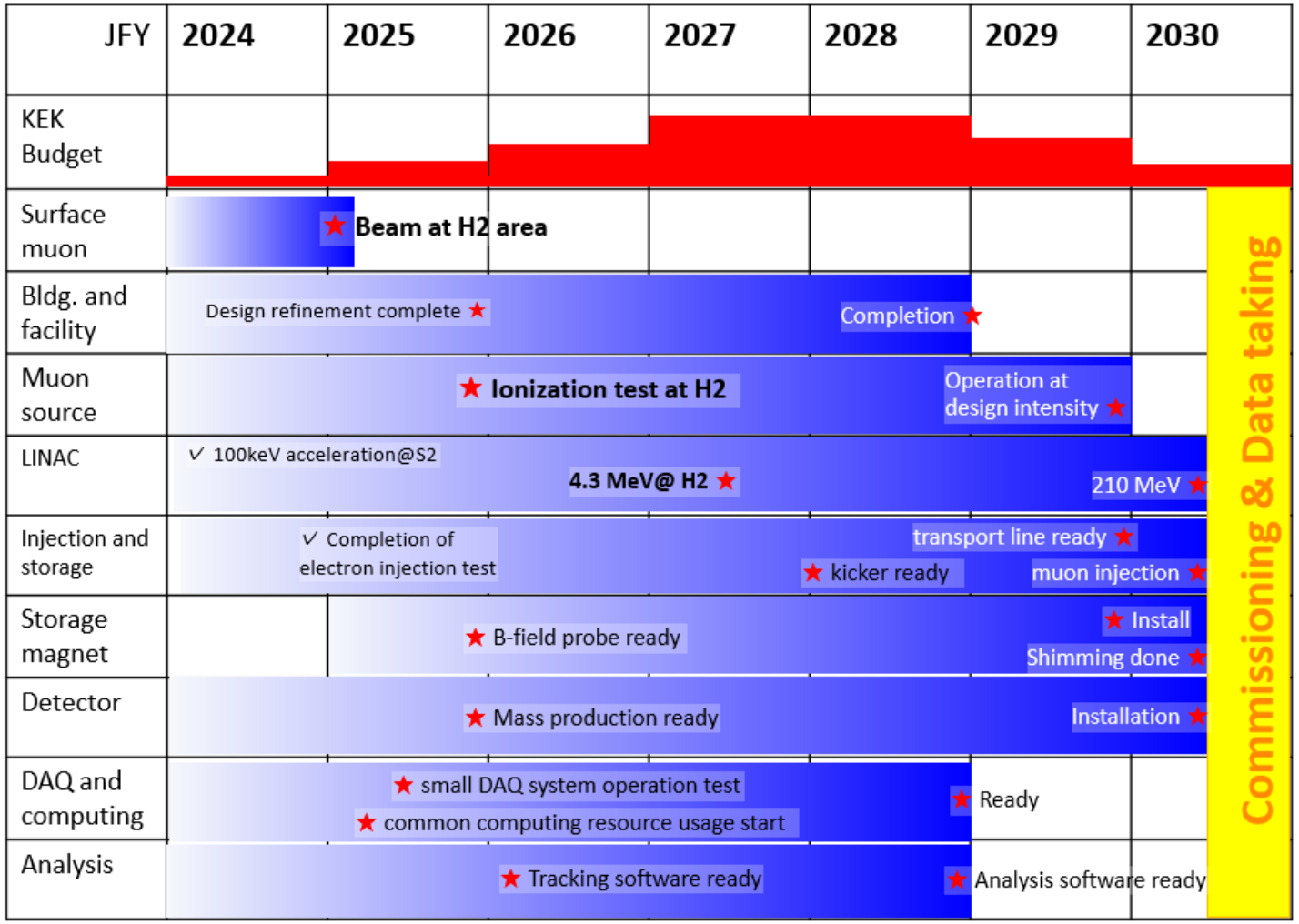
29th Collaboration Meeting at Nagoya University in December 2024

Year	Funding
2020	• Grant-in-Aid “Specially Promoted Research” (2020-2025)
2022	• Funding to prepare for construction
2023	• Funding to prepare for construction
2024	• Funding to complete H-line extension • K-program (2024-2028)

KEK plans to request funding for remaining parts including

- H-line experimental building
- Muon LINAC / Injection
- Storage magnet, etc.

Schedule and Milestones



- Construction of experimental apparatus is ongoing.
- We are aiming at the start of commissioning from 2030 JFY.

Summary

- In the J-PARC E34 experiment, measurement of muon g-2 and EDM is planned with a method different from BNL/FNAL experiments.
- Kyushu University is working on development of the positron detector and analysis software.
- Preparation of the experiment is ongoing aiming at the start of the commissioning in 2030 JFY.