

Silicon Strip Detector for J-PARC muon $g-2$ /EDM Experiment

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On behalf of the muon $g-2$ /EDM (E34) collaboration

July 7th 2018



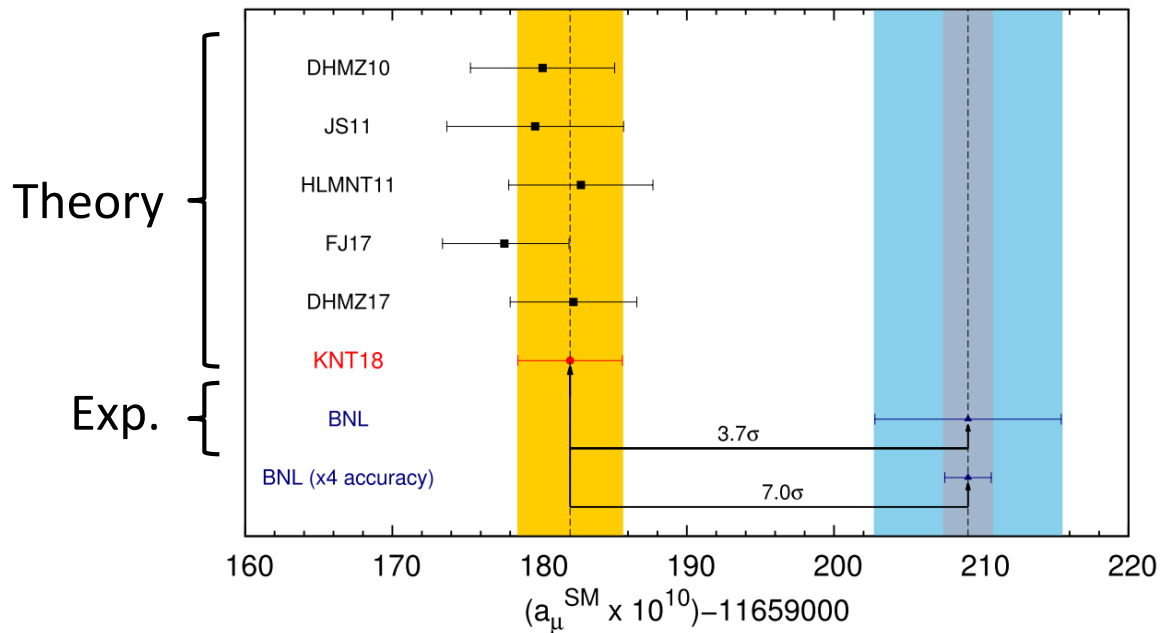
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Muon $g-2$ Anomaly and Search for EDM

- Muon $g-2$ is sensitive to new physics beyond SM.
 - 3.7 deviation between muon $g-2$ measured by BNL E821 and SM prediction.
 - Theoretical prediction is being improved by continuous efforts.
 - **Need more precise/independent measurement.**
- Muon EDM is also important.
 - If non-zero EDM exists, it indicates CP violation in the lepton sector assuming CPT invariance.
 - Current exp. limit : $d < 1.8 \times 10^{-19} e \cdot \text{cm}$ (95% C. L.) by BNL E821.



$$a_\mu = \frac{g - 2}{2}$$

@Phys. Rev. D 97 114025 (2018)

New Approach for muon $g-2$ and EDM Measurements

Anomalous precession frequency

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

“Magic momentum” by Fermilab E989

- $\gamma = 29.3$ ($P = 3.09$ GeV/c)
- Improvement of the BNL method

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

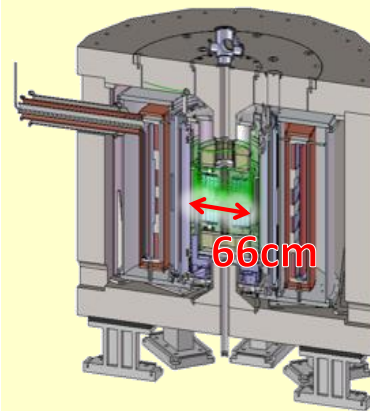


Started to take data.

“Zero E-field” by J-PARC E34

- $E = 0$ at any γ (off magic γ)
 - $P = 300$ MeV/c
- New methods with different systematics

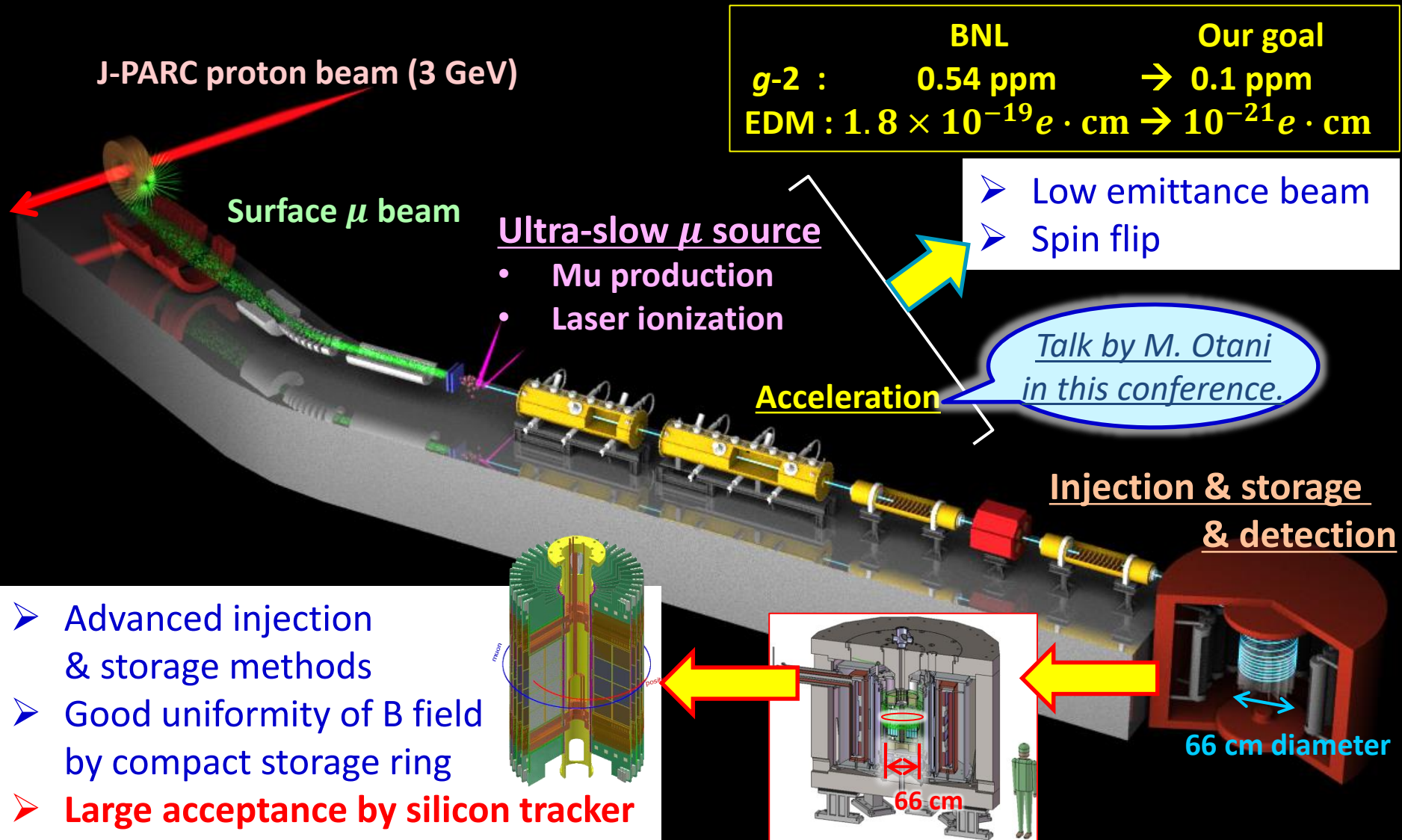
$$\vec{\omega} = -\frac{e}{m_\mu} \left[a_\mu \vec{B} + \frac{\eta}{2} (\vec{\beta} \times \vec{B}) \right]$$



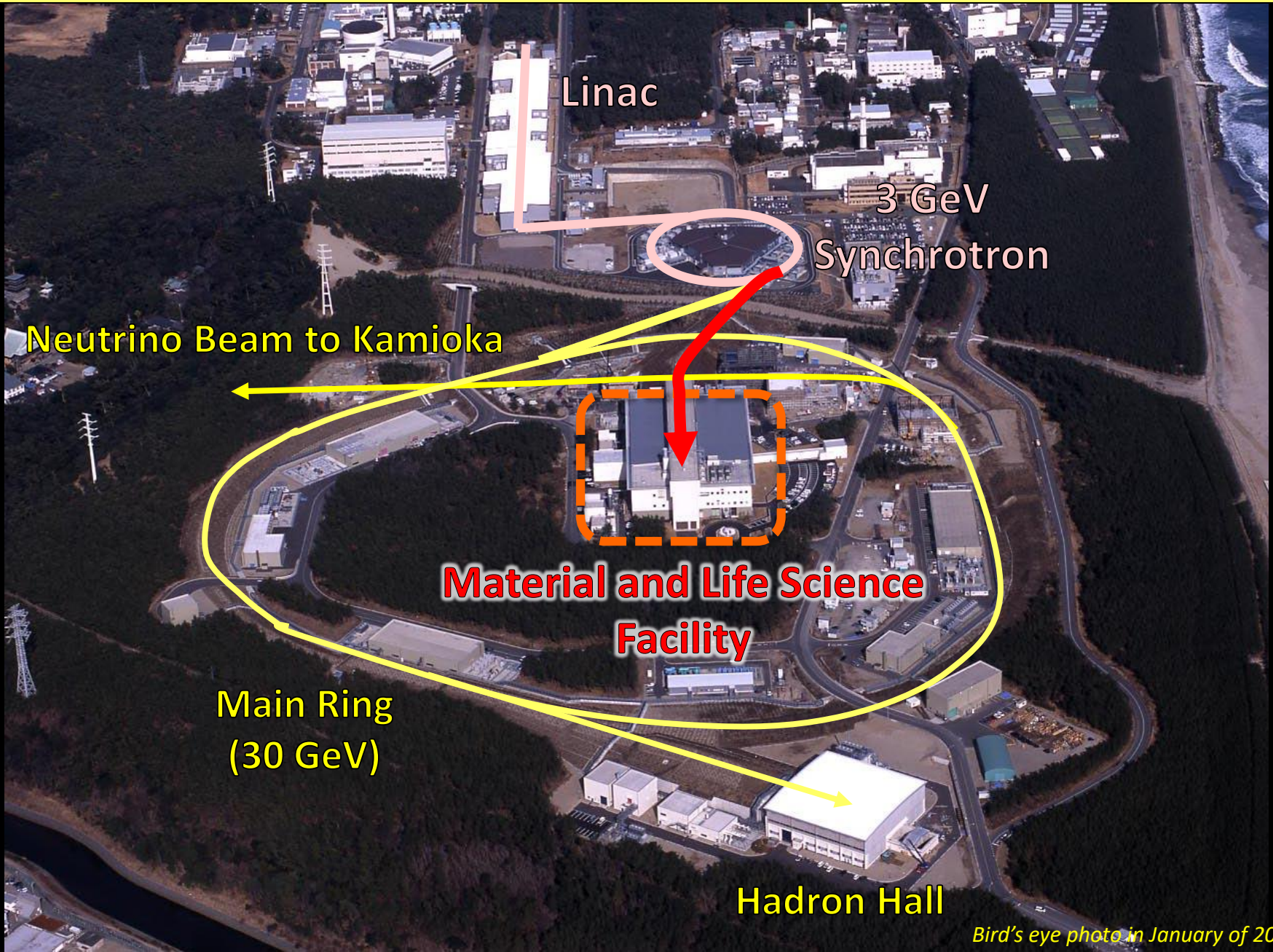
- Approved as **one of priority projects** in the future by KEK.
- Received **very positive replies** from TDR review committee and **waiting for full approval from the lab.**

J-PARC E34 Experiment

- New muon $g-2$ /EDM experiment at J-PARC with an entirely new method :
 - off-magic momentum with ultra-cold muon beam.



J-PARC Facility (KEK/JAEA)



Positron Tracking Detector

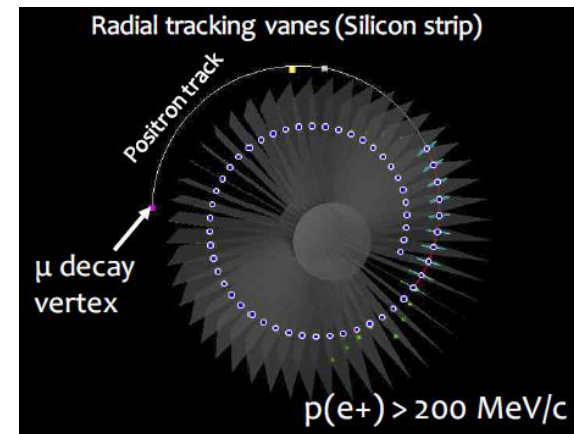
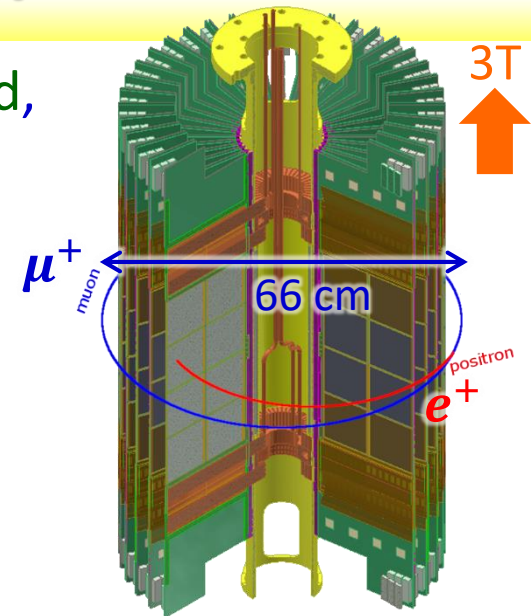
- Compact storage ring gives good uniformity of B-field, but lead to dense positron track from muon decay.

Requirements to Positron Tracking Detector

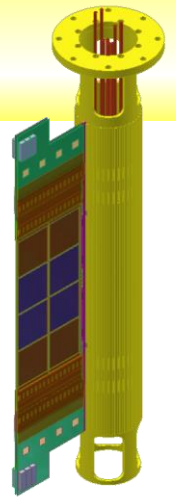
- High position resolution and tracking efficiency
 - 100-300 MeV positrons
- High hit rate capability and early-to-late stability
 - Event rate 1.4 MHz – 10 kHz/strip
- Operational in 3T magnetic field and no contamination of EM field to the muon storage region.
 - $\Delta B/B < 1$ ppm and E-field $\ll 10$ mV/cm
- Readout synchronized with J-PARC pulsed muon beam.
 - Repetition rate : 25 Hz

→ We use silicon strip detectors with a vane structure.

- 40 vanes : 640 silicon strip sensors and 5120 ASICs.

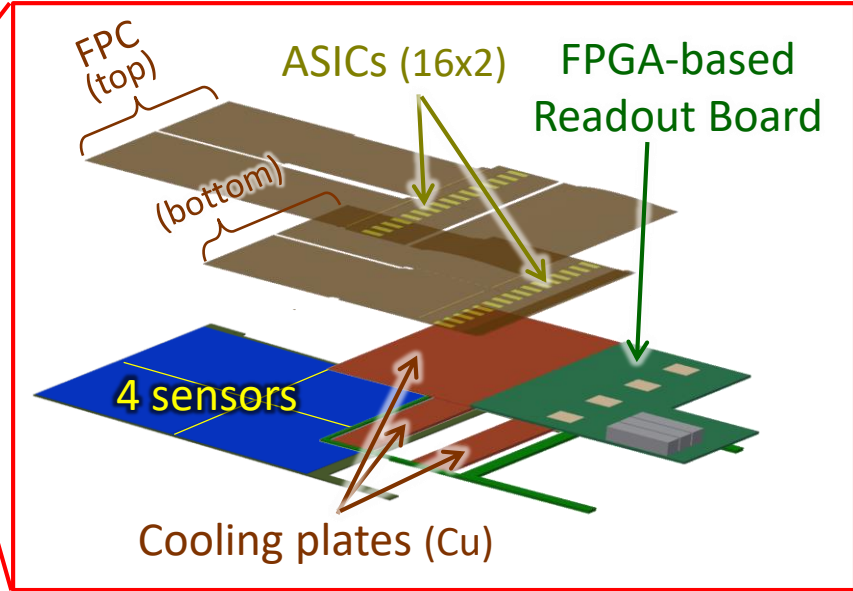
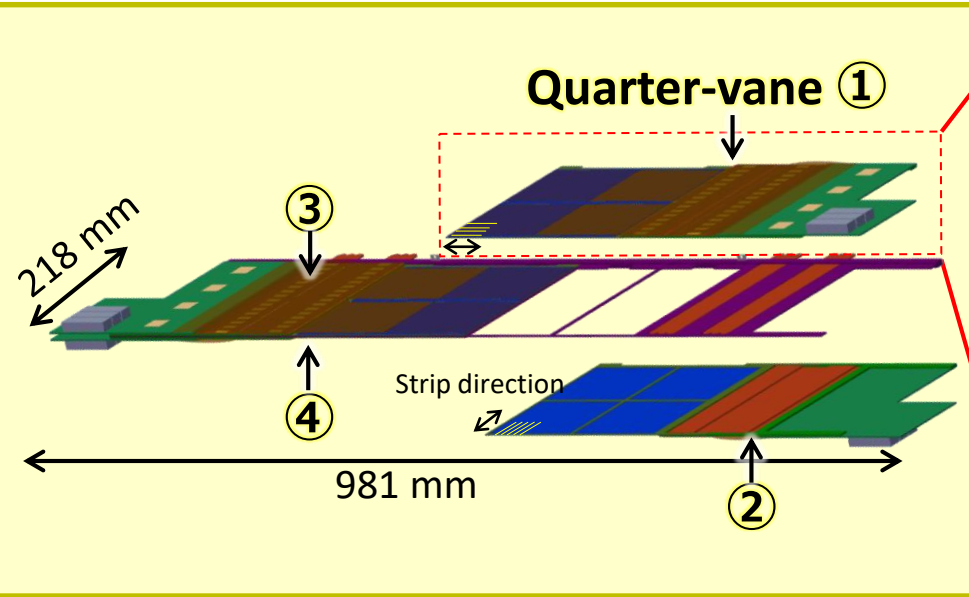


Vane Structure



- The vane consists of **4 quarter-vanes** and each quarter-vane has **4 silicon strip sensors** and **32 ASICs**.
- Two-dimensional position can be measured by two layers of the sensors with different orientations of strips.

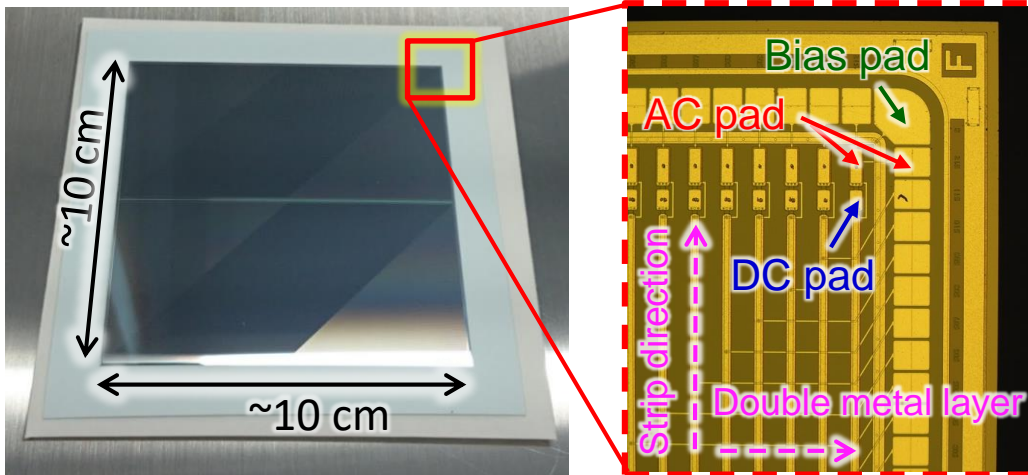
Structure of quarter-vane



→ Funded to construct a part of detector system.

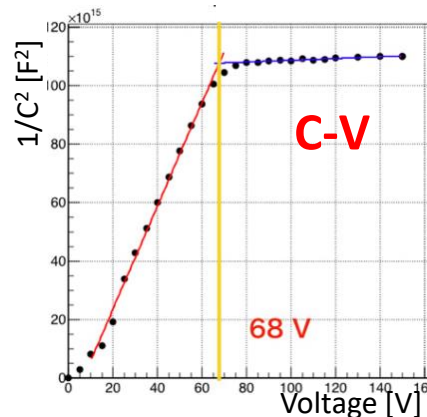
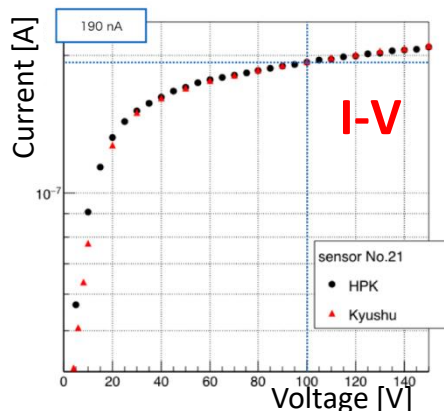
Silicon Strip Sensor

- Single sided silicon strip sensor with double metal structure produced by Hamamatsu Photonics.
 - We have already produced ~ 190 sensors.

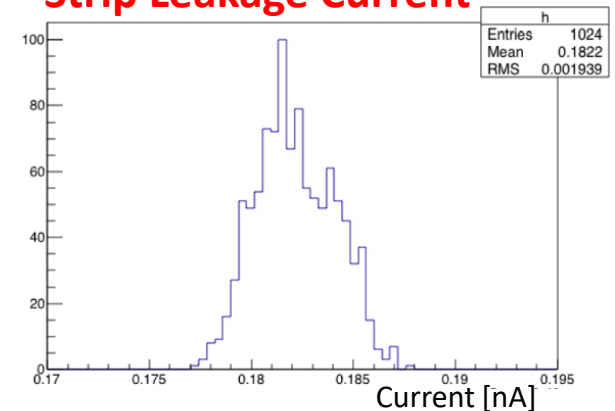


Specification	
Sensor type	p on n
Size	98.77 mm \times 98.77 mm
Active area	97.28 mm \times 97.28 mm
Strip pitch	0.19 mm
Strip length	48.575 mm
# of strips	512 \times 2 blocks
thickness	0.32 mm
Detector capacitance	17 pF

- Quality assurance (QA) system is being developed.
 - I-V & C-V characterization, strip leakage current, strip resistance, coupling capacitance, interstrip capacitance



Strip Leakage Current



Front-end ASIC “SliT”

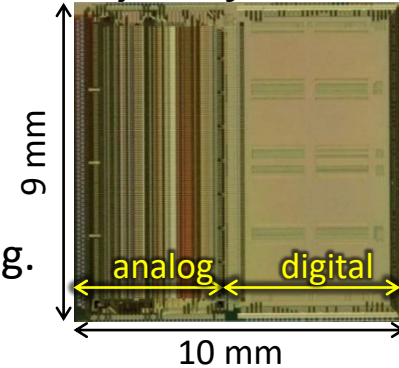
Requirements

- Dynamic range > 4 MIP
- Noise < 1600 e⁻ @C_{det} = 30 pF
- Time walk < 5 ns
- Peaking time < 50 ns
- Power consumption < 5 mW/ch

Specification

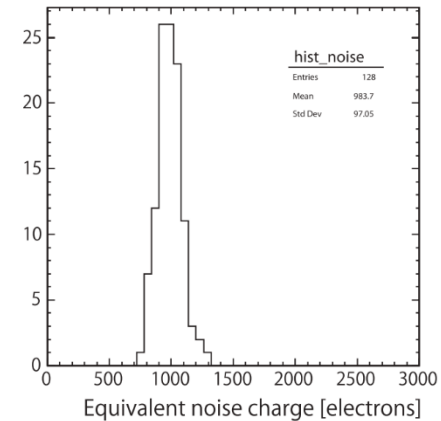
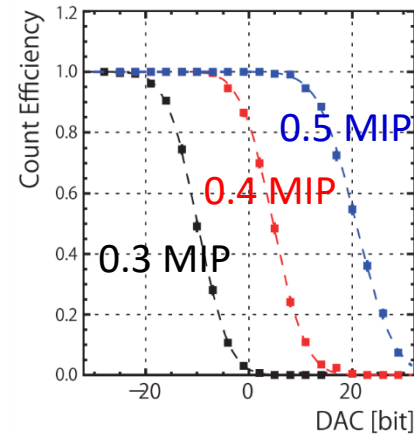
- Silterra 0.18 μm CMOS process
- 128 ch/ASIC
- Binary output with 5 ns time sampling.
- 40.96 μs buffer memory
 - Stored data is readout before the next beam comes.

Layout of SliT128A



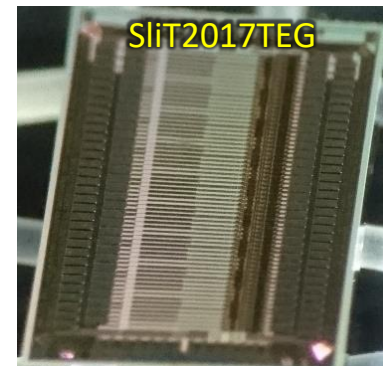
Full-scale prototype “SliT128A”

- Verified all function and has a performance close to the requirement.
- Used for test module (→ next page)



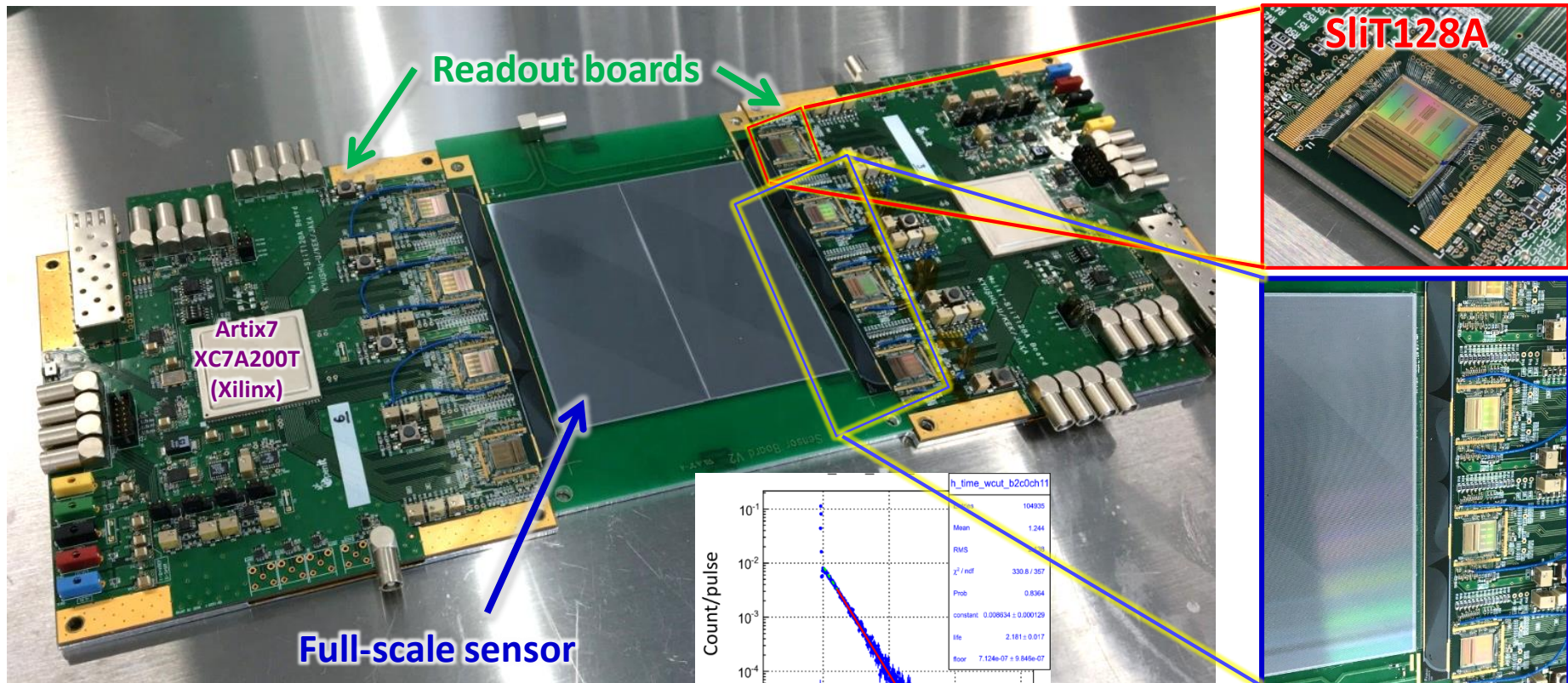
→ **Final version of ASIC “SliT128B” will be fabricated within this JFY.**

- Toward the fabrication of SliT128B, we are testing **final prototype of TEG chip now.**



Test module

- The silicon strip sensor is connected with 8 full-scale prototype ASICs “SlIT128A” on two readout boards through a pitch adapter by wire-bonding.
- Test module is used in **real experiment for precise measurement of muonium hyperfine structure (MuSEUM)** at J-PARC with muon beam.



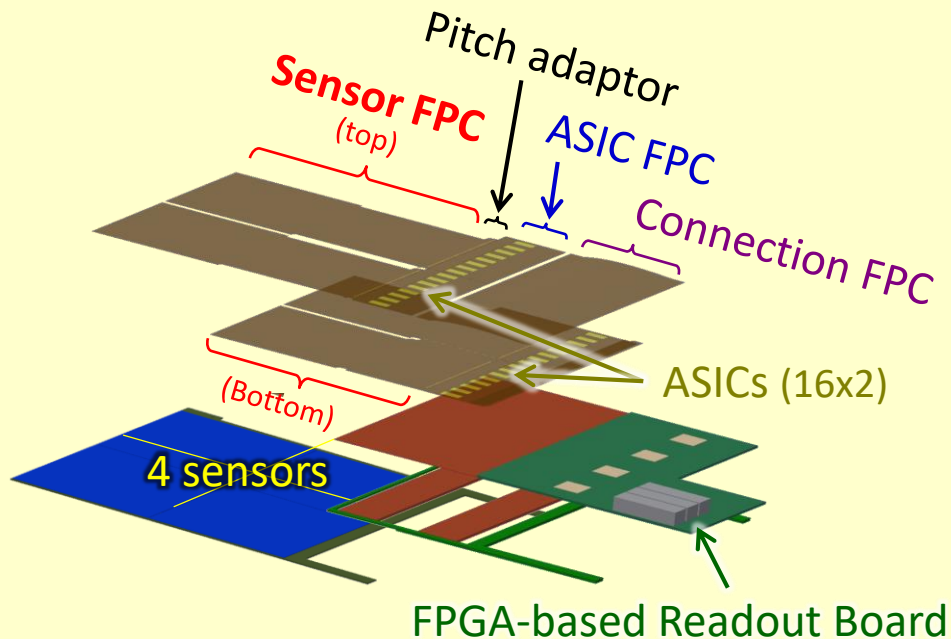
Measured muon decay spectrum

Pitch adapter by Fujikura Ltd.
(min L/S=20/22.5)

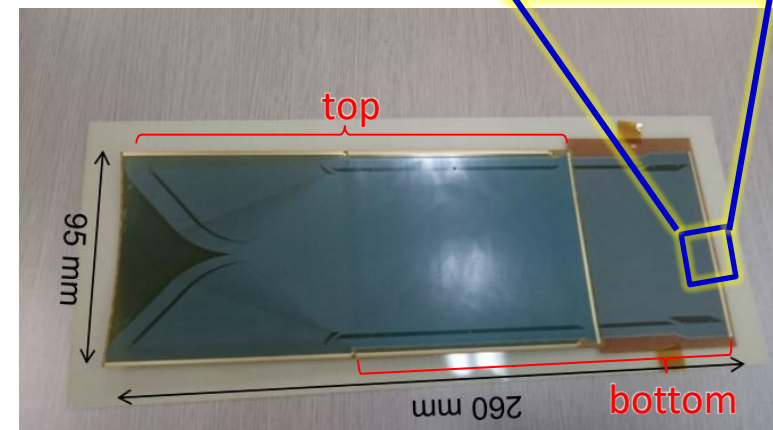
Flexible Printed Circuit (FPC)

- Signals from sensors are transmitted to ASIC followed by FPGA-based readout board through FPCs.
- Prototype sensor FPC is fabricated by Fujikura Ltd..
 - Minimum L/S $\sim 35/35 \mu\text{m}$
- Mass production of the sensor FPC will be done within this JFY.

Structure of quarter-vane



Prototype Sensor FPC



- Other FPCs is being designed.

Track Reconstruction Tool

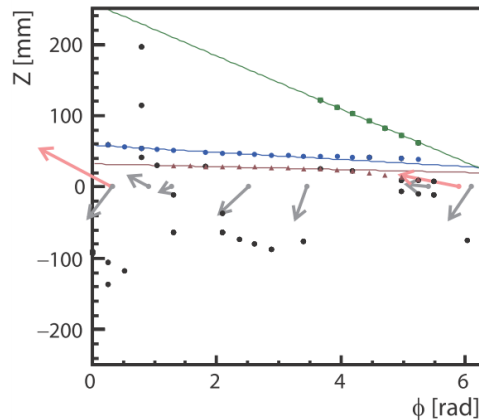
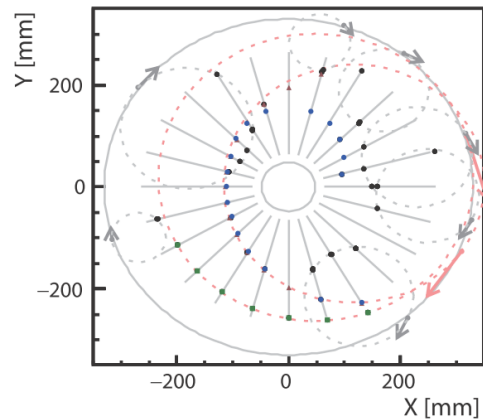
- Track reconstruction algorithm is being developed.
 - With the developed track finding algorithm based on Hough transformation, more than 90% efficiency is expected even in the highest pileup condition.

Event display

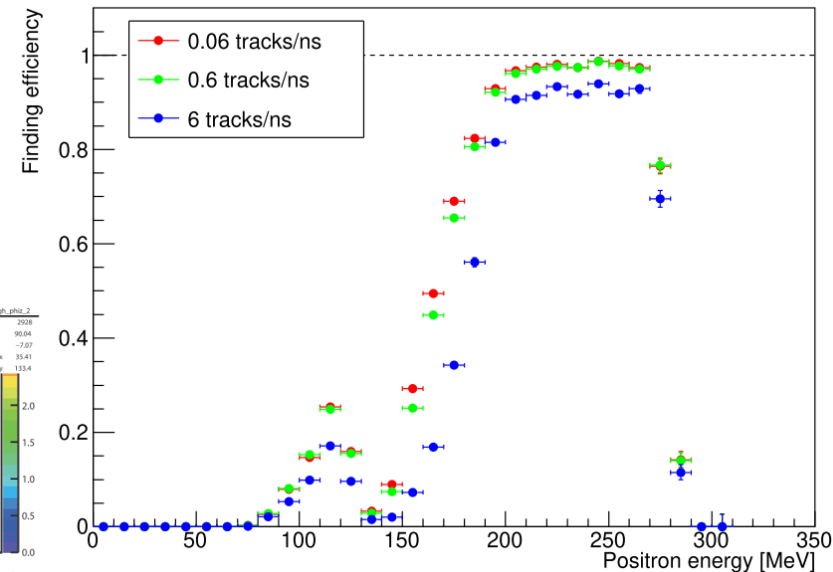
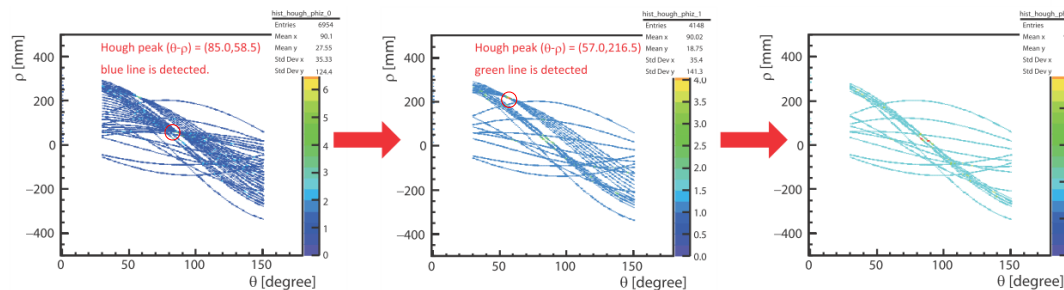
(0.6 tracks/ns, time window= 10 ns)

event display (x-y plane)

event display (ϕ -z plane)

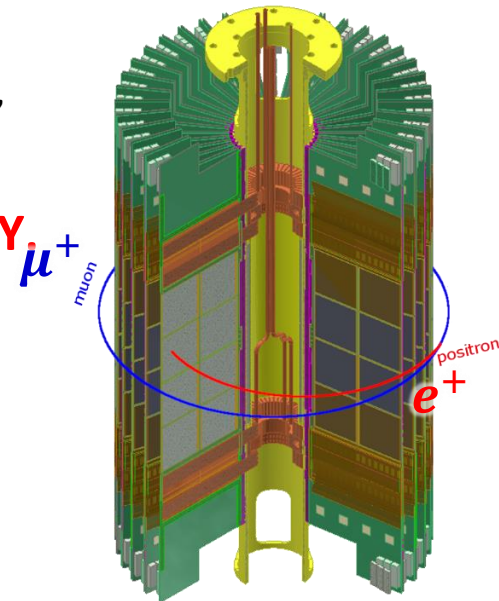


Track finding efficiency



Summary and prospect

- **J-PARC E34 experiment** measures muon $g-2$ and EDM with completely different approach : **“off-magic momentum with ultra-cold muon beam”**.
 - Approved as one of priority projects in the future by KEK.
 - Received very positive replies from TDR review committee (FRC) and waiting for full approval from the lab.
- **Silicon strip detector** is used to detect positrons from muon decay.
 - **Funded to construct a part of detector system.**
 - Toward the assembly of the real vane, the development of each component are going well.
 - Silicon strip sensor, front-end ASIC, FPC, mechanical design, test module, cooling system, DAQ system, software, ...
- **Assembly of first real quarter-vane will be started at next JFY.**



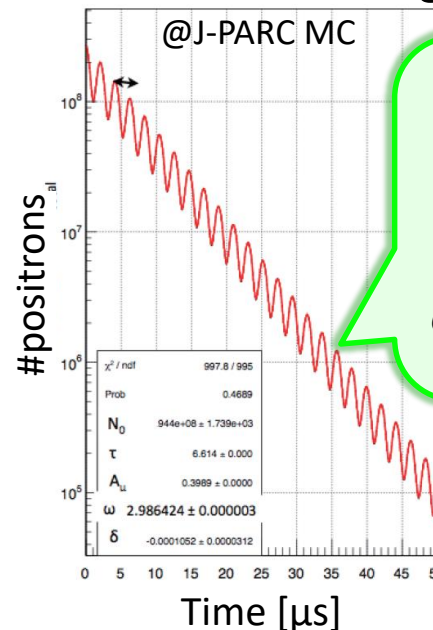
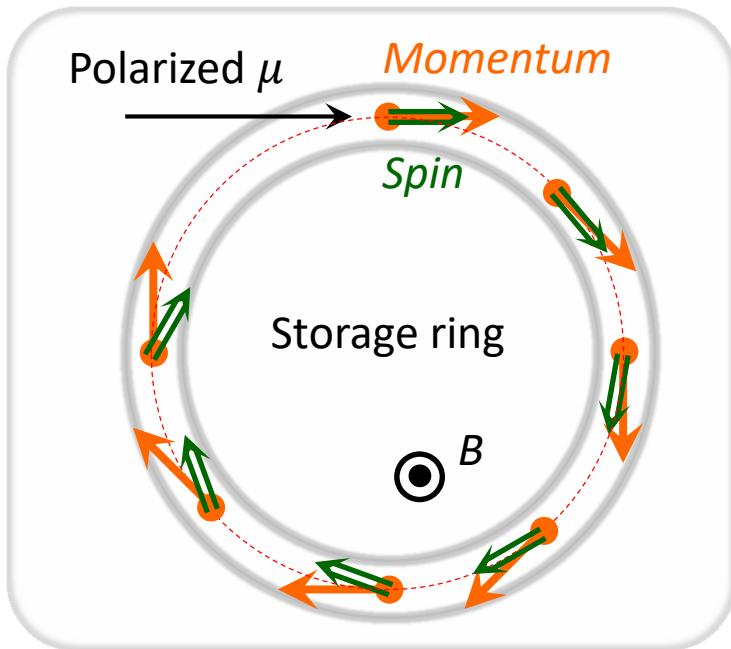
Backup

Principle of muon g-2 Measurement

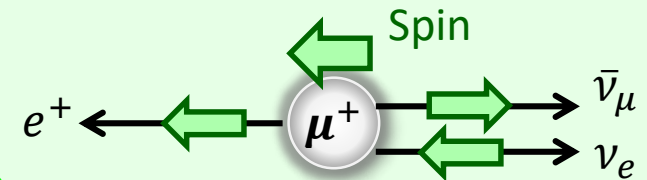
- Inject **polarized muons** to the storage ring.
 - $\pi^+ \rightarrow \mu^+ \nu_\mu$ decay
- Muon spin precession relative to momentum in cyclotron** is proportional to g-2 under “special” condition.

$$\vec{\omega} = \vec{\omega}_{\text{spin}} - \vec{\omega}_{\text{cyclotron}} = \left(\frac{g-2}{2} \right) \frac{e\vec{B}}{m_\mu c} = \mathbf{a}_\mu \frac{e\vec{B}}{m_\mu c}$$

3. Detect high energy e^+ from μ^+ decay



e^+ direction is correlated to muon spin direction.



- Precise measurement of $g - 2$ needs **precise determinations of ω and B** .
- Muon-to-proton magnetic moment ratio is also used instead of e/m_μ .

J-PARC muon facility

- MUSE (MUon Science Establishment) in the MLF

S-line

- surface μ^+
- dedicated to μ SR
- S1 area is available
- S2/S3/S4 will be constructed

3GeV proton from RCS

$2e15 /s @1MW$



H-line

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

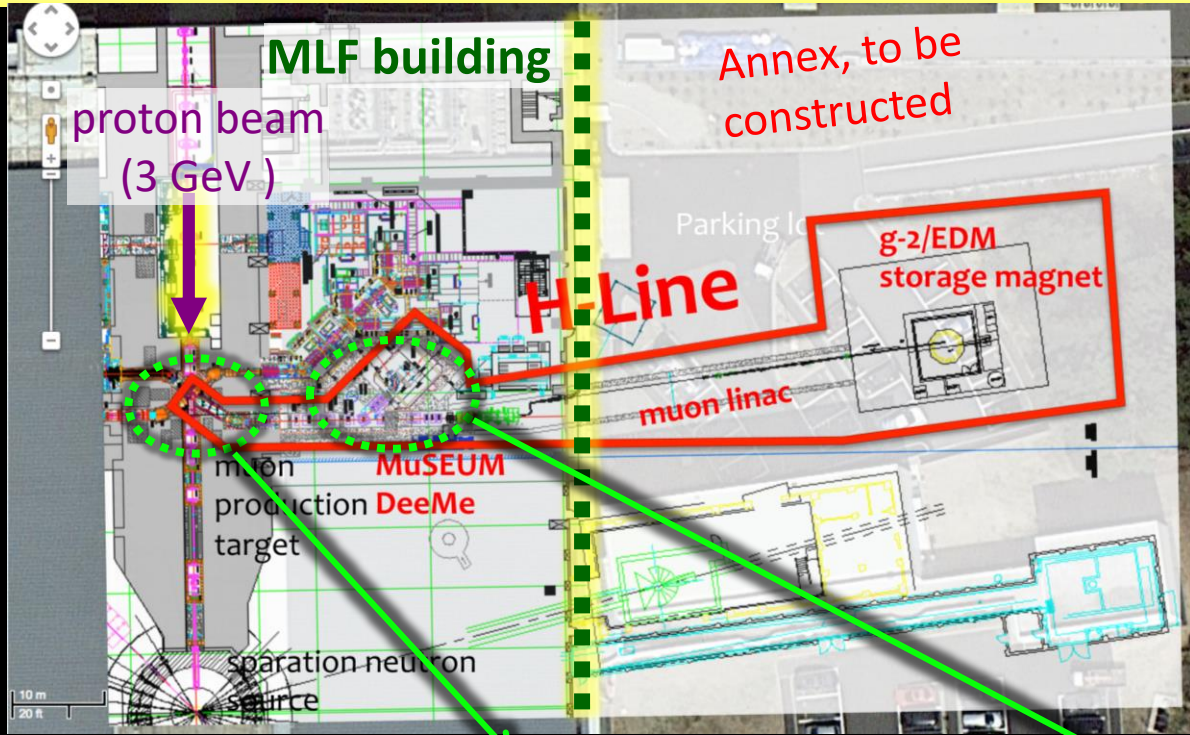
U-line

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

D-line

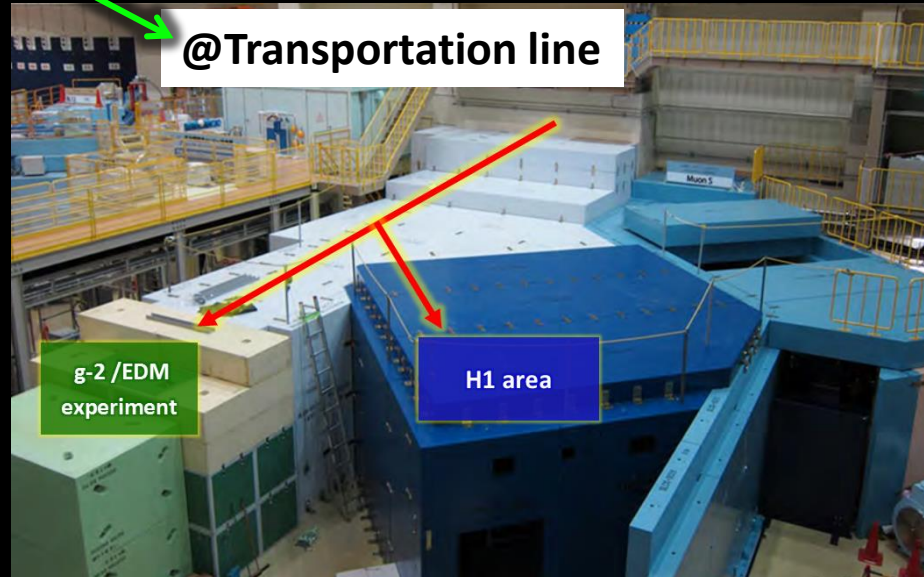
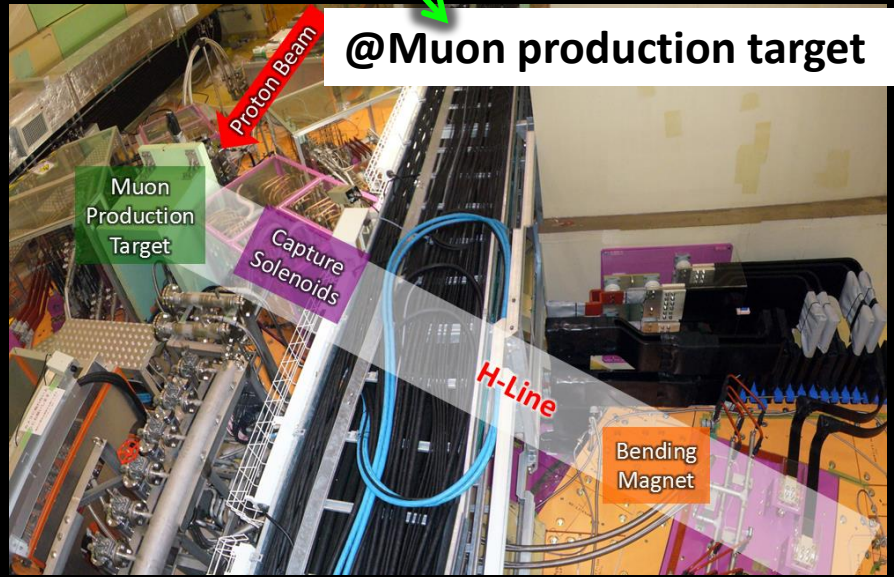
- decay μ^+/μ^- , surface μ^+
- D1 area for μ SR
- D2 for variety of science

New Muon Beam Line ~H-Line~



Three muon experiments

- g-2/EDM
- MuSEUM (Mu-HFS)
- DeeMe (muon cLFV)

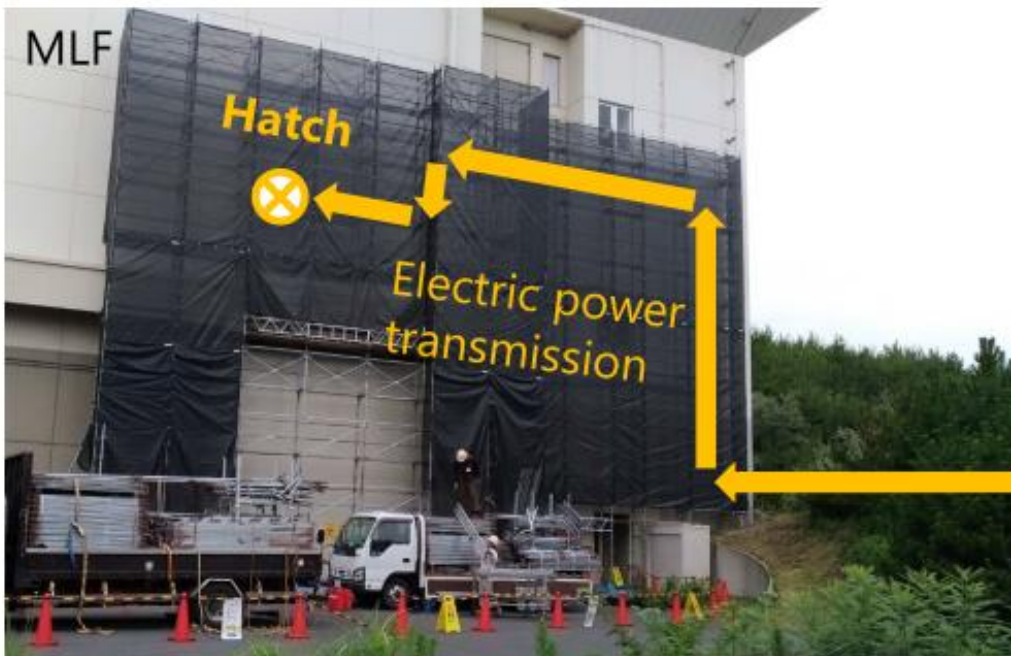


Construction status of H-line

On-going

- Construction of a new electric power sub-station for H-line has started!
 - H-line needs about **5 MW** electricity, but the surplus power of existing electric sub-stations in the MLF is only 1 MW.

Renovation of the MLF wall for electric power transmission line



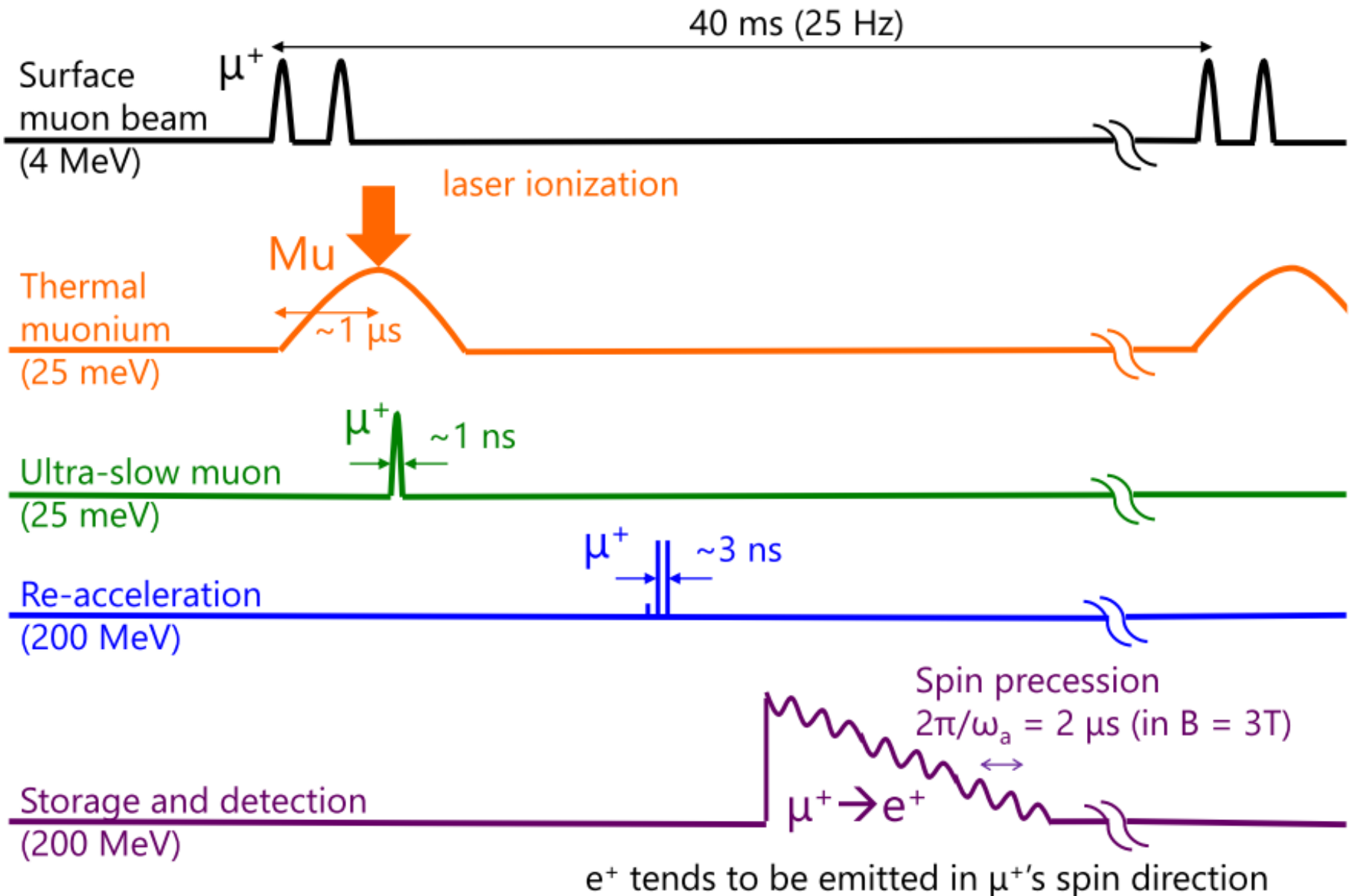
Construction of the bedding of the electric sub-station



The collaboration



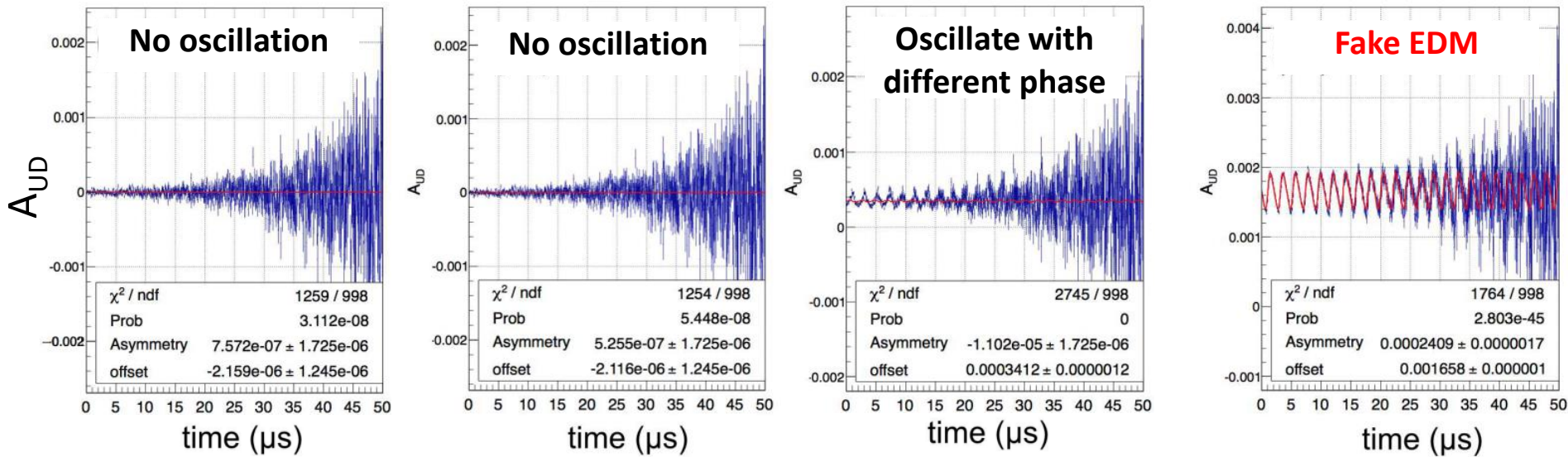
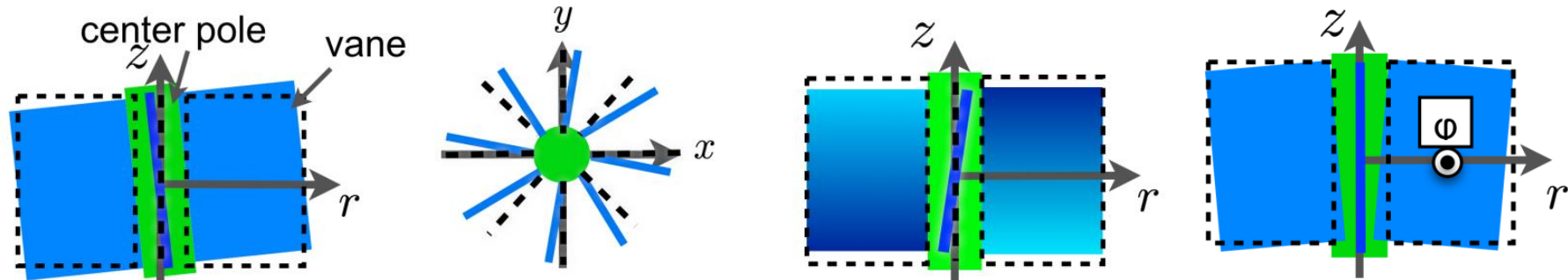
Experimental sequence



Fake EDM Signal by Misalignment

- EDM is measured from up-down asymmetry “ A_{UD} ”.

Simulation with 1 mrad misalignment and null EDM signal

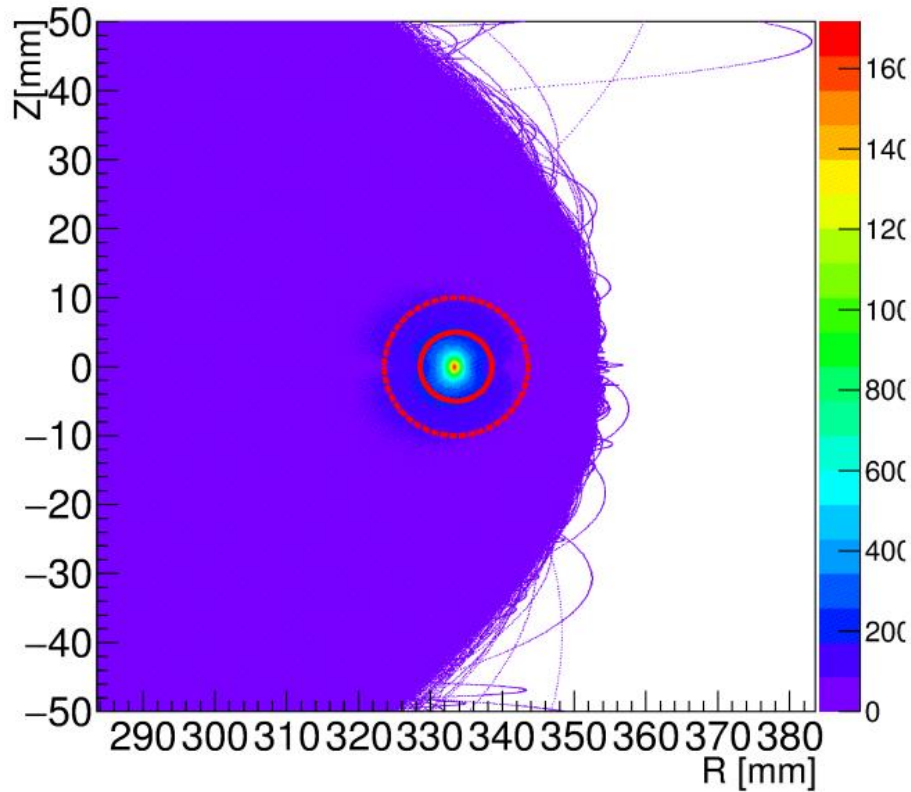


- The alignment must be controlled with $10 \mu\text{rad}$ accuracy to measure EDM with $10^{-21} e \cdot \text{cm}$.

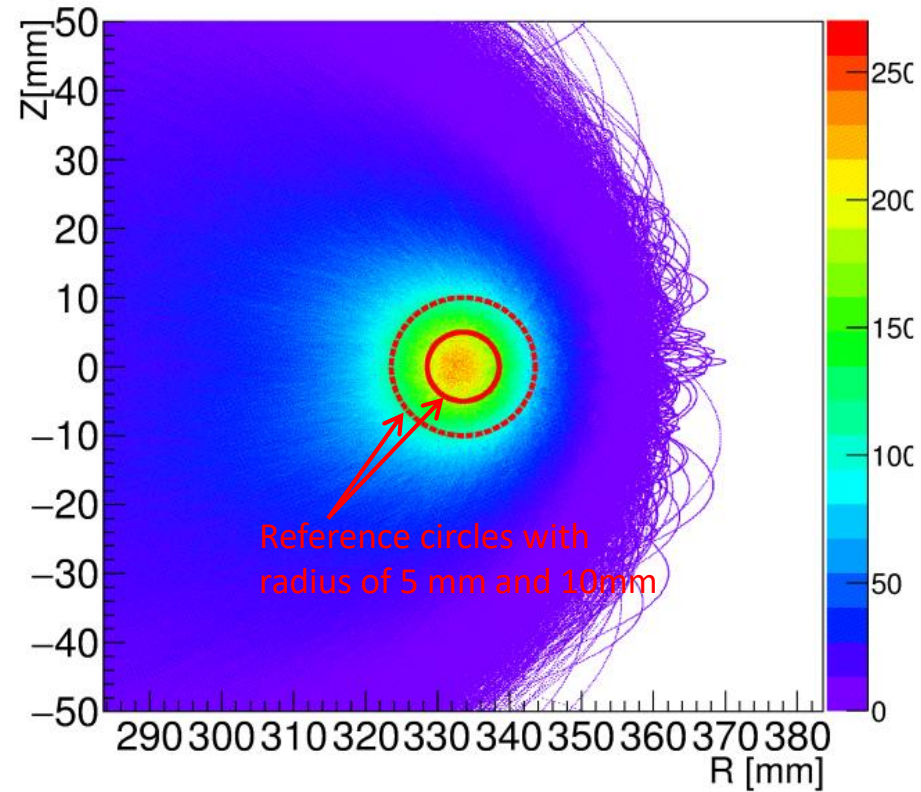
Track-back

- Superimposed event displays of 105 positron tracks

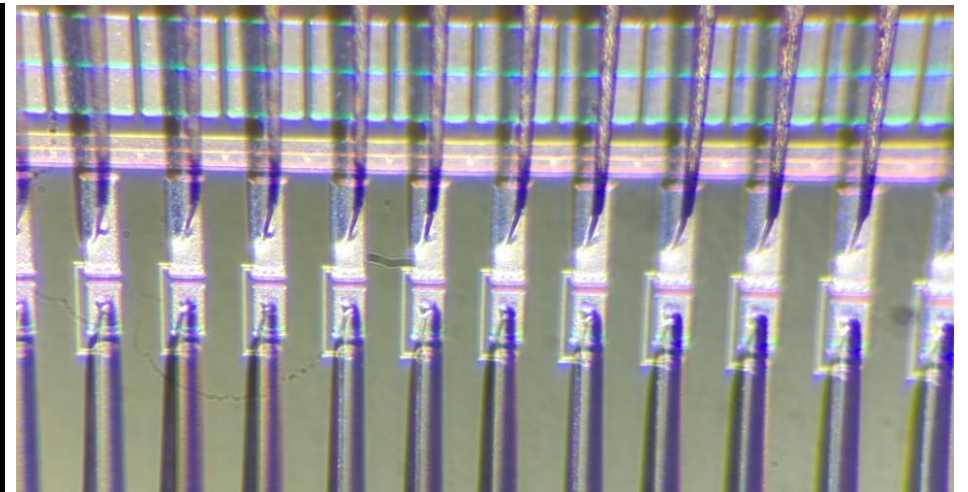
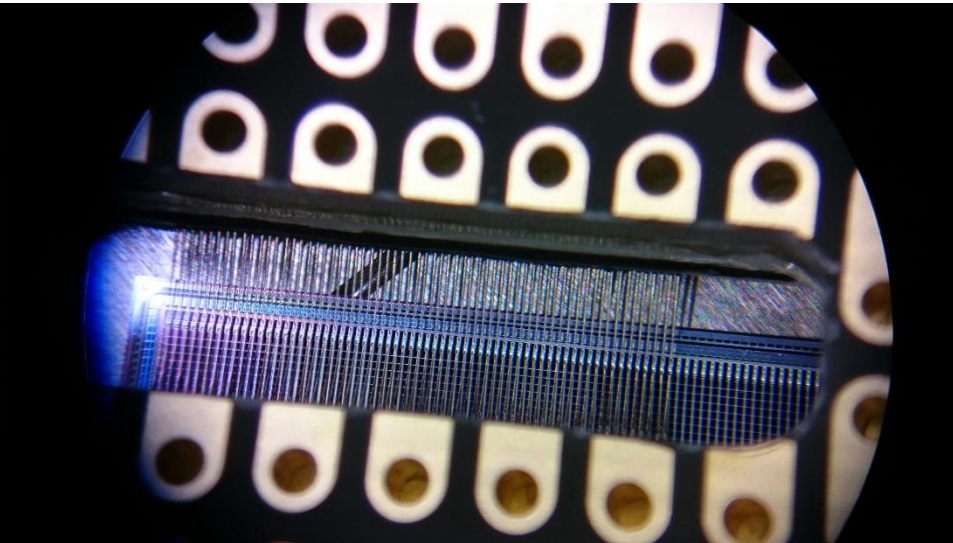
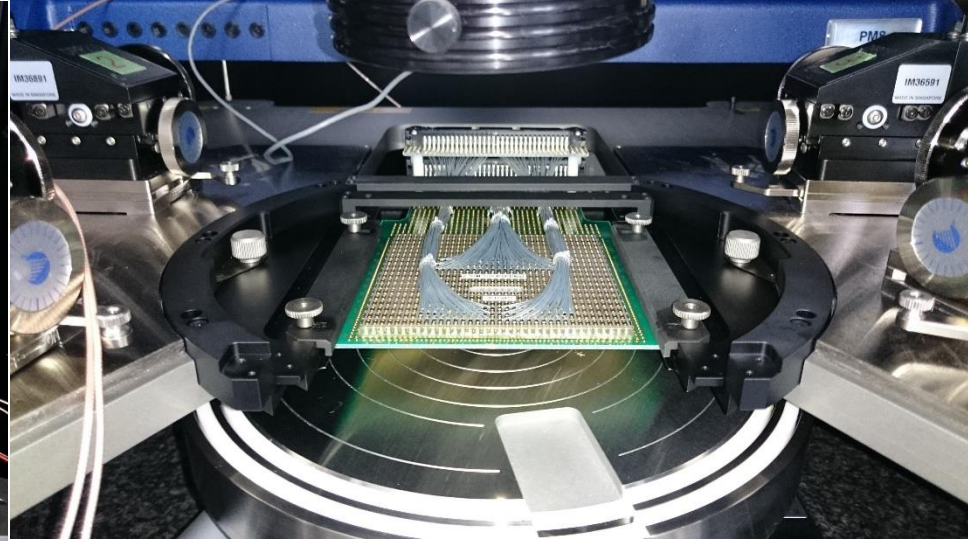
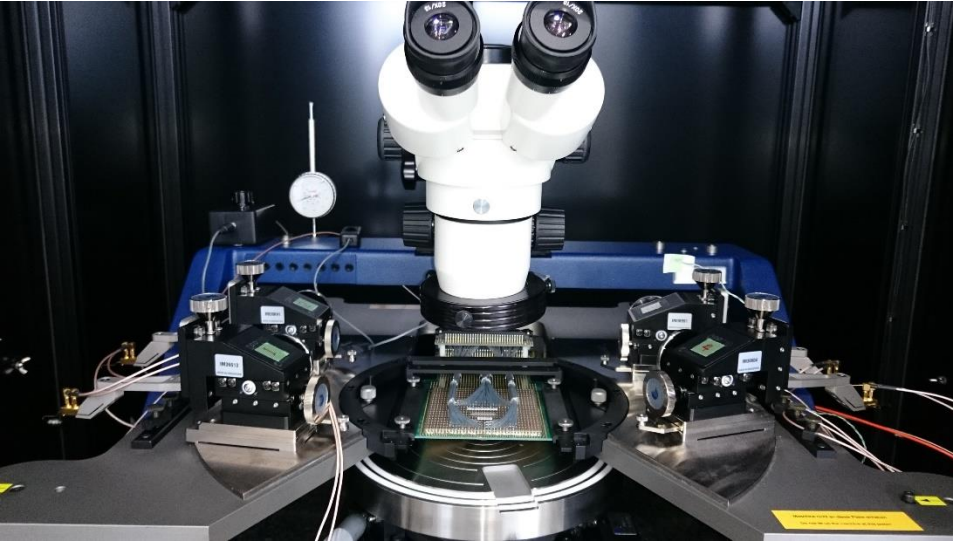
Pencil muon beam



Gaussian beam with $\sigma = 5$ mm



Sensor QA system



g-2 test module 1 in MuSEUM Experiment

