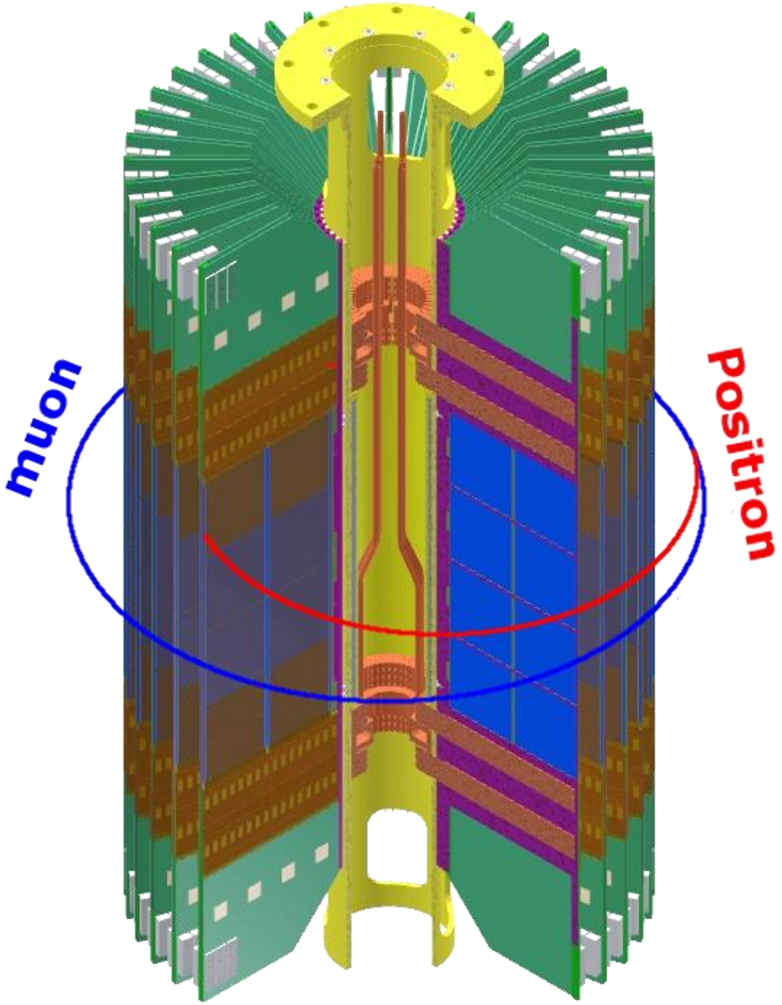


# Silicon strip detector for muon g-2/EDM experiment at J-PARC

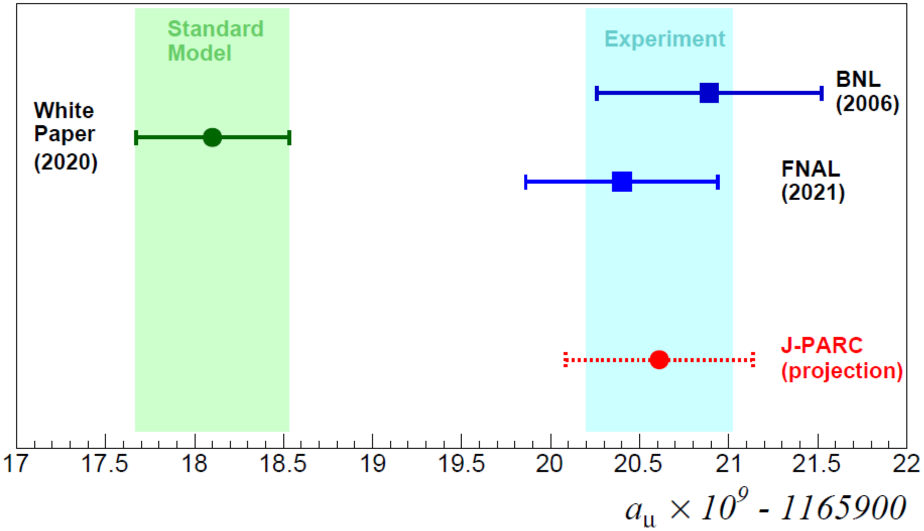
S.Ogawa (Kyushu Univ.)
on behalf of the J-PARC
muon g-2/EDM collaboration

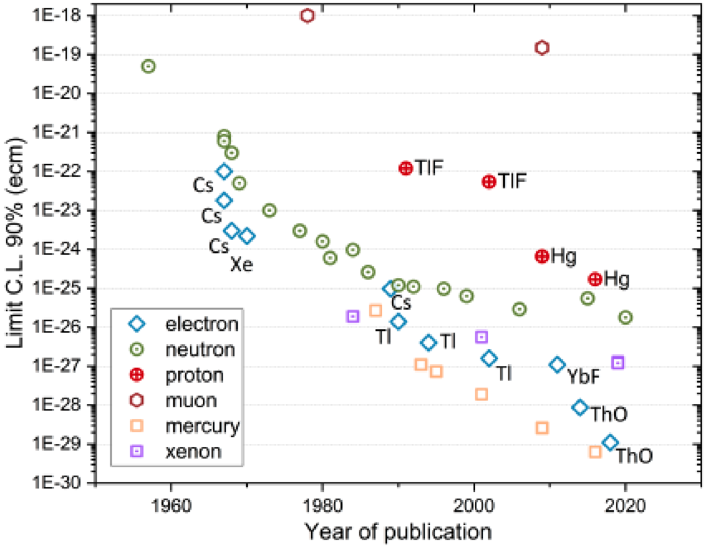
@Vertex 2022

# Muon g-2 / EDM

- Muon anomalous magnetic moment (g-2)
  - 4.2 σ tension b/w measurement & prediction
  - Measurement: 116592061(41) × $10^{-11}$ (350 ppb)
  - SM prediction: 116591810(43) × $10^{-11}$ (370 ppb)
  - This can be a contribution from new physics.
    Another measurement by an independent strategy is desired.

- Muon EDM
  - Upper limit given by BNL: $1.8 \times 10^{-19}\ \mathrm{e \cdot cm}$ (95% C.L.)
  - Indicates CP violation in lepton sector.





# Muon g-2/EDM measurement

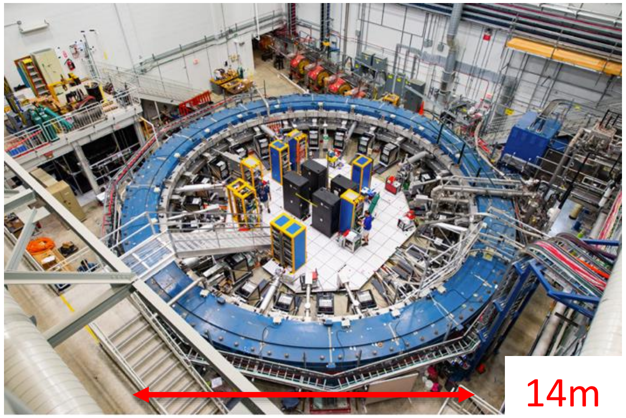
- Muon g-2/EDM can be measured from spin precession of muon in a uniform B-field.
    - time dependent spin information reconstructed from decay positron energy/momentum.

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

<u>BNL/ FNAL experiment</u>

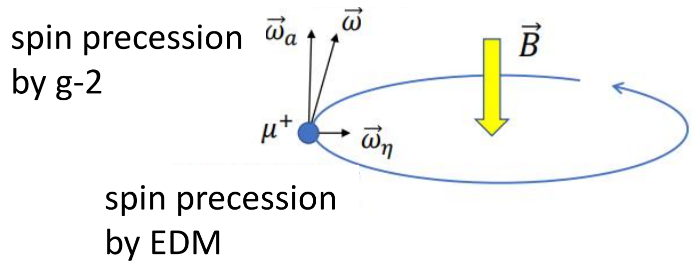
$$\vec{\omega}_a + \vec{\omega}_\eta = -\frac{\mathrm{e}}{m_\mu}\left[a_\mu \vec{B} - \underbrace{\left(a_\mu - \frac{1}{\gamma^2 - 1}\right)}_{= 0}\frac{\vec{\beta}\times\vec{E}}{c} + \frac{\eta}{2}\left(\vec{\beta}\times\vec{B} + \frac{\vec{E}}{c}\right)\right]$$

- **Measurement at magic gamma momentum.**
    - to cancel out 2nd term.
    - **p = 3.1 GeV/c, ϕ: 14 m at B = 1.45 T**
- Strong electric field focusing.



# Muon g-2/EDM measurement

J-PARC experiment



- **Measurement at $\vec{E}$ = 0.**
  - Beam storage by weak focusing B-field
  - Utilize low emittance muon beam.

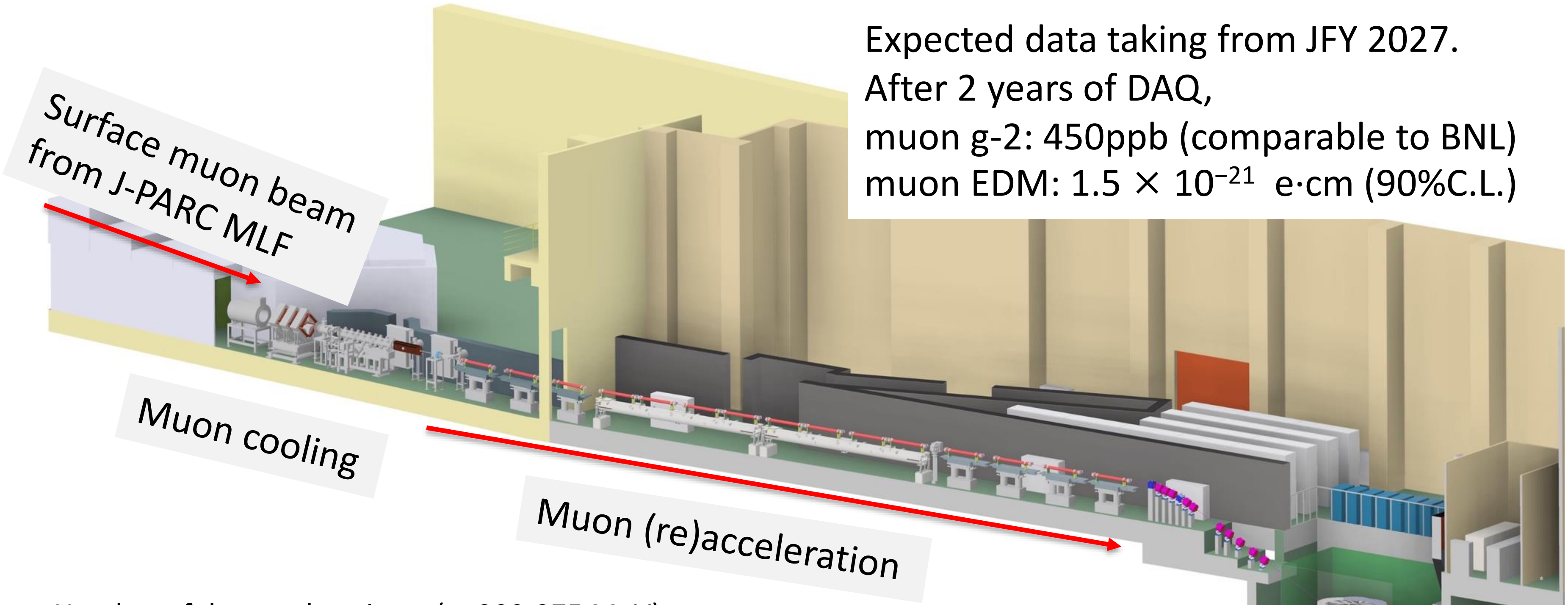
$$\vec{\omega}_a + \vec{\omega}_\eta = -\frac{e}{m_\mu}\left[\underbrace{a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2-1}\right)\overset{=0}{\frac{\vec{\beta}\times\vec{E}}{c}}}_{\text{g-2}} + \underbrace{\frac{\eta}{2}\left(\vec{\beta}\times\vec{B} + \overset{=0}{\frac{\vec{E}}{c}}\right)}_{\text{EDM}}\right]$$

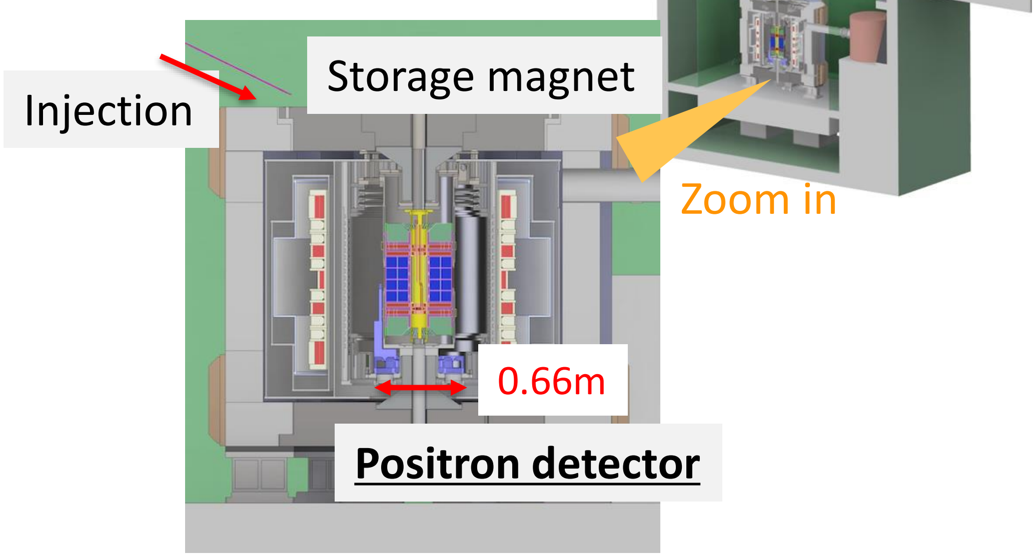
- Measurement at lower muon momentum becomes possible.
  → More compact storage region with better uniformity of B-field.
  - **p = 0.3 GeV/c, ϕ: 0.66m at B = 3 T**

- Independent measurement of muon g-2
  to validate BNL/FNAL result at different systematic uncertainty.
- Clear separation of g-2 and EDM signal.

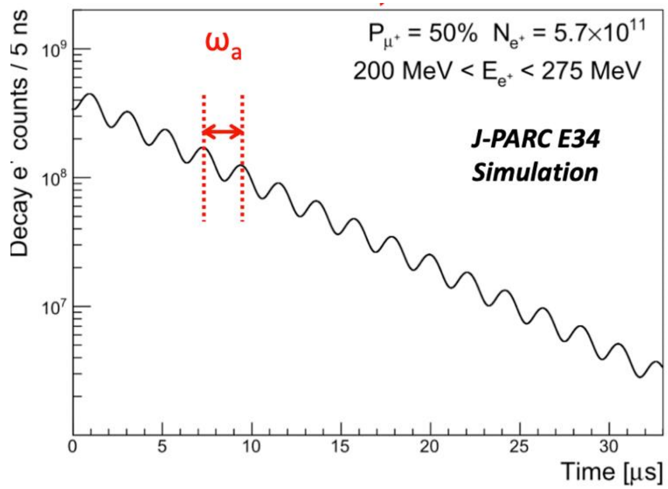
# Muon g-2/EDM experiment at J-PARC

Expected data taking from JFY 2027.
After 2 years of DAQ,
muon g-2: 450ppb (comparable to BNL)
muon EDM: $1.5 \times 10^{-21}$ e·cm (90%C.L.)

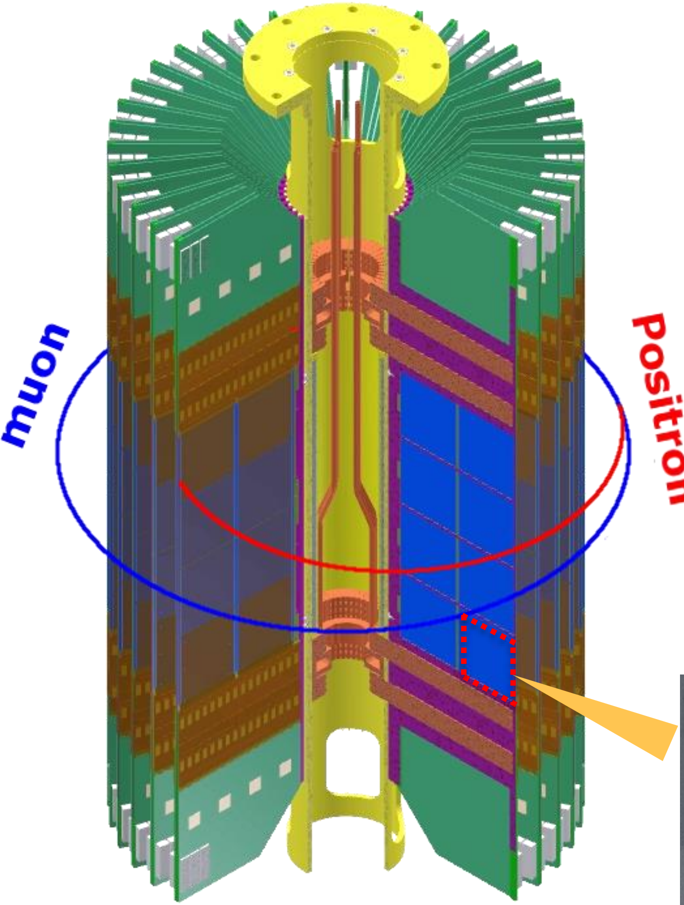




Number of detected positron (p: 200-275 MeV)

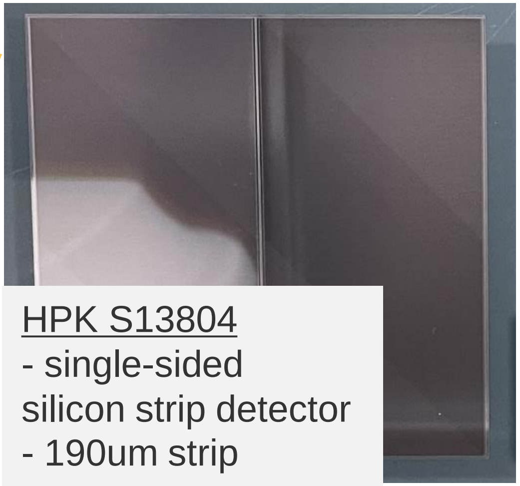


# Silicon strip positron detector



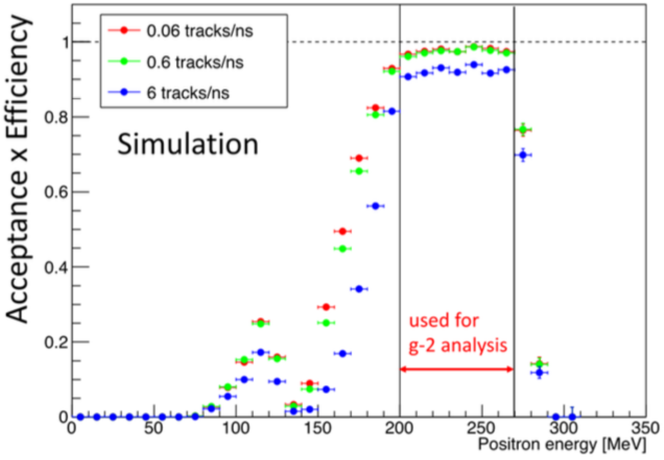
Silicon strip positron detector
for J-PARC muon g-2/EDM experiment

- Compact positron tracking detector
  by silicon strip sensors (640 100x100 mm$^2$ sensors).
- High hit rate capability (6 tracks/ns)
  and stability over rate changes (1.4 MHz→10 kHz)
- High efficiency for positrons
  in the analysis window (p=200-275 MeV/c).
- Operation in vacuum, 3T B-field.
- No EM-field contamination for muon orbit.



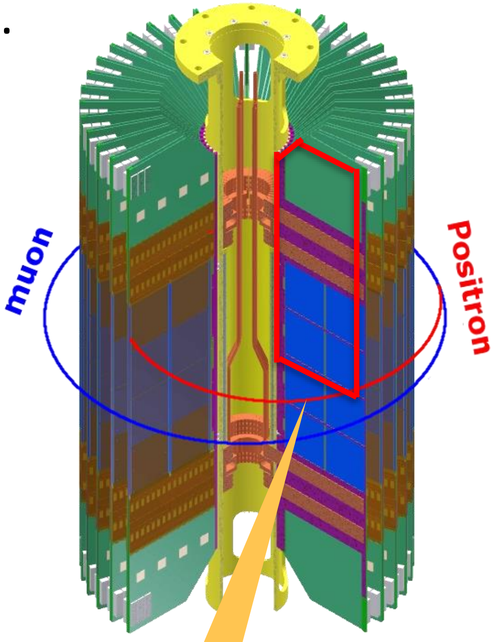
HPK S13804
- single-sided
silicon strip detector
- 190um strip

**Reconstruction efficiency**

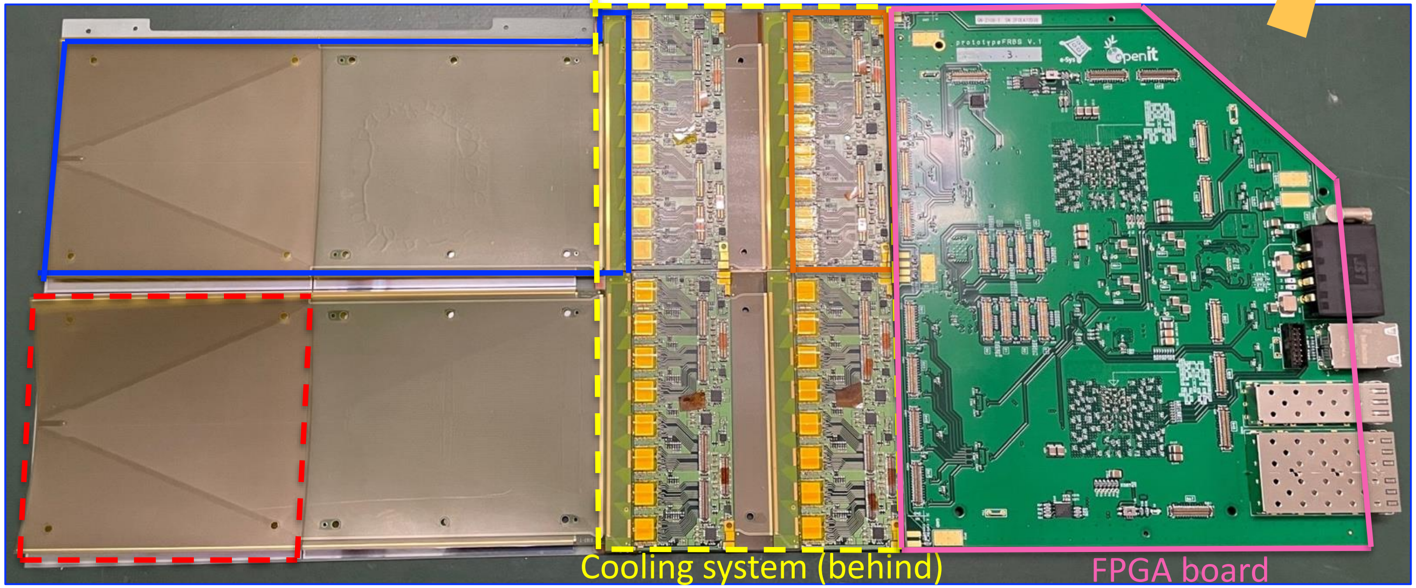


# Silicon strip positron detector

- Detector consists of 160 submodules called quarter-vane.
- Each quarter-vane consists of
  - Silicon sensor
  - FPC for analog signal transmission
  - ASIC for signal amplification/digitization
  - FPGA board for data/clock communication
  - Cooling system for cooling in vacuum
  - GFRP frame for assembly

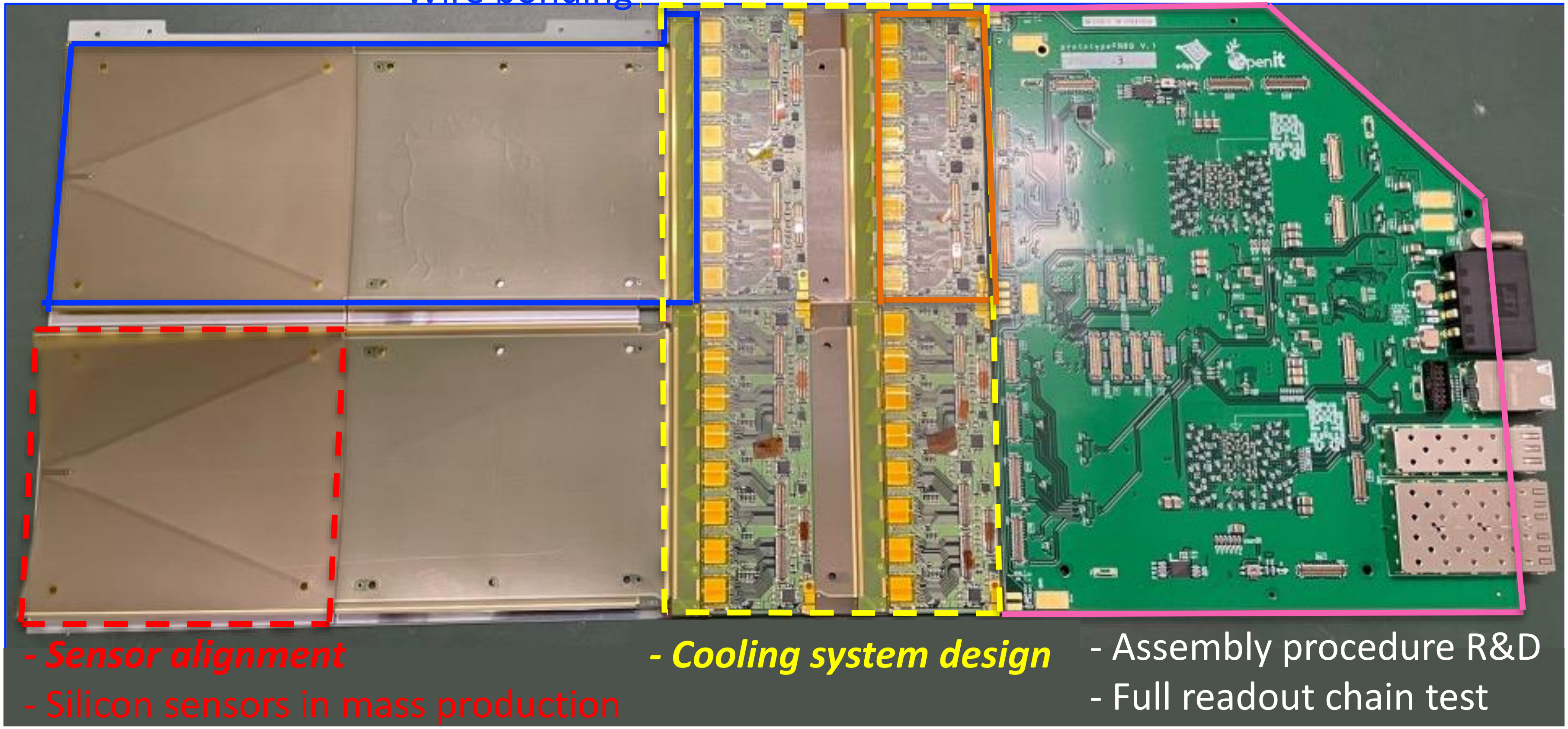


Quarter-vane: submodule of detector



# Silicon strip positron detector

- Prototyping of quarter-vane is ongoing towards real detector assembly. In my talk, three topics are picked up from many R&D activities.



*- QA of produced ASICs*

- ASIC board development

- FPGA board development

- DAQ backend development

- Wire bonding

*- Sensor alignment*

- Silicon sensors in mass production

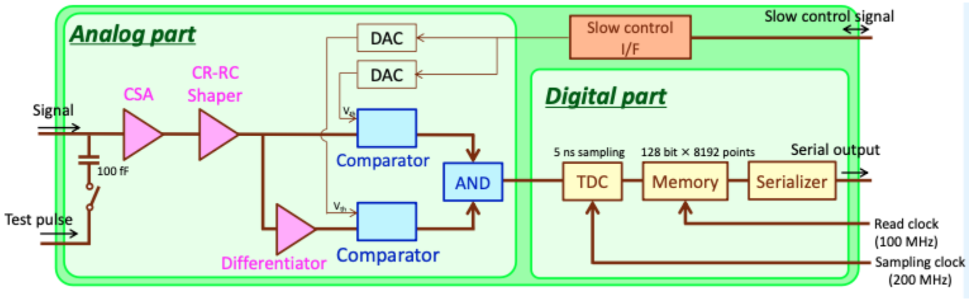
*- Cooling system design*

- Assembly procedure R&D

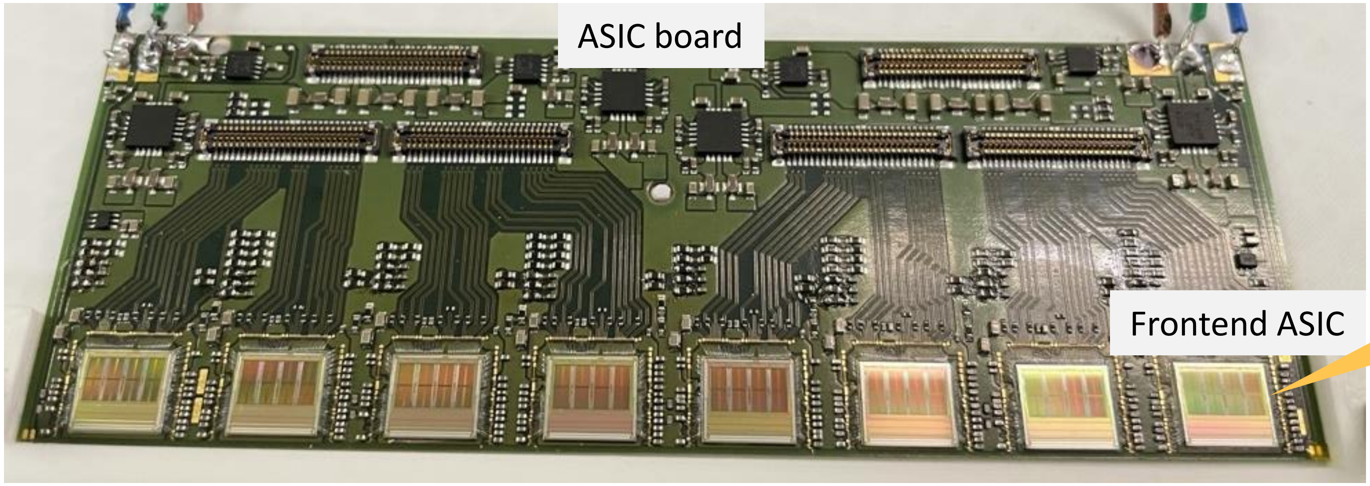
- Full readout chain test

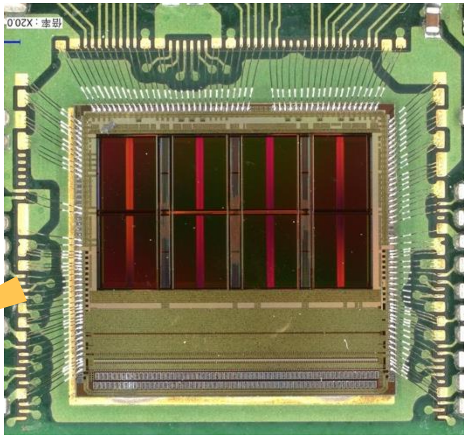
# Frontend ASIC

- Frontend ASIC ”Slit128D” has been developed
  for  amplification, digitization of silicon sensor signal.



- Slit128D
  - SilTerra 180 nm CMOS technology
  - Fast response to tolerate a high hit rate
  - Readout sequence dedicated for pulsed muon beam at J-PARC
    - 40us measurement period for each 25Hz pulsed beam
    - Binary readout with 5 ns time stamp and large memory buffer

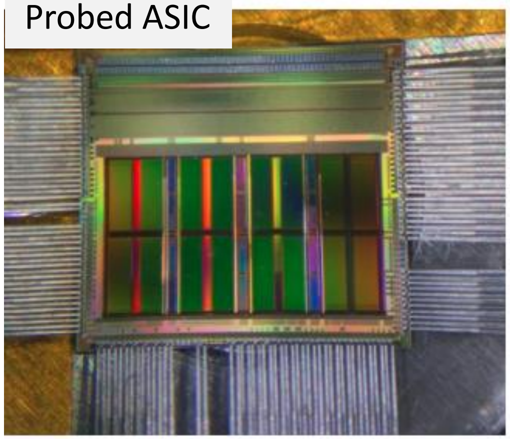




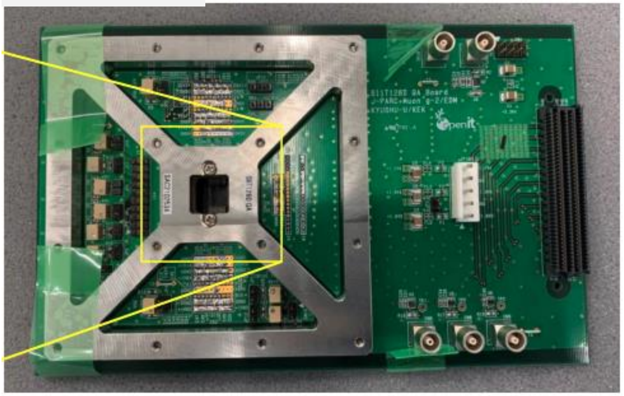
# Quality assurance of ASIC

- 15000 ASICs are produced for real detector assembly.
- Quality assurance (QA) of produced ASICs is on going.
  - QA system prepared: dedicated probe card & manual probe station.

Probed ASIC



Probe card



Probe station

- Performance check to reject bad chip before detector assembly.
  - Power consumption,  dead channel, gain, noise, and timewalk are measured.

# Quality assurance of ASIC

- So far 62 chips are tested.
  - 10 bad chips (noisy channel etc..) are identified and rejected.

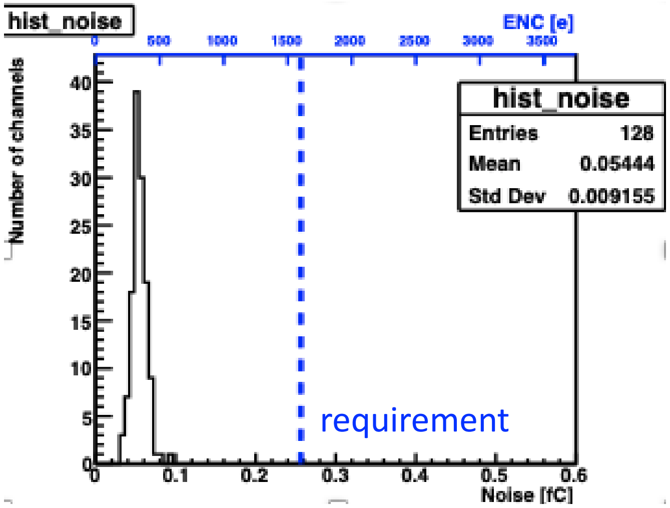
## Noise

- Estimated from “S-curve scan”.
  - voltage threshold scan
    for the signal of fixed charge
- Requirement: ENC < 1600 $e^-$

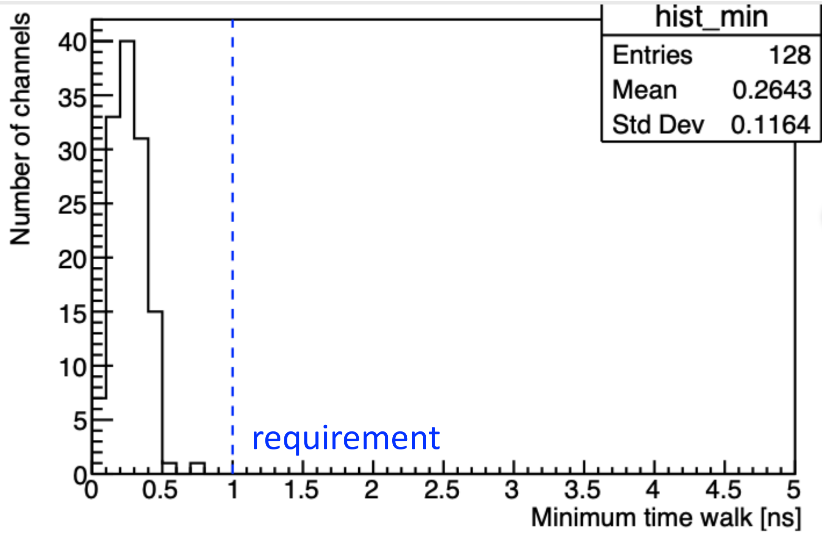
## Timewalk

- Time difference of signal btw/ 0.5 - 3MIP
- Requirement: < 1ns
  - large timewalk can deteriorate high rate tolerance, and can lead to a systematic uncertainty of g-2.

Noise of each channel (a good chip)

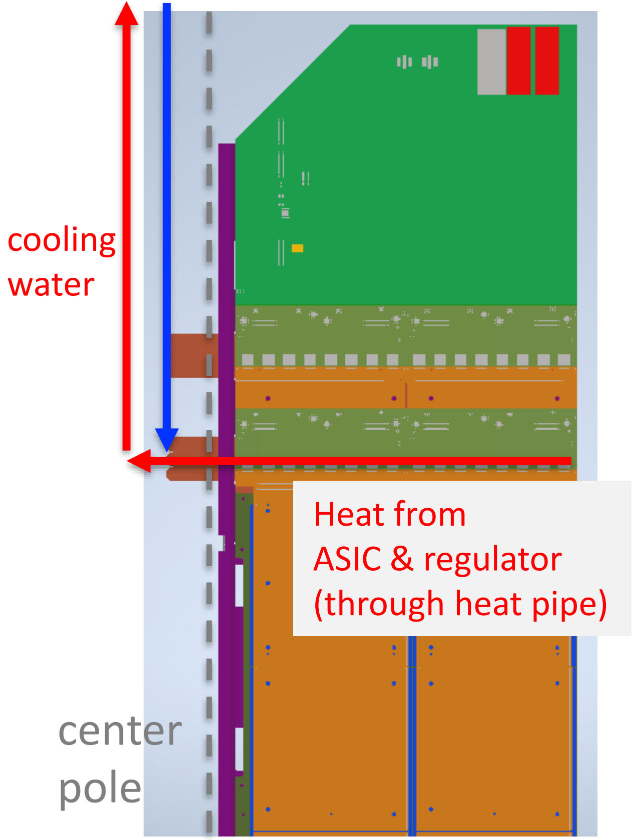


Timewalk of each channel (a good chip)

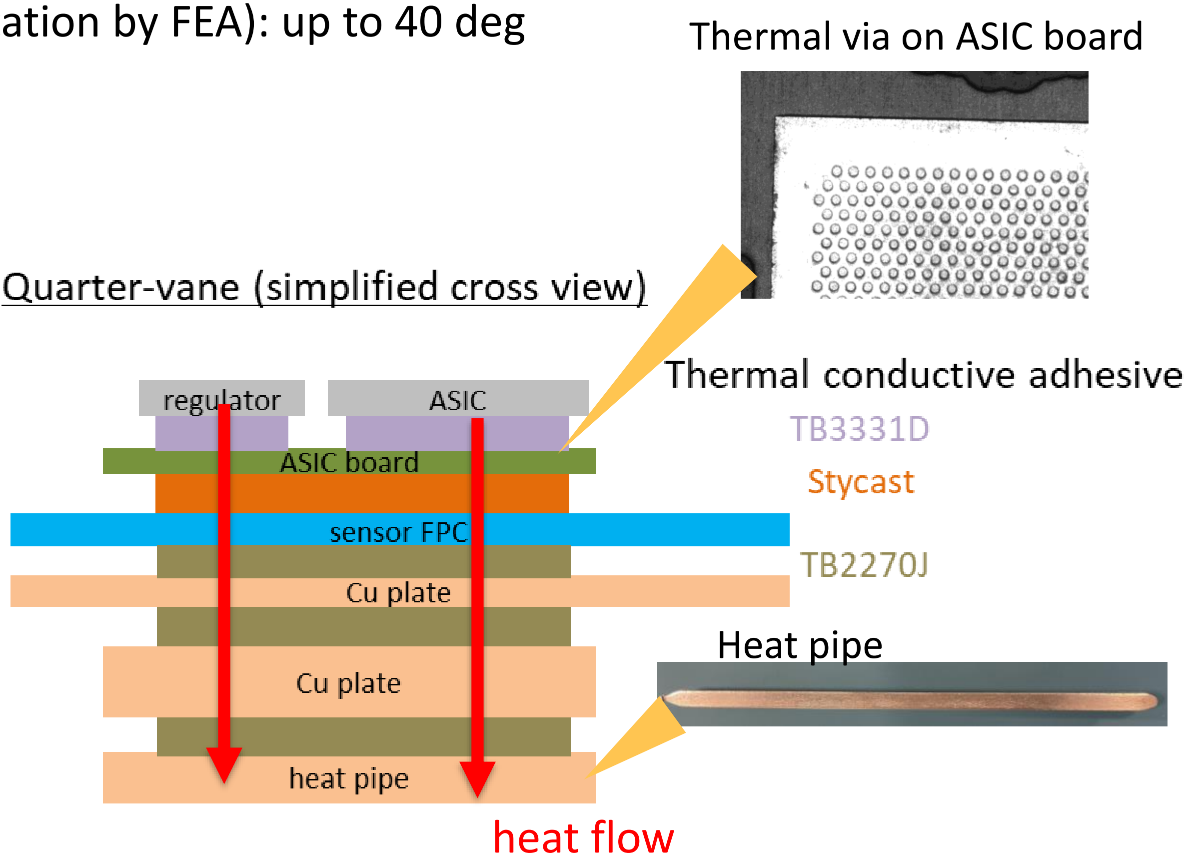


# Cooling system design

- Detector is operated inside vacuum, thus cooling of frontend ASIC, FPGA, regulator etc... is required.
  - In total 5 kW (~30 W per quarter vane) has to be cooled.
- Electric parts are thermally connected to heat pipe, which is cooled down by colling water inside the center pole.
  - ASIC temperature (expectation by FEA): up to 40 deg



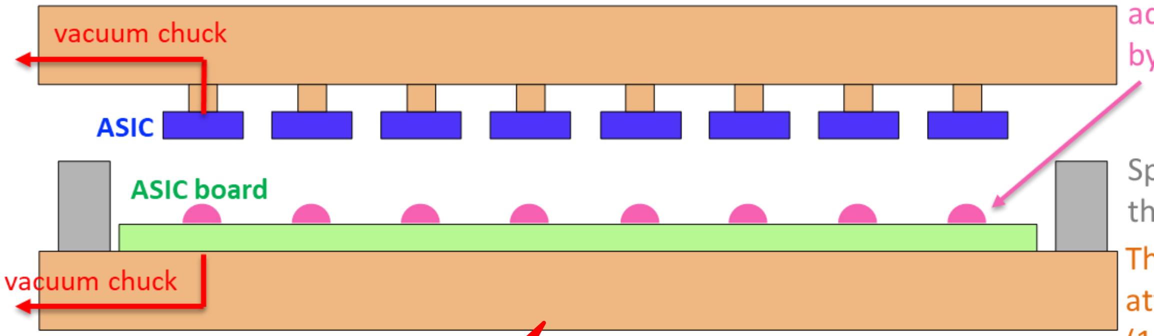
Quarter-vane (simplified cross view)



# Cooling system assembly

- Assembly procedure to realize this design has been studied.
- Thickness of thermal conductive adhesive has to be well controlled.
  - positioning of work to be glued & control of used amount adhesive
- A dedicated jig to control thickness of adhesive.

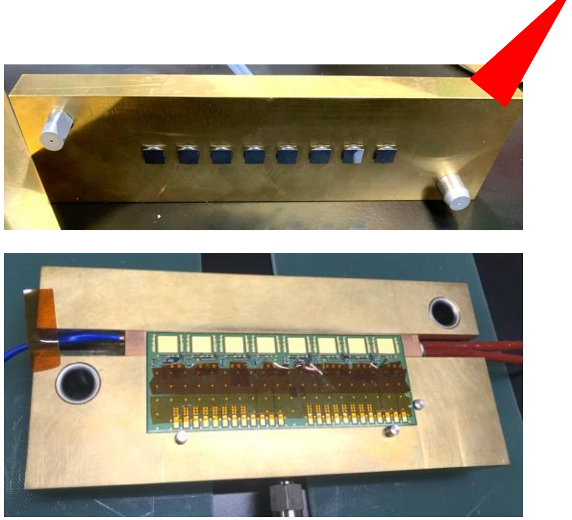
ASIC gluing jig (side view)



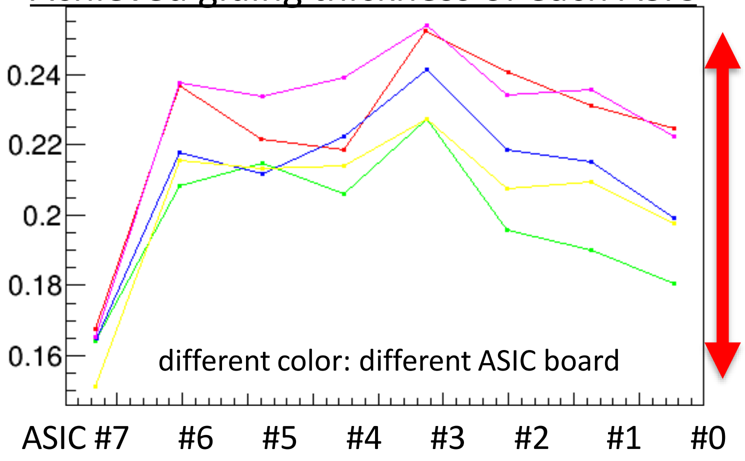
adhesive (TB3331D) by dispenser

Spacer to control thickness

Thermal curing by attached heater (1 hour at 80 deg)



Achieved gluing thickness of each ASIC

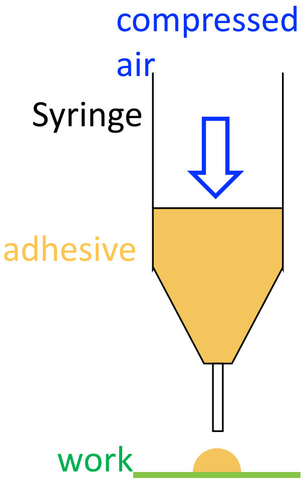


different color: different ASIC board

thickness 200±50um

# Cooling system assembly

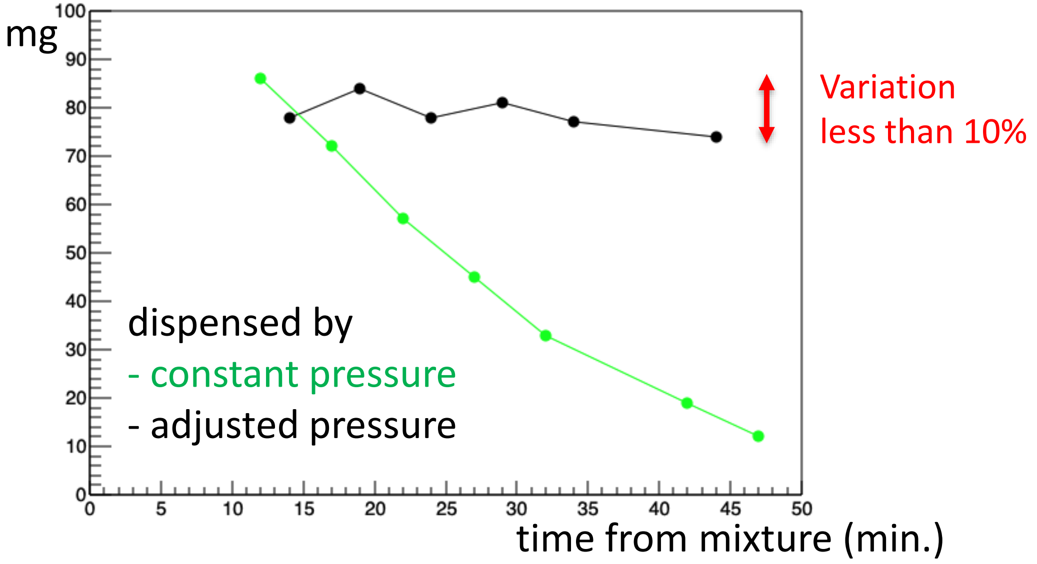
- Amount of adhesive can be controlled by using “dispenser”.
  - adhesive in syringe pushed by compressed air of a given pressure.
  - major parameter : applied pressure & adhesive viscosity
- For two component adhesive (e.g. stycast, araldite), viscosity depends on the speed of chemical reaction, whose direct control is difficult.
- A test dispense on a junk sample just before dispense on the real work → Individual difference of amount of adhesive can be reduced.
  - Pressure for real dispense is adjusted, from the amount of adhesive in test dispense.



Parameters of dispense

1. pressure of air
2. pressurized period
3. Viscosity of adhesive
4. Nozzle size

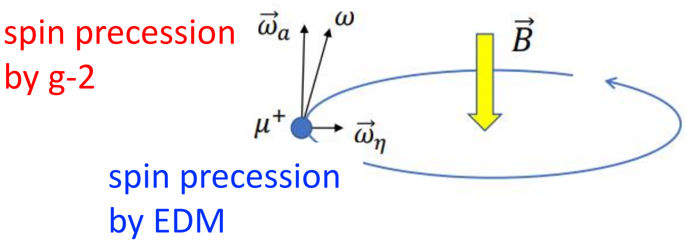
Dispenced amount of adhesive



# Requirement on sensor alignment

- Precise alignment between detector and B-field is essential for muon EDM measurement.
  - nonzero EDM can be detected as an up-down asymmetry of number of decay positrons.
  - If rotated each other, “g-2 component” of spin precession comes into “EDM component”.

$$\vec{\omega}_a + \vec{\omega}_\eta = -\frac{\mathrm{e}}{\mathrm{m}}\left[\underbrace{\frac{g-2}{2}\vec{B}}_{\text{g-2}} + \underbrace{\frac{\eta}{2}\vec{\beta}\times\vec{B}}_{\text{EDM}}\right]$$

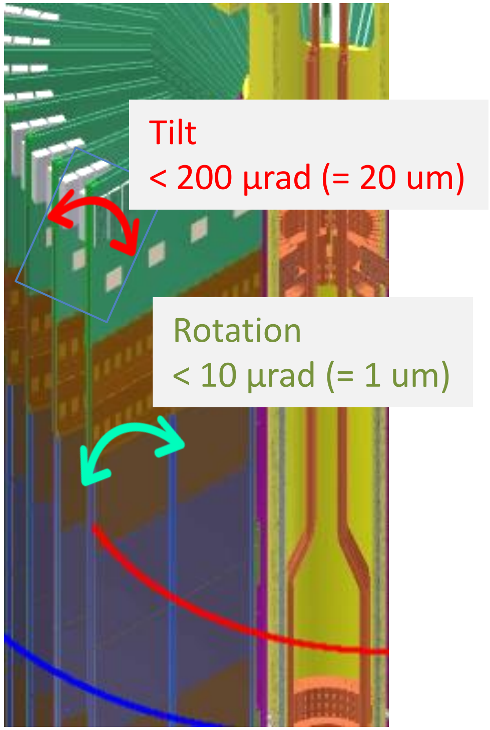


spin precession by g-2

spin precession by EDM

- Goal of sensor alignment:
  10 urad rotation & 200urad tilt.
  - This corresponds to
    1 um rotation & 20 um tilt of each sensor.

- Precise positioning of sensors in detector assembly
  + precise position monitoring of sensor in data taking.



Tilt
< 200 μrad (= 20 um)

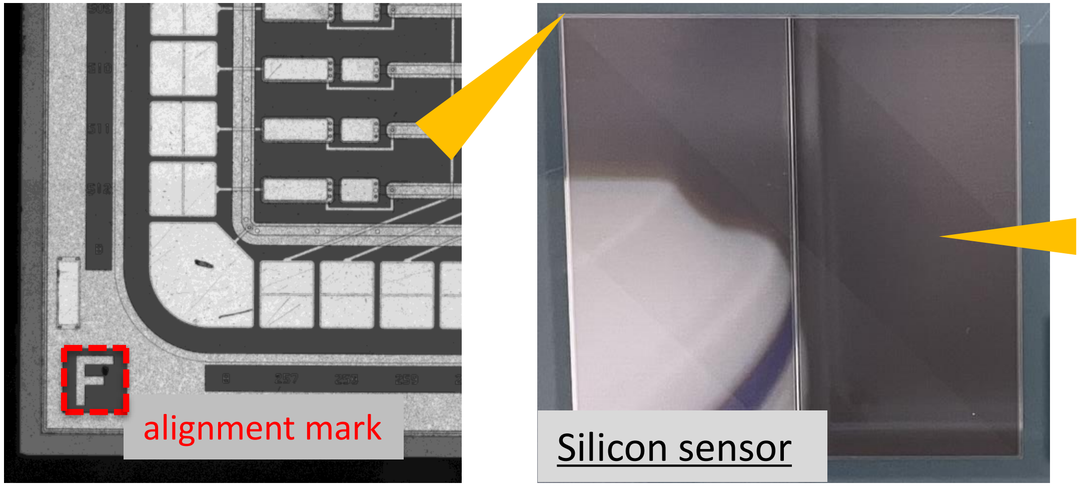
Rotation
< 10 μrad (= 1 um)

# Sensor alignment

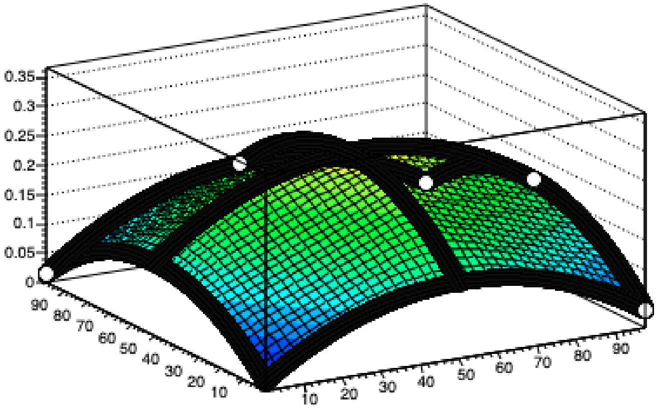
- Silicon sensors are glued on GFRP frame. Gluing procedure with an alignment of O(1) um precision is under development.

- CMM (3D coordinate measuring machine) in temperature control room
  - sensor position & shape measurement by 1um precision
  - temperature is kept to 20 ± 1 deg. , to avoid thermal expansion.

*Sensor position measurement by alignment marker*

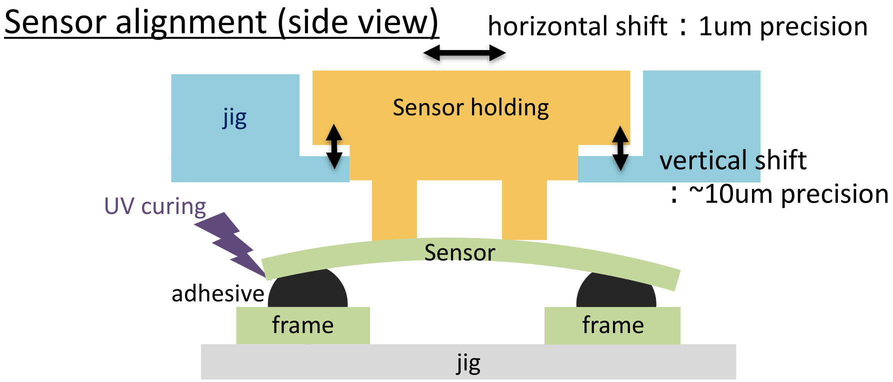


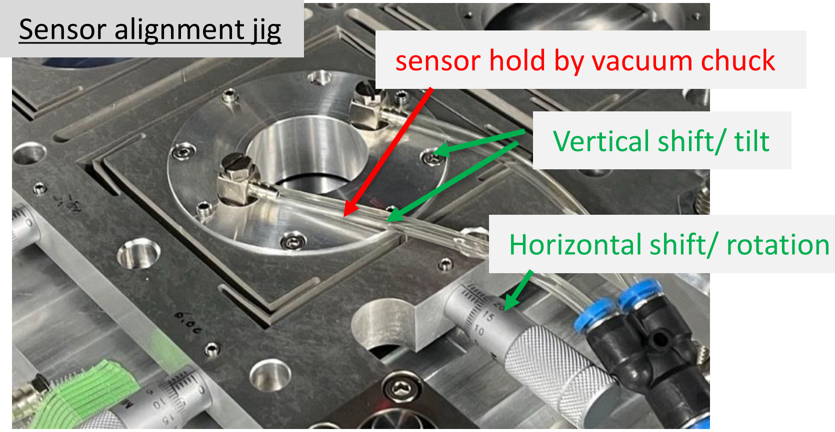
*Shape measurement by chromatic confocal sensor*



# Sensor alignment

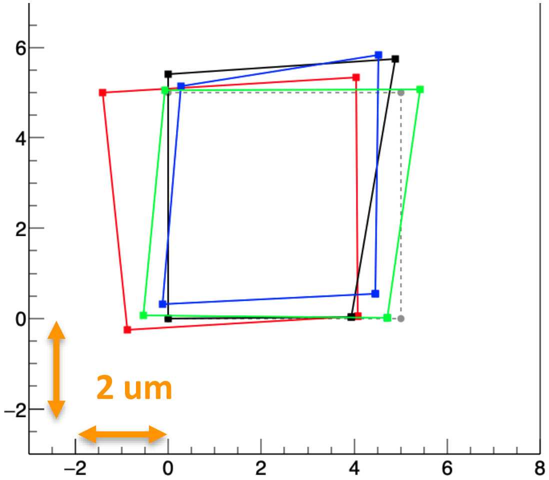
- Sensor positioning by a dedicated jig.
  - Horizontal shift (1um step) & Vertical shift (~10 um step)
  - Gluing by a UV curing adhesive.


Sensor alignment (side view)


Sensor alignment jig

- Precision better than 2um is achieved for rotation in quarter-vane plane.
  - already near to the final goal of 1 um

Glued position of each sensor (1st,2nd,3rd,4th)
Deviation from ideal (gray) position



# Summary

- Silicon strip detector for J-PARC muon g-2/EDM experiment is being developed.
  - Aims to measure muon g-2
    with an independent strategy from BNL/FNAL experiments.

- Prototyping of detector submodule (quarter-vane) is ongoing.
  - Frontend ASIC has been produced. Their quality assurance has started.
  - Cooling system has been designed.
    Assembly procedure to control adhesive thickness has been established.
  - Precise sensor alignment for EDM measurement under R&D.
    Precision of 2 um is already achieved.

- Detector assembly from JFY 2024, and physics data-taking from JFY 2027.

# BACKUP

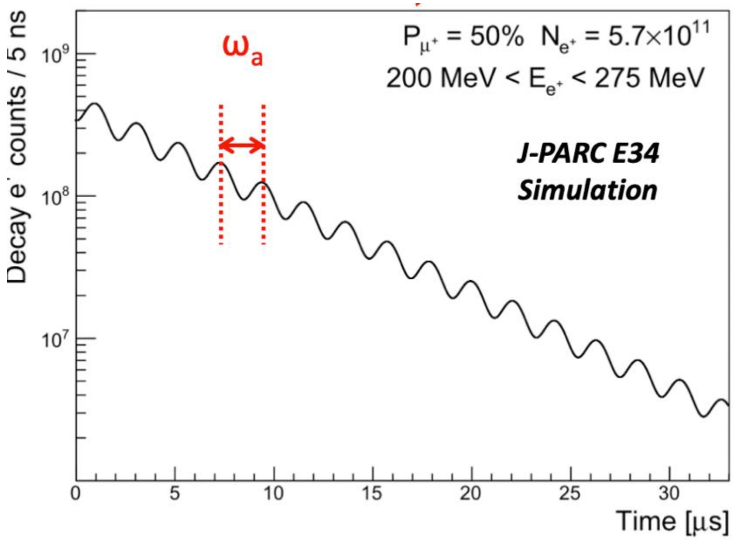
# Muon g-2/EDM measurement

J-PARC experiment

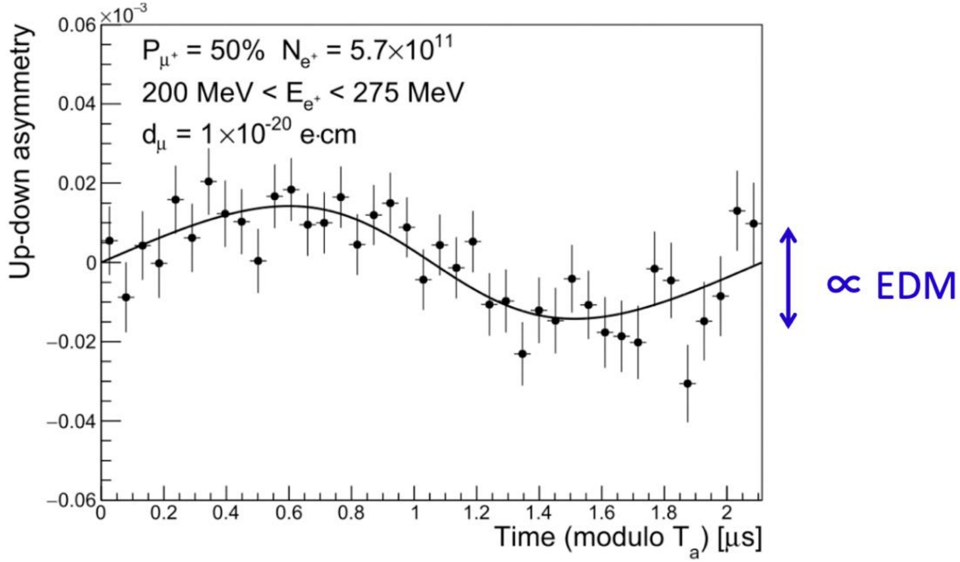
- Measurement at $\vec{E} = 0$.
  - Storage by weak focusing B-field
  - Utilize low emittance muon beam.

$$\vec{\omega}_a + \vec{\omega}_\eta = -\frac{e}{m_\mu}\left[\underbrace{a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\overset{=0}{\boxed{\frac{\vec{\beta}\times\vec{E}}{c}}}}_{\text{g-2}} + \underbrace{\frac{\eta}{2}\left(\vec{\beta}\times\vec{B} + \overset{=0}{\boxed{\frac{\vec{E}}{c}}}\right)}_{\text{EDM}}\right]$$

Number of detected positron (p: 200-275 MeV)



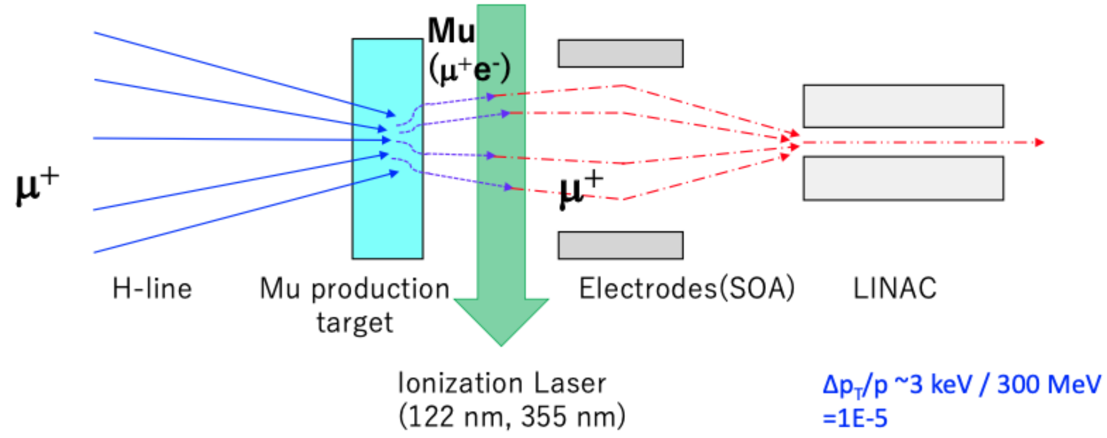
Up-down asymmetry of detected positron

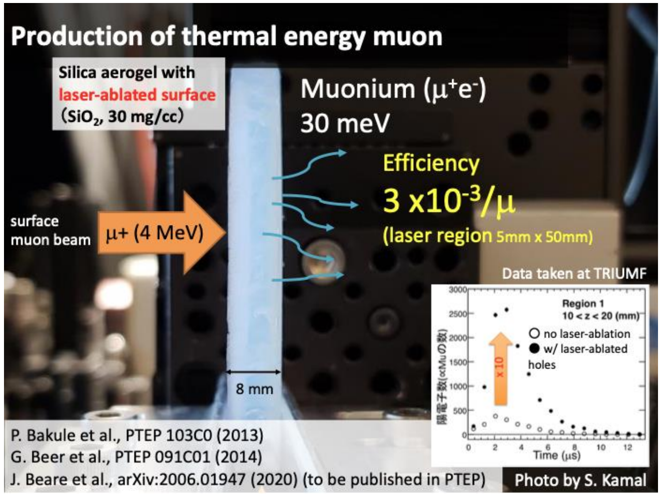


# Muon cooling

- 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.

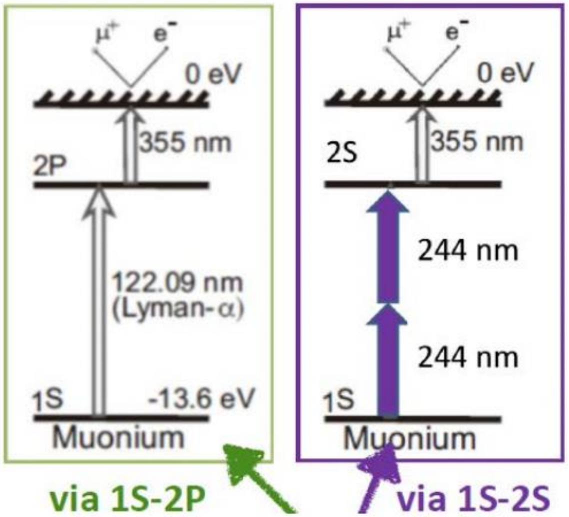
| | **surface muon** | **thermal muon** | **accelerated muon** |
|---|---|---|---|
| E | 3.4 MeV | 30 meV | 212 MeV |
| p | 27 MeV/c | 2.3 keV/c | 300 MeV/c |
| Δ p/p | 0.05 | 0.4 | $4\text{x}10^{-4}$ |





**Production of thermal energy muon**

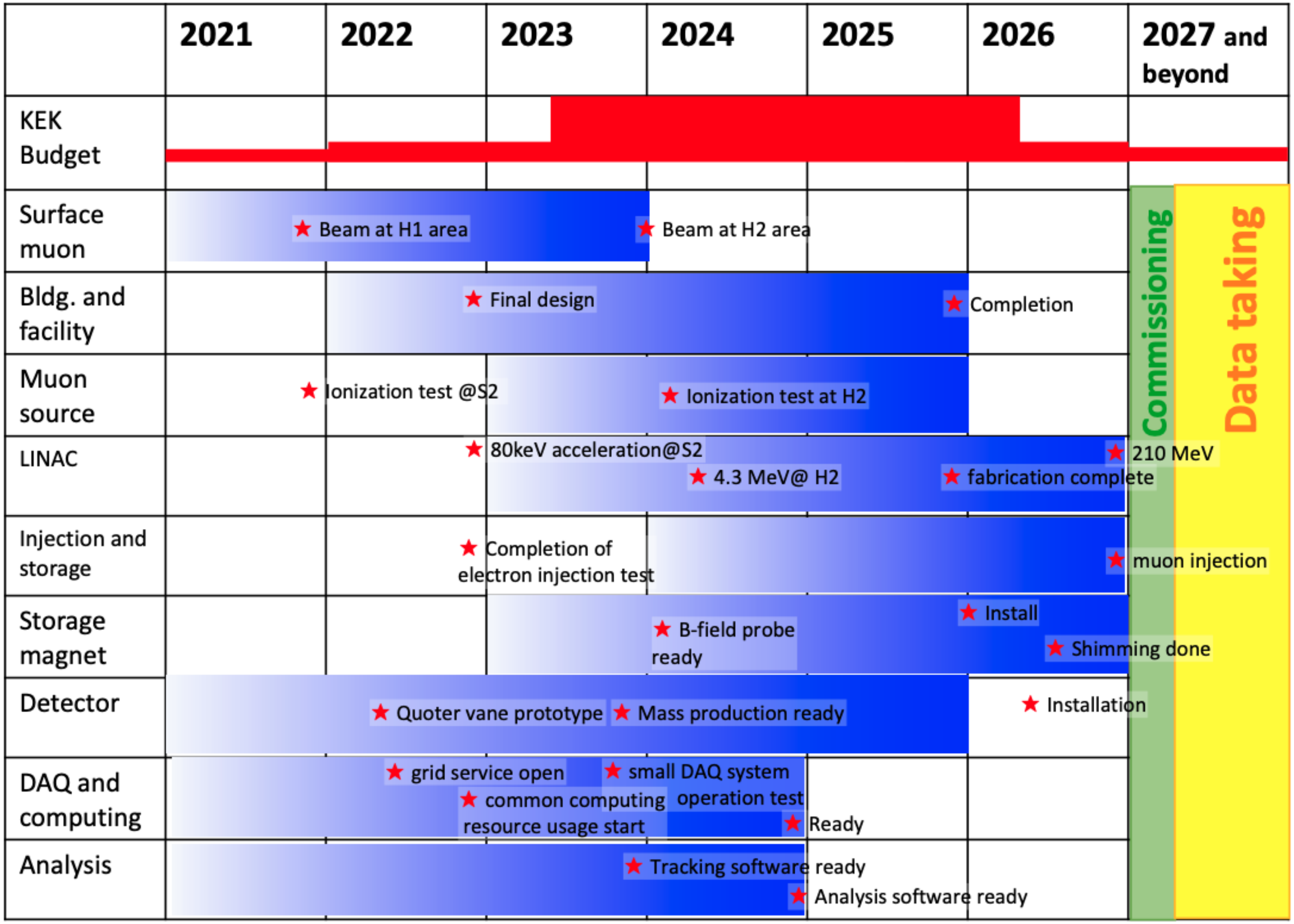
P. Bakule et al., PTEP 103C0 (2013)
G. Beer et al., PTEP 091C01 (2014)
J. Beare et al., arXiv:2006.01947 (2020) (to be published in PTEP)



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

# Schedule

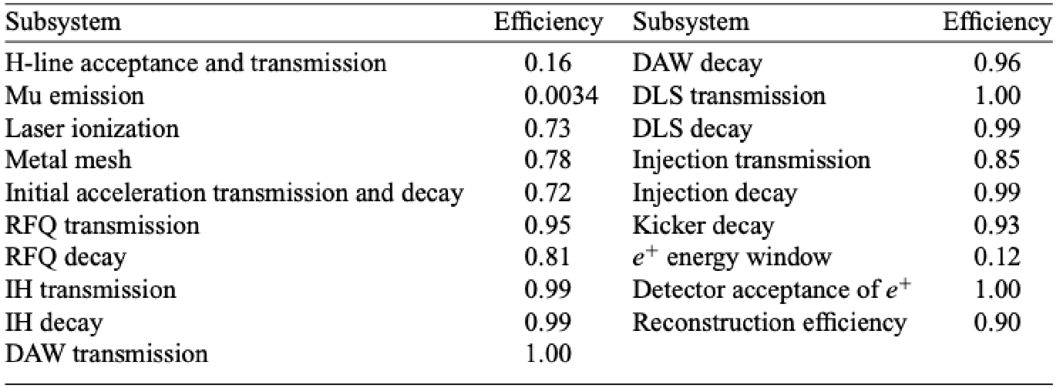
Physics data taking expected from JFY 2027.



| | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 and beyond |
|---|---|---|---|---|---|---|---|
| KEK Budget | | | | | | | |
| Surface muon | ★ Beam at H1 area | | | ★ Beam at H2 area | | | Commissioning<br>Data taking |
| Bldg. and facility | | ★ Final design | | | ★ Completion | | |
| Muon source | ★ Ionization test @S2 | | | ★ Ionization test at H2 | | | |
| LINAC | | ★ 80keV acceleration@S2 | | ★ 4.3 MeV@ H2 | ★ fabrication complete | ★ 210 MeV | |
| Injection and storage | | ★ Completion of electron injection test | | | | ★ muon injection | |
| Storage magnet | | | | ★ B-field probe ready | | ★ Install<br>★ Shimming done | |
| Detector | | ★ Quoter vane prototype | ★ Mass production ready | | | ★ Installation | |
| DAQ and computing | | ★ grid service open<br>★ common computing resource usage start | ★ small DAQ system operation test | ★ Ready | | | |
| Analysis | | | ★ Tracking software ready | ★ Analysis software ready | | | |

# Expected sensitivity

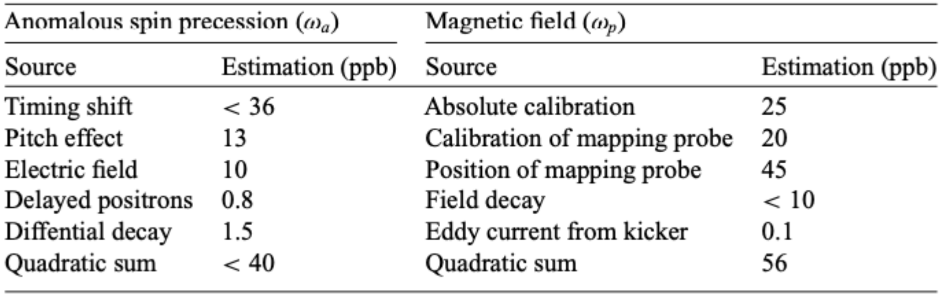
- Total efficiency of muon will be $1.3 \times 10^{-4}$.



| 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 | | |

## Muon g-2

- Statistical uncertainty: 450 ppb (2 years of data taking)
  - Uncertainty comparable to BNL can be reached
- Systematic uncertainty: less than 70 ppb.



| Anomalous spin precession ($\omega_a$) | | Magnetic field ($\omega_p$) | |
|---|---|---|---|
| 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 | $< 10$ |
| Differential decay | 1.5 | Eddy current from kicker | 0.1 |
| Quadratic sum | $< 40$ | Quadratic sum | 56 |

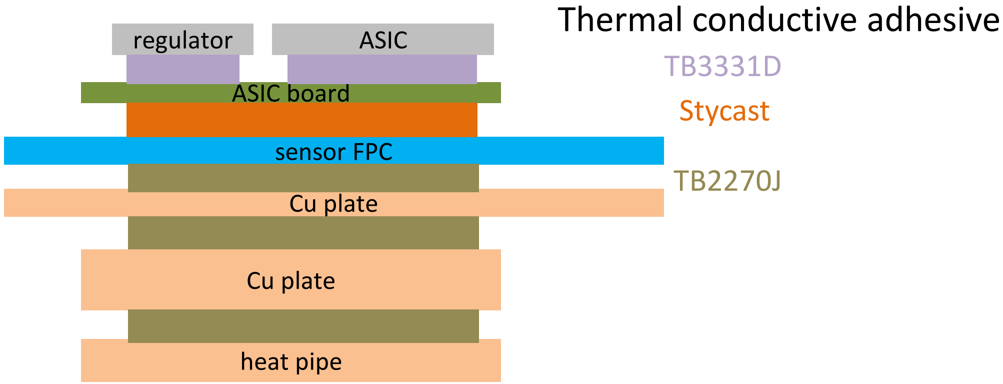
## Muon EDM

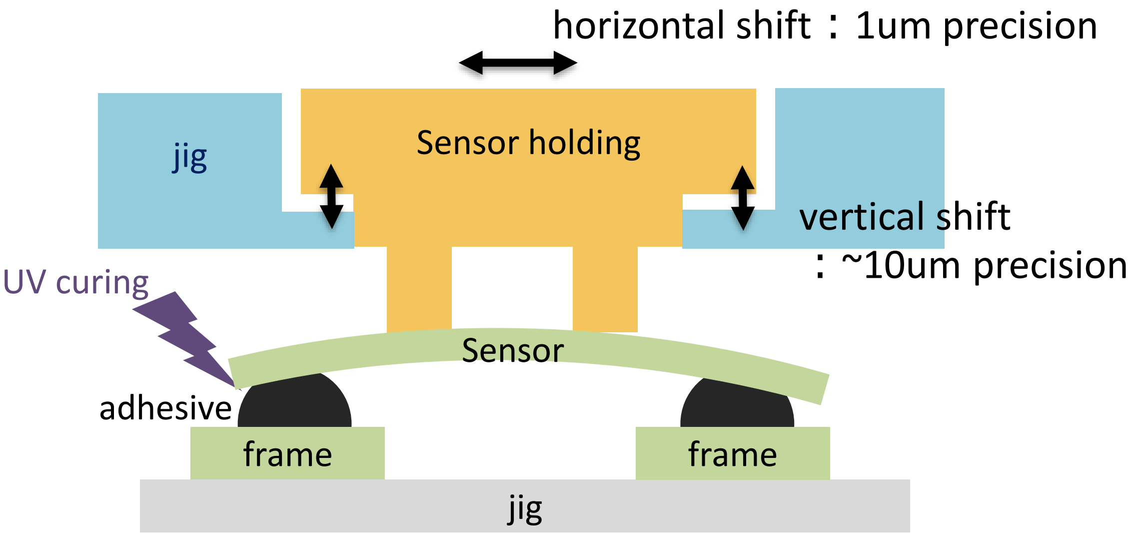
- Statistical uncertainty: $1.5 \times 10^{-21}$ e · cm
- Systematic uncertainty: $0.4 \times 10^{-21}$ e · cm
  - mainly from detector mis-alignment

# a

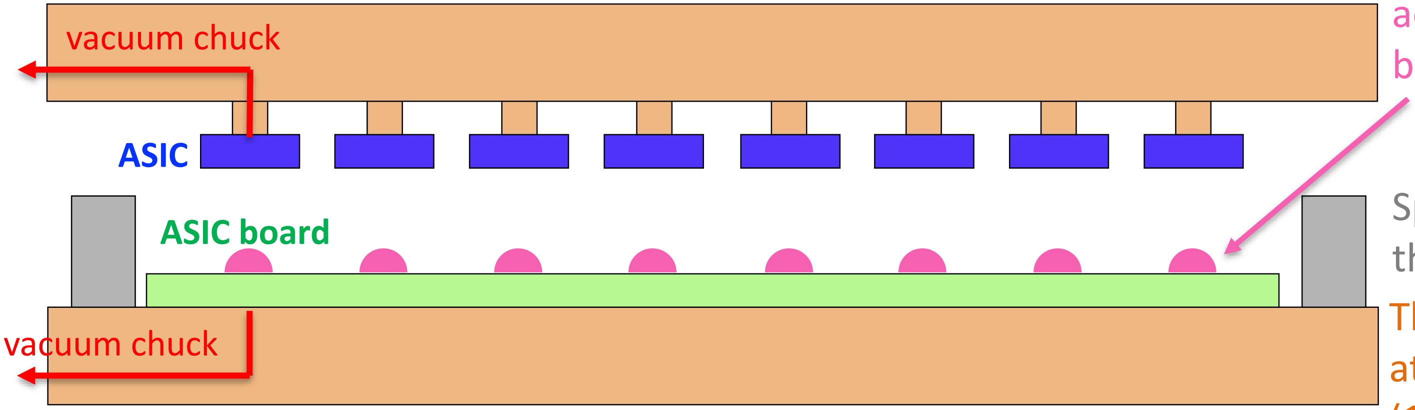
- a

Quarter-vane (simplified cross view)





ASIC gluing jig (side view)



adhesive (TB3331D)
by dispenser

Spacer to control
thickness

Thermal curing by
attached heater
(1 hour at 80 deg)