Assembly procedure of silicon strip detector module with 1 μm alignment precision for the muon g-2/EDM experiment at J-PARC

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on behalf of J-PARC muon g-2/EDM detector group

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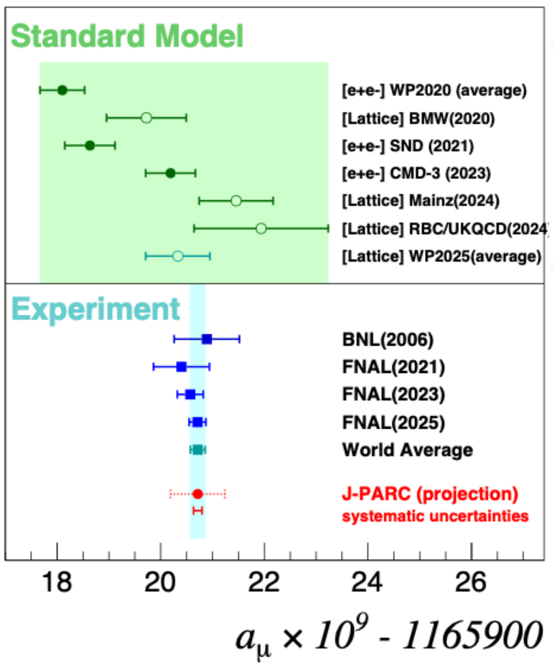
Muon g-2/EDM measurement at J-PARC

- We plan to measure muon g-2/EDM at J-PARC.

Muon g-2

Understanding of muon g-2 is still ambiguous, requiring a new measurement.



SM value depends on how HVP is evaluated.

- Filled circle: dispersive method
- Open circle: lattice QCD

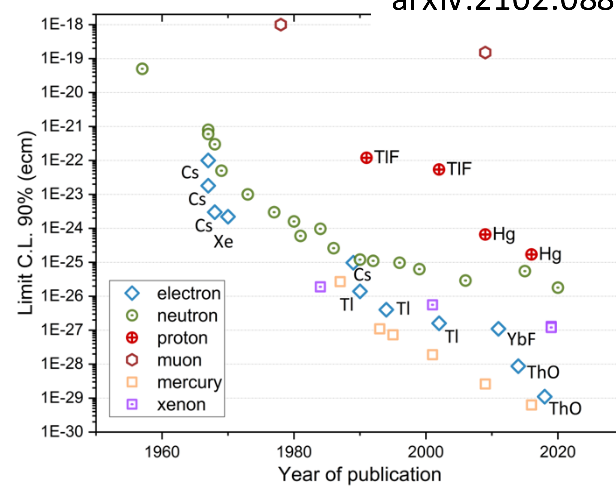
Muon EDM

Nonzero EDM would indicate CP violation.

Search for muon EDM

-> CP violation search in lepton sector.

arxiv:2102.08838



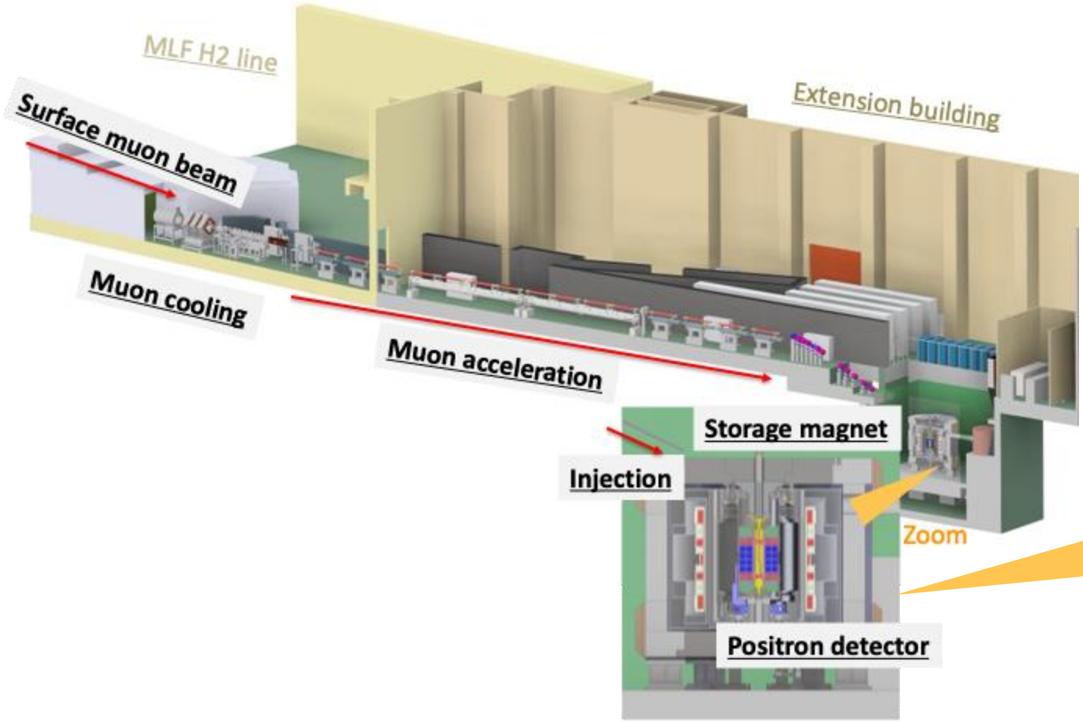
- We adopt a new approach (" zero E-field approach") for independent validation of previous muon g-2 measurements by "magic-γ approach".

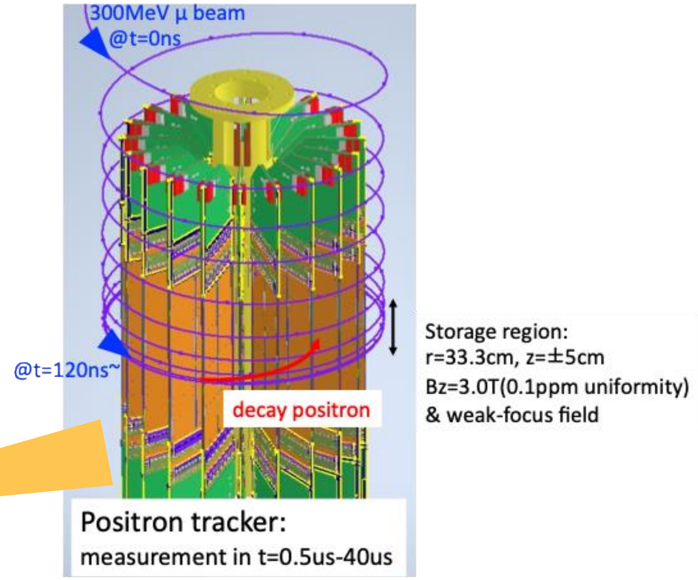
$$\vec{\omega}_a + \vec{\omega}_\eta = -\frac{e}{m_\mu}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2-1}\right)\frac{\vec{\beta}\times\vec{E}}{c} + \frac{\eta}{2}\left(\vec{\beta}\times\vec{B} + \frac{\vec{E}}{c}\right)\right]$$

= 0 at $\vec{E}$=0 = 0 at $\vec{E}$=0

J-PARC muon g-2/EDM experiment

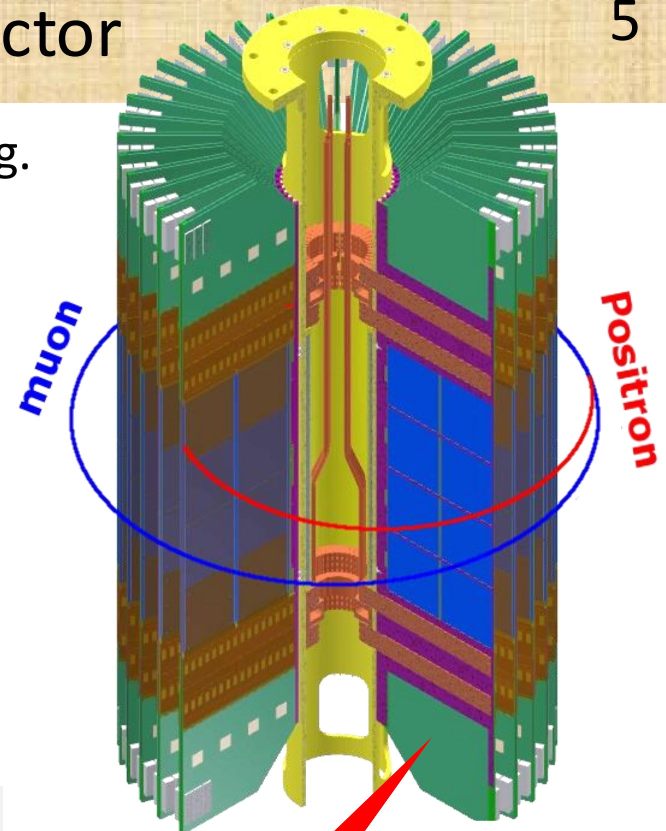
- J-PARC muon g-2/EDM experiment："zero E-field approach"
  - Utilizes low momentum (300 MeV/c) muon with compact storage ring(ϕ=0.66 m)
- This requires
  - Low emittance muon beam with a precise control.
  - Highly uniform B-field by MRI-like magnet.
  - **Compact positron tracking detector** operatable in pileup condition.



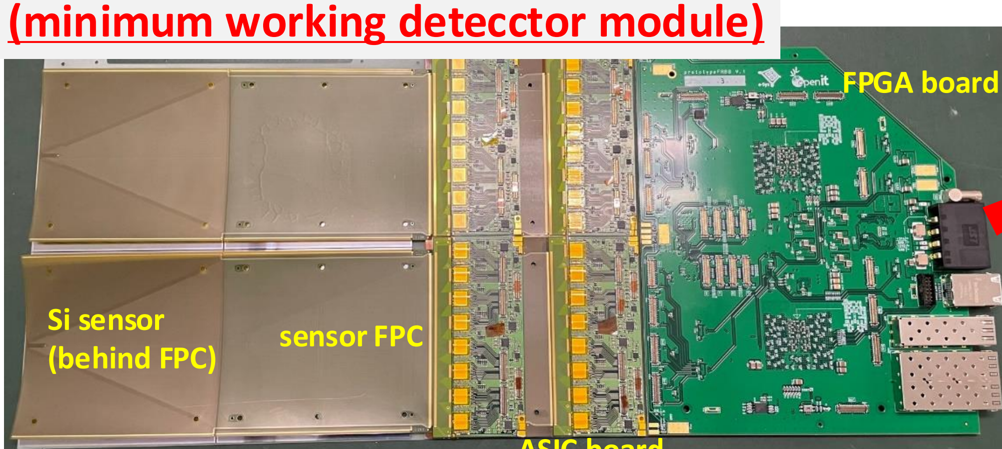


Positron tracking detector

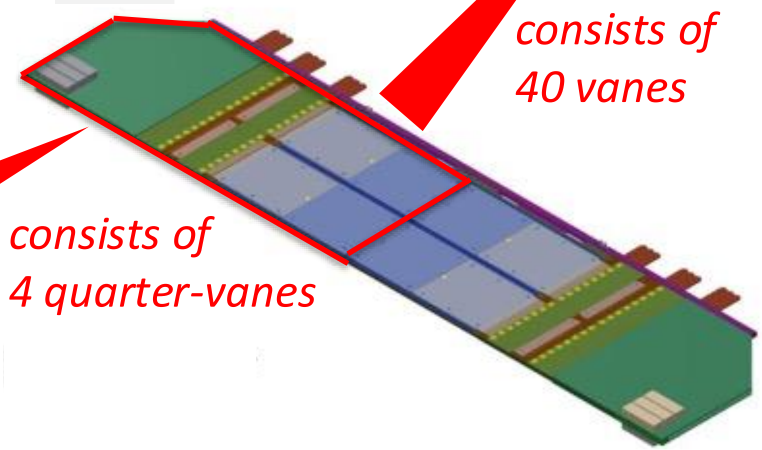
- We adopt silicon strip detector for positron tracking.
  - Sufficient detection efficiency for p=200-275 MeV/c.
    High hit rate capability (6 tracks/ns)
    and stability over rate changes (1.4 MHz→10 kHz)
  - Unbiased timing measurement (a few ps)
    by GPS synchronized digitization clock.
  - **Precise (~1um) sensor alignment**
  - Operatable just ~0.5 μs after the pulsed
    B-field for beam injection



Quarter-vane
(minimum working detecctor module)

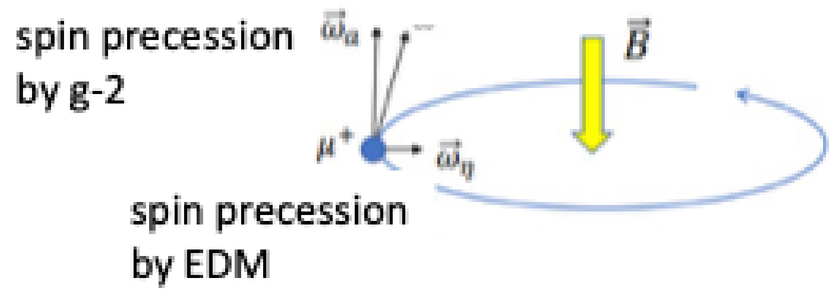


Vane



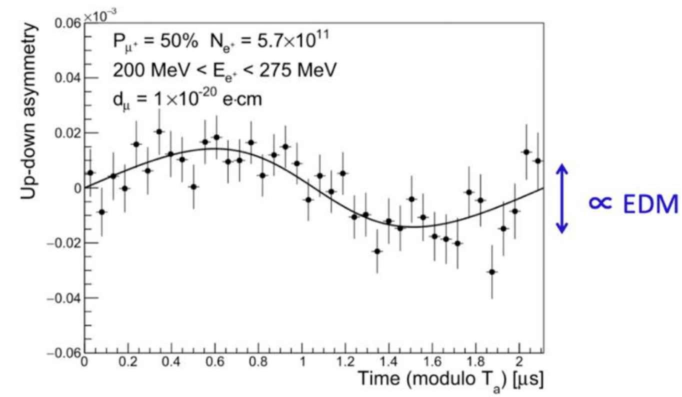
Requirement on sensor alignment

- Precise sensor alignment is needed for the muon EDM search.



- The muon EDM is detected via a tiny tilt of spin precession vector.
  - The spin precession of g-2 is ~10^5 larger than our target sensitivity on EDM
  - Thus an overlooked sysmatic 10 μrad rotation of the sensors could produce a fake tilt of spin precession vector.

Up-down asymmetry of detected positron



- Systematic misalignment must be controlled under 1 μm level (10 μrad rotation of 100 × 100 mm^2 sensors) for in-plane direction.
  - Sensor position/rotation/deformation during data-taking must be known with this precision.
  - Better precision than previously achieved in collider silicon detectors is required.
  - Needs 20 μm level precision for out-of-plane direction.

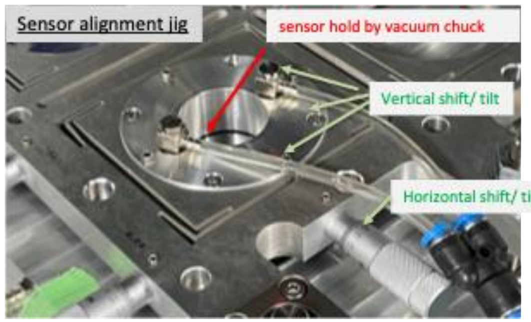
How we achieve the sensor alignment

- We aim to achieve this precise sensor alignment by combining several technologies.

Precise detector assembly This talk

: Align sensors during assembly

- Sensor position measurement by CMM & laser tracker.
- Position alignment by dedicated jig.



Track-based alignment

: Monitor sensor misalignment in operation

- Sensor position reconstructed by a minimization of positron track fitting in physic data.

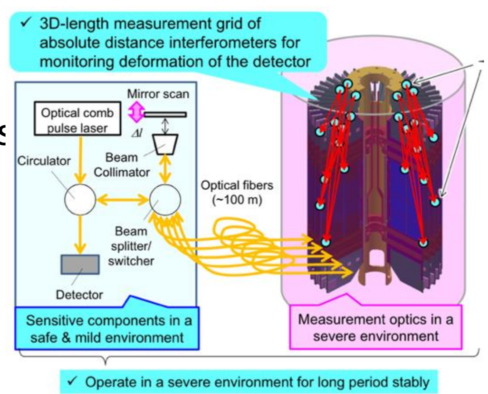
Minimize χ^2 in the positron track fitting.

$$\chi^2 = \sum_{track} \sum_{point} \frac{(x_{meas} - x_{fit})^2}{\sigma^2}$$

Laser-based alignment monitor

: Monitor sensor misalignment after assembled

- Interferometer with optical comb laser.
- Monitor distance between fixed points.
- Useful for weak-modes in track-based method

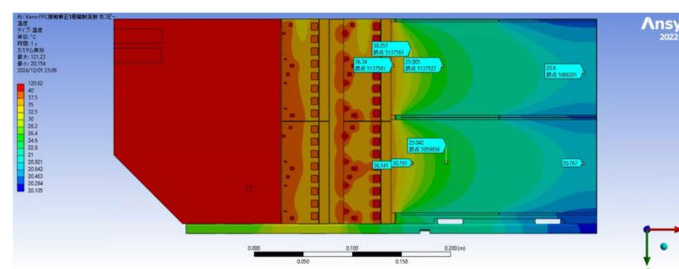


Thermal expansion countermeasures

: Reduce the misalignment

T.Sato's talk in next session

- Dedicated cooling system for temperature stabilization to mitigate thermal expansion.



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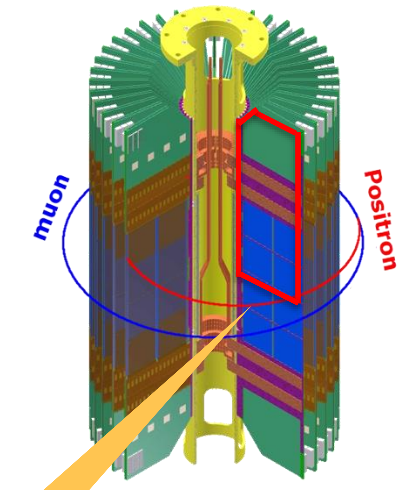
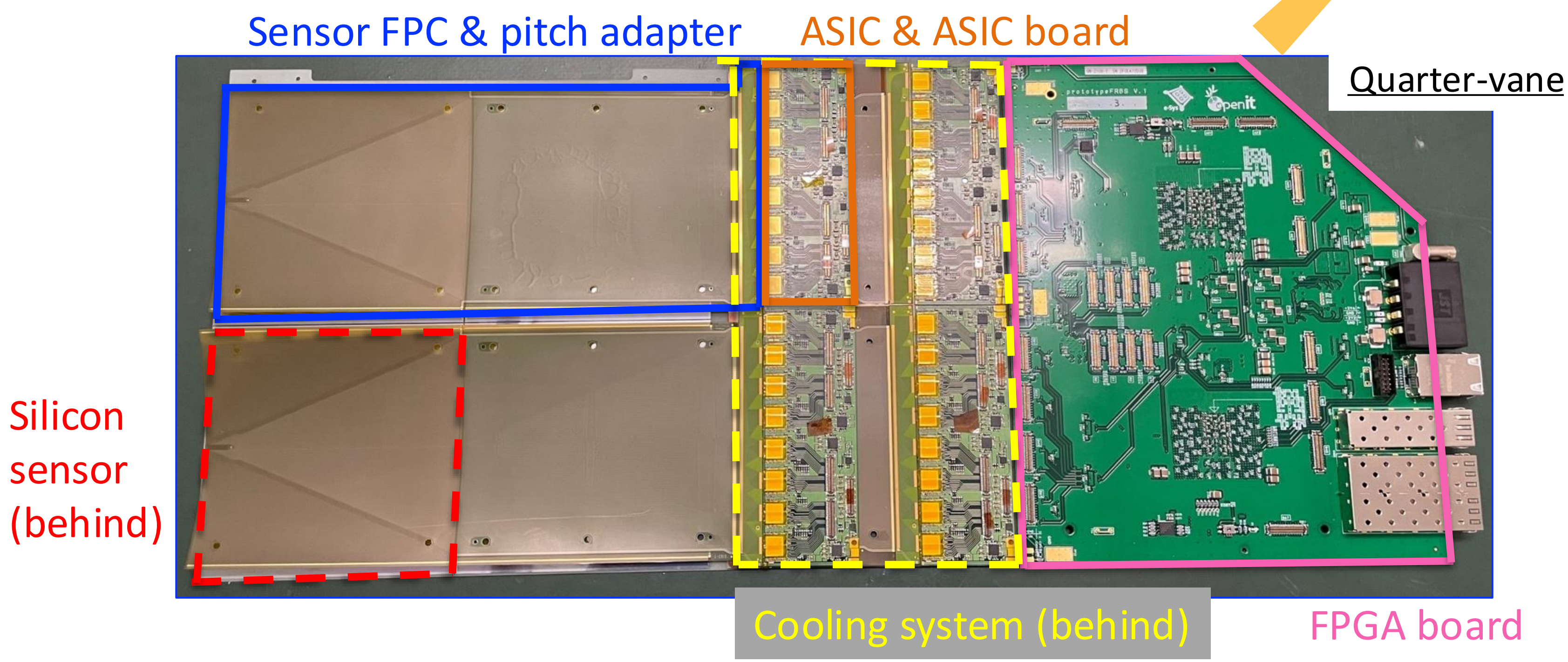
Detector module assembly procedure

- Quarter-vane, a minimum detector module, consists of
  - Silicon sensor
  - FPC: analog signal transmission
  - ASIC: signal amplification/digitization
  - FPGA board: data/clock communication
  - Cooling system: cooling in vacuum
  - GFRP frame: for assembly

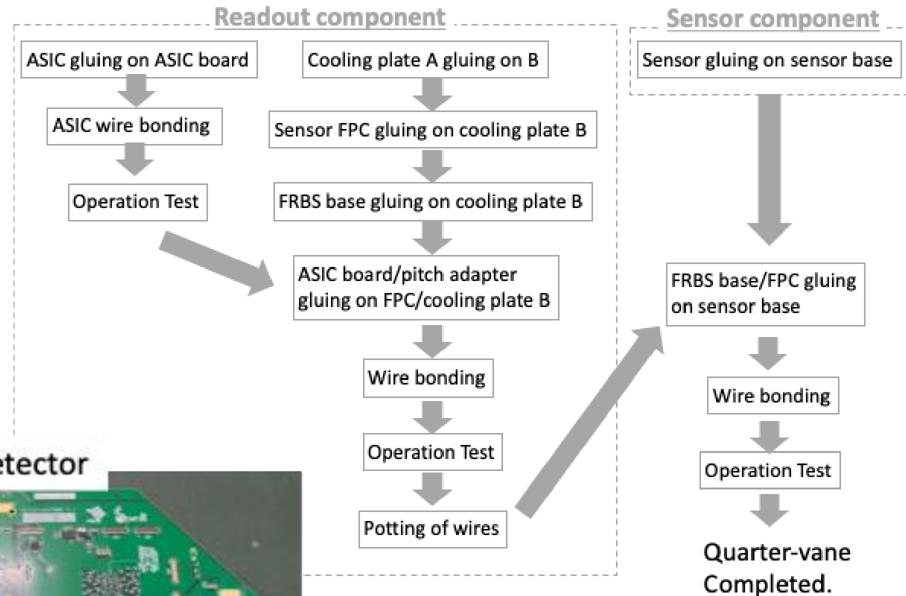


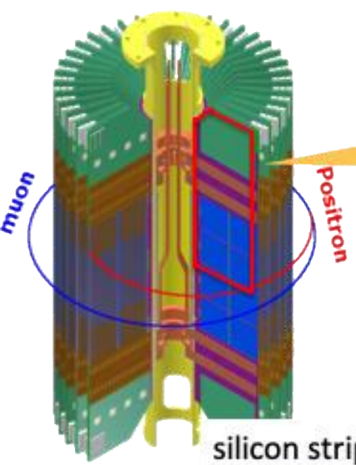


Detector module assembly procedure

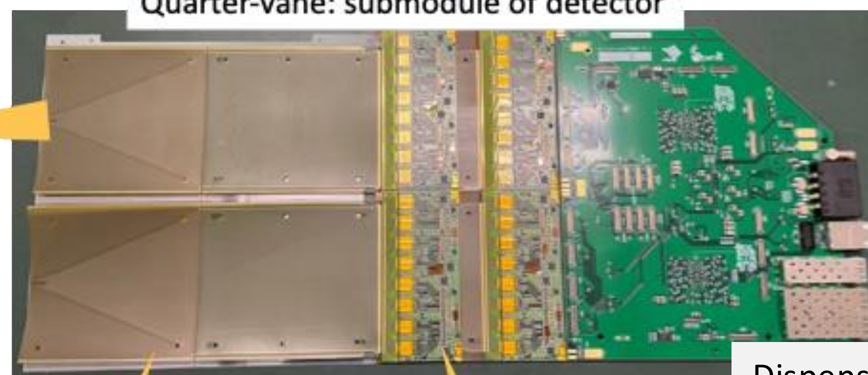
- A 14-step assembly procedure has been developed
- Each part is glued by adhesives.
  - Part positining with dedicated jigs.
  - Control of adhesive by gluing robot
- – Electrical connections via wire bonding.

Assembly procedure

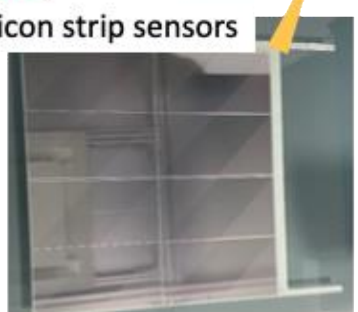




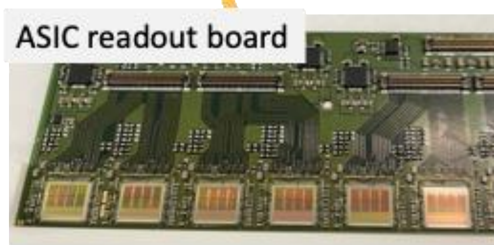
Quarter-vane: submodule of detector



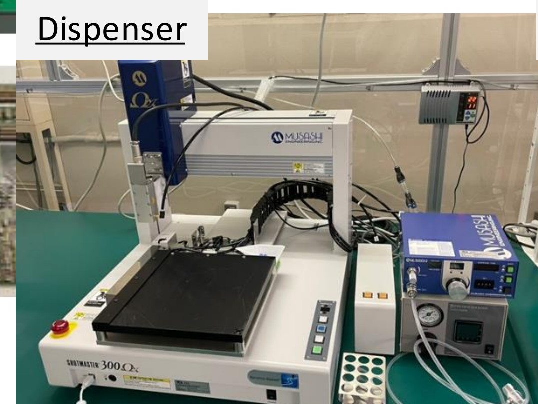
silicon strip sensors



ASIC readout board



Dispenser



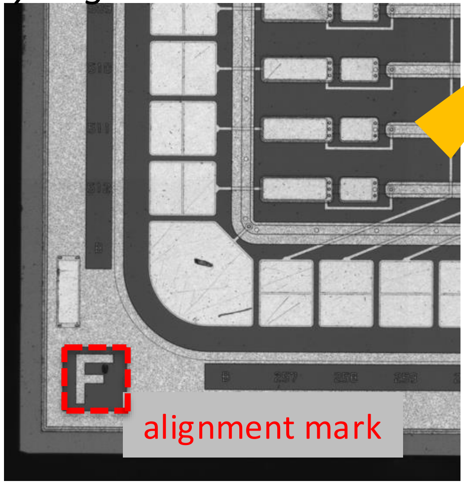
Wire bonder

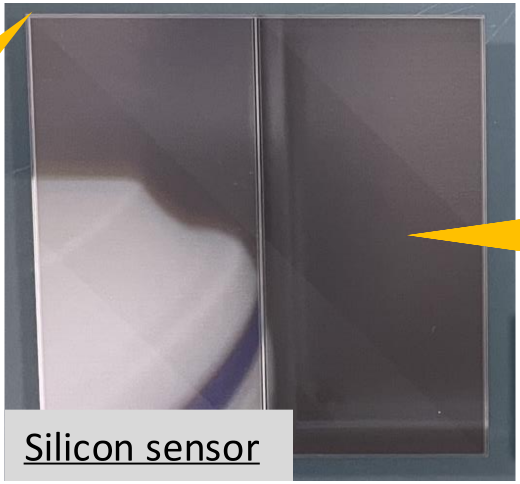
Sensor-to-sensor alignment

- Silicon sensors on the same q-vane are aligned during gluing onto a GFRP frame.

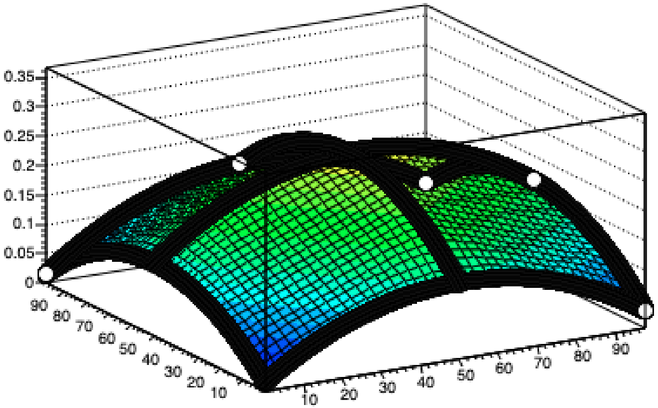
- The gluing process is performed on a CMM (3D coordinate measuring machine) in temperature control room
  - sensor position & shape measurement with 1μm precision
  - temperature is maintained at 20 ± 1 deg. , to avoid thermal expansion.

Sensor position measurement by alignment marker



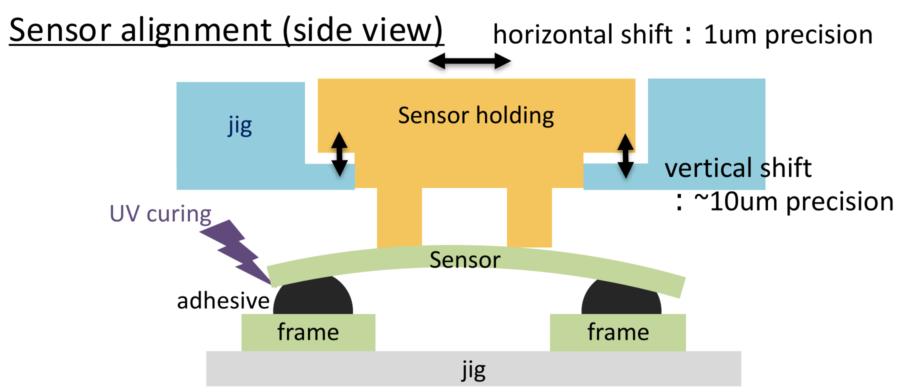


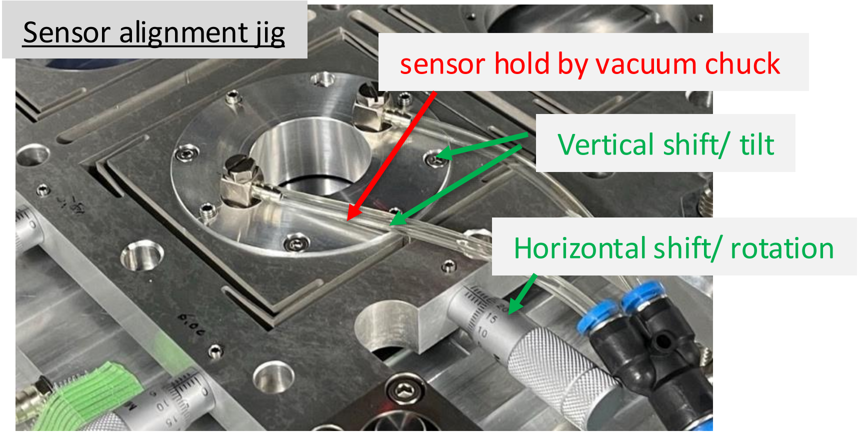
Shape measurement by chromatic confocal sensor



Sensor-to-sensor alignment

- A dedicated jig has been developed to adjust sensor position both horizontally and vertically based on CMM measurements.
  - Sensor is held by a jig whose position can be adjusted by micrometer heads.
  - Horizontal shift (~1 μm step) & Vertical shift (~10 μm step)
  - UV-curing adhesive is used allowing sufficient time for alignment.





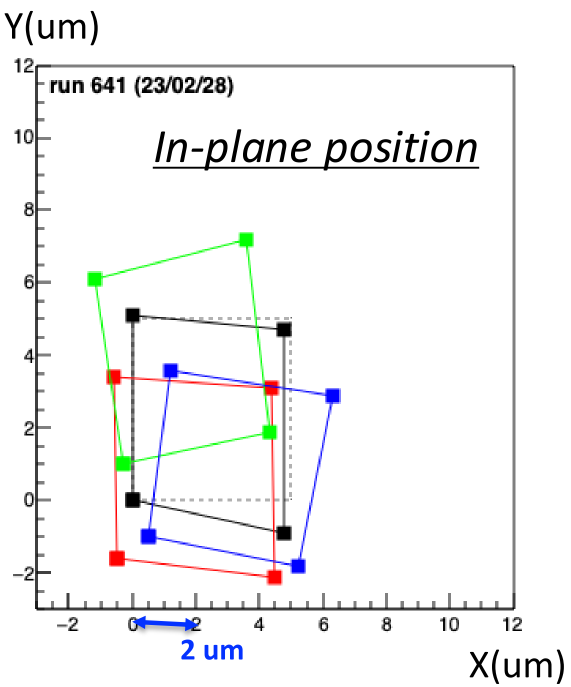
Technical details

- The sensor position is adjusted through iterative position shifts. It takes about 4 hours per sensor.
- The sensor holding part of the jig is designed to fit warped sensor shapes. The sensors make light contact with the adhesive (without pushing it so much). These are to avoid unwanted sensor deformation.

Achieved alignment precision

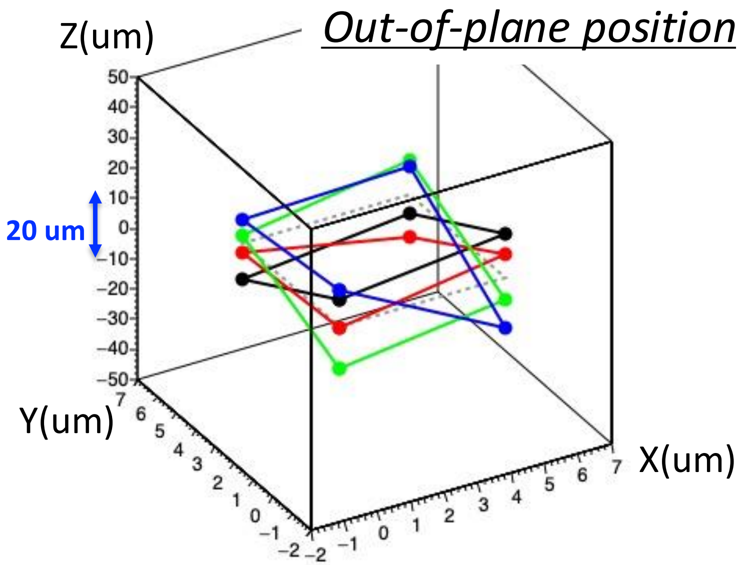
- We have succeeded in aligning the four sensors on the same GFRP frame with a 2μm precision.

Measured position of alignment marks on each sensor
(deviation from designed position, after adhesive curing)



In-plane deviation < ±2 μm

Position of each glued sensor (1,2,3,4th sensor).
Deviation from ideal position (dotted gray) is shown.



Out-of-plane deviation < ±20 μm

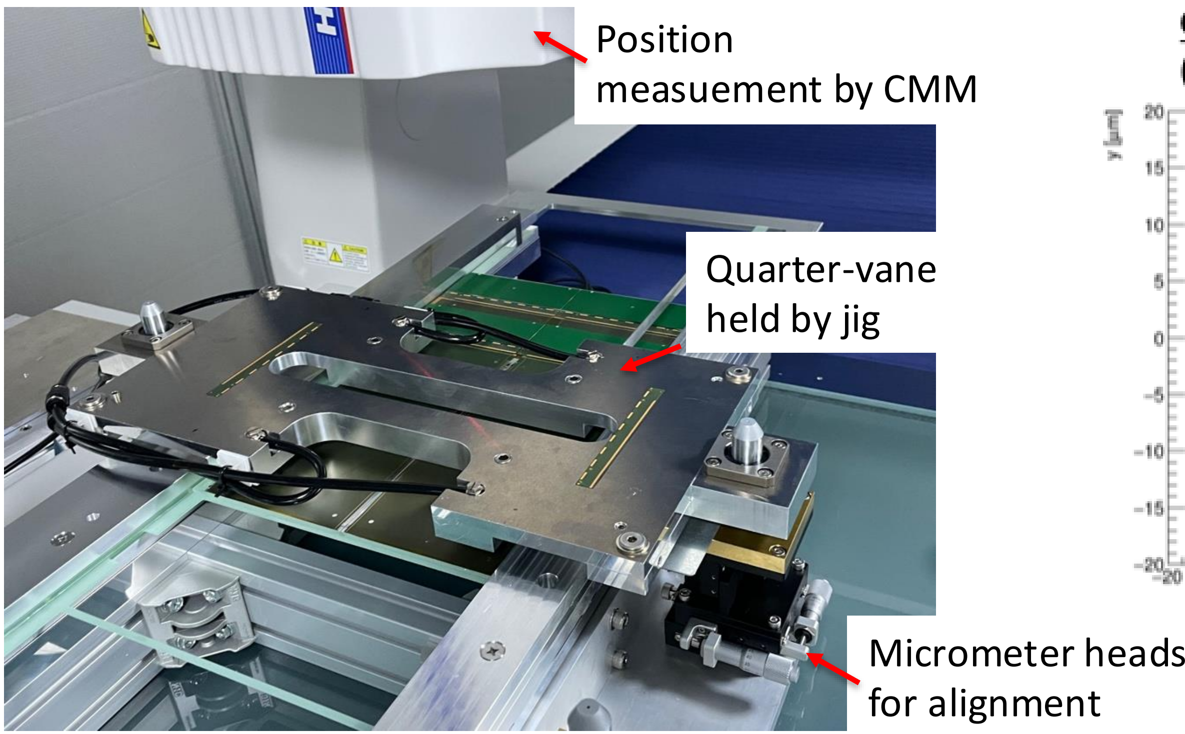
Quarter-vane to quarter-vane alignment

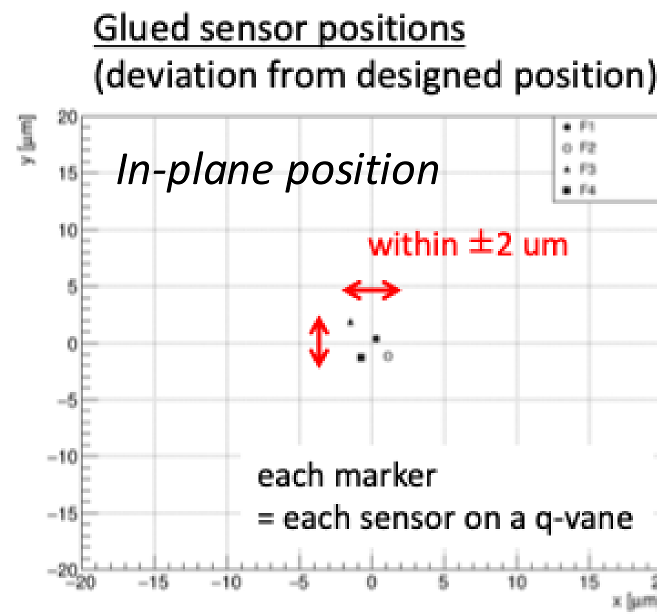
- Quarter-vane to quarter-vane alignment method is being developed based on the same principles.

<u>Challenge:</u>

No optical path for UV radiation. -> Use two-component epoxy (Araldite 2011)
-> Limited working time (~ 1 hour) before curing

- A 2 μm precision has been demonstrated in initial tests.





Summary & prospect

<u>Summary</u>

- A silicon strip tracking detector is being developed for muon g-2/EDM experiment in J-PARC.
- A precise sensor alignment with 1μm precision level is needed.
- We have developed an assembly method for detector modules achieving this precision using CMM measurement and a dedicated positioning jig.

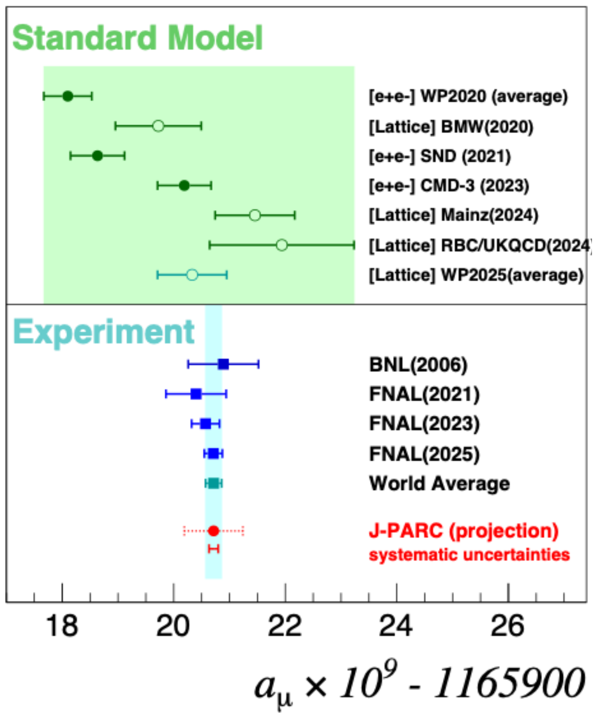
<u>Prospect</u>

- We plan to introduce digitally controlled micrometer heads so that we can reduce the assembly time.
- This method may be applicable for other detector assemblies.
  - Please contact us if you are interested.

BACKUP

Status of SM prediction of muon g-2

- SM value of muon g-2 is still ambiguous.



Recently, uncertainty of lattice QCD is largely improved. However, their result is inconsistent with (almost all) resutls from dispersive method.

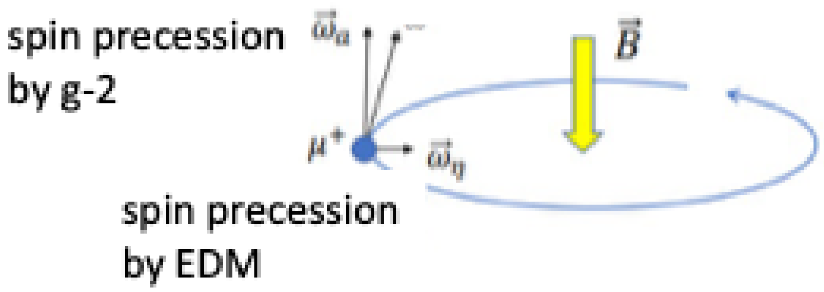
SM value dependent on HVP evaluation method.

- Filled circle：dispersive method
- Open circle：lattice QCD

- For a whole understanding of the problem, we need a new data like
  - additional e +e- hadronic cross section result (such as Belle II)
  - The third method to evaluate HVP contribution by MUonE (μe→μe elastic scattering)
  - Independent measurement of a_μ by J-PARC muon g-2

How to search for muon EDM precisely

- Both in FNAL, J-PARC experiments, the muon EDM is searched by a tiny tilt of spin precession vector.



- In previous experiments (at CERN/ BNL/FNAL) : "magic-γ approach"

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

= 0 at γ=29.3, P=3.1GeV/c

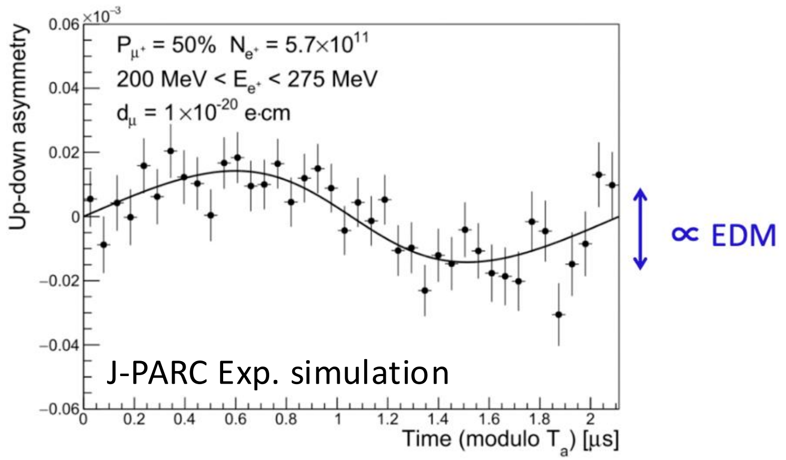
- In new experiment (at J-PARC) : "zero E-field approach"

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

= 0 at $\vec{E}$=0   = 0 at $\vec{E}$=0

- If the spin precession vector is tilted, the emitted positron direction is also tilted vertcally.
  - FNAL also utilize Straw trackers for EDM analysis.

Up-down asymmetry of detected positron



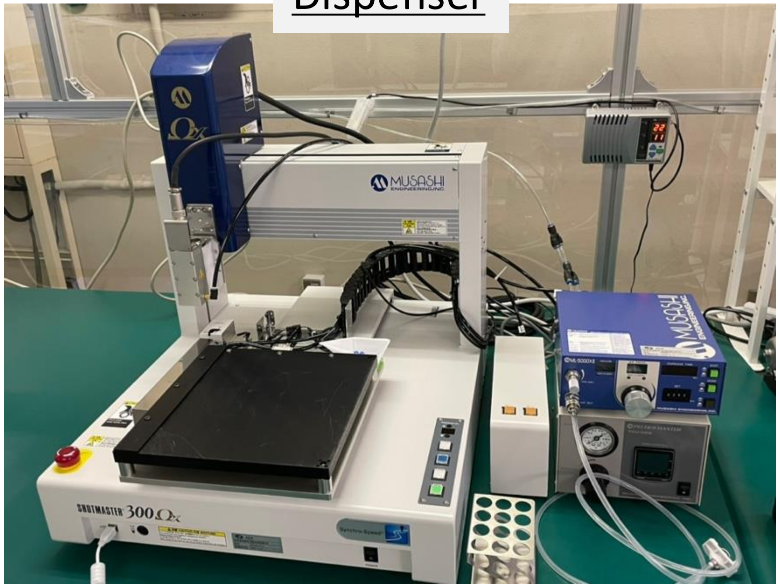
- Current limit by BNL: 1.8×10^{-19} ecm (95% C.L.)
- Expected FNAL sensitivity: (no official numbers but probably) ~ 10^{-20} ecm
- Expected J-PARC sensitivity: ~ 10^{-21} ecm

Detector assembly

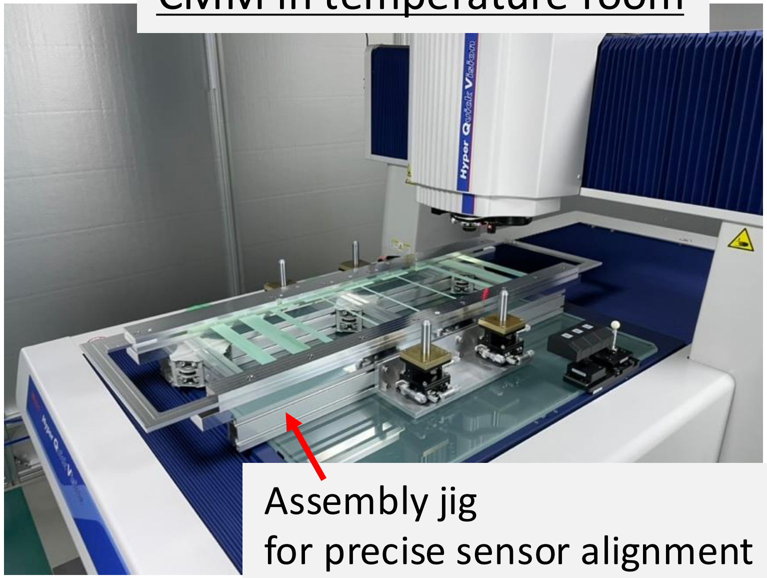
- Detector assembly procedure and environment are under preparation.

Wire bonder

Dispenser



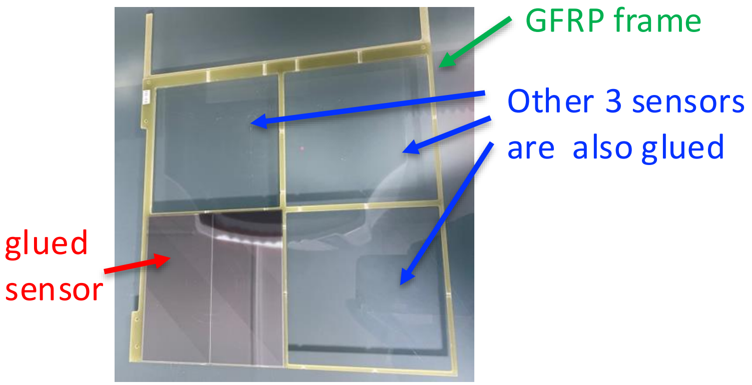
CMM in temperature room



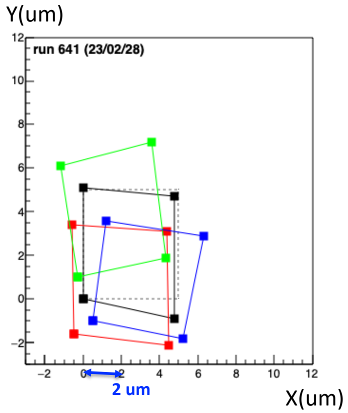
Assembly jig
for precise sensor alignment

Status of sensor gluing study

- Sensor gluing on GFRP frame (sensor base).
- Sensor position can be adjusted by using jig and CMM both horizontally and vertically.



Sensor position just after assembled (noise prototype)



Position of each glued sensor (1,2,3,4th sensor).
Deviation from ideal position (dotted gray) is shown.