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

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Anomalous magnetic moment of the muon, muon $g-2$, has been precisely measured by the experiments performed at BNL and FNAL, and there is a discrepancy of 4.2 standard deviations between the measurement and the Standard Model prediction. A new experiment based on a different strategy to measure the muon $g-2$ is planned at J-PARC. For this experiment, a silicon detector is being developed to track decay positrons. It consists of 160 sub-modules called quarter-vane, on which four $100 \times 100\,\mathrm{mm}^2$ silicon strip sensors are mounted. Assembly of the quarter-vanes will start from 2024, and its preparation is ongoing. This paper describes developed assembly procedure, including a sensor alignment method with a few μm precision.

KEYWORDS: anomalous magnetic moment of muon, tracking detector, silicon strip sensor, alignment

1. Positron tracking detector for muon g-2/EDM experiment at J-PARC

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

The anomalous magnetic moment of the muon, muon $g-2$, is a probe to search for physics beyond the Standard Model (SM). Fig.1 shows the measured result of the muon $g-2$ and its prediction from the SM. There is a 4.2 sigma discrepancy between the measurement and the prediction [1] [2], and this may be a clue for new physics beyond the SM. The muon $g-2$ can be measured from the spin precession frequency of muons stored in a uniform magnetic field. Muon spin can be known from the emission spectrum of decay positrons. The spin precession vector $\vec{\omega}$ under electromagnetic field can be written as follows:

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

where $a_\mu := (g-2)/2$. Previous experiments of muon $g-2$ utilizes muon beam of $3.1\,\mathrm{GeV}/c$ to cancel out the second term of this equation.

To understand the discrepancy of the muon $g-2$, a new experiment based on a different strategy is planned at J-PARC [3]. The key concept of this experiment is to utilize low emittance muon beam and store it in a compact magnet without a strong focusing by the electric field. Without applying any electric field on the muon storage orbit, Eq.(1) can be simplified to Eq.(2) independent from the muon momentum,

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

This enables us to use lower momentum muons (0.3 GeV/c) for the $g-2$ measurement, and to make the storage orbit smaller ($\phi = 0.66$ m with $B = 3$ T) than the previous experiments ($\phi = 14$ m with $B = 1.45$ T). A compact storage orbit will improve the uniformity of the magnetic field, and leads to a better systematic uncertainty.

The J-PARC experiment is now under construction, and its data-taking is planned from 2027. After two years of data-taking, muon $g-2$ will be measured with the statistical uncertainty of 0.45ppm, which is comparable to that in the BNL experiment.

The electric dipole moment (EDM) of muons can also be measured in this experiment. Thanks to the zero electric field on the muon storage orbit, EDM component of spin precession vector and $g-2$ component of it are perpendicular to each other. Expected statistical uncertainty will be 1.5×10^{-21} e · cm. This will improve the current upper limit by the BNL experiment by two orders of the magnitude.

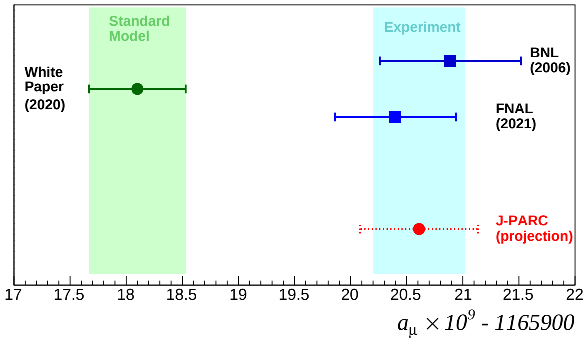

Fig. 1. Comparison of measured and predicted value of muon $g-2$. Expected uncertainty of J-PARC experiment is also shown.

1.2 Positron tracking detector

To measure the muon $g-2$ stored in a compact storage orbit, a compact positron detector is needed. Fig.2 shows the design of this positron tracking detector based on silicon strip sensors. This detector is designed to meet the requirements from the $g-2$ measurement. This detector is required to be less affected by the number of pileup positrons to reduce the systematic uncertainty of the muon $g-2$. Thanks to a fine segmentation by the silicon strip sensor, a high hit rate capability up to 6 tracks per nanosecond, and a good pileup tolerance can be achieved. Positrons in the momentum region between 200 and 275 MeV/c are used for the $g-2$ analysis, and this detector is designed to have a good detection efficiency for them as shown in Fig.3.

2. Assembly of positron tracking detector

An assembly of the positron tracking detector will start from 2024, and its preparation is ongoing. The detector consists of 40 vanes and each vane consists of four quarter-vanes. A quarter-vane consists of four silicon sensors, electric boards, cooling system, and GFRP (glass fiber reinforced plastics) frame as shown in Fig.4. Signals from the sensor strips are transferred to readout ASIC via

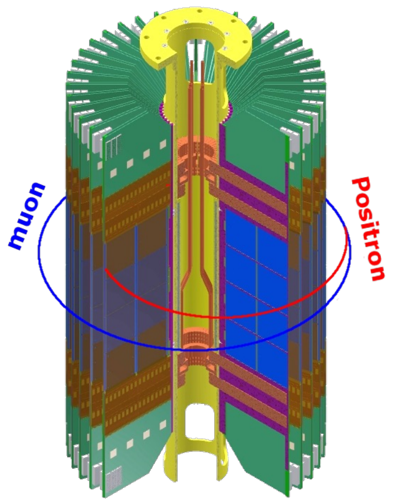

Fig. 2. Positron tracking detector for J-PARC muon $g-2$ experiment.

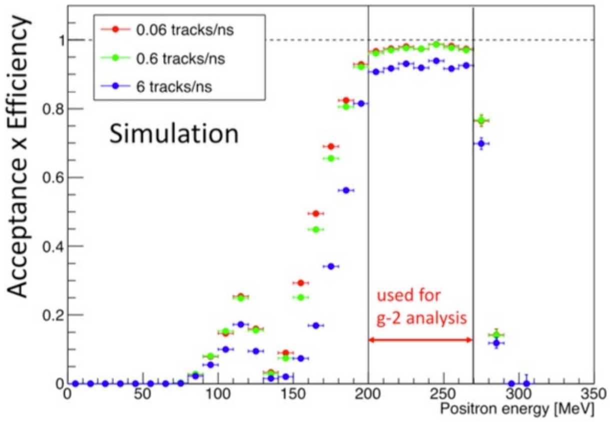

Fig. 3. Simulated detection efficiency of decay positrons as a function of their momentum.

FPC (flexible printed circuits), and are amplified and digitized in the ASIC. Digitized signals are sent to DAQ computer via FPGA on the FPGA board. Those electric parts are thermally connected to the cooling system to operate them in vacuum.

Development of silicon sensor (HPK S13804) is already completed, and its mass production is ongoing. In total, 260 sensors out of 640 sensors are already produced. All of the readout ASICs (Slit128D [4]) are already produced, and its quality assurance testing has been started. Each readout ASIC is tested by using a dedicated probe card, to identify and remove bad chips before detector assembly. Characteristics of the ASIC such as power consumption, slow control, dead channels, noise level, and timewalk are measured. Prototypes of the ASIC board, and FPGA board have also been fabricated, and they are being tested.

Since the components of this detector are getting ready for the detector assembly, a procedure to assemble them to a quarter-vane needs to be developed. This paper describes the developed assembly procedure, especially that of the gluing processes.

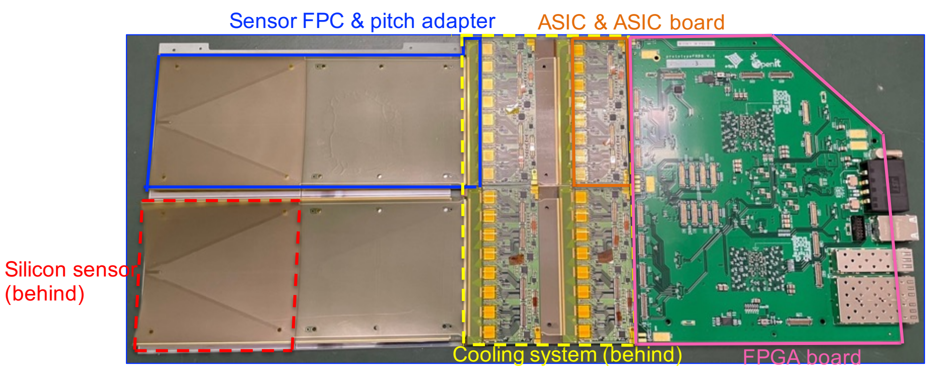

Fig. 4. A sub-module of the positron detector called quarter-vane (not assembled).

2.1 Cooling system and its assembly

Because this detector is operated in vacuum, electric parts which generate heat have to be cooled, to keep electronics correctly working and to avoid thermal expansion which can lead to sensor misalignment. The heat generation is expected to be about 32 W per one quarter-vane, and about 6 kW for the whole detector. Fig.5 is a schematic view of the cooling system for ASICs. Heat from the ASICs is transferred to three thin heat pipes (1.4 mm thick, 244 mm long, produced by Fujikura Ltd.) which are attached on the backside of the ASICs. Thermal resistance between ASICs and heat pipes are designed to be small enough. For example, thermal vias made by copper are implemented which penetrate the rigid print circuit board. The components between heat pipes and ASICs are glued by thermal conductive adhesives. The other edge of the heat pipe is cooled down by the cooling water connected to the chiller placed outside the muon storage magnet.

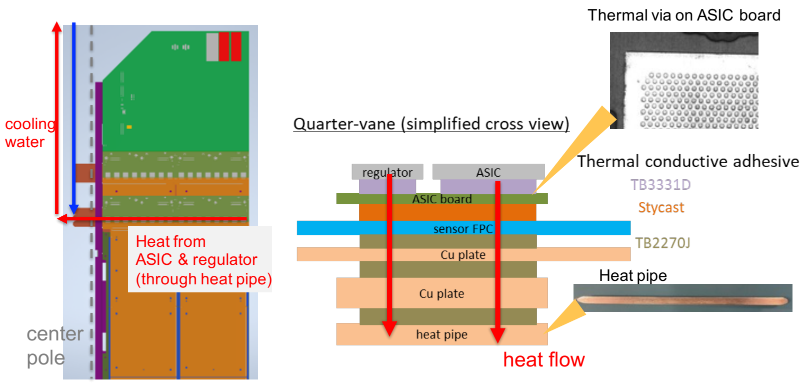

Fig. 5. A schematic view of cooling system for readout ASICs. Heat pipes are connected by a cooling water pipe installed inside the center pole (left), and the heat pipes are thermally connected to ASICs (right).

The expected cooling performance of this design is checked. The temperature difference between the heat pipe and the ASIC is calculated to be less than 10 degrees by a finite element analysis (ANSYS). The cooling performance of the heat pipe is also measured in our test setup, and its sufficient performance is already confirmed in our test (heat pipe temperature up to 35 degrees when cooled by 20 degrees water circulation). These results mean that the ASIC temperature in operation can be kept less than 45 degrees if we circulate cooling water of 20 degrees.

The assembly procedure to achieve this cooling system has been developed. Table I summarizes thermal conductive adhesives to be used for each gluing process. They are selected to meet the requirement of each process, such as curing temperature, curing time, shear strength, viscosity, and electrical conductivity.

Table I. Thermal conductive adhesives used for cooling system

Glued parts	Adhesive	thermal conductivity	requirement
ASIC on ASIC board	Three Bond 3331D	$1.6\,\mathrm{W/m\cdot K}$	electric conductivity
ASIC board on FPC	Stycast 2850FTJ	$1.3\,\mathrm{W/m\cdot K}$	room temperature curing
FPC on Cu plate A	Three Bond 2270J	$4.2\,\mathrm{W/m\cdot K}$	good thermal conductivity
Cu plate A on Cu plate B	Three Bond 2270J	$4.2\,\mathrm{W/m\cdot K}$	good thermal conductivity

Adhesive thickness has to be well controlled to achieve a good thermal conductivity between glued objects. A correct positioning of the objects to be glued and a good control of the amount of adhesive are the keys to achieve it. For this purpose, a dedicated positioning jig is developed for each gluing process. Fig.6 shows a jig used to glue ASICs on a ASIC board (a rigid board for ASIC control and readout). Both ASICs and ASIC board are held by vacuum chuck of the jigs. A given amount of adhesive is applied on the ASIC board by a dispenser (Musashi Engineering ML5000-XII). By mounting ASIC holding jig on the ASIC board holding jig, the adhesive can be pushed to have a designed thickness defined by the spacer inserted between two jigs. This setup is kept at 80 degrees for an hour to cure the adhesive.

Achieved adhesive thickness has been measured by measuring the vertical distance between the ASICs and the ASIC board. As shown in Fig.7, all the measured thicknesses are within $\pm 50\,\mu$m, and a sufficient uniformity has been achieved.

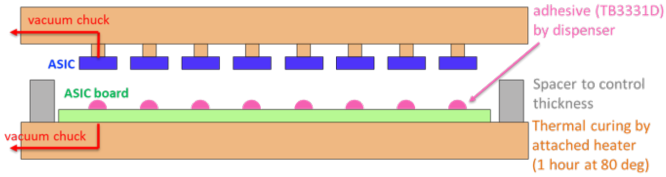

Fig. 6. A schematic view of a gluing jig (side view).

A good control of applied amount of normal adhesive can be achieved by the procedure as follows. A syringe is filled by adhesive, and bubbles inside the adhesive are removed by centrifuging of the syringe. The syringe is connected to the dispenser which can apply compressed air of a given pressure in a given time duration. Since the viscosity of normal adhesive does not change, the same amount of adhesive can be applied with the same pressure setting.

On the other hand, some gluing processes utilize two-component epoxy adhesive, Stycast. Stycast can be cured at room temperature, and thus we do not have to care about a different coefficient of thermal expansion of each component. However, due to its time dependence of the viscosity, its adhesive amount control is more difficult than the others. Fig.8 shows the time dependence of the applied amount of Stycast. Since the viscosity of Stycast increases after mixing resin and hardener, the applied amount of adhesive decreases if we apply the same pressure by the dispenser. A day-by-day variation on the amount of applied adhesive is also observed, which seems to come from some variation on the chemical reaction conditions.

To solve this, a feedback process from a test dispense just before the real dispense is found to be useful. Stycast is applied on some junk object, and weight of the applied Stycast is measured. Based on the measured weight, we can adjust the applied pressure used for the real object. Fig.8 also shows the applied amount of Stycast when we utilize this feedback method. Its time dependence is reduced to be $\pm 10\%$, which is small enough to achieve thickness uniformity.

2.2 Sensor alignment

A precise sensor alignment is required to reduce the systematic uncertainty of muon EDM measurement. As shown in Eq.(2), the spin precession caused by $g-2$ and that by EDM are perpendicular to each other. However, if the silicon sensors on the detector are rotated to the magnetic field without notice on it, the spin precession vector will be measured as rotated, and fake EDM signal appears. This sets the stringent requirements on the sensor alignment. First, each sensor has to be placed on the quarter-vane plane with a precision of $10\,\mu$rad ($1\,\mu$m precision of each $100 \times 100\,\mathrm{mm}^2$ sensor). Second, each sensor has to be placed parallel to the quarter-vane plane with a precision of $200\,\mu$rad ($20\,\mu$m precision of each sensor). To achieve these challenging precisions, a precise positioning of each sensor in detector assembly is needed as well as a precise position monitoring of sensors in

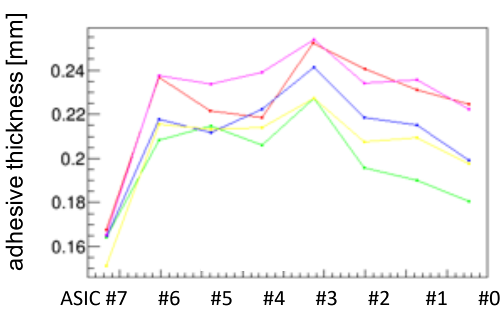

Fig. 7. Measured adhesive thickness below ASICs. Each data point corresponds to the thickness below each ASIC, and each line corresponds to each ASIC board.

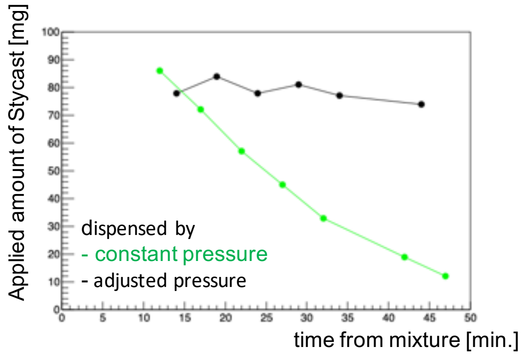

Fig. 8. Applied amount of Stycast as a function of time from mixture. Both that dispensed by constant pressure, and that dispensed by adjusted pressured based on the feedback from test dispense are shown.

data-taking.

As a first step, procedure of sensor gluing on GFRP frame to achieve sensor-to-sensor alignment on each quarter-vane is being developed. To measure sensor position, a coordinate measuring machine (CMM, Mitutoyo QVH4 Hyper 606 Pro) is used for this process. An alignment mark is implemented on each corner of the sensor, and the CMM can measure three-dimensional position of each mark with about 1 μm precision, based on an edge detection and focusing of the microscope image. To avoid thermal expansion of the object, whole gluing process is performed inside a room whose temperature is controlled to be 20 ± 1 degrees by a temperature controlled precision air processor (ORION Machinery PAP20A-F). A dedicate sensor gluing jig has been developed to precisely adjust sensor position based on the measurement by the CMM. Fig.9 shows a schematic view and picture of this jig. A sensor is hold by a jig with vacuum chuck, and the sensor and the sensor holding part of the jig can be shifted and rotated horizontally by three micrometers with 1 μm precision. Vertical position and direction of them can also be shifted by eight screws with 10 μm precision. A UV curing adhesive (Three Bond 3038) is used in this gluing process so that we can glue sensor on GFRP frame at the position after adjustment by the jig.

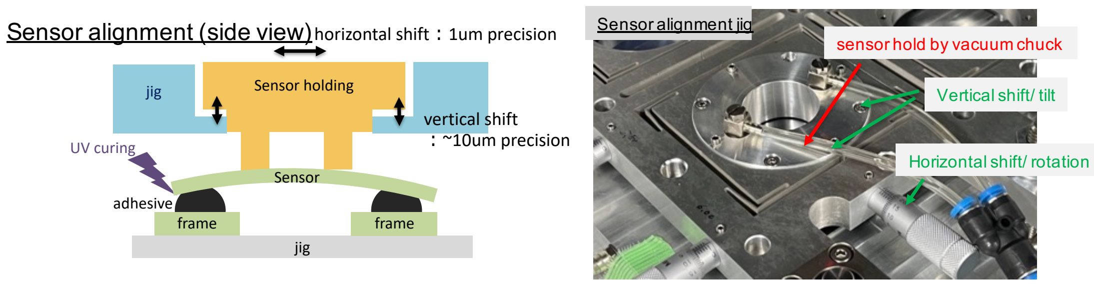

Fig. 9. A schematic side view of sensor gluing jig (left). A top view of sensor gluing jig (right).

To check the alignment precision achievable by this jig, four sensors are glued on a GFRP frame. Fig.10 shows the measured position of glued four sensors. Even though one sensor is rotated by about 2 μm from its designed position, other sensors are placed as designed. Basic concept of this jig seems working well, and further investigation is ongoing to find the cause of this 2 μm rotation to reach the final goal precision of 1 μm.

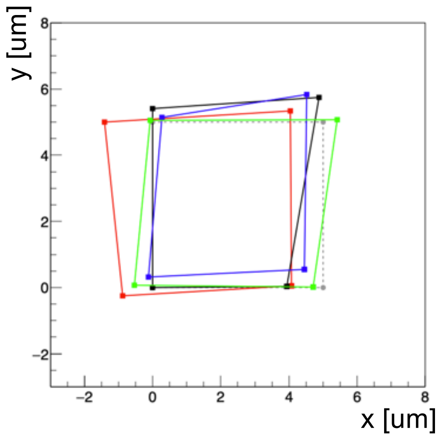

Fig. 10. Horizontal position of glued four sensors measured by the CMM. Each square corresponds to a sensor. In this plot, each side of the sensor is shrinked to 5 μm. A gray dotted square shows the designed position.

3. Summary

A positron tracking detector based on silicon strip sensors is being developed for the J-PARC muon $g-2$/EDM experiment. It consists of 160 sub-modules called quarter-vane. Assembly procedure of its cooling system has been developed, in which thickness of thermal conductive adhesive is controlled within ±50 μm precision. Precise alignment of silicon sensors with a horizontal precision of 2 μm has been achieved by utilizing dedicated sensor positioning jig and CMM under temperature controlled environment.

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References

[1] G. W. Bennett et al. (Muon g-2 Collaboration), Phys. Rev. D **73**, 072003 (2006).
[2] B. Abi et al. (Muon g-2 Collaboration), Phys. Rev. Lett. **126**, 141801 (2021).
[3] M. Abe et al., Prog. Theor. Exp. Phys. **2019**, 053C02 (2019).
[4] T. Kishishita et al., IEEE Trans Nucl Sci **vol. 67**, pp. 2089 (2020).