Fine-pitch Flexible Printed Circuit Board for Particle Physics Experiment

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The recent progress of the flexible printed circuit board (FPC) technologies has significantly contributed to the high performance and minimization of the various electric devices, typified by smartphones and wearable devices. Based on the technologies cultivated in producing these products, we have engaged in developing FPC boards for academic applications, which require more complicated designs than our current design standard for mass-produced products. This paper presents the results of development of FPC boards with fine-pitch, high-density circuits in a particle detector used in J-PARC muon g-2/EDM experiments.

1. Introduction

In recent years, electric devices such as smartphones have become smaller and more sophisticated, so flexible printed circuit boards with high-density circuits have been required to consolidate more wires in the small devices. The FPC boards with the features of thin, lightweight, and flexible have become indispensable components in recent electronics devices and have contributed to the progress of these electronic devices and met various technical demands. [1,2]

Fujikura has developed not only the FPC boards for these electronic devices but also for unique devices used in academic experiments. One of the developments for the academic experiments is fine-pitch FPC boards, which will be used in a detector for the J-PARC Muon g-2/EDM experiment, one of the next-generation particle physics experiments.

The J-PARC Muon g-2/EDM experiment is a particle physics experiment that measures the amounts of anomalous magnetic moments (g-2) and electric dipole moments (EDM) precisely to explore a new physics beyond the standard model. [3,4]

This experiment is conducted to determine the amounts of g-2 and EDM by precisely measuring the cycle of spin rotation calculated based on the track of a positron emitted from a decayed muon in the Decay e+ tracking detector. In this detector, silicon strip detectors with silicon strip sensors and readout circuit boards are used, as shown in Fig. 1.

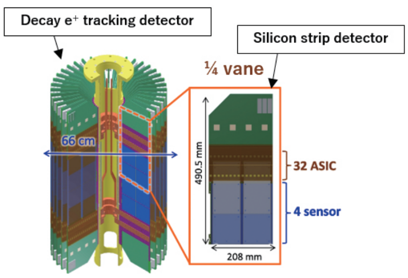

Fig. 1. Decay e⁺ tracking detector.

The silicon strip detectors can detect the track of positrons and consists of the silicon strip sensors [5,6] and the readout boards with ASICs [7].

We have developed the FPC boards, sensor FPC, and pitch adapter, which transmit signals from the silicon strip sensors to the readout boards with ASICs in Fig. 2. These two different FPC boards are laminated onto the sensors, so the boards require a low amount of substance for the material to minimize the effect of multiple scattering, which decreases the measurement accuracy of the detectors. So we need to design the FPC boards with thin conductive and insulation materials as much as possible and select materials with a low amount of substance.

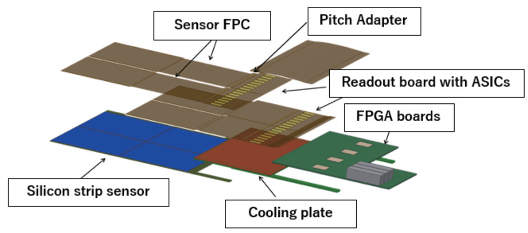

Fig. 2. FPC boards in silicon strip detector.

The complexity of the design of the sensor FPC transmitting signals from the silicon strip sensor to the pitch adapter transmitting the signals from the sensor FPC to the readout boards with ASICs presented difficulties in

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the process of the development. Nevertheless, we succeeded in developing the two FPC boards, which have satisfied the requirements for the silicon strip detector, after repeating the evaluations and trials of them.

This report outlines the development results of the two FPC boards.

2. Sensor FPC

2.1 Product description

The sensor FPC is one of the FPC boards laminated onto the silicon strip sensors and transmits electrical signals from the silicon strip sensors to near the readout boards with ASICs as shown in Fig. 3. The sensor FPC and the silicon strip sensors have connection pads on both sides of them, and the connection pads are connected each other by wire bonding. [8) 9)]

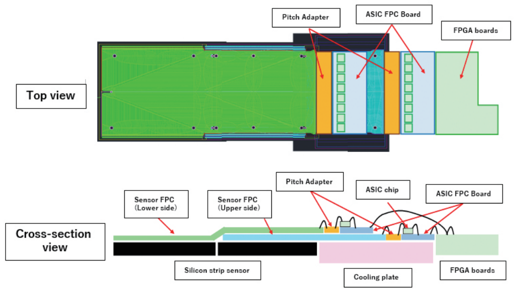

Fig. 3. Structural drawing of the silicon strip detector

Two silicon strip sensors are attached on the back surface of the sensor FPC, so the electrical signals of the two silicon strip sensors, 2,048 ch, need to be routed in the FPC board. In addition to this, the wires and connection pads also need to be arranged on one side of the sensor FPC for wire bonding. So the sensor FPC is required to be a single side FPC board with a very fine circuit pitch.

The size of the silicon strip sensor is 100 mm x 100 mm, so the size of the FPC boards with two silicon strip sensors is 94 mm x 270 mm. The size of FPC boards for various electronics devices is generally under 100 mm x 100 mm, so that the sensor FPC is very large. Generally, the larger the size of FPC boards and the finer the pitch of the circuits, the more likely the defects of the circuit will occur, so the circuit formation technologies for large areas are the key to the production.

Furthermore, the sensor FPC is laminated onto the silicon strip sensors, so it is necessary to minimize copper and polyimide thicknesses from the perspective of requirements for low amount of substance. Specifically, the copper thickness is required to be 5 μm, much thinner than the 12 μm or 18 μm of that of general FPC boards for many electric devices. From the viewpoint of FPC production, thin materials could easily cause defects, like crimps and wrinkles, when the FPC boards are handled during the various production process.

So the development of the sensor FPC with a large, thin substrate, and fine-pitch circuit, is very challenging. (Table 1)

Table 1. Required specifications of the sensor FPC

Required item	Required spec
Number of wires	2,048 lines
Wiring length	Max 200 mm
Circuit thickness	Copper 5 μm
Pad size	ASIC side : 60 μm x 200 μm
	Sensor side : 140 μm x 400 μm
FPC size	270 mm x 94 mm

2.2 Technical challenges

2.2.1 Circuit formation of fine pitch circuit

The connection pads and wires have to be arranged on only one side of the single-side FPC boards to connect the pads of the sensor FPC and the silicon strip sensors by wire bonding. So a minimum circuit pitch of 42.5 μm (Minimum Line / Space = 20 μm / 22.5 μm) is necessary to arrange 2,048 wires on one side of the FPC boards. However, it is difficult to form such fine pitch circuits without any defects in the large-size FPC boards (94 mm x 270 mm).

So we applied a design to divide the 2,048 wires in half and arrange in two FPC boards to decrease the density of the circuits. Eventually, the two FPC boards have been stacked precisely and combined into one FPC board as shown in Fig. 4.

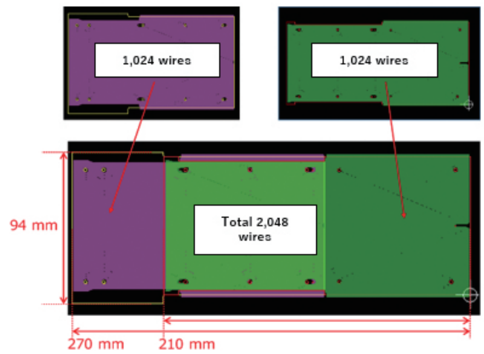

Fig. 4. Structural drawing of the sensor FPC.

With this design, we can arrange 1,024 wires with a circuit pitch of 69 μm (Minimum Line / Space = 25 μm / 44 μm) on the FPC board. However, the design of circuit pitch of 69 μm is almost the same as the minimum circuit pitch design of our mass-produced products, so the arrangement of the fine-pitch circuit of 69 μm in the large area is still challenging for our current FPC production technology, especially for the subtractive circuit formation process.

Particularly, abnormal circuit shapes, which will not be any issue in the normal mass production process, can cause critical defects, like the short defect, for such fine-pitch circuits. So we have to improve and control the process conditions of each production process more than we do for mass-produced products in the production of the sensor FPC.

2.2.2 Positional accuracy of connection pad

The sensor FPC consists of the two divided FPC boards shown in Fig. 4, so producing each FPC board needs very high dimensional accuracy. Because the position accuracy of the connection pads of the sensor FPC, which is very important for wire bonding connection between the FPC and the silicon strip sensors, highly depends on the dimensional accuracy of each board and the amount of positional shift when the boards are laminated together.

The connection pads of the silicon strip sensors and the sensor FPC are connected by wire bonding. Thus the connection pads of the sensor FPC need to be formed with high position accuracy to ensure that both pads face each other precisely when the sensor FPC is attached to the silicon strip sensors.

In terms of connection reliability, the wire needs to avoid crossing over the neighboring pads as shown in Fig. 5, even if there is a positional shift between the pads of silicon strip sensors and the sensor FPC.

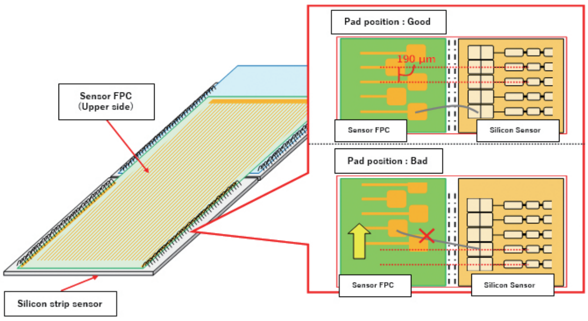

Fig. 5. Wire bonding connection image

The silicon strip sensor should be designed so that the sensor FPC has the dimensional accuracy of less than a PAD pitch (± 100um). This indicates that the dimensional accuracy and the laminating accuracy of FPC boards have to be kept within the range in the process of laminating two boards together to ensure the position accuracy of connection pads.

However, the sensor FPC is designed with thin copper and polyimide to minimize the amount of substance. Consequently, the sensor FPC is prone to the effect of dimensional shift caused by process factors, like heat, pressure, and tension. Furthermore, the large FPC size is also a factor that causes dimensional shift during various production processes.

In addition to this, high temperature and high pressure conditions are necessary to laminate the two FPC boards using a heat-curing adhesive. The dimensional shift caused by the heat and pressure in the lamination process has a more impact on the dimension shift than in other processes. So it is important to evaluate the conditions of the lamination process to minimize the dimensional shift of the sensor FPC.

2.3 Development results

Even though the FPC board with a very fine-pitch circuit and large size is very challenging to our current production technology, but we successfully produced the sensor FPC without any circuit defects by improving production conditions and environments after many trials as shown in Fig. 6.

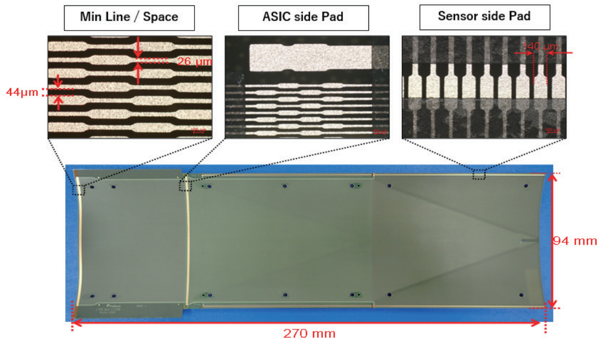

Fig. 6. Appearance of the sensor FPC.

We have been able to produce the fine circuit of a line width of 26.1 μm and space of 43.8 μm on average while the design value of the circuit pitch was 69 μm (Line / Space = 25 μm / 44 μm) as shown in table 2.

Table 2. Measurement results of the sensor FPC

Required item		Design	Measured value
Line width	Line	25 μm	26.1 ± 2.5 μm
	Space	44 μm	43.8 ± 2.8 μm
Pad width		60 μm	60.1 ± 2.4 μm
Cu thickness		5 μm	4.7 ± 0.5 μm
Ni thickness		3 μm	3.6 ± 0.8 μm

For the dimension shift of the sensor FPC, we have confirmed that the sensor FPC satisfies the pad position accuracy requirement not only by adjusting the FPC size on each production process but also by optimizing the jigs and the production condition many times in the lamination process. (Figure 7)

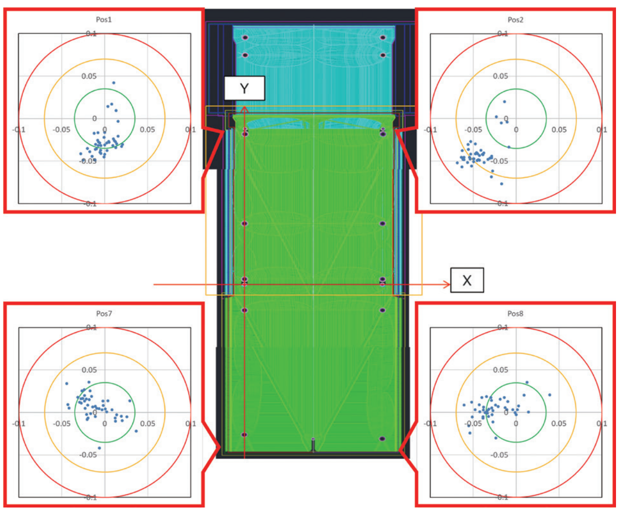

Fig. 7. Measurement Results of the position of connection pads (Green circle: 35 μm, Yellow circle: 70 μm, Red circle: 100 μm)

3. Pitch adapter FPC

3.1 Product description

The pitch adapter is a relay FPC board for connecting the wires from the sensor FPC to the readout boards with ASICs. One pitch adapter connects to a separated sensor FPC, and 1,024 wires are arranged into eight pad groups with 128 wires as shown in Fig. 8.

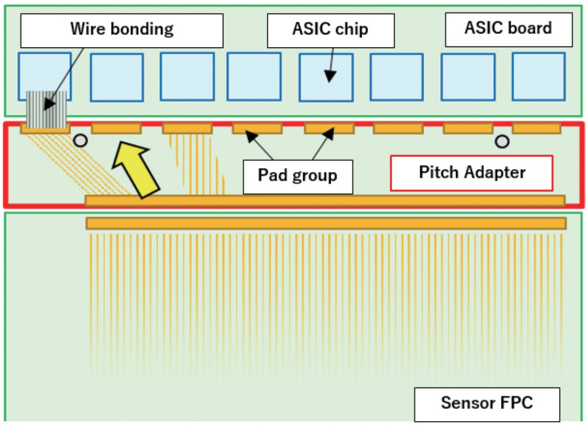

Fig. 8. Installation image of the pitch adapter

The wires of the pitch adapter are also required to be arranged on only one side of the FPC boards, as with the sensor FPC. The minimum circuit pitch needs to be 50 µm (Minimum Line/Space = 25 µm / 25 µm) to arrange 128 wires in each pad group with 6.4 mm width as shown in Table 3.

Table 3. Required specification of the pitch adapter.

Required item	Required spec
Number of wires	1,024 lines
Wiring length	Max 10 mm
Circuit thickness	Copper 6 μm
Pad size	ASIC side : 55 μm x 200 μm
	Sensor side : 60 μm x 200 μm
FPC size	104 mm x 10 mm

3.2 Technical challenges

3.2.1 Fine pitch circuit

Figure 8 shows the design of the 6.4 mm pads group connected to 128 wires on the ASICs side. In addition to this, a pad width of 50 µm or over needs to be ensured for the connection reliability in the wire bonding process. So we have set the width of connection pads to be 51.5 µm and the circuit pitch between the pads to be 30 µm (Line / Space = 11.5 µm / 18.5 µm) as shown in Fig 9.

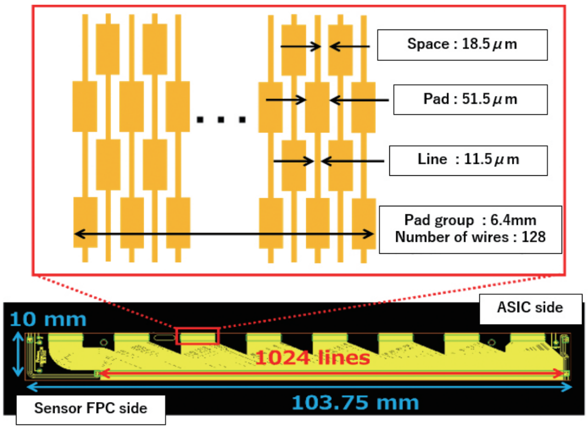

Fig. 9. Product design of pitch adapter.

However, considering the sensor FPC's development results as mentioned above, it is difficult to form the fine pitch circuits with the minimum circuit pitch of 30 µm, without any defects in 1,024 wires by using the subtractive circuit formation process.

So we have applied the semi-additive circuit formation process, which can form a finer circuit than the subtractive circuit formation process, to the circuit of the pitch adapter.

In general, controlling the semi-additive circuit formation process is more difficult than the subtractive process, and the manufacturing cost is also higher. But the semi-additive process can form a finer pitch circuit because the circuit formation by copper plating between the photosensitive dry film resist can avoid the forming of the circuit skirt at the circuit edge that occurs during the etching process as shown in Fig. 10.

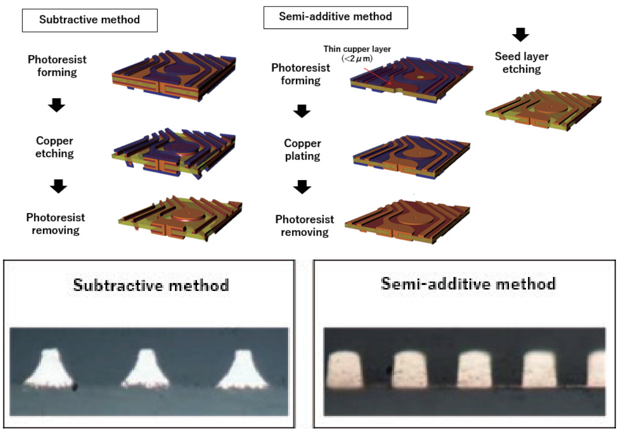

Fig. 10. Drawing of semi-additive and subtractive circuit formation process

However, as the semi-additive process is quite complicated and is prone to causing circuit defects, so it is not suitable for FPC products with large sizes.

Small-size FPC boards require a fine-pitch circuit to accommodate many wires in a small area. With a small-size FPC board, the circuit defect rate would be low even for the circuit formed by the semi-additive process. However, the defect rate in producing the FPC boards with a fine circuit pitch in a large area by using a semi-additive process is expected to be very high. Thus we need to control our production process to keep the defect rate low.

As mentioned above, developing the pitch adapter with 1,024 high–density wires, a circuit pitch of 30 µm, and a large size of 10 mm x 103.5 mm is very challenging, but we have tried to develop the pitch adapter using the semi-additive circuit formation process.

3.2.2 Dimensional accuracy requirement

The dimension of the pitch adapter is required to be within 50 µm, which is equivalent to a pad pitch on the ASICs side, to connect between the pitch adapter and readout boards with ASICs by wire bonding. So we need to develop the pitch adapter which satisfies the dimension shift of 50 µm (± 0.048%) with respect to its overall length of 103.5 mm.

3.3 Development results

We have improved the production conditions and environments several times for various production processes. We also have employed a new copper clad laminate foil, a new photosensitive dry film with higher resolution, and a direct drawing exposure machine for the exposure process to develop the pitch adapter with very fine-pitch circuits and severe dimension shift requirements. Finally, we succeeded in producing the pitch adapter as shown in Fig. 11.

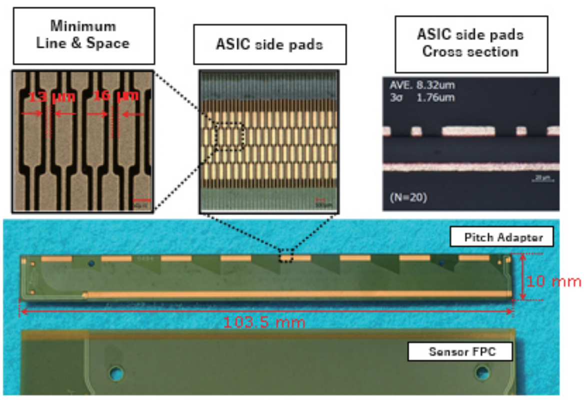

Fig. 11. The appearance of pitch adapter

3.3.1 Defects in the circuit formation process

Defects due to copper of about 5 µm width remaining between the circuits occurred frequently after the seed-layer etching process. We have judged that the remaining copper of 5 µm is fatal to forming the circuit pitch of 18.5 µm because of the insulation reliability between circuits. So the copper remaining defects significantly decreased the yield of the product, which led us to solve the problem.

As the results of cause investigation shown in Fig. 12, the problem was found to be caused by the roughness of copper of CCL foil. This indicated the need to improve the flatness of the copper surface of CCL.

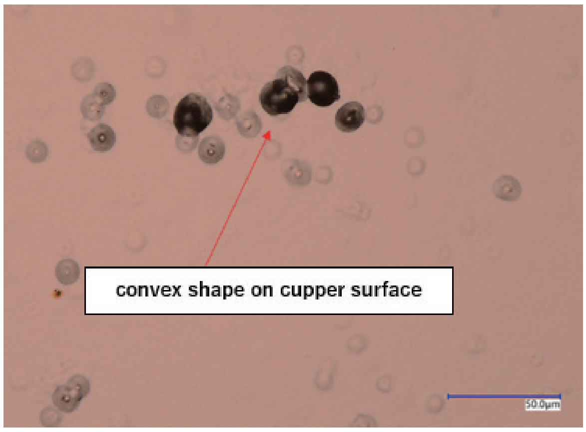

Fig. 12. Micrograph of surface of CCL for semi-additive process

We evaluated the suitability of several CCL foils to our production process, but we did not find any CCL foils among the existing products for the semi-additive process to reduce the remaining copper defect. So we have developed a new CCL foil for semi-additive process with special polyimide film, featuring low surface roughness and low dimensional change.

As a result, we succeeded in developing the pitch adapter without any circuit defects.

3.3.2 Dimension measurement results

In addition to the application of the new CCL foil with low dimensional change, we have adjusted several production conditions related to dimension change such as the tension of products during transfer in the production machine several times. As a result, we have successfully developed the pitch adapter with very low dimensional change, under 25 µm (± 0.024%) with respect to the overall length of 103.5 mm, as shown in Fig. 13. The pitch adapter which satisfies all requirements has been delivered to Kyushu University and KEK.

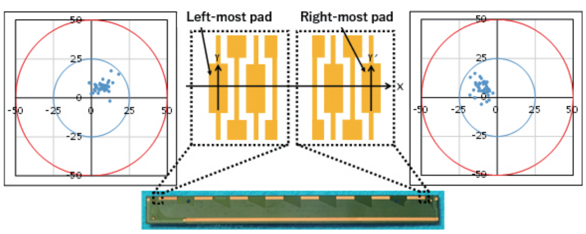

Fig. 13. Measurement results of the position of connection pads.

4. Module test results

The sensor FPC and the pitch adapter have already been installed in the test module and tested for the wire bonding by the research team of Kyushu University and KEK as shown in Fig. 14. The wire bonding test results were good, so we believe that the development of the sensor FPC and the pitch adapter was a success.

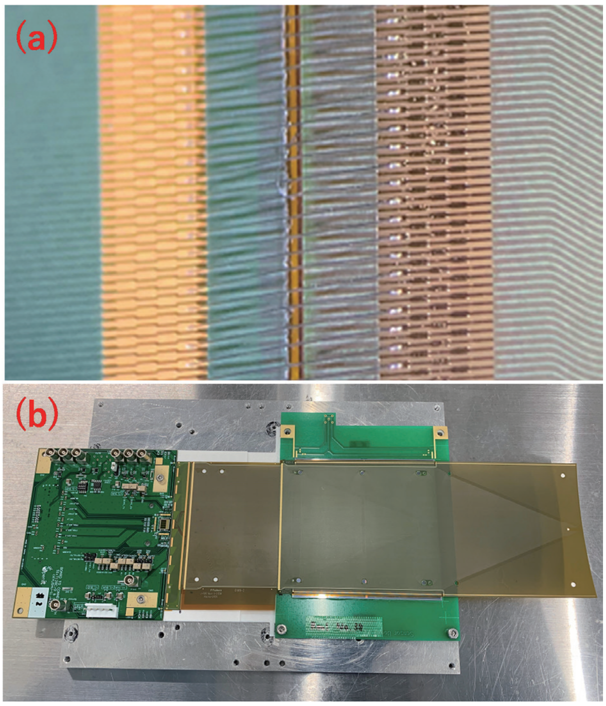

Fig. 14. Appearance of wire boing connection (a) and the test module with the FPC boards (b)

5. Conclusion

We have succeeded in developing the two types of FPC boards to be used in the silicon strip detector for the J-PARC Muon g-2/EDM experiment. The development of the two FPC boards needing a large size, fine pitch circuit, and severe dimensional control was technically demanding compared to our current production technology. However, after many trials, we finally succeeded in developing and delivering the FPC boards, which has satisfied the requirements. We also believe that we have contributed to the progress of the J-PARC Muon g-2/EDM experiment.

We will continue to search for ways to support a variety of fields with our FPC production technology.

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