The irradiation tests of Silicon pad sensors for the new ALICE FoCal detector at the LHC

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(1) A new ALICE FoCal detector at the LHC

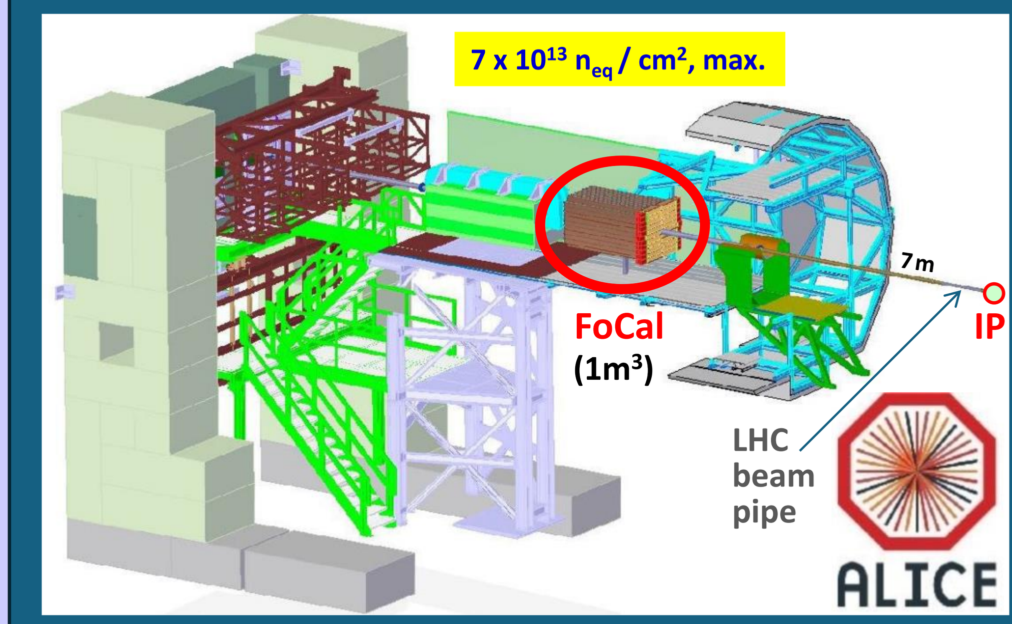

Fig. 1 A new ALICE FoCal detector at the LHC

A new forward calorimeter (FoCal) with a unique capability to measure direct photon production at the forward rapidity is going to be installed in the ALICE experiment during the next LHC long shutdown from 2027 to 2029 [1][2].

The FoCal consists of a Si+W electromagnetic component with longitudinal segmentations and a conventional scintillating-fiber hadronic component, FoCal-E and FoCal-H, respectively. It will cover the pseudorapidity interval of $3.4 < \eta < 5.8$ at a place of 7 meters from the interaction point in the ALICE cavern.

[1] Letter of Intent: A Forward Calorimeter (FoCal) in the ALICE experiment, CERN-LHCC-2020-009; LHCC-I-036.

[2] Technical Design Report of the ALICE Forward Calorimeter (FoCal), CERN-LHCC-2024-004 ; ALICE-TDR-022.

(2) The FoCal-E module

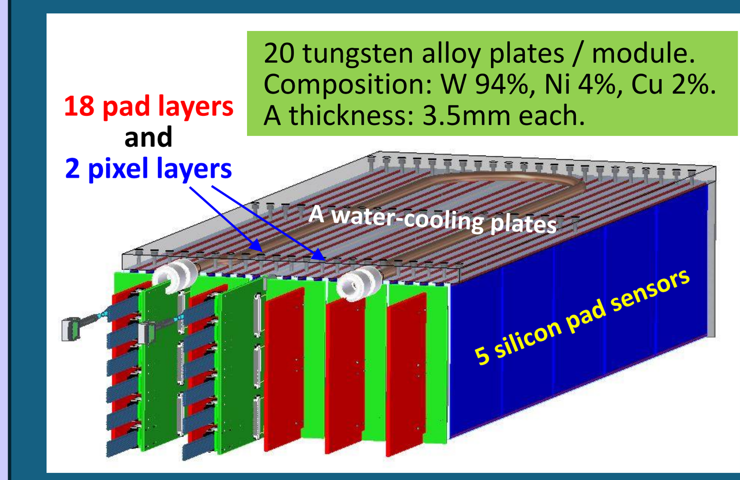

Fig. 2 One of 22 FoCal-E modules

The FoCal-E module consists of 18 low-granularity layers with silicon pad sensors and 2 high-granularity layers with silicon pixel sensors, pad layers and pixel layers, respectively.

The pad layer has 5 silicon pad sensors each on a wide tungsten alloy plate.

22 FoCal-E modules in total will be placed around the LHC beam pipe to realize the FoCal-E component.

(3) Silicon pad sensors

The main sensor for the pad layers is the p-substrate silicon PIN photodiode array with 72 main cells arranged at 10mm intervals. The size and thickness of the main sensor are 92.6mm x 82.6mm and 320µm, respectively. Two of the main cells have independent small calibration cells in that area.

The important requirements to silicon pad sensors are listed as follows:

1) the wider dynamic range,
2) a better S/N for the MIP measurement,
3) a higher radiation tolerant, and
4) no bad cell with the over leakage current.

There are small sensors called monitor photodiodes and baby sensors around the main sensor and it is available to some tests.

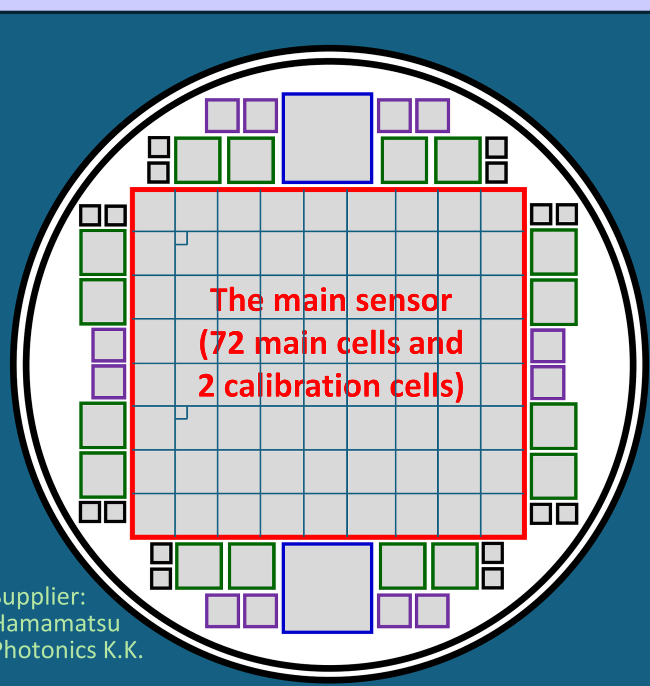

Fig. 3 Some small sensors called baby sensors and monitor PDs are available around the main sensor on the same 6-inch wafer for testing.

(4) An irradiation test

It is estimated that the FoCal will be exposed to approximately 7×10^{13} neutron equivalent per cm² at the maximum during the operation in the ALICE cavern. It is important to examine how much characteristics of the silicon pad sensors change by a radiation damage.

An irradiation test of the silicon pad sensors was carried out at the RANS (RIKEN Accelerator-driven compact Neutron Sources) in July, 2023 as shown in Figure 4. Some monitor photodiodes without guard rings and baby sensors with guard rings were glued on the surfaces of the 1st and 3rd PCBs and two main sensors with guard rings were placed on the surface and back side of the 2nd PCB each as shown in Figures 5 and 6. Some of these small sensors were connected to the DAQ system through high-voltage triaxial cables for measuring I-V characteristics . Small pieces of the indium foils and thermometers were also put on PCBs and near the sensors, respectively, in a black box.

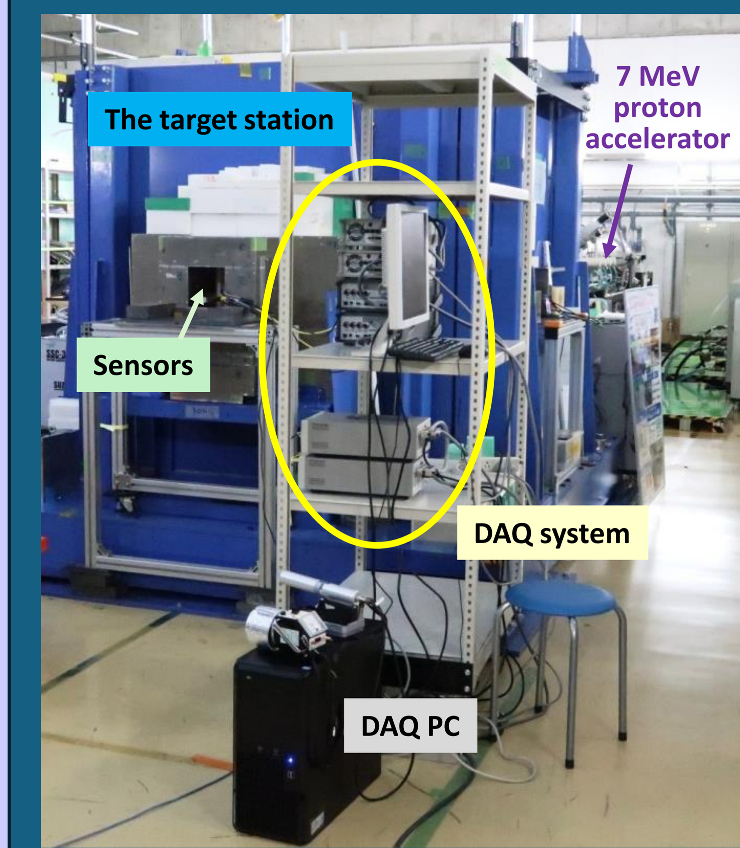

Fig. 4 A test setup at the RANS facility.

The sensors were irradiated by neutron beams in the target station in the daytimes of the 1st and 2nd days. It had no beam at nights. According to an estimation using the indium foil data, the most irradiated sensors got about 5×10^{13} neutron equivalent per cm² at the maximum in 2 days.

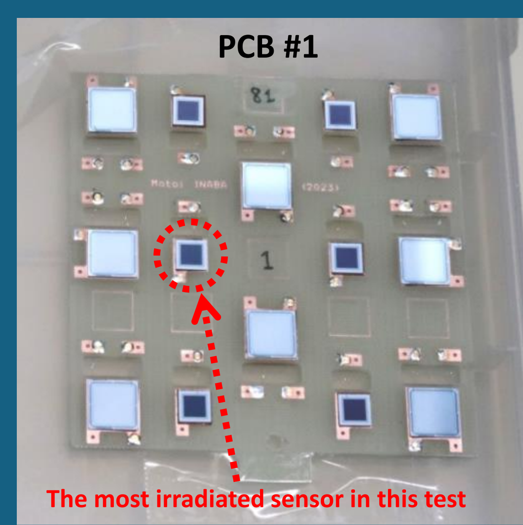

Fig. 5 Sensors on the 1st PCB.

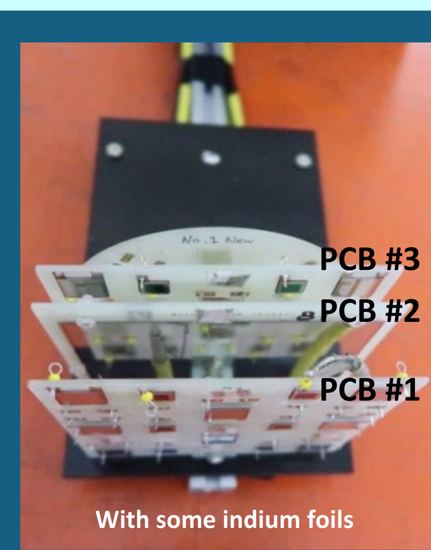

Fig. 6 Sensors in a black box.

The neutron beam was stopped at intervals of an hour for measuring the I-V characteristics of the sensors. Figure 7 shows an increase of the measured current of the most-irradiated monitor photodiode on the 1st PCB. The current went up to about 35µA at a bias voltage of 500V in the 1st day. It had no beam at night and the current decreased slowly by a short-term annealing, a self recovery in other words, in a room temperature. The current went up more by the beam in the 2nd day. The largest measured current at a bias voltage of 500V was approximately equal to 90µA, but it seems to include the temperature dependence effect caused by a large current, namely a self-heating effect. After the irradiation test for 2 days, the sensors were taken out from the target station and a change of the current was monitored in a room of the radiation control area for more than 2 months continuously as shown in Figure 8. Small fluctuations happened in a room temperature although it was an air-conditioned room. For example, a drop and an increase of the currents in the 7th and 40th day, respectively, in Figure 8 were consistent with the measured temperatures. Finally, the measured current went down to 41µA at a bias voltage of 500V when a room temperature was 24.0 degrees C.

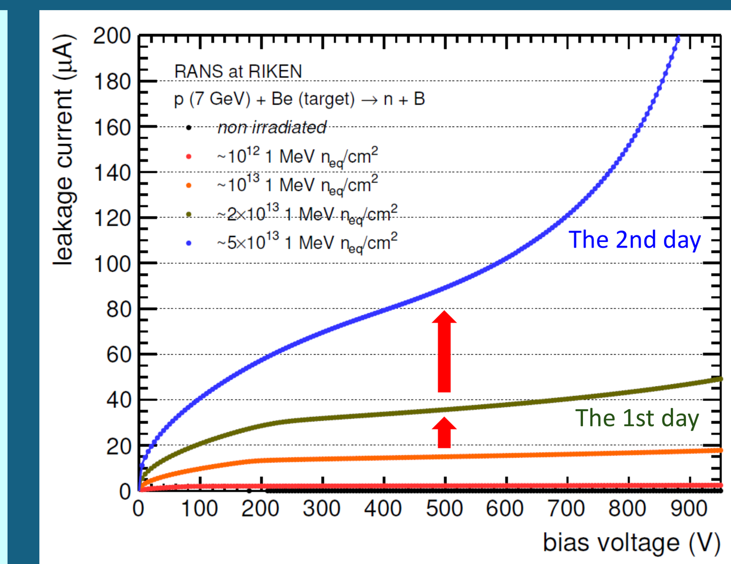

Fig. 7 An increase of the measured current.

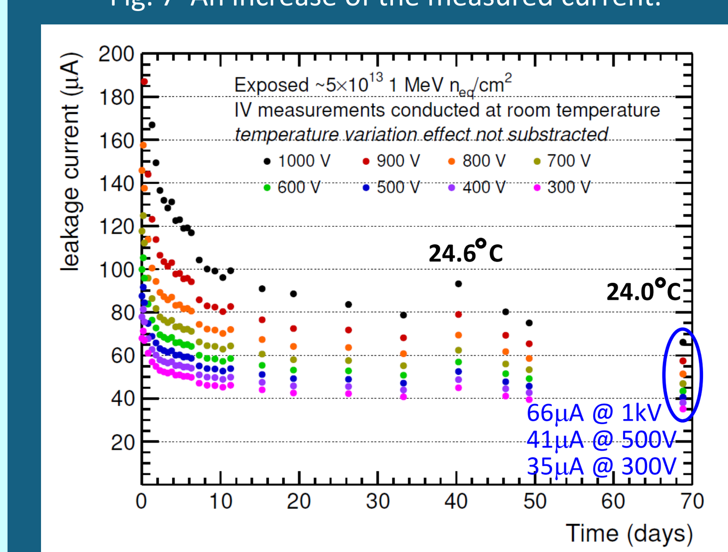

Fig. 8 A change of the current for more than 2 months.

(5) Temperature dependence

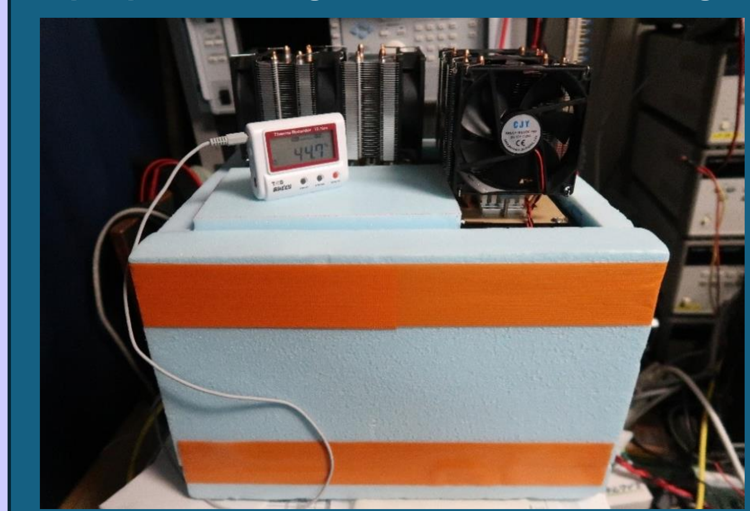

Fig. 9 A new temperature-controllable black box.

The sensors were activated by neutron beams in the irradiation test and it took us more than two months to be able to take it out from the radiation control area in Riken. After the sensors came back to our laboratory, we measured the temperature dependence of the I-V characteristics of the irradiated sensors using a new cooling / heating test bench as shown in Figure 9. It has 4 Peltier elements on a lid of the black box as shown in Figure 10 and it is possible to control a temperature of the irradiated sensors in the black box widely and precisely.

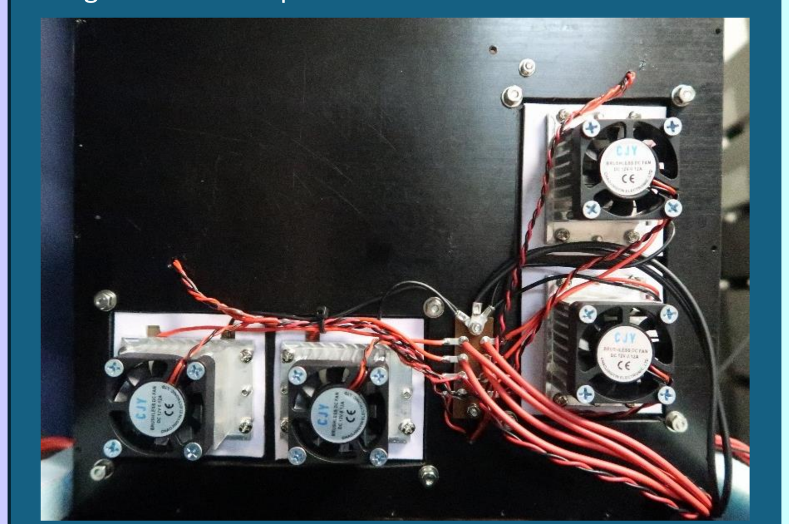

Fig. 10 Peltier elements on a lid of the black box.

Figure 11 shows the I-V characteristics of the most-irradiated sensor when the temperature was changed from 13.5 to 28.0 degrees C. It says that the leakage current of the irradiated sensor is very sensitive to a temperature.

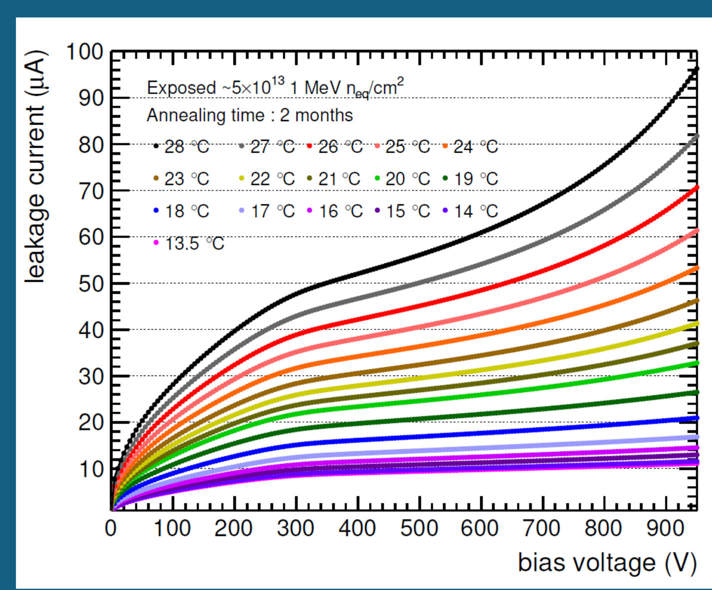

Fig. 11 The temperature dependence.

We also tried to estimate the full-depletion voltages of the irradiated sensors from the I-V characteristics. On the assumption that an increasing rate of the leakage current becomes smaller after the full-depletion point, the full-depletion voltages of the most-irradiated monitor photodiode is approximately equal to 270V and it seemed to be higher than that of irradiated baby sensor with guard rings. Therefore, 500 V is reasonable as the operation voltage for the pad layers including a voltage drop on a bias resistor.

(6) A beam test of the irradiated sensors

A 10-layer PCB with the HGCROC V2 chip was glued on the surface of one of the irradiated main sensors, and it was tested at the Tohoku Univ. ELPH test beam line as shown in Figures 13 and 14 in February, 2024 after wire bonding as shown in Figure 12. A clear signal peak separated from the pedestal peak was observed.

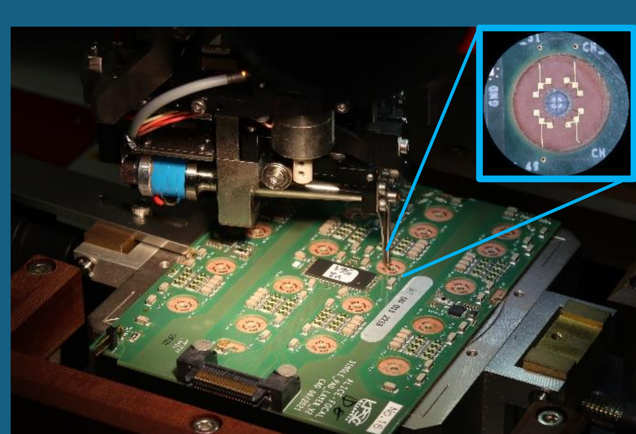

Fig. 12 Wire bonding of the single-pad-layer.

Fig. 13 A setup at the ELPH test beam line in 2024.

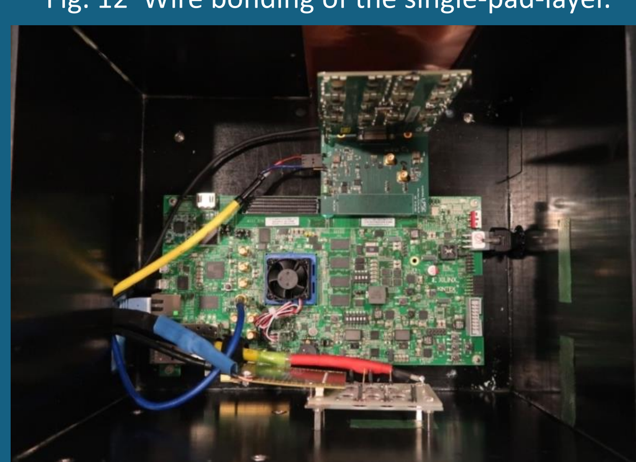

Fig. 14 The irradiated sensors in the black box.

(7) Summary

R & D of the FoCal-E module for the new ALICE FoCal detector at the LHC is coming to the final stage. To examine the influence of the radiation damage on the silicon pad sensors for the low-granularity layers, an irradiation test was carried out at the RANS facility in 2023. According to an estimation using indium foils, one of the monitor photodiodes on the 1st PCB got about 5×10^{13} neutron equivalent per cm² at the maximum in 2 days, and the measured current had increased to 90µA at a bias voltage of 500V including a self-heating effect. After a lapse of more than 2 months in a room temperature, it went down to 41µA. Test results of the temperature dependence using a new cooling / heating test bench said that a leakage current of the irradiate sensor was very sensitive to a temperature. To realize a single-pad-layer for testing, a 10-layer PCB with the HGCROC V2 chip was glued on one of the irradiated main sensors and some bonding wires were put between the sensor and PCB. A clear separation of a signal peak from the pedestal peak was confirmed at 13.0 degrees C at the Tohoku Univ. ELPH test beam line in 2024. For the overall operation of the FoCal detector in a room temperature, we are going to do a trial production of the thinner sensors in parallel with mass production of half the number of silicon pad sensors in Japan this year.

16TH PISA MEETING ON ADVANCED DETECTORS, La Biodola, Isola d'Elba, May 26 - June 1, 2024.