# Estimation of Neutron dose during the Irradiation test of p-type Silicon Sensor for ALICE FoCal detector

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**Abstract.** What is unknown about Quark-Gluon Plasma (QGP) in heavy ion collisions is that it reaches thermal equilibrium much earlier than theoretically expected. And the Color Glass Condensate (CGC) is a strong candidate to explain this. The future forward calorimeter (FoCal), consisting of an electromagnetic calorimeter and a hadron calorimeter, is being developed to detect CGC experimentally. Since this calorimeter will be installed in the forward region from collision point, where it will be exposed to a large neutron dose, so we plan to use a p-type silicon sensor, known for its high neutron tolerance. And we need to investigate this radiation tolerance. To evaluate this, a neutron irradiation test was conducted at RIKEN (RANS) in July 2023. In this test, indium foil with highly sensitive to the amount of neutron irradiation was placed around the silicon sensor and irradiated with a neutron beam of about $10^{14} n_{eq}/cm^2$ at the maximum, as assumed in the ALICE experiment. Since the neutron dose depends on the distance from the beam, then estimated the dose of the silicon sensor by analyzing the indium foil dose. As a result of this estimation, it was found that the silicon sensor with the highest neutron dose reached about $5 \times 10^{13} n_{eq}/cm^2$.

## 1 Introduction

Quarks and gluons, which are normally confined within hadrons by strong interactions, are released from this confinement at high temperatures and densities, which is called Quark-Gluon Plasma (QGP). The QGP is believed to have existed a few 10 $\mu$s after the birth of the universe and elucidating its nature will lead to an understanding of early universe. However, the fact that the QGP reached thermal equilibrium within an extremely short period of time after the collision remains a major mystery. To solve this mystery, it is essential to understand the internal state of atomic nuclei just before they collide and to experimentally verify Color Glass Condensate (CGC) [2]. The future forward calorimeter (FoCal) [3], which consists of an electromagnetic calorimeter and a hadron calorimeter, is being developed for this verification in the A Large Ion Collider Experiment (ALICE) [4], which is currently operating at Large Hadron Collider (LHC) at CERN. It is intended for experimental validation of CGC by accessing small-x region and measuring direct photons.

Since this calorimeter will be installed in the forward region, where it will be exposed to large neutron dose, we plan to use a p-type silicon sensor, known for its high neutron tolerance. In addition, this sensor is known for the more exposed to radiation ([3, 5–8]), the more their characteristics change rapidly. Therefore, it is necessary to investigate the radiation tolerance of the p-type silicon sensor and how its characteristics change if they are exposed to the amount planned for the ALICE experiment. To evaluate the radiation tolerance of p-type silicon sensor, neutron irradiation test was conducted at the RIKEN RANS (RIKEN Accelerator-Driven Compact Neutron Source, in Japan [1]) in July 2023. The goal of this test is to irradiate around $10^{14}$ $n_{eq}/cm^2$ at the maximum, which is assumed in the ALICE experiment. In this test, indium foils with highly sensitive to the amount of neutron were placed around the p-type silicon sensors and irradiated neutron beam. By determining the neutron irradiation dose from the indium foil analysis, we estimated how many neutrons were irradiated to each sensor.

In this paper, we describe the outline of this test and the status of neutron irradiation dose analysis using indium foil.

## 2 Measuring method of total neutron dose

### 2.1 Outline of Neutron Irradiation test at RANS

In this test, a total of 9 neutron irradiation was performed, which is referred to here as Run1 ~ Run9. The parameters for each Run are shown in Table.1 below. The [time] means the irradiation time of the neutron beam, the [current] means the current value for each Run, and the [irradiation amount] is the Charge of below Eq.1. In this Table.1, for Run2 ~ Run9, [time] is the total and [current] is the average for each run.

**Table 1.** proton beam parameter

| Run No. | 1 | 2~9 |
|---|---|---|
| time[sec] | 3634 | 25676 |
| current[$\mu$A] | 6.470 | 34.222 |
| irradiation amount[C] | 0.0186 | 0.8437 |

In this test, neutron irradiation was performed with indium foil only in Run 1, and the total neutron dose was determined by scaling the time and current values of each Run based on the results of the analysis. The RANS (RIKEN Accelerator-Driven Compact Neutron Source) used in this test irradiates a proton beam to the target (Be) and irradiates the sensor with neutrons emitted the result of this interaction. The parameters in the table 1 are the values for the proton beam, since the number of protons irradiated is proportional to the neutron dose emitted, so this value is used. The relation of each value is shown in Eq.1 below.

$$\text{Charge(proton beam)[C]} = \text{current}[\mu\text{A}] \times \text{time[sec]} \quad (1)$$

The goal of this test is to irradiate around $10^{14} n_{eq}/cm^2$. In addition, as shown in the figure 1 below, the 4 layers of the substrate to which the sensor was installed were placed in order from left to right and irradiated from the front of the first layer (left).

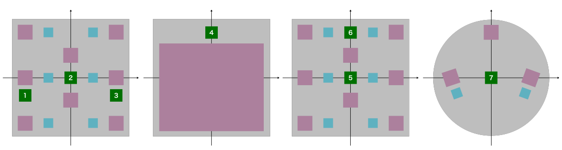


**Figure 1.** 4 layers substrate (figure)

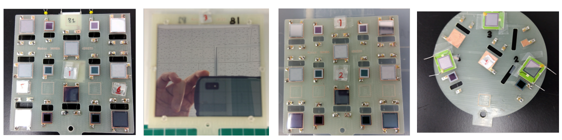

**Figure 2.** 4 layers substrate (picture)

In Figure 1, the green color shows the indium foil and others show silicon sensors. In this test, seven indium foils were used, the arrangement of which is shown in Figure 2.

## 2.2 Evaluation of neutron dose

Next, a method for estimating the neutron dose using indium foil will be described. When a neutron hits the indium foil, it moves to the excited state, and then moves from the excited to the ground state by emitting $\gamma$-rays at 336 keV, and this $\gamma$ dose is proportional to the neutron dose (following Eq.2).

$$N = \frac{1}{\sigma} \cdot \frac{\lambda M t_i}{m R N_A B_\gamma \epsilon_{cap} (1 - e^{-\lambda t_i}) e^{-\lambda t_c} (1 - e^{-\lambda t_m})} \cdot A \quad (2)$$

In this Eq.2, N is the neutron dose, A is the gamma dose, and the others are variables that can be determined by each indium foil. (describe below) M is the Atomic weight, R is Isotopic presence ratio, m is the mass of indium foil, $\epsilon_{cap}$ is Detection efficiency, $t_i$ is irradiation time, $t_c$ is cooling time, and $t_m$ is measurement time.

As the next step, we will describe how to analyze the $\gamma$ dose emitted from indium foil. In this test, $\gamma$ doses were measured using a germanium detector. The $\gamma$ rays are incident on the detector, and because of their interaction, secondary electrons are generated. The ionizing action of these electrons creates electron-hole pairs in the germanium crystal, and this number corresponds to the number of energies. Measurements are made by collecting these charges and converting them into electrical signals.

The following Figure 3 shows the measured energy spectrum, with the horizontal axis representing the channels corresponding to each energy, and the vertical axis representing the number of counts for that channel. To obtain the $\gamma$ dose at 336 keV, the $\gamma$ dose by integrating the peaks around the 1340 channels corresponding to the energy of 336 keV using the Gaussian function.

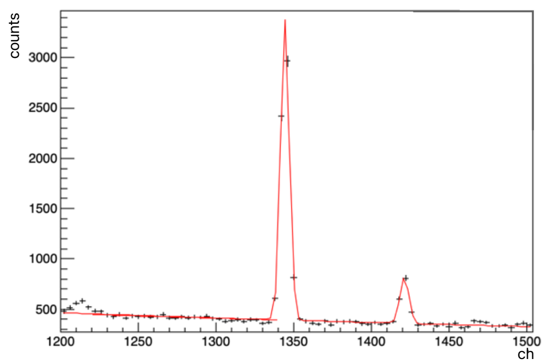


**Figure 3.** 336keV (around 1340 channel) peak

In the case of Figure 3, the $\gamma$ dose is around 5300 counts and the neutron count is $2.43 \times 10^{12}$ $n_{eq}/cm^2$ based on the above formula. Using this value, the total neutron dose is determined using the proton beam parameters in Table.1.

The following Eq.3 is used to determine the total neutron dose.

$$N_{eachRun} = N_{Run1} \cdot \frac{I_{each} \cdot t_{i_{each}}}{I_{In} \cdot t_{i_{In}}} \tag{3}$$

Calculate the neutron dose for each Run by scaling from the beam amount of Run 1 (denominator, using indium foil) to the beam amount of each Run (numerator) [Table.1]. In this equation, $I_{In}$ and $t_{i_{In}}$ are the beam current value and beam irradiation time of Run1, respectively, and $I_{each}$ and $t_{i_{each}}$ are also the beam current value and beam irradiation time of each Run, respectively.

### 2.3 Results

The following Figure 4 shows the result of adding up the neutron doses for each Run obtained by the above method.

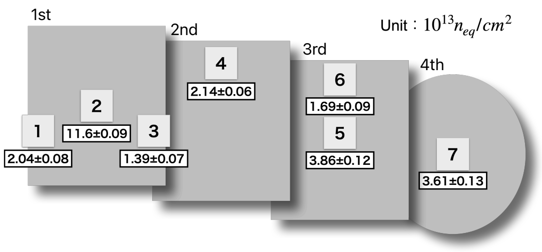


**Figure 4.** Results of the indium foils total neutron dose

As a result, the total neutron dose achieved the target value of $10^{14}$ $n_{eq}/cm^2$. In addition, when comparing the indium foils (#1, 3) in the 1st layer, the neutron dose of #1 is higher than the neutron dose of #3. Therefore, it was also found that the neutron beam is off-center and on the left. In addition, the indium foils (#2, 5, and 7) located in the center are reduced by $1/z^2$ in the depth direction relative to the beam axis z, this indicating that neutrons are irradiated in a conical shape.

## 3 Neutron dose for sensors

### 3.1 Estimation method

Next, we describe the method for estimating the neutron dose of the sensors around the indium foil from the results of the above Figure 4. The neutron dose of the sensor is calculated assuming that the neutron radiation spreads from the center and decreases exponentially, as shown in Figure 5.

The neutron dose of the sensor was determined from the neutron dose of the central indium foil and the rest of the indium foil and the distance between them. The Eq.4 is shown below.

$$N_{sen} = N_c \cdot exp\left(\frac{1}{L_{In}} ln\left(\frac{N_{In}}{N_c}\right) \times L_{sen}\right) \tag{4}$$

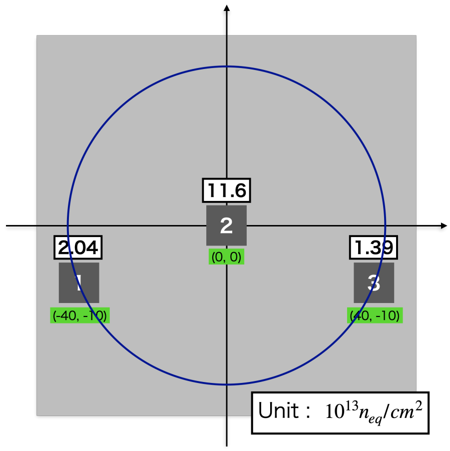


**Figure 5.** Estimation method of sensor

This equation is used to estimate the neutron dose of the sensor ($N_{sen}$), where $N_c$ is the neutron dose of the indium foil located at the center, $N_{In}$ is the neutron dose of the other indium foils, $L_{sen}$ is the distance between the sensor and the indium foil (center), $L_{In}$ is the distance between the center and the other indium foils.

### 3.2 Results: Neutron dose (sensor)

The following figure shows the estimated neutron dose of the sensor, estimated from the total neutron dose of the indium foil.

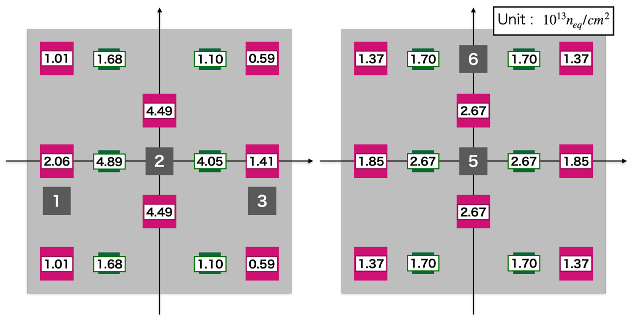


**Figure 6.** Estimation method of sensor [1st layer (left), 3rd layer(right)]

From these results, the neutron dose was estimated to be about $5 \times 10^{13}$ $n_{eq}/cm^2$ for the most irradiated sensor (in Figure 6, left, green-colored sensor, $4.89 \times 10^{13}$ $n_{eq}/cm^2$), and the neutron dose irradiated by each sensor was different. In addition, when comparing the neutron doses of sensors located in the center and corners of the 1st and 3rd layers (see Figure 6), it was found that the difference between the 3rd layer was small. As shown in Section 2.3, it was found that neutrons were irradiated in a conical shape,

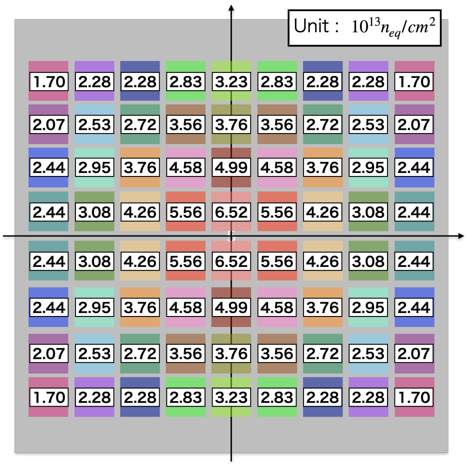


**Figure 7.** Estimation method of sensor [2nd layer]

so they are uniformly irradiated in the depth direction with respect to the beam axis.

In addition, when the neutron dose of the $8 \times 9$ $cm^2$ silicon sensor (in Figure 7, a large sensor equipped with $8 \times 9$ $1 \times 1$ $cm^2$ sensors) on the second layer of the substrate was estimated for each sensor, it was found that the neutron dose of each sensor was also different.

To investigate the radiation tolerance of the p-type silicon sensor, this result is used to confirm the correlation between the change in the characteristics of the sensor before and after irradiation and the irradiation neutron dose. (See Mr. Inaba ’ s proceeding)

## 4 Summary

In order to evaluate the performance of the p-type silicon sensor, neutron irradiation test was conducted at RIKEN RANS (the neutron source) in July 2023. Since the neutron dose irradiated to the sensor is unknown, indium foil, which is highly sensitive to neutrons, was lined up on the substrate together with the sensor and irradiated with neutrons to obtain the neutron dose. The neutron dose was obtained by measuring the amount of $\gamma$-rays emitted when the indium foil was irradiated with neutrons.

The results show that the total neutron dose achieved the target value ($10^{14} n_{eq}/cm^2$), which is assumed in the experiment. It was also found that the neutron beam is off-center, and the indium foils (#2, 5, and 7) located in the center are reduced by $1/z^2$ in the depth direction relative to the beam axis z. This indicates that the neutrons are irradiated in a conical shape.

In addition, from this result, it was possible to estimate the neutron dose of each p-type silicon sensor, and it was found that the neutron dose was different for each sensor. And it was found that the neutron dose was spread out in the depth direction with respect to the beam axis and irradiated uniformly.

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