

Master's Dissertation
修士論文

Impact of Radiation Damage on
Performance of Monolithic CMOS
Pixel Sensor for Vertex Detector
Upgrade at Belle II
(Belle II実験の崩壊点位置検出器高度化
に向けたモノリシックCMOSピクセルセ
ンサーの性能への放射線損傷の影響)

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Abstract

Belle II, a particle physics experiment operating at the B factory, SuperKEKB accelerator, explores physics beyond the Standard Model using large amount of $\Upsilon(4S) \rightarrow B\bar{B}$ events generated from e^+e^- collisions. Due to the re-design of Interaction Region for further performance improvement of SuperKEKB, an upgrade project of the innermost vertex detector named VTX, is being studied. It is also expected to provide better background tolerance and physics performance. VTX makes use of Depleted Monolithic Pixel Sensor (DMAPS) technology in its sensor unit. The same matrix design with a DMAPS prototype, TJ-Monopix2, is used in the sensor development. Since the innermost vertex detector is exposed to a large amount of radiation during the operation of the Belle II experiment, it is necessary to evaluate the impact of radiation to the characteristics and performance of the TJ-Monopix2 prototype, in order to understand the potential performance degradation and characteristic change of VTX after long-term operation.

In this work, a TJ-Monopix2 sensor is irradiated up to accumulated NIEL flux of $5.57 \times 10^{14} \text{ } n_{\text{eq}}\text{cm}^{-2}$ corresponding to irradiation expectation at Belle II experiment using the 90 MeV electron beam at RARiS (Research Center for Accelerator and Radioisotope Science), Tohoku University. Laboratory characterization and test beam campaigns at DESY II Test Beam facility and KEK PF-AR Test Beam Line were performed before and after irradiation, to check the performance degradation and whether the performance still meets the requirement at the Belle II experiment. The performance comparison between DC and AC front-end designs of TJ-Monopix2 also provides a reference for the future design of sensors which is being developed based on the TJ-Monopix2 design.

As a result, after irradiated with electrons up to the accumulated NIEL flux of $5.57 \times 10^{14} \text{ } n_{\text{eq}}\text{cm}^{-2}$, detection efficiency of TJ-Monopix2 degrades but can be restored back to more than 99% by applying higher bias voltage and using configurations with low detection threshold. The spatial resolution remains within the requirement of upgrade baseline. After irradiation, the DC front-end remains a higher charge collection efficiency than the AC front-end, while the AC front-end shows better restoration on depletion and detection efficiency, indicated by the IV curves of leakage current. Sensitivities of threshold and noise to temperature change increased significantly after irradiation, corresponding to which the detection efficiency degradation is observed under high temperature. Clock signal propagation delay slightly changed for around 2 ns after irradiation and can be compensated by adjusting the value of IDEL register. Clock signal crosstalk is found to induce large variations of thresholds, which are more than 11 ΔDAC in the DC front-end and more than 3 ΔDAC in the AC front-end, indicating the importance of improving clock signal transmission buffers in future sensor development to suppress such effect.

37 The electron-irradiated TJ-Monopix2 sample produced in this work is also compared
38 with other proton-irradiated samples in a test beam campaign, where the electron-
39 irradiated sample showed a milder performance degradation compared with proton-irradiated
40 sample even though the accumulated NIEL fluxes are the same. In the evaluation of ra-
41 diation damage in the real operation of VTX, the actual performance degradation is
42 expected to be at an intermediate level between electron-irradiated sample and proton-
43 irradiated sample, because the actual radiation damage is caused by a combination of
44 different particles including electrons and protons.

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Chapter 1

Belle II experiment

Belle II is a High Energy Physics experiment located in KEK, Tsukuba (Japan), collecting electron-positron collision data most of which is at $\Upsilon(4S)$ resonant energy 10.58 GeV from the SuperKEKB accelerator. Its goal is to explore new physics (NP) beyond the Standard Model (SM) in the flavor sector and improve the precision of measurement for the SM parameters [16]. Specifically, the boosted center-of-mass system from the asymmetric beam energies allows precise measurements of time-dependent CP violation. To achieve its target of extreme measurement precision, Belle II is expected to accumulate an integrated luminosity of 50 ab^{-1} during its full operation period. Hence, SuperKEKB is upgraded from its predecessor KEKB with nano-beam scheme, larger crossing angle and various other improvements, aiming to achieve an instantaneous luminosity of $6 \times 10^{35} \text{ cm}^{-2}\text{s}^{-1}$. Corresponding to the high luminosity, Belle II upgraded its detector from Belle experiment to deal with higher event rate and to have higher irradiation tolerance. The operation began in 2018, initiated with accelerator and detector commissioning and formal data collection started in 2019. The facility is set to progressively increase the collision intensity, aiming to reach its target luminosity in the late 2030s, as shown in Figure 1.1.

In this chapter, overviews of physics topic, detector and accelerator will be introduced in Section 1.1, 1.2 and 1.4, respectively. Specifically, the vertex detector will be introduced in detail in Section 1.3. Then, upgrade project of vertex detector will be discussed in Section 1.5.

1.1 Physics at Belle II experiment

The SM is the best tested theory describing the elementary particles, composing the matters and interactions. As shown in the Figure 1.2, it contains 3 generations of fermions, vector bosons carrying interactions, and a scalar Higgs boson. Despite its success in explaining and predicting experimental results, there are still many mysteries that are not explained by the SM.

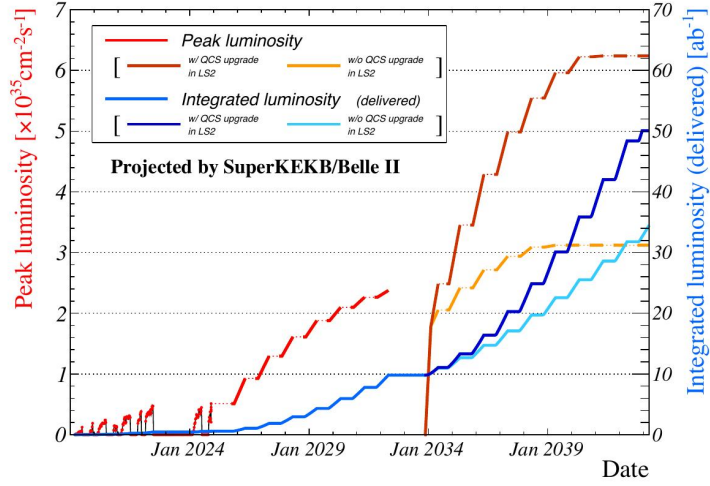


Figure 1.1: Instantaneous luminosity and integrated luminosity projection of Belle II experiment.

In the SM, the reason why there are only three generations of elementary fermions with obvious mass hierarchy is unknown. The origin of mass is explained within the SM by spontaneous electroweak symmetry breaking, resulting in the Higgs boson, while it is not clear if this Higgs mechanism accounts for the mass of neutrinos. It is either not clear that whether there is only one Higgs sector or there exists another Higgs sector with Higgs-like particles. The asymmetry between matter and anti-matter originates from the CP (charge, parity) violation, while the asymmetry observed in our known universe is larger than the SM explanation by many orders of magnitudes. Besides, it remains a mystery whether dark matter is composed of elementary particles, which are not part of the Standard Model. To address these problems, many NP scenarios have been proposed. The precise measurement of elementary particle behaviors is important to test the SM and provides experimental evidence for NP theories.

Belle II is a powerful general-purposed experiment providing experimental evidence for many physics topics. Several of which are introduced below.

1.1.1 CP violation

In the SM, the mixing of quark flavors in weak interactions is described by the Cabibbo-Kobayashi-Maskawa (CKM) matrix V_{CKM} [17, 18]:

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}. \quad (1.1)$$

where the absolute value of the matrix elements determines the relative amplitude of weak transitions between different quark flavors. The CKM matrix contains 18 free parameters.

Standard Model of Elementary Particles

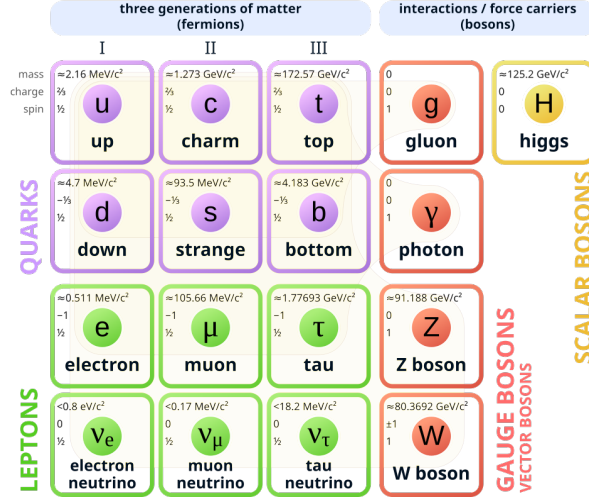


Figure 1.2: The Standard Model of elementary particles [1].

The unitary condition $V_{CKM}V_{CKM}^\dagger = 1$ reduces the number of free parameters to 9. Furthermore, by quark field redefinition, the number of free parameters of CKM matrix is finally reduced to 4, which can be represented by three Euler angles (θ_{12} , θ_{23} , θ_{13}) and one complex phase δ . Hence, the CKM matrix can be parameterized as:

$$\begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}. \quad (1.2)$$

where $s_{ij} = \sin \theta_{ij}$ and $c_{ij} = \cos \theta_{ij}$. The matrix elements determine the possibilities of corresponding flavor-changing transitions in weak interactions and CP violation is induced by the complex phase δ . For now, the amount of CP violation in the SM quark sector is too small to explain the matter-dominated universe.

The Belle II experiment is able to search for new CP-violating phases. The most important examination is the difference of decay possibilities through $b \rightarrow s$ or $b \rightarrow d$ processes [19–21], between B^0 and $\bar{B}^0$, which mix with each other in time:

$$(|B^0(t)\rangle, |\bar{B}^0(t)\rangle) = \begin{pmatrix} g_+(t) & -\frac{q}{p}g_-(t) \\ -\frac{q}{p}g_-(t) & g_+(t) \end{pmatrix} (|B^0\rangle, |\bar{B}^0\rangle). \quad (1.3)$$

where the matrix elements are coefficients describing the mixing behavior and encode the CP violation information. Hence the time-dependent decay possibilities of decay process to CP eigenstate f are:

$$|\langle f | \mathcal{H} | B^0(t) \rangle|^2 = |g_+(t) \langle f | \mathcal{H} | B^0 \rangle - \frac{q}{p}g_-(t) \langle f | \mathcal{H} | \bar{B}^0 \rangle|^2 \quad (1.4)$$

$$|\langle \bar{f} | \mathcal{H} | \bar{B}^0(t) \rangle|^2 = |-\frac{p}{q}g_-(t) \langle \bar{f} | \mathcal{H} | \bar{B}^0 \rangle + g_+(t) \langle \bar{f} | \mathcal{H} | B^0 \rangle|^2 \quad (1.5)$$

The difference of these two time-dependent decay rates indicates the amount of CP asymmetry, which is the so called time dependent CP violation, providing important insights to new CP-violating phase. Besides, the understanding of large amounts of CP violation produced in the time-integrated decay rates of charmless B hadronic decay is also an important area [16].

1.1.2 Flavor violation

In the Standard Model (SM), flavor-changing processes are governed by the mismatch between the mass and weak interaction eigenstates, described by the CKM matrix in the quark sector and the Pontecorvo–Maki–Nakagawa–Sakata (PMNS) matrix [22, 23] in the lepton sector. These mixing matrices are unitary, and this property plays a crucial role in suppressing flavor-changing neutral current (FCNC) processes in both sectors.

In the quark sector, flavor-changing transitions can occur at tree level via charged current interactions mediated by the W boson. These processes, such as $u \rightarrow d$, $c \rightarrow s$, or $t \rightarrow b$, are governed by the CKM matrix shown in Eq. 1.1. In contrast, FCNC processes where the quark flavor changes but its electric charge remains the same such as $s \rightarrow d$, $b \rightarrow s$, or $t \rightarrow c$, are forbidden at tree level and only arise via loop-level diagrams. These include penguin and box diagrams with internal W bosons and up-type quarks. The example of amplitude for the process $s \rightarrow d$ takes the form [24]:

$$\mathcal{A}(s \rightarrow d) \propto \sum_{i=u,c,t} V_{is}^* V_{id} f(m_i^2), \quad (1.6)$$

where V is the CKM matrix, and $f(m_i^2)$ is a loop function sensitive to the mass of the internal quark. In the case of degenerate masses, unitarity of the CKM matrix ensures exact cancellation of the amplitude, which is known as the Glashow–Iliopoulos–Maiani (GIM) mechanism [25]. However, the large mass splitting among the up-type quarks, particularly due to the top quark, breaks the cancellation and results in observable FCNC processes. Predicted SM branching ratios span a wide range, e.g., from $\text{BR}(b \rightarrow s\gamma) \sim 10^{-4}$ to $\text{BR}(t \rightarrow cZ) \sim 10^{-14}$ [24].

In the lepton sector, the observation of neutrino oscillations [26] implies that neutrinos have mass and mix via the PMNS matrix. This allows lepton flavor violation (LFV), although it is absent at tree level for charged leptons. At loop level, processes such as $\mu \rightarrow e\gamma$ are allowed and proceed via internal W bosons and neutrinos. The amplitude is:

$$\mathcal{A}(\mu \rightarrow e\gamma) \propto \sum_{i=1}^3 U_{\mu i}^* U_{ei} \left(\frac{m_{\nu_i}^2}{m_W^2} + \mathcal{O}\left(\frac{m_{\nu_i}^4}{m_W^4}\right) \right), \quad (1.7)$$

where U is the PMNS matrix. Again, unitarity leads to cancellation when neutrinos are massless or degenerate. In reality, the neutrino masses are tiny but split, resulting in incomplete cancellation. The suppression due to the small neutrino masses (on the order of 0.1 eV) leads to an extremely small branching ratio [27]:

$$\text{BR}(\mu \rightarrow e\gamma)_{\text{SM}} \sim 10^{-54}, \quad (1.8)$$

which is far below current experimental sensitivity.

In both sectors, the GIM-like suppression from mixing matrix unitarity, combined with loop-level dynamics, makes flavor-violating processes extremely rare in the SM. However, the degree of suppression is much weaker in the quark sector due to the large top-quark mass, while it is overwhelming in the lepton sector due to the tiny neutrino masses. This makes FCNCs in the quark sector and LFV in the lepton sector powerful probes of NP.

1.1.3 Other new physics

To address the remaining mysteries in the SM, many new particles are proposed by theories like SUSY [28] and 2HDM [29]. One of the most cared new particles is the charged Higgs boson $H^\pm$ as a charged scalar sector which does not exist in the SM. Charged Higgs boson brings new coupling structure, resulting in extra contribution to some decay channels such as $B^+ \rightarrow l^+\nu$. At the Belle II experiment, precise measurement of such decay channels to examine the difference from the SM prediction is possible, providing evidence of contributions from charged Higgs boson.

In astronomy observations, large amount of dark matters exist widely in our universe. Such dark matters participate in gravity interactions but nearly free from electroweak and strong interactions. The particle candidate for dark matters remains one of the biggest physics mysteries nowadays [30]. With electron-positron collisions, Belle II experiment has a clean environment almost free from background processes, making it able to detect missing energy and momentum. Searching for invisible particles would provide important hints for dark matter studies.

1.2 Belle II detector overview

Belle II is a general-purposed detector composed of 7 sub-detector layers surrounding the interaction point (IP) of SuperKEKB accelerator [3]. The global coordinate system is shown in Figure 1.3. The X axis points outside, perpendicular to the storage ring of SuperKEKB. Y axis points upward and the Z axis points to the bisector of two beams, roughly towards the direction of electron moves along. ϕ is the azimuthal angle around the z axis. The direction along x axis is defined to be $\phi = 0$. θ is zenith angle with respect to z-axis. $\theta = 0$ is defined to be the direction along z-axis.

A sketch of the whole detector is shown in the figure 1.4. It is designed based on its predecessor, Belle detector, to have better physics performance under higher luminosity and tolerance to the higher beam background. Each sub-detector is introduced in the order of innermost to the outermost [3].

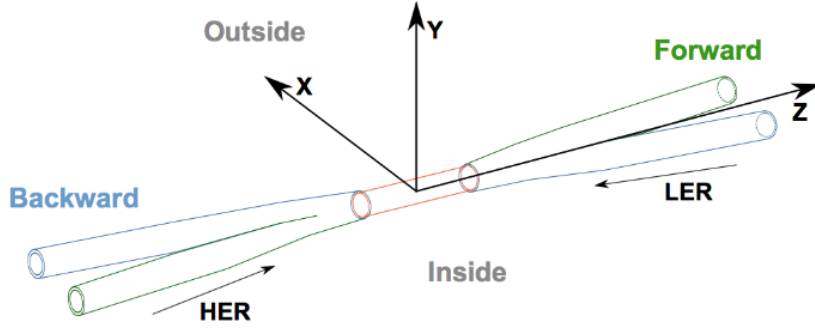


Figure 1.3: Global coordinate system of Belle II experiment.

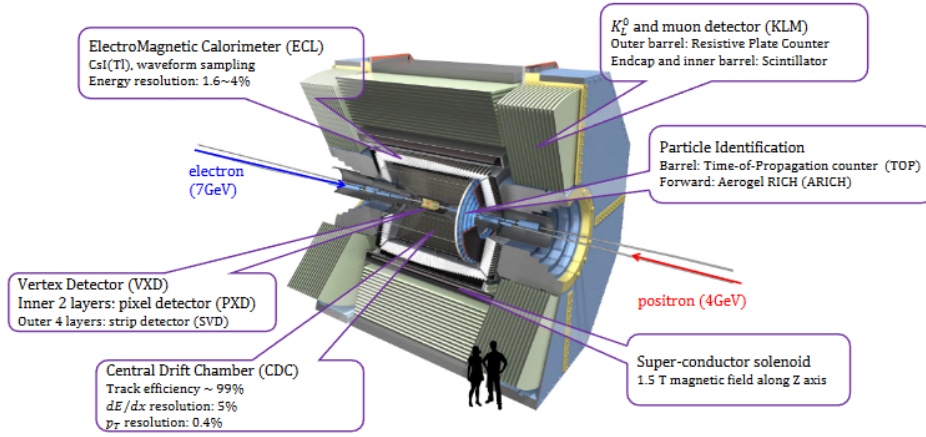


Figure 1.4: Sketch view of Belle II detector [2].

VXD, Vertex Detector, is the innermost detector directly attached to the beam pipe around IP. It is a 6-layer silicon vertex detector, contributing to tracking of charged particles and vertexing. Two further sub-detectors compose the VXD, which will be introduced in detail in Section 1.3. The resolution of impact parameter along the Z axis is $\sigma(z_0) \sim 20 \mu\text{m}$.

CDC, Central Drift Chamber, is a wire chamber consisting of 42240 field wires and 14336 sense wires, filled with a 50/50 mixture He and C_2H_6 gasses. The sense wires are classified into axial wires along Z axis, providing position information in XY plane, and stereo wires having a small angle with respect to the Z axis to provide position information along the Z axis. This design enables CDC to perform 3 dimensional tracking. By collecting the ionizing signal from charged particles, CDC reconstructs tracks and measures the momenta of the charged particle from the track bending in the 1.5 T magnetic field. It can also contribute to particle identification by measuring the specific energy losses. The spatial resolutions of CDC in each direction are $\sigma_{r\phi} \sim 100 \mu\text{m}$ and $\sigma_z \sim 2 \text{ mm}$. The uncertainties of measured transverse momentum p_t and energy loss dE/dx are $\sigma_{p_t} \sim 0.4\%$ and $\sigma_{dE/dx} \sim 5\%$, respectively.

Particle identification system contains two detectors, **TOP** (Time-Of-Propagation counter) covering the barrel, and **ARICH** (Aerogel Ring Imaging Cherenkov detector) covering the forward end-cap. TOP uses long quartz radiators having charged particles to generate Cherenkov light and collect it at the end with Micro-Channel Plate (MCP). Particle species can be identified with the timing information of the arrival of the Cherenkov light. ARICH uses silica aerogel to generate Cherenkov light, which is collected using Hybrid Avalanche Photon Detector (HAPD). Particle identification is performed based on the light pattern. The main task for TOP and ARICH is to identify $K^\pm$ and $\pi^\pm$. A reference performance is the $K^\pm$ identification efficiency being 99% with 0.5% $\pi^\pm$ fake rate for $B \rightarrow \rho\gamma$ decays on TOP and efficiency being 96% with 1% fake rate for 4 GeV K/π separation on ARICH.

ECL, Electromagnetic Calorimeter, consists of 6624 thallium doped iodide CsI(Tl) crystals in the barrel and 2112 CsI(Tl) crystals in the end-caps. Energy of photons and electrons will be collected in the form of scintillation photons by photodiodes. ECL covers the barrel and end-cap areas, measuring deposited energy and position of electrons and photons. Additionally, it provides identification information of electrons based on the deposit energy and the momentum measured in CDC. The energy uncertainty is parameterized as $\sigma_{E/E} = (0.2\%/E) \oplus (1.6\%/\sqrt[4]{E}) \oplus 1.2\%$ and the position uncertainty is $\sigma_{\text{pos}} = 0.5 \text{ cm}/\sqrt{E}$ where E is in GeV.

KLM, K_L^0 and μ detector, is the outermost layer. The forward(backward) end-cap sections have a sandwich structure of 14(12) iron plates and 14(12) plastic scintillator layers, with signal being collected by Silicon Photomultiplier (SiPM). The barrel part has 14 iron plates and 15 Resistive Plate Chambers (RPC) and scintillator layers, with signal being collected by pick up strips and transported to frontend electronics. KLM provides identification information for muon and K_L^0 and the direction of K_L^0 . The muon detection efficiency plateaus at 89% above 1 GeV with hadron fake rate of about 1.3% while for K_L^0 the detection efficiency plateaus at around 80% at 3 GeV. The resolution of K_L^0 is 1.5% for candidates detected by both ECL and KLM.

A super conducting solenoid magnet is placed between ECL and KLM, providing a 1.5 T magnetic field environment for the inner layers. The acceptance of the Belle II detector covers θ range from 17° to 150° . The trigger system takes input from the CDC, ECL, TOP and KLM and output trigger signal through Global Decision Logic (GDL). Triggered data is transmitted to the Data Acquisition (DAQ) system, whose bandwidth requires the upper limit of trigger rate to be 30 kHz with a event size of 300 kB.

1.3 Vertex detector (VXD)

The VXD contains 6 layers of silicon detectors, located at the radii of 14 mm, 22 mm, 39 mm, 80 mm, 104 mm and 135 mm respectively, working as an inner tracker system. With high spatial resolution of $\sigma_{z_0} \sim 20 \mu\text{m}$, it contributes to tracking and provides pre-

cise vertex information, playing a critical role for time-dependent CP violation measurement and other measurement involving long-lived particles. As shown in the Figure 1.5, it contains two sub-systems in different radius, which are introduced in this section in detail.

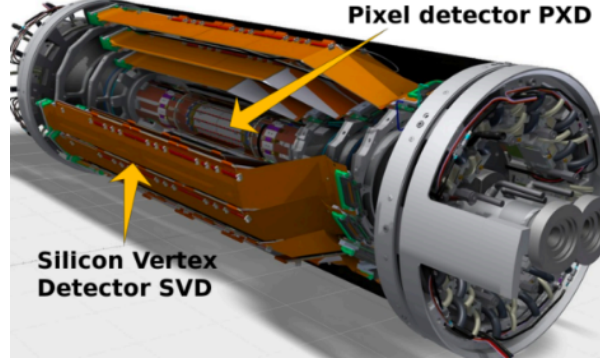


Figure 1.5: Image of VXD. The 2 innermost layers form PXD and outer layers form SVD.

1.3.1 Pixel detector (PXD)

PXD, Pixel Detector, is the 2 innermost layers of VXD, designed to be a fully pixilated sensor using Depleted Field Effect Transistor (DEPFET) sensors [31]. DEPFET concept is shown in the Figure 1.6. A p-channel MOSFET is integrated onto a silicon detector substrate. By applying a sufficient high negative voltage to the p^+ contact on the backside, the sensor bulk is fully depleted. A potential minimum, which is called “internal gate”, is formed by sideward depletion directly underneath the transistor channel at about $1\ \mu\text{m}$ depth. When a charged particle passes through the DEPFET sensor, electron-hole pairs are generated. The holes drift to the back contact while the electrons are accumulated at the internal gate. When the transistor is switched on, the current flowing from the p^+ drain are modulated by the accumulated charge hence the signal is amplified. Removal of the signal charge and thermally generated charge from the internal gate is called “Clear”. By applying a positive voltage to the neighboring n^+ contact, punch through would happen hence the entire charge is removed. Thanks to the internal amplification, the sensor can be manufactured very thin to reduce the multiple scattering induced by the material.

There are three types of ASICs for the readout electronics. “Drain Current Digitizers” (DCD) digitize the MOSFET current from the pixels. “Digital Handling Processors” (DHP) perform the zero-suppression of the pixels that are not actually hit by charged particles. “SWITCHERS” switch on a row of pixels to readout the current to the DCD.

The geometric layout of the PXD is shown in the Figure 1.7. The inner layer contains 8 planar modules, which are called “ladders” and the outer layer contains 12 ladders. All ladders have a width of 15 mm while the ladders in the inner layer have a sensitive length of 90 mm and the ladders in the outer layer have a sensitive length of 123 mm. Each

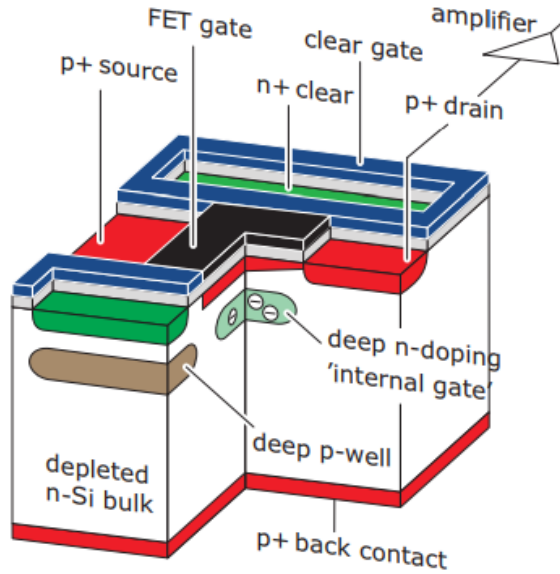


Figure 1.6: DEPFET structure. [3]

ladder has 250×1600 pixels, divided into two identical parts that are glued together. The pixel size ranges from $50 \times 55 \mu\text{m}^2$ to $50 \times 85 \mu\text{m}^2$. At the end of the sensitive part of each ladder, there is a 25 mm-wide space where the DCDs and DHPs are placed. SWITCHERS are placed beside the long side of the sensitive area. Since DEPFET sensors are only powered on during the readout, heat dissipation is dominated by the readout electronics, which are cooled using cooling pipes transmitting gas-liquid two-phase carbon dioxide. The whole system is attached to the beam pipe through a support structure and the sensitive area covers the angle from 17° (forward) to 150° (backward). The whole system is applied with a rolling shutter readout mode, which reads out the signal row by row. Each part (half of a ladder, containing 800 rows) consumes $20 \mu\text{s}$ for an entire readout frame.

1.3.2 Silicon vertex detector (SVD)

SVD, Silicon Vertex Detector, comprises the 4 outer layers of VXD. It is a silicon strip detector making use of Double-sided Silicon-Strip Detector (DSSD) technology [32], which is shown in Figure 1.8. In DSSD, p^+ strips and n^+ strips are placed perpendicularly to each other on two sides of the silicon bulk. Inverse bias voltage of 100 V is applied between p^+ strips and n^+ strips to make the silicon bulk fully depleted. When charged particles pass through the sensor, electron-hole pairs are generated, where the holes drift to the p^+ strips and electrons drift to the n^+ strips. The charge signal is collected by the strip shaped aluminum electrodes attached to the readout strips on the outer side of the sensor. Hence 2-dimensional hit position information can be derived from the perpendicular strip signal. To improve the spatial resolution without increasing readout channels, floating

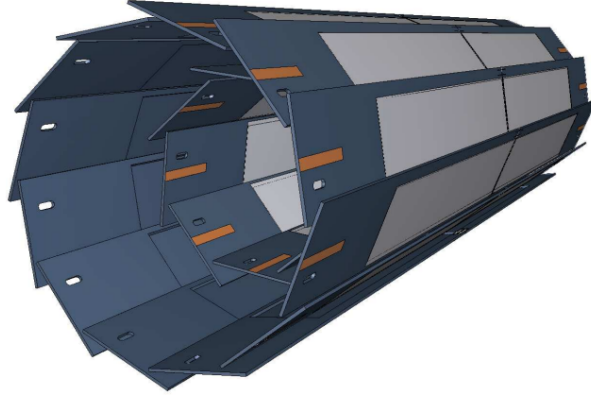


Figure 1.7: Schematic view of the geometry of PXD layers. The light gray surfaces are the sensitive area with DEPFET pixels, which are thinned to 50 μm . [3]

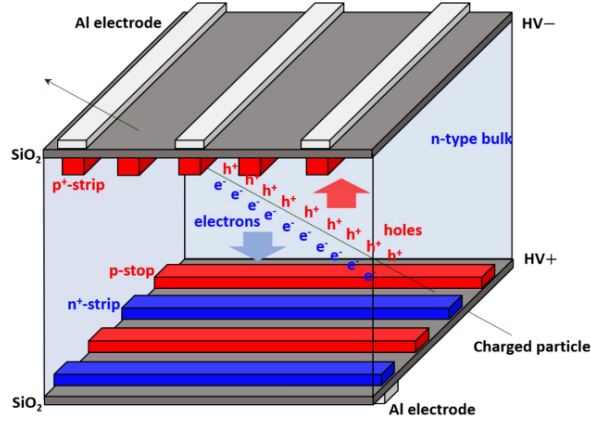


Figure 1.8: DSSD structure. [3]

readout strips that are not attached to Al electrodes are placed in between every two readout strips. Charge signal collected by floating strips will be shared by its neighboring electrodes, weighted according to the actual hit position. The silicon dioxide layer on the surface contains fixed positive charges, attracting and accumulating electrons, which would short the n^+ strips. Therefore, p -type stop strips are placed in between n^+ strips to prevent shorting.

The charge pulse readout by the Al electrodes are input to front-end ASIC APV25 [33], which amplifies and shapes the signal. It has a fast shaping time of 50 ns and samples the signal in 32 MHz. The output from APV25 is then transmitted to Flashing Analog-to-Digital Converter (FADC) to be digitized, where zero-suppression is also performed.

The layout of SVD layers are shown in Figure 1.9. The sensitive part are classified into large rectangular (green), small rectangular (blue) and trapezoid (orange). The rectangular sensors cover the barrel area and the trapezoidal sensors cover the forward area. All the layers are mounted to a supporting structure surrounding the beam pipe. The specification of the sensors in each part are shown in Table 1.1. APV25s are directly

Table 1.1: Specifications of the DSSD sensor used in the SVD. [3]

	Small rectangular	Large rectangular	Trapezoidal
Location	Layer 3	Layer 4–6 (except FW)	Layer 4–6 (FW)
Readout strips <i>P</i> -side	768	768	768
Readout strips <i>N</i> -side	768	512	512
Readout pitch <i>P</i> -side	50 μm	75 μm	50–75 μm
Readout pitch <i>N</i> -side	160 μm	240 μm	240 μm
Sensor active area [mm^2]	122.90×38.55	122.90×57.72	$122.76 \times (38.42\text{--}57.59)$
Sensor thickness	320 μm	320 μm	300 μm

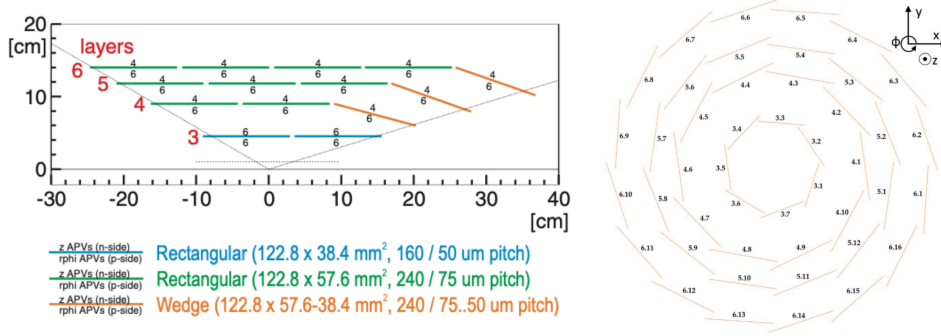


Figure 1.9: Cross section view of SVD layers in x (left) and z (right) axis directions. [3]

placed on the sensor ladders, connected through flexible circuits named “Origami (折り紙)”. Due to the large amount of heat dissipation of APV25, cooling pipes transferring carbon dioxide are attached.

1.4 SuperKEKB and beam background

The SuperKEKB accelerator [4] is an electron-positron collider with the center-of-mass energy of 10.58 GeV, corresponding to the resonant energy of $\Upsilon(4S)$, which decays into B meson pairs, providing large amount of B meson events for the Belle II experiment.

1.4.1 SuperKEKB

As shown in Figure 1.10, the SuperKEKB accelerator consists of several components. The linear accelerator LINAC accelerates electrons to the energy of 7 GeV. Positrons are generated in LINAC by shooting the electrons to a tungsten target and then pass through a damping ring to reduce their emittance. Finally the positrons are accelerated to the energy of 4 GeV. Through the Beam Transport (BT, yellow part in Figure 1.10), accelerated electrons are injected into the High Energy Ring (HER) while the positrons are injected into the Low Energy Ring (LER). At the storage rings, radio frequency cavities are also set to compensate the beam energy loss in the ring orbitals. The Belle II

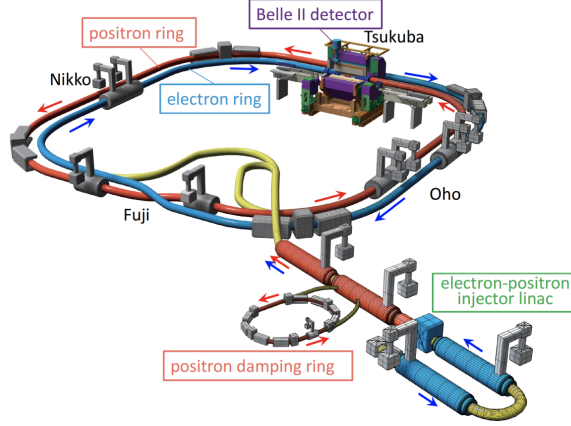


Figure 1.10: Schematic view of SuperKEKB accelerator. [4]

detector is located at the interaction region of the electrons and positrons. The asymmetric collision brings a Lorentz boost to the e^+e^- center-of-mass system of $\beta\gamma = 0.28$, enabling precise measurement of the two B-meson vertex displacements for the sake of the time-dependent CP violation measurements.

The instantaneous luminosity in e^+e^- collider is proportional to the following factors:

$$L \propto \gamma_{\pm} \frac{I_{\pm} \xi_{y\pm}}{\beta_y^*}. \quad (1.9)$$

where the $+$ ($-$) represents positrons (electrons). γ is the Lorentz factor. I is the beam current. ξ_y represents the beam-beam effect in vertical direction and β_y^* is the vertical beta function at the collision point. To increase the luminosity for the demand of Belle II experiment, SuperKEKB is upgraded from KEKB accelerator to upgrade its electron (positron) beam currents from 1.6 A (1.2 A) to 2.8 A (2.0 A), and squeeze the β_y^* from 5.9 mm to 0.3 mm. As the beam size is squeezed to an extremely small level at the collision point, the beam before and after the collision point expands steeply, resulting in “Hourglass effect”: The electron and positron beams overlap at the expanded region, inducing collisions which enlarges the beam emittance without contributing much to the luminosity. To address this, SuperKEKB is applied with a larger beam crossing angle as shown in the Figure 1.11. The beam parameters of KEKB and SuperKEKB are shown in Table 1.2.

1.4.2 Beam background

At Belle II experiment, except for the expected daughter particles generated from e^+e^- collision, other secondary particles generated from the beam pipe or detector material can also be detected, causing background on the Belle II detector. The background generated from the SuperKEKB accelerator is the most significant part, called “beam background”, which can be classified into 3 categories [34].

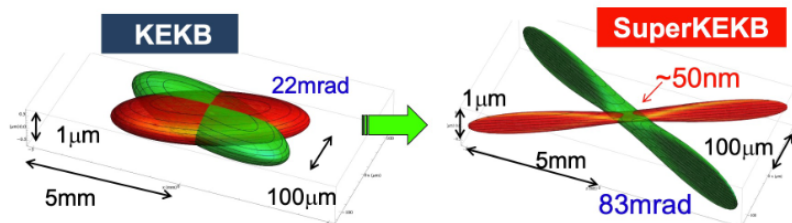


Table 1.2: Comparison of beam parameters between KEKB and SuperKEKB. [4]

Beam parameters	KEKB achieved	SuperKEKB target
β_y^* (LER/HER)[mm]	5.9 / 5.9	0.27 / 0.3
β_x^* (LER/HER)[mm]	1200 / 1200	32 / 25
I (LER/HER)[A]	1.64 / 1.19	2.80 / 2.00
number of bunches	1584	1761
θ [mrad]	22	83
L [$\times 10^{35}$ cm $^{-2}$ s $^{-1}$]	0.21	6

Touschek effect [35] refers the phenomena that, in a storage ring, the charged particles is scattered with the other particles in the same beam bunch, and get kicked out of the bunch, hitting the beam pipe materials and generating secondary particle showers, which are background and can be detected by the Belle II detector. The rate of Touschek effect is proportional to the following component:

$$R_{\text{Touschek}} \propto \frac{I^2}{\sigma_x \sigma_y \sigma_z n_b}. \quad (1.10)$$

where I is the beam current, σ stands for bunch size in each direction and n_b is the number of bunches.

Beam gas effect refers to the phenomena that, in a storage ring, the charged beam particles is scattered with the residual gas atoms inside the beam pipe, and get kicked out of the beam bunch, hitting the beam pipe materials and generating secondary particle showers, which are background and can be detected by the Belle II detector. The rate of beam gas effect is proportional to the following component:

$$R_{\text{Beamgas}} \propto IP. \quad (1.11)$$

where I is the beam current and P is the residual pressure inside the beam pipe.

Luminosity background refers to that the particles generated from collision events hit

the beam pipe or detector material and generate secondary particles, which are detected by the Belle II detector as background. In the case of Belle II, such background is mainly from pure Quantum Electrodynamics (QED) process such as two photon and Bhabha scattering besides $q\bar{q}$ generations and $\tau^+\tau^-$ generations. Such events are regarded as luminosity background from the SuperKEKB accelerator in the Belle II experiment, which only appear when both HER and LER are in operation and hence collision happens. The rate of luminosity background is proportional to the luminosity L .

Beam background exists and is causing radiation and extra occupancy to the detectors, especially the VXD, which is the innermost detector hence closest to the background source. SuperKEKB, with extremely small beam size and high beam current, produces large amount of beam background which possibly degrades the detector performance. Specifically, too much extra occupancy on tracking detectors induces degradation on tracking efficiency, and accumulated radiation dose in a long-term operation results in significant radiation damage. In the case of silicon detectors, lattice defect created by radiation damage degrades the detection efficiency, which will be introduced in detail in Chapter2. Therefore, it becomes a very important subject to investigate the radiation tolerance and background impact on the detectors, to ensure the long-term operation performance.

1.5 Vertex detector upgrade

1.5.1 Necessity of vertex detector upgrade

Currently, the initial instantaneous luminosity goal for SuperKEKB is to achieve $1 \times 10^{35} \text{ cm}^{-2}\text{s}^{-1}$ after Long Shutdown 1 (completed in 2023) and to achieve $2.4 \times 10^{35} \text{ cm}^{-2}\text{s}^{-1}$ by Long Shutdown 2 in the future. Further upgrade work is needed for SuperKEKB to achieve the ultimate target instantaneous luminosity of $6 \times 10^{35} \text{ cm}^{-2}\text{s}^{-1}$, one of which is the redesign of Interaction Region (IR). Redesign of the IR brings change in the mechanics, requiring a corresponding redesign of the innermost detector [5], which is VXD. This is also a good opportunity to upgrade the physics performance by designing a new vertex detector.

Sudden Beam Loss (SBL) is a phenomena that the beam in the storage ring becomes unstable and is bent towards other direction instead of the stable orbits due to unknown reasons. Hence a significant loss of beam current in the storage ring is shown. SBL happens frequently in SuperKEKB and usually causes large dose radiation accidents with the high current beam directly irradiated to the Belle II detectors. PXD has been suffering from radiation damage due to SBL, resulting in dead channels for $1.5\% \sim 2\%$. Even though the study about SBL at SuperKEKB is progressing and the frequency of SBL has been reduced, a spare of vertex detector is still needed in the case of possible VXD failure due to other radiation accidents.

Considering this, a new vertex detector “VTX” is proposed, whose physics perfor-

mance is improved compared with the current vertex detector, VXD. The design of VTX will be introduced in Section 1.5.2 and the performance improvement will be described in Section 1.5.3.

1.5.2 VTX project

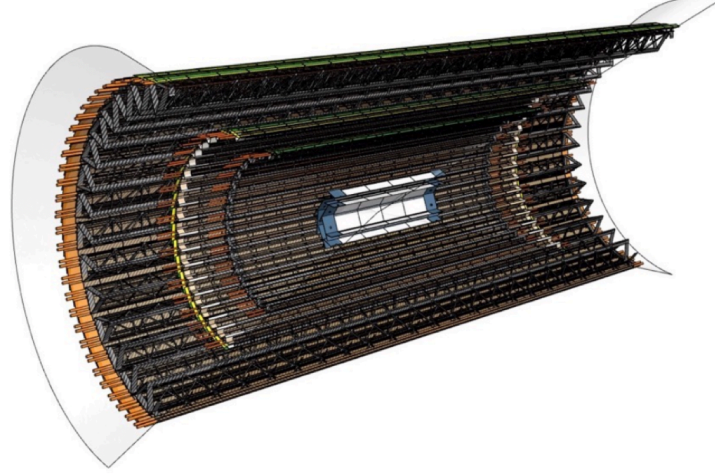


Figure 1.12: Schematic 3D cut view of VTX detector. The layers are grouped into inner VTX (blue-white layers in the middle where sensors are supported directly with the silicon wafer) and outer VTX (dark outer layers where sensors are supported on carbon fiber structure with cooling pipe.) [5]

VTX detector shown in Figure 1.12 is proposed as the vertex detector upgrade for the Belle II experiment, utilizing CMOS-based pixel detector, specifically Depleted Monolithic Pixel Sensor (DMAPS), which will be described in detail in Section 2.2, for all its five layers [5]. It will be the first light and compact DMAPS-based vertex tracker operating at a high-rate e^+e^- collider. Even though a six-layer design is proposed and being studied, the well-understood five-layer design is introduced in this section.

(1) OBELIX sensor

The Optimized BELle II monolithic pIXel (OBELIX) sensor utilized by VTX detector is a DMAPS developed based on another DMAPS prototype, TJ-Monopix2, which will be introduced in Section 2.3. The matrix design of the OBELIX sensor is kept the same with that of the TJ-Monopix2 sensor with modifications to optimize the sensor for Belle II experiment.

The pixel of OBELIX sensor has a pitch size of $33.04 \times 33.04 \mu\text{m}^2$, being the same with TJ-Monopix2 and utilizes the same analog and digital layout. The sensor matrix dimensions follow various constraints. Firstly, the chosen CMOS technology offers a maximal reticule size of $30 \times 25 \text{ mm}^2$. It is beneficial to maximizing the OBELIX sensor matrix size

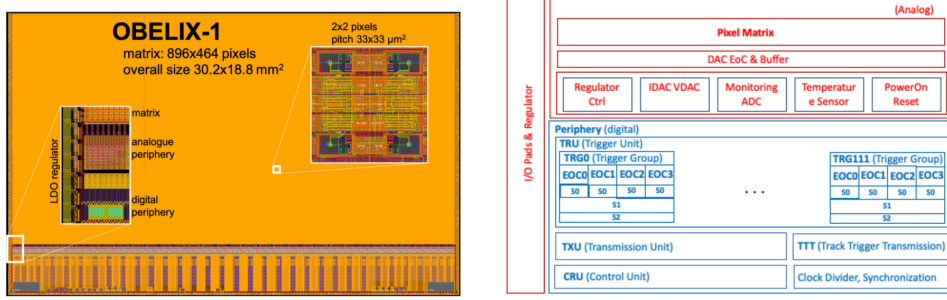


Figure 1.13: Physical layout (left) and functional layout (right) of OBELIX-1 prototype. [5]

hence to minimize the number of chips needed to cover the detecting area. However, inner VTX (iVTX) layer concept uses four consecutive chips diced out of the wafer, forming a ladder. Considering the expected yield of 60%, it is necessary to maximize the number of such 4 consecutive dies on the wafer to minimize the number of wafers needed. The optimized result is a chip dimension of $30 \times 19 \text{ mm}^2$. The pixel number in the matrix is determined to be 896×464 considering a 3 mm width for the periphery. Layout of OBELIX-1 is shown in Figure 1.13.

The digitization of hit signal utilizes the same strategy with TJ-Monopix2 and will be described in Section 2.3. New functional modules and individual End-of-Column (EoC) logic are implemented for the realization of trigger function at the Belle II experiment. The detailed descriptions of OBELIX specification and trigger function are introduced in Appendix A.1.

(2) Structure

The VTX proposal consists of five barrel-shaped layers, equipped with the OBELIX sensors. The design of the ladders differs according to the position radius, with varying active length from 12 cm to 70 cm, to cover the required acceptance of $17^\circ < \theta < 150^\circ$. VTX detector targets an low overall material budget [36] of $\sim 2.0\% X_0$ and is divided into inner VTX(iVTX) layers and outer VTX(oVTX) layers. The parameters of all layers are shown in Table 1.3.

Table 1.3: Parameters of VTX layers. Position of layer 3 is now being discussed and has two options (layer 3a and 3b) [5].

Layer	1	2	3a	4	5	Total	3b	Total
Radius (mm)	14.1	22.1	39.1	89.5	140.0		69.1	
# Ladders	6	10	17	40	31	104	30	117
# Sensors/ladder	4	4	7	16	2×24	2311	12	2552
Mat. budget ($\% X_0$)	0.2	0.2	0.3	0.5	0.8	2.0	0.4	2.1

866 The two innermost layers are iVTX with a material budget of about $0.2\% X_0$ for each
 867 later. iVTX layers are made of four consecutive OBELI sensor blocks diced out of the
 868 silicon wafers and the silicon wafer serves as the supporting structure. The three outer
 869 layers are oVTX, where the sensors are attached to carbon fiber supporting structures,
 870 resulting material budgets varying from $0.3\% X_0$ to $0.8\% X_0$ per layer. The detail of
 871 layer design is described in Appendix A.2.

872 1.5.3 Physics performance improvement

873 The VTX proposal is expected to improve the physics performance of Belle II detector
 874 mainly in tracking and vertexing. Besides, VTX is designed to be able to contribute to
 875 the first level trigger decision, which would improve the trigger performance. The im-
 876 provement in trigger is still under investigation and the physics performance improvement
 877 is introduced below.

878 (1) Tracking efficiency

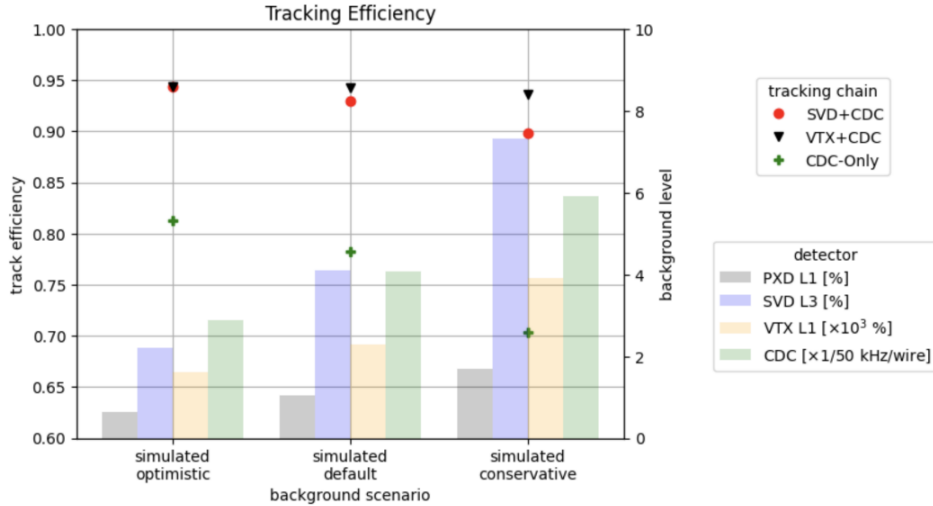


Figure 1.14: Track efficiency and background level (in the unit of occupancy for PXD, SVD, VTX and wire hit frequency for CDC) for each detector simulations under different background prediction scenarios. PXD does not directly participate in tracking but in vertexing after tracking [5].

879 For vertex detectors, the tracking efficiency degrades when hit occupancy increases,
 880 especially for strip detectors such as SVD at the current Belle II detector, where under
 881 a high occupancy “ghost hits” appear in addition to the real hits, further increasing the
 882 occupancy. In the future operation of Belle II experiment, the luminosity is expected to
 883 increase by an order of magnitude, resulting in extra occupancy from the beam back-
 884 ground introduced in Section 1.4.2. In the prediction of beam background in final high

luminosity run, three scenarios are considered. i) **Optimistic Scenario (v1)** comes from the simple extrapolation of all single beam background component according to the beam parameters. ii) **Nominal Scenario (v2)** uses a scaling factor to elevate the single beam background component to 2.5 times of optimistic scenario while iii) **Conservative Scenario (v3)** scales even larger to 5 times of optimistic scenario. Luminosity background under all scenarios are simulated without extra scaling using the target luminosity of $6 \times 10^{35} \text{ cm}^2\text{s}^{-1}$. In all simulations of single beam background and luminosity background, data/MC ratios are well considered and applied [5].

Tracking efficiency under high occupancy situation is improved with VTX, which has higher granularity both in space and time compared with the current VXD. The tracking efficiency and detector occupancy simulations are shown in Figure 1.14. Degradation of tracking efficiency using SVD + CDC is evident and the improvement using VTX is seen.

(2) Reconstruction efficiency of low momentum tracks

With much reduced material budget, energy loss of particles in VTX detector is suppressed hence more charged particles with low momentum would survive. In the Belle II experiment, the most notable component of such particles are soft pions from the decays of $D^{*\pm}$ mesons. Simulation study of reconstructing the decay chain $B^0 \rightarrow D^{*-}(\rightarrow \bar{D}^0 \pi_{\text{soft}}^-) \ell^+ \nu$, with minimum cut is applied. With the current Belle II detector, the reconstruction efficiency yields $\sim 30\%$ and the VTX upgrade can increase the efficiency to $\sim 50\%$, with a signal purity of $\sim 25\%$. The comparison of reconstruction efficiency as a function of transverse momentum and zenith angle of soft pion under different background scenarios after VTX upgrade and the current Belle II detector is shown in Figure 1.15. Remarkable improvement can be seen in most of the bins.

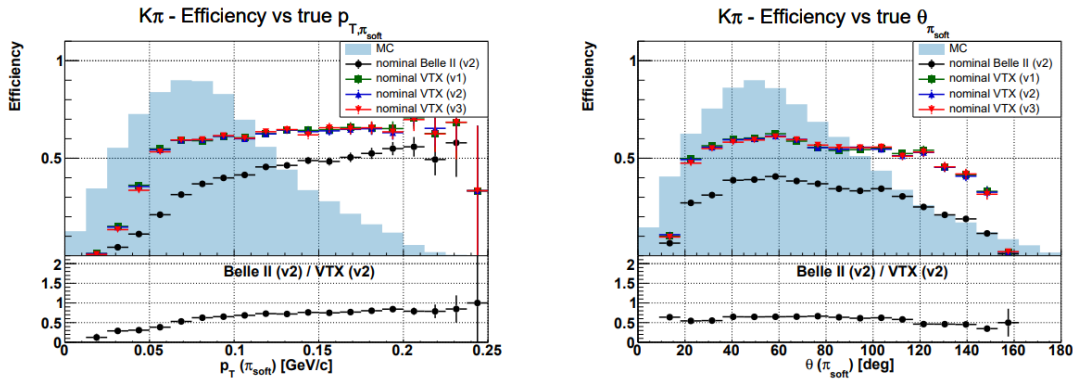


Figure 1.15: Reconstruction efficiency of $B^0 \rightarrow D^{*-} \ell^+ \nu$ depending on transverse momentum P_T of π_{soft}^- (left) and the zenith angle θ of π_{soft}^- (right). $K\pi$ in the plot title indicates the specific decay channel is chosen to be $\bar{D}^0 \rightarrow K^+ \pi^-$. v1, v2 and v3 corresponds to the background prediction scenario-1, 2 and 3. Ratios of reconstruction efficiency in current Belle II detector over VTX upgrade under background scenario-2 are plotted underneath [5].

(3) Vertexing resolution

Fully pixilated design of VTX with smaller pixel pitch compared with the current VXD improves the vertex resolution. Besides, low material budget suppressing multiple scattering is also an important source of better vertex resolution. The study of this improvement is performed by reconstructing a simulated sample of $B^0 \rightarrow J/\psi K_s^0$ events, fully reconstructed through charged tracks. The residuals of reconstructed Z-positions of B^0 meson and the true Z-positions of B^0 meson decay are evaluated. Vertex resolution is determined as the full width at half maximum of the residual distribution $\sigma(z_{\text{reco}} - z_{\text{true}})$. The result is shown in Table 1.4. Improvement of around $\sim 35\%$ can be foreseen under every background prediction scenario.

Table 1.4: Comparison of vertex resolution of B^0 mesons reconstructed using simulated $B^0 \rightarrow J/\psi K_s^0$ events, between current Belle II detector and VTX, upgrade under different background scenarios [5].

B^0 z vertex resolution (μm)	Optimistic	Nominal	Conservative
Belle II	21.9	23.0	24.9
Nominal VTX	14.5	14.4	14.1

Chapter 2

Silicon sensor

Silicon semiconductor sensors are widely used in vertex detectors of High Energy Physics (HEP) experiments. The basic structure of detectors made from silicon sensors consists of the part where the charged particles pass through thus generate signals, and the readout front-end electronics. Silicon is by far the most widely used material for semiconductor sensors because it is abundant, stable and has relatively low band-gap allowing sufficient charge signal generation. Additionally, high quality insulator SiO_2 can be formed. The rapid development of electronics in industry brings the advanced technology of silicon production and processing, significantly enhancing the performance of silicon sensors.

In this chapter, the fundamentals of silicon sensor and the main types of silicon sensors will be introduced in Section 2.1. A brand new advanced technology of DMAPS will be introduced in Section 2.2 and then a DMAPS prototype TJ-Monopix2 will be introduced in Section 2.3. At last, radiation damage and the potential resulting performance degradation will be introduced in Section 2.1.2.

2.1 Silicon sensor fundamentals and the sensor types

2.1.1 Signal generation and processing

Silicon sensors detect charged particles and X-ray photons from their energy loss when they are passing through silicon bulks, where the lost energy is converted into electron-hole pairs, and they induce a current on the sensor electrodes. This transient current is then transmitted to the readout front-end for amplifying, shaping and digitizing.

(1) Charged particle energy loss

When charged particles pass through mediums, they interact with the atoms and lose energy by contributing to the ionization and excitation of atoms. Additionally,

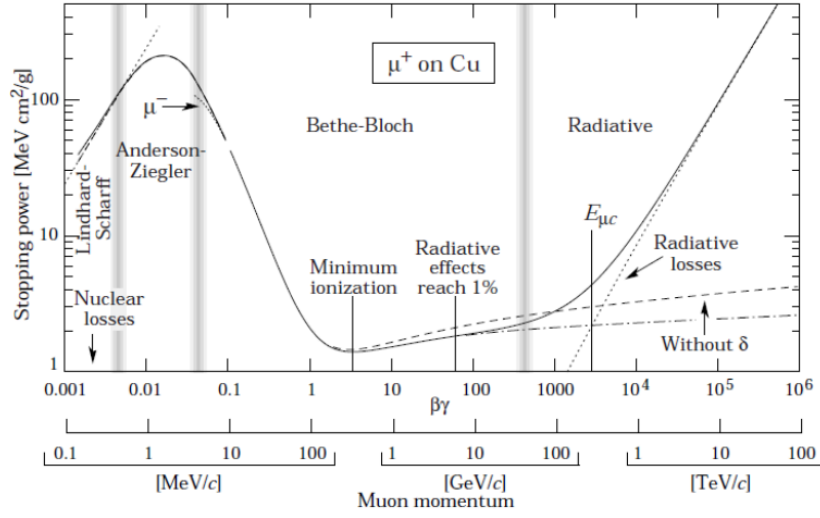


Figure 2.1: The stopping power of μ^+ in copper medium. [6]

the bremsstrahlung radiation of charged particles is also an important source of energy loss. These processes are stochastic depending on their cross section, therefore, the average energy loss per distance, which is called “stopping power”, is used to describe how charged particles lose their energy and hence stopped in mediums. Since the energy loss is a complex mixture of many processes, it depends on the medium type, particle type and the energy of the incident particle. An example of μ^+ losing energy in copper medium is plotted in Figure 2.1. In high energy region, the energy loss is dominated by the bremsstrahlung radiation. The center region mainly contains the contribution of ionization and excitation and can be described by Bethe-Bloch formula. At low energy region, Bethe-Bloch formula is no longer valid since the quantum mechanical interference effects and energy-depended shell corrections become relevant. For the very low energy region, the energy loss is mainly caused by elastic nuclear recoil.

In most HEP experiment cases, the energy of incident charged particles lies in the Bethe-Bloch region, where the energy loss is described by Bethe-Bloch formula [36]:

$$\left\langle -\frac{dE}{dx} \right\rangle = K \frac{Z}{A} \rho \frac{z^2}{\beta^2} \left[\frac{1}{2} \ln \left(\frac{2m_e c^2 \beta^2 \gamma^2 T_{\max}}{I^2} \right) - \beta^2 - \frac{\delta(\beta\gamma)}{2} - \frac{C(\beta\gamma, I)}{Z} \right]. \quad (2.1)$$

where:

- $K = 4\pi N_A r_e^2 m_e c^2$. N_A is Avogadro’s number, m_e is the electron mass and r_e is classical electron radius ($\simeq 2.8$ fm).
- z , β are the charge and velocity of the incident particle.
- Z , A are atomic number and atomic mass of the medium.
- I is the mean excitation energy of the medium atomic.

- $T_{\max}$ is the maximum energy transfer to a shell electron (central collision).
- δ is the density correction, which is significant at high energy.
- C/Z is the shell correction factor, which is significant at low energy.

According to Bethe-Bloch formula, at low energy the term $1/\beta^2$ is dominant thus the average energy loss decreases while at high energy the term $\ln \gamma$ is dominant thus the average energy loss increases. In between these regions there is a minimum at about $\beta\gamma = 3 \sim 3.5$. Charged particles with kinetic energy in such minimum region are called Minimum Ionizing Particles (MIPs). The average energy loss increase right after the minimum point is moderate so MIPs can also refer to particles in this wider region.

To describe the energy loss behavior in a simpler way, radiation length X_0 is defined as the mass thickness into the material at which the energy of a high energy electron is reduced by the factor of $1/e$. A useful approximation of radiation length is [36]:

$$X_0 = (716.4 \text{ g} \cdot \text{cm}^{-2}) \frac{A}{Z(Z+1) \ln(287/\sqrt{Z})}. \quad (2.2)$$

where Z and A are atomic number and atomic mass, respectively. In the context of particle physics detector, the thickness of a material is usually referred to as material budget which is defined as the ratio of the mass thickness and radiation length X/X_0 , where the X is the actual mass thickness of the material.

As mentioned above, Bethe-Bloch formula describes the average value of energy loss. The actual energy loss of charged particles inside a medium is stochastic. For thin silicon medium, which is the usual case in vertex detectors or trackers in HEP experiments, the energy loss follows Landau distribution [9]. An example of pions with energy of 500 MeV traversing through silicon medium in different thickness are shown in Figure 2.2.

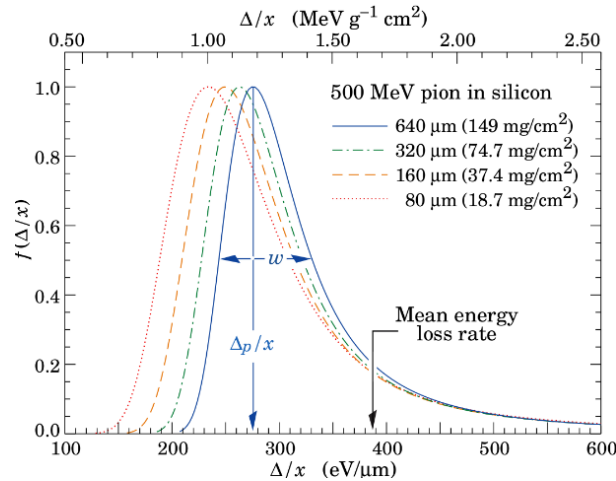


Figure 2.2: Energy loss of 500 MeV traversing through through silicon medium. Different curves stand for different thicknesses of the silicon mediums. [6]

(2) Charge generation in sensor bulk

The energy lost by particles in sensor bulk through ionization is absorbed by semiconductor sensor bulk, creating electron-hole (e/h) pairs. To excite one electron to the conductive band, at least the band-gap energy should be provided (in silicon $\Delta E_{\text{gap}} = 1.1$ eV). However, part of the deposited energy is absorbed by the lattice due to momentum conservation, creating phonons. The average energy w_i required to create one e/h pair in 300 K silicon is $w_i = 3.65$ eV, which is about three times of the band-gap energy. In the case of MIPs traversing a silicon sensor, the most probable value of energy loss is approximately 0.28 keV/ μm . Therefore, the average number of produced e/h pairs is given by [8]:

$$N_{\text{e/h}} = \frac{\Delta E}{w_i} = \frac{0.28 \text{ keV}/\mu\text{m}}{3.65 \text{ eV}} \cdot d(\mu\text{m}) \simeq 80(\mu\text{m}^{-1}) \cdot d(\mu\text{m}). \quad (2.3)$$

where d is the thickness of the silicon bulk.

For each event, the energy is randomly split between generating e/h pairs and being absorbed by the lattice, hence the number of generated e/h pairs fluctuates and usually follow a Poisson distribution, which for a large number resembles a Gaussian distribution. Therefore, the standard deviation of number of generated e/h pairs is $\sigma_{\text{e/h}} = \sqrt{N_{\text{e/h}}}$.

To make the lifetime of the generated e/h pairs long enough to efficiently collect them with the electrode, depletion is needed for semiconductor sensors. Therefore, bias voltage is applied usually from the signal collection electrode, forming an electric field inside the sensor bulk. Generated electrons or holes drift along the electric field to be collected by the collection electrode as signal charge.

(3) The p-n junction and sensor depletion

As shown in Figure 2.3, when a n-doped and a p-doped silicon crystal contact with each other, at the boundary between the two types, the majority carriers diffuse to the opposite part to recombine with the opposite majority carriers. A space free of carriers between the two types forms, which is the depletion area. Such structure is called p-n junction. In the depletion area, an electric field is formed, causing an intrinsic potential difference δV .

In the case of silicon particle detector, the doping of one side is very high and the other side is low. Depletion area grows from the heavily doped side into the slightly doped side more. Due to the 3 times higher mobility of electrons than holes, high dope n-type collection electrode and low dope p-type sensor bulk is the usual case, where the depletion area grows more into the sensor bulk. Ideally, a depletion area fulfilling the entire sensor bulk is desired to have a stronger charge signal. Such full depletion can be realized by applying an external reverse bias voltage V_{ext} with regard to the intrinsic potential difference δV . The depletion depth d in a naive p-n junction structure is [37]:

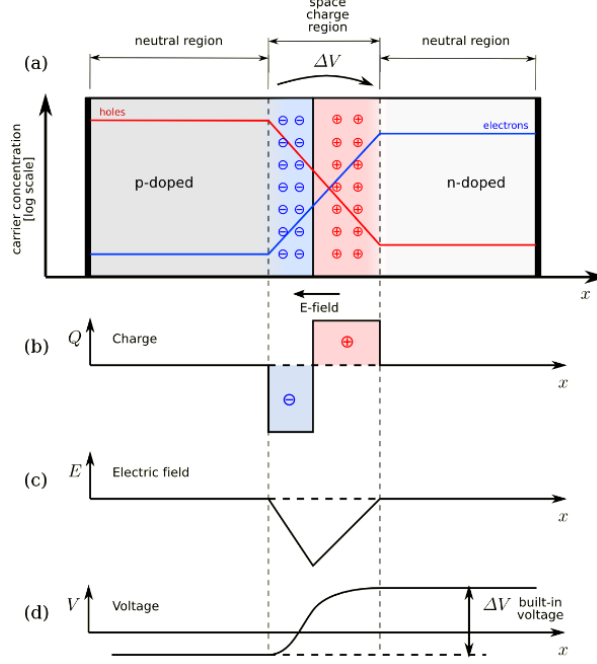


Figure 2.3: The p-n junction structure a), space charge distribution b), electric field distribution c), potential distribution d) [7].

$$d = \sqrt{\frac{\epsilon_{\text{Si}}\epsilon_0}{e} \frac{1}{N_A} (\delta V + V_{\text{ext}})} \simeq \sqrt{\frac{\epsilon_{\text{Si}}\epsilon_0}{e} \frac{1}{N_A} V_{\text{ext}}}. \quad (2.4)$$

where the ϵ_0 is the vacuum permittivity and ϵ_{Si} is the relative permittivity in Silicon. e is the elementary charge. N_A is the acceptor concentration in the p-type region.

(4) Signal processing at the front-end electronics

Before being transmitted to the DAQ system, the charge signal collected from the sensor is firstly processed by the readout front-end electronics. A typical example is shown in Figure 2.4. Charged signal collected from the sensor is a short current pulse as an input to the active integrator, which works as a signal amplifier with capacitive feedback loop. The amplifier amplifies the pulse signal and can be reset by the discharge of the feedback capacitor. The amplified signal is then input to a shaper, which is essentially a band-pass filter with properly tuned time constant. The combination of amplifier and shaper is also called pre-amplifier. The following discriminator compares the pre-amplifier output with a reference voltage, and output the digital pulse when the signal amplitude exceeds the reference voltage. Signal amplitude is encoded in the Time-Over-Threshold (TOT) information [8].

Typical signal waveforms from the signal electrode, pre-amplifier and the discriminator is shown in Figure 2.5. In the final digital output, “time walk” effect, meaning that signal with smaller amplitude requires longer time to be detected, can be clearly seen. To deal

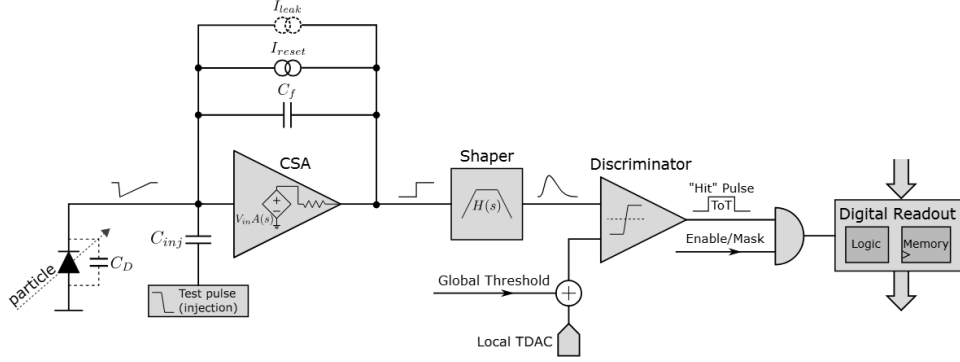


Figure 2.4: A typical example of readout front-end, containing an amplifier, a shaper and a discriminator [8].

with the delay of lower amplitude signal, the signal of a sufficiently large amplitude is firstly aligned with a global event time, and then regard the delayed signal within a fixed time window to be detected in time [8]. Even though most of the readout front-end designs contain the pre-amplifier structure, the digitization could vary, using different digitizer such as ADC to sample the waveform from the pre-amplifier.

The input capacitance of the readout front-end C_{in} , which is usually dominated by the detector capacitance C_D , plays an important role in the analog performance, influencing many properties such as:

Time constant of a pre-amplifier determines how quickly it discharges, which is how quickly the output signal “falls down”. The time constant is proportional to the component [9]:

$$\tau \propto \frac{C_D}{g_m C_f}. \quad (2.5)$$

where C_f is the feed back capacitance and g_m is the transconductance of the input transistor inside the pre-amplifier.

Signal to noise ratio(SNR) describes the ability to distinguish signal from noise fluctuation, where the noise refers to electronic noise in the readout front-end electronics specifically. The SNR is proportional to the component [38]:

$$\frac{S}{N} \propto \frac{Q_S}{C_D} \sqrt{g_m}. \quad (2.6)$$

where Q_S is the input signal charge.

2.1.2 Radiation damage

During experiment operation, silicon sensors are exposed to high irradiative environment with intense flux of charged and neutral particles, causing radiation damage on the sensors. In long-term operation, the radiation damage accumulates and degrade the

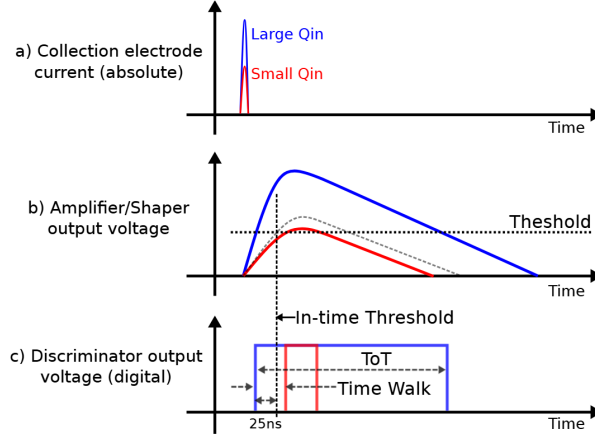


Figure 2.5: Waveforms from the collection electrode a), pre-amplifier b) and discriminator c). Time walk effect can be seen in the output of discriminator [8].

physics performance significantly. In the topic of silicon sensor performance, the Non-Ionizing Energy Loss (NIEL) damage to the sensor bulk plays a dominant role, which refers to the direct collision of radiation particles with the atomic nuclei of the crystal lattice, dislocating or changing the atoms and creating lattice defect. The main types of NIEL damage and the corresponding performance degradation is introduced below.

(1) Lattice defect and quantification

Main NIEL damage types are concluded in Figure 2.6. Single-point defect mainly refers to impurity atoms, vacancy and interstitial. Impurity atom is generated through the absorption of radiation particles by the lattice atoms. Interstitial and vacancy happens when atoms are dislocated through collision. The combinations of different types of single-point defects further form more types of complex defects.

NIEL damage depends on the particle type and energy of radiation. Charged particles create more single-point defects and smaller defect clusters than neutrons. To quantify the NIEL damage and compare the damage caused by different particles, the defect is normalized to the damage effect of 1 MeV neutrons and described in terms of neutron equivalent flux ($n_{eq}cm^{-2}$) [9]. The scaling factor κ from the actual flux of radiation particle with specific energy to the neutron equivalent flux is called the hardness factor.

(2) Impact on sensor operation

Three main implications of bulk damage to the operation of a silicon detector are identified [9]:

Change of the doping: The effective doping concentration N_{eff} of the silicon bulk could change due to the generation or deactivation of donor or acceptor. Doping concentration change is a function of NIEL damage and can even lead to the doping type

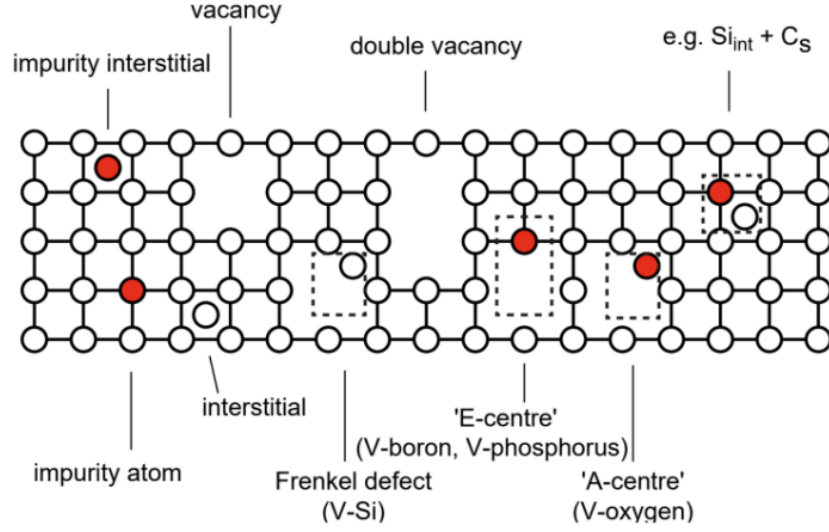


Figure 2.6: Defect types in a silicon lattice due to radiation damage. Red circles refer to impurity atoms [9].

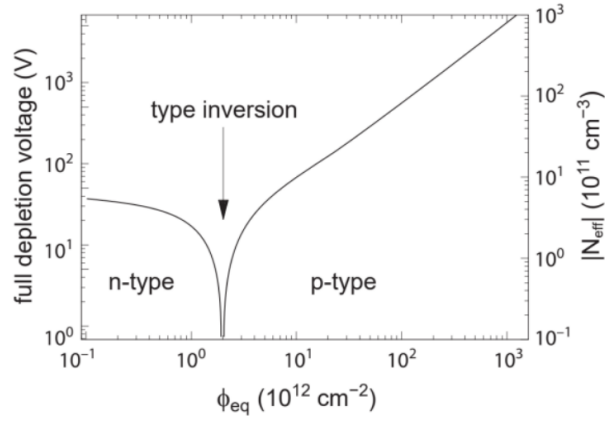


Figure 2.7: Effective doping concentration and bias voltage for full depletion of an initially n-type silicon sensor depending on NIEL flux [9].

inversion. An initially n-type silicon becoming effectively p-type is shown in Figure 2.7. The bias voltage required for full depletion, which is related to N_{eff} , firstly decreases and then increases. Type-inversion happens at the minimum point. Generally, sensors fabricated from p-type substrate material, which has p-type epitaxial layer, do not type-invert but the bias voltage required for full depletion increases with larger N_{eff} .

Leakage current: Defect with the energy level near the middle of the band-gap act as generation-recombination centers for carriers, increasing the probability of e/h pair thermal generation. Therefore, the leakage current increases proportionally to the NIEL flux, resulting in increased noise in signal detection. Assuming the leakage current is negligible when NIEL flux is 0 $n_{\text{eq}}\text{cm}^{-2}$, the relation ship between leakage current and NIEL flux is:

$$I_{\text{leak}} = \alpha \Phi_{\text{eq}} V. \quad (2.7)$$

where Φ_{eq} is the accumulated NIEL flux and V is the volume of the depletion area. The slope α is damage constant. Typical value of damage constant is in the order of $\mathcal{O}(10^{-17})$ A/cm [39] while the specific value depends on the type and energy of the radiation particle. Increased leakage current leads to larger power consumption and heats up the sensor, while at higher temperature, the leakage current further increases. Such positive feedback loop happens and becomes a thermal runaway after a certain temperature point, which would break the sensor. Proper cooling of the sensor is important for protection and remaining good performance.

Charge trapping: Electrons and holes generated by incident particle can be trapped in the lattice defect for sometime or even be lost by recombination at a deep level. This results in decreased carrier lifetime and mean free path length. Such mechanism reduce the signal amplitude or the detection efficiency, which is more significant for charges generated around the corner of a pixel who need to travel longer path to be collected hence have larger risk of being lost. To compensate this effect, full depletion is mandatory to prevent the signal collection through diffusion since the diffusion is slow in time, increasing the risk of signal loss, and higher bias voltage can be applied for a stronger electric field, enhancing the signal collection through drift.

2.1.3 Silicon sensor types

Strip sensor uses readout strips as collection electrodes, which covers a large volume of silicon sensor bulk. Such design has fewer readout channels, reducing the DAQ bandwidth pressure, while remaining a high spatial resolution. The relatively low manufacturing cost and large sensitive area are also the main advantages of it. However, strip design makes such sensor unable to remain its tracking performance under high occupancy environment. Besides, requirement of external readout chip increases the effect of multiple scattering. An example of the strip sensor is the SVD on Belle II detector, which was introduced in Section 1.3.2.

Hybrid pixel sensor is a long established technology widely used in LHC ATLAS and CMS experiment [8]. As shown in Figure 2.8 (left), it is made of two parts: the sensor part generating charge signal, produced in specialized silicon material and the readout part, containing the front-end circuit, as an additional layer attached to the sensor part through flip-chipping bump-bonding. The main benefit of hybrid pixel sensor is that the sensor and the readout front-end can be optimized separately, to achieve a high radiation tolerance and charge collection efficiency with readout electronics of high-rate capability. The pixel design also enhances the spatial resolution and the tolerance to high occupancy environment. The disadvantage of hybrid pixel sensor emerges when considering the manufacturing and the effect of multiple scattering. Bonding procedure is labor intensive and increases cost. Extra material budget from the additional readout

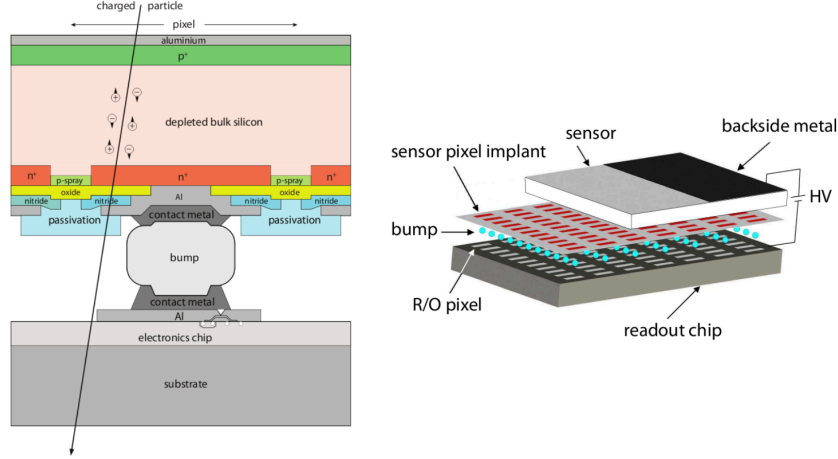


Figure 2.8: Design of hybrid pixel sensor (left) and the hybrid pixel detector matrix (right) [10].

layer induces more multiple scattering to incident particles. Besides, the lower limit of pixel size is induced by the bump-bonding.

Monolithic pixel sensor is an alternative approach to hybrid pixel sensor, which integrates the sensitive pixel matrix and the readout electronics into the same silicon bulk. Such design does not require laborious bump-bonding thus can be produced in large volumes by commercial semiconductor foundries. The material budget of monolithic pixel sensor can be small, offering lower material budget smaller than $0.5\% X_0$ compared with hybrid pixel sensor of around $1.5\% X_0$, which reduces the multiple scattering. Another advantage of monolithic pixel sensor is that, without large bump, the collection electrode can be very small ($< 30 \mu\text{m}$), resulting in small sensor capacitance, lowering the power consumption and increasing the Signal-to-Noise ratio (SNR). The difficulty in monolithic pixel sensor design is that, due to the small collection electrode and implants inside the sensor bulk, the depletion process becomes complex, making full depletion difficult to achieve. Incomplete depletion makes the signal amplitude smaller and reduces the radiation tolerance [8]. R&D regarding this problem will be introduced in Section 2.2.

2.2 State-of-the-art monolithic pixel sensors

2.2.1 Monolithic Active Pixel Sensor (MAPS)

Monolithic Active Pixel Sensor (MAPS) is produced based on CMOS imaging processes using an epitaxial silicon layer, which has a high electrical resistivity, grown on a substrate wafers. An example of MAPS design with p-type epitaxial layer and an n-well collection electrode is shown in Figure 2.9. Each pixel has its independent readout circuits integrated directly on the sensor bulk with NMOS and PMOS, making it “monolithic” and “active”. The whole epitaxial layer works as the sensing volume, while as introduced

in Section 2.1, the depletion area within the allowed biasing voltage is limited around the collection electrode. When charged particles pass through the sensor bulk, the generated signal charge in the non-depletion area have risks of recombination with the carries, reducing the signal amplitude. Besides, the charge signal generated in the non-depletion area can only be collected through diffusion instead of drifting due to the lack of electric field, which extends the signal collection time (in the order of 100 ns). The small signal requires a low noise in the readout electronics to achieve a reasonable SNR, hence a deep p-well layer offered by multiple well processes is required to isolate the circuits.

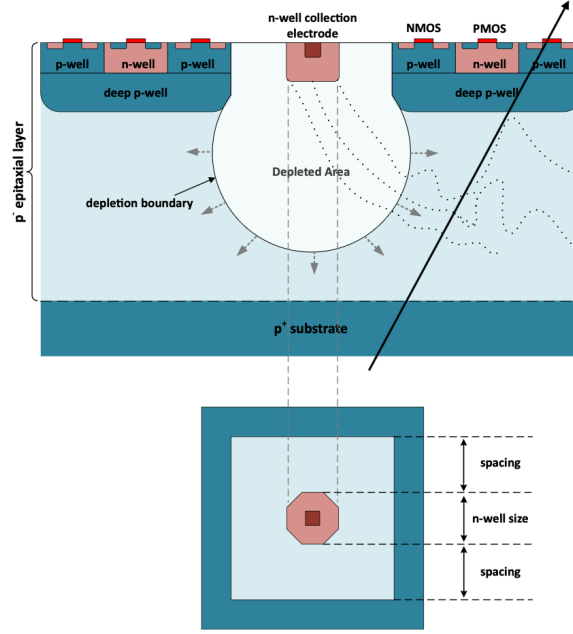


Figure 2.9: Cross section view of the MAPS design with slightly dosed p-type epitaxial later and n-well collection electrode. NMOS and PMOS circuits are isolated by deep p-well [8].

Detectors applying MAPS have been successfully used in STAR detector at Relativistic Heavy Ion Collider (RHIC) [40]. The ALICE experiment also chose MAPS for Inner Tracking System (ITS) upgrade [41].

2.2.2 Depleted Monolithic Active Pixel Sensor (DMAPS)

In HEP experiments that require fast response and high radiation tolerance, adequate depletion inside the sensor bulk is essential, where the signal charges are collected through drift without significant loss. Improvement from MAPS design making use of commercial CMOS processes with some add-ons and modifications have been pursued, leading to the development of **Depleted Monolithic Active Pixel Sensor (DMAPS)**. The main concepts for DMAPS is to achieve full depletion by 1) using epitaxial layers with higher resistivity to allow higher bias voltage and avoid punch through, a phenomena that the

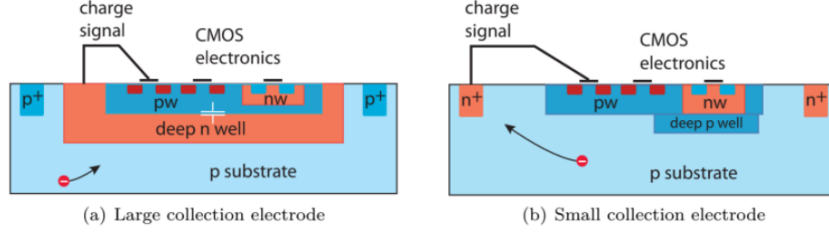


Figure 2.10: Two DMAPS concepts: (a) A large n-well working as collection electrode and isolation of readout electronics; (b) A small n-well collection electrode outside of the electronic area [9].

current starts to flow between p-well and p-substrate under high bias voltage; 2) modify the nested wells to have a planar depletion process, which is easier to be extended to the full sensor bulk. Two preliminary DMAPS scenarios are introduced below [8].

DMAPS with large collection electrode is shown in Figure 2.10 (a). In this case, the collection electrode is realized by a large deep n-well that also hosts the in-pixel readout electronics. The electric field configuration is similar to the hybrid sensor due to the large collection electrode, hence provide a planar depletion process, which can be extended to the entire pixel area, benefiting the charge collection properties and the radiation tolerance. However, the disadvantage of this geometry is that large collection electrode induces large input capacitance C_D to the readout front-end. As introduced in Section 2.1, larger C_D results in larger time constant, which slows the readout response and more importantly, a smaller SNR. To compensate these effects, increasing the transconductance g_m is possible while this increases the power consumption also.

DMAPS with small collection electrode is shown in Figure 2.10 (b). It realizes full depletion only utilizing the high resistivity epitaxial layer and keep the collection electrode small, outside of the readout electronic area, which is still isolated by the deep p-well. The small electrode has a small input capacitance, hence can keep a high SNR while keeping a low transconductance. However, the depletion depth is larger compared with planar geometry hence a higher bias voltage is required for full depletion. The drift length of the signal charge is longer, reducing the tolerance to radiation damage. To keep the bias voltage in an allowed value and a relatively high radiation tolerance, such sensor has to be small in size. Although smaller pixel and higher granularity are beneficial to physics performance, they would increase the manufacturing cost and power consumption of a whole detector.

The R&D of DMAPS with small collection electrode which can remain a sizable geometry is the frontier of silicon pixel detector. Recent development, resulting in a prototype named TJ-Monopix2, will be introduced in Section 2.3.

2.3 TJ-Monopix2 prototype

TJ-Monopix2 [8] is a DMAPS prototype originally designed for upgrade of ATLAS Inner Tracker (ITk) detector. It is fabricated in a modified TowerJazz (TJ) 180 nm CMOS imaging process, providing integrated standalone fast readout architecture and ToT capability, developed by a collaboration between the University of Bonn and CERN detector group, aiming to achieve a performance of low noise, low power consumption by small collection electrode and fast charge collection, high radiation tolerance by planar full depletion.

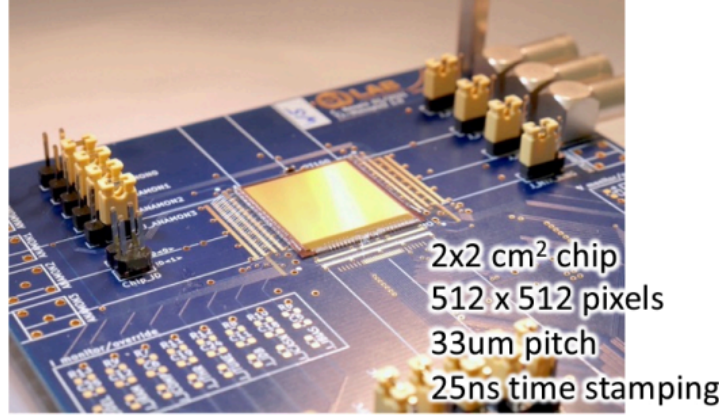


Figure 2.11: Photo of TJ-Monopix2 sensor matrix.

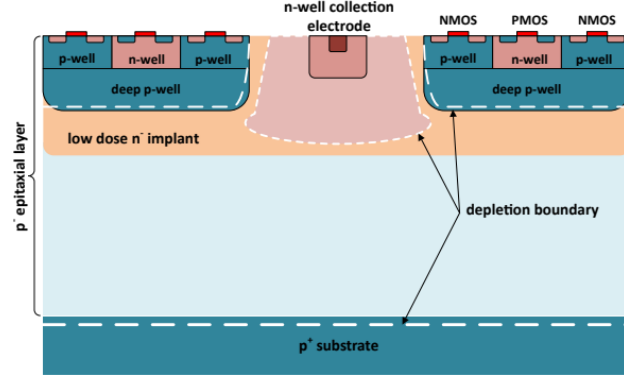
A photo of TJ-Monopix2 sensor is shown in Figure 2.11. The sensor matrix contains 512×512 pixels with pixel size of $33.04 \mu\text{m} \times 33.04 \mu\text{m}$ where the epitaxial layer is $25 \mu\text{m}$, which can be fully depleted. Sensor size is in total $2 \times 2 \text{ cm}^2$ including the pixel matrix and periphery. The timestamp distributed with Bunch Crossing ID (BCID) throughout the whole matrix is counted with a clock of 40 MHz, resulting in timing precision of 25 ns. Detailed matrix design, digital design and the characteristics of TJ-Monopix2 will be introduced in subsection 2.3.1, 2.3.2 and 2.3.3.

2.3.1 Matrix design

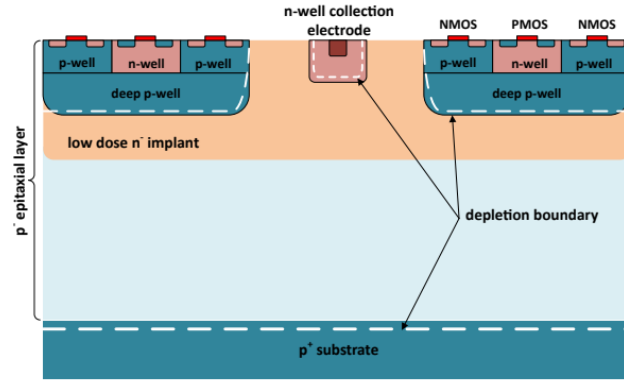
(1) Process modification towards full depletion

In the standard process fabricating MAPS shown in Figure 2.9, the depletion starts at the junction of the small collection electrode at the pixel center. In this case, it is difficult to laterally extend the depletion into the epitaxial layer since an electric field configuration similar to a planar junction is needed. To achieve full depletion without compromising the sensor capacitance, a process modification is developed, which is shown in Figure 2.12.

In this modification, a low dose, deep, n-type layer is implemented into the epitaxial layer below the wells hosting the readout electronics. As shown in the figure, the depletion



(a) At very low reverse bias voltage the depletion of the n^- implant layer is only partial around the collection electrode



(b) For higher reverse bias voltages, the depletion reaches the n^- well implant of the collection electrode yielding a low sensor capacitance

Figure 2.12: Process modification and the corresponding depletion process [8].

starts from two p-n junctions: 1) the junction between deep p-well and the low dose n-type implant, 2) the junction between the p-type epitaxial layer and the low dose n-type implant. Such depletion immediately extends over full pixel area and is finalized towards the n-type collection electrode. In order to fully deplete the area around the collection electrode, only a moderate bias voltage (up to 6 V) is required for non-irradiated sensors. During operation, since the whole sensor bulk including the low dose n-type implant is depleted, the deep p-well and the collection electrode are still isolated. A low sensor capacitance ($C_D \simeq 3$ fF) is also achieved. A potential minimum is formed at the collection electrode for charge collection by drifting.

Compared with standard process, the depletion isolates the deep p-well and the p-substrate hence they can be biased independently. A reverse bias voltage on the deep p-substrate can help enhancing the vertical electric field and the full depletion can also be achieved by biasing the deep p-well and p-substrate. Depending on the depth of the epitaxial layer, the punch through voltage between the deep p-well and p-substrate ranges from 20 V – 30 V.

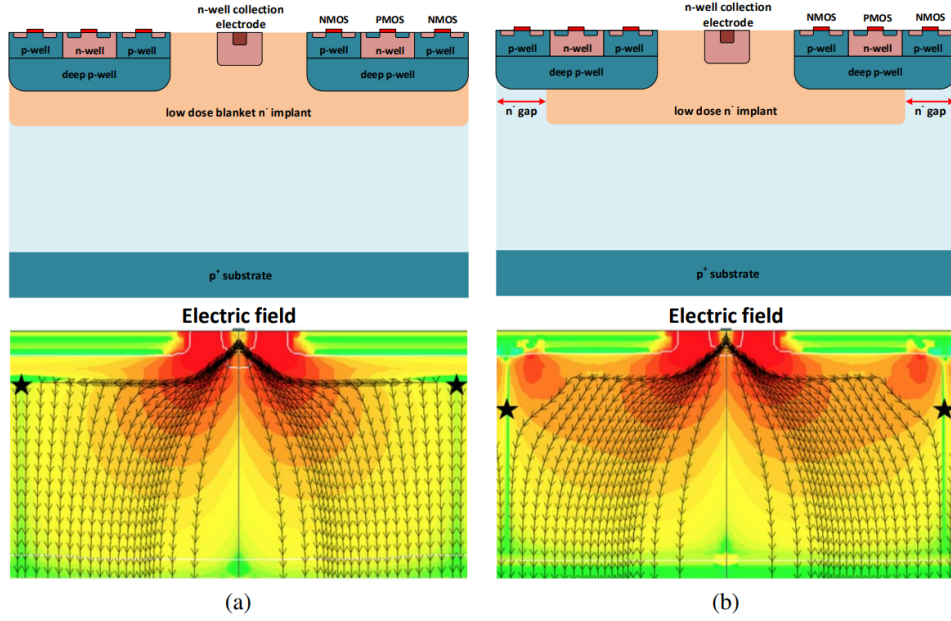


Figure 2.13: Electrostatic simulation of modified process (a) and optimized process (b). Electric field minimum points are indicated by star marks. In optimized process, the lateral electric field components are enhanced around the pixel edge [8].

(2) Optimization for lateral field enhancement

In the modified process introduced above, lateral electric field inside the sensor bulk forms a minimum (zero) at the pixel corners under the deep p-well. Combined with the vertical component of the electric field along the sensor depth which reaches zero at top junction boundary, they form a “ridge” in the potential landscape under the deep p-well and a saddle point at pixel corners. Part of the generated electrons are pushed by the electric field to the saddle point and the trapping probability is high, reducing the charge collection efficiency.

Introducing junctions along the sensor depth direction is the key to create potential gradient and electric field towards the collection electrode at the saddle point area. The optimization method on TJ-Monopix2 is to modify the low dose n-type implant to create a gap at the edge of the pixel. An electrostatic simulation of before optimization and after optimization is shown in Figure 2.13. After optimization, the electrical isolation between deep p-well and p-substrate becomes weaker hence the punch through begins at lower reverse bias voltage of p-substrate. The top-view illustration of the actual TJ-Monopix2 2×2 pixel group silicon well layout is shown in Figure 2.14, where the deep p-well is actually not symmetric around the collection electrode.

(3) Pixel matrix and front-end flavors

The layout and floor plan of TJ-Monopix2 is shown in Figure 2.15. The sensor contains a matrix of 512×512 pixels and a digital periphery. The pixel matrix is split into four

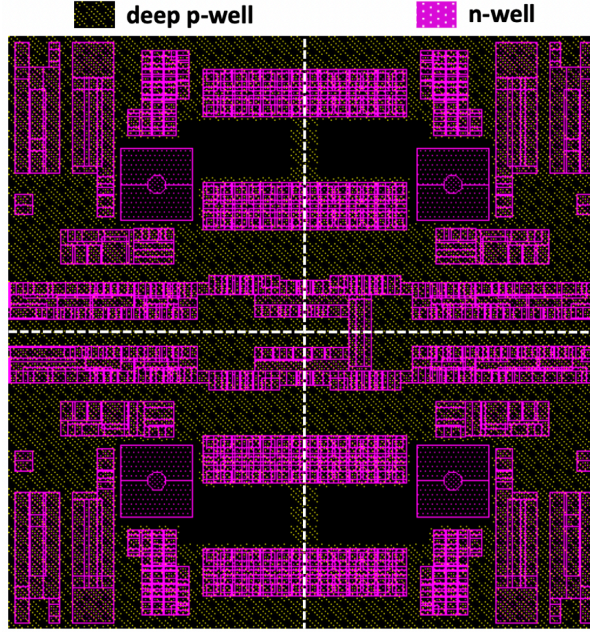


Figure 2.14: The top-view illustration of the actual TJ-Monopix2 2×2 pixel group silicon well layout.

sectors (flavors) that contain different variations of front-end circuit. The front-end flavors can be classified into DC/AC coupled and Normal/Cascode.

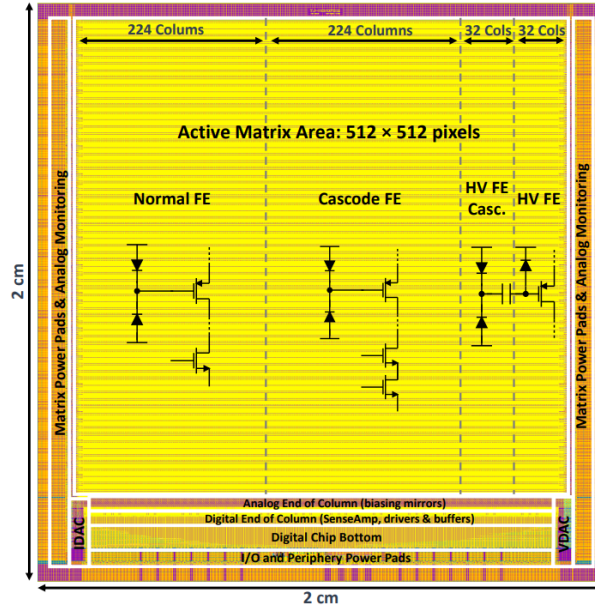


Figure 2.15: Layout of the TJ-Monopix2 sensor matrix, including the pixel matrix and the digital periphery [8].

DC coupled front-end have the input electrode directly coupled with the pre-amplifier. In this scenario, a maximum reverse bias voltage of -6 V is applied to the p-well and p-substrate instead of the collection electrode to avoid the malfunction or break down of

the MOSFET in the readout electronics and punch through. The collection electrode is kept to be at 0 V.

AC coupled front-end, which is also referred as HV front-end, have the collection electrode AC coupled to the pre-amplifier though a metal-oxide-metal (MoM) capacitor as shown in Figure 2.16. Such design allows high bias voltage directly applied to the collection electrode without interfering the MOSFET electronics. In this scenario, the p-well and p-substrate are kept at 0 V. Compared with DC front-end, the signal current is divided by the coupling capacitor and the parasitic capacitor, increasing the signal loss hence a lower gain is expected.

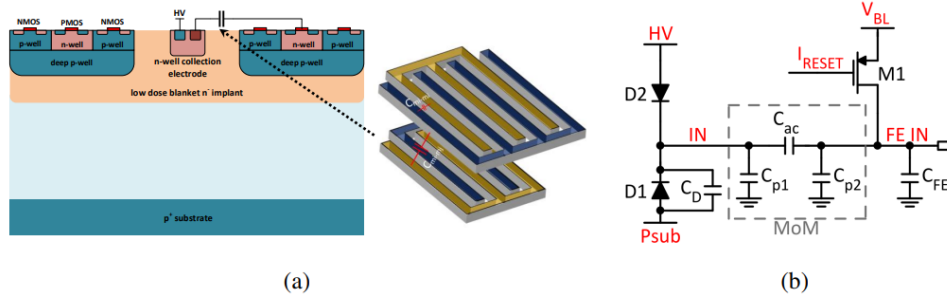


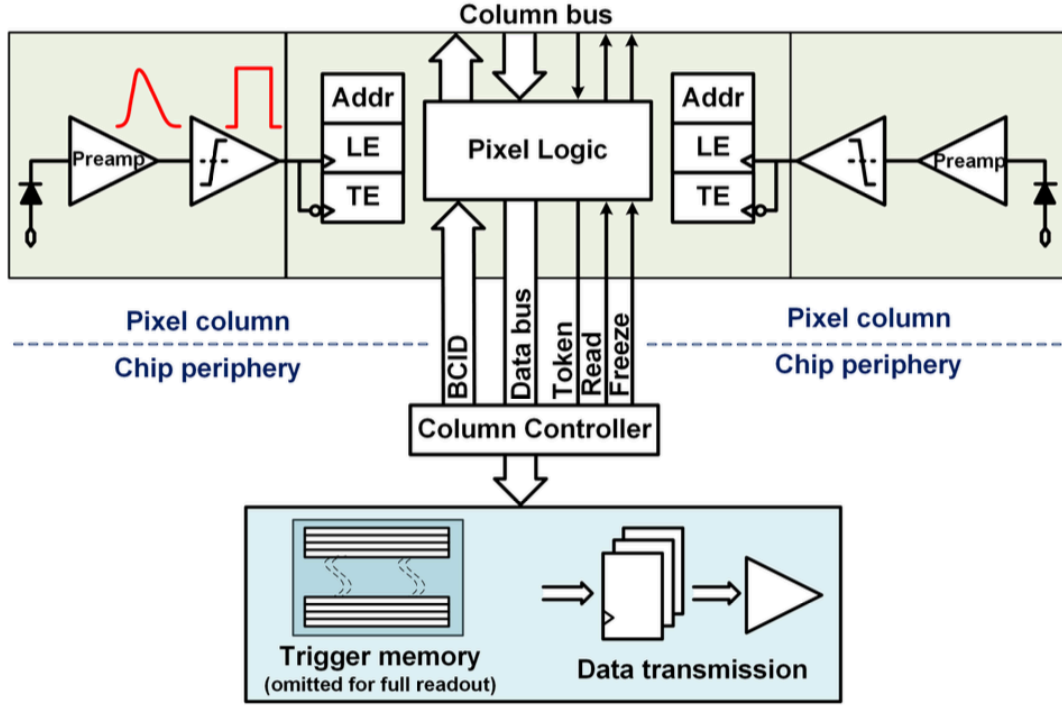
Figure 2.16: Cross-section view of AC coupling in the HV front-end (a) and the schematic view of the input to the pre-amplifier (b) [8].

Cascode front-end induces a cascode transistor in the pre-amplifier for gain boosting, which can also reduce the detection threshold dispersion among pixels. The disadvantage is the increased power consumption and complexity of readout front-end.

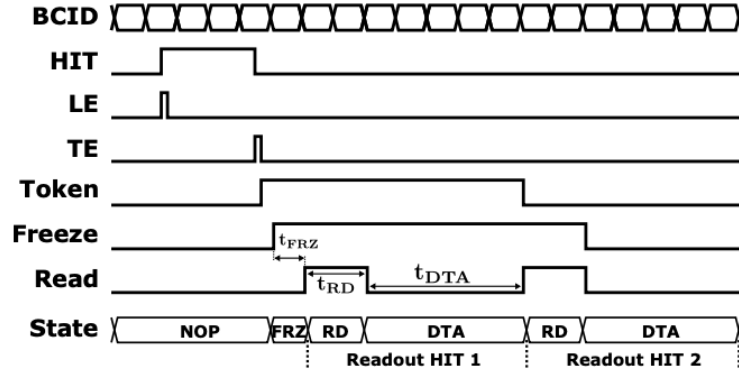
2.3.2 Digital design

TJ-Monopix2 utilizes a column-drain readout architecture whose operating principle is shown in Figure 2.17 (a). The in-pixel circuitry consists of Random Access Memory (RAM) cells to store the hit pulse Leading Edge (LE) and Trailing Edge (TE) timing information, a Read-Only Memory (ROM) to store the pixel address and the control and arbitration logic. The LE timestamp corresponds to the time of arrival of the hit pulse and the ToT can be calculated from the TE timestamp and LE timestamp difference. The buffer depth is one, which means only one hit can be stored in the pixel until the hit data is transferred to the periphery. The pixel matrix readout is column based. All pixels of a double column share a common column-bus that includes the BCID from the signal drivers, the data-bus and the necessary control signals. The column data-bus can be accessed by one pixel at a time with a pre-defined priority. Therefore, each column can be viewed as a queuing system operating at a specific speed that transfers hit information to the chip periphery.

The periphery includes the End of Column (EoC) block and Digital Chip Bottom (DCB) circuitry. The EoC block supports the transmission and readout of the column-



(a) Schematic representation of the column-drain readout architecture.



(b) Readout sequence timing diagram. In this example two hits are being processed.

Figure 2.17: Column-drain readout architecture schematic view (a) and readout sequence timing diagram (b) of TJ-Monopix2. In the readout sequence diagram, NOP represents no-operation; FRZ represents Freeze; RD represents read and DTA represents data transfer. The corresponding time delay and time consumption is also marked on the diagram [8].

bus signals. The DCB process the hit information and its implementation differs by the choice of triggered or full readout. In the case of a triggered readout, the received data from each double column readout is stored in a trigger memory until the trigger arrives or the trigger latency is expired. Hit data with the requested BCID by the trigger is transmitted to the DAQ. In the case of full readout, hit data is continuously transmitted

with an intermediate buffer First in First out (FIFO).

The readout sequence is shown in Figure 2.17 (b). When a hit pulse is produced, the timestamp of its LE and TE are stored in the in-pixel RAM. The readout sequence starts with the assignment of TE timestamp. A token signal is asserted to signify that the pixel is available to be readout and propagates across the column following the pixel priority. Token signal is received by the column controller, which activates two signals: “freeze” and “read”, to control the readout sequence. Freeze signal is activated during the readout phase, prohibiting new hits which disrupt the pixel priority logic. Read signal is activated after a short time delay, initiating the access of pixel with hit to the data-bus to transmit the hit information. After the read of data, data transfer is processed.

2.3.3 Characteristics

The physics performance, such as detection efficiency, spatial resolution, operation stability and timing accuracy, of TJ-Monopix2 is significantly affected by its operating characteristics. The most important aspects are introduced below.

(1) Detection threshold

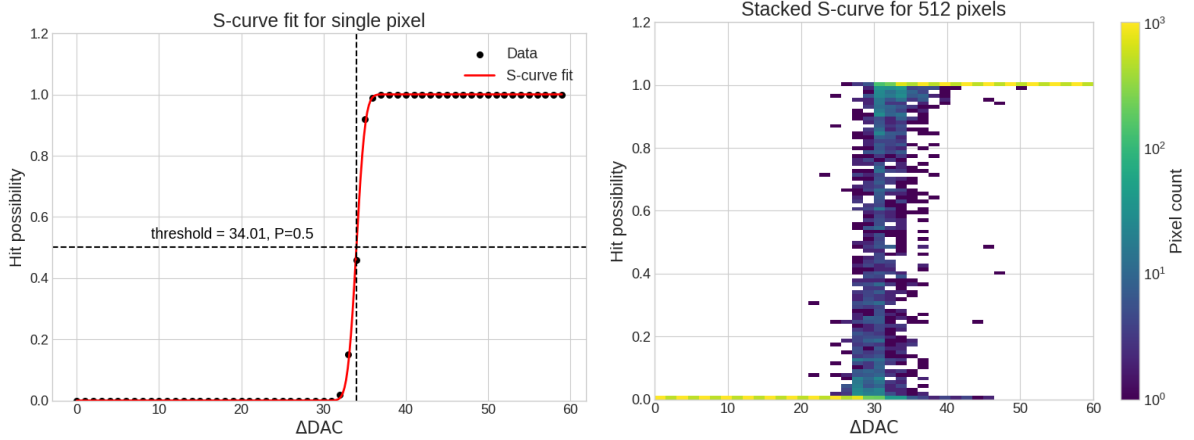


Figure 2.18: Example of an S-curve scan for a single pixel with an S-curve fit (left) and stacked S-curve data for 512 pixels in a 2D histogram (right).

Detection threshold of TJ-Monopix2 refers to the minimum detectable deposited charge in the sensor bulk. It is a result from the combined effect of global parameters, which is adjusted simultaneously for all pixels in the matrix, controlling pre-amplifier gain, pre-amplifier time constant and overall discriminator reference level. Additionally, the detection threshold is also influenced by a local parameter, which is adjusted pixel by pixel, as a fine tuning of discriminator threshold at the front-end of each pixel. In this work, the procedure of adjusting global parameters and local parameters on TJ-Monopix2

1317 is referred to as tuning and the set of global parameters and local parameters is referred
 1318 to as configuration.

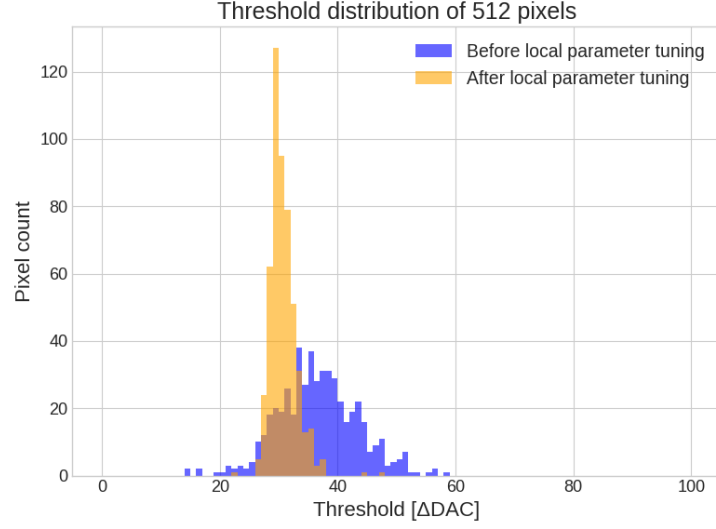


Figure 2.19: Example of a comparison of threshold distributions before and after local parameter tuning. After local parameter tuning, a more centralized threshold distribution can be achieved, representing a more uniform detection threshold in the sensor matrix.

1319 In TJ-Monopix2, a capacitor at the readout input is set to mimic the signal pulse of
 1320 deposit charge collected at the collection electrode, by charging the capacitor to a high
 1321 voltage level and discharging it to a low voltage level. The signal amplitude differs with
 1322 voltage difference between high level and low level, mimicking the different amount of
 1323 deposit charge. The voltage on the input capacitor is controlled by a Digital-to-Analog
 1324 Converter (DAC), and what matters is the difference between high level and low level
 1325 Δ DAC. Measurement of detection threshold for a pixel is performed by injecting test
 1326 signal pulses from the input capacitor at different Δ DAC and record the probabilities of
 1327 passing through the discriminator hence generating a signal hit at each Δ DAC, which
 1328 is also called “S-curve” scan since the curve of possibilities of signal hit depending on
 1329 Δ DAC forms an S shape as shown in the Figure 2.18. After taking the S-curve data, an
 1330 S-curve fitting using function:

$$f(x) = \frac{1}{2} \left(1 + \operatorname{erf} \left(\frac{x - \mu}{\sqrt{2}\sigma} \right) \right). \quad (2.8)$$

1331 is performed, where $f(x)$ is the hit possibility at injection pulse height x . $\operatorname{erf}(x)$ is the
 1332 error function. Fitted parameter μ is the detection threshold at which the possibility
 1333 of generating a signal hit is 50%. σ stands for the noise level which will be introduced
 1334 below.

1335 Due to the individual differences among pixels, the thresholds could variate signifi-
 1336 cantly throughout the matrix even if all the pixels are set with the same global parameters.
 1337 Tuning the local parameter on each pixel while injecting the signal pulses with Δ DAC

of target threshold to make the signal hit possibilities yield 50% is the method to reduce the threshold variation, hence to have a uniform threshold distribution. A comparison between untuned and tuned pixel thresholds is shown in Figure 2.19.

Detection efficiency of TJ-Monopix2 is sensitive to detection threshold. High detection threshold lowers the detection efficiency while low detection threshold results in unstable operation due to noise. Small threshold variation among pixels is important for a uniform detection efficiency distribution in the matrix. The standard deviation of thresholds of pixels is used to evaluate such uniformity, which is referred to as threshold deviation later in this thesis. Therefore, fine threshold tuning is important to optimize the performance of TJ-Monopix2, especially after irradiation when charge collection performance is degraded and noise level increases.

(2) Noise

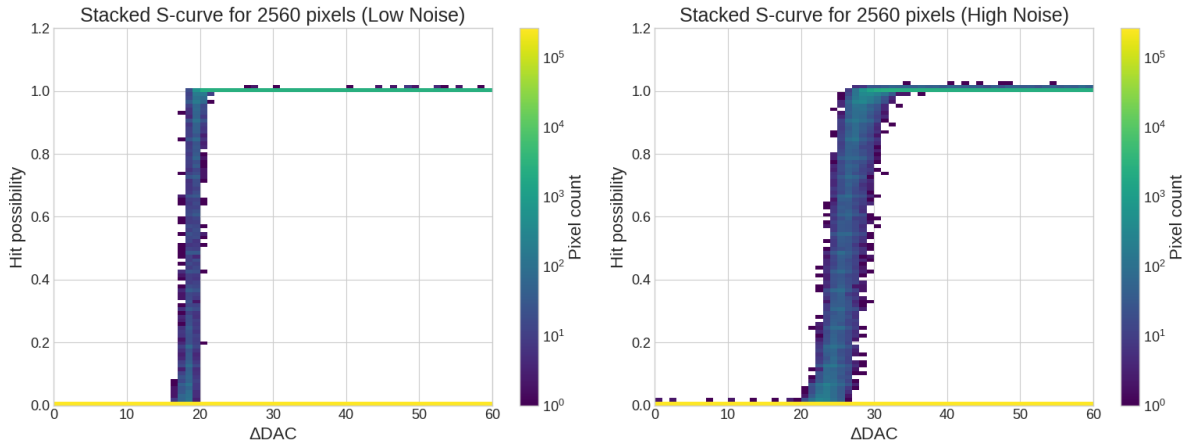


Figure 2.20: Example of S-curves with low noise (left) and high noise (right) level. The high noise level is from the measurement on irradiated TJ-Monopix2 prototype, showing a larger slope in the S-curve.

Noise acts as the charge fluctuation added on the collected signal, following gaussian distribution. In the S-curve measurement mentioned above, when injecting test signal pulse with the signal amplitude being μ , the actual signal amplitude influenced by noise follows a gaussian distribution:

$$f(s : \mu, \sigma) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{(s-\mu)^2}{2\sigma^2}}. \quad (2.9)$$

where s stands for the actual detected signal amplitude and σ describes the noise level. Assuming that the detection threshold is t , the yielding signal hit possibility is:

$$P(\mu) = \int_t^\infty f(s : \mu, \sigma) ds. \quad (2.10)$$

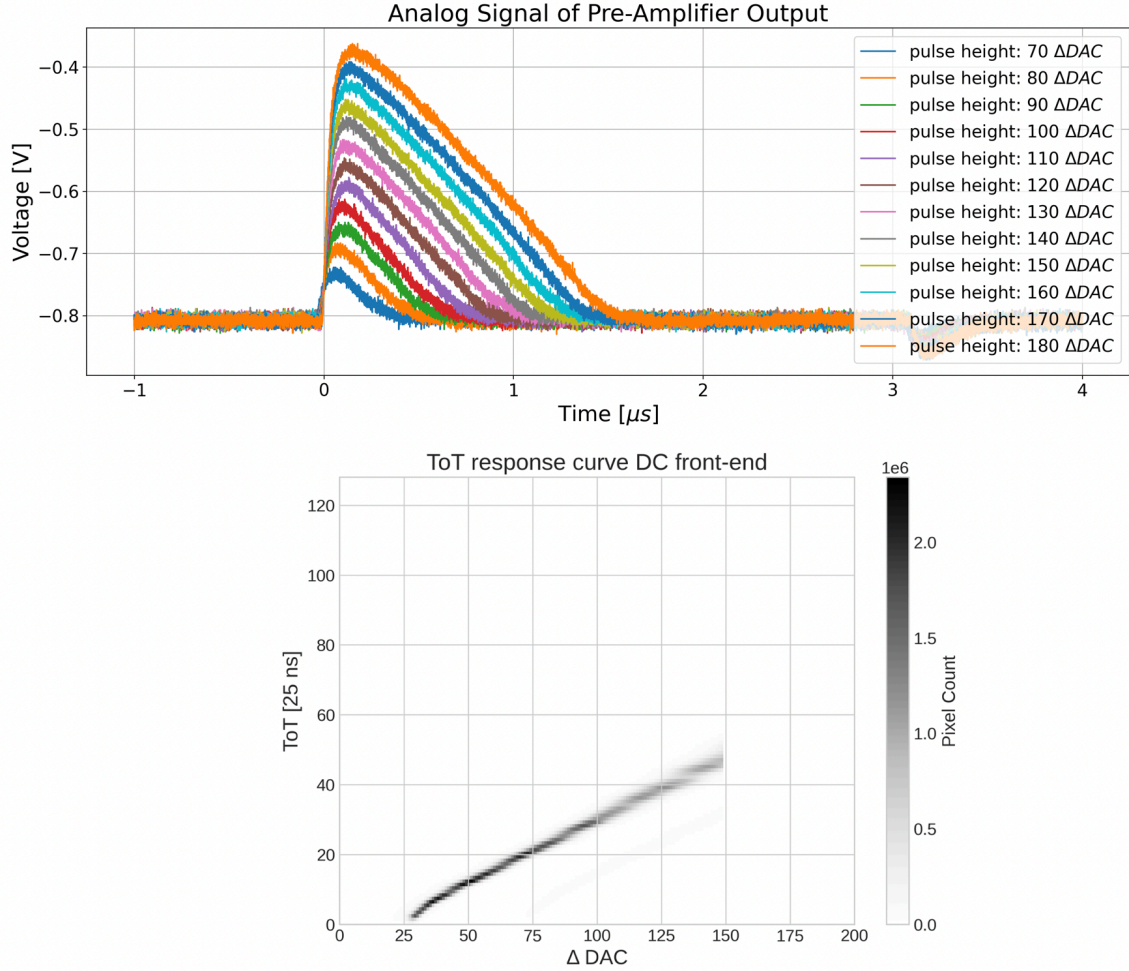


Figure 2.21: Analog signals output from the pre-amplifier in different ΔDAC level (above) and the corresponding ToT response curves of a group of pixels produced in S-curve scan (below). The baseline of the pre-amplifier output is moved to -0.8 V in the oscilloscope.

When injected test signal pulses equals to the threshold level ($\mu = t$), the resulted signal hit probability $P(t) = 50\%$. The slope k of S-curve at this point is:

$$k = \left. \frac{dP(\mu)}{d\mu} \right|_{\mu=t} = f(t : t, \sigma) = \frac{1}{\sigma\sqrt{2\pi}}. \quad (2.11)$$

Therefore, the noise level measured in S-curve scan actually behaves as the slope at the point on S-curve where the injected test signal pulse equals to the operating threshold. S-curves with different noise level are shown in Figure 2.20.

To optimize the detection performance of TJ-Monopix2, the detection threshold tends to be adjusted at a low level. In this case, high noise level would result in fake hits. In serious situation, large amount of noise hits continuously flood into the readout front-end, causing significant crosstalk among pixels which also acts as noise, and eventually result in the simultaneous fake hit of all pixels in the matrix. Such chain effect is called “flashing”. Careful measurement and control of noise level is important to the stable

operation of TJ-Monopix2.

(3) ToT response curve

In the S-curve scan, the increased test signal pulse amplitude results in increased analog signal output from the pre-amplifier, which passes through the discriminator at the front-end electronics and is turned into larger ToT signal. Continuous test signal pulses with increasing ΔDAC creates the continuously increasing ToT response for each pixel, which is referred as ToT response curve.

An example of increasing analog signal and ToT response curve produced in S-curve scan is shown in Figure 2.21. Due to the rounded peaking point of the analog signal, the ToT response curve begins with a curved shape but becomes linear later. Since the response of real particles is reflected with ToT information without directly knowing the corresponding ΔDAC , the ToT response curve is important to convert the ToT and ΔDAC level with each other, which is used in the gain calibration.

(4) Clock signal crosstalk

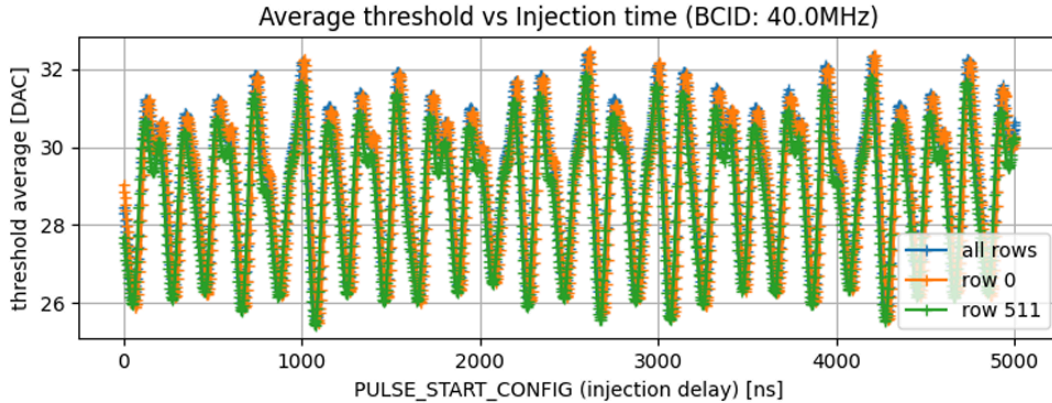


Figure 2.22: Threshold oscillation resulted from clock signal crosstalk, measured by changing the injection timing of test signal pulses to different clock signal phase. Since clock signal propagates in column direction, pixels on the same row share the same clock phase, the threshold is presented as the average of specific rows or all rows [11].

Clock signal, which is also called bunch-crossing ID (BCID) signal, is a counter incremented by the 40MHz clock, which is transmitted through a series of buffers on column-bus shown in Figure 2.17 (a) with a certain reset interval. When multiple columns transmit clock signal at the same time, the large amount of digital shifts can interfere with the in-pixel front-end, varying the baseline level of the amplifier output and leading to a shift in the effective threshold. The oscillation of threshold caused by this crosstalk effect is shown in Figure 2.22.

In the S-curve measurement, since the test pulses are injected always at the same clock signal phase after resetting, the measured threshold does not show the impact of crosstalk and is at a fixed level. However, in real operation, the incident particles come in arbitrary time hence in arbitrary clock signal phase. Therefore, the incident particles are actually detected by an oscillating threshold. This threshold fluctuation effectively has the same impact as introducing additional noise, influencing the signal height and detection efficiency. If not specifically mentioned, the threshold mentioned in this thesis refers to the result of S-curve scan with a test pulse injection delay of 36.1 ns, which corresponds to the first minimum point in the oscillation on DC front-end.

(5) Clock signal propagation delay

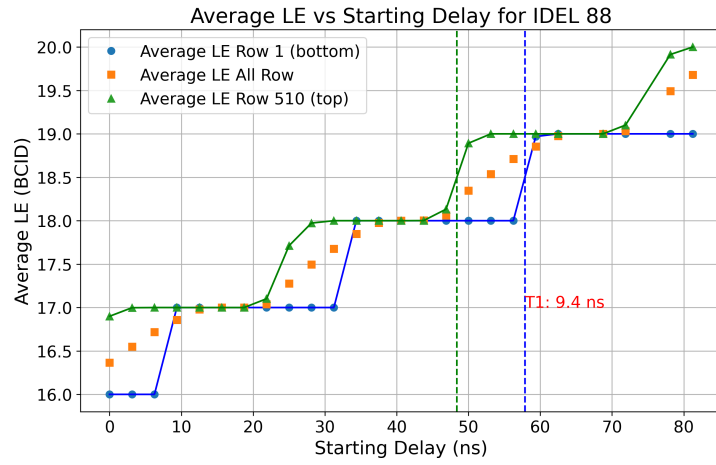


Figure 2.23: Average LE timestamp (in the unit of 25 ns) evolution depending on injection delay of test pulse in row 510, row 1 and all rows. Dotted lines indicate the delay times at which row 1 and row 510 yield the same LE timestamp. Red text T1 shows the time difference of two dotted lines, representing the combined time delay of clock signal and injection signal.

Clock signal propagates through the column-bus from the digital periphery (close to row 0) to the top of the matrix (row 511). At each specific time point, the clock count at the pixels in larger row number is always smaller than the pixels in smaller row number due to propagation delay, resulting in inconsistency in the timestamp of hits from different row positions, which leads to a degradation of time resolution. To assign the same timestamp to these hits, compensation of clock signal propagation delay is necessary. In TJ-Monopix2, a register called IDEL is provided to delay the timestamp assignment depending on row numbers, which is set manually depending on the clock signal propagation delay measurement.

Measurement of clock signal propagation delay is a combination of a series of measurements, involving the delay measurement of many different digital signals. One example of measuring the LE timestamp difference evolution by injecting the test signal pulses in

different time delay is shown in Figure 2.23. The measured LE timestamp delay between row 0 and row 511 under a certain compensation IDEL value is a combined value of clock signal propagation delay and delay of test pulse injection signal (which also propagates through the column-bus). Therefore, other measurements are needed to exclude the effect from test pulse injection signal, which will be introduced in Chapter 4.

(6) Charge collection efficiency

When signal charge is generated from the incident particle and deposited inside the sensor bulk, it will be collected by the collection electrode through drifting following the electric field. The efficiency of deposit charge being collected is of interest since it is directly related to the signal detection.

The actual charge collection efficiency can not be precisely measured. Instead, we use the conversion factor from the signal amplitude at the collection electrode to the deposited signal charge $\text{Conversion} = \text{deposit charge}[e^-]/\text{signal amplitude}[\Delta\text{DAC}]$ to reflect the charge collection efficiency, where the signal amplitude is in the unit of test signal pulse amplitude ΔDAC as described above. Higher charge collection efficiency results in lower conversion factor, which can be interpreted as the deposit charge needed to form 1 ΔDAC of signal amplitude. The measurement will be introduced in Chapter 4.

Chapter 3

Goal and procedures of this work

An upgrade of vertex detector, VTX, is proposed as described in Section 1.5. The VTX detector is required to meet an upgrade baseline, which is set to make sure the expected performance after implementation, one of which is high radiation tolerance. To confirm the radiation tolerance of VTX detector, the impact of radiation damage to the its sensor performance is necessary, being the goal of this work.

In this Chapter, the upgrade baseline of VTX detector will be firstly introduced in Section 3.1 and then the outline of this work will be described in Section 3.2.

3.1 Upgrade baseline

As described in Section 1.5.3, the VTX detector would improve the tracking robustness against large beam backgrounds from the accelerator, track reconstruction efficiency for low momentum particles and vertex resolution. Corresponding to the performance expectation, the upgrade baseline requirement is set.

Spatial resolution below $15\ \mu\text{m}$ is required for better vertex resolution along with low material budget around $0.2\% X_0$ per inner layer and $0.8\% X_0$ per outer layer, which can also improve the vertex resolution by reducing multiple scattering and the tracking reconstruction for low momentum particles with less energy loss. Besides, a detection efficiency of its pixel sensor more than 99% is mandatory.

Belle II is a long-term experiment with a lifetime of decades as shown in Figure 1.1. As the innermost layers, vertex detector is exposed to a high radiation environment, where the beam background from SuperKEKB constantly creates damage to the sensors, especially in the future operation under high instantaneous luminosity. Therefore, high radiation tolerance is required. Corresponding to the high instantaneous luminosity, VTX detector is also required to have a capability to handle high hit rate, which can be achieved by its fully pixilated design with higher granularity compared with PXD. The reference hit rate in future high luminosity run and accumulated radiation dose/flux for the innermost layer are [5]:

- Hit rate: 120 MHz/cm²
- Total ionizing dose [36]: 100 Mrad
- NIEL flux: $5 \times 10^{14} \text{ } n_{\text{eq}}/\text{cm}^2$

As the sensitive part of VTX, the DMAPS design of OBELIX sensor is naturally required to endure the same accumulated radiation dose/flux and be able to cope with the same hit rate.

3.2 Research outline

The research activities studying the impact of NIEL flux to the sensor performance are being performed in VTX collaboration. The particle components creating NIEL flux are shown in Figure 3.1. Two of the main sources of the NIEL flux are 10 MeV-level electrons and MeV-level neutrons. A study investigating the impact of neutron irradiation is being performed within the VTX collaboration in parallel using proton-irradiated TJ-Monopix2 samples, and in this study electron irradiation, which has not been tested before, is focused on.

The goal of this work is to evaluate the impact of radiation damage caused by electrons to the performance of the DMAPS design used in VTX detector and to confirm that the sensor performance remains within the upgrade requirement after irradiated to the expected NIEL flux. Specifically, an electron-irradiated DMAPS sample is created using 90 MeV electrons with the target accumulated NIEL flux of $5 \times 10^{14} \text{ } n_{\text{eq}}/\text{cm}^2$, whose performance is measured and compared before and after irradiation.

As described in Section 1.5.2, the OBELIX sensor utilizes the same matrix design with TJ-Monopix2 prototype. From the preliminary testing of TJ-Monopix2 prototype, the first OBELIX prototype OBELIX-1 is determined to keep the Cascode front-end design of both DC and AC coupling types, which are described in Section 2.3. Therefore, this study is performed on the DC and AC coupled Cascode front-ends of TJ-Monopix2. The performance comparison between DC and AC front-end also provides reference for the future development of OBELIX. Detection performance including detection efficiency and spatial resolutions are measured in test beam campaigns and compared with upgrade requirements, for both non-irradiated and irradiated TJ-Monopix2 prototype. The specific procedures are as follow:

1. Measuring the detection performance of non-irradiated TJ-Monopix2, including detection efficiency and spatial resolution, in a test beam campaign.
2. Irradiating the TJ-Monopix2 prototype using 90 MeV electron beam up to the NIEL flux of $5 \times 10^{14} \text{ } n_{\text{eq}}/\text{cm}^2$.

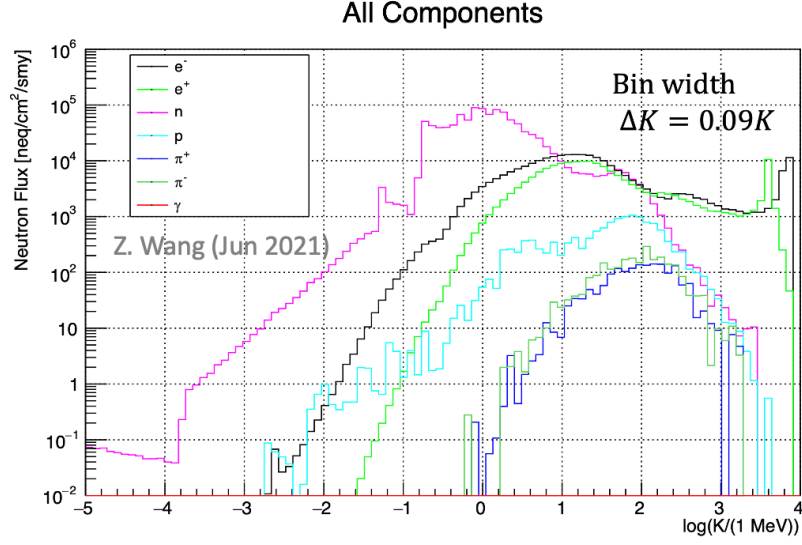


Figure 3.1: Particle sources and their flux creating NIEL damage to the third layer of VXD under the assumption of nominal SuperKEKB [12].

3. Measuring the detection performance of electron-irradiated TJ-Monopix2 prototype in a test beam campaign, to investigate the possible performance degradation and the method to compensate such degradation. Detection performance depending on temperature is investigated to confirm the proper working temperature. Performance of the electron-irradiated TJ-Monopix2 sample produced in this work is also compared with proton-irradiated TJ-Monopix2 samples produced by other groups within VTX collaboration.

Except for detection performance that can only be measured in test beam campaigns, the other characteristics are measured in the laboratory of KEK:

1. Charge collection efficiency. By comparing charge collection efficiency before and after irradiation, the degradation of charge collection performance of TJ-Monopix2 can be understood. This also provides insights for the potential degradation of detection efficiency.
2. Temperature sensitivity of threshold, threshold deviation and noise of TJ-Monopix2. This property provides important reference for the design of cooling strategy on VTX detector. High sensitivity to temperature change, either before or after irradiation, suggests potential performance degradation under high temperature.
3. IV curve of leakage current. After irradiation, leakage current increases. The IV curve of leakage currents provides information of depletion process, especially after irradiation when the expanding of depletion region becomes difficult. This is also strongly related to the dependency of detection efficiency to the bias voltage.

1510 4. Clock signal propagation delay. As described in Section 2.3.3, compensation of clock
1511 signal propagation delay is important to make sure the correct timing alignment of
1512 hit data. The potential change of compensation register IDEL needs to be confirmed
1513 by comparing clock signal propagation delay measurement before and after the
1514 irradiation of the sensor.

1515 5. Clock signal crosstalk. As described in Section 2.3.3, clock signal crosstalk results in
1516 threshold oscillation according to clock phases. Since the fluctuation in thresholds
1517 effectively induces the same impact with noise, if this effect is found to be significant,
1518 suppression of clock signal crosstalk will be an important research topic in future
1519 sensor development.

1520 The laboratory measurement before and after irradiation will be described in Chap-
1521 ters 4 and 7, respectively. The test beam measurement before and after irradiation will
1522 be described in Chapters 5 and 8, respectively. The irradiation campaign is described
1523 in Chapter 6. Summary of the results, the conclusion and outlook will be discussed in
1524 Chapter 9.

Chapter 4

Laboratory measurement before irradiation

Except for the detection efficiency and spatial resolution which can only be measured in beam test, the other characteristics including charge collection efficiency, temperature sensitivity and BCID propagation delay of an non-irradiated TJ-Monopix2 prototype is measured in the laboratory of KEK. A photo of this laboratory is shown in Figure 4.1. These results are to be compared with that of after irradiation.

In this chapter, the test bench setup of KEK will be introduced in Section 4.1, including the data acquisition, power control and temperature control setup. The measured characteristics of charge collection efficiency, threshold tuning temperature dependency and BCID propagation will be introduced in Sections 4.2, 4.3 and 4.4, respectively.



Figure 4.1: Photo of the laboratory in KEK testing TJ-Monopix2.

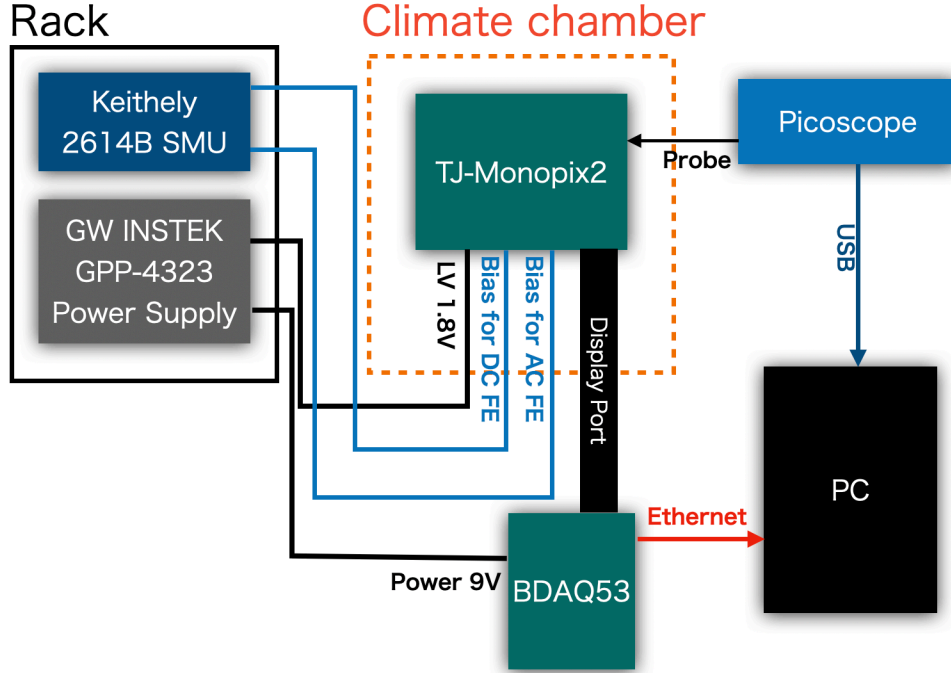


Figure 4.2: Schematic view of KEK test bench for TJ-Monopix2 prototype. The Keithely 2614B source meter and GW INSTEK GPP-4323 power supply are also connected to the PC through Ethernet cables for remote control, which are not indicated in the figure.

4.1 KEK test bench

The floor plan of KEK test bench is shown in Figure 4.2. TJ-Monopix2 prototype is placed in a climate chamber for temperature control. A power supply, GPP-4323 from GW INSTEK is used to provide power for low voltage ($LV = 1.8\text{ V}$) for TJ-Monopix2 front-end and the power supply (9 V) for a BDAQ53 board. The bias voltages for TJ-Monopix2 are provided by a Keithely 2614B source meter. Since the bias voltages for DC and AC front-end are applied to different parts of the sensor as described in Section 2.3, two channels of the source meter are used. The BDAQ53 [42] board is used to transfer the data from TJ-Monopix2 to the PC and transfer the control command from the PC to TJ-Monopix2. The communication between BDAQ53 board and TJ-Monopix2 is through a Display Port cable while the communication from the BDAQ53 board to the PC is done through an Ethernet cable with SiTCP [43]. A Picoscope oscilloscope is set up to monitor the analog and digital signal from TJ-Monopix2, which is connected to the PC. A `tj-monopix2-daq` software environment [44] is running on the PC. A remote controlling and monitoring software for the whole powering system is developed and running on the PC to make sure the low voltage, bias voltage and BDAQ53 are powered in the correct sequence.

The tuning of TJ-Monopix2 is performed in KEK test bench. For the DC front-end, a stable tuning is confirmed at detection threshold of $\sim 30\ \Delta\text{DAC}$. Even though the detection threshold can be lowered, the pixels tend to be noisy and even flashing described

in Section 2.3.3 can happen if a large portion of matrix is enabled and put in the beam line. For the AC front-end, the tuning is confirmed at a lowest detection threshold of $\sim 20 \Delta\text{DAC}$. When the bias voltage is applied, no matter DC or AC front-end is in use, both of the source meter channels are kept connected hence the current can flow. The leakage current from the sensor bulk flows into the collection electrode according to the electric field distribution, which is connected to the source meter channel providing bias voltage for AC front-end. Before irradiation, the leakage current is in the level of $\mathcal{O}(10 \sim 100 \text{ pA})$, which is negligibly small compared to the expected radiation effect and not sensitive to temperature, bias voltage and other factors. Therefore, the detail of leakage current measurement before irradiation is not reported in this chapter. Before irradiation, the maximum bias voltage for the DC front-end is 6 V and for the AC front-end is 20 V, without the risk of punch through. However, the maximum depletion happens at the bias voltage of 6 V already.

4.2 Charge collection efficiency

The conversion factor from test pulse amplitude ΔDAC to the deposited charge inside the sensor bulk is measured, which is used to reflect the charge collection efficiency as described in Section 2.3.3. The measurement is performed using Fe-55 radiation source at room temperature environment (about 25 ΔDAC). The energy of $K\alpha$ X-rays emitted from Fe-55 peaks at $\Delta E = 5.9 \text{ keV}$, which can be fully absorbed in silicon sensor. As introduced in Section 2.1, average deposit energy needed to create one e/h pair inside silicon bulk is $w_i = 3.65 \text{ eV}$. Hence, the characteristic peak of Fe-55 radiation in ToT distribution corresponds to the number of e/h pairs of:

$$\#_{\text{e/h}} = \frac{\Delta E}{w_i} = \frac{5.9 \text{ keV}}{3.65 \text{ eV}} \simeq 1616. \quad (4.1)$$

The ToT distributions after clustering and fitting with gaussian functions for DC and AC front-end is shown in Figure 4.3. To the configurations used in this measurement, the fitted peak positions are at $\text{ToT}/25 \text{ ns} = 53.95$ and $\text{ToT}/25 \text{ ns} = 32.84$ for DC (6 V biased) and AC (10 V biased) front-end, respectively.

At the same configurations in which the Fe-55 radiation data is taken, the ToT response curves described in Section 2.3.3 need to be fitted and extrapolated. In the S-curve scan described in Section 2.3.3, the ToT response depending on the injected test signal pulse amplitude is also measured. Due to the rounded shape at the top of waveforms that pre-amplifier output, the ToT response is curved when injected test signal pulse is around the detection threshold and become linear shortly after. Such ToT response is fitted with curve:

$$f(x) = ax + b + \frac{c}{x - t}. \quad (4.2)$$

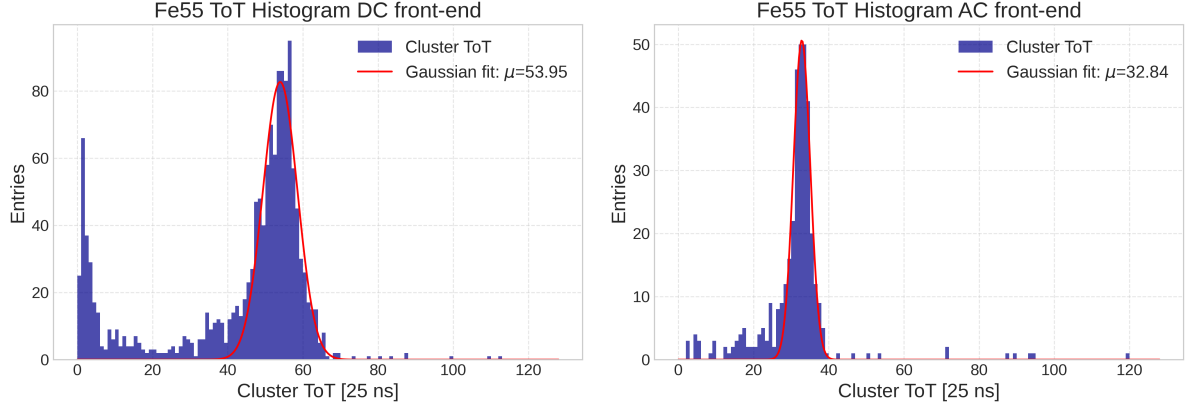


Figure 4.3: ToT distributions and gaussian fittings of Fe-55 response for DC (left) and AC (right) front-end. The ToT peak around 0 in DC front-end is from the noisy pixels which were not totally excluded.

where x stands for the injected test signal pulse. The term $ax + b$ express the linear response in large injection pulse area and $c/(x - t)$ describe the threshold effect which rounds up the ToT response curve. Therefore, parameter t is expected to be around the detection threshold. After fitting, the ToT response curve is extrapolated to the Fe-55 ToT peaking point, to convert the fitted ToT peak to test pulse unit ΔDAC .

The result of DC and AC front-end is shown in Figure 4.4. In this measurement, the test pulse amplitude corresponding to the Fe-55 deposited charge are 168.84 ΔDAC and 88.52 ΔDAC for DC and AC front-end. Hence the measured conversion factors are:

$$\text{Conversion}_{\text{DC}} = \frac{1616 e^-}{168.84 \Delta DAC} = 9.57 \pm 0.05 e^-/\Delta DAC \quad (4.3)$$

$$\text{Conversion}_{\text{AC}} = \frac{1616 e^-}{88.52 \Delta DAC} = 18.26 \pm 0.07 e^-/\Delta DAC \quad (4.4)$$

where the uncertainties of conversion factors are evaluated by the uncertainties of fitting parameters and their covariance.

As explained in Section 2.3, AC front-end suffers from signal loss due to the extra coupling capacitor. The larger conversion factor for AC front-end, which stands for lower charge collection efficiency, compared with DC front-end, is as expected.

4.3 Temperature dependency: threshold and noise

The impact of sensor temperature on the characteristic of TJ-Monopix2 is investigated, including the detection threshold, threshold deviation and noise level under a specific tuning configuration. In this measurement, two configurations for DC front-end and one configuration for AC front-end are tested. For each configuration, an S-curve scan is performed after the temperature is stabilized, which is controlled through the climate chamber. The result is shown in Figure 4.5, 4.6 and 4.7. It is necessary to note that

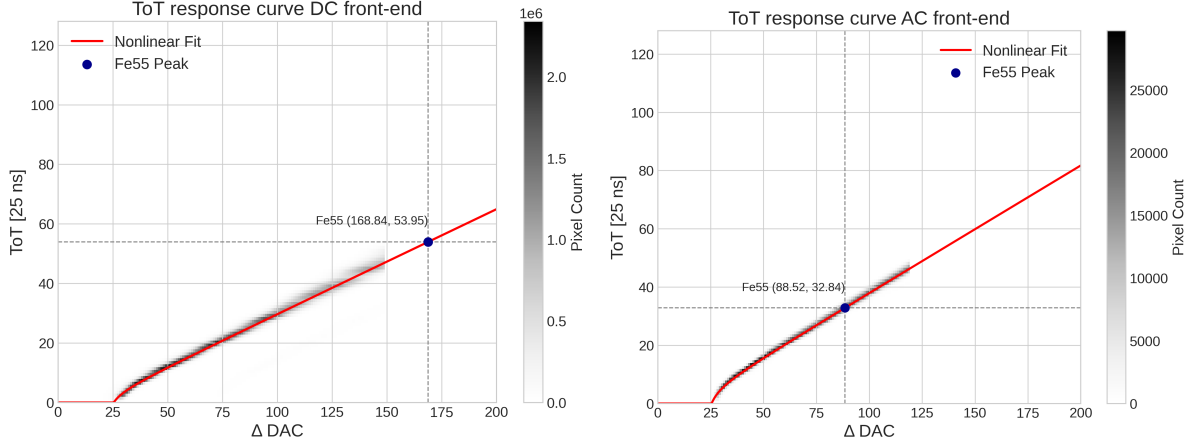


Figure 4.4: Fitting and extrapolation of ToT response curves for DC (left) and AC (right) front-end. The black lines are ToT response curves of a group of pixels in each front-end and the red lines are the fitting result.

the actual temperature throughout the pixel matrix is higher than the climate chamber set value by $2 \sim 5$ °C due to the power consumption of the chip.

The general tendency is that the detection threshold and threshold deviation increases along with temperature, when the local parameter described in Section 2.3.3 is not retuned in the middle of the temperature scan, as shown in the behavior of configuration 2 of the DC front-end and the AC front-end. The AC front-end shows a larger change by about $4 \Delta \text{DAC}$ from 0 °C to 45 °C while the change in the DC front-end is around $2 \Delta \text{DAC}$ in threshold from 0 °C to 45 °C. The change of threshold deviation is much smaller, being within $1 \Delta \text{DAC}$ for both the DC and AC front-end. However, for some tuning, the dependency is totally different such as the configuration 1 of DC front-end. This complexity in temperature dependency is from that the front-end tuning is a combined effect of many transistors controlled by registers. The measured noise level from S-curve scan increases with the temperature, as expected. Since the leakage current is quite small before irradiation, the noise increase is also small, in the order of $\mathcal{O}(0.1 \Delta \text{DAC})$.

Assuming full depletion of the $25 \mu\text{m}$ epitaxial layer, the typical number of electrons collected as signal from MIPs is $2000 e^-$, which is calculated using to Equation 2.3. The typical detection thresholds are around $300 e^-$ at the DC front-end and around $350 e^-$ at the AC front-end, according to the results of charge collection efficiency reported in Section 4.2. The threshold increases from 0 °C to 45 °C are roughly around $20 e^-$ for the DC front-end and $72 e^-$ for the AC front-end. For non-irradiated TJ-Monopix2 prototype, the sensitivities of threshold, threshold deviation and noise to temperature change are small enough compared with the signal charge of MIPs. Therefore, degradation of detection performance under high temperature is not expected before irradiation.

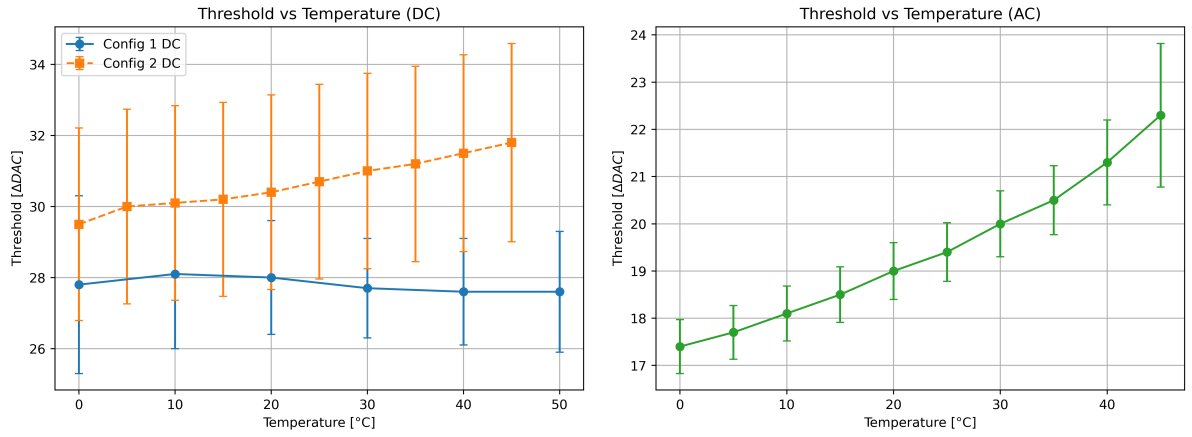


Figure 4.5: Threshold dependency to climate chamber set temperature of DC (left) and AC (right) front-end. The error bars represent the deviations of thresholds. The general tendency is that the detection threshold and threshold deviation increases along with temperature while the configuration 1 at the DC front-end behaves differently.

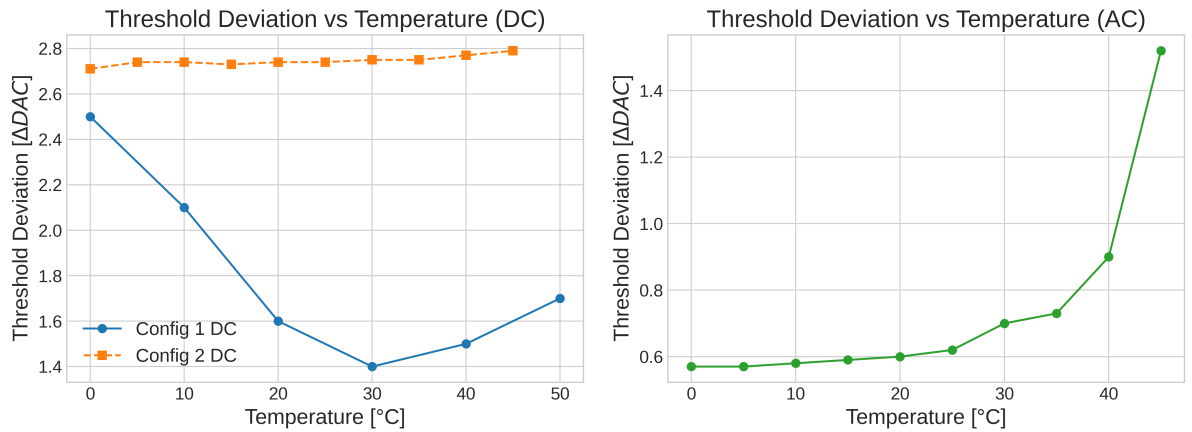


Figure 4.6: Threshold deviation dependency to climate chamber set temperature of DC (left) and AC (right) front-end. The total changes are within 1 Δ DAC for all configurations in both the DC and AC front-end.

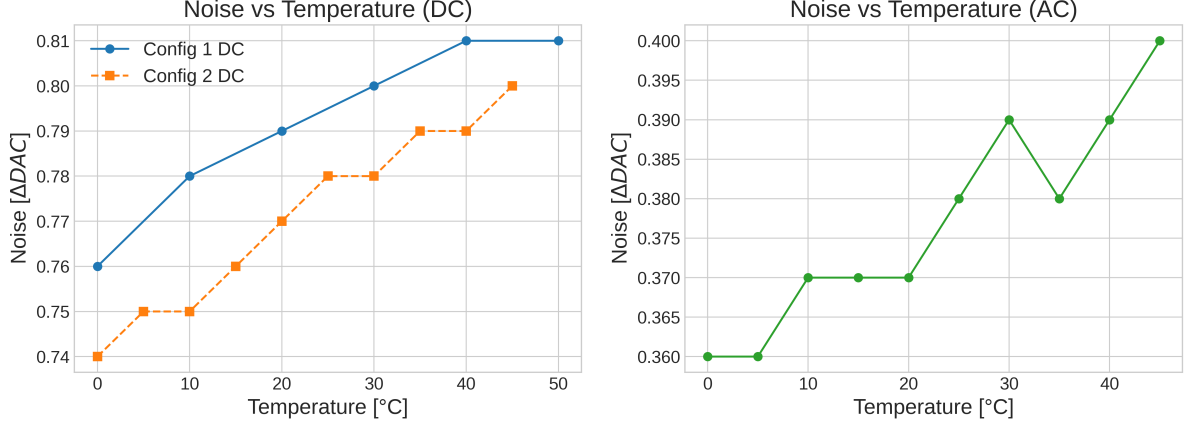


Figure 4.7: Noise dependency to climate chamber set temperature of DC (left) and AC (right) front-end. For both the DC and AC front-end, noise level increases with the temperature.

4.4 Clock signal propagation delay

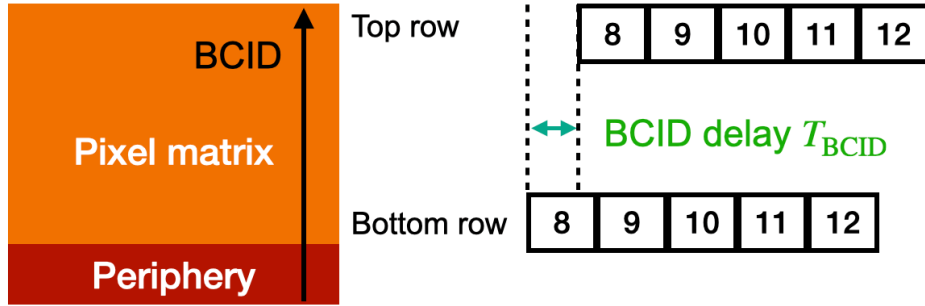


Figure 4.8: Illustration of clock signal propagation delay. The number in the black boxes indicates the clock count, which is smaller in top row (row 511) than bottom row (row 0).

As introduced in Section 2.3.3, propagation time of clock signal, which is also called BCID signal, results in a smaller clock count in a larger row. An illustration is shown in Figure 4.8. The time difference of clock count between bottom row (row 0) and top row (row 511) is noted as T_{BCID} . In TJ-Monopix2, a register IDEL is adjusted to compensate the clock signal propagation delay by delaying the assignment of LE timestamp within a clock reset session. The postponed time for row 511 is noted as T_{IDEL} . In operation, the ideal value for IDEL is such that it makes T_{IDEL} equals to T_{BCID} . It is not easy to evaluate the clock signal propagation delay with a single measurement at the test bench. Therefore, we performed three independent timing measurements and disentangle the contribution from the clock signal propagation delay from the results, which will be described in the following subsections 4.4.1, 4.4.2, 4.4.3 and 4.4.4.

4.4.1 LE timestamp evolution delay

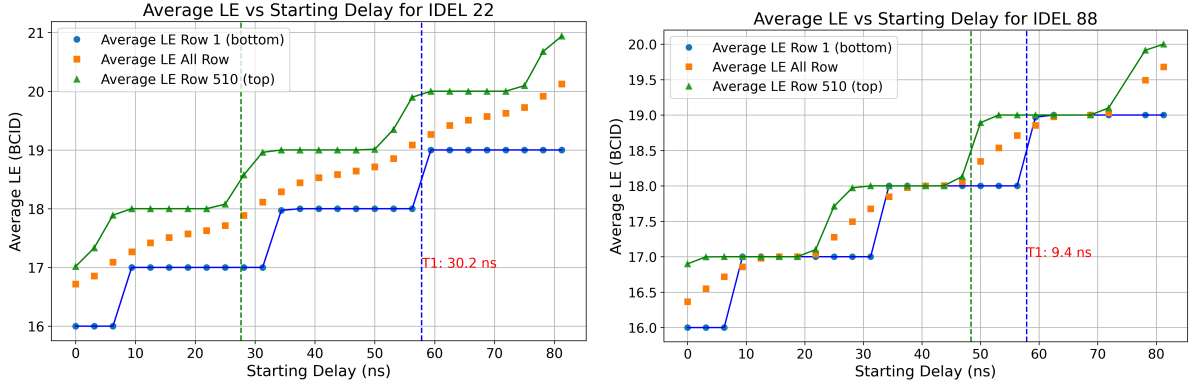


Figure 4.9: Examples of T_1 measurement at IDEL values of 22 (left) and 88 (right). The LE timestamp evolution curve of row 510 is closer to that of row 0 with larger IDEL value due to smaller T_{IDEL} . The T_1 is calculated from the time difference at LE timestamp = 18.5 from the fitted splines, representing the LE timestamp transition points. In actual practice, the bottom row is chosen to be row 1 and top row is chosen to be row 510, to avoid unstable timing behavior of edge rows. The difference of measured T_1 from the actual value of edge rows is expected to be smaller than 0.1 ns.

When injecting test signal pulse, the injection command for each pixel is also propagated through the column-bus, in which process delay also happens. Therefore, the actual injection time in row 511 is later than row 0 even though the injection is activated from the digital periphery at the same time. This timing difference is noted as T_{inj} . For hit data created from injecting test signal pulses, the LE timestamp assigned in row 511 is smaller than row 0 in time of:

$$T_1 = T_{inj} + T_{IDEL} - T_{BCID}. \quad (4.5)$$

However, the LE timestamp is in the unit of 40MHz clock count, whose precision is limited at 25 ns. The direct comparison of LE timestamp can not reflect the precise delay time. To measure T_1 precisely, we intentionally delay the activation of injection in each clock reset session, which can be adjusted in the step of 1.9 ns, and scan this intentional delay. The LE timestamp of row 0 and row 511 evolve corresponding to the intentional delay scan, which is fitted with `spline`. The time difference of fitted transition points at the same LE timestamp between row 0 and row 511 corresponds to T_1 . This process is performed with various T_{IDEL} values, which were controlled by the IDEL register setting. Results with IDEL values of 22 and 88 are shown in Figure 4.9. The measured T_1 as a function of the IDEL register value is shown in Figure 4.10.

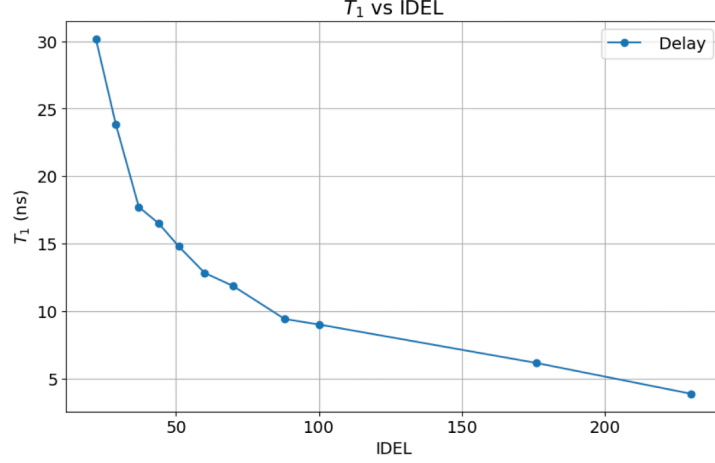


Figure 4.10: T_1 result in different IDEL values. Larger IDEL value has smaller T_{IDEL} compensation.

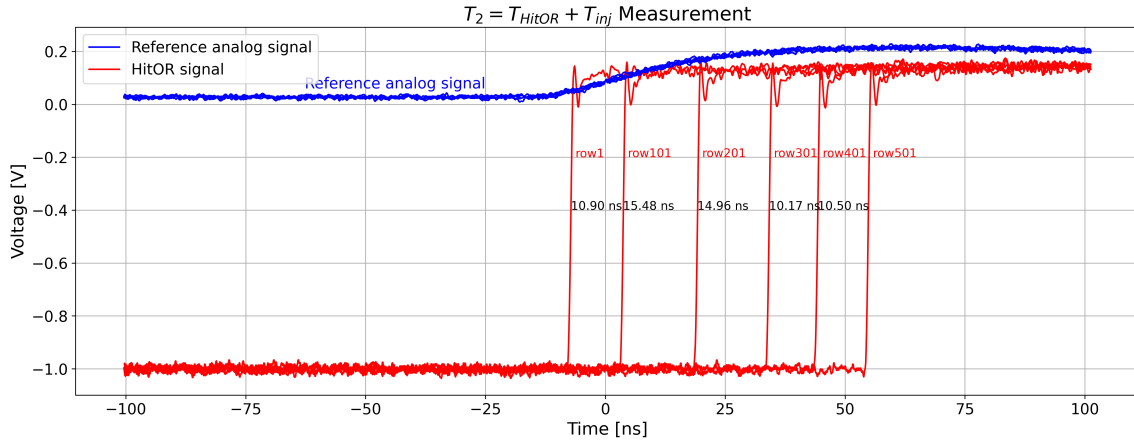


Figure 4.11: Measurement of T_2 . Red waveforms are the measured HitOR signals from different rows. Blue waveforms are the stacked reference analog signals (pre-amplifier output) from a fixed pixel. A single blue curve indicates that the timing of each measurement is aligned properly. The time differences between neighboring measurements are noted with black text.

4.4.2 Injection and HitOR delay

When pixels are hit, a HitOR signal can be read out using oscilloscope, which is a flat voltage level indicating the hit data is read out from the pixel of interest. HitOR signal propagates from the pixel of interest to the digital periphery, whose time consumption from row 511 to row 0 is noted as T_{HitOR} . The time difference of total injection and HitOR propagation time between row 0 and row 511 is:

$$T_2 = T_{\text{inj}} + T_{\text{HitOR}}. \quad (4.6)$$

The method to measure T_2 is to inject test pulse and read out HitOR signal from bottom row (row 0) and top row (row 511). The timing difference of the HitOR signal from bottom row and top row can be compared in picoscope, hence the T_2 is measured. The measurement is shown in Figure 4.11. Practically, the measurement is performed for row 1, 101, 201, 301, 401 and 501. Average time difference of each 100 rows are calculated to be 12.4 ns. Therefore, T_2 (timing difference between row 0 and 511) is estimated to be 63.5 ns.

4.4.3 HitOR delay

HitOR propagation delay T_{HitOR} can be measured without influenced by T_{inj} , using the hit created by real particles instead of test pulse injection. A schematic view of the measurement setup is shown in Figure 4.12. Beta rays from Sr-90 source pass through the scintillator and the TJ-Monopix2. Trigger signal from the scintillator and the HitOR signal from TJ-Monopix2 are sent to BDAQ53 board, where the timing difference between these two signals is counted using a 640 MHz clock, which is noted as "trigger distance". The row from which the HitOR signal comes can be identified by its neighboring hit data package in the data stream. The difference of trigger distance from row 511 and row 0 is HitOR propagation delay:

$$T_3 = T_{\text{HitOR}}. \quad (4.7)$$

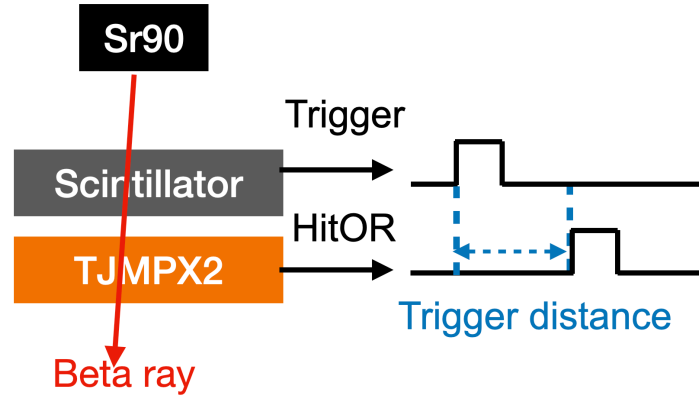


Figure 4.12: Schematic view of setup to measure T_3 .

The measurement result is shown in Figure 4.13. Trigger distance increases linearly depending on the row number. Due to the scintillator sensitive area coverage limitation, the trigger distance data are only taken up to about row 430. A linear fit is performed and the trigger distance is extrapolated to row 511 according to the fit result. The resulting HitOR delay is $T_3 = 45.5$ ns.

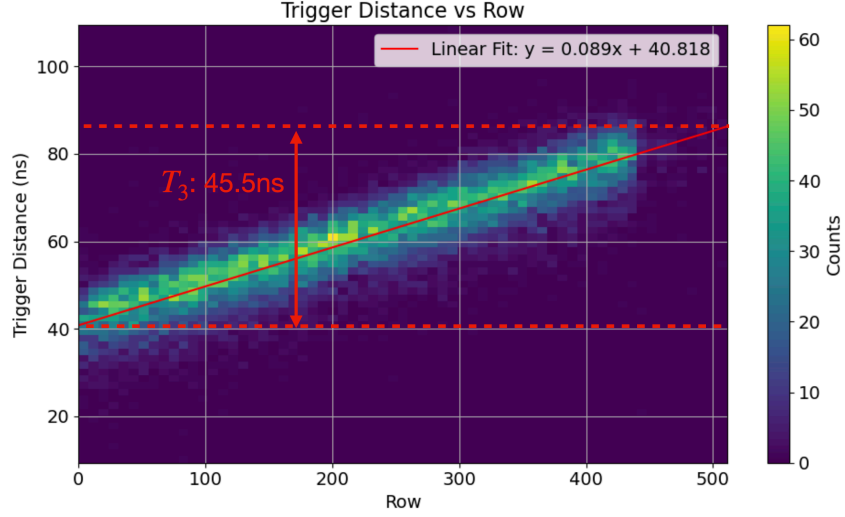


Figure 4.13: Measurement result of trigger distance depending on row number. The timing of scintillator trigger and HitOR signal is adjusted before input to BDAQ53 board so that row 0 yields a trigger distance of about 40 ns.

4.4.4 Result combination

Having the result from the measurement introduced above, clock signal propagation delay compensation can be derived by:

$$T_{\text{IDEL}} - T_{\text{BCID}} = T_1 - T_2 + T_3. \quad (4.8)$$

Among the scanned IDEL points, the best compensation happens at IDEL = 37, which results in $T_{\text{IDEL}=37} - T_{\text{BCID}} = -0.3$ ns. This result is to be compared with that of irradiated TJ-Monopix2 prototype to check if this compensation changes under the effect of irradiation.

Chapter 5

Test Beam measurement before irradiation

non-irradiated TJ-Monopix2 prototype is put into a test beam campaign, where the detection efficiency and spatial resolution to beam particles are measured. This test beam campaign is performed at DESY II Test Beam facility [45], using 4.2 GeV electron beam and EUDET telescope for tracking. `Corryvreckan` framework is used for data analysis.

In this chapter, test beam setup including layer arrangement and event definition will be introduced in Section 5.1. Analysis framework `Corryvreckan` will be introduced in Section 5.2. A newly developed module in `Corryvreckan` to simulate the impact of multiple scattering, telescope spatial resolution and tracking algorithm uncertainty to the spatial resolution of TJ-Monopix2 will be introduced in Section 5.3. Finally, the measurement result of detection efficiency and spatial resolution will be reported at Section 5.4.

5.1 Test beam setup

5.1.1 EUDET telescope

The EUDET telescope is a particle tracking system developed by the DESY EUDET project and is currently being used in DESY test beam facility. It contains six layers of MIMOSA-26 sensors, providing high tracking precision and two scintillators, whose signal coincidence is taken by a programmable Trigger Logic Unit (TLU) for triggering. The whole system is compatible with a cross-platform data acquisition framework named EUDAQ [46].

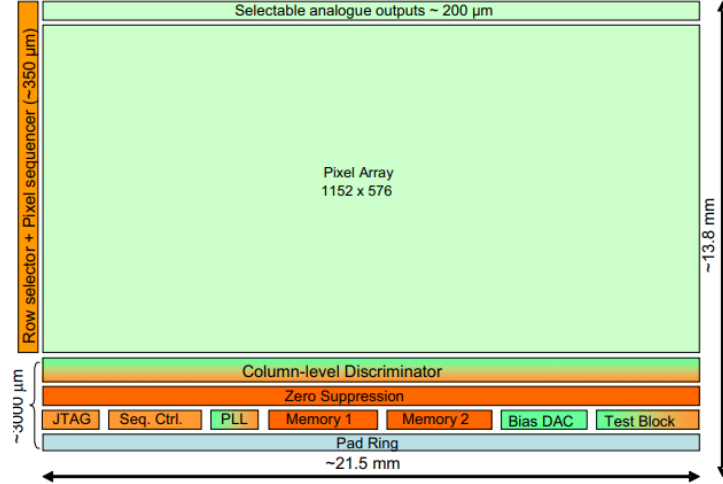


Figure 5.1: Block diagram of MIMOSA-26 sensor [13].

(1) MIMOSA-26 sensor

The MIMOSA-26 sensor [46] shown in Figure 5.1 is a CMOS silicon pixel sensor with pixel size of $18.4 \mu\text{m} \times 18.4 \mu\text{m}$, arranged in 1152 columns and 576 rows, covering a sensitive area of $21.2 \text{ mm} \times 10.6 \text{ mm}$. The total thickness of the pixel matrix is $50 \mu\text{m}$ including a $20 \mu\text{m}$ depth of high resistivity (about $400 \Omega\text{cm}$) epitaxial layer where the e/h pairs generated from the incident charged particles can be collected. The charge collection inside the sensor bulk is through drift and diffusion in depleted and non-depleted areas, respectively. The binary spatial resolution considering only the pitch size is calculated to be $\sigma_{\text{binary}} = 18.4 \mu\text{m} / \sqrt{12} \simeq 5.3 \mu\text{m}$. However, the actual intrinsic spatial resolution of a single MIMOSA-26 sensor is measured to be $\sigma_{\text{intrinsic}} = 3.24 \mu\text{m}$ [46]. The improvement comes from the charge sharing within cluster pixels which can be used to calculate hit position by weighting the position with charge.

The readout of MIMOSA-26 sensor applies a rolling-shutter strategy, taking 16 cycles of an 80 MHz clock per row, with all columns being read out in parallel. Zero suppression is performed on-chip using the digital circuitry placed outside of the sensitive area. The total integration time is $115.2 \mu\text{s}$. Therefore, this EUDET telescope utilizing MIMOSA-26 sensor can not provide time information comparable with TJ-Monopix2, if no extra time information is provided.

(2) Trigger and DAQ system

In this test beam campaign, the trigger signal is produced by the coincidence of two scintillator sensors, assembled with Hamamatsu PMTs and light-guides. The crossed area of scintillators defines a rectangular acceptance area of $20 \text{ mm} \times 10 \text{ mm}$, matching the size of MIMOSA-26 sensor. Signal output from scintillator sensors are connected to the input of a TLU module named AIDA, which asserts trigger signal with a serially counted trigger number once the coincidence happens. The assertion of trigger signal is replied

by a busy signal from the DAQ system and is stopped until the busy line turns low.

The zero-suppressed hit data from MIMOSA-26 sensors are transmitted over a ribbon cable to the auxiliary boards, which establish the connection to the data concentrator board, collecting data from all 6 MIMOSA-26 sensors and the trigger/busy lines from the TLU. Readout cycle of MIMOSA-26 happens consistently, and only the triggered data packets are selected. The capability of a large data stream up to 960 MB/s is high enough to read out MIMOSA-26 data without any dead time.

(3) EUDAQ framework

EUDAQ framework is a cross-platform DAQ framework controlling the readout of different subsystem globally, including the telescope sensor, device under test (DUT) and TLU. This framework is designed for synchronous DAQ systems requiring one event per trigger per subsystem, hence the trigger rate is always limited by the slowest device. The starting, stopping of DAQ and event building of the whole test beam setup is controlled by EUDAQ. Each subsystem has a so-called producer, sending control signals and collecting data and transmit them to a data collector, where the event building happens. Basic sanity check such as testing the consistency of event number reported by each subsystem is performed. Data packets assigned with trigger number and event number are produced. A graphical user interface (GUI) is provided by EUDAQ framework for shifters, where the global run control, configuring for each subsystem and log monitor can be done. The DUT of this test beam, TJ-Monopix2, has been implemented into EUDAQ framework.

5.1.2 Layer arrangement

In this test beam campaign, three MIMOSA-26 layers are put at the upstream of the DUT, TJ-Monopix2, and another three MIMOSA-26 layers are put at the downstream to make sure the quality of tracking extrapolation to the DUT position. One scintillator is put at the most upstream and another one is put at the most downstream of the whole system, with aligned cross-section covering the MIMOSA-26 sensitive area. The schematic view and photo of the setup are shown in Figure 5.2, where the spatial intervals between the sensors are also noted.

5.1.3 Event definition

The association of TJ-Monopix2 hits to the trigger (event) can not be performed by comparing the timestamp since no time information is provided by the TLU. Given that the data packets of TLU data and hit data are recorded in the order of the arrival timing at the DAQ, the hits from TJ-Monopix2 between two TLU data packets are duplicated and assigned to both of the neighboring TLU event, ensuring no efficiency loss happens, as illustrated in Figure 5.3. Even though the order is not perfectly aligned considering

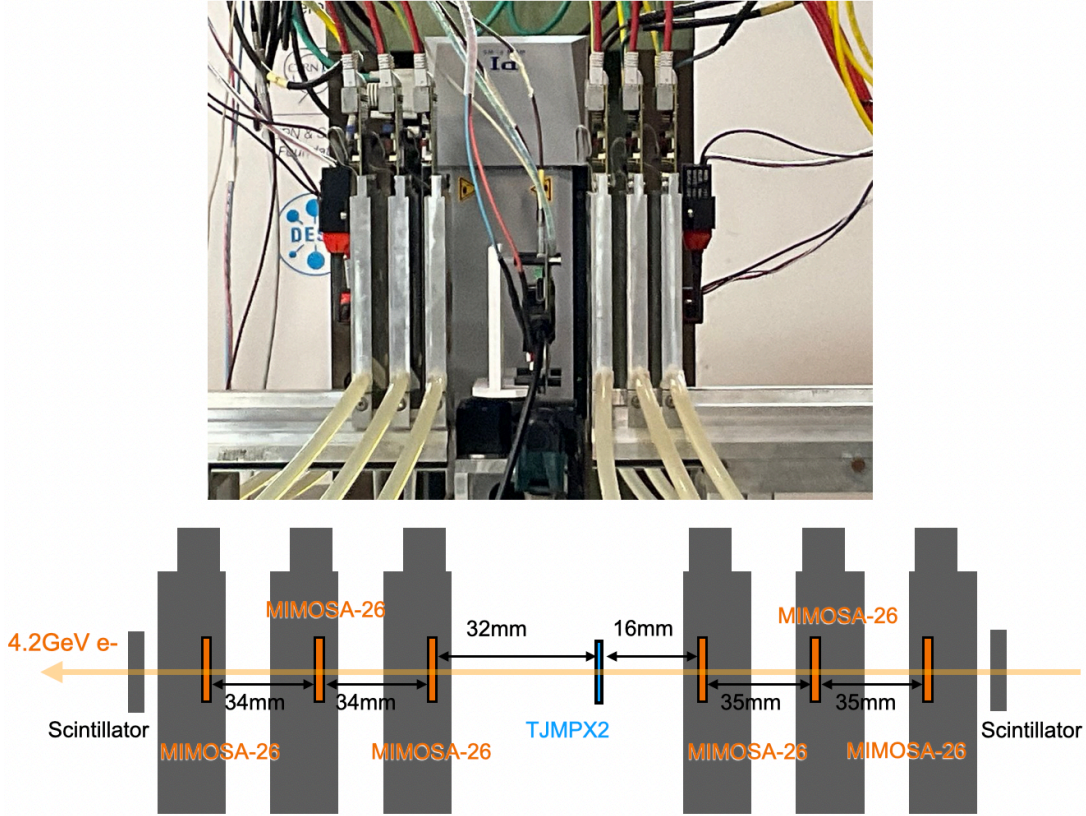


Figure 5.2: Photo (above) and schematic view (below) of layer arrangement. MIMOSA-26 sensors are mounted on aluminum support structures and TJ-Monopix2 is mounted to a plastic support with its PCB board. The supporting structures of MIMOSA-26 layers are connected to cooling pipes through which water cooling is performed. Spatial intervals of each sensors are noted.

the deviation of transmitting time between hit data and TLU data, which is in the order of $\mathcal{O}(1 \mu s)$, the time interval of TLU data packets is in the order of $\mathcal{O}(1 \text{ ms})$ since the trigger rate in this setup is about 1 kHz. Therefore, the probability of mis-association is small enough to be negligible.

5.2 Corryvreckan framework

Corryvreckan is an open-source, versatile, highly configurable and modular software framework designed to reconstruct and analyze test beam data [47]. It provides a flexible offline event building facility to combine detectors with different readout schemes, with or without trigger information, and includes the possibility to correlate data from multiple devices based on timestamps. The coordinate system in **Corryvreckan** is a right-handed Cartesian coordinate system as shown in Figure 5.4.

In the analysis of this test beam data, **Corryvreckan** is used to assigning hits from the telescope and TJ-Monopix2 with the same trigger numbers to the same events, and then

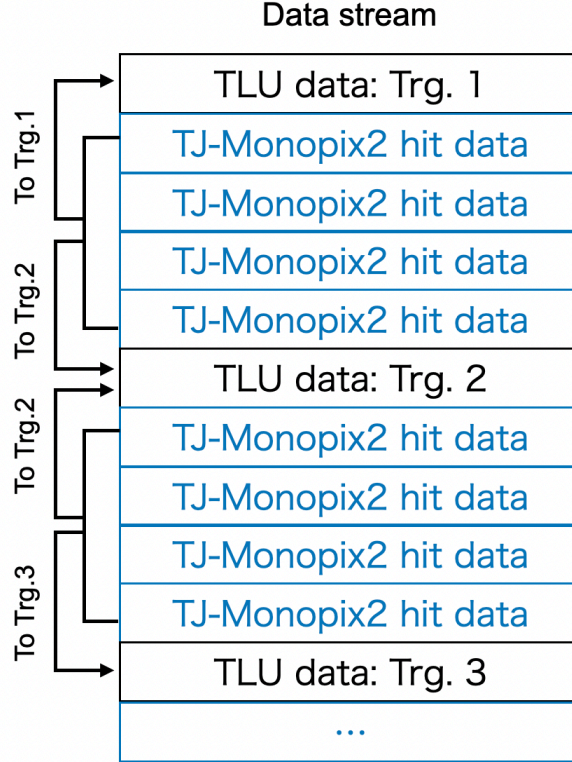


Figure 5.3: Illustration of association of hit data to TLU events. The hit data between TLU data with trigger number 1 (2) and 2 (3) are duplicated and associated with both event of trigger number 1 (2) and 2 (3).

perform tracking using clustered telescope hits. The reconstructed tracks are extrapolated to the position of TJ-Monopix2, and associated to clustered hits on TJ-Monopix2 based on the position difference. Before the full analysis, alignment of layer positions and rotations are performed using alignment tuning module provided by `corryvreckan`. Further analysis calculating detection efficiency and spatial resolution of TJ-Monopix2 is also conducted within `Corryvreckan` framework.

5.2.1 Clustering

After assigning hits with correct trigger number from different layers to the event, clustering of hits is performed for each layers using `ClusteringSpatial` module in `Corryvreckan`. A breadth-first search is performed for grouping neighboring hit pixels. Specifically, all eight neighboring patterns of $(\Delta\text{row}, \Delta\text{col}) = (0, 1), (0, -1), (1, 0), (-1, 0), (1, 1), (-1, -1), (1, -1), (-1, 1)$ are clustered.

The charge (or properties that reflects charge, such as ADC output or ToT) of a cluster is the summation of all hit pixels in the cluster. Seed pixel is identified as the hit pixel with the largest charge. Cluster position is calculated by weighting the hit pixel position with charge:

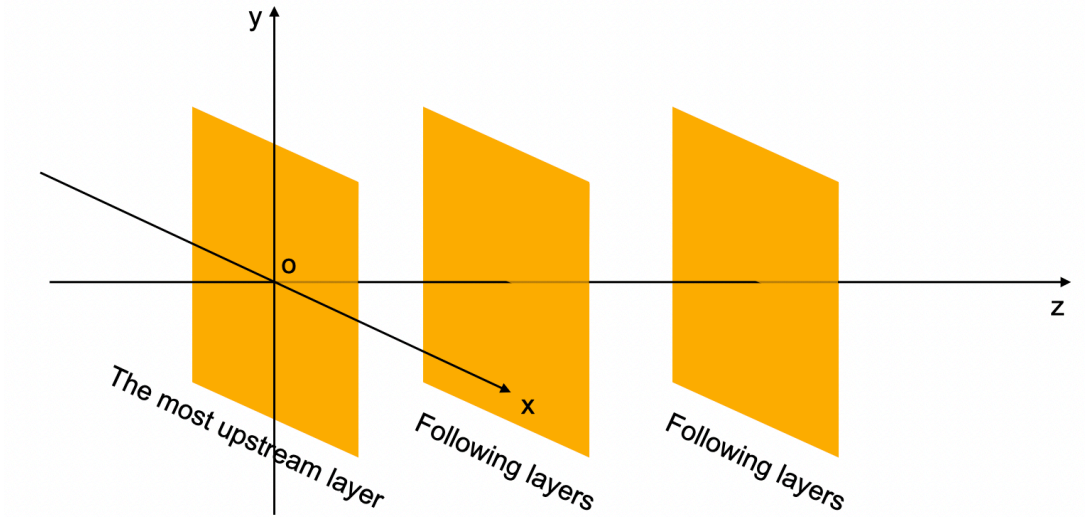


Figure 5.4: Coordinate system in Corryvreckan. Original point is placed at the center of the most upstream layer with z axis pointing at the downstream direction. The x axis and y axis are pointing at the column and row direction of the first sensor plane, respectively.

$$(x, y)_{\text{cluster}} = \left(\frac{\sum_i w_i x_i}{\sum_i w_i}, \frac{\sum_i w_i y_i}{\sum_i w_i} \right). \quad (5.1)$$

where index i iterates over hit pixels within the cluster and w stands for the property representing deposited charge. An example of cluster maps are shown in Figure 5.5, where only a part of the DC front-end of TJ-Monopix2 (column 360 to column 448) is enabled while the whole matrix of MIMOSA-26 is enabled.

An example of hit pixel charge, cluster charge and cluster size histograms of TJ-Monopix2 are shown in Figure 5.6. After clustering, the ToT distribution follows Landau distribution as expected. The average cluster size is 1.5 pixels.

5.2.2 Tracking

A tracking algorithm with the General Broken Line (GBL) model [48] implementation is provided in module `Tracking4D` of Corryvreckan framework. The GBL model takes into account of the multiple scattering on each material layer, outputting a track in the form of a series of straight lines with kinks at each layer, forming a broken line. The workflow is introduced below.

(1) Seeding

The tracking starts with finding one cluster on both the most upstream layer and the most downstream layer. A preliminary straight line track is formed using these two

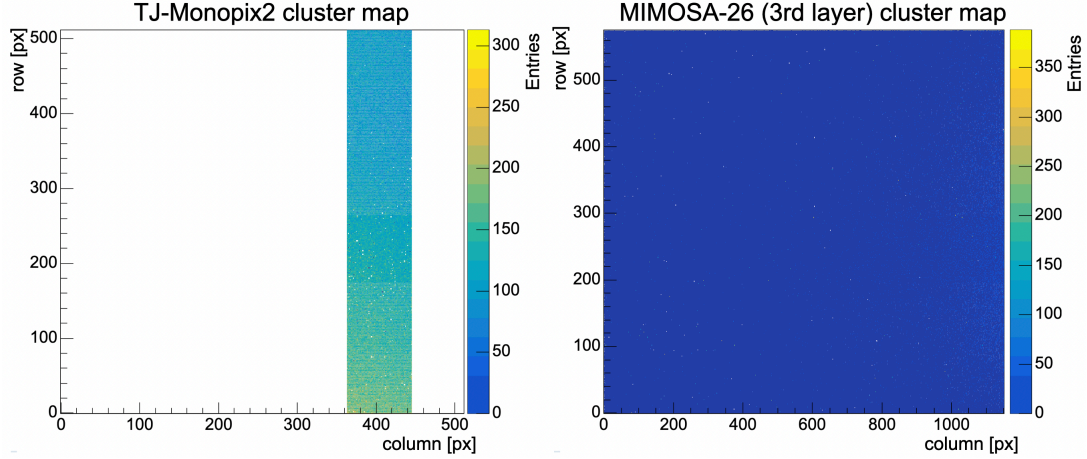


Figure 5.5: Cluster map of TJ-Monopix2 (column 360 to column 448) and the third layer of MIMOSA-26 (full matrix enabled). The bin with white color indicates there is no entry due to the masked noisy pixels.

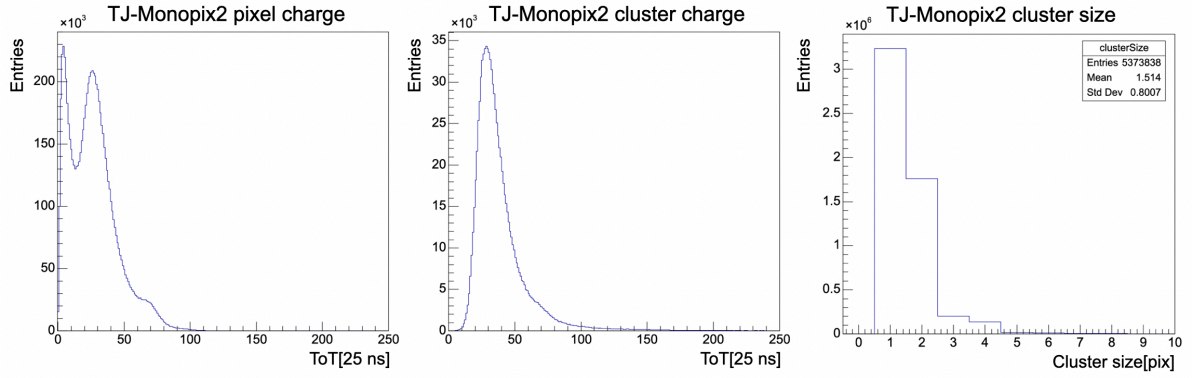


Figure 5.6: Histograms of hit pixel charge (left), cluster charge (middle) and cluster size (right) distribution. This data is taken from the DC front-end with threshold of $30 \Delta\text{DAC}$ and bias voltage of 6 V.

clusters. The straight line track is extrapolated to the position of other telescope layers. On each intermediate layer, cluster is searched within an elliptical neighboring area around the extrapolated position, whose size can be configured by the x-distance and y-distance. In this test beam, they are both configured to be $50 \mu\text{m}$ and one cluster on each telescope layer is required.

(2) GBL fitting

Once seeding is finished and number of searched clusters meets the requirement (in this test beam, in total six clusters on six telescope layers), the clusters are put into the GBL fitting to form a track. In the GBL model, a local coordinate system (u, v, w) pointing at the same direction with (x, y, z) is defined at each layer, sharing the x, y origin with global coordinate system but the z origin is moved to the z position of each

1835 layer. There fore, the track can be parameterized as a series of vectors $\mathbf{q}_i$:

$$\mathbf{q}_i = \begin{pmatrix} u_i \\ v_i \\ \theta_{u,i} \\ \theta_{v,i} \end{pmatrix}. \quad (5.2)$$

1836 where u_i and v_i are the u and v coordinate of the track position at layer i . $\theta_{u,i} = \partial u / \partial w$
 1837 and $\theta_{v,i} = \partial v / \partial w$, indicating the output angles of the track at layer i . The preliminary
 1838 straight line track produced in seeding process is regarded as reference track $\mathbf{q}_i^0$. The
 1839 difference between the reference track and actual GBL track is noted as $\Delta \mathbf{q}_i = \mathbf{q}_i -$
 1840 $\mathbf{q}_i^0$. Linear transportation between layers brings constraints of $\Delta \mathbf{q}_j = \mathbf{T}_{ji} \Delta \mathbf{q}_i$. The
 1841 transportation matrix $\mathbf{T}_{ij}$ is:

$$\mathbf{T}_{ji} = \begin{pmatrix} 1 & 0 & \Delta s_{ji} & 0 \\ 0 & 1 & 0 & \Delta s_{ji} \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}. \quad (5.3)$$

1842 where Δs_{ji} is the path length between layer i , j . Multiple scattering is considered as
 1843 kinks at each layer:

$$\boldsymbol{\kappa}_i = \begin{pmatrix} \kappa_{u,i} \\ \kappa_{v,i} \end{pmatrix} = \begin{pmatrix} \theta_{u,i}^{\text{out}} - \theta_{u,i}^{\text{in}} \\ \theta_{v,i}^{\text{out}} - \theta_{v,i}^{\text{in}} \end{pmatrix}. \quad (5.4)$$

1844 which is modeled as zero-mean Gaussian distributions with covariance $\mathbf{G}_i = \theta_0^2 \mathbf{I}_{2 \times 2}$ where
 1845 θ_0 is calculated as [6]:

$$\theta_0 = \frac{13.6 \text{ MeV}}{\beta c p} z \sqrt{\frac{x_i}{X_0}} \left[1 + 0.038 \ln \left(\frac{x_i z^2}{X_0 \beta^2} \right) \right]. \quad (5.5)$$

1846 as an approximation of root-mean-square (RMS) of angle change caused by multiple
 1847 scattering. Here p , βc and z are the momentum, speed, and charge number of the
 1848 incident particle. x_i is the material budget of the i -th layer. Residual between measured
 1849 cluster position and fitted track position is noted as:

$$\mathbf{r}_i = \mathbf{m}_i - (\mathbf{H}_i \Delta \mathbf{q}_i), \quad \mathbf{H}_i = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{pmatrix}. \quad (5.6)$$

1850 where $\mathbf{m}_i$ is the measured cluster position on the local coordinate of each layer. Residuals
 1851 of u and v coordinate are uncorrelated, hence the covariance matrix is $\mathbf{V}_i = \text{diag}(\sigma_{u,i}^2, \sigma_{v,i}^2)$.

1852 Given the modeling above, the GBL fitting minimize the total χ^2 which is defined as:

$$\chi^2 = \sum_{i \in \text{telescope layers}} \mathbf{r}_i^\top \mathbf{V}_i^{-1} \mathbf{r}_i + \sum_{i \in \text{all layers}} \boldsymbol{\kappa}_i^\top \mathbf{G}_i^{-1} \boldsymbol{\kappa}_i. \quad (5.7)$$

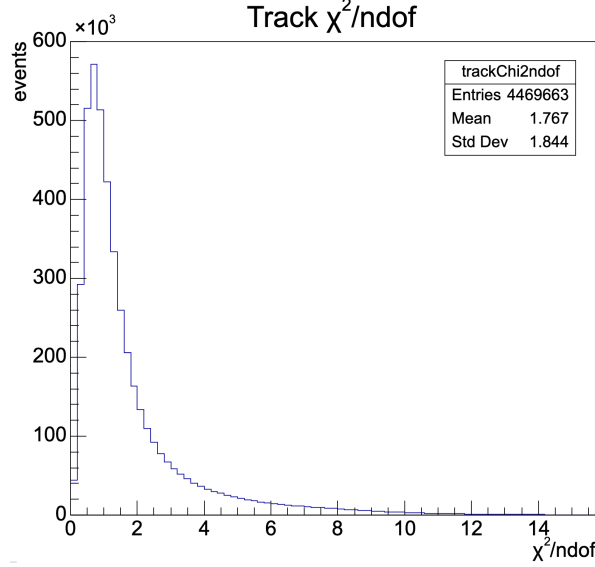


Figure 5.7: χ^2/ndof distribution of tracking in DESY test beam.

1853 by finding the best fit $\mathbf{q}_i$. The term $\sum_{i \in \text{all layers}} \boldsymbol{\kappa}_i^\top \mathbf{G}_i^{-1} \boldsymbol{\kappa}_i$ takes into account of multiple
 1854 scattering expectation directly.

1855 (3) Number of degrees of freedom

1856 In this test beam, clusters used for tracking come from six telescope layers and multiple
 1857 scattering happens in five internal layers including TJ-Monopix2. In total, number of
 1858 measurement involves the cluster positions and angle change expectations from multiple
 1859 scattering in both u, v direction. Hence we have:

$$N_{\text{measurement}} = 2 \times N_{\text{telescope layers}} + 2 \times N_{\text{scattering layers}} = 22. \quad (5.8)$$

1860 The GBL track $\mathbf{q}_i$ contains four fitting parameters for each layer. However, the fitting
 1861 is constrained by the linear transportation, which induces two constrain equations for each
 1862 two neighboring layers. Besides, the angle elements of $\Delta \mathbf{q}_i$ at the most downstream layer
 1863 are meaningless in this context hence are fixed. Therefore, the number of free fitting
 1864 parameters is:

$$N_{\text{free parameter}} = 4 \times N_{\text{layers}} - 2 \times N_{\text{linear transportation}} - 2 = 14. \quad (5.9)$$

1865 The final number of degrees of freedom is then $N_{\text{ndof}} = N_{\text{measurement}} - N_{\text{free parameter}} = 8$.

1866 An example of tracking χ^2/ndof distribution is shown in Figure 5.7. In the final
 1867 analysis, only tracks with $\chi^2/\text{ndof} < 5$ is used to ensure the high quality of tracking.

5.2.3 DUT Association

After tracking with clusters on six telescope layers, the GBL track is extrapolated to the DUT layer, which is TJ-Monopix2. The extrapolated position is just the parameter (u_i, v_i) in GBL track where i stands for the DUT layer. Around this extrapolated position, the cluster on DUT is searched within an elliptical neighboring area whose size can be configured by the x-distance and y-distance. If multiple clusters exist within the searching area, the cluster closest to the track is selected. However, the number of clusters is mostly 1 since the searching area is small enough and all hits within the area are likely to be clustered together. In this test beam, they are both configured to be $100 \mu\text{m}$. The residual in x and y direction is the difference between track position and cluster position:

$$\mathbf{r} = (x_{\text{track}} - x_{\text{DUT}}, y_{\text{track}} - y_{\text{DUT}}). \quad (5.10)$$

An example of residual histograms after alignment tuning described in subsection 5.2.4 is shown in Figure 5.8. It is evident that a $100 \mu\text{m}$ cut in both x and y direction does not result in efficiency loss and no fake hit background found in the distribution.

(1) Detection efficiency

Detection efficiency is calculated as the ratio of number of tracks associated with a DUT cluster to the total number of tracks:

$$\epsilon = \frac{N_{\text{associated tracks}}}{N_{\text{tracks}}}. \quad (5.11)$$

where the tracks have to be fiducial, meaning that the tracks meet the required χ^2/ndof and their extrapolated positions on DUT are within the region of interest (ROI). The ROI corresponds to the enabled region on TJ-Monopix2, excluding 1-pixel marginal area at the edges.

(2) Spatial resolution

The standard deviation σ_{residual} , which is obtained through the RMS of DUT residual histogram as calculated in the Equation 5.10 is used to evaluate the spatial resolution of TJ-Monopix2, whose uncertainty follows:

$$\Delta\sigma_{\text{residual}} = \frac{\sigma_{\text{residual}}}{\sqrt{2(N-1)}} \quad (5.12)$$

where N is the number of entries in the histogram. To exclude the impact of outliers, the calculation is limited in a range of $[-60 \mu\text{m}, +60 \mu\text{m}]$ in the histogram is limited. However, σ_{residual} is a combined effect of TJ-Monopix2 spatial resolution, resolution of telescope sensors and uncertainty of tracking algorithm:

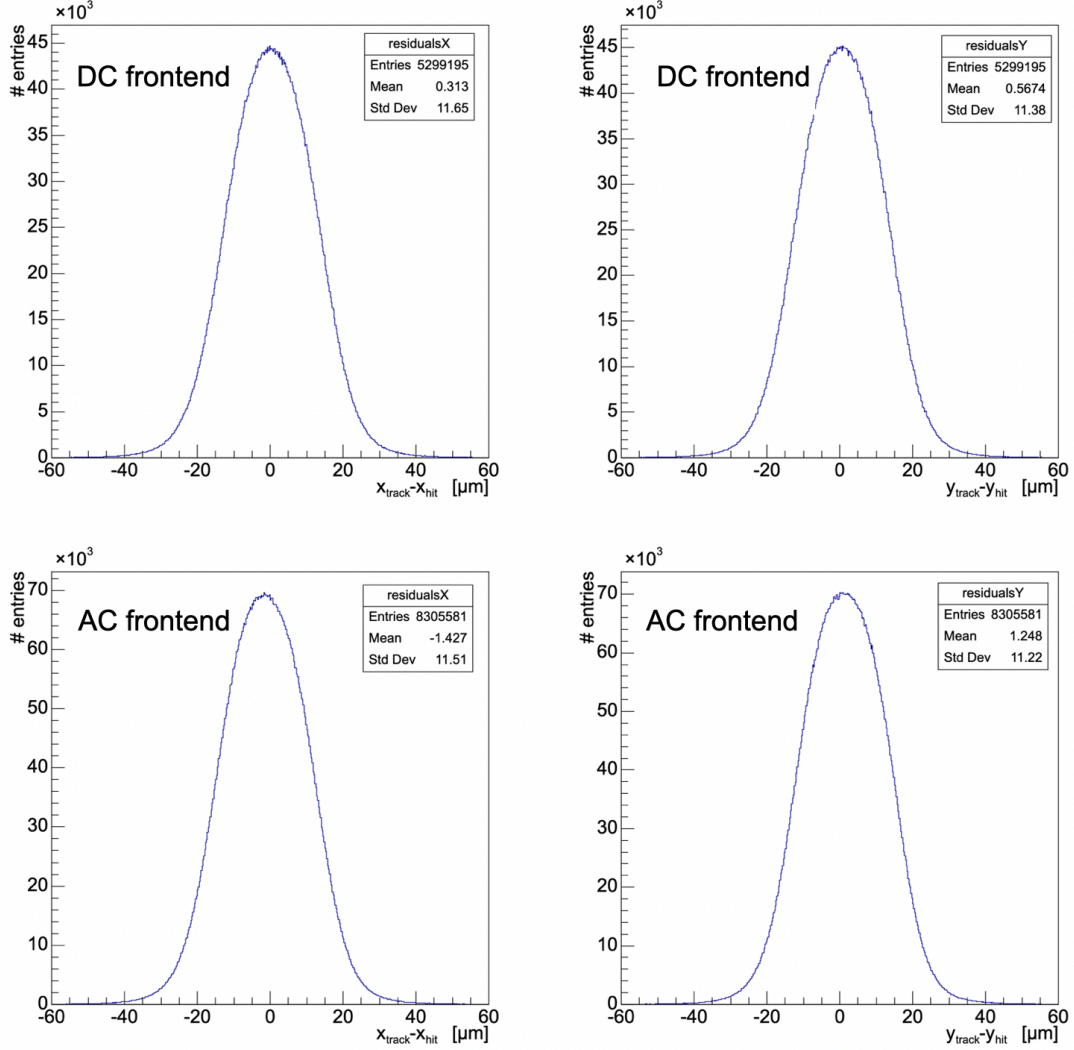


Figure 5.8: Spatial residuals between extrapolated track position and TJ-Monopix2 cluster position of DC (above) and AC (below) front-end after alignment tuning. The standard deviations are noted.

$$\sigma_{\text{residual}} = \sqrt{\sigma_{\text{TJ-Monopix2}}^2 + \sigma_{\text{tracking}}^2}. \quad (5.13)$$

To exclude the impact of tracking for spatial resolution calculation, simulation is performed to identify σ_{tracking} , which is introduced in Section 5.3.

5.2.4 Alignment tuning

In real operation, the alignment of the layers always deviate from the designed situation. To reconstruct the tracks and associate DUT hits precisely, adjusting the position and rotation of layers to the actual alignment is needed.

Alignment tuning in `Corryvreckan` is performed through two modules: `AlignmentTrackChi2`

and `AlignmentDUTResidual`, tuning the x, y displacement dx, dy and rotations around three axes $\theta_x, \theta_y, \theta_z$ for telescope layers and DUT layer respectively. Since the displacement in z direction is not sensitive to data, it is not adjusted in alignment tuning. In `AlignmentTrackChi2` module, the most upstream layer is fixed and the alignment of other telescope layers are tuned. It updates the cluster positions after tuning and recalculates the tracking χ^2 as the Equation 5.7 as a minimized object using `Minuit` [49]. In `AlignmentDUTResidual`, the alignment of DUT layer is tuned and DUT cluster positions are updated. The minimized object in `Minuit` is the square of DUT residuals $(x_{\text{track}} - x_{\text{DUT}})^2 + (y_{\text{track}} - y_{\text{DUT}})^2$. Therefore, it is performed using the tracks that are successfully associated to DUT clusters.

Since `AlignmentTrackChi2` module does not re-fit the tracks, it is repeated three times for each setup configuration. After telescope layers are aligned, the DUT is aligned by repeating `AlignmentDUTResidual` two times to make sure the tuning converges by confirming the alignment parameters are stabilized. One way to check the quality of alignment tuning is to check the DUT residual dependency on the hit position. The example is shown in Figure 5.9 and 5.10. For an ideal alignment, the DUT residuals should be completely independent from the hit position, just like the dependency on row position shown in the example. However, slight dependency on column position shown, indicating that the residual is imperfect.

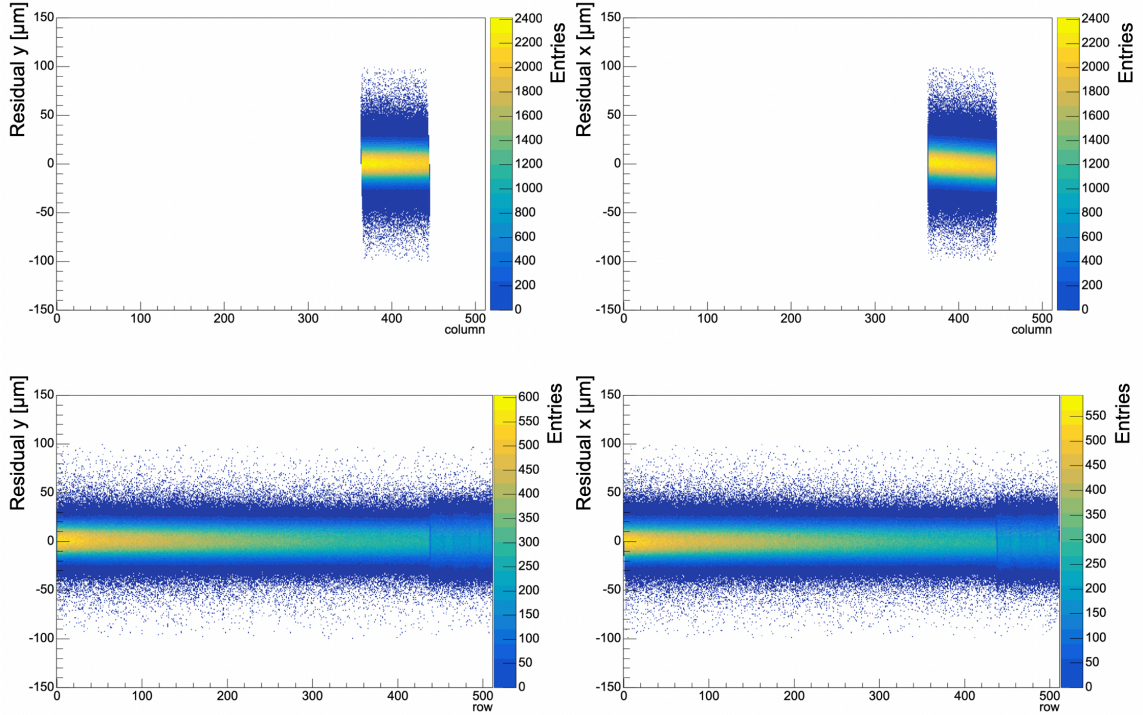


Figure 5.9: DUT residual dependency on the hit position on TJ-Monopix2 (DC front-end). Impact of a PCB board coverage resulting in more multiple scattering can be seen at top row area, rows number 440-511. Slight dependencies of residuals on column position can be seen.

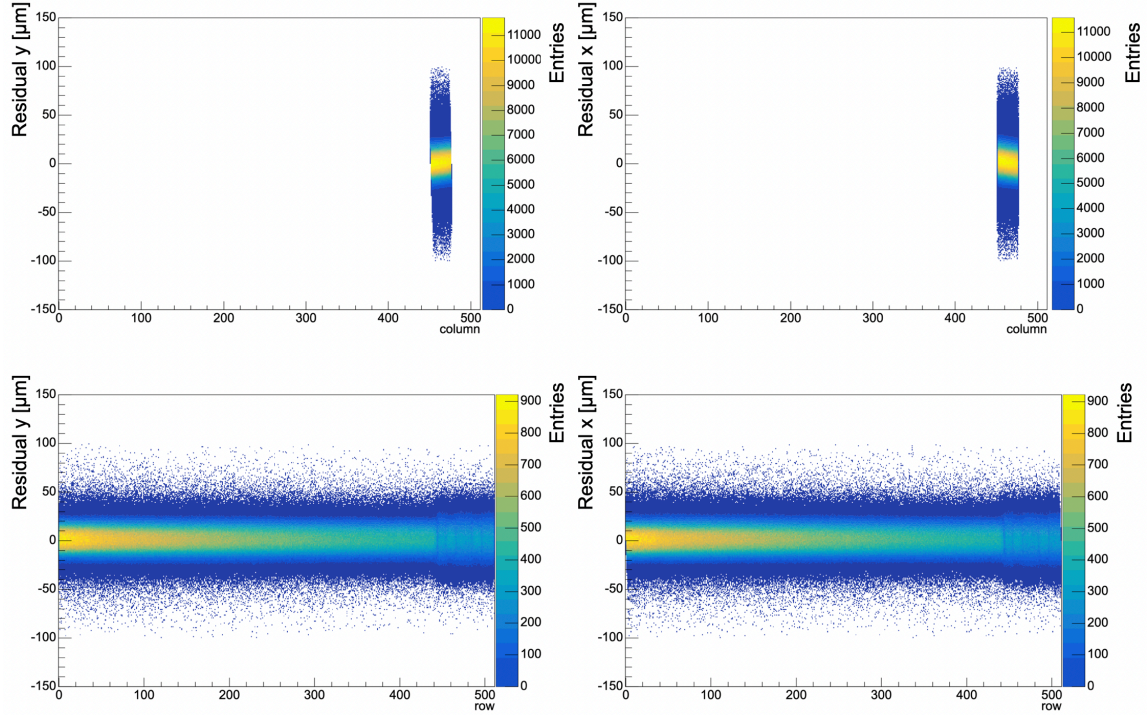


Figure 5.10: DUT residual dependency on the hit position on TJ-Monopix2 (AC front-end). Impact of a PCB board coverage resulting in more multiple scattering can be seen at top row area, rows number 440-511. Slight dependencies of residuals on column position can be seen.

5.3 ToyMC simulation of beam track reconstruction

A simulator module `MultiScatterSimulator` within `Corryvreckan` framework is developed in this work to generate ToyMC sample (Monte Carlo samples generated simply following a known distribution) of tracking reconstruction in this test beam setup. By comparing track extrapolated position on DUT layer and the simulated true DUT hit position, the impact from telescope sensors and tracking algorithm, the tracking resolution, σ_{tracking} can be derived.

5.3.1 Simulation

`MultiScatterSimulator` reads the geometry configuration file to generate layer planes for each detector, including the information of material budget, spatial resolution of the detector and the coordinates. A particle input is firstly generated to the most upstream layer within the defined position and incident angle:

$$\mathbf{p}_0^{\text{in}} = \begin{pmatrix} x_0 \\ y_0 \\ \theta_{x,0} \\ \theta_{y,0} \end{pmatrix}. \quad (5.14)$$

1934 where $\theta_{x,0} = \arcsin(\partial x / \partial z)$, $\theta_{y,0} = \arcsin(\partial y / \partial z)$. At each layer i , once input particle is
 1935 determined, the output particle is calculated as:

$$\mathbf{p}_i^{\text{out}} = \mathbf{p}_i^{\text{in}} + \begin{pmatrix} 0 \\ 0 \\ G(0, \theta_0^2) \\ G(0, \theta_0^2) \end{pmatrix}. \quad (5.15)$$

1936 where G stands for the value is random and follows a gaussian distribution. The RMS
 1937 θ_0 follows the same calculation with Equation 5.5. The input of i -th layer is calculated
 1938 by the linear propagation of the output of $(i - 1)$ -th layer $\mathbf{p}_i^{\text{in}} = \mathbf{T}_{i,i-1} \mathbf{p}_{i-1}^{\text{out}}$ where the
 1939 transportation matrix $\mathbf{T}_{i,i-1}$ is:

$$\mathbf{T}_{ji} = \begin{pmatrix} 1 & 0 & \Delta s_{ji} & 0 \\ 0 & 1 & 0 & \Delta s_{ji} \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}. \quad (5.16)$$

1940 which is the same with Equation 5.3. The whole simulation process starts from $\mathbf{p}_0^{\text{in}}$,
 1941 calculate the input and output across every layer.

1942 After the process described above, a series of $\mathbf{p}_i^{\text{in}}$ and $\mathbf{p}_i^{\text{out}}$ are derived corresponding
 1943 to all layers, whose x_i , y_i components stand for the true positions of particle trajectories.
 1944 Before assigning the simulated cluster position to the event data pool of **Corryvreckan**,
 1945 a smearing based on the spatial resolution of each detector is performed:

$$\mathbf{c}_i = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{pmatrix} \mathbf{p}_i^{\text{in/out}} + \begin{pmatrix} G(0, \sigma_{xi}^2) \\ G(0, \sigma_{yi}^2) \end{pmatrix}. \quad (5.17)$$

1946 where σ_{xi} and σ_{yi} stand for the spatial resolution in x and y direction of detector in i -th
 1947 layer. This smearing process is only performed for telescope layers and cluster position
 1948 for DUT keeps the simulated true value. The final $\mathbf{c}_i$ are assigned as clusters to the
 1949 event data pool of **Corryvreckan**. The tracking, DUT association and further analysis
 1950 are performed based on these simulated clusters. Since the cluster position of DUT keeps
 1951 the true value, the DUT residuals in the simulation reflects the pure tracking resolution
 1952 σ_{tracking} .

5.3.2 Tracking resolution

For this test beam setup, 1 million ToyMC sample tracks with 4.2 GeV electron beam is simulated. The injected particles are generated randomly within the sensor matrix of the first layer, whose incident angle is set randomly within $\pm 1^\circ$ for both x and y direction. Examples of cluster maps are shown in Figure 5.11 and the DUT residual histograms are shown in Figure 5.12. Tracking resolutions σ_{tracking} are derived from the RMS of simulated DUT residuals. For both x and y direction, the $\sigma_{\text{tracking}} = 3.4 \mu\text{m}$ with an uncertainty of $0.003 \mu\text{m}$.

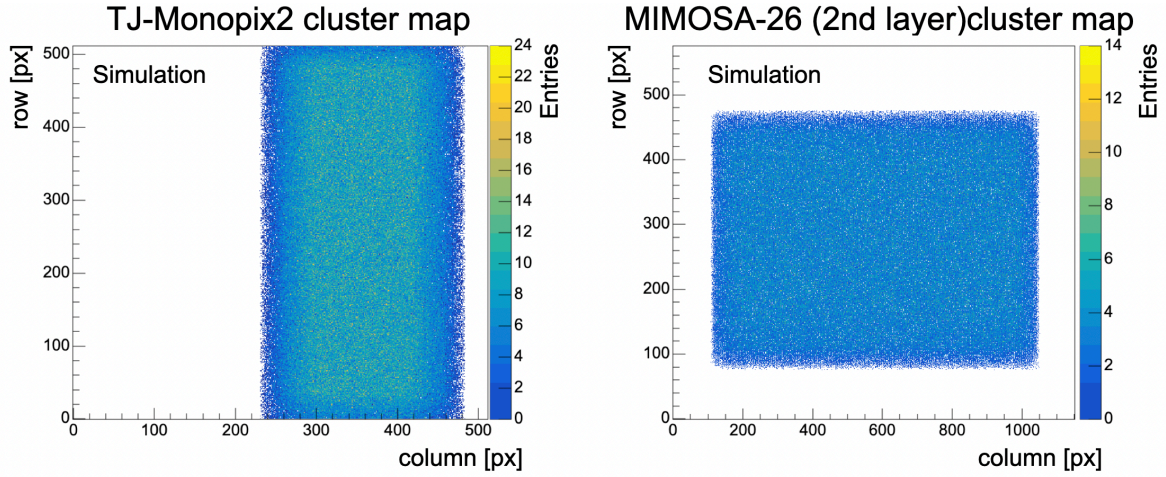


Figure 5.11: Simulated cluster map for TJ-Monopix2 (left) and 2nd layer of MIMOSA-26 sensor (right). The blue edges in TJ-Monopix2 cluster map are resulted from the aborted tracks which did not pass the sensor area of the next MIMOSA-26 layer.

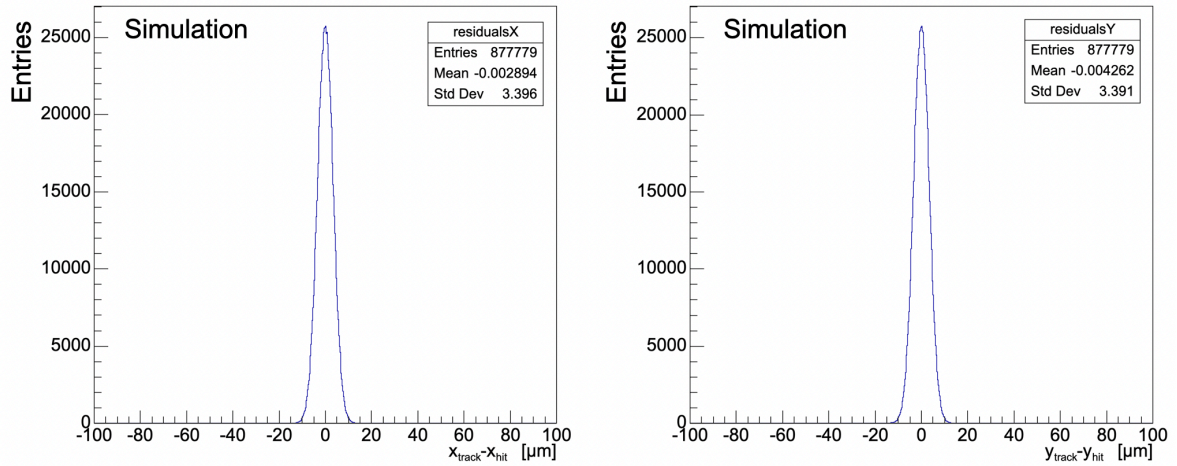


Figure 5.12: Simulated DUT residual distribution in x and y direction.

5.3.3 Data/MC ratio

In the simulation, all the layers are assumed to be aligned perfectly. However, in actual operation, the imperfect alignment, especially the rotations around X and Y axes, cause inconsistency with simulation. The deviation of the actual spatial resolution of tracking layer sensors from their reference value is also a source of data-MC inconsistency.

Data/MC ratio is calculated for the standard deviation of residual between track positions and cluster positions on tracking layers, for each data taking run. One of the results is shown in Figure 5.13. Except for MIMOSA-26(1) and MIMOSA-26(4) which are simulated well since the data/MC ratio is around 1.0, the residuals of all other layers are underestimated in simulation, hence the resulted tracking resolution is also an underestimated value, making the spatial resolutions of TJ-Monopix2 overestimated. In this work, correction of ToyMC simulation is not performed, instead, a conservative evaluation of TJ-Monopix2 spatial resolution is given using current simulation.

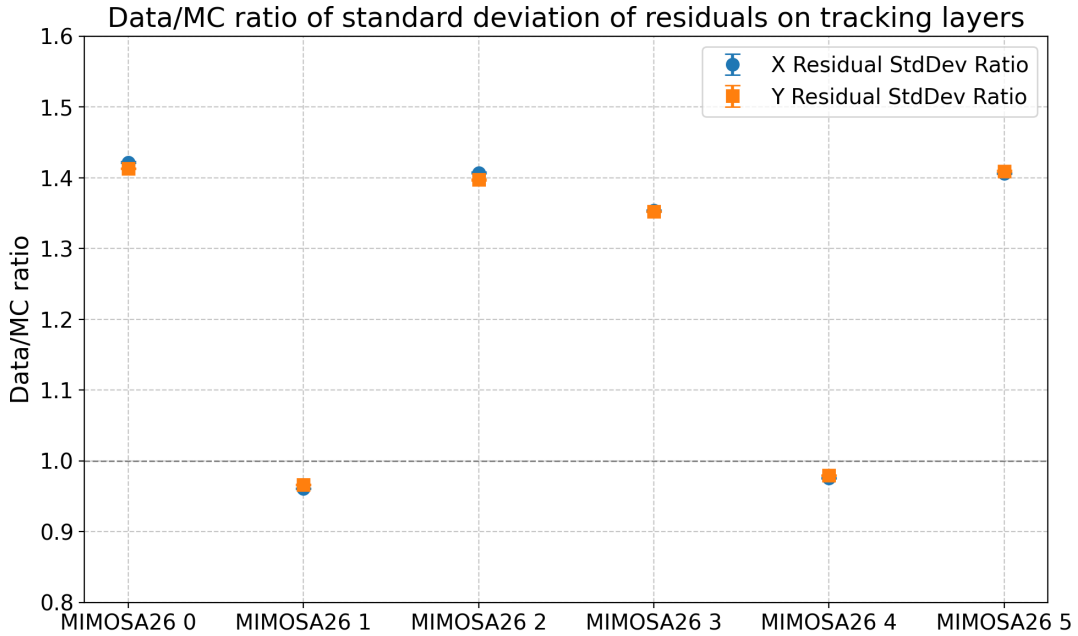


Figure 5.13: Data/MC ratios of residual between track positions and cluster positions on tracking layers. The MIMOSA-26 sensors are indexed from the most upstream position (0) to the most downstream position (5).

5.4 Measurement result

The summary of test beam analysis criteria is concluded in Table 5.1. In this test beam, data taking is performed for DC front-end with threshold of 30 Δ DAC at bias voltage of 6 V, and for AC front-end with threshold of 20 Δ DAC at bias voltages from 6 V to 20 V in the step length of 2 V. The result is reported below.

Table 5.1: Summary of selection criteria in test beam analysis before irradiation

Category	Requirement
Tracking	At least one hit on each telescope layer
Tracking	Cluster search within $\Delta x < 50 \mu\text{m}$, $\Delta y < 50 \mu\text{m}$
DUT Association	Cluster match within $\Delta x < 100 \mu\text{m}$, $\Delta y < 100 \mu\text{m}$
Analysis	Tracking quality of $\chi^2/\text{ndof} < 5$

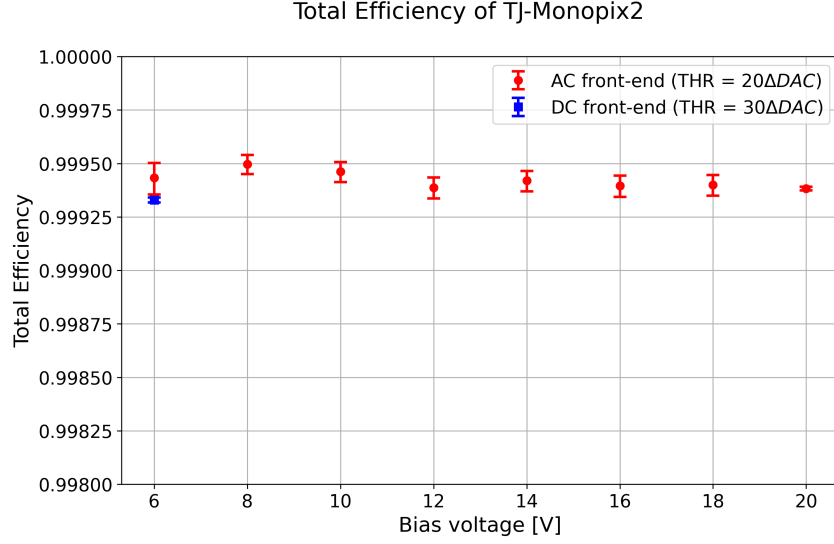


Figure 5.14: Detection efficiency result of DC and AC front-end of non-irradiated TJ-Monopix2. All configurations are measured to have detection efficiencies more than 99%.

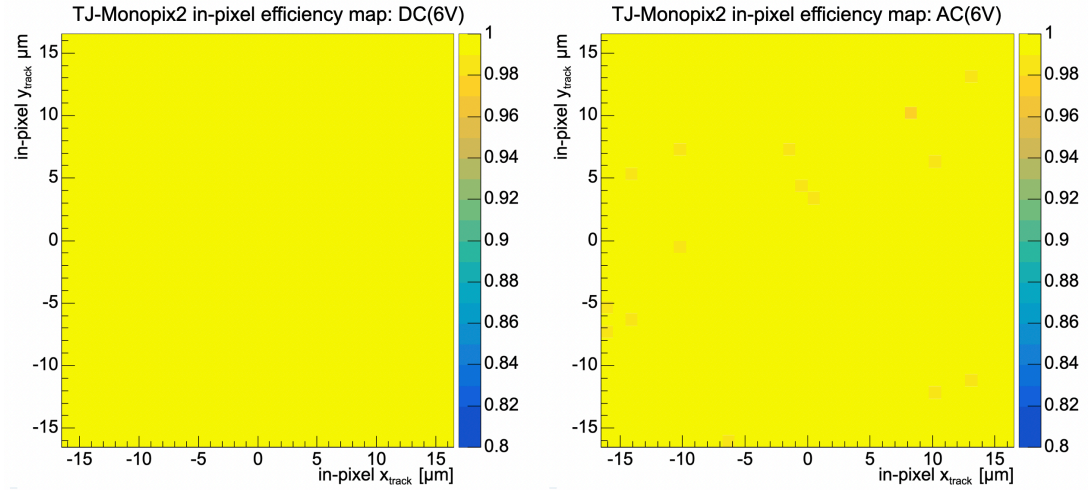


Figure 5.15: In-pixel efficiency maps for DC (bias voltage 6V) and AC (bias voltage 6V) front-end. High efficiency is seen all over the pixel. The bins with lower efficiency in right plot is due to less statistics.

5.4.1 Detection efficiency

Measured detection efficiency is shown in Figure 5.14 and listed in Table 5.2. Both DC and AC (at all bias voltages taken) front-end yield efficiencies of $> 99\%$. Since the telescope provides high precision in tracking, in-pixel detection efficiency can be calculated by classifying the tracks based on their extrapolated positions within pixels of TJ-Monopix2. For non-irradiated TJ-Monopix2 prototype, the in-pixel efficiency maps show flattened distribution with nearly every bin exceeds 99% efficiency. Example of in-pixel efficiency maps of this test beam is shown in Figure 5.15.

Table 5.2: Detection efficiency measured with non-irradiated TJ-Monopix2 prototype.

Front-end	Bias (V)	Efficiency [%]	Fiducial tracks
AC (20 Δ DAC)	6	$99.943^{+0.007}_{-0.008}$	120248
AC (20 Δ DAC)	8	$99.950^{+0.004}_{-0.005}$	267052
AC (20 Δ DAC)	10	99.946 ± 0.005	264293
AC (20 Δ DAC)	12	99.939 ± 0.005	274781
AC (20 Δ DAC)	14	99.942 ± 0.005	276227
AC (20 Δ DAC)	16	99.940 ± 0.005	265270
AC (20 Δ DAC)	18	99.940 ± 0.005	277310
AC (20 Δ DAC)	20	99.938 ± 0.001	8310755
DC (30 Δ DAC)	6	99.933 ± 0.001	5303016

5.4.2 Spatial resolution

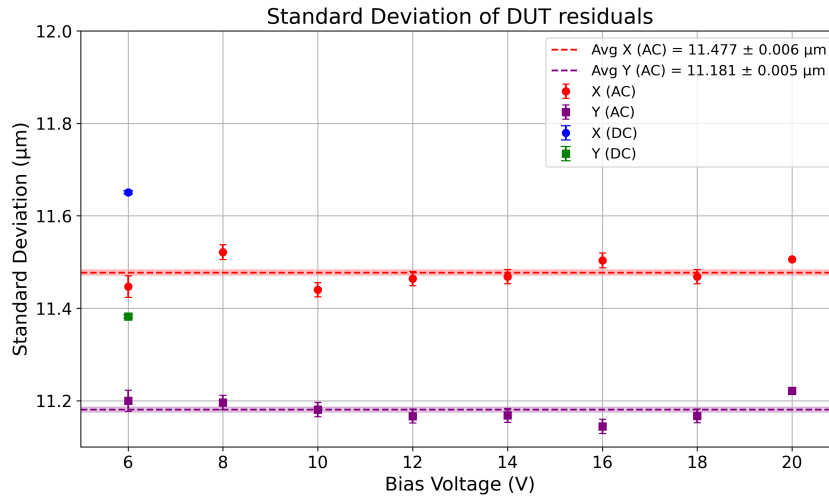


Figure 5.16: Standard deviations of DUT residual histograms for DC and AC front-end. The average values of x, y standard deviation for all bias voltages of AC front-end are noted as dashed lines.

The standard deviations of the DUT residual histograms is shown in Figure 5.16. For the AC front-end, since no obvious dependency of standard deviation on the bias voltage is observed, the average value among all bias voltages is used. For the DC front-end the spatial resolutions are:

$$\sigma_{\text{TJ-Monopix2(DC)}, x} = \sqrt{\sigma_{\text{residual}, x}^2 - \sigma_{\text{tracking}, x}^2} = 11.144 \pm 0.005 \text{ } \mu\text{m}. \quad (5.18)$$

$$\sigma_{\text{TJ-Monopix2(DC)}, y} = \sqrt{\sigma_{\text{residual}, y}^2 - \sigma_{\text{tracking}, y}^2} = 10.863 \pm 0.005 \text{ } \mu\text{m}. \quad (5.19)$$

and for AC front-end:

$$\sigma_{\text{TJ-Monopix2(AC)}, x} = \sqrt{\sigma_{\text{residual}, x}^2 - \sigma_{\text{tracking}, x}^2} = 10.962 \pm 0.007 \text{ } \mu\text{m}. \quad (5.20)$$

$$\sigma_{\text{TJ-Monopix2(AC)}, y} = \sqrt{\sigma_{\text{residual}, y}^2 - \sigma_{\text{tracking}, y}^2} = 10.652 \pm 0.006 \text{ } \mu\text{m}. \quad (5.21)$$

Since the TJ-Monopix2 is rotated for 90° in this test beam, the x coordinate represents row direction and y coordinate represents column direction on TJ-Monopix2. The difference between x, y direction is considered to be coming from the imperfect alignment tuning. Specifically, the worse alignment of y rotations causes larger RMS in the x direction of DUT residuals. The difference between DC and AC front-end is still unclear, which might be also from the imperfect alignment tuning since DC and AC are in different positions in the pixel matrix. However, it is also possible that this is an intrinsic property of TJ-Monopix2. As described in Section 5.3, mis-alignment is not considered when simulating tracking resolution, hence the precise result of spatial resolutions can not be derived. Instead, we conclude a very conservative result only considering the residual resolutions, which is that the spatial resolutions are confirmed to be better than $12 \text{ } \mu\text{m}$, meeting the requirement of upgrade as introduced in Section 3.1.

Chapter 6

Sensor irradiation

An electron-irradiated TJ-Monopix2 sample with accumulated NIEL flux of $5.57 \times 10^{14} n_{eq}cm^{-2}$ is produced at RARiS, Tohoku University. This sample work as the irradiated prototype in the scenario of long-term operation at Belle II experiment and is characterized later.

In this chapter, the irradiation campaign will be described. The irradiation setup and floor plan will be firstly given in Section 6.1 and then the irradiation plan will be explained in Section 6.2. Measurement of S-curve scan and analog waveforms during the irradiation will be reported in Section 6.3.

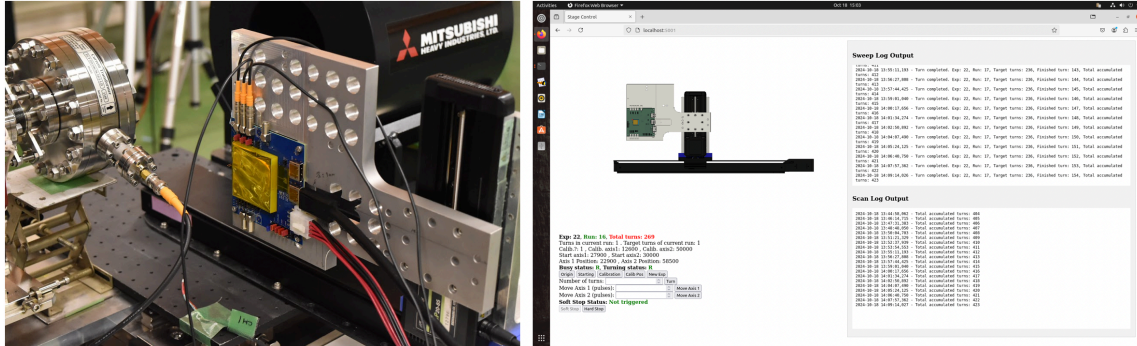


Figure 6.1: Photo of the irradiation setup (left) and the controlling webapp interface (right).

6.1 Irradiation setup

Irradiation is performed at 90 MeV electron beam line from the linear accelerator of RARiS facility, whose beam spot size is in the order of $\mathcal{O}(1 \text{ mm})$. Two OptoSigma [50] moving stages are used to sweep the beam around across the sensor matrix for uniform irradiation, controlled through an OptoSigma two-axis controller. TJ-Monopix2 prototype is mounted to the moving stages through an aluminum support structure. The whole

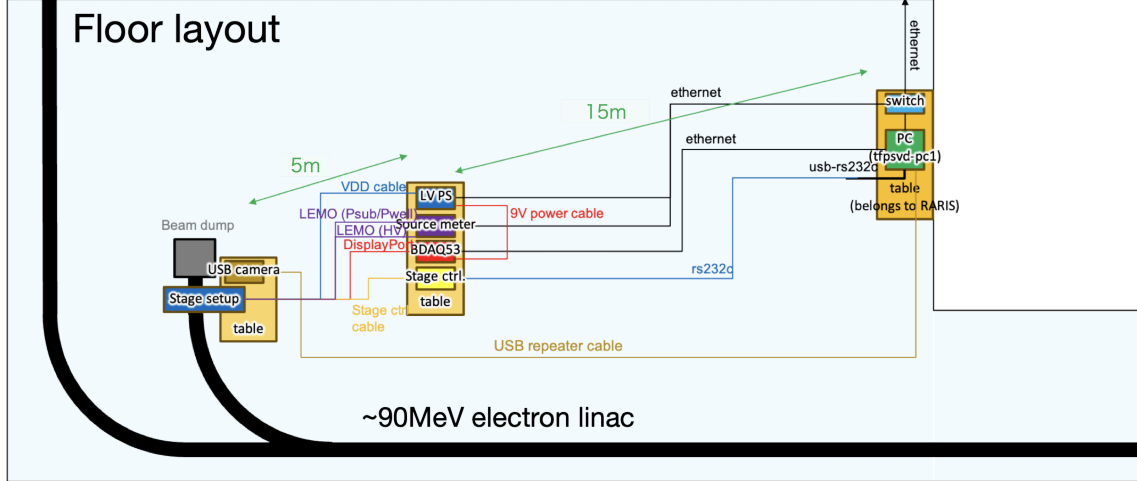


Figure 6.2: Floor plan of irradiation campaign at RARiS facility.

system is programmed to scan the beam position across the matrix in a specific pattern which is explained in Section 6.2, and a webpage application with GUI is developed to control and monitor the sweeping. The photo and GUI is shown in Figure 6.1.

As shown in the floor plan of Figure 6.2, the whole set of power controlling system at KEK test bench described in Section 4.1 is moved to RARiS facility, placed and shielded with the lead plates at around 5 m distance from the irradiation position along with the OptoSigma stage controller. The controlling PC is placed at 15 m distance from the irradiation position to lower the possibility of SEU. Shifter PC is at the upper floor, monitoring and controlling the system through the controlling PC.

6.2 Irradiation plan

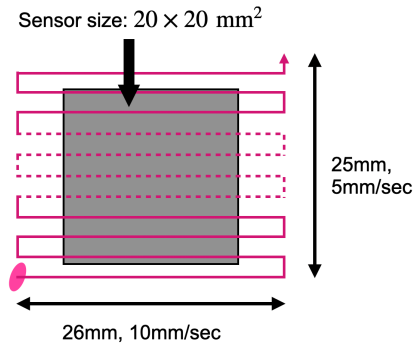


Figure 6.3: Scanning pattern of beam across the sensor matrix.

The pattern of beam scanning across the sensor matrix is shown in Figure 6.3. One full sweeping turn contains 25 vertical scans and 26 horizontal scans. The total scanning area is $\Sigma = 26 \text{ mm} \times 25 \text{ mm} = 650 \text{ mm}^2$. To calculate the accumulated flux, only the

sensor area is considered, where only horizontal scans is relevant. An effective scanning time only taking into account of horizontal scans is $\tau = 65$ s. Taking the beam current as I , electron charge as q_e , the effective number of electrons passing through the sweeping area in each sweep is:

$$N_\Sigma = I\tau/q_e. \quad (6.1)$$

Therefore the number of electrons passing the sensor area in each sweep turn is:

$$N_S = (S/\Sigma) \times N_\Sigma = (S/\Sigma) \times I\tau/q_e. \quad (6.2)$$

where $S = 400 \text{ mm}^2$, being the sensor area, hence $S/\Sigma = 0.62$. At RARiS facility, the 90 MeV electron beam is able to operate at low current mode ($I_{\text{low}} = 29 \text{ nA}$) and high current mode ($I_{\text{high}} = 217 \text{ nA}$). Taking $q_e = 1.6 \times 10^{-19} \text{ C}$, the numbers of electrons passing through the area at low current mode and high current mode are:

$$N_\Sigma^{\text{low}} = \frac{I_{\text{low}} \tau}{q_e} = \frac{(2.9 \times 10^{-8} \text{ A})(65 \text{ s})}{1.6 \times 10^{-19} \text{ C}} \simeq 1.18 \times 10^{13}. \quad (6.3)$$

$$N_S^{\text{low}} = \frac{S}{\Sigma} N_\Sigma^{\text{low}} = 0.62 \times 1.18 \times 10^{13} \simeq 7.25 \times 10^{12}. \quad (6.4)$$

$$N_\Sigma^{\text{high}} = \frac{I_{\text{high}} \tau}{q_e} = \frac{(2.17 \times 10^{-7} \text{ A})(65 \text{ s})}{1.6 \times 10^{-19} \text{ C}} \simeq 8.82 \times 10^{13}. \quad (6.5)$$

$$N_S^{\text{high}} = \frac{S}{\Sigma} N_\Sigma^{\text{high}} = 0.62 \times 8.82 \times 10^{13} \simeq 5.42 \times 10^{13}. \quad (6.6)$$

Taking the hardness factor of 90 MeV electron to be $\kappa(e^- 90 \text{ MeV}) = 7.791 \times 10^{-2} n_{\text{eq}} [51]$, the accumulated NIEL flux of each sweep turn is:

$$\Phi_{\text{NIEL}}^{\text{low}} = (N_S^{\text{low}}/S) \times \kappa(e^- 90 \text{ MeV}) \simeq 1.41 \times 10^{11} n_{\text{eq}} \text{cm}^{-2}. \quad (6.7)$$

$$\Phi_{\text{NIEL}}^{\text{high}} = (N_S^{\text{high}}/S) \times \kappa(e^- 90 \text{ MeV}) \simeq 1.06 \times 10^{12} n_{\text{eq}} \text{cm}^{-2}. \quad (6.8)$$

According to the calculated flux accumulation per sweep turn, the irradiation plan shown in Table 6.1 targeting an accumulated NIEL flux of $5 \times 10^{14} n_{\text{eq}} \text{cm}^{-2}$ is followed. In real operation, the current at RARiS facility was around 30 – 70 nA for low current mode and $\sim 240 \text{ nA}$ for high current mode, which is higher than the expectation. The accumulated NIEL flux is evaluated by integrating the current recorded in the operation log and finally a flux of $5.57 \times 10^{14} n_{\text{eq}} \text{cm}^{-2}$ is reached. It needs to be noted that this value is still not accurate due to the effect of varying beam spot size. The uncertainty is expected to be smaller than 8%, reasonably keeping the level of NIEL flux. After the irradiation, TJ-Monopix2 prototype stayed at RARiS for two weeks for annealing at the room temperature.

Table 6.1: Irradiation Plan

Step ID	Beam current	# of sweeps / step	NIEL flux / sweep [n _{eq} /cm ²]	Total # of sweeps	Total NIEL flux [n _{eq} /cm ²]
1	29 nA	1	1.42×10^{11}	1	1.42×10^{11}
2	29 nA	1	1.42×10^{11}	2	2.84×10^{11}
3	29 nA	2	1.42×10^{11}	4	5.68×10^{11}
4	29 nA	3	1.42×10^{11}	7	9.94×10^{11}
5	29 nA	11	1.42×10^{11}	18	2.56×10^{12}
6	29 nA	17	1.42×10^{11}	35	4.97×10^{12}
7	217 nA	5	1.06×10^{12}	40	1.03×10^{13}
8	217 nA	14	1.06×10^{12}	54	2.51×10^{13}
9	217 nA	24	1.06×10^{12}	78	5.06×10^{13}
10	217 nA	47	1.06×10^{12}	125	1.00×10^{14}
11	217 nA	141	1.06×10^{12}	266	2.50×10^{14}
12	217 nA	155	1.06×10^{12}	421	4.14×10^{14}
13	217 nA	81	1.06×10^{12}	502	5.00×10^{14}

6.3 Measurement during irradiation

After each irradiation step, S-curve scans are performed for several tuning configurations, both for DC and AC front-end, in order to check the dependency of threshold, threshold deviation and noise on the irradiation flux. Besides, analog signal monitoring using oscilloscope is also performed after several steps to check the impact of increased leakage current. The results are reported in this section. It needs to be noted that the NIEL flux values reported in this section are the values in Table 6.1 calculated from expected current, since only tendency of characteristics to the NIEL flux is discussed without quantitative calculation.

6.3.1 S-curve scan

Three tuning configurations for the DC front-end with average thresholds of about 27 Δ DAC, about 33 Δ DAC, about 55 Δ DAC and two tuning configurations for the AC front-end with average thresholds of about 12 Δ DAC, about 19 Δ DAC are prepared for measurement to investigate potential different behaviors in different tunings and thresholds.

The thresholds and their deviations as a function of the NIEL flux are shown in Figure 6.4 and 6.5, with dashed lines indicating the measurement before irradiation. The thresholds in the DC front-end generally increase and then decrease along with increase in the NIEL flux while in the AC front-end the thresholds keeps increasing. The difference from the result before irradiation varies depending on the specific tuning. For both the AC

and DC front-end, threshold deviations increase along with the NIEL flux. The specific amount of change depends on the specific tuning configuration as shown in the figures. While threshold shifts and increased deviations are observed during irradiation, they do not impact the VTX performance in practice, as periodic re-tuning ensures thresholds remain within optimal ranges over the course of long-term irradiation.

The noise level as a function of the NIEL flux is shown in Figure 6.6. For both of the DC and AC front-end, and independent on the specific tuning, the difference of measured noise is small since it is mainly related to the leakage current from the sensor bulk, and it increases with the accumulated NIEL flux as expected. The increased amount of noise level in the unit of ΔDAC is different between DC (about $2.5 \Delta\text{DAC}$) and AC (about $1.0 \Delta\text{DAC}$) front-end. This is resulted from lower gain in AC front-end. The increased noise level suggests that the detection threshold of sensors needs to be increased to reduce the impact of noise.

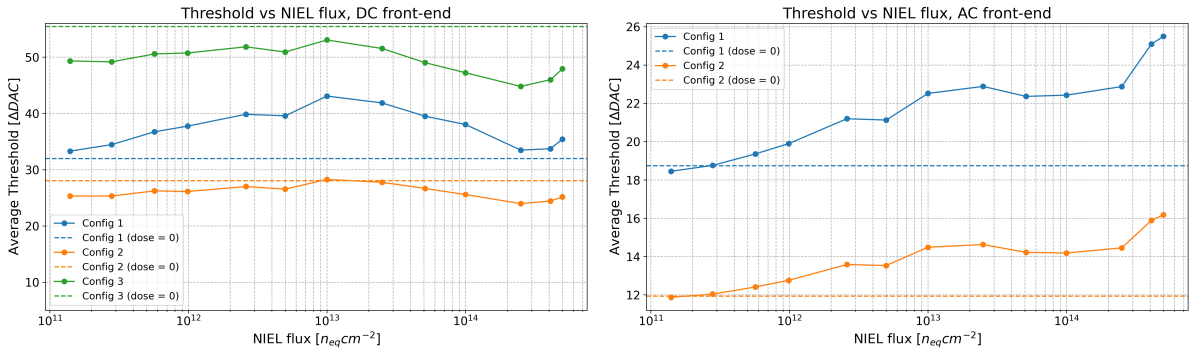


Figure 6.4: Threshold dependency to accumulated NIEL flux of DC (left) and AC (right) front-end. Dashed lines indicate the measurement before irradiation. The thresholds in the DC front-end generally increase and then decrease with larger accumulated NIEL flux while in the AC front-end the thresholds keeps increasing.

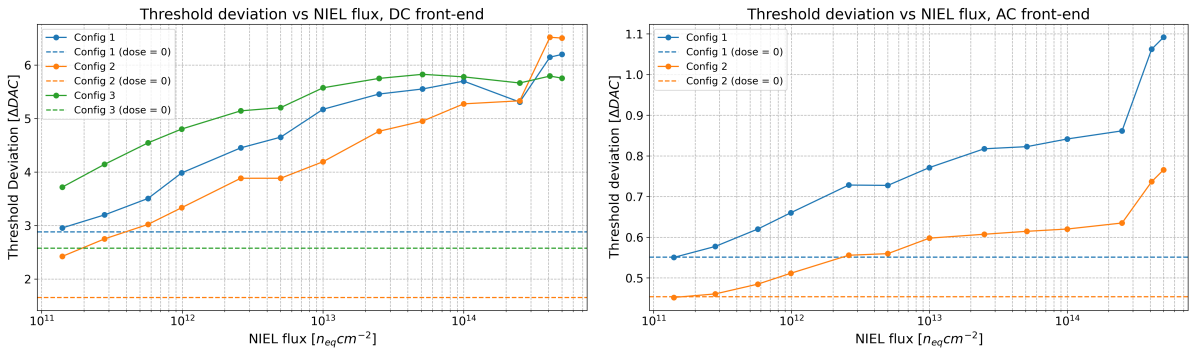


Figure 6.5: Threshold deviation dependency to accumulated NIEL flux of DC (left) and AC (right) front-end. Dashed lines indicate the measurement before irradiation. For both the AC and DC front-end, threshold deviations increase with larger accumulated NIEL flux.

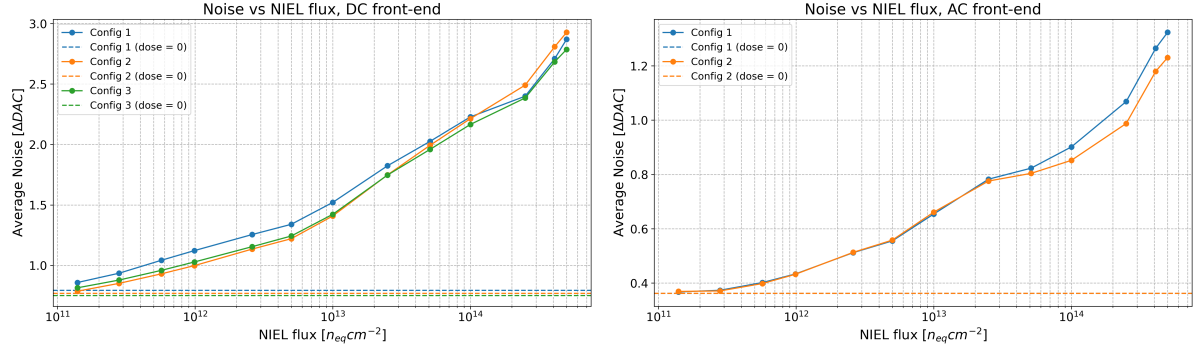


Figure 6.6: Noise dependency to accumulated NIEL flux of DC (left) and AC (right) front-end. For both of the DC and AC front-end, and independent on the specific tuning, the noise increases with larger accumulated NIEL flux.

6.3.2 Analog monitor

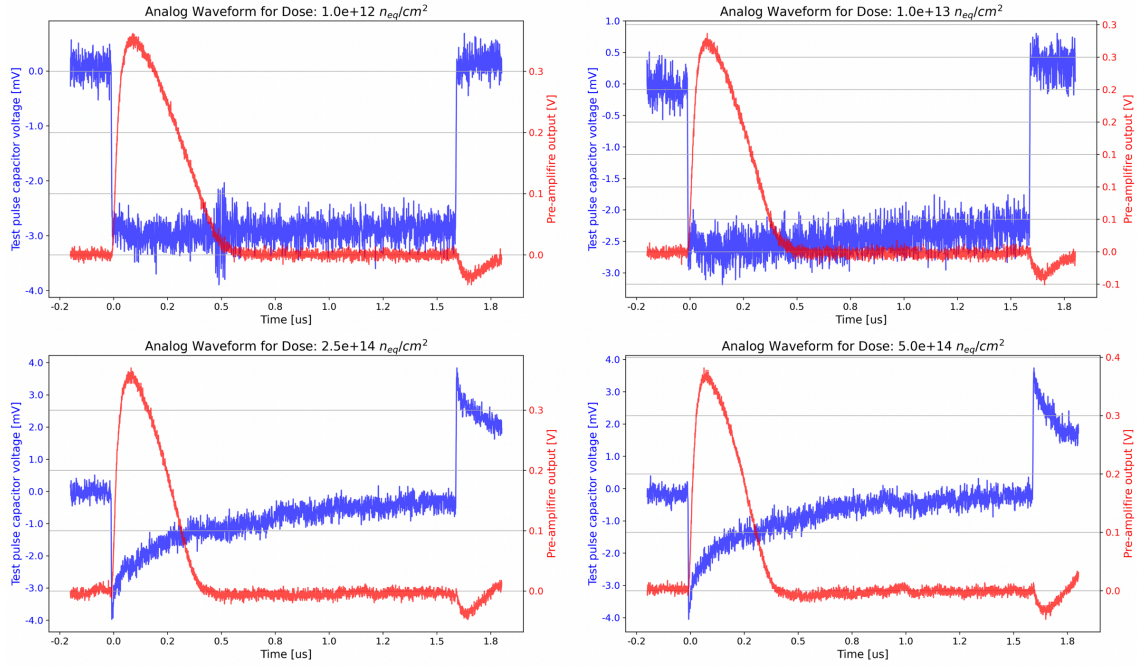


Figure 6.7: Voltage level of the test pulse injection capacitor (blue) and the output from pre-amplifier (red) changing at the accumulated NIEL flux of around $1.0 \times 10^{12} \text{ n}_{\text{eq}}\text{cm}^{-2}$, $1.0 \times 10^{13} \text{ n}_{\text{eq}}\text{cm}^{-2}$, $2.5 \times 10^{14} \text{ n}_{\text{eq}}\text{cm}^{-2}$ and $5.0 \times 10^{14} \text{ n}_{\text{eq}}\text{cm}^{-2}$. These are taken by injecting pulse of 140 ΔDAC to DC front-end with the tuning yielding $\sim 33 \Delta\text{DAC}$ threshold.

Voltage level of the test pulse injection capacitor and the output from pre-amplifier are monitored in between irradiation steps. Observed test pulse voltage levels and waveforms in different accumulated NIEL flux are shown in Figure 6.7. The voltage of test pulse injection capacitor drops to release charges, forming a pulse input to the pre-amplifier,

from which a shaped and amplified signal is output. After a specific time duration, the voltage of test pulse injection capacitor recovers. However, for both the DC front-end and AC front-end, with the accumulated NIEL flux increasing, the impact of leakage current makes the low level of test pulse injection capacitor increases gradually before the designed recovery. This affects the resulting analog output shape of the test pulse, which has a slightly shorter time duration.

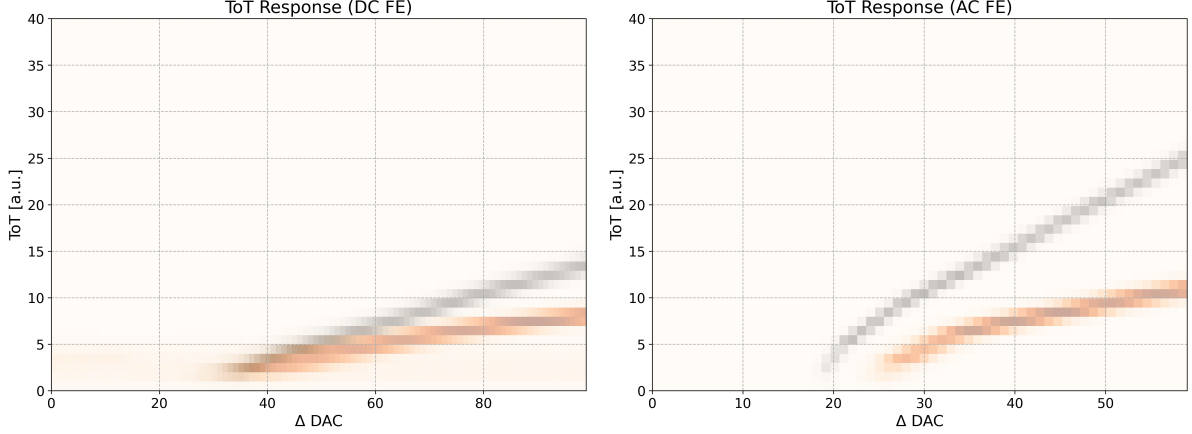


Figure 6.8: Measured ToT response curves of a group of pixels before (grey) and after (orange) irradiation of DC (left) and AC (right) front-end. This is measured with tuning configurations of about 33 Δ DAC for DC front-end and about 20 Δ DAC for AC front-end.

The behavior observed from analog monitoring directly results in smaller ToT response when injecting test pulses of the same amplitude. Lower ToT response curves measured after irradiation are shown in Figure 6.8. Low ToT response degrades the charge resolution of the pixels on TJ-Monopix2 since it represents the deposited charge, which is used in calculating cluster positions. If this effect is totally resulted from the early recovery of test pulse injection capacitor, gain calibration procedure would become inaccurate after irradiation due to the change of ToT levels. However, considering that the injected charges are already released at the dropping of capacitor voltage level, this effect is possibly from the leakage current affecting pre-amplifier. In this case, the gain calibration procedure still remains valid. In this work, we take the assumption of the later explanation while further investigation is to be performed in the future.

Chapter 7

Laboratory measurement after irradiation

The electron-irradiated TJ-Monopix2 described in Chapter 6 is brought back to KEK test bench, which is described in Section 4.1, after annealing. Characterization described in Chapter 4 and additional measurements are performed for comparison with non-irradiated prototype. As explained in Section 2.1.2, since TJ-Monopix2 has a p-type silicon sensor bulk, its biasing voltage for maximum depletion increases due to the change of doping concentration. Even though no specification is given for irradiated TJ-Monopix2 prototype, safe bias voltages under which punch through does not happen of 20 V for DC front-end and 45 V for AC front-end has been confirmed in actual operations, which is larger than the safe voltages specified for non-irradiated TJ-Monopix2, in order to restore the detection performance. In DC front-end, if the total bias voltage is larger than 6 V, the inverse voltage in p-well keeps in -6 V and total bias voltage is applied at p-substrate. Besides, the leakage current has increased to a measurable level of $\mathcal{O}(\mu\text{A})$. By measuring the evolution of leakage current while increasing the bias voltage, the depletion detail can be investigated.

In this chapter, charge collection efficiency measurement result will be reported in Section 7.1. S-curve scan result depending on temperature will be reported in Section 7.2. Measurement of leakage current will be reported in Section 7.3. BCID propagation delay measurement will be reported in Section 7.4. Finally the measurement of BCID crosstalk will be described in Section 7.5.

7.1 Charge collection efficiency

The measurement procedure of charge collection efficiency as described in Section 4.2 is performed for both DC and AC front-end, at different bias voltages and temperature points controlled by the climate chamber. The example of Fe-55 ToT histograms, ToT response curves taken at 15°C and maximum bias voltages for DC and AC front-end are

shown in Figure 7.1 and 7.2. After irradiation, the ToT peaks of Fe-55 $K\alpha$ X-rays yield smaller values of around $(13 - 14) \times 25$ ns compared with before irradiation, when the DC front-end yielded 53.95×25 ns and AC front-end yielded 32.84×25 ns, due to both worse charge collection and lower ToT response curves. The measured conversion factors depending on bias voltage and temperature are shown in Figure 7.3. A break down is given in Table 7.1.

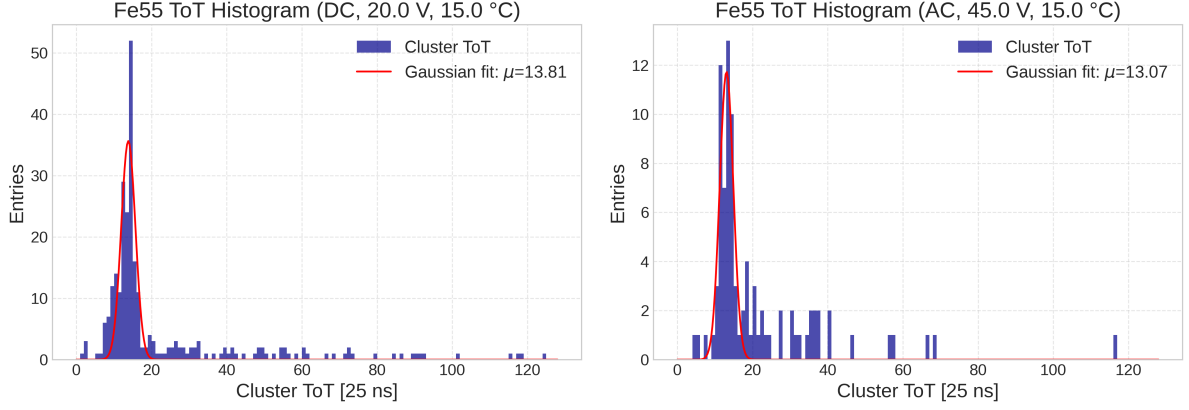


Figure 7.1: ToT distributions and gaussian fittings of Fe-55 response for DC (left) and AC (right) front-end, at maximum bias voltages and 15 °C set on climate chamber.

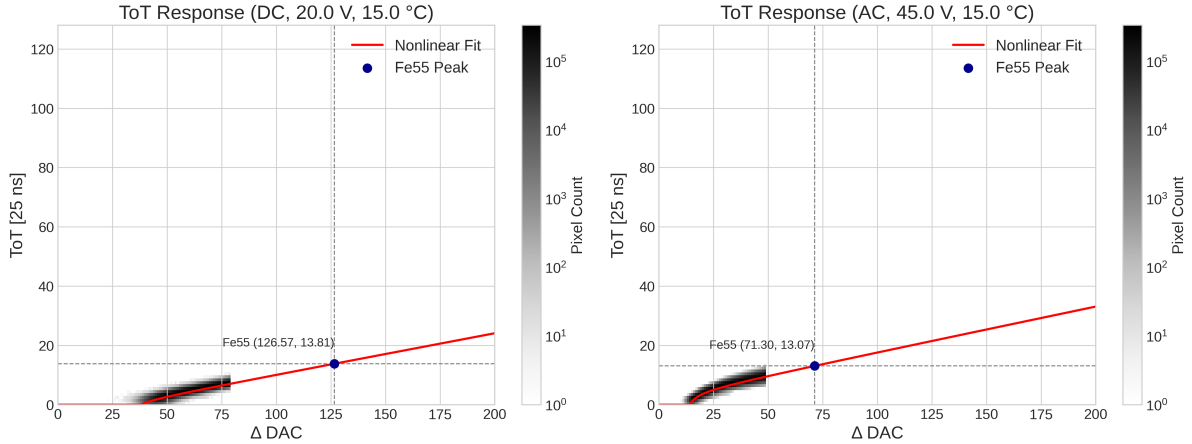


Figure 7.2: Fitting and extrapolation of ToT response curves for DC (left) and AC (right) front-end, at maximum bias voltages and 15 °C set on climate chamber.

Due to irradiation damage, the charge collection performance becomes worse hence higher conversion factor is measured compared with non-irradiated sample which yields $9.53 e^-/\Delta DAC$ for DC front-end and $18.26 e^-/\Delta DAC$ for AC front-end. Charge collection efficiency degradation after irradiation means that at the same amount of deposited charge, the resulted signal amplitude at the collection electrode is smaller, causing detection efficiency degradation.

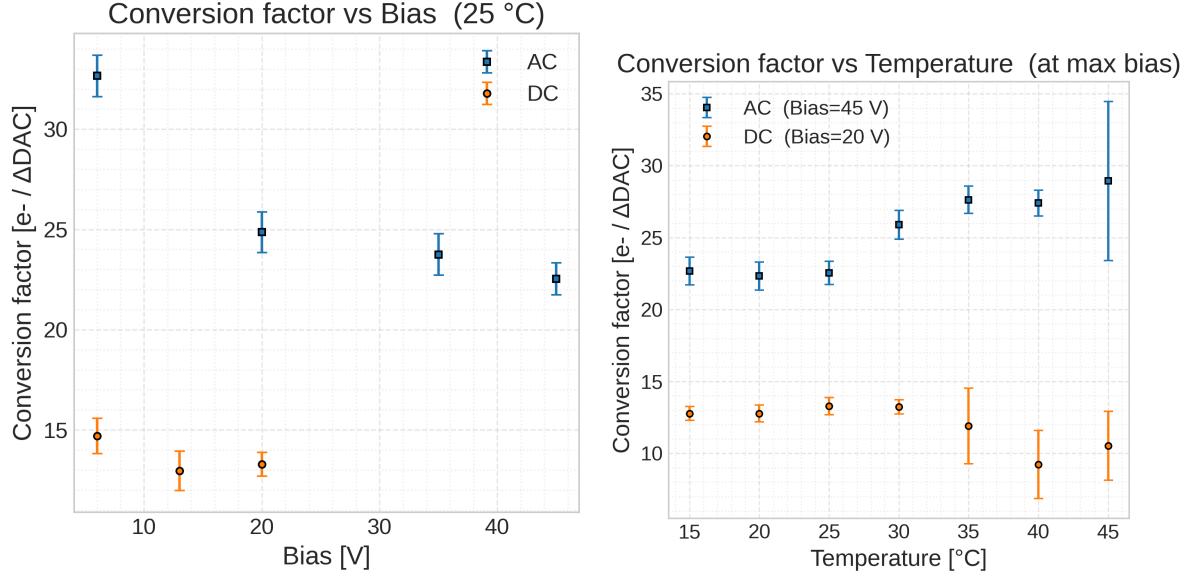


Figure 7.3: Conversion factors depending on bias voltage and temperature. For both the DC and AC front-end, charge collection efficiency increases with higher bias voltage and lower temperature.

From the measurement of conversion factors depending on bias voltage at room temperature (25 °C), it can be observed that by applying higher bias voltage to strengthen the charge collection electric field, degraded charge collection efficiency can be compensated for about $2 e^-/\Delta DAC$ at DC front-end and $10 e^-/\Delta DAC$ at AC front-end. At high temperature environments, the ToT response curve leans down too much so that the fitting gives large uncertainty as shown in the temperature points larger than 35 °C of DC front-end and at 45 °C of AC front-end, where the conversion factor measurement becomes imprecise. For the temperature points smaller than those, the result shows a trend of smaller charge collection efficiency at higher temperature.

7.2 Temperature dependency: threshold and noise

Since the tuning configurations of non-irradiated TJ-Monopix2 prototype become unusable after irradiation, the TJ-Monopix2 is re-tuned. In total four configurations for the DC front-end and five configurations for the AC front-end at different detection thresholds are used to perform S-curve scan at different temperature environment. The results of threshold, threshold deviation and noise dependency on the temperature are shown in Figure 7.4, 7.5 and 7.6, respectively.

The threshold and threshold deviation of all tuning configurations on electron-irradiated TJ-Monopix2 prototype increase along with the environment temperature. From 15 °C to 45 °C, the amount of increasing ranges from 20 ΔDAC to 30 ΔDAC in the DC front-end and 10 ΔDAC to 20 ΔDAC in the AC front-end, which is much larger compared

Table 7.1: Conversion factors at different bias voltages and temperature points.

Front-end	Bias voltage [V]	Temperature [°C]	Conversion factor [$e^-/\Delta\text{DAC}$]
DC	6	25	14.70 ± 0.88
DC	13	25	12.96 ± 0.98
DC	20	15	12.77 ± 0.48
DC	20	20	12.77 ± 0.59
DC	20	25	13.22 ± 0.60
DC	20	30	13.24 ± 0.49
DC	20	35	11.91 ± 2.63
DC	20	40	9.23 ± 2.37
DC	20	45	10.53 ± 2.40
DC (un-irrad.)	6	room temperature (~ 25)	9.57 ± 0.05
AC	6	25	32.66 ± 1.03
AC	20	25	24.86 ± 1.01
AC	35	25	23.75 ± 1.04
AC	45	15	22.66 ± 0.96
AC	45	20	22.33 ± 0.98
AC	45	25	22.51 ± 0.81
AC	45	30	25.89 ± 1.00
AC	45	35	27.63 ± 0.95
AC	45	40	27.40 ± 0.91
AC	45	45	28.94 ± 5.52
AC (un-irrad.)	10	room temperature (~ 25)	18.26 ± 0.07

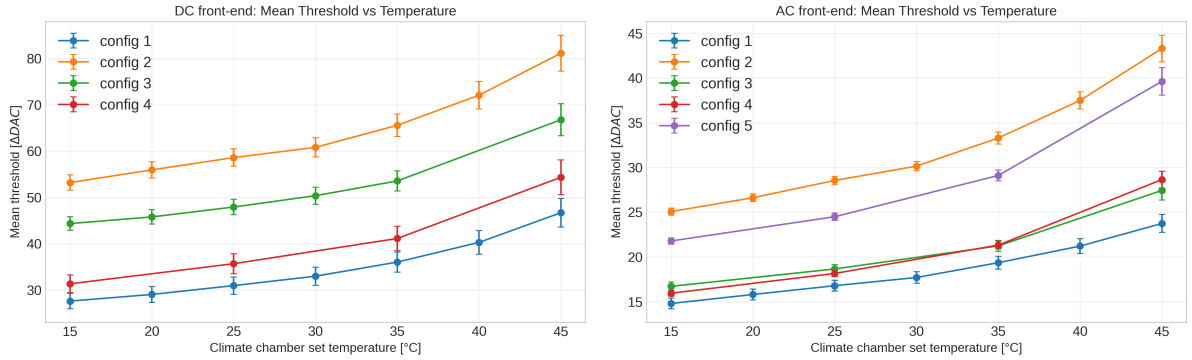


Figure 7.4: Mean threshold dependency on climate chamber set temperature of DC (left) and AC (right) front-end. The error bar represents the standard deviation of noise distribution. The threshold increases along with the environment temperature.

with the threshold change in non-irradiated TJ-Monopix2 prototype (2 ΔDAC in the DC front-end and 4 ΔDAC in the AC front-end). The threshold deviation is a result of local parameter tuning, which can remain the same level (around 2 $\sim$ 3 ΔDAC in the DC front-end and $< 1.5 \Delta\text{DAC}$ in the AC front-end) with non-irradiated prototype, while

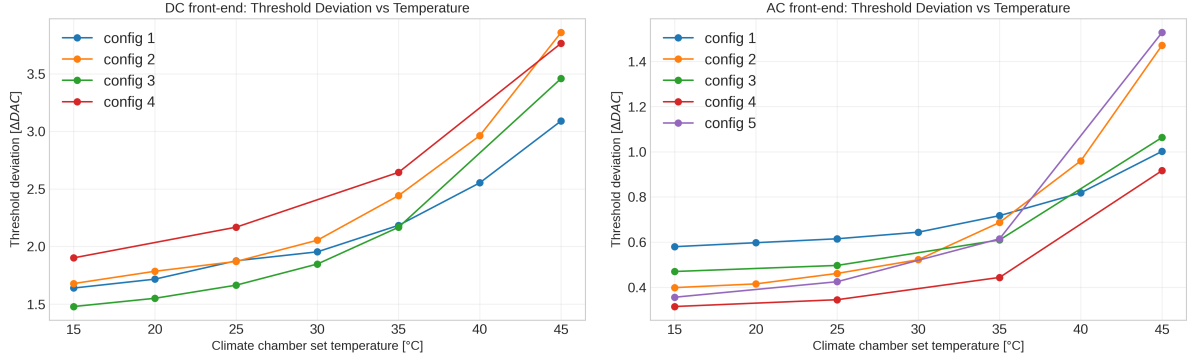


Figure 7.5: Threshold deviation dependency on climate chamber set temperature of DC (left) and AC (right) front-end. The threshold deviation increases along with the environment temperature.

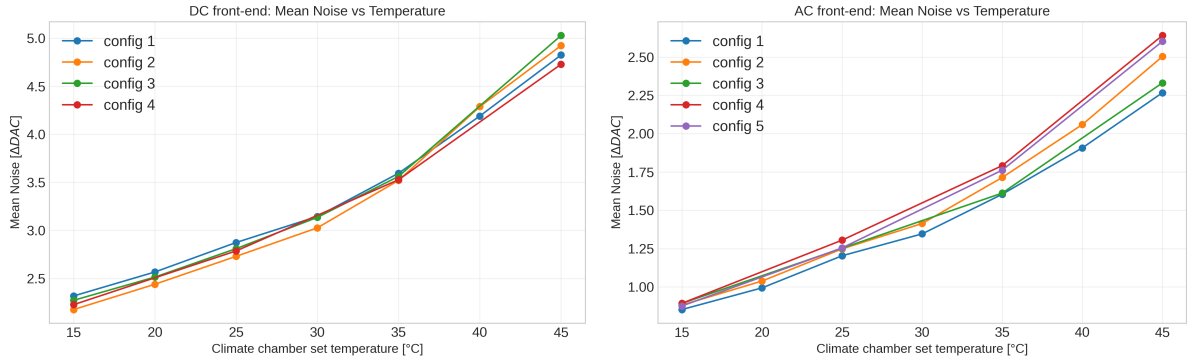


Figure 7.6: Noise dependency on climate chamber set temperature of DC (left) and AC (right) front-end. The noise increases along with the environment temperature.

obvious increase happens when local parameters described in Section 2.3.3 TJ-Monopix2 is not re-tuned in the middle of the temperature scan.

After irradiation, noise level measured from S-curve scan has increased and becomes more sensitive to temperature due to the increased leakage current. Since the noise is dominated by leakage current, the differences of noise level among all tuning configurations are small. From 15 $^{\circ}C$ to 45 $^{\circ}C$, the noise increases for about 2.5 ΔDAC in the DC front-end and about 1.5 ΔDAC in the AC front-end. As a reported in Section 4.3, the change of noise level on non-irradiated TJ-Monopix2 from 15 $^{\circ}C$ to 45 $^{\circ}C$ is $< 0.1 \Delta DAC$ for both DC and AC front-end.

Compared with non-irradiated TJ-Monopix2 prototype, higher sensitivity of threshold and noise to temperature change has been observed. Assuming full depletion of epitaxial layer, the number of electrons created from MIPs in TJ-Monopix2 is around 2000 e^{-} as calculated in Section 4.3. According to the charge collection efficiency measurement result reported in Section 7.1, the typical detection thresholds are 364 e^{-} at the DC front-end and 414 e^{-} at the AC front-end, while from 15 $^{\circ}C$ to 45 $^{\circ}C$, the thresholds could increase for up to 390 e^{-} at the DC front-end and 460 e^{-} at the AC front-end, being

significant compared with signal charge. The increased threshold and noise under high temperature suggests potential degradation of detection performance. Therefore, a test beam investigating the detection performance depending on temperature is performed, which is described in Section 8.5.

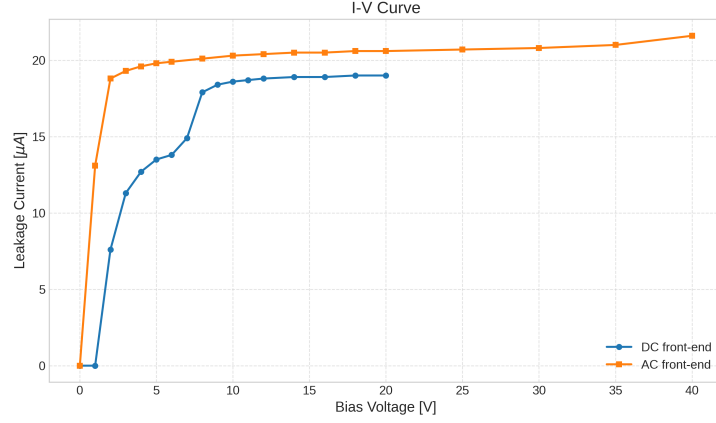


Figure 7.7: I-V curves for DC and AC front-end. The IV curve in the DC front-end shows an obvious 2-stage depletion process while in the AC front-end the depletion area quickly expands and is almost saturated already at about 3V.

7.3 Leakage current

Leakage current has increased significantly to $\mathcal{O}(\mu A)$ level. The I-V curves measured at 30 °C for the DC and the AC front-end, which are biased in different ways as described in Section 2.3, are shown in Figure 7.7.

The leakage current represents the volume of the depletion area in the sensor bulk as shown in Equation 2.7. The IV curve at DC front-end, where inverse bias voltage is applied on p-well and p-substrate, shows an obvious 2-stage depletion process where at around 5 V the depletion area stabilizes for the first time and then expands to larger area, which is almost saturated at about 9 V. In AC front-end where the bias voltage is applied directly to the collection electrode, the IV curve indicates that the depletion area quickly expands to a larger volume and almost saturated already at about 3V. After the stabilization, the leakage current still increases slowly along with the bias voltage, suggesting that the sensor bulk is not fully depleted and the depletion area is still expanding. The insights to the depletion process provided by IV curves of leakage current agrees well with the detection efficiency measurement after irradiation, which will be discussed in Section 8.4.

7.4 Clock signal propagation delay

The same measurement described in Section 4.4 is performed using electron-irradiated TJ-Monopix2 prototype. The measurement of T_1 , T_2 and T_3 are shown in Appendix B. Compared with non-irradiated TJ-Monopix2 prototype, the electron-irradiated one yields larger values for all the timing measurement, with result of:

$$T_2 = T_{\text{inj}} + T_{\text{HitOR}} = 69.3 \text{ (63.5) ns.} \quad (7.1)$$

$$T_3 = T_{\text{HitOR}} = 49.1 \text{ (45.5) ns.} \quad (7.2)$$

The results measured with non-irradiated TJ-Monopix2 are noted in the brackets. The slightly larger delay values are likely due to the changes in properties of signal drivers after the irradiation.

When IDEL is set to 37, which is the best compensation value measured in non-irradiated TJ-Monopix2 prototype, the combined result of $T_{\text{IDEL}} - T_{\text{BCID}} = T_1 - T_2 + T_3$ on electron-irradiated TJ-Monopix2 is 2.0 ns, while for non-irradiated TJ-Monopix2 it yields -0.3 ns. The change is small enough to still be compensated by adjusting the IDEL register value. After irradiation, the best compensation among the scanned IDEL points happens when IDEL is set to 44, with a result of -1.0 ns.

7.5 Clock signal crosstalk

Table 7.2: Minimum and maximum points in the threshold oscillation due to BCID crosstalk.

Front-end	T [°C]	Min (Delay, THR) ([ns], [Δ DAC])	Max (Delay, THR) ([ns], [Δ DAC])	Max THR - Min THR [Δ DAC]
DC	15	(38.0, 26.51)	(85.5, 37.49)	10.98
DC	25	(38.0, 29.35)	(85.5, 41.26)	11.91
DC	35	(38.0, 38.89)	(85.5, 52.76)	13.87
DC	45	(123.5, 61.93)	(85.5, 77.31)	15.38
AC	15	(47.5, 13.41)	(133.0, 16.42)	3.01
AC	25	(57.0, 15.24)	(123.5, 18.42)	3.18
AC	35	(47.5, 18.03)	(133.0, 21.35)	3.32
AC	45	(57.0, 23.57)	(133.0, 27.49)	3.92

As described in Section 2.3, the actual detection threshold of TJ-Monopix2 oscillates depending on the clock phase while in one S-curve scan the test pulse is injected in a fixed clock phase. The method to measure the threshold oscillation is to repeat the S-curve scan in different test pulse injection clock phases. This measurement is performed for

both the DC and AC front-end using one configuration for each in different temperature environments, as shown in Figure 7.8 and 7.9.

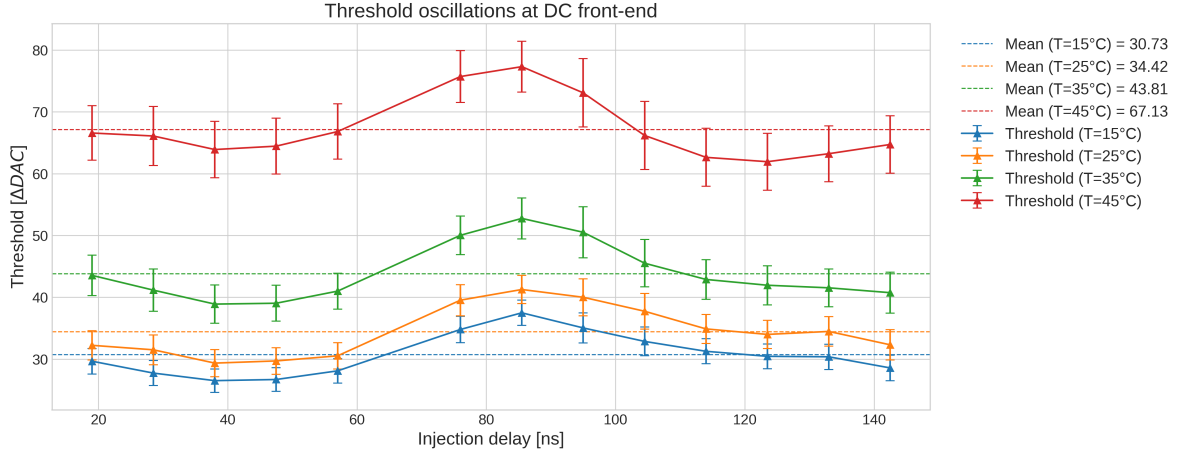


Figure 7.8: Detection threshold oscillation depending on the test pulse injection phase of DC front-end, measured in different temperature points. The error bars stand for the standard deviations of threshold. The mean values throughout the oscillation are indicated with dashed lines.

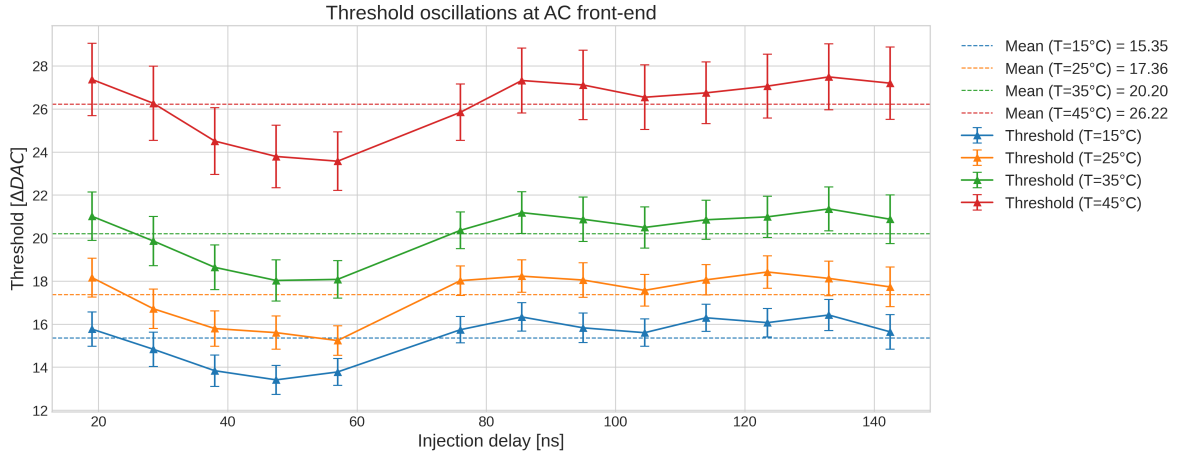


Figure 7.9: Detection threshold oscillation depending on the test pulse injection phase of AC front-end, measured in different temperature points. The error bars stand for the standard deviations of threshold. The mean values throughout the oscillation are indicated with dashed lines.

The minimum and maximum threshold points in the measurement are given in Table 7.2. Depending on the clock phase, the detection threshold could vary for about 11 Δ DAC to 15 Δ DAC in the DC front-end and about 3 Δ DAC to 4 Δ DAC in the AC front-end. The difference between maximum and minimum threshold increases along with the temperature. In different temperature points, the clock phase where minimum and maximum threshold shows stays roughly the same. According to this measurement,

2236 it is found that clock signal crosstalk results in significant variations in thresholds, which
2237 are larger than the noise level after irradiation reported in Section 7.2. In real opera-
2238 tion, effective noise larger than actual electronic noise will be induced by clock crosstalk.
2239 Therefore, the suppression of this effect will be an important research topic in the devel-
2240 opment of OBELIX sensor.

Chapter 8

Test Beam measurement after irradiation

The electron-irradiated TJ-Monopix2 prototype with NIEL flux of $5 \times 10^{14} \text{ n}_{\text{eq}}\text{cm}^{-2}$ is put into a test beam campaign conducted at KEK PF-AR Test Beam Line [52], utilizing the SOI telescope and 3 GeV electron beam. In this test beam, the detection efficiency after irradiation is investigated in detail including the dependency on threshold and bias voltage. Spatial resolution is also derived. Besides, since this is the first time to implement the non-SOI detector like TJ-Monopix2 to the SOI telescope system, the synchronization strategy between TJ-Monopix2 and SOI telescope had to be developed. Additionally, the implementation of SOI telescope to the **Corryvreckan** framework needed to be developed.

Another test beam at DESY II Test Beam facility is performed which involves different irradiated TJ-Monopix2 samples produced by other groups within VTX collaboration. The EUDET telescope and 4.2 GeV electron beam are used again. A device controlling the temperature of TJ-Monopix2 developed by HEPHY (the Institute of High Energy Physics, Austria) group is used in this test beam in order to investigate the dependency of detection performance on the temperature. Since the detailed analysis of the data from this test beam is still on-going, a qualitative comparison of detection efficiency and leakage between electron-irradiated sample and proton-irradiated sample will be briefly discussed, along with the detection dependency on the temperature.

In this chapter, the setup of test beam in KEK will be introduced in Section 8.1, including the SOI telescope and layer arrangement. The synchronization strategy between SOI telescope and TJ-Monopix2 will be introduced in Section 8.2. **Corryvreckan** implementation will be briefly described in Section 8.3 and the result will be reported in Section 8.4. Finally, the comparison between electron/proton-irradiated sample and the detection efficiency under different temperature points will be briefly discussed in Section 8.5.

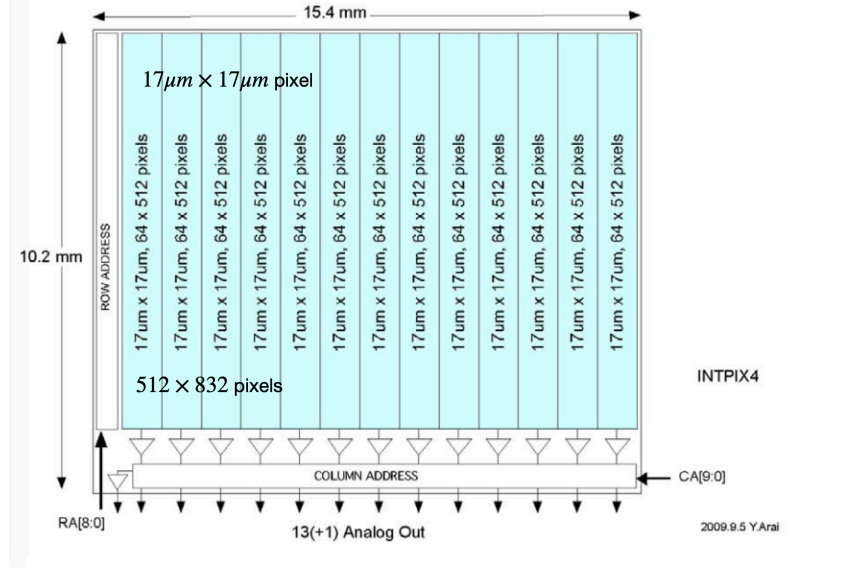


Figure 8.1: Block diagram of INTPIX4NA sensor [14].

8.1 Test beam setup

8.1.1 SOI telescope

The SOI telescope is a tracking device utilizing silicon pixel sensors produced with Silicon-On-Insulator(SOI) technology. SOI technology is another solution for monolithic silicon pixel sensor besides CMOS DMAPS. The SOI concept is that the MOSFET forming the readout circuit is implemented on a SiO_2 layer for isolation [15], which is just above the silicon sensor bulk. An electrode stretch down into the silicon bulk to collect signal charge. In this test beam, four SOI INTPIX4NA sensors are used for tracking and one SOI XRPIX5 sensor is used for triggering [53].

(1) INTPIX4NA sensor

As shown in Figure 8.1, INTPIX4NA sensor [54] contains $512 \text{ rows} \times 832 \text{ columns}$ pixels with pitch size of $17 \times 17 \mu\text{m}^2$. The total sensitive area is $14.1 \times 8.7 \text{ mm}^2$. The sensor bulk is in the thickness of $300 \mu\text{m}$, which can be fully depleted hence the charge collection is mainly by drifting. The binary resolution of INTPIX4NA is calculated to be $17 \mu\text{m}/\sqrt{12} \simeq 4.91 \mu\text{m}$ and the measured spatial resolution is $4.01 \pm 0.10 \mu\text{m}$ for 3 GeV electrons, improved by charge sharing.

The DAQ of INTPIX4NA is controlled by SEABAS2 board [14], which receives timing, trigger and control LVDS signals from the DAQ master board through an Ethernet cable. The charge integration period is approximately 100 ns in INTPIX4NA [55]. If a trigger signal is assigned from the DAQ master board, the read out sequence would be initiated and BUSY signal is put at the same time, stopping the acceptance of trigger signals.

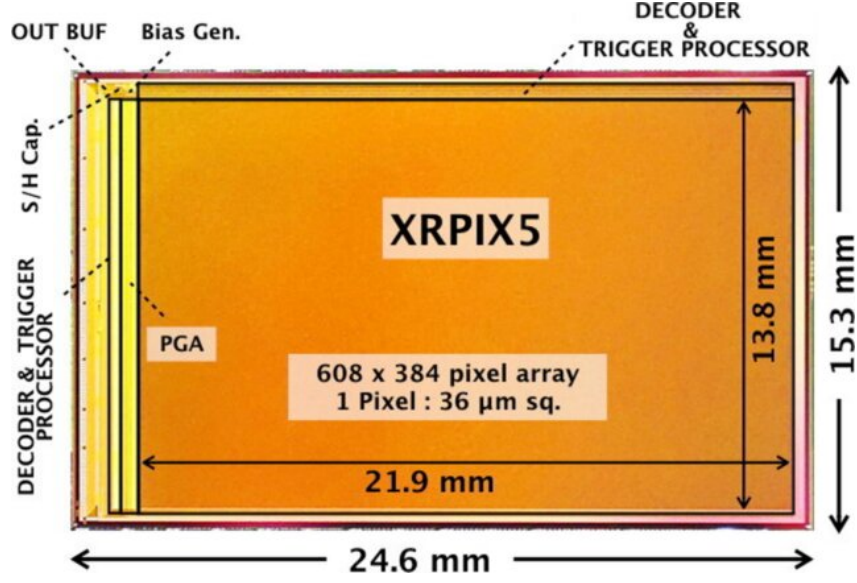


Figure 8.2: Chip size of XRPIX5 sensor [15].

Pixels on INTPIX4NA are grouped into 13 blocks, with each block containing 64 columns and 512 rows. Pixels on each block shares one common analog output. In the read out of INTPIX4NA, the analog signal of all pixels are output and converted to digital signals through ADCs. The ADC map of the full enabled matrix is read out to the DAQ master board. The DAQ rate is mainly limited by the bandwidth due to the large data size, which is in the level of about 100 Hz while the trigger timestamp is recorded with a 1 kHz clock.

(2) XRPIX5 sensor

As shown in Figure 8.2, XRPIX5 sensor [15] contains 608×384 pixels with pitch size of $36 \times 36 \mu\text{m}^2$. The total sensitive area is $21.9 \times 13.8 \text{ mm}^2$. In this test beam, the enabled matrix area on XRPIX5 is adjusted to match the enabled area on INTPIX4NA and TJ-Monopix2. When a hit happens on the enabled area of XRPIX5, it generates a trigger signal and sends it to the DAQ master board which distributes it to all other sensors.

8.1.2 Layer arrangement

The test beam setup is shown in Figure 8.3, where the space interval between layers are noted. An XRPIX5 sensor is placed at the most upstream position for triggering. Two INTPIX4NA layers are placed at the upstream of TJ-Monopix2 and two INTPIX4NA layers are at the downstream for tracking. The SOI telescope sensors are mounted on aluminum supporting structures, where rectangular cut-outs corresponding to the sensor areas are made, avoiding induce extra material budget. Correspondingly, an aluminum

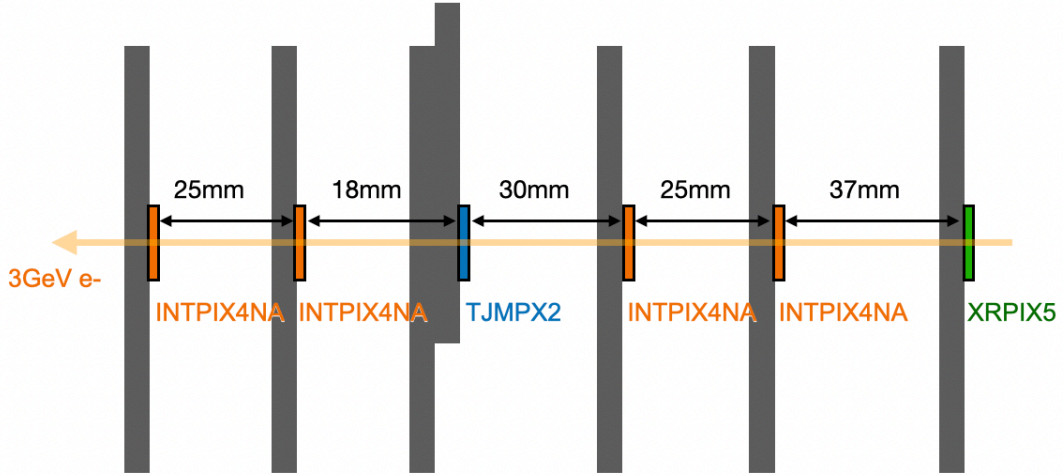
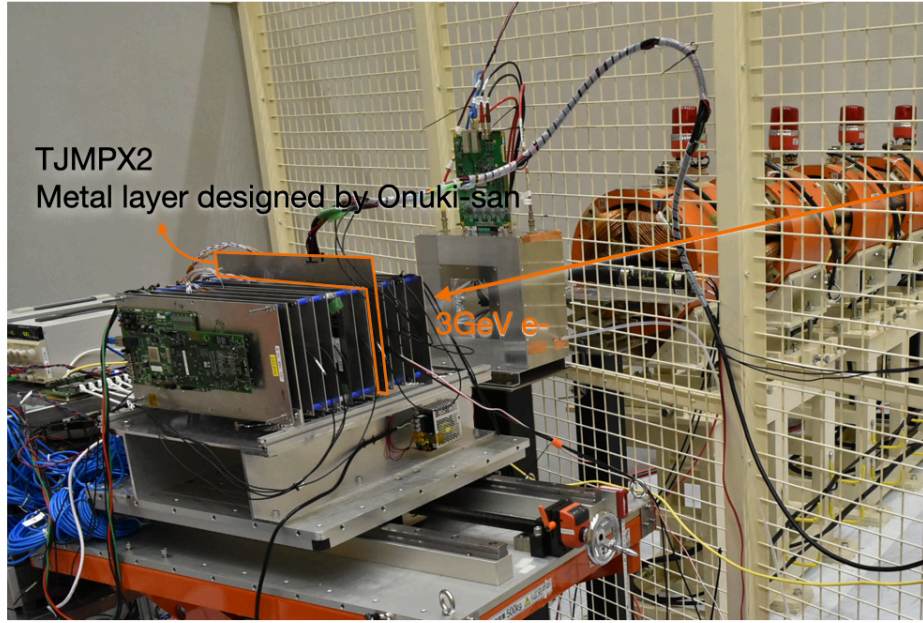


Figure 8.3: Photo (above) and schematic view (below) of layer arrangement in KEK PFAR test beam. Spatial intervals between sensors are noted. Downstream layers including DuTip sensor are not plotted since they are not used in the data taking for TJ-Monopix2.

supporting structure for TJ-Monopix2 compatible with SOI telescope mechanics is developed, with the cut-outs at the sensor area.

8.2 Detector synchronization and event definition

The trigger signal from the DAQ system of the SOI telescope is assigned in LVDS format transmitted through Ethernet cables. Two pins of the Ethernet connector carry a 1 kHz clocking signal and other two pins carry the trigger signal. The trigger timestamp

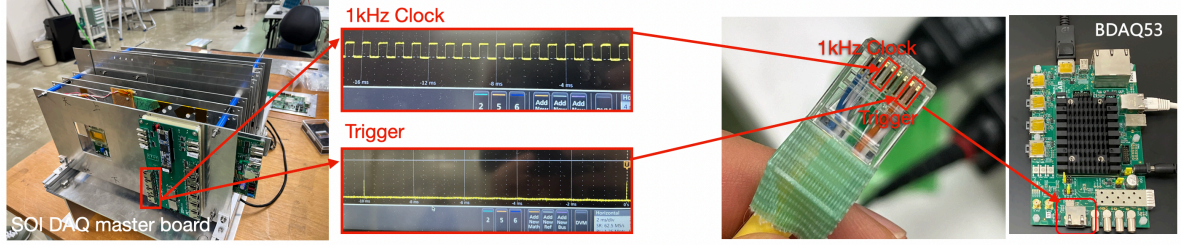


Figure 8.4: Schematic view of synchronization setup between SOI telescope and TJ-Monopix2.

Table 8.1: Modified TLU data format for TJ-Monopix2.

bit	31	30–16	15–0
	header	1 kHz SOI timestamp	625 kHz TJ-Monopix2 timestamp

is the clock number when a trigger signal is assigned, which is referred as SOI timestamp in later context. A special Ethernet cable with adjusted pin order is made to transfer the LVDS signal from the SOI DAQ system to the TLU port of the BDAQ53 board, which is the data readout electronics of TJ-Monopix2. A schematic view is shown in Figure 8.4. A modified firmware for the BDAQ53 board is developed so that when a trigger signal is accepted by the TLU port, a TLU data packet shown in Table 8.1 is output to the data stream. The SOI timestamp is the same with SOI telescope DAQ system, recorded by counting a 1 kHz clock, hence in the precision of 1 ms. TJMPX2 timestamp refers to the internal timestamp of TJ-Monopix2 which is used by the hit data. This timestamp in TLU data packet is recorded by counting a 625 kHz clock, in the precision of $1.6 \mu\text{s}$. Besides, a 1 bit header is used to indicate that this is a TLU data packet.

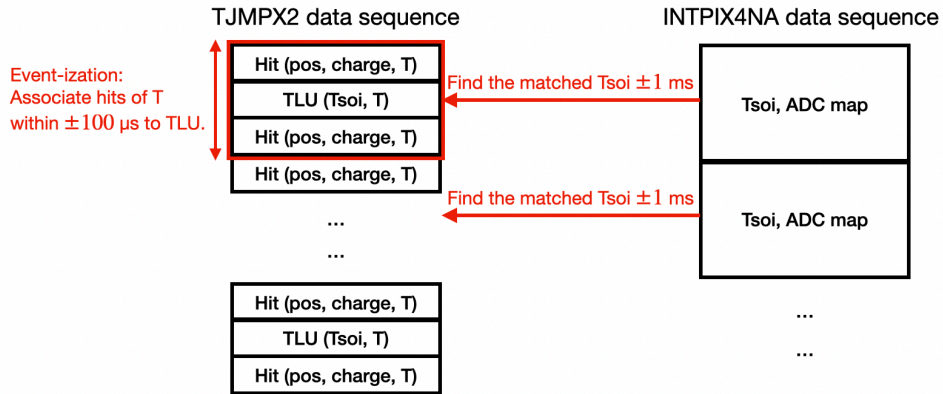


Figure 8.5: Illustration of event definition in KEK PF-AR test beam. Tsoi stands for the SOI timestamp and T is the internal TJMPX2 timestamp.

The event is defined by each trigger. In INTPIX4NA data, the ADC map data of each triggered frame contains the SOI timestamp hence the hit assignment to each event is performed naturally. In TJ-Monopix2, the hit data packets are associated to TLU data

packets through the internal TJMPX2 timestamp. To ensure the coverage of $\sim 100 \mu\text{s}$ charge integration time on INTPIX4NA, a time window of $[-100 \mu\text{s}, +100 \mu\text{s}]$ around each TLU data packet is defined. The hit data within this time window is associated to the TLU data and assigned to the corresponding event.

In actual operation, due to the BUSY status in the read out period of INTPIX4NA, during which the acceptance of trigger signal is stopped, the triggers recorded in the TJ-Monopix2 data are more than those recorded in the SOI telescope data. Therefore, the event definition should be based on the SOI telescope data and the corresponding trigger events with matched SOI timestamp are searched in the TJ-Monopix2 data (with a $\pm 1 \text{ ms}$ window due to the possible delay or different counting in BDAQ53 board). A schematic view is illustrated in Figure 8.5. Synchronization test is performed in the laboratory using a Sr-90 radiation source and 100% of trigger events in SOI telescope data can find their matched event in TJ-Monopix2 data, as shown in figure.8.6

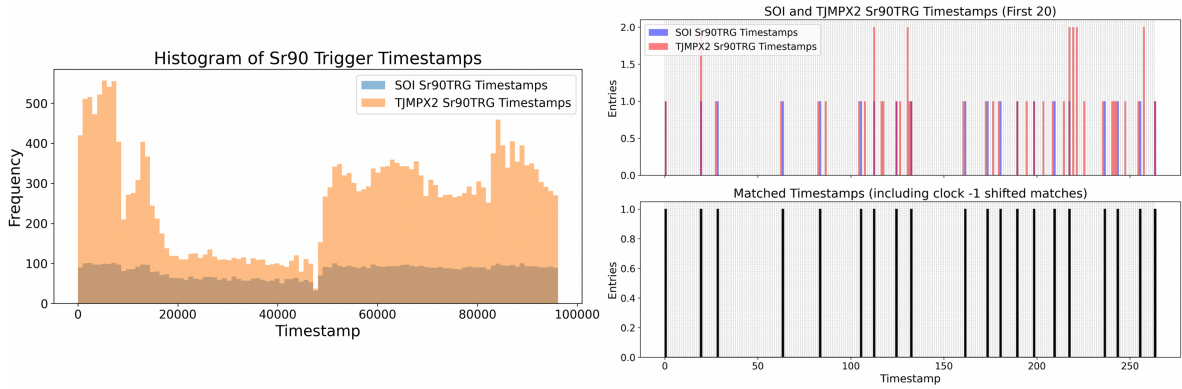


Figure 8.6: Synchronization test. Trigger signal is assigned from XRPIX5 which is irradiated by Sr90. The histogram of trigger timestamps (left) shows that in TJ-Monopix2 there are more triggers recorded. All trigger events in SOI telescope data are confirmed to be able to find their matched trigger events in TJ-Monopix2 data. An closer look of first 20 triggers is shown (right).

8.3 Corryvreckan implementation

To perform the same analysis using Corryvreckan framework as described in Section 5.2, the implementation of the SOI telescope is developed. This implementation involves two Corryvreckan modules named `ConvertINTPIX4` and `EventLoaderTJMPX2SOITRG`, decoding and load the event hits for INTPIX4NA and TJ-Monopix2 with the modified TLU data packet.

8.3.1 ConvertINTPIX4

Module **ConvertINTPIX4** contains two working modes: converting and loading. Since the data from INTPIX4NA is the full ADC map without zero suppression in binary form, whose decoding and zero-suppression is very time consuming, a pre-process is performed in the converting mode. In converting mode, **ConvertINTPIX4** decode the binary data to extract the trigger timestamp (a 32-bit counter in the precision of 1 ms) and ADC map of the matrix. Zero suppression based on the ADC map data is performed in the following procedure which is the procedure suggested by the SOI group [55]:

Pedestal is the average ADC output throughout N triggered frames for each pixel:

$$\text{Pedestal}(b, c, r) = \frac{\sum_e \text{ADC}(b, c, r, e)}{N_{\text{event}}}. \quad (8.1)$$

where b , c , r is the block (0 to 12) column (0 to 63), row (0 to 511) address, respectively, for pixels and e iterates over N_{event} triggered event frames.

Baseline of each block is the average ADC output throughout N_{event} triggered frames and all pixels in the corresponding block:

$$\text{Baseline}(b) = \frac{\sum_{c,r,e} \text{ADC}(b, c, r, e)}{N_{\text{event}} \times N_{\text{column}} \times N_{\text{row}}}. \quad (8.2)$$

Frame average is the average ADC output throughout all pixels in the corresponding block for one specific event e :

$$\text{FrameAve}(b, e) = \frac{\sum_{c,r} \text{ADC}(b, c, r, e)}{N_{\text{column}} \times N_{\text{row}}}. \quad (8.3)$$

This value describes the common mode shift of each block depending on the triggered frame.

Having the variables described above, the variable describing the ADC deviation of a pixel (b , c , r) is calculated as:

$$\sigma(b, c, r) = \sqrt{\frac{\sum_e (\text{ADC}(b, c, r, e) - \text{FrameAve}(b, e) + \text{Baseline}(b) - \text{Pedestal}(b, c, r))^2}{N_{\text{event}}}}. \quad (8.4)$$

In practice, the first 1000 events of each data taking are used to calculate the pedestal and baseline. The 0.2% events having the maximum ADC values and 0.2% events having the minimum ADC values are removed to exclude the impact of outliers. The same event set is used in the calculation of ADC deviation $\sigma(b, c, r)$. The judgment of hit for pixel (b , c , r) at event frame e is:

$$(\text{ADC}(b, c, r, e) - \text{FrameAve}(b, e) + \text{Baseline}(b) - \text{Pedestal}(b, c, r)) / \sigma(b, c, r) > 10. \quad (8.5)$$

and the numerator serves as a variable linear to the deposited charge, which is saved as charge and used for position calculation in clustering.

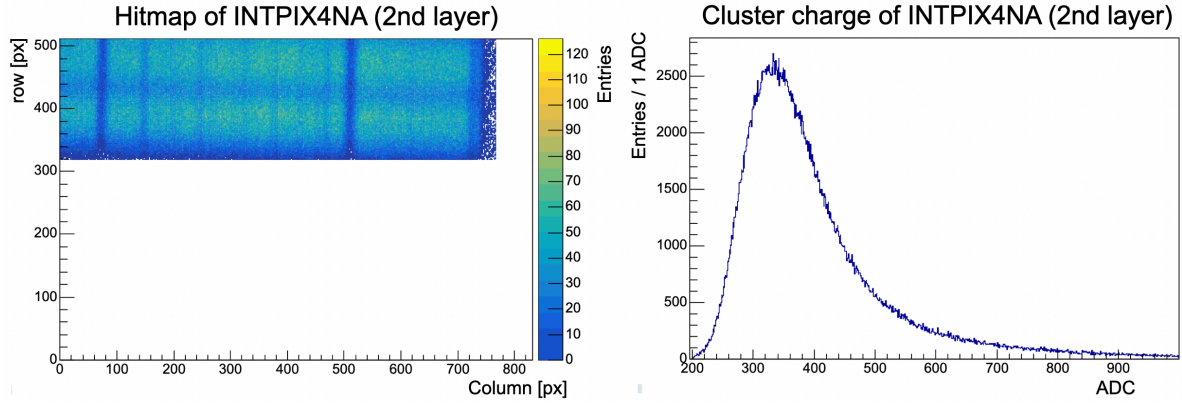


Figure 8.7: The hit map (left) and charge distribution of clusters with successful tracking (left) on the second layer of INTPIX4NA. The enabled matrix is adjusted to match the AC front-end of TJ-Monopix2. Shadow on the hit map comes from the masked area on XRPIX5.

After zero suppression, for each INTPIX4NA layer the events containing timestamp and selected hits are saved into a root file which is the input data file of loading mode. The example of hit map and cluster charge (in ADC unit) is shown in Figure 8.7, where the charge distribution shows an expected Landau distribution.

In loading mode, `ConvertINTPIX4` iterates through every event saved in the root file and extract the timestamp and hit pixels. A `Corryvreckan` event in the width of 2 ms centered at the extracted timestamp is defined and the corresponding hit data are put into this event.

8.3.2 EventLoaderTJMPX2SOITRG

Zero suppression of the TJ-Monopix2 is on-pixel so the data size is small. Therefore, `EventLoaderTJMPX2SOITRG` is able to directly process the binary data without consuming much time. Given that the timestamp of `Corryvreckan` event is already defined by `ConvertINTPIX4`, `EventLoaderTJMPX2SOITRG` firstly iterates over all TLU data packets to find the matched trigger event. After a matched trigger event is found, the hits are searched around the TLU data in the data sequence. Searched hits within a time window of $[-100 \mu\text{s}, +100 \mu\text{s}]$ around the internal TJMPX2 timestamp of the TLU data are assigned to this event. The example of time difference histogram between hit data and TLU data is shown in Figure 8.8. Most of the hits are within $\pm 10 \mu\text{s}$ around the TLU data, and no obvious background distribution observed.

Since the SOI timestamp counter is limited to 15-bit, which overflow every 32.768 s. When the SOI timestamp of a TLU data is smaller than its previous TLU data, an overflow is counted in the offline analysis and 32.768 s is added for each counted overflow

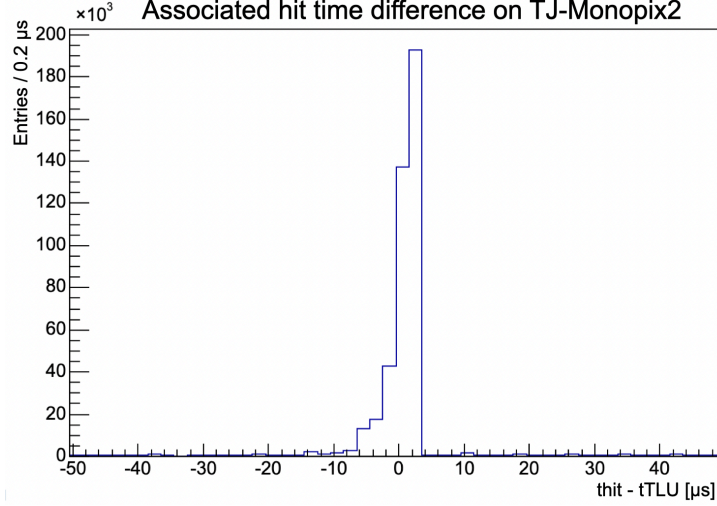


Figure 8.8: Internal timestamp difference between hit data and TLU data in TJ-Monopix2. The asymmetry distribution is resulted from the trigger latency property of the SOI telescope.

when calculating the actual SOI timestamp. Considering the trigger rate of 50 Hz – 70 Hz in this test beam, the possibility that the time interval of two triggers is larger than 32.768 s is small enough to be negligible, ensuring the synchronization between TJ-Monopix2 and SOI telescope.

8.4 Measurement result

Table 8.2: Summary of selection criteria in test beam analysis after irradiation

Category	Requirement
Tracking	At least one hit on each telescope layer
Tracking	Cluster search within $\Delta x < 50 \mu\text{m}$, $\Delta y < 50 \mu\text{m}$
DUT Association	Cluster match within $\Delta x < 100 \mu\text{m}$, $\Delta y < 100 \mu\text{m}$
Analysis	Tracking quality of $\chi^2/\text{ndof} < 10$

In this test beam, four tuning configurations for the DC front-end with threshold ranging in 31–57 ΔDAC and five for the AC front-end with threshold ranging in 17–29 ΔDAC are prepared to investigate the impact of threshold to detection performance after irradiation. Bias voltage is scanned from 6 V to 20 V on DC front-end and 6 V to 45 V on AC front-end.

Alignment tuning and analysis are performed within **Corryvreckan** framework as described in Section 5.2. Analysis criteria are listed in Table 8.2 and χ^2/ndof from GBL tracking is shown in Figure 8.9. In this test beam setup, the number of degrees of freedom is 4. Due to less tracking layers compared with the test beam before irradiation, the

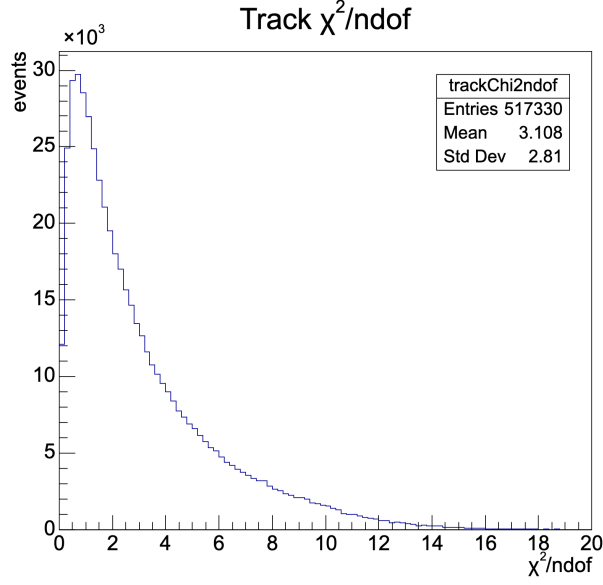


Figure 8.9: χ^2/ndof distribution of tracking in KEK PF-AR test beam campaign.

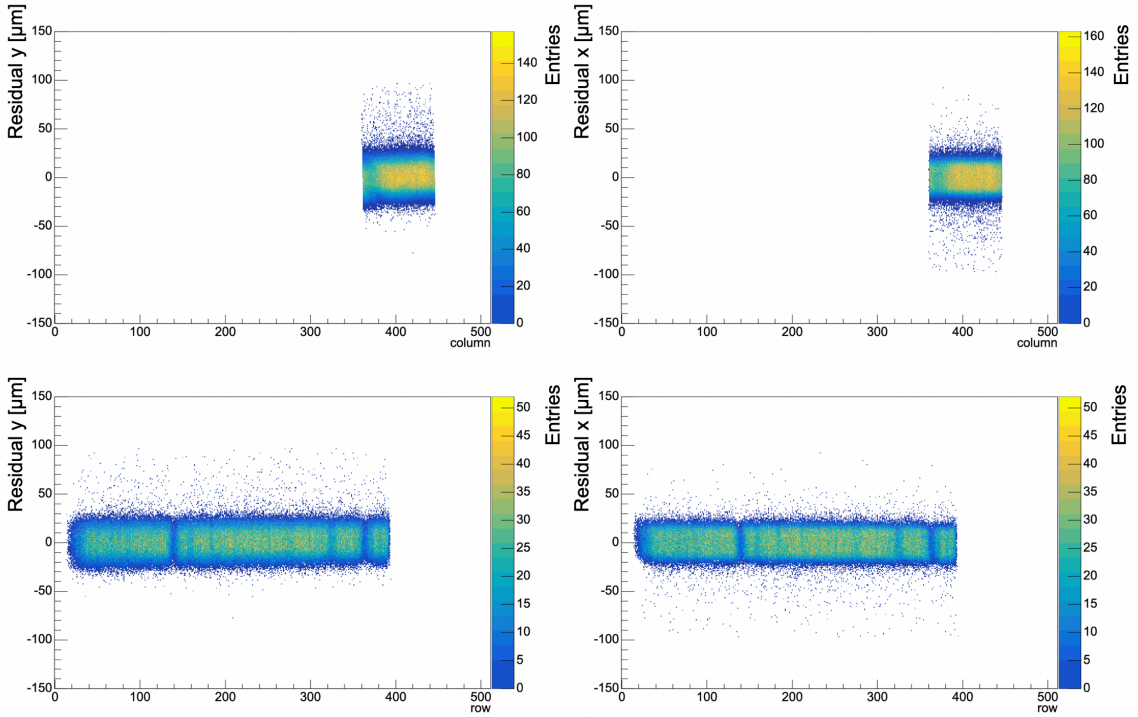


Figure 8.10: DUT residual dependency on the hit position on electron-irradiated TJ-Monopix2 (DC front-end). Slight dependencies of residuals on the positions are seen, especially the dependencies of residuals in y direction.

2411 χ^2/ndof tends to have a larger value compared with Figure 5.7. Therefore, the selection
 2412 of fiducial tracks is decided to be $\chi^2/\text{ndof} < 10$. A check of alignment quality is shown
 2413 in Figure 8.10 and 8.11. Slight dependencies of residuals on the positions are seen in
 2414 both the DC and AC front-end, especially the dependencies of residuals in y direction,

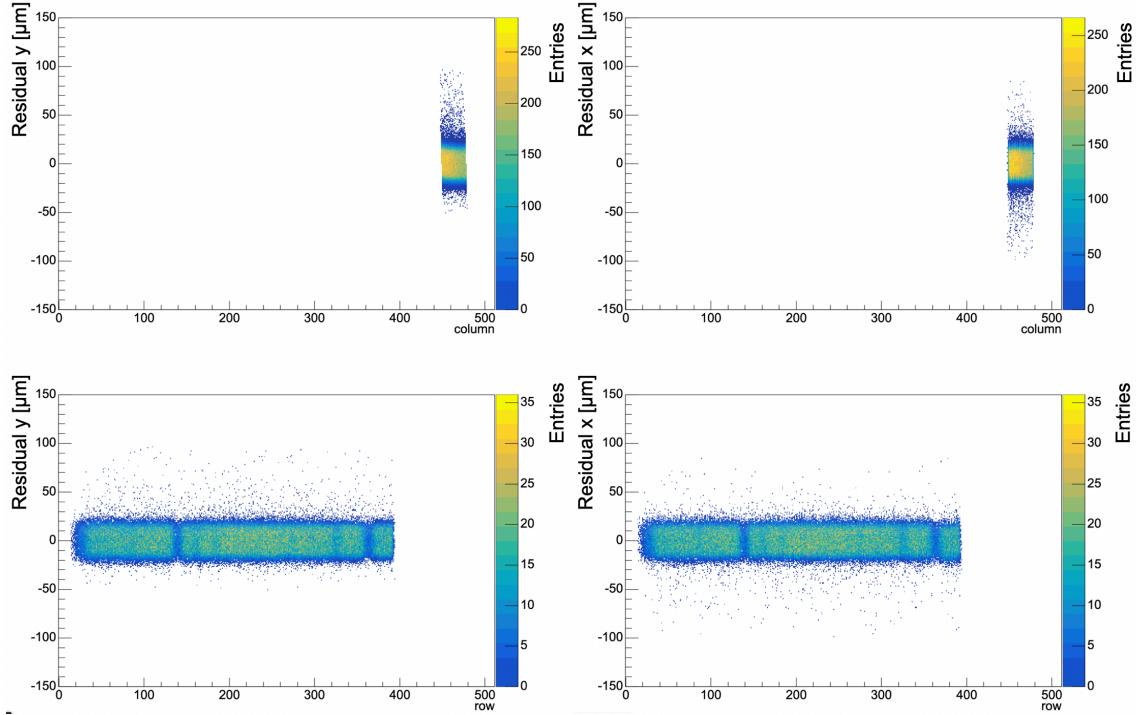


Figure 8.11: DUT residual dependency on the hit position on electron-irradiated TJ-Monopix2 (AC front-end). Slight dependencies of residuals on the positions are seen, especially the dependencies of residuals in y direction..

meaning the alignment tunings are still imperfect.

8.4.1 Total efficiency

The total efficiencies of different configurations and bias voltages are shown in Figure 8.12 and 8.13. The results and corresponding numbers of fiducial tracks taken in the beam test are listed in Table 8.3

Compared with result before irradiation when all measurements resulted efficiencies more than 99.9% even at low bias voltages, degradation in detection efficiency, which is resulted from the lattice defect trapping the signal charge and incomplete depletion reducing drifting area, is evident, especially at low bias voltage. Much more severe degradation at low bias voltage on the DC front-end compared with the AC front-end indicates less depletion or weaker electric field coming from the different way of applying bias voltage. This result is compatible with the leakage current measurement introduced in Section 7.3. The degraded detection efficiency can be compensated by applying higher bias voltage, which enlarges the depletion field and induces a stronger electric field, strengthening the charge drifting. The recovery of the DC front-end is sharper than the AC front-end, which is resulted from a 2-stage depletion and after the recovery around 10 V, the efficiency does not increase much compared with the AC front-end where the efficiency still increases slowly at high bias voltage. Such behavior is also compatible with the leakage current

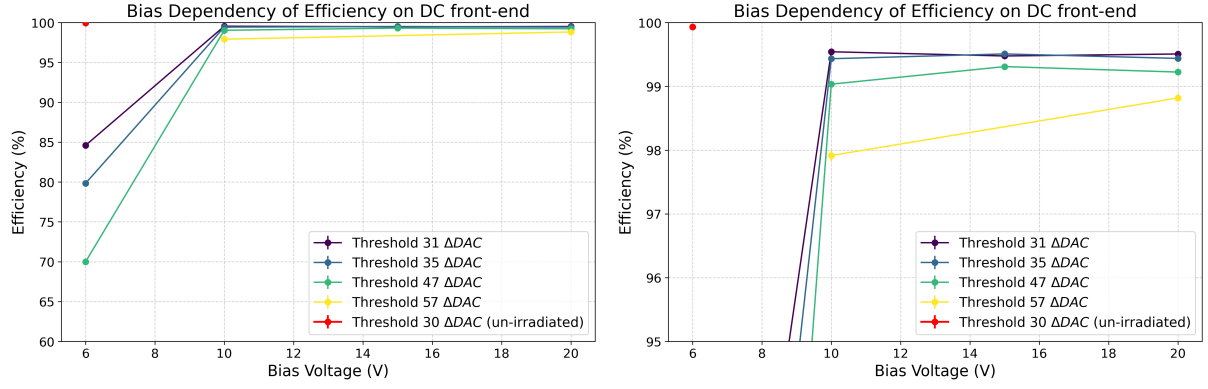


Figure 8.12: Efficiency depending on bias voltages on the DC front-end (left) and its trimmed view (right). Result measured with non-irradiated TJ-Monopix2 is noted with red data point. The results are plotted with error bars with are small and barely seen.

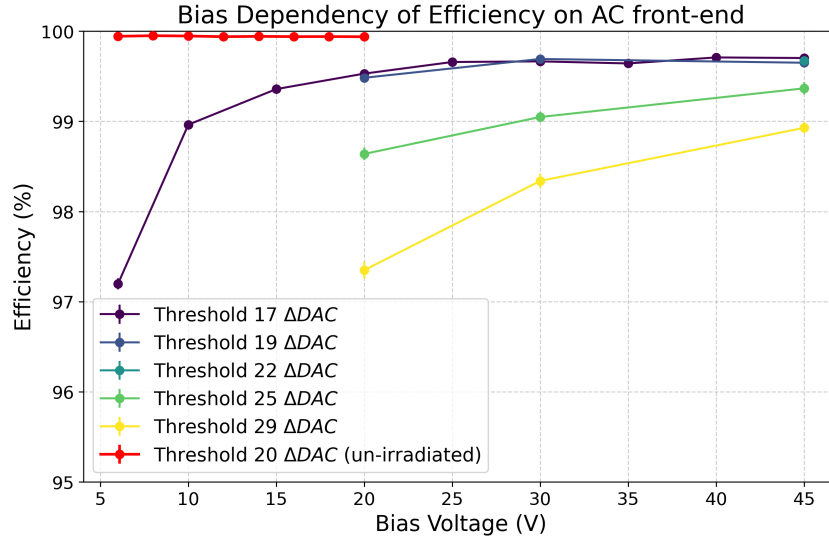


Figure 8.13: Efficiency depending on bias voltages on AC front-end. Results measured with non-irradiated TJ-Monopix2 are noted with red data points. The results are plotted with error bars with are small and barely seen.

measurement introduced in Section 7.3, where slight increasing of leakage current at high bias voltage can be seen on AC front-end, indicating the extension of depletion area. Detection efficiency is also observed to be strongly sensitive to the detection threshold, which is expected due to the degradation of the charge collection after irradiation.

Even though the degradation of detection efficiency is obvious, compensation by high bias voltage at low detection threshold can still result in a detection efficiency of more than 99%, ensuring the performance after long-term operation.

Table 8.3: Efficiency results measured with electron-irradiated TJ-Monopix2 and the corresponding number of fiducial tracks.

Front-end	Threshold (Δ DAC)	Bias (V)	Efficiency [%]	Fiducial Tracks
DC	31	6	84.60 ± 0.12	96319
DC	31	10	99.54 ± 0.03	63603
DC	31	15	99.48 ± 0.02	96987
DC	31	20	99.51 ± 0.01	317059
DC	35	6	79.84 ± 0.23	31788
DC	35	10	99.43 ± 0.03	62978
DC	35	15	99.51 ± 0.03	58579
DC	35	20	99.44 ± 0.03	64241
DC	47	6	70.00 ± 0.26	32322
DC	47	10	99.03 ± 0.04	63684
DC	47	15	99.31 ± 0.05	32304
DC	47	20	99.22 ± 0.03	95741
DC	57	10	97.91 ± 0.08	31701
DC	57	20	98.82 ± 0.06	32402
DC (un-irrad.)	30	6	99.933 ± 0.001	5303016
AC	17	6	97.20 ± 0.06	73730
AC	17	10	98.96 ± 0.05	44744
AC	17	15	99.36 ± 0.05	29418
AC	17	20	99.53 ± 0.03	59455
AC	17	25	99.66 ± 0.03	44138
AC	17	30	99.66 ± 0.02	73399
AC	17	35	99.64 ± 0.02	73749
AC	17	40	99.71 ± 0.02	74446
AC	17	45	99.70 ± 0.01	201210
AC	19	20	99.48 ± 0.04	29395
AC	19	30	99.69 ± 0.03	29496
AC	19	45	99.65 ± 0.02	73633
AC	22	45	99.67 ± 0.02	73762
AC	25	20	98.64 ± 0.07	29522
AC	25	30	99.05 ± 0.06	29512
AC	25	45	99.37 ± 0.07	14819
AC	29	20	97.35 ± 0.10	29460
AC	29	30	98.34 ± 0.08	29320
AC	29	45	98.93 ± 0.06	29743
AC (un-irrad.)	20	6 ~ 20	> 99.9	N/A

8.4.2 In-pixel efficiency

Detail of detection efficiency degradation can be investigated by checking the in-pixel efficiency map as introduced in Section 5.4. The results are shown in Figure 8.14 and 8.15.

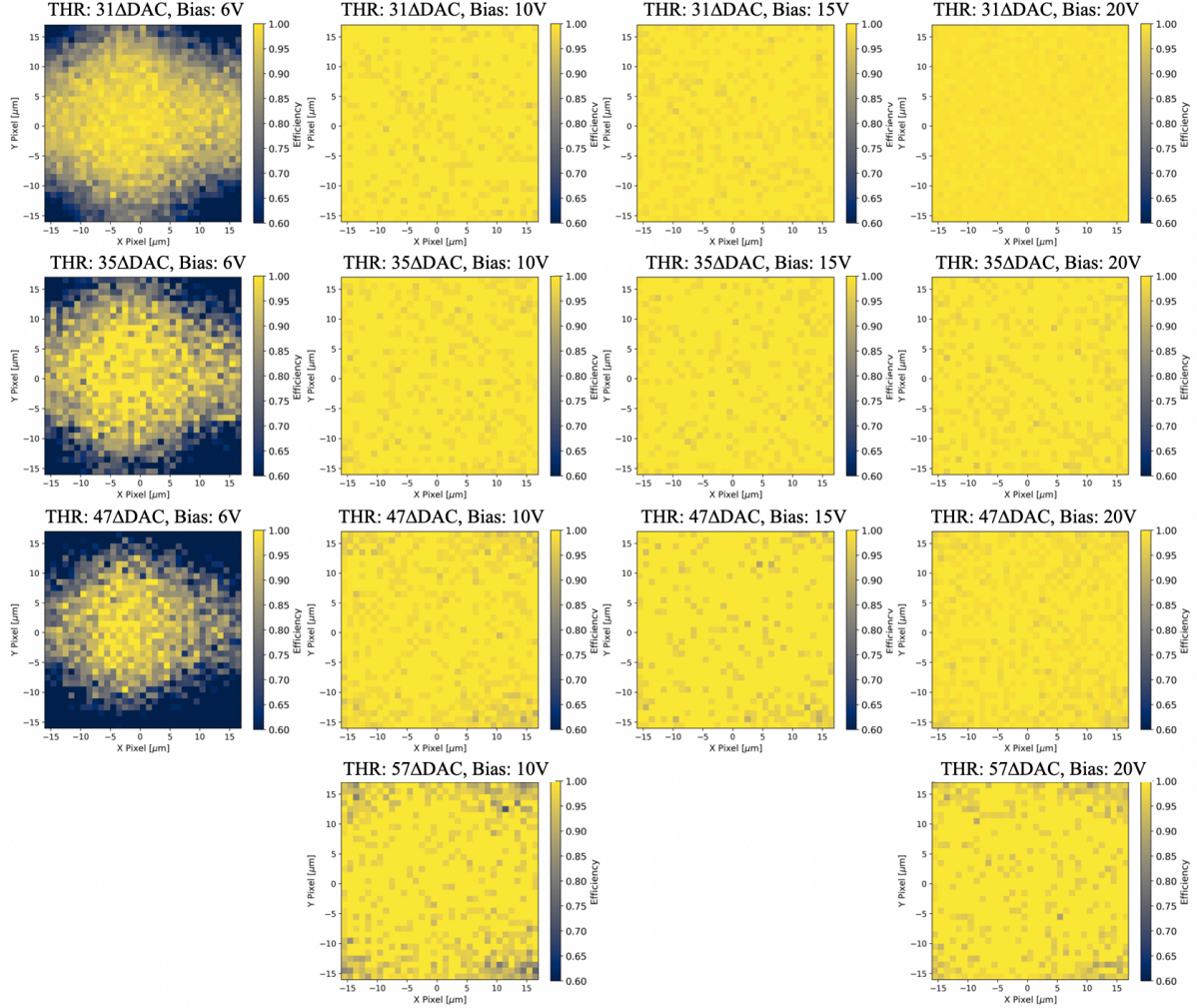


Figure 8.14: The in-pixel efficiency maps depending on thresholds and bias voltages measured on DC front-end. The low efficiency is observed at the corner area of the pixel under low bias voltage, which is recovered with higher bias voltage.

The detection efficiency degradation at low bias voltage is seen to come from the corner area of the pixel where the depletion area can hardly stretch into. The large in-efficient area shown in the DC front-end at low bias voltage indicates an obvious incomplete depletion. Besides, the charge from the corner area of the pixel has longer drifting path, resulting in higher probability of being trapped by a lattice defect. Such in-efficient corner can be recovered with higher bias voltage, which enlarges the depletion area and strengthens the charge drifting. However, it is seen that with high detection threshold, the in-efficient corners still exist.

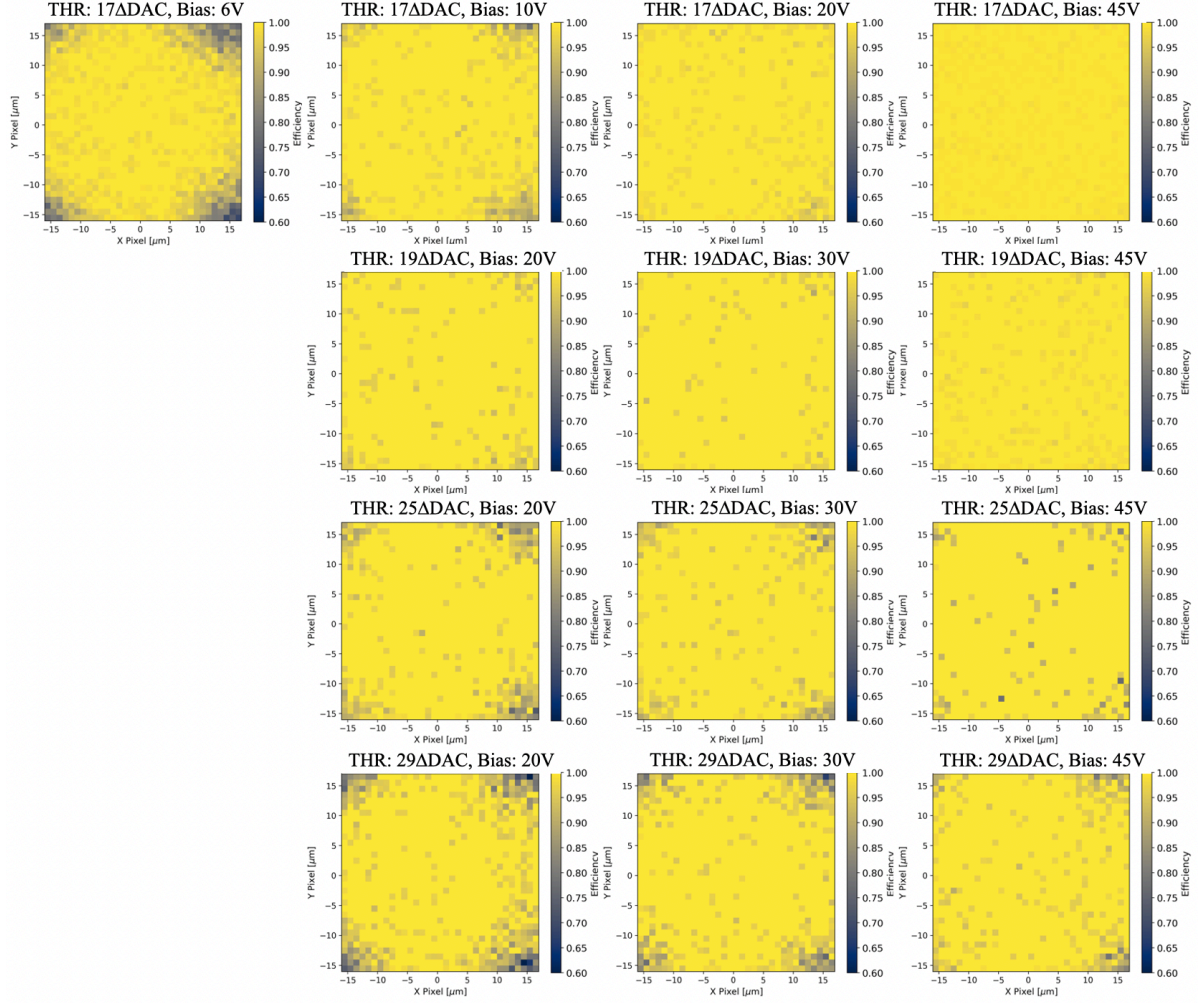


Figure 8.15: The in-pixel efficiency maps depending on thresholds and bias voltages measured on AC front-end. The low efficiency is observed at the corner area of the pixel under low bias voltage, which is recovered with higher bias voltage.

8.4.3 Spatial resolution

The simulation described in Section 5.3 is performed for this test beam setup, resulting in a tracking resolution of $\sigma_{\text{tracking}} = 3.7 \mu\text{m}$ with an uncertainty of $0.003 \mu\text{m}$. The simulated DUT residual histograms are shown in Figure 8.16. Similar to the test beam before irradiation, data/MC ratios of the standard deviation of residual between track positions and cluster positions on tracking layers are calculated for each data taking run. One of the results is shown in Figure 8.17. Since the TJ-Monopix2 is rotated for 90° in this test beam, the x coordinate represents row direction and y coordinate represents column direction on TJ-Monopix2. Compared with the data/MC ratios at the test beam before irradiation shown in Figure 5.13, tracking resolution is more underestimated and asymmetry between x and y direction appears, indicating a worse alignment tuning. Using this simulation, a conservative estimation of spatial resolutions for TJ-Monopix2

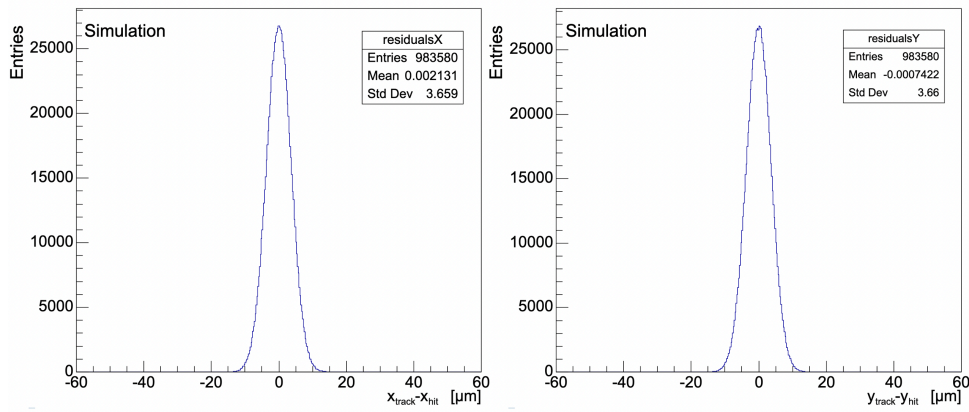


Figure 8.16: Simulated DUT residual histograms of x direction (left) and y direction (right).

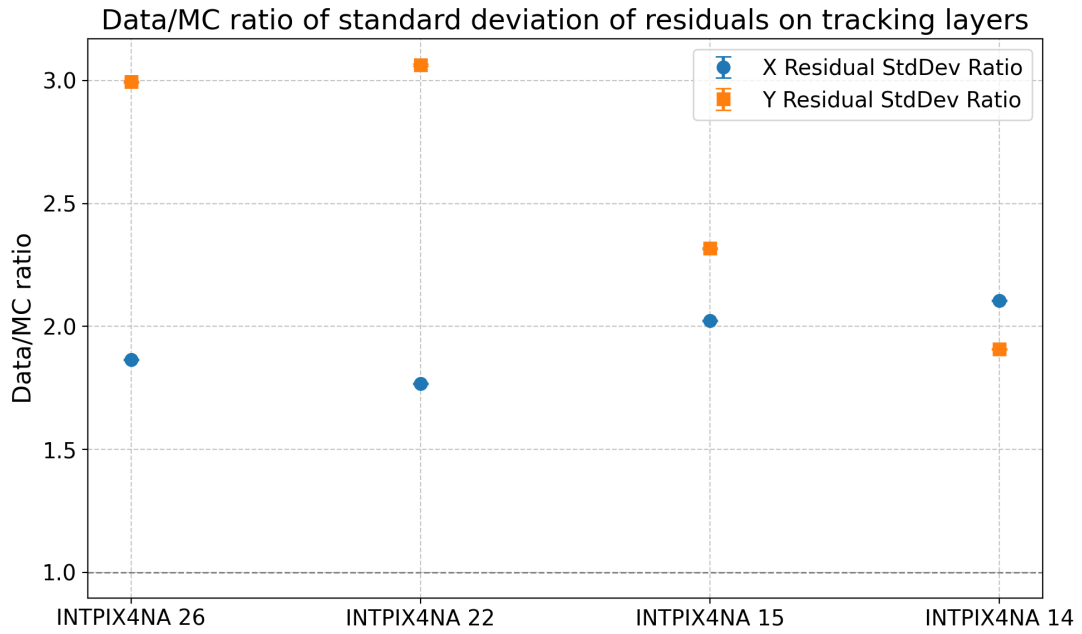


Figure 8.17: Data/MC ratios of residual between track positions and cluster positions on tracking layers. From the upstream to downstream, the order INTPIX4NA sensors is 26, 22, 15 and 14. This result is from the data taking run for AC front-end, threshold of 17 ΔDAC and 45 V bias voltage.

is performed.

After irradiation, the charge sharing becomes greatly suppressed and the cluster size is dominated by 1 since charge drifting is worsened due to radiation damage as shown in Figure 8.18. This makes the DUT residual histograms appear a shape of smeared stage function instead of gaussian distribution as shown in the example of Figure 8.19. Similar to Section 5.4, the standard deviation is derived with a cut range of $[-60 \mu\text{m}, +60 \mu\text{m}]$ and tracking resolution is subtracted. The results of all configurations and bias voltages

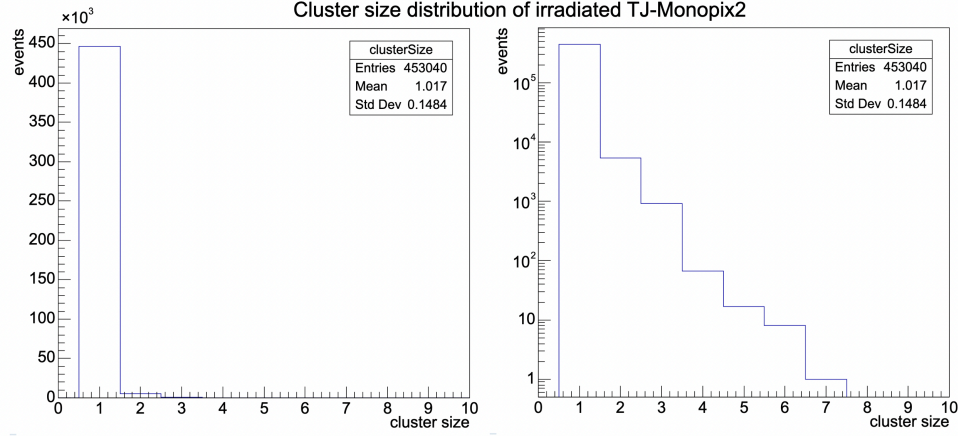


Figure 8.18: Cluster size distribution of irradiated TJ-Monopix2 (left) and its view with logarithmic y axis (right), where 1-pixel clusters are dominant. This data is taken from DC front-end with threshold of 31 Δ DAC and bias voltage of 20 V.

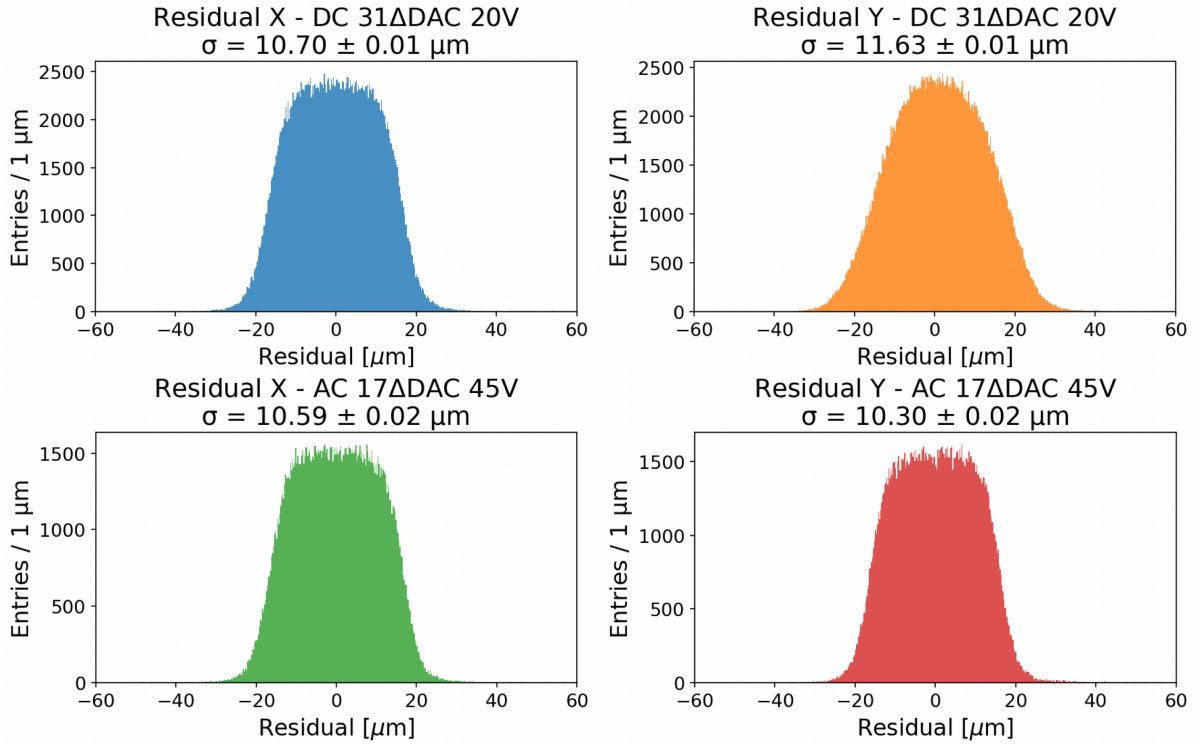


Figure 8.19: Histograms of DUT residuals. The distributions behave as smeared stage functions.

are shown in Figure 8.20. Even though obvious systematic asymmetry due to imperfect alignment tuning is seen between x and y direction, which is more severe in DC front-end, a conservative evaluation can still be made by averaging the result for each front-end:

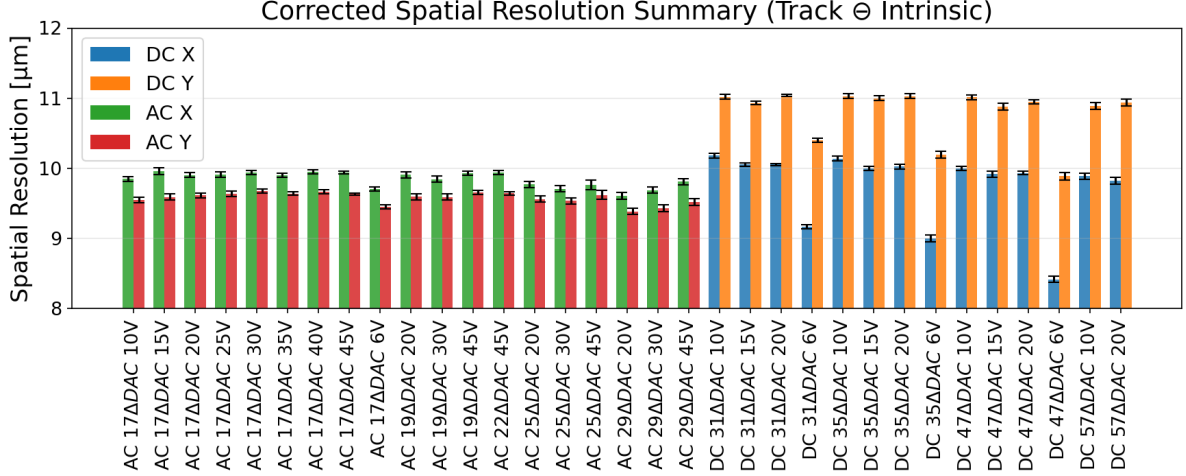


Figure 8.20: Measured spatial resolutions of all configurations and bias voltages. Obvious asymmetry between x and y direction is seen, which is resulted from imperfect alignment tuning.

$$\sigma_{\text{TJ-Monopix2(DC)}, x} = 9.877 \pm 0.008 \mu\text{m}. \quad (8.6)$$

$$\sigma_{\text{TJ-Monopix2(DC)}, y} = 10.896 \pm 0.008 \mu\text{m}. \quad (8.7)$$

$$\sigma_{\text{TJ-Monopix2(AC)}, x} = 9.875 \pm 0.008 \mu\text{m}. \quad (8.8)$$

$$\sigma_{\text{TJ-Monopix2(AC)}, y} = 9.599 \pm 0.008 \mu\text{m}. \quad (8.9)$$

Similar to the measurement before irradiation reported in Section 5.4, imperfect alignment tuning results in underestimation of tracking resolution and overestimation of DUT residuals. The actual spatial resolutions of electron-irradiated TJ-Monopix2 is smaller than the measured value. A conservative result derived from the residual resolutions confirms that the spatial resolutions are still better than $12 \mu\text{m}$, meeting the upgrade requirement introduced in Section 3.1.

8.5 Comparison with proton-irradiated sample

Another test beam is performed in DESY II Test Beam facility using the EUDET telescope and EUDAQ system introduced in Section 5.1, with injected particle of 4.2 GeV electron. The photo of test beam setup is shown in Figure 8.21.

A temperature controller using Peltier material developed by HEPHY shown in Figure 8.21 is used to investigate the impact of temperature to detection efficiency and spatial resolution, on which the TJ-Monopix2 can be mounted and a hole is opened to reduce multiple scattering. The copper structure for heat transfer touches the PCB around TJ-Monopix2 sensor matrix tight and the TJ-Monopix2 temperature is monitored by a resistor temperature monitor near the sensor matrix. A feedback control determining

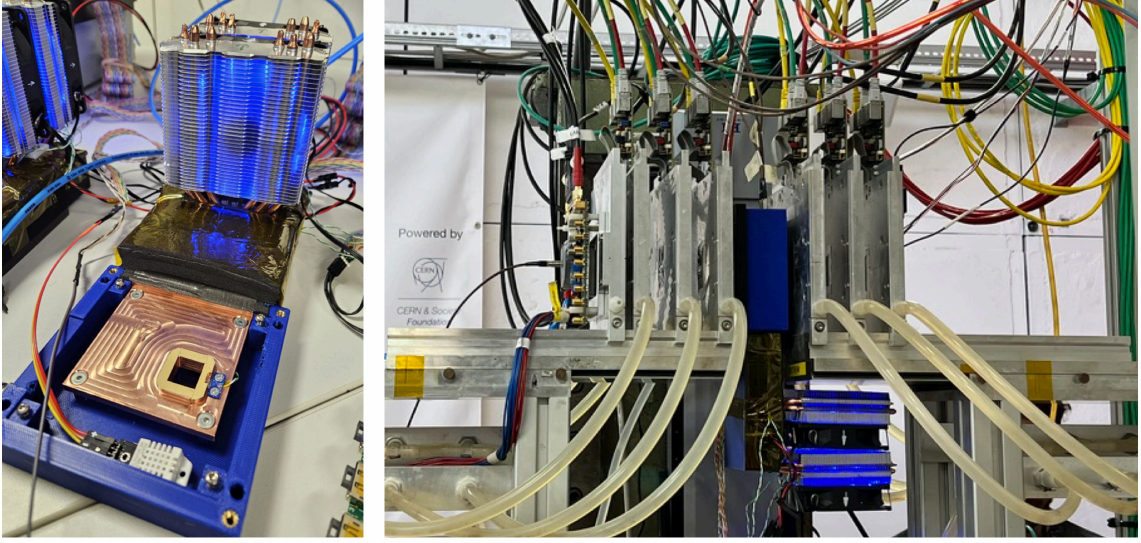


Figure 8.21: Photos of temperature controller (left) and the test beam setup (right).

the current direction and amplitude in the Peltier material stabilizes the TJ-Monopix2 temperature around the set value.

In total four irradiated TJ-Monopix2 samples participated in this test beam as shown in Table 8.4. The detailed analysis is still on-going within VTX collaboration. Therefore, only qualitative discussions of preliminary observations is given in this section.

Table 8.4: Irradiated TJ-Monopix2 samples and their NIEL flux.

Serial Number	Irradiation Type	NIEL flux
W8R4	24 MeV Proton	$1 \times 10^{14} \text{ n}_{\text{eq}}/\text{cm}^2$
W2R17 (AC front-end broken)	24 MeV Proton	$2 \times 10^{14} \text{ n}_{\text{eq}}/\text{cm}^2$
W8R6	24 MeV Proton	$5 \times 10^{14} \text{ n}_{\text{eq}}/\text{cm}^2$
W2R5 (irradiated in this work)	90 MeV Electron	$5.57 \times 10^{14} \text{ n}_{\text{eq}}/\text{cm}^2$

8.5.1 Detection efficiency

A qualitative observation from the detection efficiency study in this test beam campaign is that only slight degradation is seen on W8R4 and W2R17, whose detection efficiency remains more than 99% even with low bias voltages and high detection thresholds. Electron-irradiated sample W2R5 with NIEL flux of $5.57 \times 10^{14} \text{ n}_{\text{eq}}/\text{cm}^2$ shows larger detection efficiency degradation, which is reported in Section 8.4. Compared with W2R5, the proton-irradiated sample W8R6 with NIEL flux of around $5 \times 10^{14} \text{ n}_{\text{eq}}/\text{cm}^2$ shows a detection efficiency lower for around 1% under the same bias voltage and detection threshold situation. This phenomena that electron irradiation causes milder damage than proton irradiation of the similar NIEL flux is also seen in the measurement of leakage current, which will be reported in Section 8.5.2.

Since higher sensitivities of threshold and noise to temperature change is observed after irradiation as reported in Section 7.2, the detection efficiency depending on temperature is also investigated. For electron-irradiated W2R5, detection efficiency is observed to degrade with increasing temperature. From 25 °C to around 45 (50) °C, the detection efficiency drops for more than 0.5 (1.0)% under the maximum bias voltages.

8.5.2 Leakage current

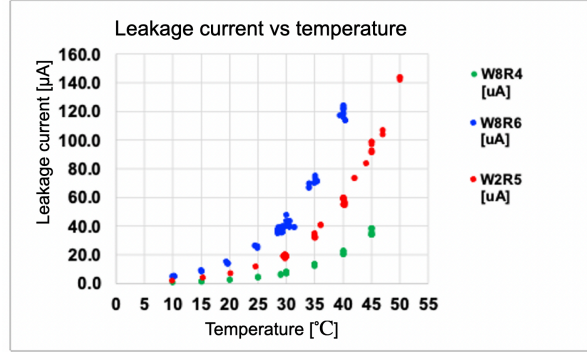


Figure 8.22: Leakage current depending on temperature at max bias voltage measured on different irradiated samples. Electron-irradiated sample (W2R5) shows lower leakage current compared with the proton-irradiated sample (W8R4) which is irradiated to a similar accumulated NIEL flux.

The effect of milder damage of electron-irradiation compared with proton-irradiation can also be seen from the leakage current as shown in Figure 8.22, measured on the AC front-end. As described in Section 2.1.2, the leakage current in sensor bulk is known to increase proportionally with the NIEL flux:

$$I_{\text{leak}} = \alpha \Phi_{\text{eq}} V. \quad (8.10)$$

AC front-end contains 64 columns and 512 rows. Assuming that the epitaxial layer with 25 μm thickness is fully depleted, the total volume of depletion region in AC front-end is:

$$V = 64 \times 512 \times (33.4 \times 33.4 \times 10^{-8}) \times 25 \times 10^{-4} \text{ cm}^3 \simeq 8.92 \times 10^{-4} \text{ cm}^3. \quad (8.11)$$

For electron-irradiated TJ-Monopix2 at NIEL flux of $5.57 \times 10^{14} \text{ n}_{\text{eq}}/\text{cm}^2$ the leakage current measured at 20 °C is 7.2 μA while for proton-irradiated TJ-Monopix2 at NIEL flux of $5 \times 10^{14} \text{ n}_{\text{eq}}/\text{cm}^2$ the leakage current measured at 20 °C is 15.3 μA . The damage constants for electron-irradiated sample and proton-irradiated sample are:

$$\alpha_{e^-} \simeq 1.44 \times 10^{-17} \text{ A/cm.} \quad (8.12)$$

$$\alpha_p \simeq 3.43 \times 10^{-17} \text{ A/cm.} \quad (8.13)$$

at an ambient temperature of 20 °C. Smaller damage constant of 90 MeV electrons suggests a milder bulk damage compared with protons. The similar difference in damage constant between electron irradiation and hadron irradiation is also reported in the radiation test of Silicon Vertex Tracker at the BaBar experiment, where the damage constant of 900 MeV electrons is 2.7×10^{-17} A/cm, being around 1/3 of the damage constant of 1 MeV neutrons, which is 8.0×10^{-17} A/cm [39]. In the radiation test of SVD at the Belle II experiment, damage constant of the sensor irradiated by the 90 MeV electron beam is 5.1×10^{-17} A/cm, being around 0.65 times of the result of 1 MeV neutrons [56]. It needs to be noted that the correct measurement of damage constant is very difficult, requiring careful examination. Therefore, the damage constant results among different research activities could vary a lot. However, the comparison between electron-irradiation and neutron-irradiation is still valid and shows reasonable agreement. In the actual operation at the Belle II experiment, the actual radiation is caused by a combination of neutrons and electrons. In a specific NIEL flux level, the expected actual damage is in an intermediate level between proton irradiation and electron irradiation.

Chapter 9

Conclusion and outlook

In this chapter, the conclusion of this work will be given in Section 9.1. The side products from development work will be introduced in Section 9.2. Finally, an outlook will be presented in Section 9.3.

9.1 Conclusion

A new silicon sensor technology named DMAPS is chosen to be used in the vertex detector upgrade, VTX, of the Belle II experiment, where the innermost vertex detector is exposed in a high-radiation environment. The performance characterization of DMAPS prototype TJ-Monopix2 after irradiation and detailed understanding of the irradiation effect on the performance were crucial to ensure that the performance of VTX still meets the requirement of detector upgrade after long-term operation. Specifically, the sensor is required to keep a detection efficiency of more than 99% and the spatial resolution of better than $15\text{ }\mu\text{m}$, after irradiated to an accumulated NIEL flux of $5 \times 10^{14}\text{ }n_{\text{eq}}\text{cm}^{-2}$.

In this work, a test bench for TJ-Monopix2 is set up in KEK and an electron-irradiated TJ-Monopix2 sample with an accumulated NIEL flux of $5.57 \times 10^{14}\text{ }n_{\text{eq}}\text{cm}^{-2}$ is produced using the 90 MeV electron beam at the RARiS facility, Tohoku University. Characterization of TJ-Monopix2 in the laboratory and test beam campaigns at DESY and KEK before and after irradiation are performed in order to investigate the impact of radiation damage on sensor performance, which are summarized in Table 9.1. A good performance of more than 99% detection efficiency and spatial resolutions meeting the upgrade requirement are confirmed on non-irradiated TJ-Monopix2 prototype. Even though performance degradations after irradiation such as lower charge collection efficiency, lower ToT response curve, increased noise level and decrease in detection efficiency at low bias voltage are observed, a performance meeting the upgrade requirement can still be achieved by applying sufficiently high bias voltages (DC front-end: more than 10 V, AC front-end: more than 15 V) and using configurations with sufficiently low detection thresholds (DC front-end: lower than $35\text{ }\Delta\text{DAC}$, AC front-end: lower than $20\text{ }\Delta\text{DAC}$),

Table 9.1: Summary of measurements on non-irradiated TJ-Monopix2 prototype and electron-irradiated TJ-Monopix2 prototype with accumulated NIEL flux of $5.57 \times 10^{14} n_{\text{eq}}\text{cm}^{-2}$.

Measurement	non-irradiated	Electron-irradiated
Charge Conversion Factor (Charge collection efficiency)	DC: $9.57 \pm 0.05 e^-/\Delta\text{DAC}$ AC: $18.26 \pm 0.07 e^-/\Delta\text{DAC}$	DC: $12 \sim 15 e^-/\Delta\text{DAC}$ AC: $22 \sim 33 e^-/\Delta\text{DAC}$
Threshold Change (0°C to 45°C)	DC: 2 ΔDAC AC: 4 ΔDAC	DC: 20 $\sim$ 30 ΔDAC AC: 10 $\sim$ 20 ΔDAC
Threshold Deviation Change (0°C to 45°C)	DC: $\sim 1 \Delta\text{DAC}$ AC: $\sim 1 \Delta\text{DAC}$	DC: 2 $\sim$ 3 ΔDAC AC: $< 1.5 \Delta\text{DAC}$
Noise Level at 25°C	DC: $\sim 0.8 \Delta\text{DAC}$ AC: $\sim 0.4 \Delta\text{DAC}$	DC: $\sim 2.8 \Delta\text{DAC}$ AC: $\sim 1.3 \Delta\text{DAC}$
Noise Change (0°C to 45°C)	DC: $< 0.1 \Delta\text{DAC}$ AC: $< 0.1 \Delta\text{DAC}$	DC: $\sim 2.5 \Delta\text{DAC}$ AC: $\sim 1.5 \Delta\text{DAC}$
Clock Signal Propagation Delay	T2 = 63.5 ns T3 = 45.5 ns $T_{\text{IDEL}=37} - T_{\text{BCID}} = -0.3 \text{ ns}$	T2 = 69.3 ns T3 = 49.1 ns $T_{\text{IDEL}=44} - T_{\text{BCID}} = -1.0 \text{ ns}$
Max. Threshold Change due to Clock Signal Crosstalk	N/A	DC: $\sim 15 \text{ DAC}$ AC: $\sim 4 \text{ DAC}$
Leakage Current	10 $\sim$ 100 pA	DC: $\sim 18 \mu\text{A}$ @ 20V AC: $\sim 22 \mu\text{A}$ @ 45V
ToT Response Curve	High	Low
Detection Efficiency	$> 99.9\%$	DC: 70% $\sim$ $> 99\%$ AC: 97% $\sim$ $> 99\%$
Spatial Resolution	better than 12 μm	better than 12 μm

which can restore the detection efficiency back to more than 99%. The spatial resolutions also remain within the requirement at a conservative evaluation after irradiation. Additionally, detection performance depending on the temperatures is investigated in a test beam campaign at DESY since increased sensitivities of threshold and noise are observed with irradiated TJ-Monopix2 prototype. The very preliminary observation confirms the degradation of detection efficiency with high temperature, where the detection efficiency can drop by 0.5 (1.0)% from 25 °C to around 45 (50) °C. In the measurement of clock signal propagation delay, slight decrease of around 2 ns is observed after irradiation, which is small enough to be compensated by adjusting the value of IDEL register. Clock signal crosstalk has shown significant impact in the measurement on electron-irradiated TJ-Monopix2, varying the threshold for more than 11 ΔDAC on the DC front-end and more than 3 ΔDAC on the AC front-end. Therefore, in the development of OBELIX sensor, the improvement of clock signal transmission buffers, reducing electronic noise from digital shift, will be an important research topic to suppress such crosstalk effect.

Through the comparison between electron-irradiated sample and proton-irradiated sample, it is observed that radiation damage created by electrons results in a milder performance degradation, even though they are at the similar accumulated NIEL flux of around $5 \times 10^{14} \text{ n}_{\text{eq}}\text{cm}^{-2}$. In practical operation at Belle II experiment, the radiation damage is a result from a mixture of the effects from different particles mainly composed of neutrons and electrons. Therefore, the actual performance degradation is expected to be at an intermediate level between proton-irradiated sample and electron irradiated sample.

9.2 Side products

To achieve the goal of evaluating radiation tolerance for TJ-Monopix2, many development work is done, including simulation module in **Corryvreckan** and SOI telescope synchronization with TJ-Monopix2.

Monte Carlo study is the most proper way to evaluate the impact of tracking system including the telescope and analysis method to the DUT resolution. **MultiScattSimulator** module developed in this thesis is the first attempt to generate toyMC sample within the **Corryvreckan** framework, fully respect the tracking method that is applied in actual data analysis. This module is designed to be compatible with different detector setups and beam conditions, which can be used in other test beam experiments as a fundamental software infrastructure.

The SOI telescope which consists of the INTPIX4NA sensors and the XRPIX5 sensor is a tracking device providing a high spatial resolution on DUT, which can be used in many other test beam experiments. The synchronization strategy designed in this work for TJ-Monopix2 can also be used in the future test of OBELIX sensor for VTX project, which holds similar design with TJ-Monopix2. The implementation of INTPIX4NA into **Corryvreckan** framework is developed for the first time in this work, enabling fast and sophisticated analysis for the SOI telescope data.

9.3 Outlook

The detailed alignment tuning and correction of simulations in test beam analysis are still needed to be done to derive precise results of spatial resolutions. The analysis of test beam data involving proton-irradiated samples is progressing and a precise comparison of detection performance among different irradiated TJ-Monopix2 prototypes will be available. In the clustering of TJ-Monopix2 hits, the positions of pixels are weighted directly using ToT. However, due to the individual differences among pixels, pixel-by-pixel charge calibration using the ToT response curve of each pixel in clustering can be developed to improve the accuracy of cluster position. Combined with these further developments and testing efforts within the VTX collaboration, this study will eventually contribute to the

first and most complete performance evaluation of the DMAPS prototype TJ-Monopix2, especially for irradiated samples.

The OBELIX-1 sensor is approaching. Testing experience and result on TJ-Monopix2 serve as important reference for the upcoming testing activities for OBELIX-1, where the design of DC or AC front-end will be finally determined and suppression of clock signal crosstalk will be studied. A design for massive production, OBELIX-2 is expected to be determined by 2028 and the massive production will begin in 2029, targeting the installation of VTX detector in 2032.

According to the result of this work, VTX detector in future Belle II upgrade is expected to keep an outstanding detection performance after being irradiated in its long-term operation. Its cooling strategy will be researched and developed based on the observation of increased sensitivities of threshold and noise to the temperature after irradiation, and the degraded detection efficiency at high temperature. The performance comparison between DC and AC front-end, where DC shows higher charge collection efficiency but AC shows better depletion and efficiency recovery, provides informative reference for the future development of OBELIX sensor to decide the front-end design.

Currently, the ToyMC generator `MultiScattSimulator` simply calculate the smearing resulted from multiple scattering and sensor spatial resolution and then apply it as a gaussian distribution. However, in reality the smearing resulted from sensor spatial resolution may not totally follow gaussian distribution but smeared stage function for example, depending on the sensor type. Besides, the simulation of particle hit under a complex geometry with rotations is not implemented. A possible future development is implementing the GEANT4 simulation using its C++ interface to achieve an accurate simulation for test beam experiment.

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修士課程の修了は旅の終わりではなく、「路漫漫其修遠」。今後ともよろしくお願いします。

Appendix A

Detail of VTX detector

A.1 OBELIX design

The digitization through a 7-bit Time-Over-Threshold method and the column-drain readout architecture implemented for pairs of columns stay unchanged. However, each column-pair is equipped with individual End-of-Column (EoC) logic for the implementation of trigger function at the Belle II experiment through three entirely new modules, trigger logic unit (TRU), Track trigger transmission (TTT) and transmission unit (TXU) shown in Figure 3.2. Compared with 40 MHz BCID in TJ-Monopix2, in OBELIX-1 BCID frequency is changed to 20 MHz to reduce the power consumption.

The TTT unit is responsible for sending rough but fast hit data from the sensor to the Belle II trigger system, for fast tracking and trigger decision. In this unit, the sensor matrix is divided into eight regions. In each region, OR signal of all pixel discriminator outputs is sent to the TTT unit through the EoC logic, where the LE of the OR signal is detected as the hit signal in the region. Eventually, TTT outputs a single byte signal indicating which regions have hits to the Belle II trigger system. The light data load allows the transmission to be completed within 100 ns on a line parallel to the main data output of the sensor.

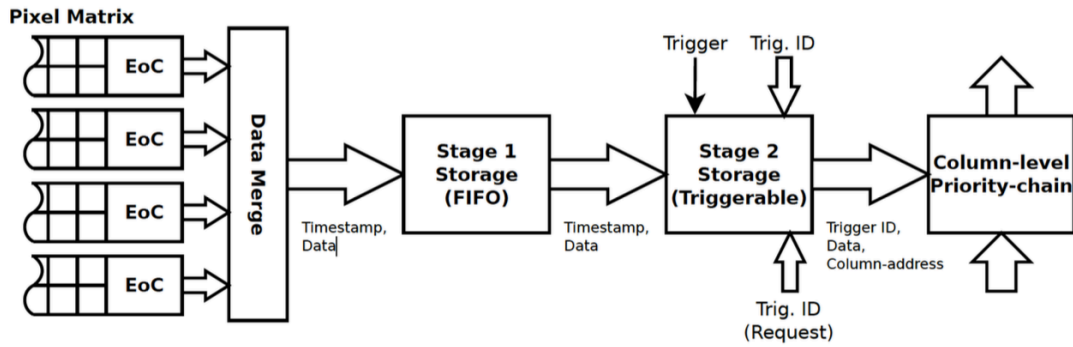


Figure A.1: Schematic illustration of TRU operation principle. [5]

TRU handles the incoming data (with full precision) from the sensor matrix and the association with the Belle II level-1 triggers. The schematic operation flow is shown in Figure A.1. When data is sent to TRU, it passes through two memory stages. The first stage simply holds the data in FIFO until the level-1 trigger arrives, and in the second stage, the BCID of hit data is compared with the trigger time. When matched, the hit data is passed to the trigger transmission unit (TXU). The size of the TRU memories have been optimized to ensure full efficiency at the maximum hit rate of 120 MHz/cm², taking into account the 30 kHz with a latency of 10 μ s.

Specification comparison of OBELIX-1 sensor and TJ-Monopix2 sensor is shown in Table A.1. Pitch size of $33 \times 33 \mu\text{m}^2$ is small enough to reach a spatial resolution below 15 μm . The high rate capability is ensured by the low data load pressure resulted from the in-pixel zero suppression and the fast trigger logic. Monolithic design of the pixel is the key to achieve a low material budget. Full depletion in the sensor bulk is expected to bring high radiation tolerance, and the research on specific performance degradation after accumulation of the expected dose/flux is performed in this work.

Table A.1: OBELIX-1 sensor specifications, compared to the relevant specification of the TJ-Monopix2 sensor. [5]

Specification	OBELIX-1	TJ-Monopix2
Pixel pitch	33 μm	33 μm
Sensitive layer thickness	$\sim 30 \mu\text{m}$	$\sim 30 \mu\text{m}$
Sensor thickness	$< 100 \mu\text{m}$	-
Hit rate capability	$> 120 \text{ MHz/cm}^2$	$> 100 \text{ MHz/cm}^2$
Trigger delay	$\sim 10 \mu\text{s}$	-
Trigger rate	30 kHz	-
Overall integration time	$< 100 \text{ ns}$	-
Time precision	50 ns	25 ns
Total ionizing dose tolerance	100 Mrad	-
NIEL flux tolerance	$5 \times 10^{14} \text{ n}_{\text{eq}}/\text{cm}^2$	$1.5 \times 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$
Sensitive matrix dimensions	around $30 \times 16 \text{ mm}^2$	$19 \times 19 \text{ mm}^2$
Overall sensor dimensions	around $30 \times 19 \text{ mm}^2$	$20 \times 19 \text{ mm}^2$
Powering	through voltage regulators	-

A.2 Layer design

The two innermost layers are iVTX placed at radius of 14.1 and 22.1 mm, respectively, targeting an individual material budget of about 0.2% X_0 of each layer. Such thin layer is possible due to the monolithic design shown in Figure A.2. iVTX layers are made of four consecutive OBELIX sensor blocks diced out of the silicon wafers. The sensitive regions are thinned to 40 μm while the border areas are kept to be a few hundred μm thick for

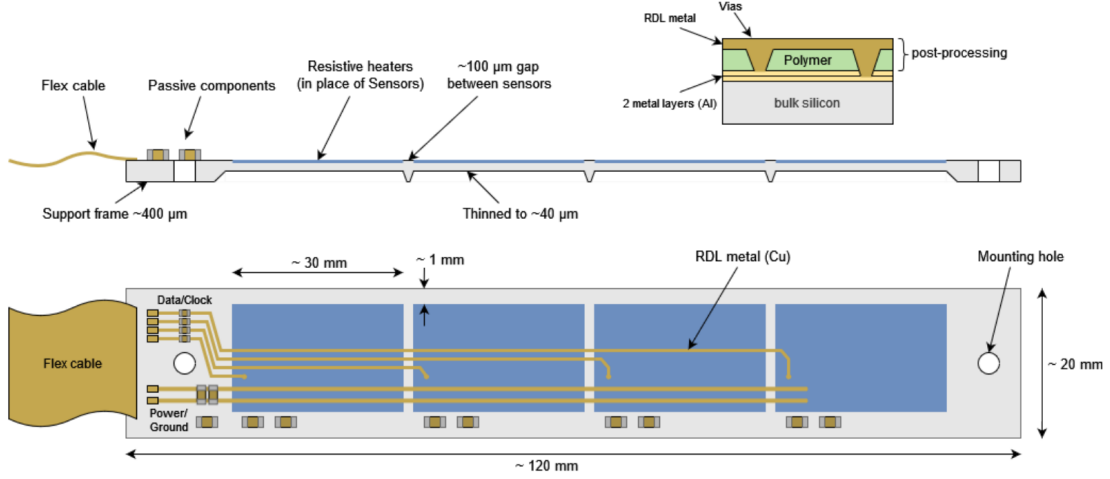


Figure A.2: Side and top view of an iVTX ladder prototype design. As a demonstrator, the sensor areas are replaced with resistive heaters to imitate the power consumption of OBELIX sensors [5].

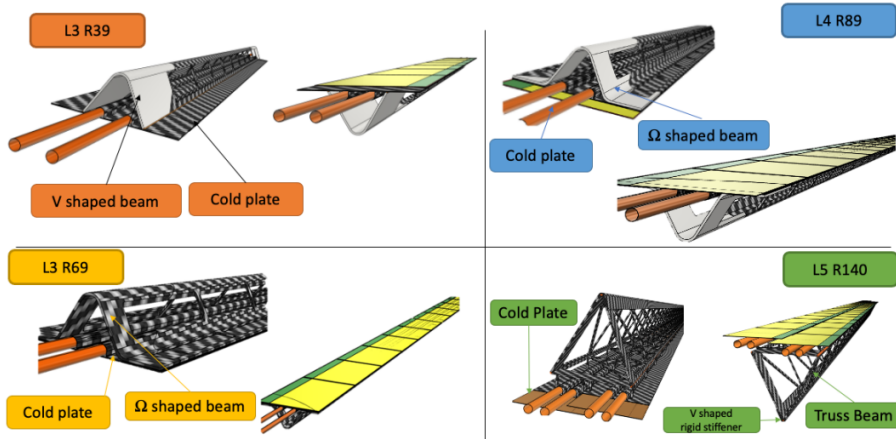


Figure A.3: Schematic view of oVTX ladder design. Yellow area shows the sensitive area while the green part is the periphery. Ω and V shaped support structure solution are now being studied for different mechanical demand [5].

mechanical rigidity. Mounting holes are added via laser-cutting. To interconnect sensors along the ladder, a post-processing step etches additional metal strips on a redistribution layer(RDL) is applied, which also provide a unique connector at the ladder backward end connecting the power and data transmission through a flex cable. At the current stage, the cooling strategy for iVTX is not yet decided but an air cooling scenario is being considered. Depending on the study of power consumption for OBELIX sensor, additional cooling structure may be developed.

The three outer layers of oVTX follows a more traditional design as shown in Figure A.3, placed at radius of 39.1, 89.5 and 140.0 mm. Each layer is made of carbon fiber

2722 support structure, a cold plate including cooling pipes and a row of OBELIX sensors
2723 glued on the cold plate. Flex cables are used to connect each half ladder to the cor-
2724 responding connectors. Depending on the radius, the material budget of oVTX layers
2725 varies from 0.3% to 0.8% X_0 .

Appendix B

Plots of BCID propagation delay measurement after irradiation

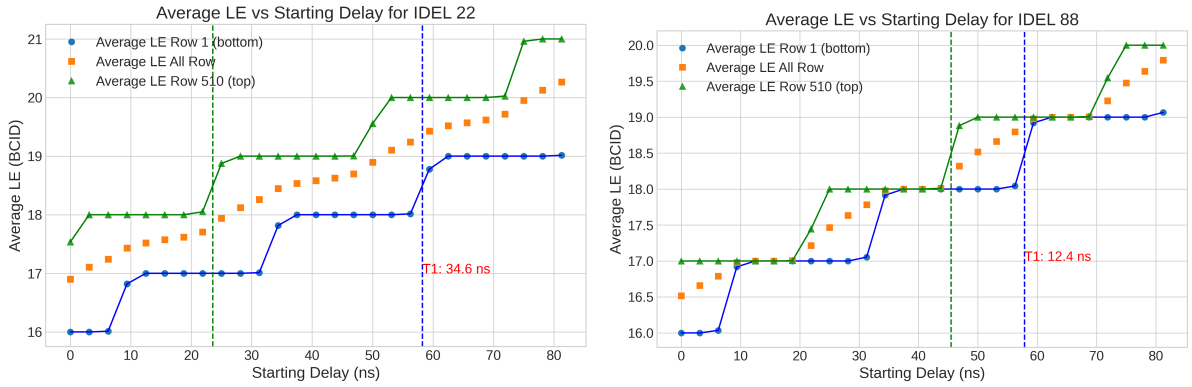


Figure B.1: Examples of T_1 measurement at IDEL values of 22 (left) and 88 (right) for electron-irradiated TJ-Monopix2 prototype.

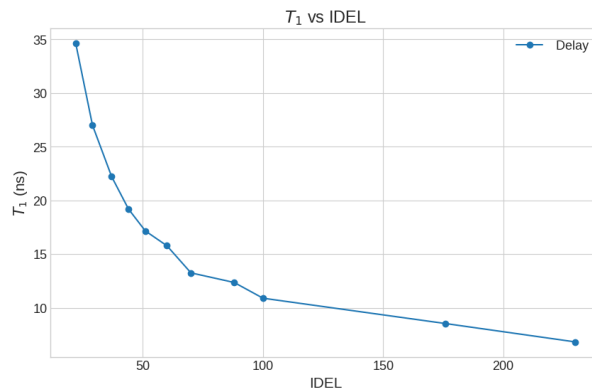


Figure B.2: T_1 result in different IDEL values measured on electron-irradiated TJ-Monopix2 sample.

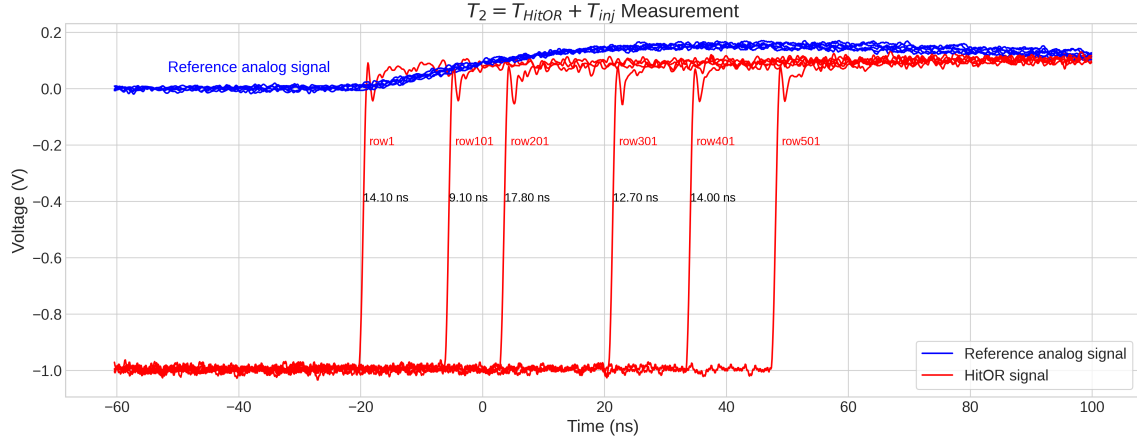


Figure B.3: Measurement of T_2 for electron-irradiated TJ-Monopix2 prototype. Red waveforms are the measured HitOR signals from different rows.

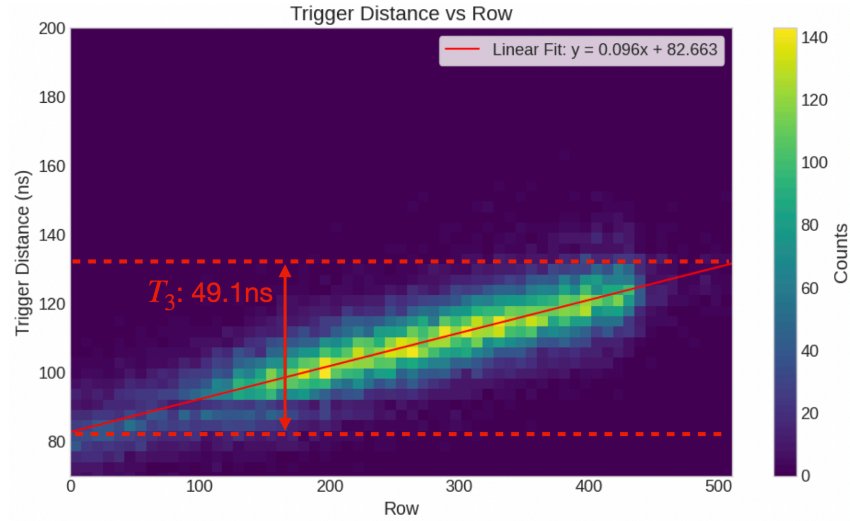


Figure B.4: Trigger distance measurement result of trigger distance depending on row number for electron-irradiated TJ-Monopix2 prototype. The timing of scintillator trigger and HitOR signal is adjusted before input to BDAQ53 board so that row 0 yields a trigger distance of 80 ns.

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