Subpixel mapping and test beam studies with a HV2FEI4v2 CMOS-Sensor-Hybrid Module for the ATLAS inner detector upgrade

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Abstract: The upgrade to the High Luminosity Large Hadron Collider will increase the instantaneous luminosity by more than a factor of 5, thus creating significant challenges to the tracking systems of all experiments. Recent advancement of active pixel detectors designed in CMOS processes provide attractive alternatives to the well-established hybrid design using passive sensors since they allow for smaller pixel sizes and cost effective production.

This article presents studies of a high-voltage CMOS active pixel sensor designed for the ATLAS tracker upgrade. The sensor is glued to the read-out chip of the Insertable B-Layer, forming a capacitively coupled pixel detector. The pixel pitch of the device under test is $33 \times 125 \, \mu m^2$, while the pixels of the read-out chip have a pitch of $50 \times 250 \, \mu m^2$. Three pixels of the CMOS device are connected to one read-out pixel, the information of which of these subpixels is hit is encoded in the amplitude of the output signal (subpixel encoding). Test beam measurements are presented that demonstrate the usability of this subpixel encoding scheme.

Keywords: Electronic detector readout concepts (solid-state); Instrumentation for particle accelerators and storage rings - high energy (linear accelerators, synchrotrons); Particle tracking detectors (Solid-state detectors)

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1 Introduction

The Large Hadron Collider (LHC) is scheduled to be upgraded to the High Luminosity Large Hadron Collider (HL-LHC) from 2023 onwards. After this Phase-II Upgrade, the instantaneous peak luminosity is expected to reach nominal (ultimate) values of $5 \times 10^{34}$ cm$^{-2}$s$^{-1}$ ($7.5 \times 10^{34}$ cm$^{-2}$s$^{-1}$). The challenges resulting from increasing hit rates in the innermost part of the ATLAS detector, expected to reach 300 hits per readout chip every 25 ns, and particle fluence of up to $2 \times 10^{16}$ 1-MeV neutron equivalent particles per cm$^2$ will be met by a full replacement of the current ATLAS Inner Detector (ID) with an all-silicon tracking system, the ATLAS Inner Tracker (ITk) [1–3].

The ITk foresees a pixel detector as its innermost component that will cover an area of approximately 10 m$^2$, corresponding to about ten times that of the pixel detector of the ID. More cost-effective technologies than the hybrid pixel module concept connecting sensor and read-out chip pixel by pixel with bump bonds are therefore attractive.

Industrial high-voltage CMOS processes allow a combination of standard CMOS transistors, which are used to implement internal electronics, and a bias voltage of the sensor of few tens of volts. This creates a depleted zone of a depth of 10 $\mu$m to 100 $\mu$m depending on the CMOS process
and the bulk resistivity. The charge carriers released by ionising particles in the depleted volume are collected by drift, allowing a fast read-out that fulfils the HL-LHC requirements.

CMOS processes are typically applied to wafers larger than those used for passive, high-resistivity bulk sensors. In combination with cost-effective interconnection methods, such as wafer to wafer bonding or gluing techniques, active CMOS pixel sensors are a promising candidate for future applications. In addition, CMOS designs allow to realise smaller pixel sizes than would be possible with devices designed for bump bond interconnection, which is beneficial in a high track density environment.

This report describes studies with the HV2FEI4v2 active pixel sensor [4] which is implemented in the Austria Microsystems (AMS) 180 nm high-voltage CMOS process [5]. This process allows a bias voltage of up to -90 V, resulting in a depth of the depleted region of approximately 15 µm. Studies of operating parameters of the CMOS sensor as well as test beam measurements are presented, that specifically address the subpixel encoding implemented in this prototype. This paper is based on the results and contains sections from ref. [6].

2 The device under study

The device used for the following measurements consists of an HV2FEI4v2 active pixel sensor glued to an FE-I4 readout chip [7, 8], forming a capacitively coupled pixel detector (CCPD) [9]. The HV2FEI4v2 sensor was designed to fit the FE-I4 bump bond footprint, with the bump pads on the HV2FEI4v2 and the FE-I4 chips forming the coupling capacitor which transmits the output signal of the active sensor to the readout chip.

The FE-I4 contains read-out circuitry for 26 880 pixels arranged in 80 columns of 250 µm pitch by 336 rows of 50 µm pitch. Each FE-I4 pixel is composed of an amplification stage followed by a discriminator with an independently adjustable threshold. For each hit passing the discriminator threshold, the time at which the threshold is crossed is recorded along with the 4 bit Time over Threshold (ToT), measured in units of 25 ns. The ToT is defined as the time that the amplifier output signal remains above threshold. The calibration of collected charge into ToT can be adjusted individually for each cell by the feedback current of the amplifier, controlled by a pixel register DAC. Information from all discriminators which detected a hit is kept in the chip for a programmable latency interval after which the information is sent on the output link if a trigger is supplied. Hits from up to 16 consecutive LHC clock cycles (25 ns) are sent upon trigger reception with their respective timing noted by a trigger counter.

The HV2FEI4v2 sensor prototype has a size of approximately 2.2 × 4.4 mm², which is much smaller than the FE-I4. The sensor pixels are arranged in 240 unit cells, each containing six pixels of pitch 33 × 125 µm². Three sensor pixels are connected to one FE-I4 readout chip pixel as shown in figure 1(a). The arrangement of the three subpixels connected to the same FE-I4 pixel in one unit cell is shown in figure 1(b). The standard HV2FEI4v2 pixel cell consists of an amplifier, the corresponding feedback circuit and a discriminator. The working points of the transistors are set by external bias voltages, most importantly the external threshold voltage. Other parameters are controlled by global and pixel registers. The adjustment of the feedback current is controlled by the VNFB DAC. The parameters VNOut1, VNOut2, and VNOut3 adjust the amplitude of the binary output signal of the discriminators of the three subpixels, which we will refer to respectively as subpixel type 1, 2, and 3.
Figure 1. ((a)) Cross-section of CCPD, showing the capacitive coupling between three HV2FEI4v2 subpixel types and one FE-I4 pixel. ((b)) One HV2FEI4v2 unit cell connected to two FE-I4 pixels. The three white (light) sensor pixels of one unit cell are capacitively coupled to the FE-I4 readout chip pixel with the white pad and the green (dark) ones to the FE-I4 pixel with the green pad. ((c)) Arrangement of neighbouring unit cells. The white (light) and green (dark) rectangles represent the subpixels connected to the same FE-I4 pixels, the unit cells are bounded by the black frames. The position of subpixels of types 1, 2, and 3 within the unit cells are also indicated.

3 Parameter studies

3.1 Read-out system and injection-based measurements

Data acquisition and control of both the HV2FEI4v2 and the FE-I4 of the CCPD hybrid under study were carried out with the USBpix system [10]. Operation of FE-I4 chips with USBpix was fully implemented in the course of module tests for the Insertable B-layer (IBL) [11]. While communication between USBpix and FE-I4 relies on the programmable digital electronics of the USBpix main board, a General Purpose Adapter Card (GPAC) connected to the main board provides additional DC and slow input signals needed to control the HV2FEI4v2. Both boards are steered by a software package that permits simultaneous control and read-out of HV2FEI4v2 and FE-I4 as would be required during ATLAS data taking and calibration [12].

Test and calibration of the HV2FEI4v2 are performed using an internal injection mechanism: a well-defined charge is injected directly into the analogue part of all pixels of the HV2FEI4v2 at the same time via an injection circuit on the GPAC. The generated signal is then read out by the FE-I4.

Using this injection mechanism it is possible to measure the threshold of the HV2FEI4v2 pixel discriminators. During a Threshold Scan the charge injected into the HV2FEI4v2 pixels is varied, counting the number of hits in the corresponding FE-I4 pixel. The resulting number of hits as function of the injection voltage is fitted with an error function. The fit determines the injection voltage at the discriminator threshold of the HV2FEI4v2 pixel discriminator, which we will refer to as threshold equivalent voltage. The threshold equivalent voltage is defined as the injection voltage for which the occupancy of the FE-I4 pixel reaches 50%, while the slope of the occupancy turn-on corresponds to the equivalent noise of the HV2FEI4v2 analogue cell.

3.2 HV2FEI4v2 discriminator threshold

The external threshold voltage of the HV2FEI4v2 pixel discriminator is assumed to be the parameter that influences the threshold equivalent voltage the most. Figure 2(a) shows the threshold equivalent voltage...
Figure 2. Threshold equivalent voltage, $Th_{EV}$, of the HV2FEI4v2 as measured with a Threshold Scan for different parameter settings. The error bars show the pixel dispersion.

Voltage as a function of the external threshold voltage from its minimum stable value\(^1\) of 0.89 V up to 1 V. The error bars indicate the spread over all pixels. Both the average of the threshold equivalent voltage and its dispersion increase with increasing external threshold voltage.

In addition, the influence of the feedback parameter VNFB was studied by measuring the threshold equivalent voltage for three VNFB settings. It was observed that VNFB has a stronger influence on the threshold equivalent voltage than the external threshold voltage. For large feedback currents the amplitude of the amplifier output signal is reduced, because part of the signal charge is compensated. This effect is known as ballistic deficit and leads to an increase of the effective discriminator threshold for large feedback currents. Furthermore, the dispersion of the distribution increases with VNFB. The maximum setting of VNFB corresponds to a feedback current per pixel on the order of 50 pA [6]. Variations in transistor parameters between pixels can therefore have a significant impact on the dispersion of the feedback current, which in turn affects the threshold equivalent voltage.

Because the VNOut1/2/3 DACs play an important role in the subpixel mapping, their influence on the threshold equivalent voltage was investigated. Figure 2(b) shows the measurement of the threshold equivalent voltage as function of the VNOut values for all three subpixels. The error bars again indicate the pixel dispersion. The measurement was performed at the minimum stable external threshold voltage of 0.89 V. In the measurement for VNOut1 only subpixels of type 1 were enabled, as for the measurements with VNOut2 and VNOut3 only subpixels of types 2 and 3, respectively. It was observed that the VNOut1/2/3 DACs influence the threshold equivalent voltage. The origin of this effect is still under investigation.

\(^1\)For voltages below 0.89 V no measurement was possible, because for some pixels the threshold was so low that only noise hits were registered.
3.3 Tuning towards subpixel mapping

Since the information which subpixel registered a hit is encoded in the amplitude of its binary output signal, for a successful subpixel decoding, the ToT response of the FE-I4 needs to be adjusted to maximise the separation between signals from different subpixels [13]. In preparation for this fine-tuning, the impact of the VNOut1/2/3 DACs on the ToT was investigated.

Only one subpixel type was enabled at a time and the ToT response to different VNOut settings was measured. The same was repeated for all three subpixel types. Figure 3 shows the ToT response as a function of VNOut1/2/3 DAC values. ToT saturates for VNOut DAC settings above 12.

![Figure 3](image1.png)

**Figure 3.** ToT response as a function of VNOut1/2/3 DACs for the three subpixel types for a given feedback tuning of the FE pixels. The error bars show the standard deviation of the distribution.

Considering the result above, the feedback current of the FE-I4 pixels was adjusted to the sensor output. The feedback currents were tuned to produce a ToT value of 3 for a signal with VNOut1 set to 3 to get the lowest possible ToT response. To get the largest possible separation between the ToT response of the three subpixels, VNOut2 was set to 60 and VNOut3 was set to 5.

With these VNOut1/2/3 settings charges significantly above the discriminator threshold were injected into the HV2FEI4v2 pixels using the charge injection mechanism described above. Figure 4 shows the resulting ToT distributions for the three subpixels. Most of the subpixels can be separated, but there is some overlap between the distributions.

![Figure 4](image2.png)

**Figure 4.** ToT distribution of the HV2FEI4v2 module for the three subpixel types.

4 Test beam measurements

4.1 Set-up

A EUDET-type beam telescope [14] was used to reconstruct the tracks of the particles passing through the assembly under test. Thus, hit information from the assembly (hit position, timing) can be compared to the extrapolated track position at the position of the assembly, allowing the calculation of spatially resolved hit efficiency and the spatial resolution of the HV2FEI4v2.
Figure 5. The DESY II test beam setup. Shown are the CCPD with the FE-I4 reference plane, together with the six planes of the telescope.

The high resolution EUDET-type beam telescope is based on monolithic active pixel sensors. It consists of six planes of Mimosa26 sensors, the positions of which can be adjusted to optimise the tracking resolution. The pixel pitch is 18.4 $\mu$m in both directions, and the single-point resolution of each plane is below 4 $\mu$m. Data acquisition is provided by the EUDAQ framework [15]. Scintillators placed in front of the telescope provide track triggers over an area of $2 \times 1 \text{ cm}^2$, which is much larger than the area of the assembly under test. The coincidence with a planar silicon pixel detector positioned downstream of the assembly under test and read out by an FE-I4 chip allows the definition of a trigger region-of-interest, adapted to the size of the HV2FEI4v2. Operation of HV2FEI4v2 and FE-I4 was realised with the USBpix system described in section 3.1. The existing USBpix software provides full integration with the EUDAQ framework. The integration time of the beam telescope is 115.2 $\mu$s, while the assembly under test integrates for 400 ns. This necessitates using the FE-I4 module used for the trigger region-of-interest also as a timing reference.

Data was taken at test beam line 21 at the DESY II accelerator [16]. This beam line provides 1-6 GeV electrons. For the measurements presented here, a beam energy of 5 GeV was used to achieve a high beam intensity, leading to a trigger rate of approx. 1 kHz.

To take data at the DESY II test beam, the assembly under test, together with the USBPix readout hardware, was mounted on a custom made mechanical holder between the third and fourth planes of the beam telescope. The sample was oriented perpendicular to the beam direction. The planes of the telescope were arranged to optimise track resolution given the level of multiple scattering expected at the particular beam energy. A track resolution of about 10 $\mu$m was reached [6].

The coordinate system for the test beam is right-handed with positive $z$ pointing in the direction of the beam (from right to left in figure 5), $x$ in the horizontal and $y$ in the vertical direction. The sample is mounted such that columns of the FE chip and rows of the HV2FEI4v2 are oriented vertically.

4.2 Track reconstruction

Two software frameworks are used to reconstruct and analyse the test beam data samples. Track finding and reconstruction is carried out with EUTelescope [17]. The telescope tracks and hits
from the assembly under test are stored in ROOT ntuples [18], which are read by the second software framework, TBmonII [6] to run the analysis.

The track reconstruction is done in five steps:

1. Data conversion:
   Raw data from the telescope and device under test DAQ systems are converted into an internal format. In the process, noisy pixels are identified based on their firing frequency and stored in a database for the following steps.

2. Clustering:
   Individual hits are grouped into clusters based on their spatial distance, with an additional cut on the FE-I4 trigger counter of the hits. After having discarded clusters containing pixels that were flagged as noisy, the remaining clusters are stored in a database for further analysis.

3. Hitmaking:
   Cluster coordinates are derived from all the pixels contained within the cluster. A centre-of-gravity algorithm is used to determine the cluster central position. Correlations between hit positions are used to calculate a rough pre-alignment for the planes.

4. Alignment:
   Pre-aligned hits are used for fitting of preliminary tracks, which then serve as input for alignment in MillipedeII [19]. The resulting alignment constants are stored in a database.

5. Track fitting:
   Tracks are fitted to the aligned hits using a Deterministic Annealing Filter Fitter [20], which takes into account multiple scattering. Tracks are required to have hits attached to them on at least five out of the six telescope planes.

4.3 Analysis

Additional cuts are applied to the ensemble of reconstructed tracks to select only those tracks that are meaningful for the analysis of the device under test.

- Tracks are required to have a hit attached to them in the reference plane in order to select tracks that pass through the device under test during its integration time of 400 ns. In the analysis framework, a hit is matched to a track if the distance between the hit coordinate and the extrapolated track position is less than the pixel pitch of the respective sensor plus 10 µm in either direction.

- Highest track reconstruction quality is ensured by cutting on $\chi^2$/ndof $\leq$ 25 for all reconstructed tracks. This cut rejects about 10% of all tracks due to large multiple scattering angles.

- Tracks that pass through pixels at the edge of the device under test sensor, defined as pixels in the outermost column or row of the sensor, are only regarded in special analyses, but are ignored for general analysis. This is done to suppress possible effects of the electric field at the sensor edge.
• Pixels with a hit occupancy above $5 \times 10^{-4}$ hits per trigger are defined as noisy, while those that show no hits at all in a significantly long run are defined as defect. Tracks passing through such pixels are rejected, since the measured total charge of a cluster containing such pixels could be wrong.

Tracks passing these additional cuts are referred to as good tracks and are used for further analysis.

5 Subpixel decoding

To achieve the maximum resolution possible with the HV2FEI4v2, hits in the three subpixels have to be distinguished from each other. To study ways to identify the hit subpixel, test beam measurements were performed with only one subpixel type enabled at a time. The optimised settings for VNOut1/2/3 and the feedback current of the FE-I4 pixels found in section 3.3 were used during these measurements.

The most straightforward separation of the three subpixel types uses only the ToT values measured by FE-I4. Since the overlap between the ToT distributions of the subpixel types (see figure 4) prevents an unambiguous distinction, additional variables are studied to obtain larger separation power. Figure 6 shows the FE-I4 trigger counter distributions of the three subpixel types. The peaks of the distributions of the three subpixel types differ by two bins from each other. This behaviour can be attributed to a combination of the time constant of the capacitive coupling and time walk in the FE-I4 amplifiers.

![Figure 6](image)

**Figure 6.** Distributions of the FE-I4 trigger counter from three separate test beam measurements with only one enabled subpixel type at a time.

For the analysis of the test beam measurements the additional information from the trigger counter is used together with the ToT information to define a two-dimensional likelihood function for each subpixel. Figure 7 shows the normalised likelihood distributions for the subpixel types. These functions were measured in dedicated runs with only one subpixel type active at a time. Since the tuning of both HV2FEI4v2 and FE-I4 read-out chip is not changed, they are used in subsequent measurements with all subpixels enabled.
Figure 7. Distributions of FE-I4 ToT and trigger counter C from dedicated test beam measurements with only one subpixel type active at a time. These distributions serve as reference templates for the likelihood.

6 Resolution studies

Data from test beam measurements with one subpixel type enabled are used to study spatial resolution. Due to the layout and arrangement of the HV2FEI4v2 unit cells (see figure 1(c)) the distance between neighbouring active subpixels is large in three of the four directions. Therefore, only clusters with one hit pixel are analysed.

The expected resolution is $37.5 \, \mu m$ in $x$- and $13.8 \, \mu m$ in $y$-direction, given by the quadratic sum of the geometrical resolution and the measured telescope pointing resolution of approximately $10 \, \mu m$ (see section 4.1). The standard deviations of the measured residual distributions are $(35.6 \pm 0.1) \, \mu m$ in $x$-direction and $(15.65 \pm 0.06) \, \mu m$ in $y$-direction. The stated uncertainties are purely statistical. The size of the systematic uncertainties was not estimated but is partially reflected by the difference between expected and measured values. One source of systematic uncertainties is the fact that neighbouring pixels in $y$-direction were switched off during the measurement, which results in a broader distribution of the residuals. The smaller value for the $x$-direction can be attributed to charge sharing not being considered (single-hit clusters), which reduces the effective size of the pixel in that direction.

Test beam measurements were carried out with all subpixel types enabled and at a sensor bias voltage of $-40 \, V$. Residual distributions for single-hit clusters are studied using the likelihood
method for subpixel decoding, as described in section 5. The standard deviations of the residuals are measured to be \((40.85 \pm 0.05) \mu\text{m}\) in \(x\)- and \((15.25 \pm 0.02) \mu\text{m}\) in \(y\)-direction. The value in \(x\)-direction is larger than that obtained with only one subpixel enabled, an effect expected from a wrong assignment of the subpixel type. Subpixels being mapped to the wrong position cause tails on both sides of the \(x\)-residual distributions. The number of mismatched hits was estimated from the tails of the \(x\)-residual distributions to be approximately 5%.

7 Hit efficiency studies

The detection efficiency of the HV2FEI4v2 is studied in test beam measurements with all subpixel types enabled. It is defined as the fraction of good tracks matched to hits on the HV2FEI4v2 within a matching radius of pixel pitch plus 10 \(\mu\text{m}\) around the extrapolated track position, divided by the total number of good tracks passing through the device under test. Data was taken at room temperature with sensor bias voltages of -30 V to -80 V, with most results based on measurements at -60 V. The errors induced by a subpixel mismatch rate of approx. 5% (see section 6) propagate to the hit efficiency. Hence, the relative uncertainty on the hit efficiency is dominated by the mismatch rate.

The mean hit efficiencies and the standard deviation measured at the minimum stable external threshold voltage of 0.89 V are presented in table 1. The mean hit efficiency of subpixel type 2 and 3 is approximately 80%, with maximum pixel efficiency exceeding 95%. The hit efficiency distribution of subpixel type 1 is very broad and the mean hit efficiency is lower than for the other subpixel types, which lowers the average hit efficiency across the whole sensor. This effect is attributed to two separate issues. First, the hit efficiency of subpixel type 1 is measured to be intrinsically lower than for the others. Second, the low ToT response of subpixel type 1 together with the high HV2FEI4v2 discriminator threshold further reduces the efficiency.

| Module average Efficiency | Subpixel 1 Efficiency | Subpixel 2 Efficiency | Subpixel 3 Efficiency |
|---------------------------|-----------------------|-----------------------|-----------------------|
| 72%                       | 55%                   | 81%                   | 80%                   |
| 21%                       | 28%                   | 9%                    | 9%                    |

The average in-pixel efficiency plotted separately for the six pixels of one unit cell is shown in figure 8. To increase statistics, pixel hits and tracks from all unit cells are projected into one cell, taking the cell orientation into account. The hit efficiency in the centre of the subpixel reaches values in excess of 90% for subpixel types 2 and 3, decreasing towards the edges of the subpixel due to charge sharing. This effect, together with the low efficiency of subpixel type 1, creates the asymmetry of the efficiency at the long edges of subpixel types 2 and 3 (see also figure 1(c)).

The hit efficiency as a function of the external threshold voltage is shown in figure 9(a) for external threshold voltages between 0.89 V and 0.95 V. It decreases with increasing external threshold voltage determined by the difference of the external threshold voltage to the baseline voltage \([21]\), the latter being set to 0.8 V for all measurements. This has to be compared with a signal voltage of approximately 100 mV measured for a Fe55 line \([4]\) which generates 1660 e\(^{-}\) of charge in silicon, while the most probable charge deposited by a MIP-like particle in 10 \(\mu\text{m}\) of silicon is approximately 1000 e\(^{-}\).
Figure 8. In-pixel hit efficiency maps for the 6 different subpixel geometries. All subpixel types were enabled. The external threshold voltage is 0.89 V and the sensor bias voltage -60 V. The colour scale ranges from 0 to 1.

old voltage, as expected from the corresponding increase in HV2FEI4v2 discriminator threshold discussed in section 3.2.

Figure 9(b) shows the hit efficiency as a function of the sensor bias voltage for bias voltages between -30 V and -80 V. Again, the large standard deviation of subpixel type 1 can be seen. No significant increase in the mean hit efficiency for a decreasing sensor bias voltage is observed.
However, the hit efficiency distributions at -60 V (see figure 10(a)) and -80 V (see figure 10(b)) exhibit a shift of the peak position of the distribution. This indicates an increase of the efficiency with the sensor bias voltage as expected from faster charge collection due to an increased drift field.

**Figure 9.** Hit efficiency as a function of the external threshold voltage at a sensor bias voltage of -60 V ((a)) and the sensor bias voltage for an external threshold voltage of 0.89 V ((b)). All subpixel types are enabled. The error bar shows the standard deviation of the efficiency distribution.

**Figure 10.** Hit efficiency distribution for a test beam measurement with all subpixel types enabled for different sensor bias voltages. The external threshold voltage is 0.89 V.

### 8 Conclusion

This paper describes the characterisation of a CCPD module with HV2FEI4v2 sensor, which is implemented in the AMS 180 nm high-voltage process. The investigated CCPD module connects every FE-I4 pixel to three HV2FEI4v2 subpixels, the position of which is indicated by the output signal amplitude.
Several HV2FEI4v2 parameters were studied, including adjustment of the ToT response of the FE-I4 to the sensor signal for a successful subpixel mapping. The parameter range in which a significant change of the output voltage is possible was found to be small, which makes subpixel decoding a challenging task. The challenge is met by a subpixel mapping with a likelihood based on the ToT and the trigger counter of the FE-I4 hits.

Data from test beam measurements were analysed with all subpixel types enabled and subpixel mapping based on the likelihood method. Residual distributions show a mismatch rate of 5%. The mean hit efficiency was measured to be 72% with a large standard deviation of 21%. The mean hit efficiency of subpixel types 2 and 3 is approximately 80%. The measurement of the in-pixel efficiency showed that the hit efficiency in the centre of the pixel is higher than at the edges due to charge sharing.

The HV2FEI4v2 is a very early prototype towards a CCPD module for the ITk. The feasibility of the subpixel de- and encoding concept was successfully demonstrated, resulting in an improved pixel resolution compared to that of the larger pixels of the read-out chip. The measured mean hit efficiency of the module of 72% is clearly below ITk specifications. This feature can be addressed by reducing the HV2FEI4v2 discriminator threshold.

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