Characterization of the prototype CMOS pixel sensor JadePix-1 for the CEPC vertex detector

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Abstract

The proposed Circular Electron Positron Collider (CEPC) will allow measurement of the Higgs properties with precision beyond the (HL-)LHC. To meet the stringent physics requirements, its vertex detector will have to be constructed with the state-of-the-art pixel detector technologies that promise high spatial resolution, low power consumption and low material budget. We have conducted R&D based on the emerging CMOS pixel sensor technology and developed the first prototype JadePix-1. In this poster, we describe the sensor structures that are primarily designed to evaluate the impacts of diode geometry on charge collection. We present the detailed test results obtained with radioactive sources and electron beams, and the sensor performance before and after neutron irradiation up to 10^{13} 1 MeV n_{eq}/cm^2.

Introduction

The CEPC is proposed to measure the Higgs boson properties as precise as possible, which will impose stringent requirements on the CEPC detector performance. The innermost vertex detector will play a critical role in heavy-flavor tagging. Therefore, the CEPC vertex detector must be facilitated with silicon pixel sensors with high spatial resolution ($\sigma_{sp}\sim3$ μm), fast readout (20 μs), low material budget (0.15 % X/X_0 per layer) and radiation tolerance (TID 1MRad/y, NIEL 2×10^{12} 1 MeV $n_{eq}/cm^2/y$). Monolithic active pixel sensors (MAPS), fabricated with standard CMOS processes, have already demonstrated its excellent performance in several high energy physics experiments. We have conducted R&D and developed the first prototype JadePix-1. As illustrated in Figure 1, the readout electronics is integrated with the sensitive volume on the same silicon substrate.

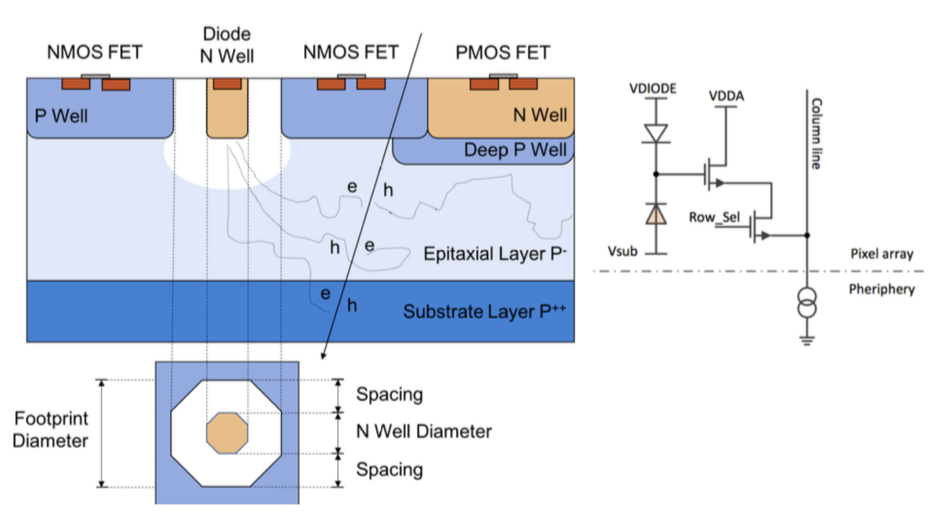


Figure 1. Cross sectional view of a CMOS pixel sensor and schematic of its in-pixel readout circuitry. Charges generated by the passing through charged particle are collected by the diode N-well mostly by diffusion.

The collecting diode consists of the collecting N-well and the surrounding P-well. Footprint defined as the total area formed by the surrounding P-well. As listed in Table 1, several geometry parameters are implemented to evaluate the collected signal charge over the equivalent input capacitance ratio (Q/C), which is critical for reducing the analogue power consumption.

Sector	Diode Surface	Footprint
A1	4 μm²	30 μm²
A2	8 μm²	30 μm²
A3	15 μm²	30 μm²
A4	4 μm²	20 μm²
A5	4 μm²	15 μm²

Table 1. Diode geometries implemented in JadePix-1.

DAQ System

The data acquisition (DAQ) system consists of "Three-Part" structures, as shown in Figure 2. The analog signal generated in sensor is first amplified on the daughter board, and then converted to digital signal on the mother board. Data processed on the KC705 evaluation board are transmitted to PC via PCIe. A modern multi-thread C++ software with Qt based online GUI take data automatically.

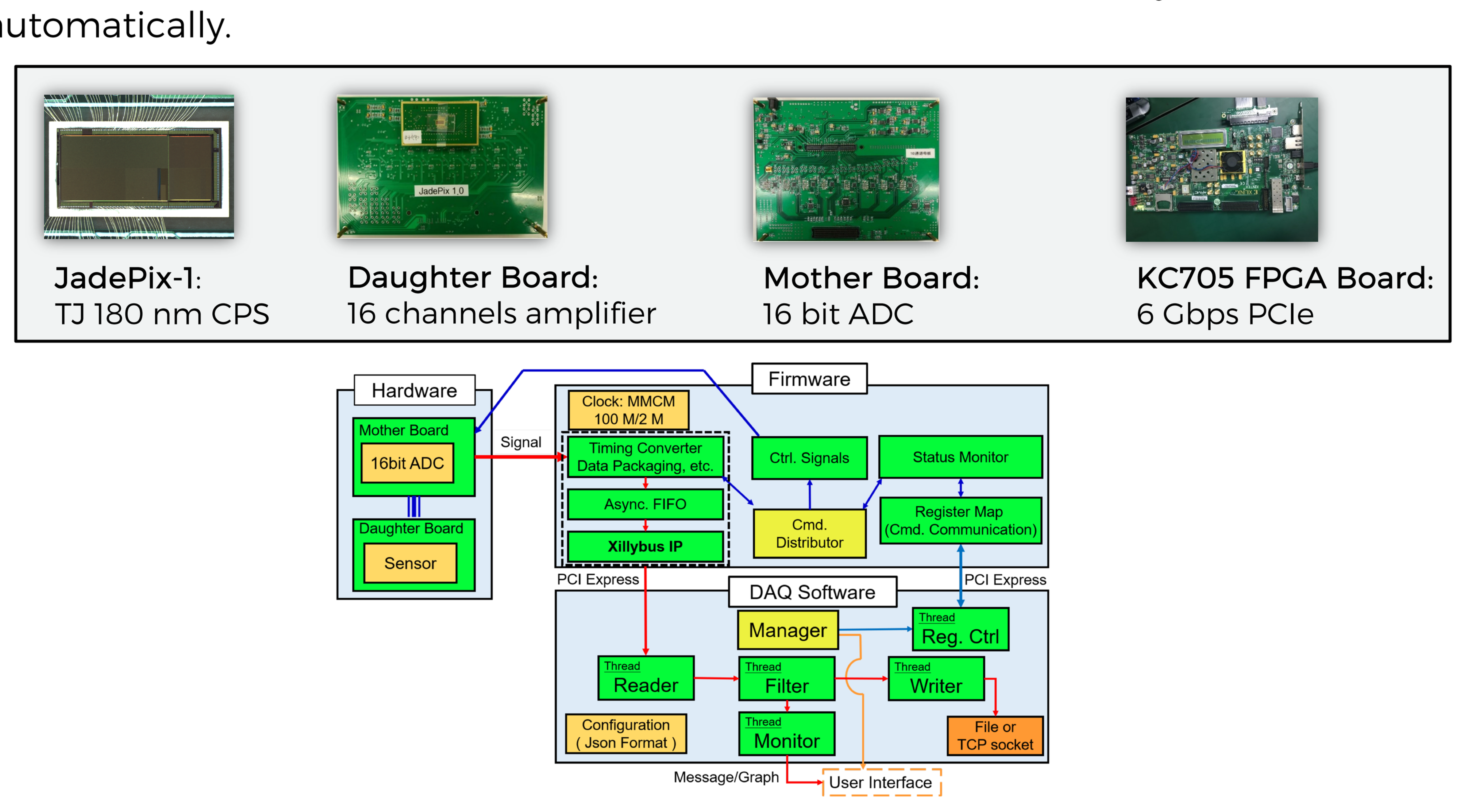
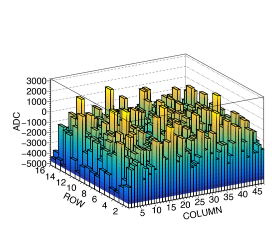


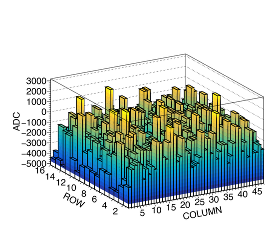
Figure 2. Components and the architecture of the DAQ system.

Offline Analysis

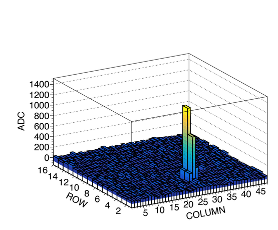
The Correlated Double Sampling (CDS) method is used to suppress noise and extract the signal, as illustrated in Figure 3a, 3b and 3c. Noise can be measured with or without radioactive source and results are shown in Figure 3d, 3e and 3f.



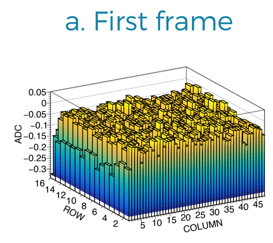
a. First frame



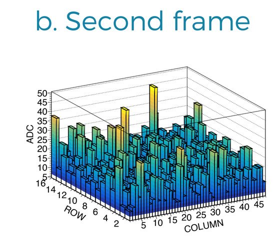
b. Second frame



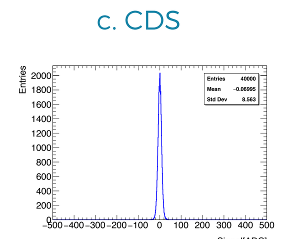
c. CDS



d. Pedestal distribution for one sector



e. Noise distribution for one sector



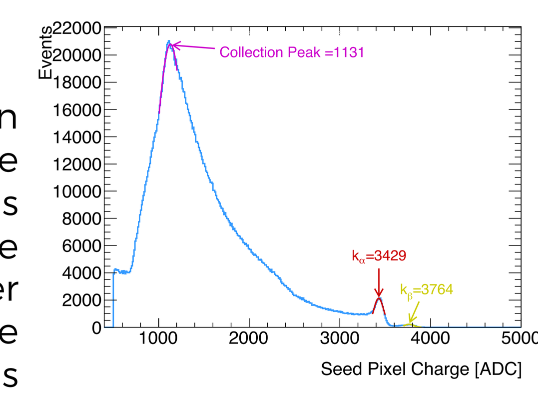
f. CDS signal for one sector

Figure 3. Correlated Double Sampling method and the obtained results.

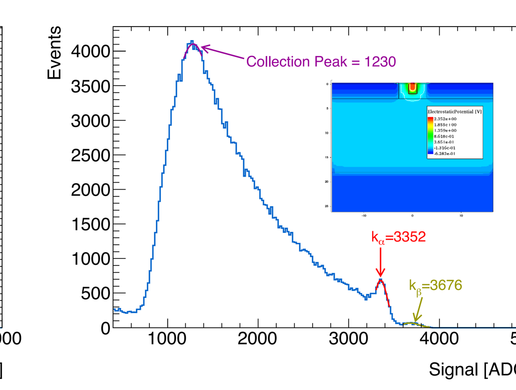
Results

Tests with low-energy X-rays

^{55}Fe is used to calibrate the pixel gain based on the assumptions that the charges with X-ray hitting on diode is complete conversion while the charges with X-ray hitting other place disperse slowly towards diode on thermal. The phenomenon is verified with AllPix² and TCAD simulation, as illustrated in Figure 4.



a. Seed signal distribution for ^{55}Fe measurement



b. Seed signal distribution for AllPix²+TCAD simulation

Figure 4. Example of seed signal distribution from experiment and simulation

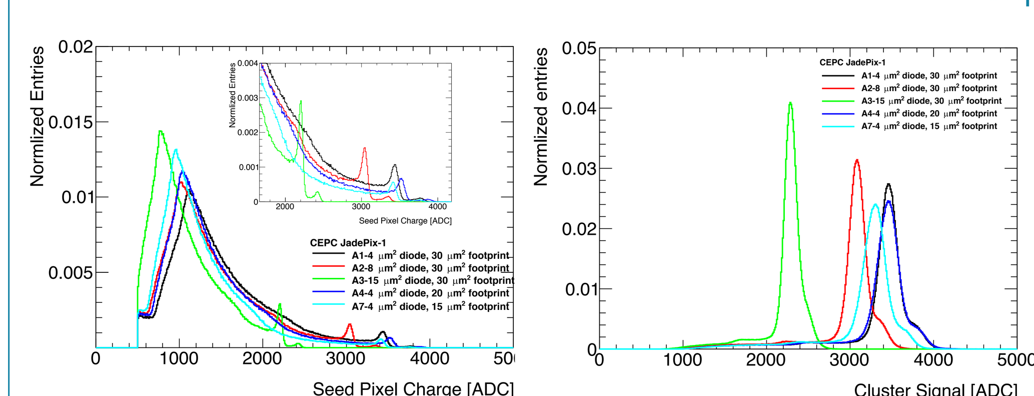
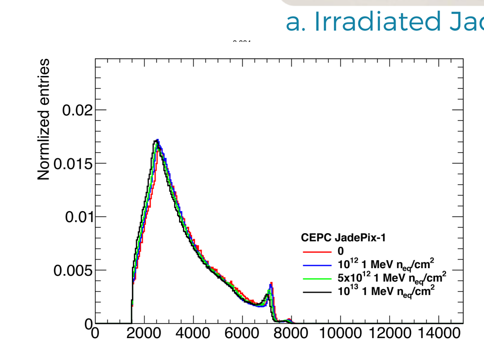


Figure 5. JadePix-1 response to X-rays from ^{55}Fe source for pixels with 33 μm pitch

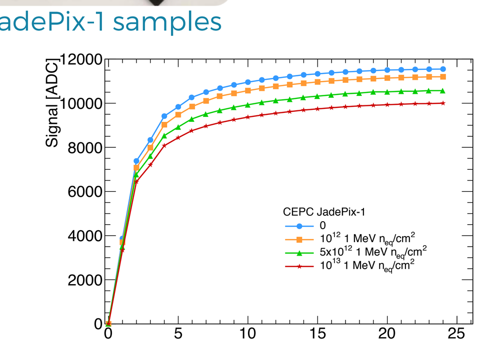
Two calibration peaks can always be recognized from the spectra of the seed pixels for different diode geometries. Charge spreading into neighboring pixels can be studied by grouping the specific pixels (cluster). Seed and cluster charge distributions are shown in Figure 5. The cluster charge collection efficiencies are shown in Table.2.

Sensor performance after irradiation

a. Irradiated JadePix-1 samples



b. Seed signal distribution of sector A3



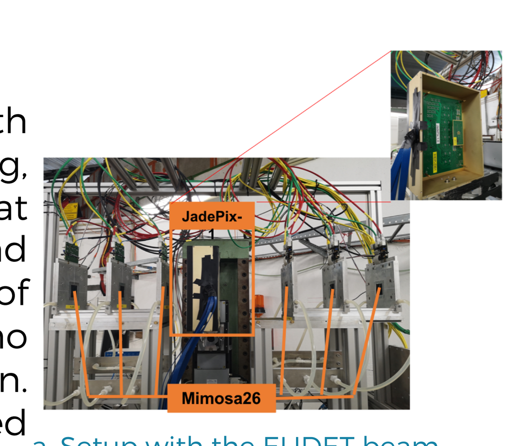
c. Cluster charge as a function of the pixel multiplicity for sector A1

Figure 6. JadePix-1 response to ^{55}Fe source before and after neutron irradiation

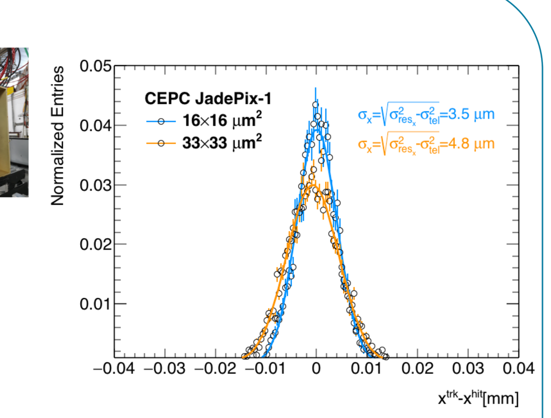
JadePix-1 samples were sent to pulsed neutron reactors for neutron irradiation to 10^{12}, 5×10^{12}, and 10^{13} 1 MeV n_{eq}/cm^2 fluences. The irradiated sensors are also characterized with ^{55}Fe source. Even for small diode array, A1, the cluster charge decrease less than 15%, shown in Figure 6.

Tests with electron beams

JadePix-1 has been characterized with electron test beam at DESY in Hamburg, Germany. Preliminary results show that spatial resolutions better than 5 μm and 3.5 μm can be achieved for pixel sizes of 33x33 μm² and 16x16 μm². And there is no significant degradation after irradiation. The most probable values estimated from the Landau-like shape of seed signal distributions are used to calculate signal to noise, shown in Table.2.



a. Setup with the EUDET beam telescope



b. Residual distributions with 33 μm pitch and 16 μm pitch

Figure 7. JadePIx-1 with the DESY test beam

Sector	CVF [μV/e]	CCE (Radioactive source)	S/N (Test Beams)
A1	33.4	94.39%	64
A2	29.0	95.23%	64
A3	20.8	97.09%	52

Table 2. Summary the JadePix-1 characterizations

Conclusion

We have developed the first prototype JadePix-1 according to the requirements of the CEPC vertex detector. The sensors have been characterized by radioactive resources and the electron test beam by using our designed DAQ system. The performance evaluation of irradiated sensors are critically conducted in the next step.

Acknowledgements

This R&D project has been jointly supported by the State Key Laboratory of Nuclear Detection and Nuclear Electronics, the IHEP Innovation Fund and Yifang Wang's science studio.