CHARACTERIZATION OF JADEPix-1

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OUTLINE

• CEPC vertex detector requirements
• JadePix-1 pixel design
• Characterization with radioactive sources
• Neutron irradiation and beam tests
• Conclusion
CEPC Vertex Detector Requirements

- High precision vertex detector essential for heavy-flavor and $\tau$-lepton identification; designed to achieve

$$\sigma_{r\phi} = 5 \mu m \oplus \frac{10 \mu m}{\rho(\text{GeV}) \cdot \sin^{3/2} \theta}$$

- With the baseline design, this implies:
  - Single point resolution < 3 $\mu m$ → small pixel pitch, e.g. 16 $\mu m$
  - Material budget 0.15%$X_0$ per layer → thin & low power 50 mW/cm²
  - Detector occupancy below 0.5% → small pixel & fast readout
  - Radiation tolerance (annual): 1 MRad and $2 \times 10^{12}$ 1 MeV $n_{eq}$/cm²
JadePix-1 Pixel Design

- 1st prototype sensor developed with TJ 0.18 μm CIS process
- **Primary goal**: diode geometry optimization

**Supported by the State Key Lab of Particle Detection and Electronics & IHEP Innovation fund**

Impacts of electrode size and footprint on charge collection performance

- Submission in November 2015, test system developed and verified in 2016 & 2017; detailed performance characterization in 2017 & 2018
TEST SYSTEM

Amplification

Digitization

Experimental Setup

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Offline correlated double sample (CDS) technique applied to extract signal
Response to $^{55}\text{Fe}$

- Response to low energy X-ray photons for calibration

Seed Pixel

Collection peak, incomplete charge collection when photons hitting at other positions

Calibration peak, X-ray photons hitting the electrode area and generated charge nearly 100% collected

$V_{\text{calib}} = k_\alpha \cdot [\text{ADC}] \times \frac{2.5 [V]}{2^N - 1} \times \frac{1}{g_a}$

Conversion Gain $[\mu\text{V/e}^-] = \frac{V_{\text{calib}} [V] \times 10^6}{1640 e^-}$

5.9 keV photon generates $\sim 1640$ eh pairs
CONVERSION GAINS

- Larger electrode size yields lower conversion gain (larger input capacitance);
- Negligible impact from footprint on the conversion gain.
**NOISE PERFORMANCE**

- Larger electrode/input capacitance leads to higher noise; similarly negligible impact from footprint.
Device Simulation

- TCAD + AllPix$^2$ simulation

- Build Sentaurus TCAD model

- Interpolate on regular mesh

- Extract electric field

- 3D TCAD simulations are used to calculate the Electric Field Map
- Barycentric interpolation using nearest neighbors is used to calculate results on regular mesh in AllPix$^2$
- Monte Carlo sampling algorithm used for radioactive source
Simulation Result

- TCAD + AllPix2 combined simulation managed to reproduce most of the features observed in measurements.
**Response to MIPs**

- Experimental setup to evaluate performance with $^{90}\text{Sr}$
- Scintillator read out with **SiPM** to provide trigger signal

Seed Pixel

- Landau Distribution
- $\chi^2/\text{NDF} = 0.74$
- MPV = 498
- Sigma = 142

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**Signal-to-Noise**

- **Small electrode size** and **large footprint** can yield high S/N ratio → preferred for efficient detector operation
**Charge-over-Capacitance**

- **Small electrode** and **large footprint** preferred to achieve high Q/C ratio → reduction in analog power consumption

\[
C [fF] = \frac{1640 \ [e] \times 1.6 \times 10^{-19} \ [C/e]}{V_{\text{calib}} [V]/g_b} \times 10^{15}
\]

*Results obtained with radioactive sources consistent with that derived for, e.g., MIMOSA32/34 and Explorer*
NEUTRON IRRADIATION

• Samples sent to a pulsed reactor for neutron irradiation to the fluence levels of $10^{12}$, $5 \times 10^{12}$ and $10^{13}$ 1MeV n$_{eq}$/cm$^2$

• Larger diode size ($A_1 > A_2 > A_3$) more radiation hard
MORE RESULTS

• Larger diode size ($A1 > A2 > A3$) more radiation hard
Beam Test @ DESY

- JadePix-1 sensors brought to DESY for beam tests last Sept.

Special acknowledgements to the DESY Test Beam Facility

TESTBEAM

Beam energy 4.4 GeV

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**Track Reconstruction**

- Offline track reconstruction with **EUTelescope**
Resolution Calculation

- To derive JadePix-1 resolution as follows:

\[ \text{Residual}(z) = \text{Unbiased}_\text{Trk}(z) - \text{Local}_\text{Local}(z) \]

\[ \sigma^2_{\text{residual}(z)} = \sigma^2_{\text{unbiased}_\text{Trk}} + \sigma^2_{\text{local}_\text{hit}(z)} \]

\[ \sigma_{\text{local}_\text{hit}(z)} = \sqrt{\sigma^2_{\text{residual}(z)} - \sigma^2_{\text{local}_\text{hit}(z)}} \]

Derived from unbiased track fit with EUTelescope track reconstruction

Taken from the resolution estimator developed by S. Spannagel and H. Jansen

[https://github.com/simonspa/resolution-simulator](https://github.com/simonspa/resolution-simulator)

RESOLUTIONS

• Resolutions derived for different pixel geometries before and after neutron irradiation

• Performance of sector 2 still to be understood
**Detection Efficiency**

- Inefficiency due to “mis-triggered” events

  ![Diagram showing triggering and JadePix-1 tracks]

- Read time window opened for two frames ... not long enough to catch the second track that indeed passes through JadePix-1 left. Adding FE-I4 could have eliminated this issue, but ...

- Trying to identify “mis-triggered” events offline
CONCLUSION

• 1st CMOS pixel sensor prototype for the CEPC vertex detector designed and characterized → a full exercise of CMOS pixel sensor development

  • Radioactive sources ($^{55}$Fe, $^{90}$Sr), beam test, neutron irradiation
  • Charge-to-voltage conversion gain, noise level, charge collection efficiency, signal-to-noise ratio, charge-over-capacitance ratio, resolution and detection efficiency

• Obtained valuable knowledge and experience (and lessons) that will be important for future sensor development

Thank you!