环形正负电子对撞机
Circular Electron Positron Collider

中国科学院高能物理研究所
Institute of High Energy Physics
Chinese Academy of Sciences

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

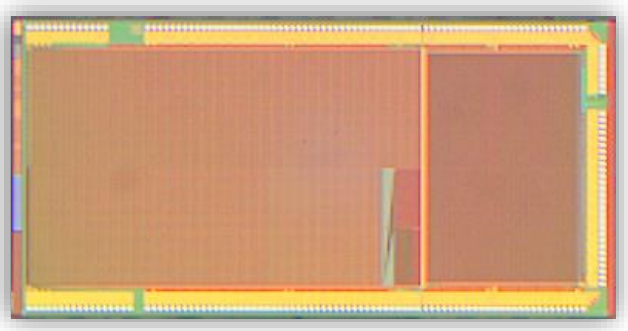
Liejian Chen[1,2], Jia Tao[1,2], Hongbo Zhu[1,2], Ying Zhang[1,2], Xiaocong Ai[1,3], Yi Liu[3], Chenfei Yang[4], Ryuta Kiuchi[1,2], Xin Shi[1,2], Ke Wang[1,2] , Na Wang[1,2], Zhenan Liu[1,2], Qun Ouyang[1,2], Xinchou Lou[1,2]

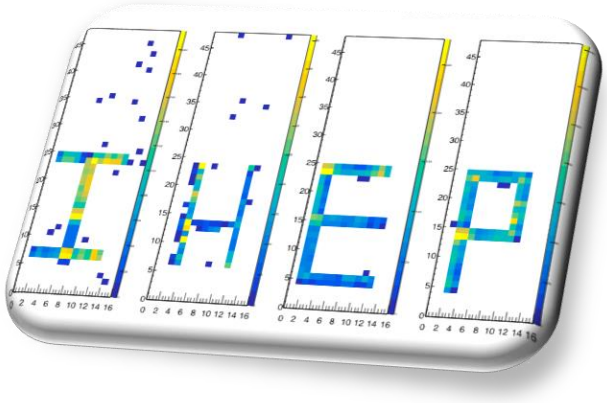
[1]Institute of High Energy Physics, CAS
[2]State Key Laboratory of Particle Detection and Electronics
[3]Deutsches Elektronen-Synchrotron DESY
[4]University of Science and Technology of China

9th International Workshop on Semiconductor Pixel Detectors for Particles and Imaging, PIXEL2018, December 10-14, 2018, Taipei

Outline

- Introduction
- Pixel design
- Prototype performance
- Summary and outlook

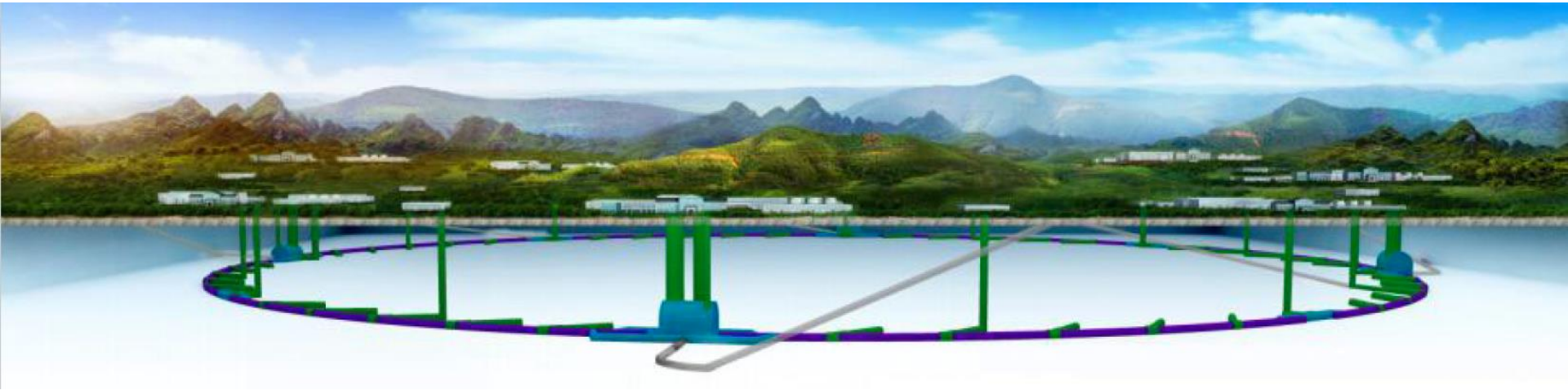




Introduction - CEPC & SppC

- Phase 1: Circular Electron Positron Collider (CEPC)
  - **Higgs(Z) factory:** $E_{cm} \approx 240$ GeV, luminosity ~2×10^{34} $cm^{-2}s^{-1}$, 2 Interaction Points(Detectors), 1M clean Higgs over 10 years + operation at Z-pole (91 GeV) and WW (160 GeV)
  - Higgs boson + EW precision measurements

- Phase 2: Super proton proton Collider (SppC)
  - **Discovery machine for new physics**: upgrade to pp collision with $E_{cm} \approx 50$-100 TeV (+ ep, HI options), luminosity ~1×10^{35} $cm^{-2}s^{-1}$

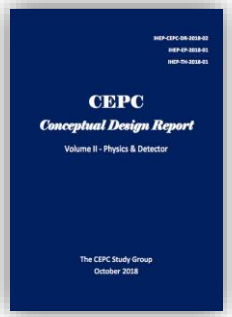


CEPC Vertex Detector

- Vertex detector of CEPC, essential for identification of heavy-flavor quarks and τ leptons, designed to achieve excellent impact parameter resolution:

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

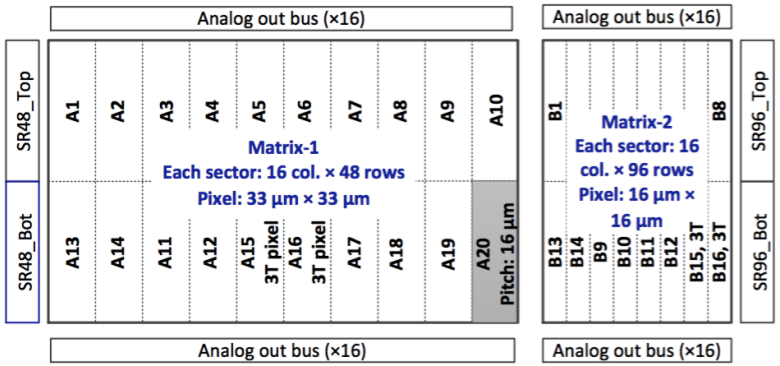
- Baseline design: three double layers pixelated vertex detector

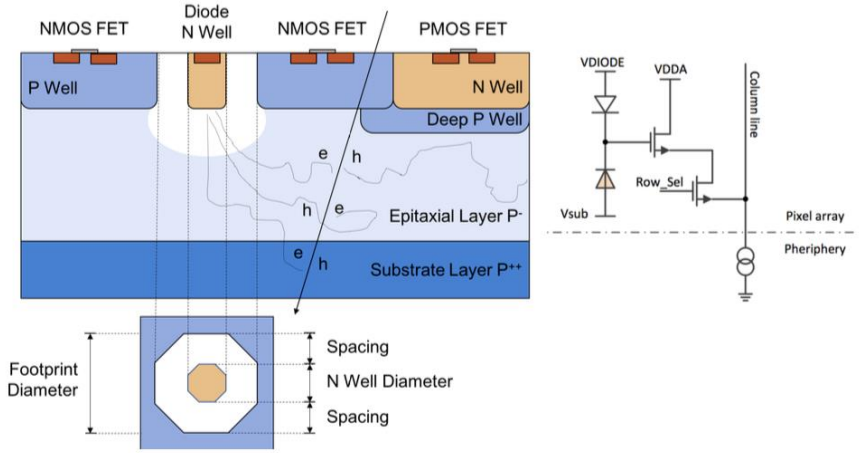


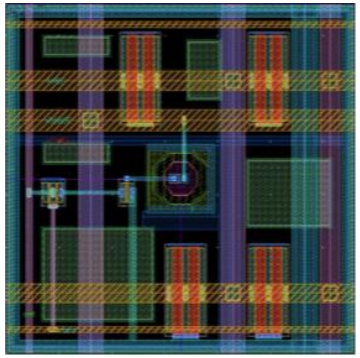
Physics driven requirements	Sensor specifications
Single−point resolution < 3 μm	Small pixel 16 μm?
Material budget 0.15% X_0 per layer	Thinning 50 μm
	Low power 50 mW/cm^2
R of Inner most layer 16 mm	Fast readout
	Radiation tolerance (Higgs mode) TID 0.93 Mrad/y NIEL 2.1x10^{12} 1 MeV n_{eq}/cm^2/y

Prototype Design– JadePix-1

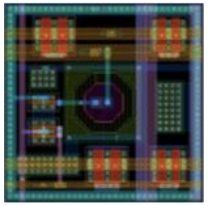
- TJ 0.18 μm CMOS image process with high resistance epi-layer
- Goal: sensor diode geometry optimization
- Design remarks:
  - diode area, footprint
  - pixel pitch







33 x 33 μm^2

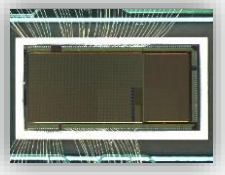


16 x 16 μm^2

- Submission in Nov 2015, test system developed and validated in 2017, detailed performance characterization this year

DAQ System

- Analog signal from sensor amplified on the daughter board
- Converted to digital signal on the mother board
- Data transmitted to PC via PCIe after processed on evaluation board
- Data took automatically with modern multi-thread C++ software

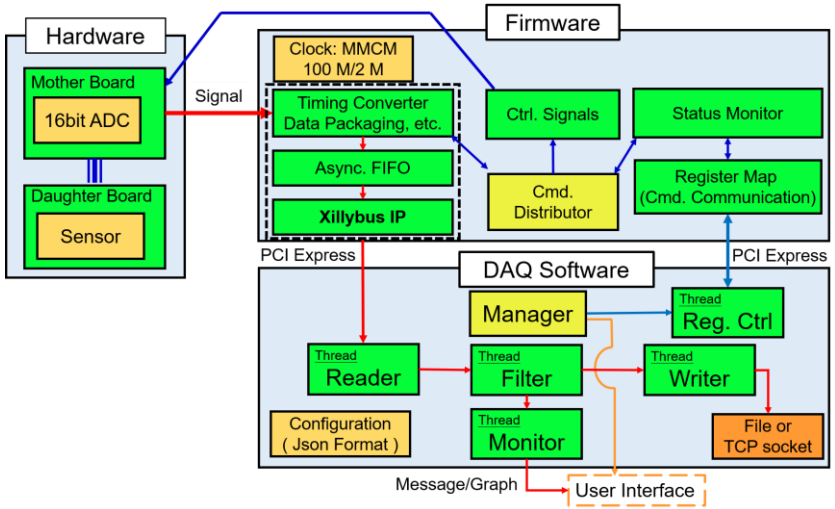


JadePix-1:
TJ 180 nm CPS

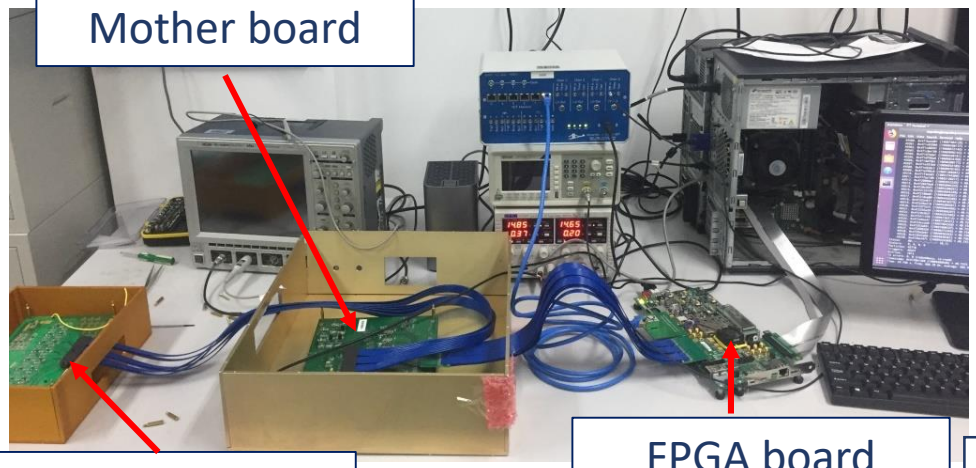
Daughter Board:
16 channels amplifier

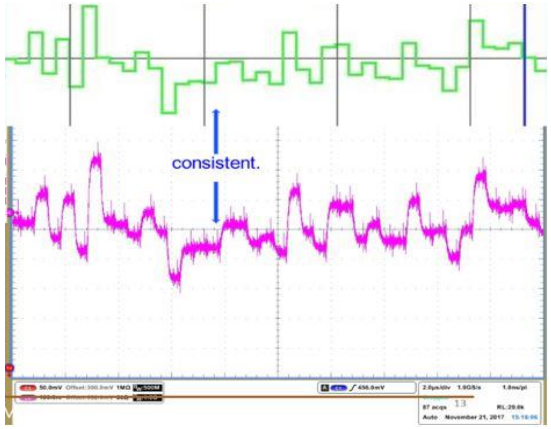
Mother Board:
16 bit ADC

KC705 FPGA Board:
6 Gbps PCIe



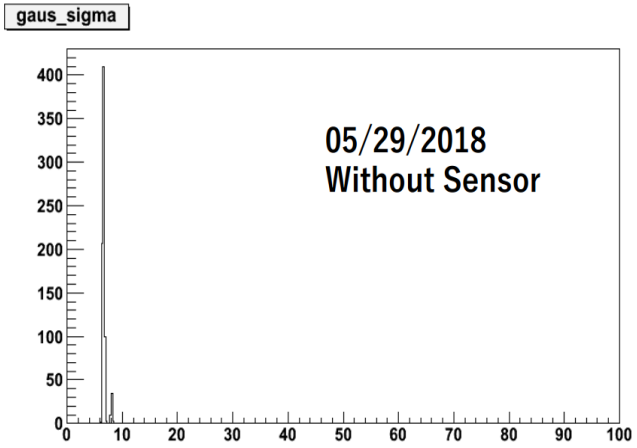
Performance of DAQ system





Output waveform comparison(after amplified)
(VIVADO ILA and Oscilloscope)

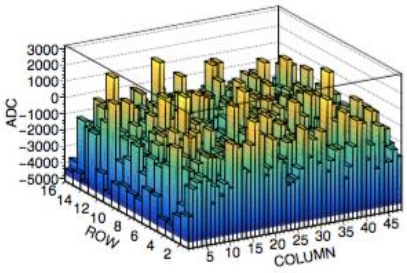
- The reference voltage of ADC Vref = 4.096 V:
  1 LSB = $Vref/2^{N-1}$=0.125 mV
- Output signal from sensor responding to 1 LSB responds:
  0.125mV/8 = 15.6uV
- Without chip test to estimate DAQ system noise:
  ~170μV~3.5e-



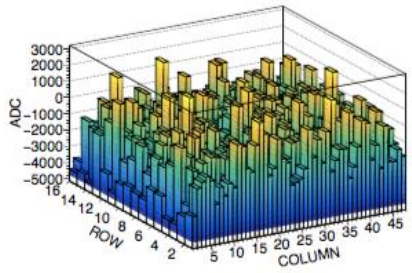
DAQ system noise distribution without chip

Tests with ^{55}Fe

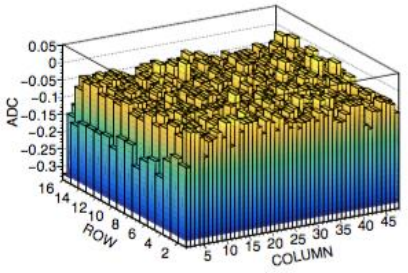
- Correlated Double Sampling (CDS) to suppress noise and extract signals
- Noise measured with/without radioactive source (exclude suspected signals and get multiple frames average)



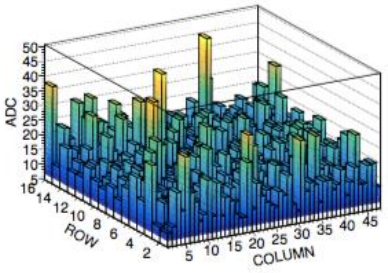
(a) First frame raw data



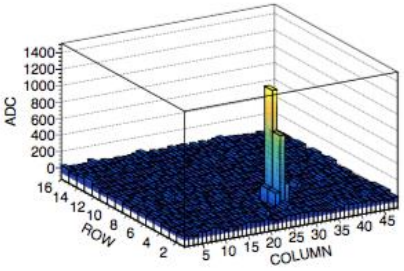
(b) Second frame raw data



(a) Pedestal distribution for 1 frame



(b) Noise distribution for 1 frame



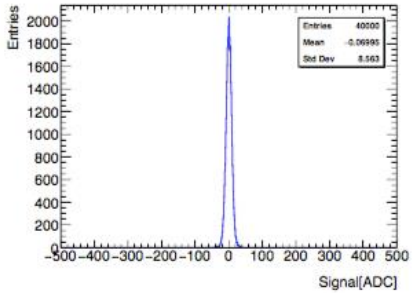
(c) CDS

$$r_k^i = s_k^i + p_k^i + c^i$$

$$p_{k,N} = \frac{1}{N}\sum_{i=1}^{N}(r_k^i - s_k^i) = \frac{1}{N}\sum_{i=1}^{N}\tilde{r}_k^i$$

$$p_{k,N}^{\text{est}} = \frac{1}{N'}\sum_{j=1}^{N'}\tilde{r}_k^j$$

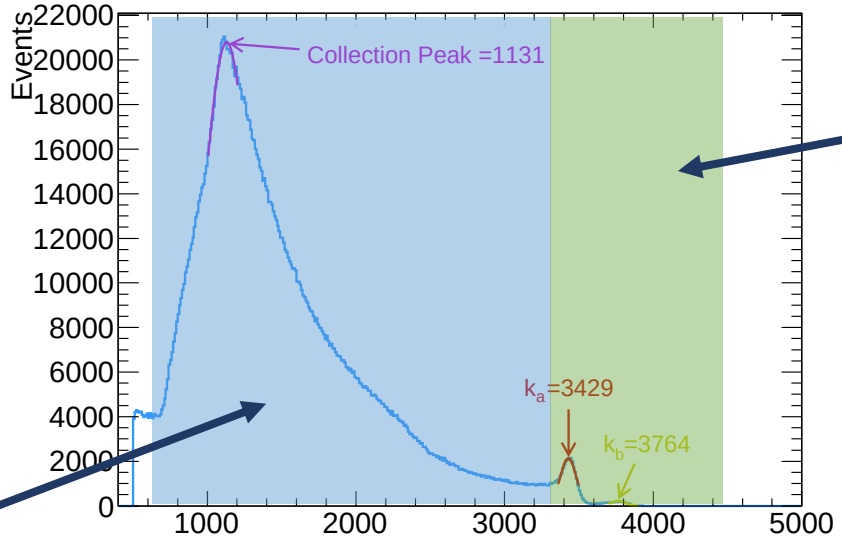
$$n_{k,N} = \sqrt{\frac{N'}{N'-1}}\sqrt{\left(\frac{1}{N'}\sum_{j=1}^{N'}(\tilde{r}_k^j)^2\right) - (p_{k,N}^{\text{est}})^2}$$



(c) CDS signal for 1 pixel

^{55}Fe Calibration

- ^{55}Fe used to calibrate the pixel gain on the assumptions:



the charges with X-ray hitting on diode is complete conversion

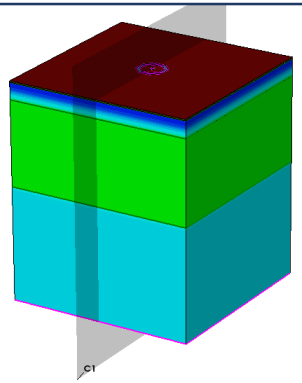
the charges with X-ray hitting other place disperse slowly towards diode on thermal diffuse to neighbor pixel

- ^{55}Fe generate two low energy X-ray:
  - 5.9 keV (90%)
  - 6.49 keV (10%)
- 5.9 keV X-ray produced electron-hole pairs:

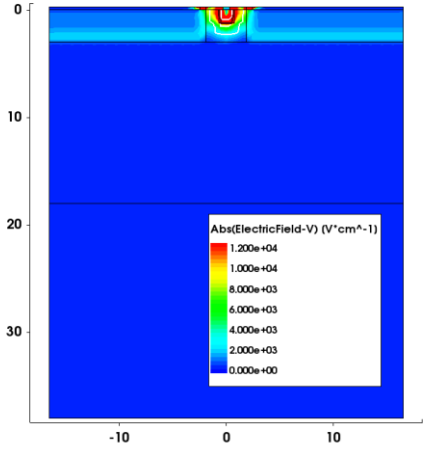
$$N_{e-h} = \frac{E_\alpha}{\varpi} = 1640$$

Simulation

Build Sentaurus TCAD model



Extract electric field

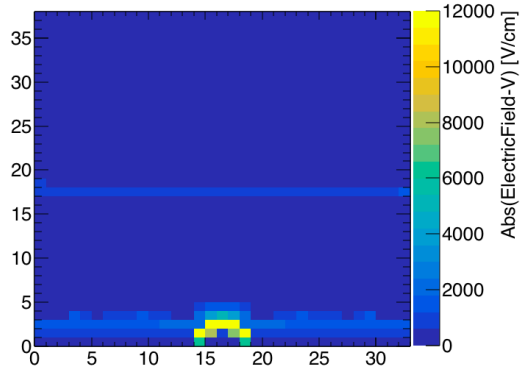


TCAD → AllPix²

TCAD geometry → Create Mesh → Device simulation

Geant4 geometry → TCAD e-field → Charge deposition → Project charges → Transfer charges → Digitization → Cluster reconstruction

Interpolate on regular mesh

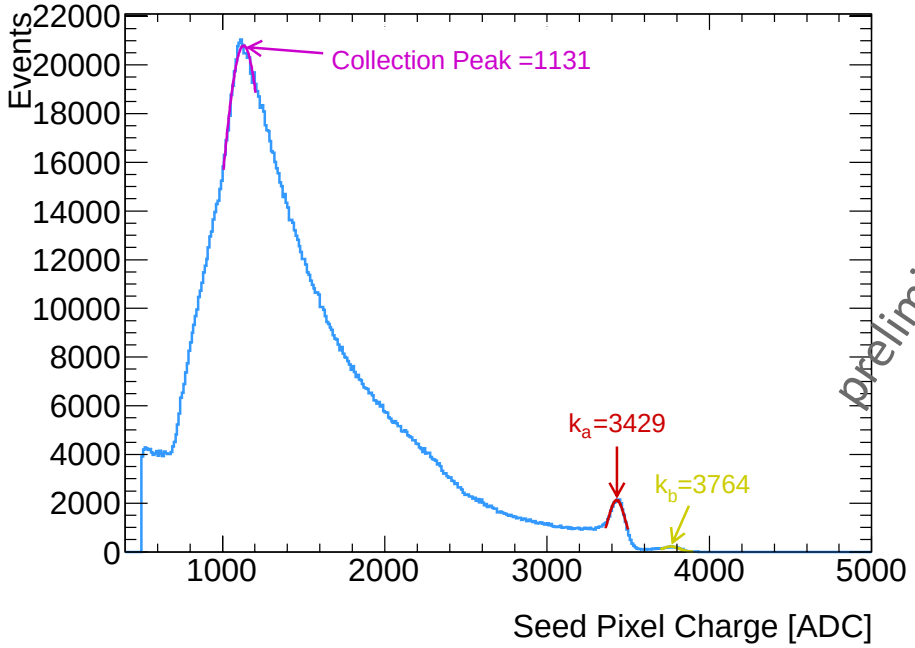


- 3D TCAD simulations are used to calculate the Electric Field Map
- Barycentric interpolation using nearest neighbors is used to calculate results on regular mesh in AllPix²
- Monte Carlo sampling algorithm used for radioactive source

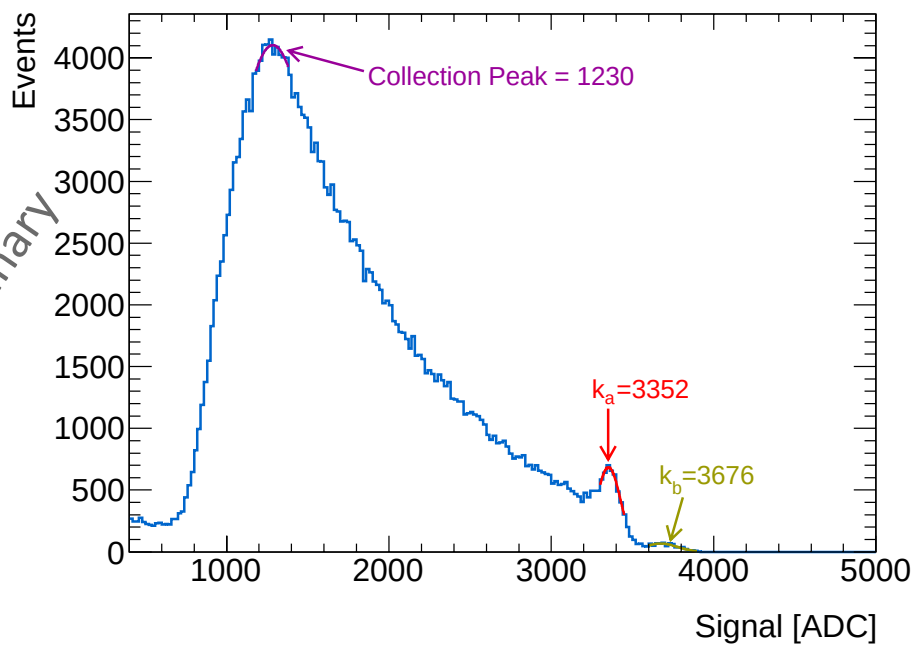
Simulation vs Measurement

- TCAD + AllPix2 combined simulation managed to re-produce most of the features observed in measurements

Measurement



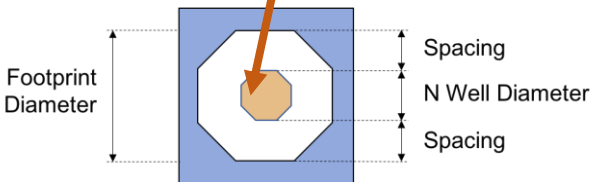
Simulation（TCAD+AllPix²）



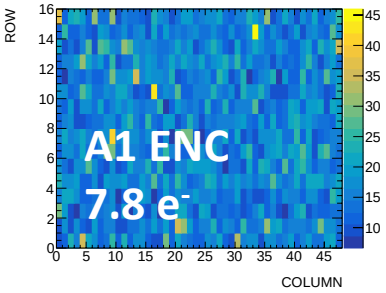
preliminary

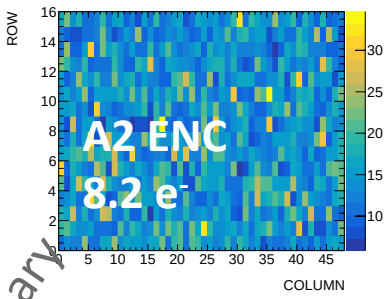
Diode Surface

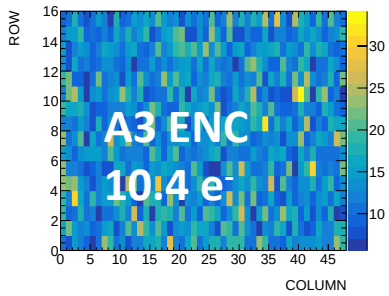
- Lager diode surface -> more effective charge collection
- Lager capacitance -> more sensor noise



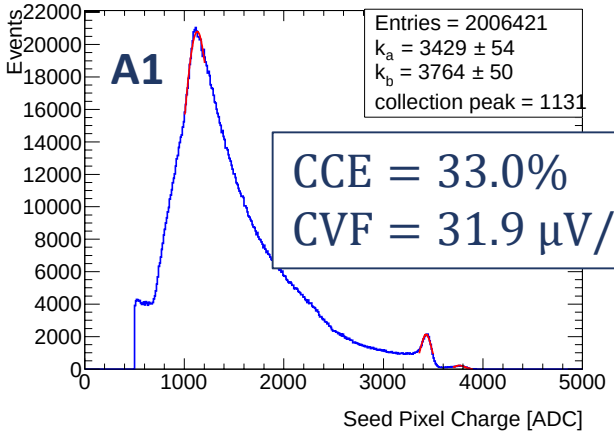
Sector	*Diode surface*	*Footprint*
A1	4 μm²	30 μm²
A2	8 μm²	30 μm²
A3	15 μm²	30 μm²



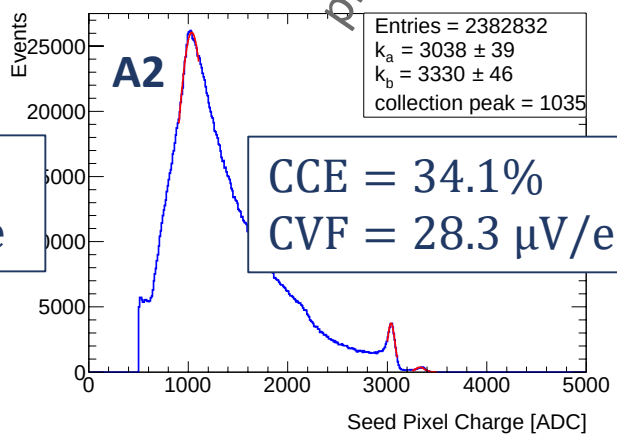




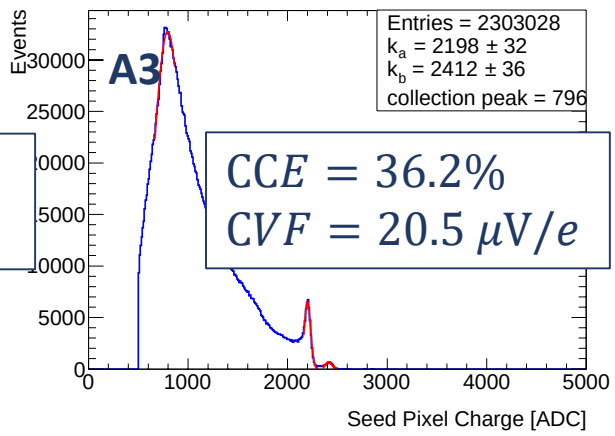
preliminary



CCE = 33.0%
CVF = 31.9 μV/e



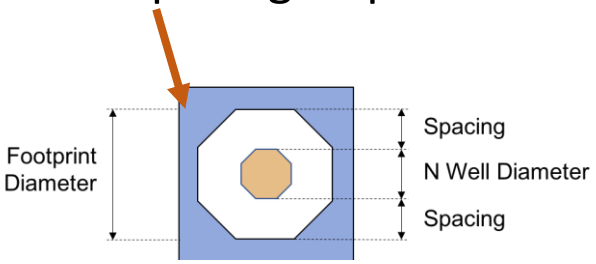
CCE = 34.1%
CVF = 28.3 μV/e



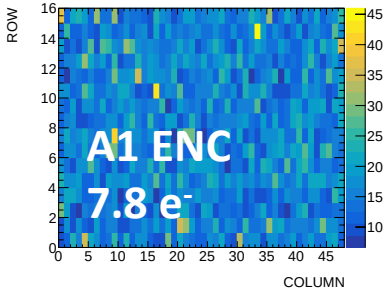
CCE = 36.2%
CVF = 20.5 μV/e

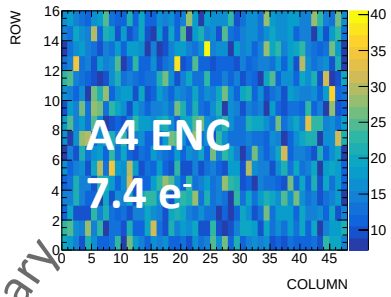
Footprint

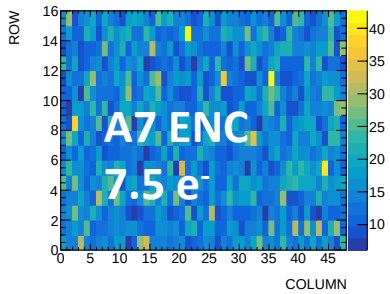
- Spacing: separation between diode and readout electronics



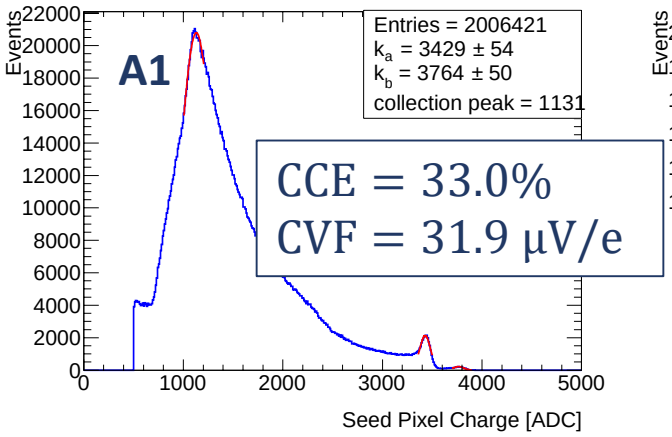
Sector	*Diode surface*	*Footprint*
A1	4 μm²	30 μm²
A4	4 μm²	20 μm²
A7	4 μm²	15 μm²

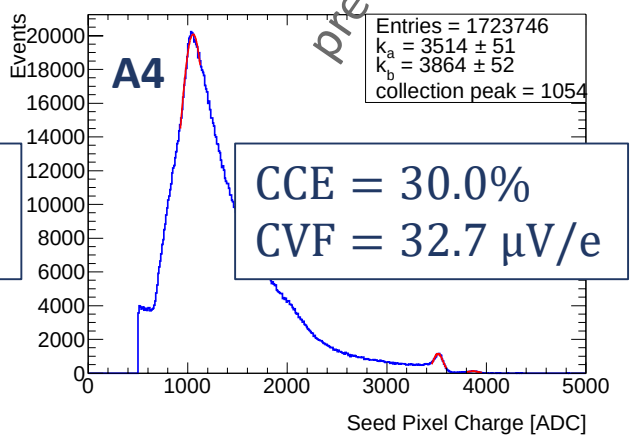


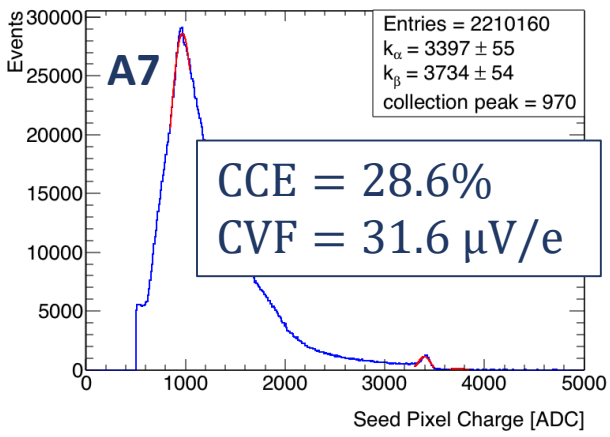




preliminary

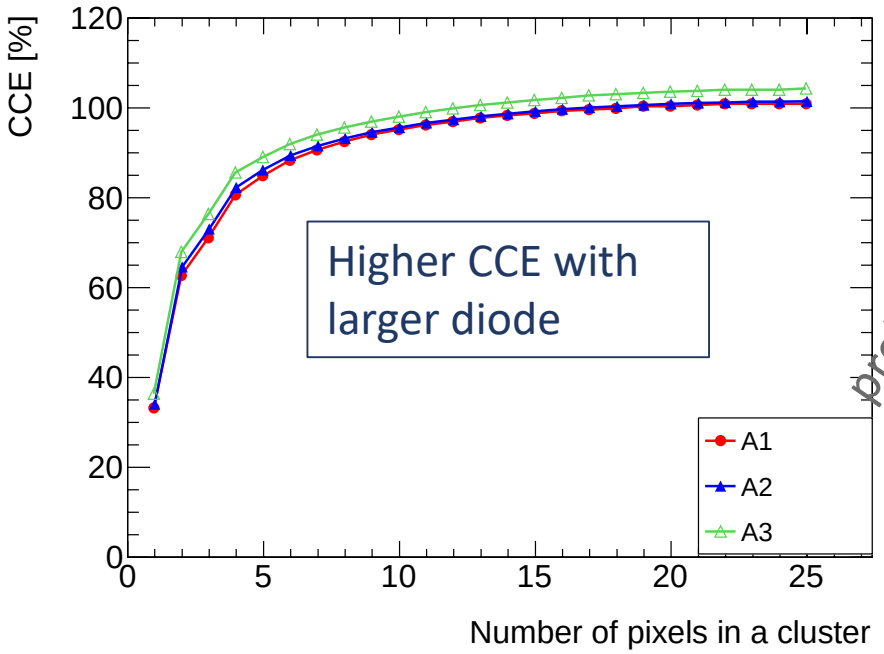




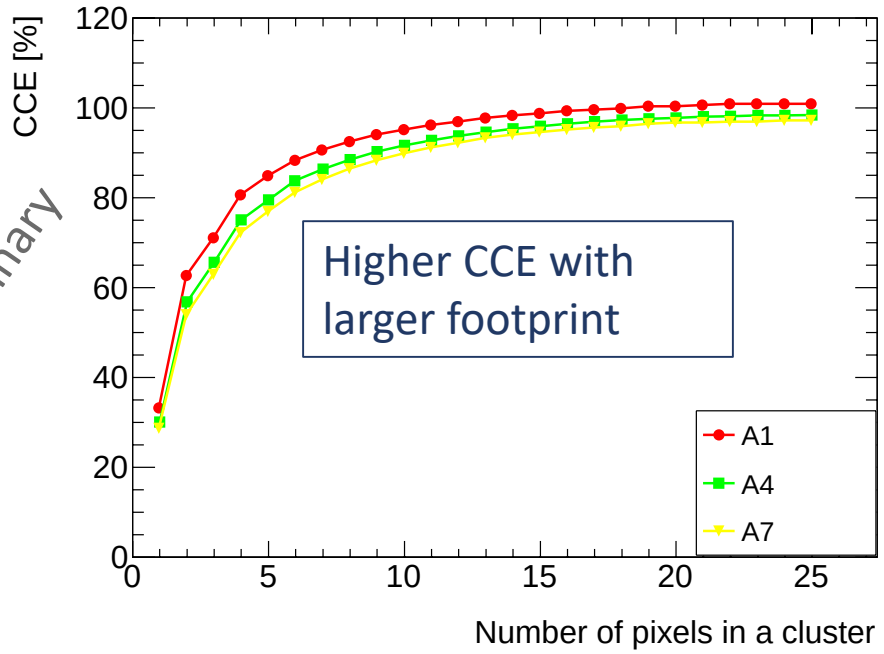


Cluster Charge Collection

- Cluster CCE=Cluster collection peak/Seed pixel calibration peak
  - Almost complete charge collection with 5x5 clusters
  - 3X3 cluster can collect most charges

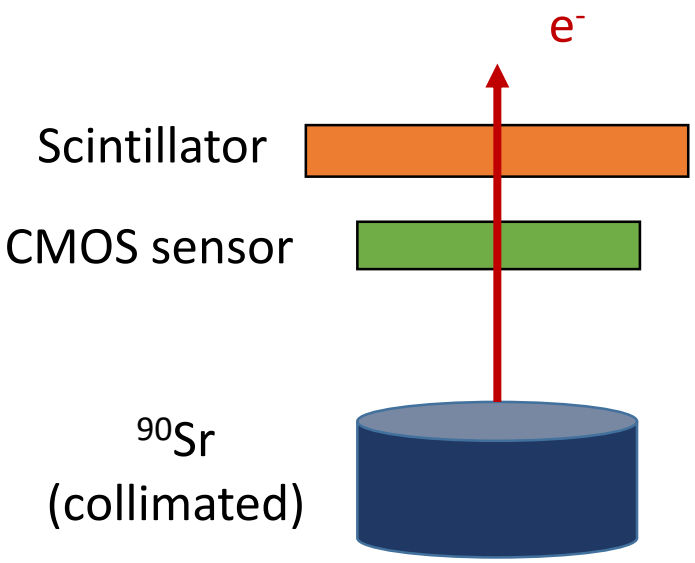


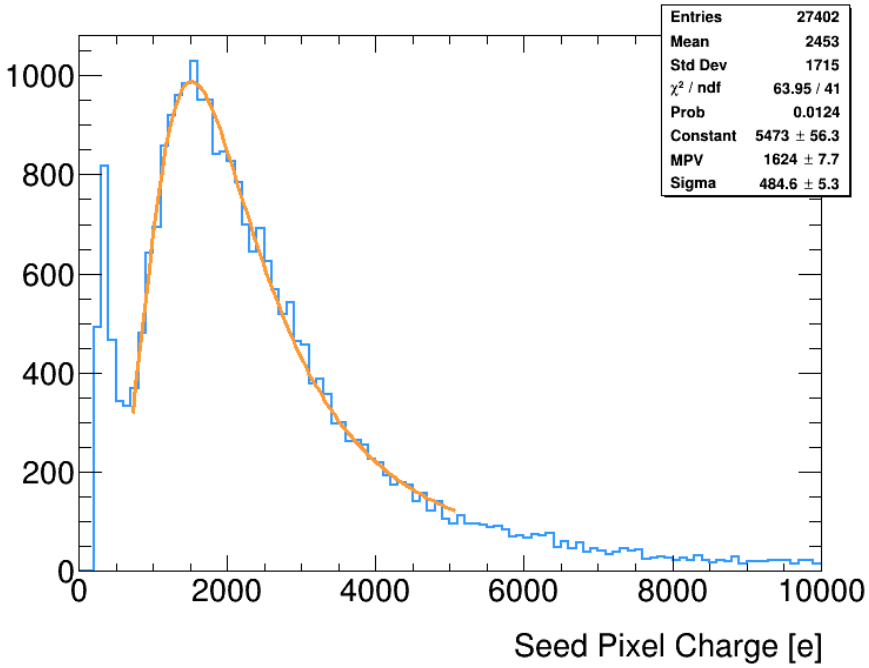
preliminary



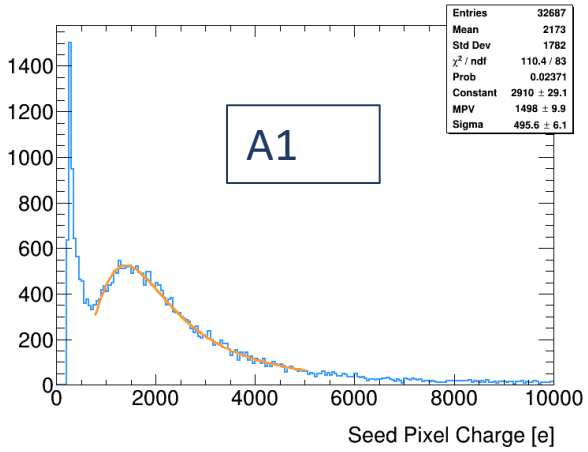
Tests with ^{90}Sr

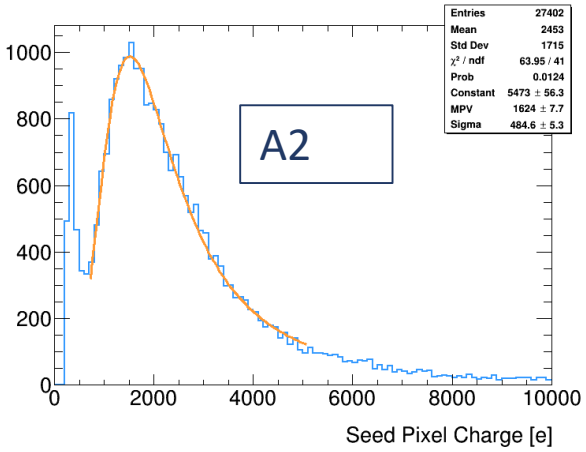
- Scintillator+ SiPM to provide the trigger signal
- Charged collected by the seed pixel estimated as the most probable value derived from the Landau function fit to the charge distribution

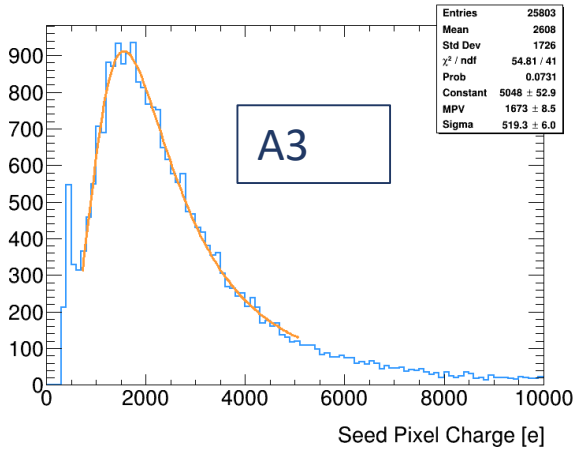




Charge Collection





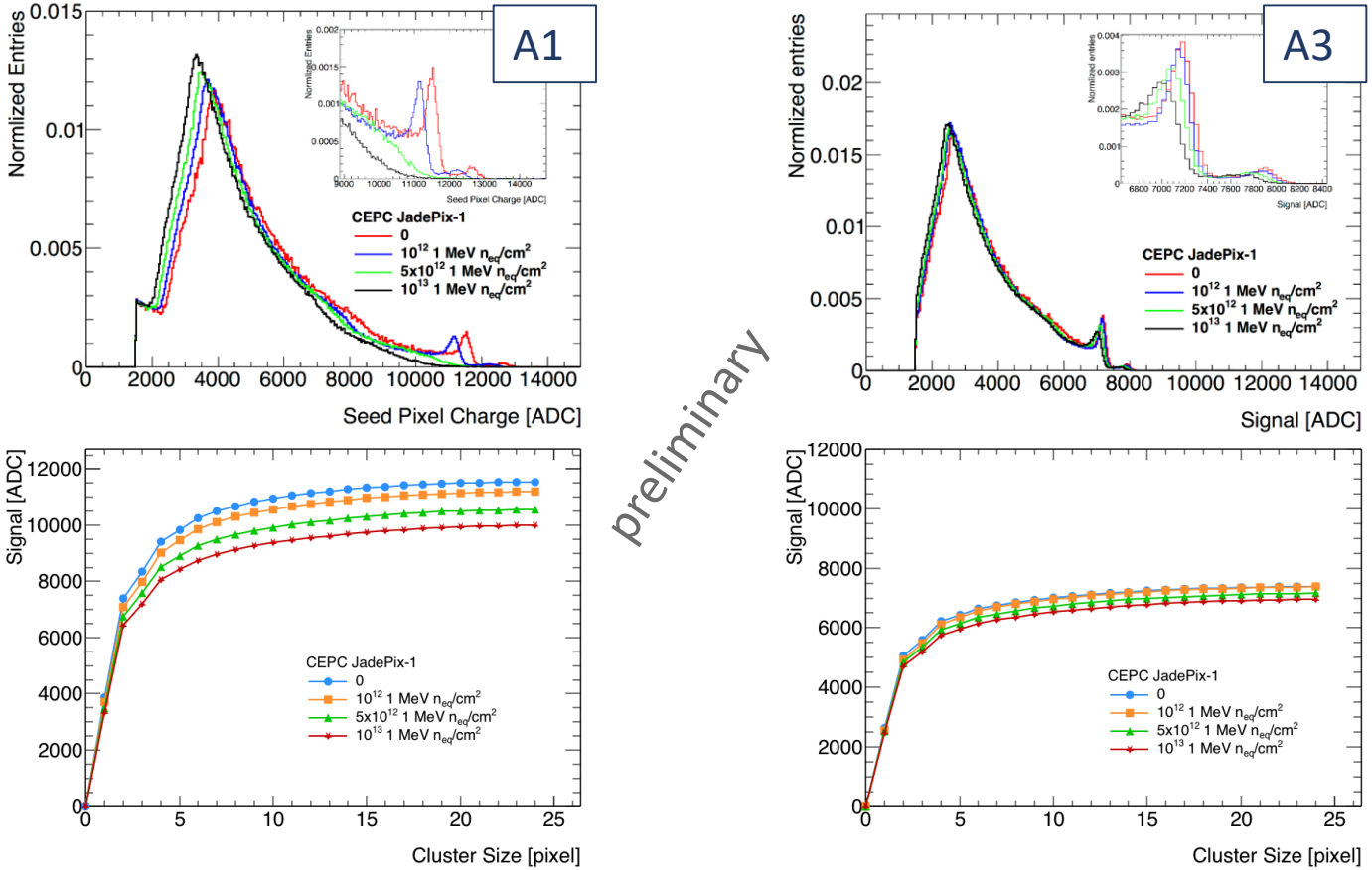


preliminary

Sector	Seed Charge [e⁻]	Cluster Charge [e⁻]	CCE	S/N
A1	1498	3893	38.48%	237
A2	1624	3973	40.87%	229
A3	1673	3784	44.22%	180
A4	1391	3822	36.39%	234
A7	1361	3985	34.15%	220

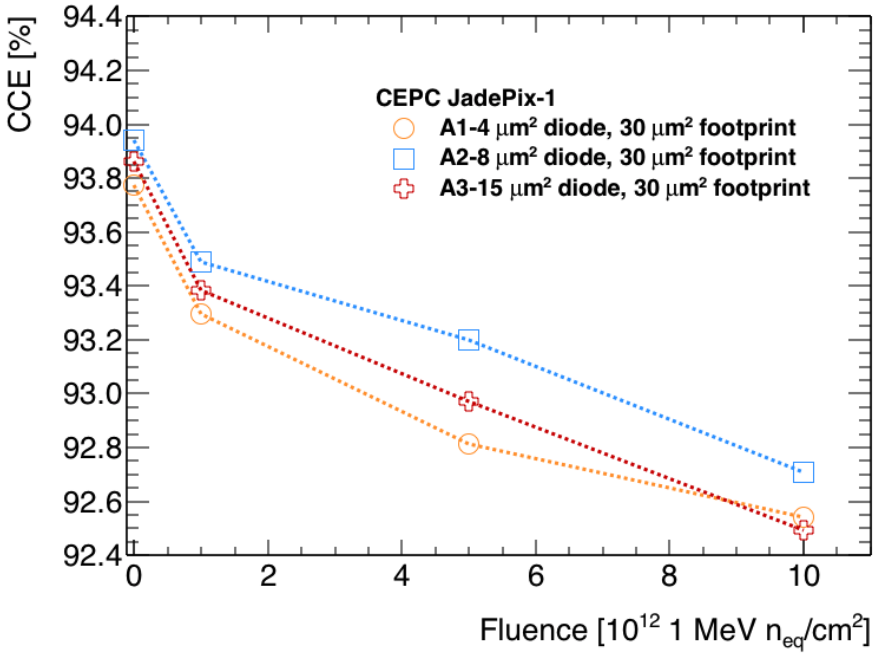
Performance After Irradiation

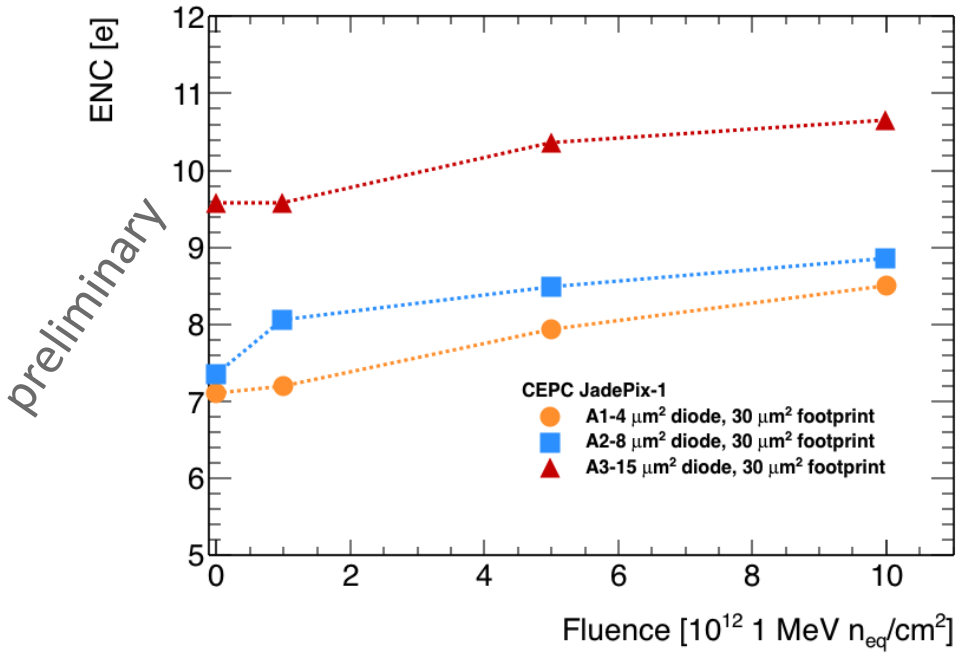
- Samples sent to a pulsed neutron reactors and irradiated to fluences of 10^{12}, 5×10^{12}, and 10^{13} 1 MeV n_{eq}/cm^2
- Larger diode (A3 >A1) more radiation hard as expected



Performance After Irradiation

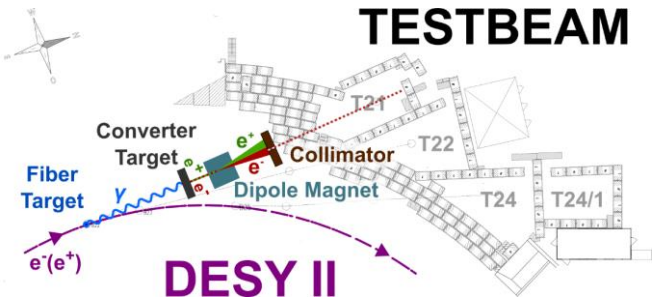
- Charge collection efficiency decreases but noise increases as the neutron fluence goes higher

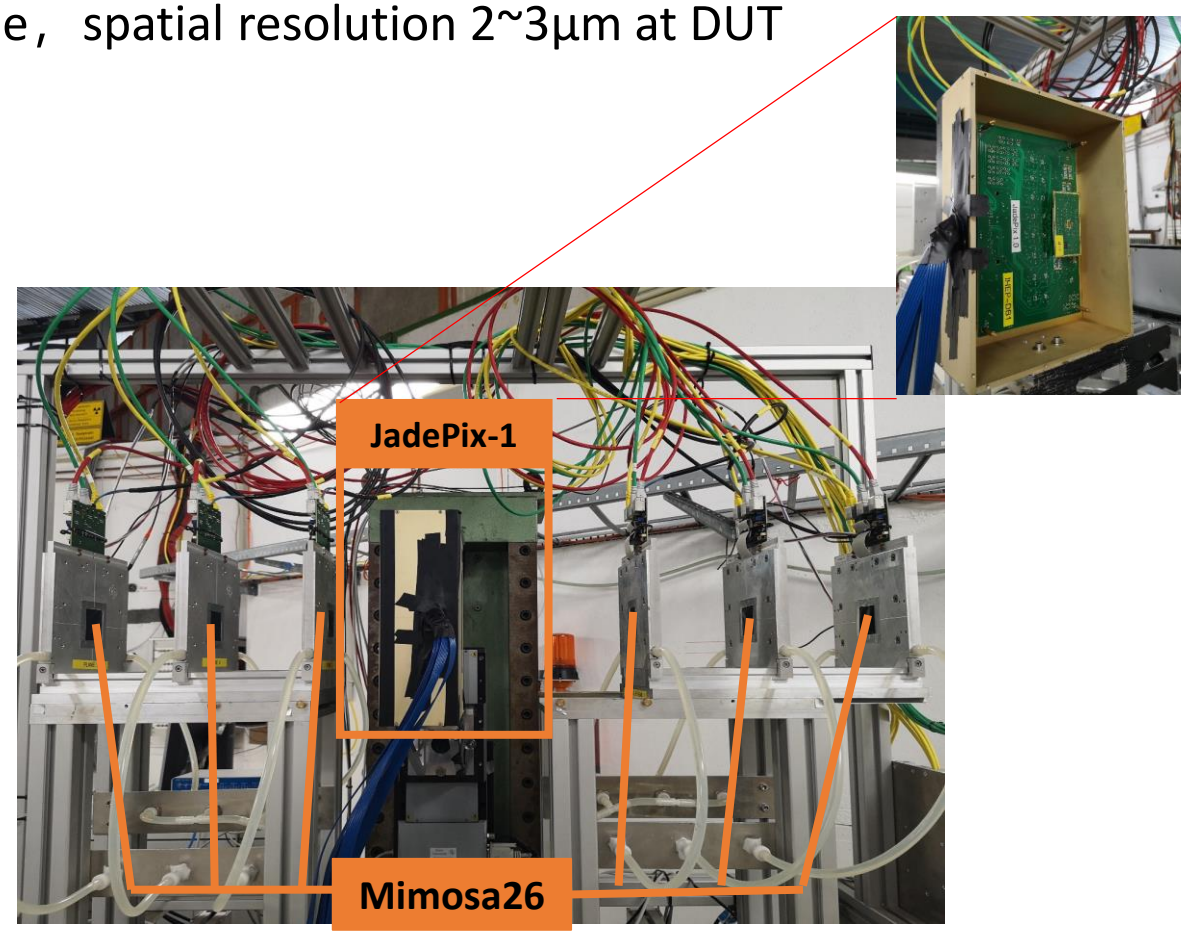




Tests with Electron Beams

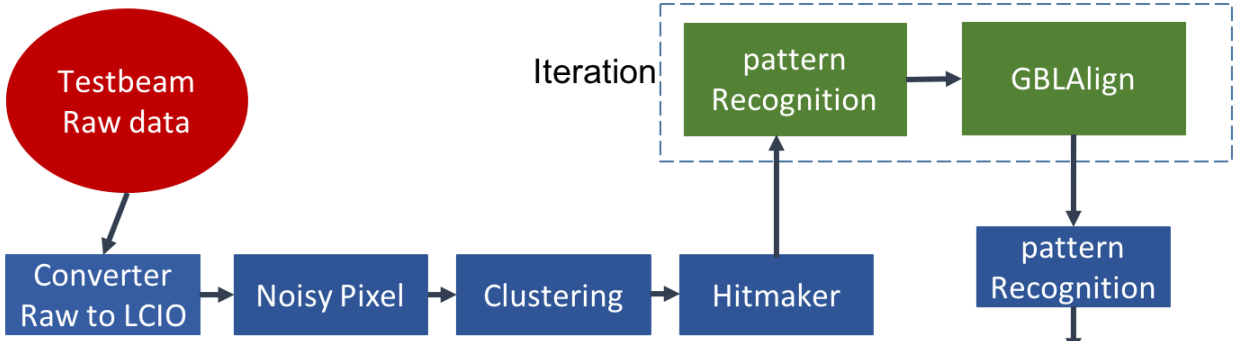
- Sensor characterized with the DESY electron beam in September
  - Beam energy 1-6 GeV, beam size 1x1 cm^2, data taken at 4.4GeV
  - EUDET beam telescope, spatial resolution 2~3μm at DUT



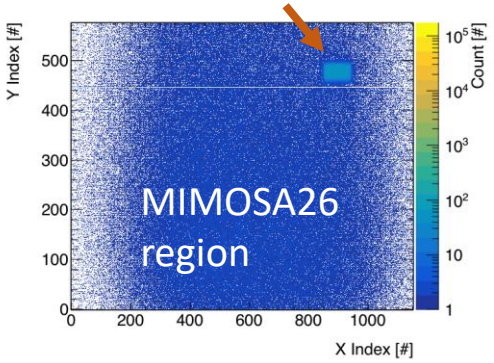


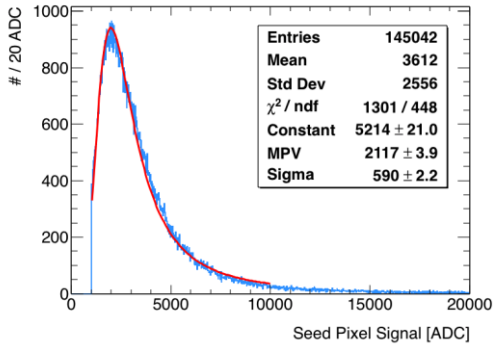
Track Reconstruction

- Raw data converted to LCIO format using a customized EUDAQ version
- Sparse clustering to group pixels if they are within the defined distance
- General Broken Lines (GBL) algorithm to align reference planes and DUT



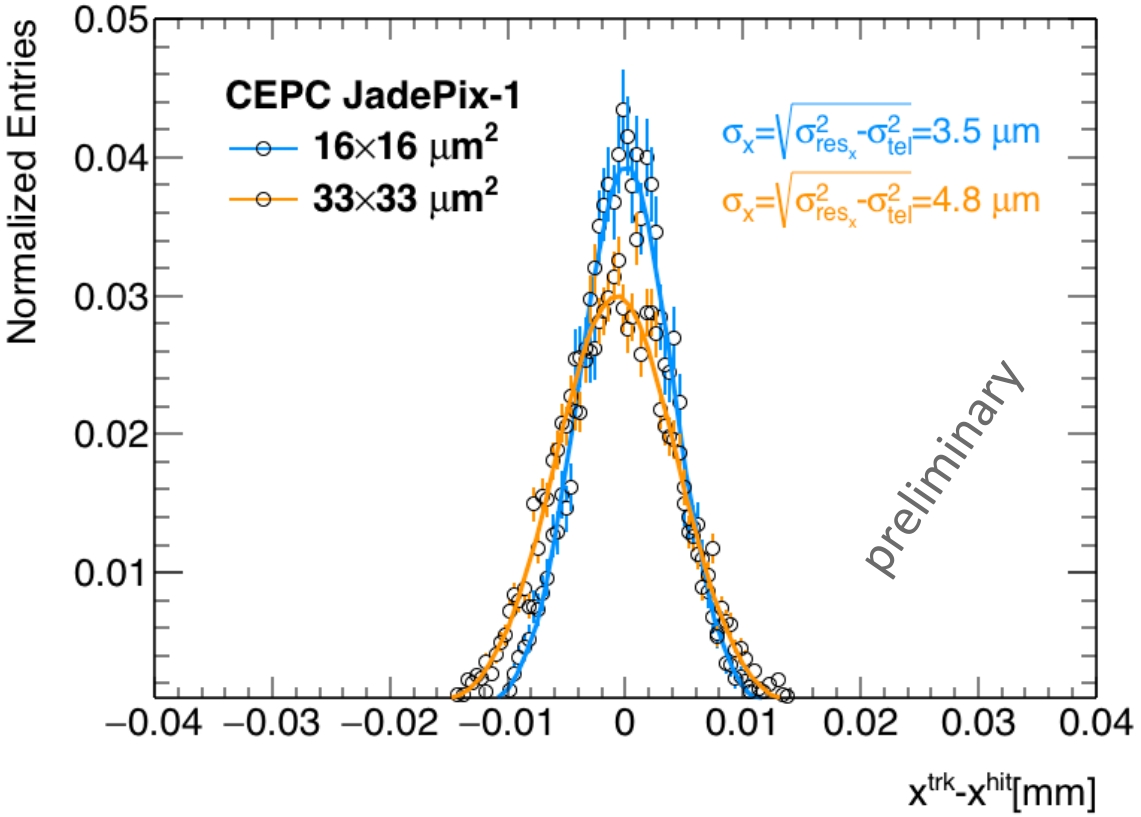
JadePix-1 region





Spatial Resolutions

- Spatial resolutions better than 5 μm and 3.5 μm achieved for pixel sizes of 33x33 μm^2 and 16x16 μm^2

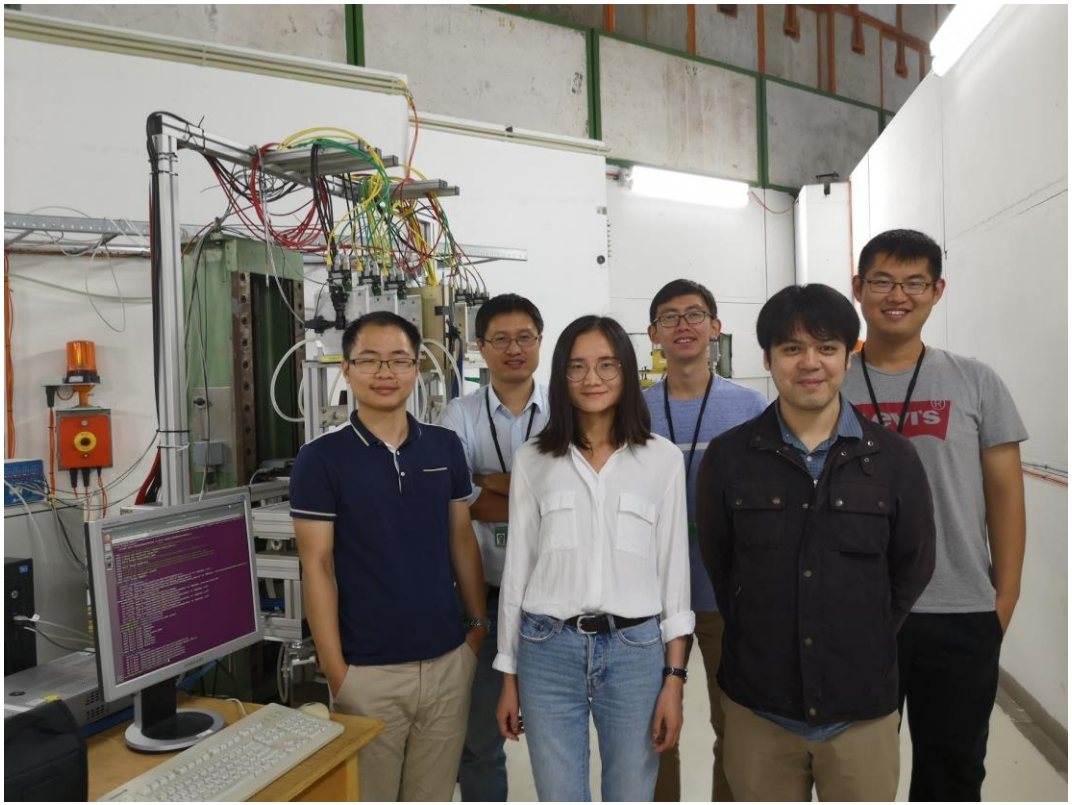


Summary and Outlook

- Developed the first prototype JadePix-1 for the CEPC vertex detector.
- Sensors characterized with radioactive resources and the DESY electron test beam using a customized DAQ system; obtained useful information for future designs
- Performance evaluation of the irradiated samples still ongoing

Thanks for your attention!

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.



Test beam participants:

Back: Hongbo Zhu, Chenfei Yang, Jia Tao

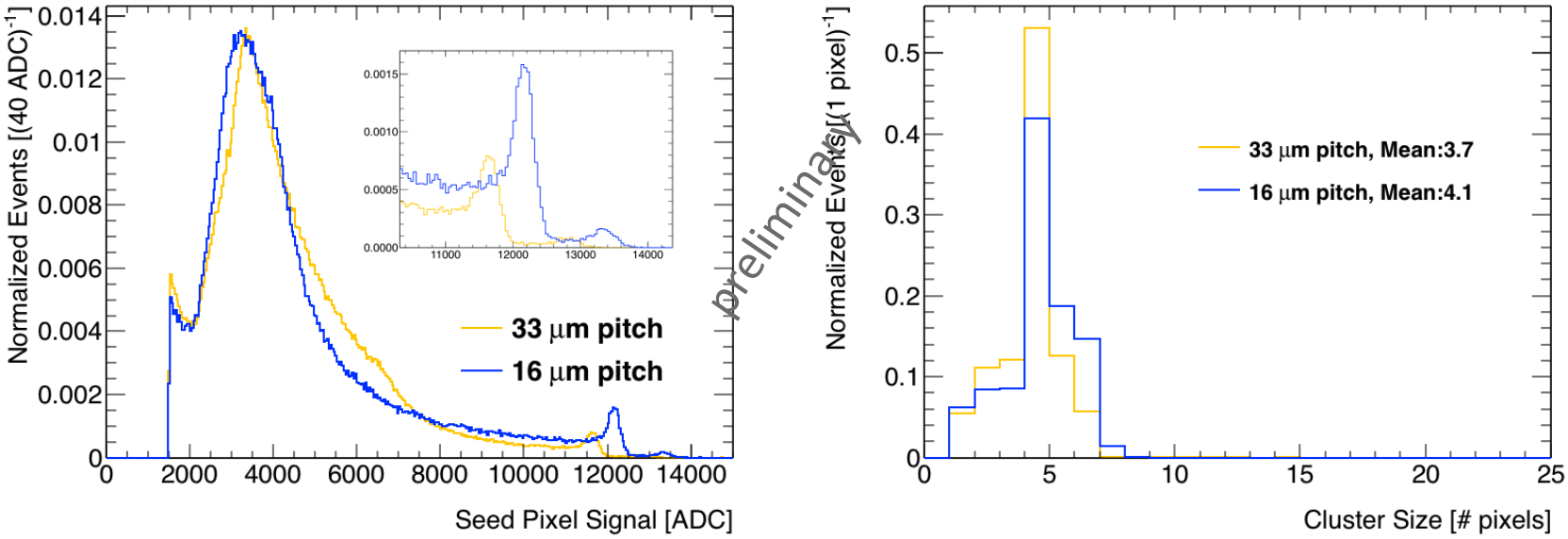
Front: Liejian Chen, Xiaocong Ai, Ryuta Kiuchi

Not in picture:

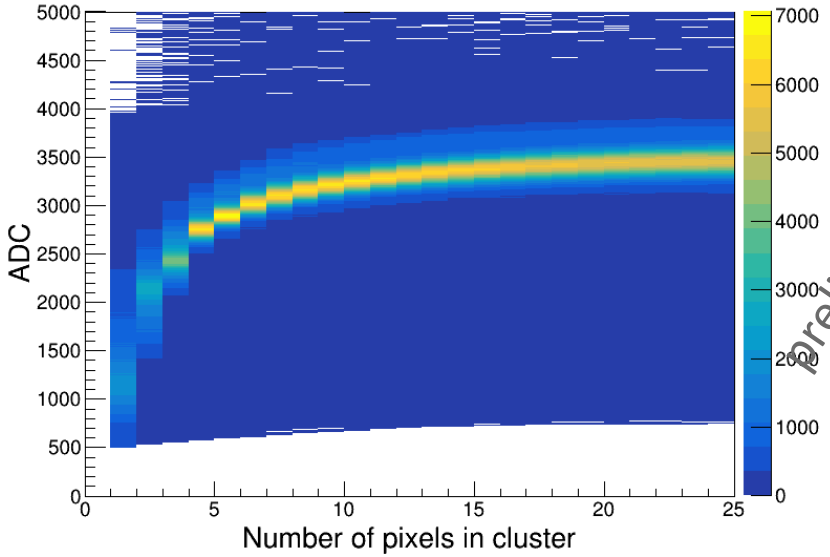
Yi Liu, Shuo Han, Yanping Huang, Yifan Hu, Ying Zhang, Ke Wang

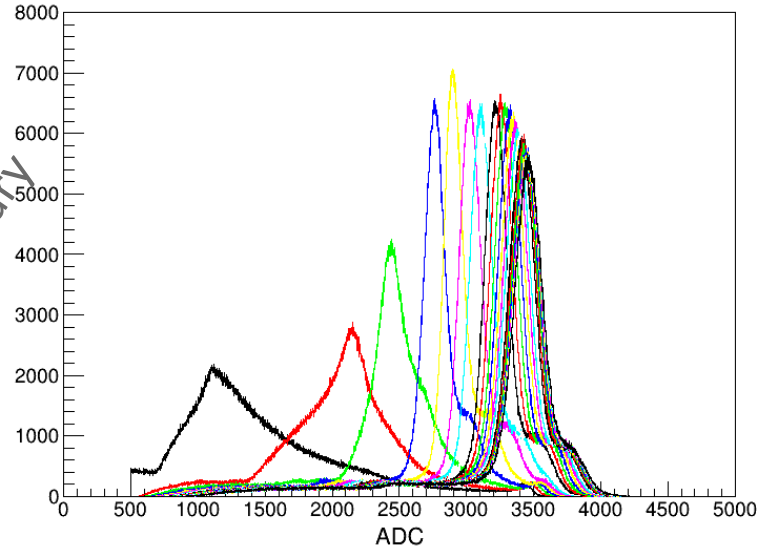
Pixel Pitch

- 4 μm^2 diode surface, 20 μm^2 footprint
- Small pixel larger gain and cluster size

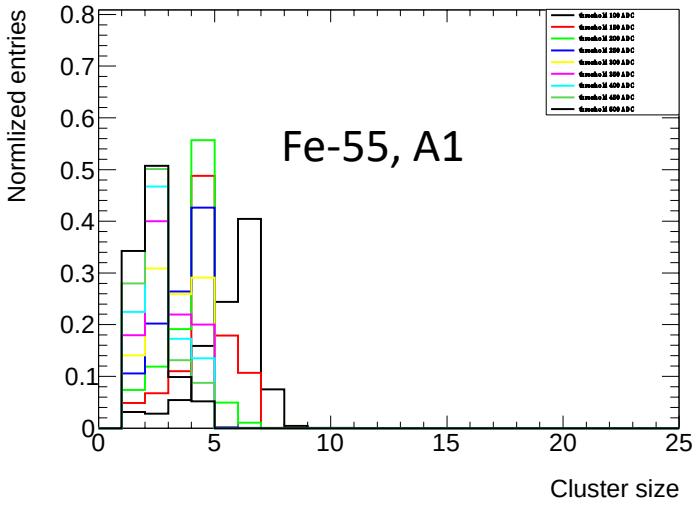


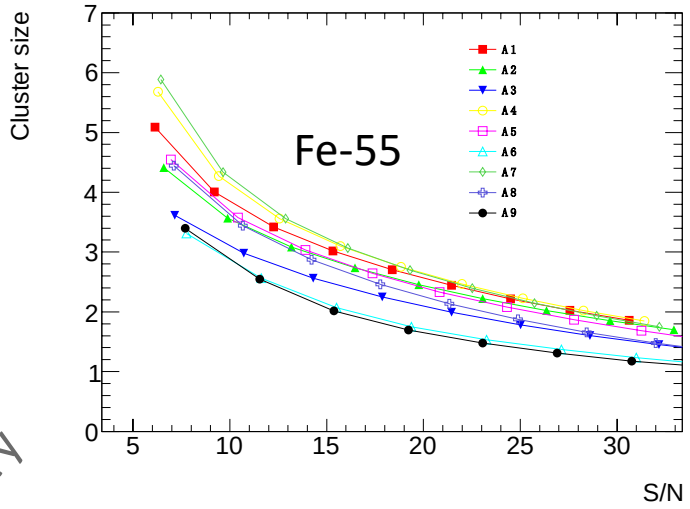
Cluster Charge Distribution





Cluster Size





preliminary