“Sensor Prototypes for CEPC Vertex Detector”

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on behalf of CEPC pixel sensor development teams

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Outline

- Introduction

  -- General requirement for the CEPC vertex detector

- Pixel prototype

  -- Sensor prototypes

  -- Test results of “Jadepix1”

  -- MOST2 pixel project

- Summary

Main Beam Parameter for CEPC operation

	Higgs	W	Z (3T)	Z (2T)
Center-of-mass energy (GeV)	240	160	91	
Number of IPs	2			
Luminosity/IP (10^{34} cm^{-2} s^{-1})	3	10	16	32
Number of years	7	1	2	
Total Integrated Luminosity (ab^{-1}) - 2 IP	5.6	2.6	8	16
Total number of particles	1×10^6	2×10^7	3×10^{11}	7×10^{11}
Bunch numbers (**Bunch spacing**)	242 (**680 ns**)	1524 (**210 ns**)	12000 (**25ns + 10% gap**)	

from CDR

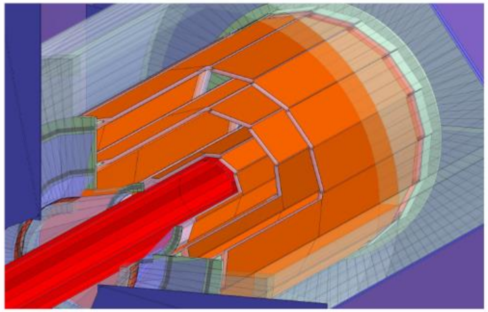
- Continuous colliding mode
  - Duty cycle ~ 50% @ Higgs, close to 100% @ W/Z
- General requirement on the detector development:
  - Precise measurement, Low power, Fast readout, Radiation-hard

Baseline Silicon Tracker Layout

- Tracker

  -- SIT, SET, ETD, and 3 outer disks of FTD, ETD: single-sided strips mounted back to back

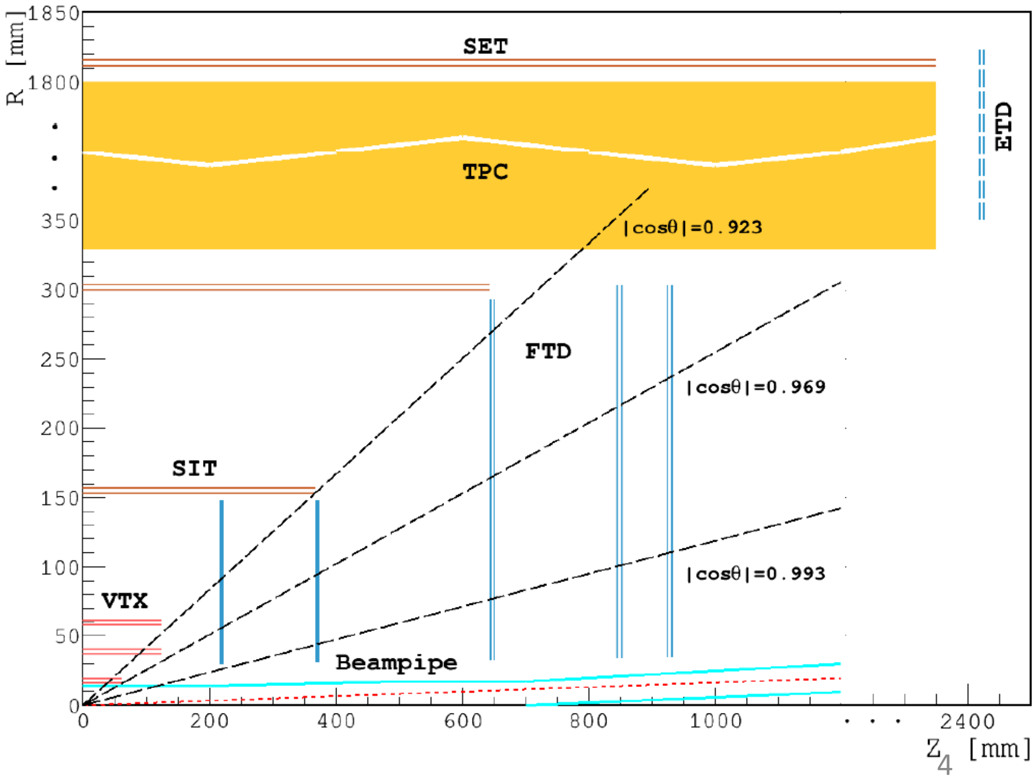
  -- 2 inner disks of FTD: pixel



- Vertex detector

  -- 3 double-sided pixel layers

	R (mm)	$\lvert z \rvert$ (mm)	$\lvert\cos\theta\rvert$	$\sigma(\mu m)$
Layer 1	16	62.5	0.97	2.8
Layer 2	18	62.5	0.96	6
Layer 3	37	125.0	0.96	4
Layer 4	39	125.0	0.95	4
Layer 5	58	125.0	0.91	4
Layer 6	60	125.0	0.90	4



Performance Requirements

B = 3T

- Momentum Resolution: $\sigma_{1/p_T} = 2\times10^{-5} \oplus 1\times10^{-3} / (p_T \sin\theta)$
- Impact Parameter Resolution: $\sigma_{r\phi} = 5\mu m \oplus \frac{10}{p(GeV)\sin^{3/2}\theta}\mu m$

Vertex specifications:

- σ_{SP} near the IP: ≤ 3 μm
- Material budget: ≤ 0.15% X_0 / layer
- First layer located at a radius: ~1.6 cm
- Pixel occupancy: ≤ 1 %

Tracking specifications:

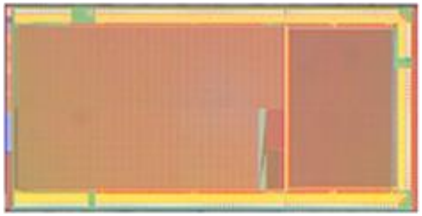
- σ_{SP} : ≤ 7 μm
- Material budget: ≤ 0.65% X_0 / layer

Pixel Sensor Specification

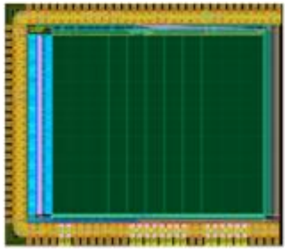
- To achieve single point resolution
  - Pixel size ~ 16 μm (Binary readout)
- To lower the material budget
  - Sensor thickness ~ 50 μm
  - Air cooling, heat load < 50 mW / cm^2
- To tackle beam-related background
  - Fast readout 1 ~ 100 μs / frame
  - 3.4Mrad / year & $6.2\times10^{12} n_{eq}$ / ($cm^2\cdot$year)?

Pixel Sensor Prototypes

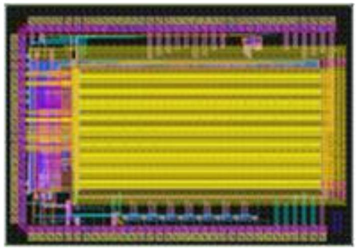
	Process	Pixel Pitch (μm^2)	Matrix size	R/O architecture
"JadePix1"	CMOS	33x33/16x16	96x160/192x128	Rolling Shutter
"JadePix2"	CMOS	22x22	128x64	Rolling Shutter
"MIC4"	CMOS	25x25	112x96	Asynchronous
"CPV2"	SOI	16x16	64x64	Rolling Shutter



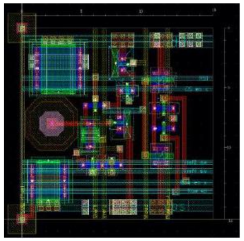
JadePix1
(3.9 x 7.9 mm^2)



JadePix2
(3 x 3.3 mm^2)



MIC4
(3.2 x 3.7 mm^2)



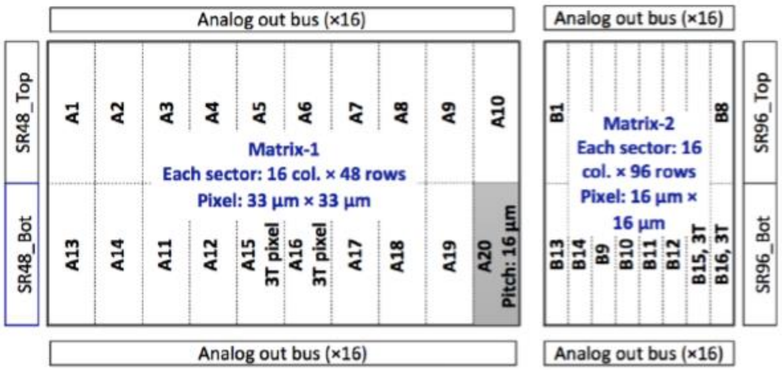
CPV2

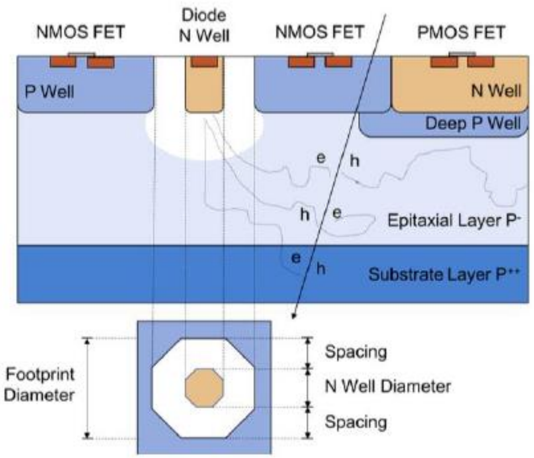
Detail will be presented by Dr. Yang Zhou (next talk)

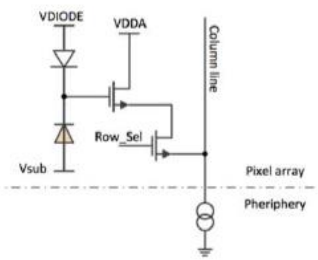
Hereafter, introduce JadePix1

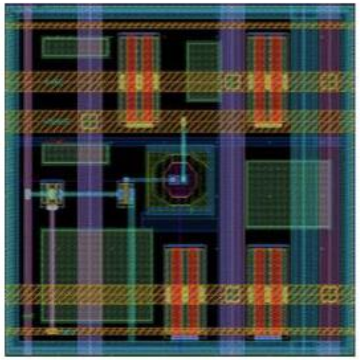
Prototype CMOS Pixel Sensor : JadePix1

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

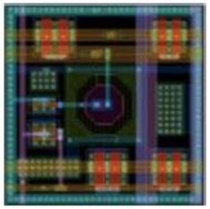








33 x 33 µm^2

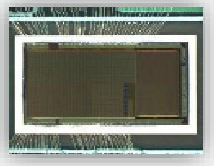


16 x 16 µm^2

- 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

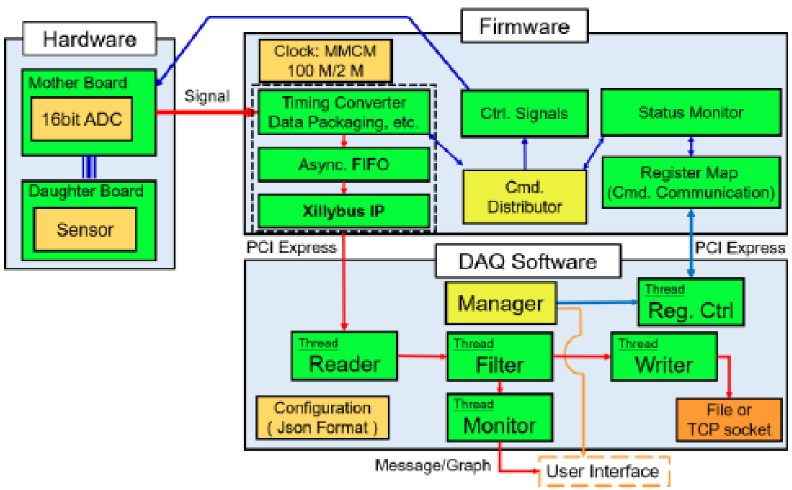


JadePix-1:
TJ 180 nm CPS

Daughter Board:
16 channels amplifier

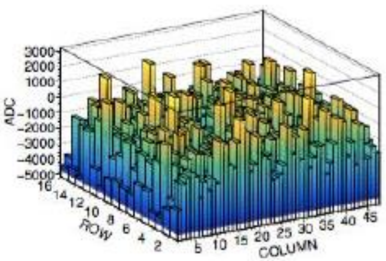
Mother Board:
16 bit ADC

KC705 FPGA Board:
6 Gbps PCIe

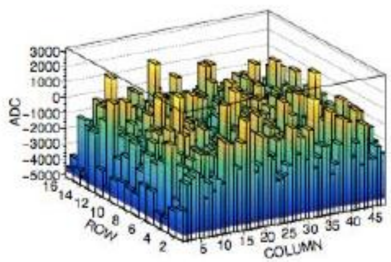


Test with ^{55}Fe

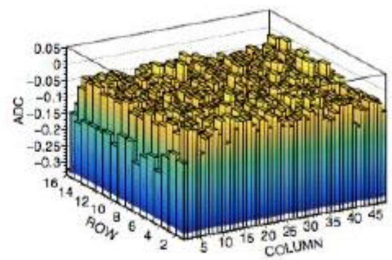
- Correlated Double Sampling (CDS) to suppress noise and extract signals
- Noise measured with/without radioactive source (exclude suspected signals and get multiple frames average)



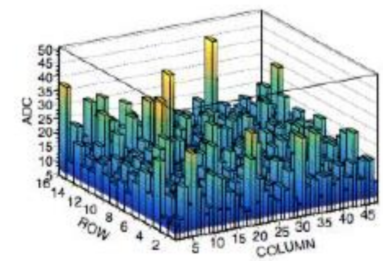
(a) First frame raw data



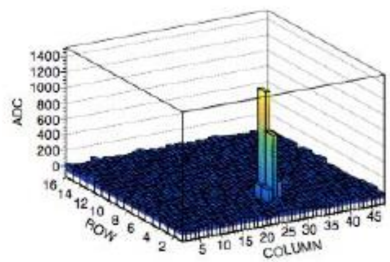
(b) Second frame raw data



(a) Pedestal distribution for 1 frame



(b) Noise distribution for 1 frame



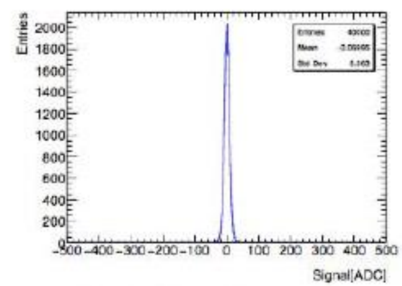
(c) CDS

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

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

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

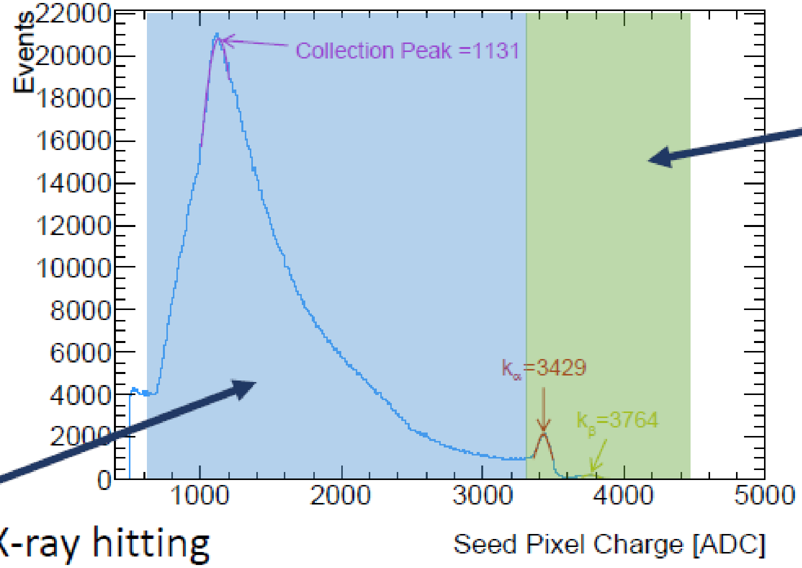
$$n_{k,N} = \sqrt{\frac{N'}{N'-1}}\sqrt{\left(\frac{1}{N'}\sum_{j=1}^{N'}(\tilde{r}_k^j)^2\right) - (p_{k,N}^{\text{est}})^2}$$



(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

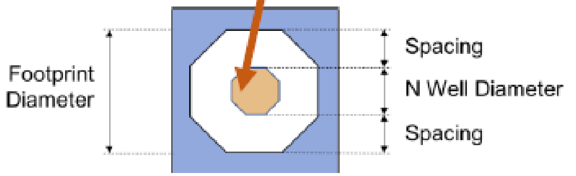
the charges with X-ray hitting other place disperse slowly towards diode on thermal diffuse to neighbor pixel

- ^{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:

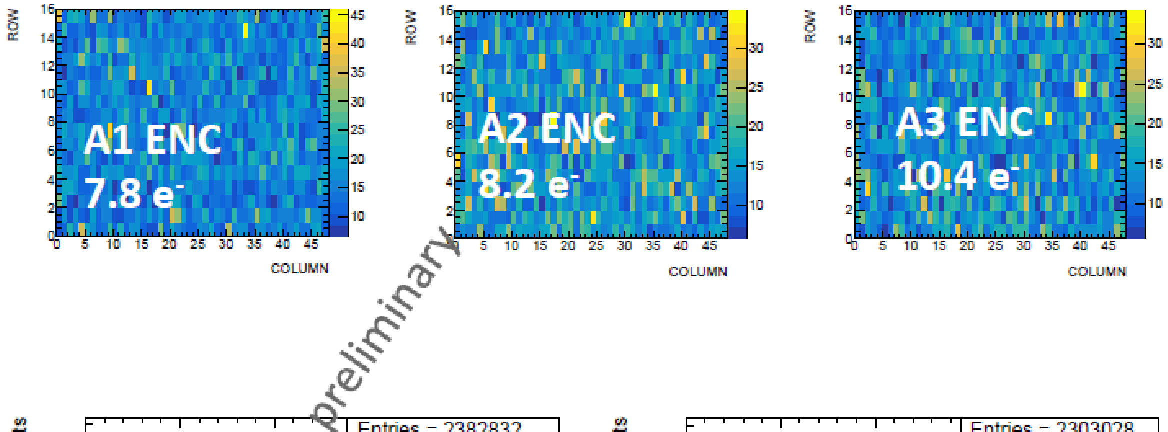
$$N_{e-h} = \frac{E_\alpha}{\varpi} = 1640$$

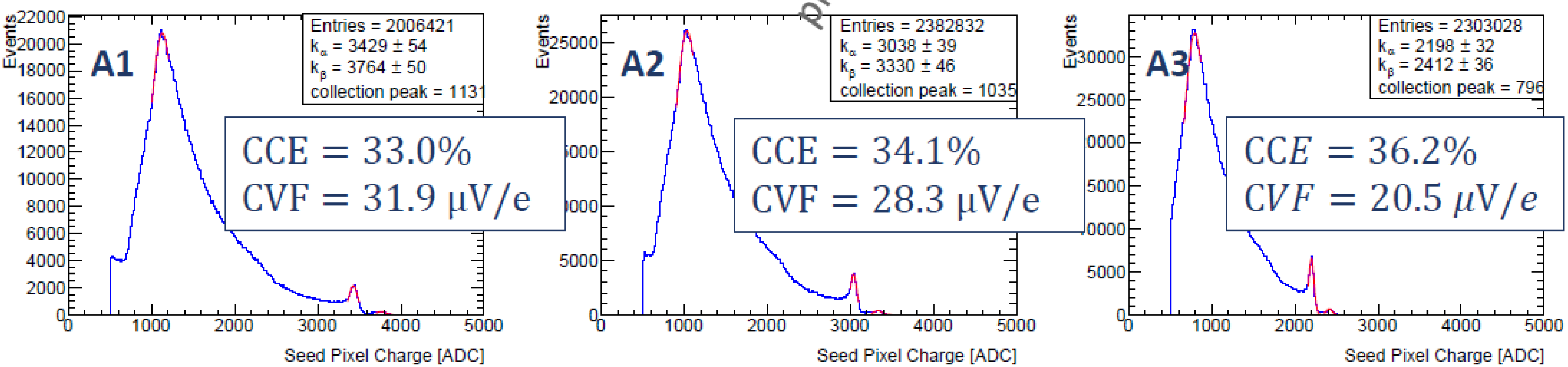
Diode Surface

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



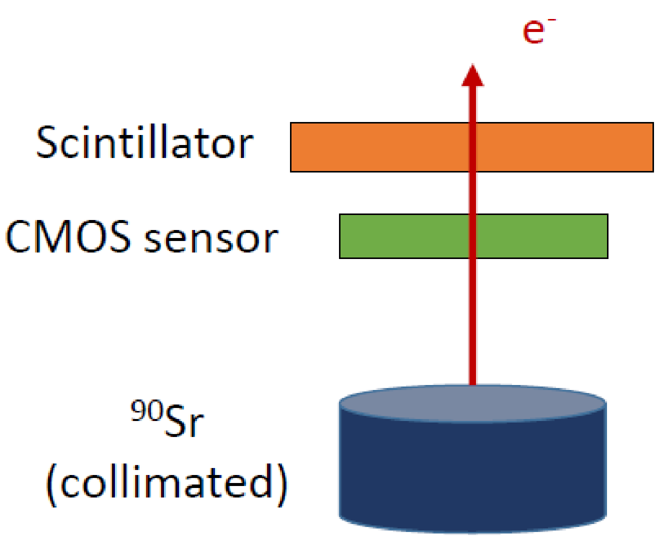
Sector	*Diode surface*	*Footprint*
A1	4 μm²	30 μm²
A2	8 μm²	30 μm²
A3	15 μm²	30 μm²

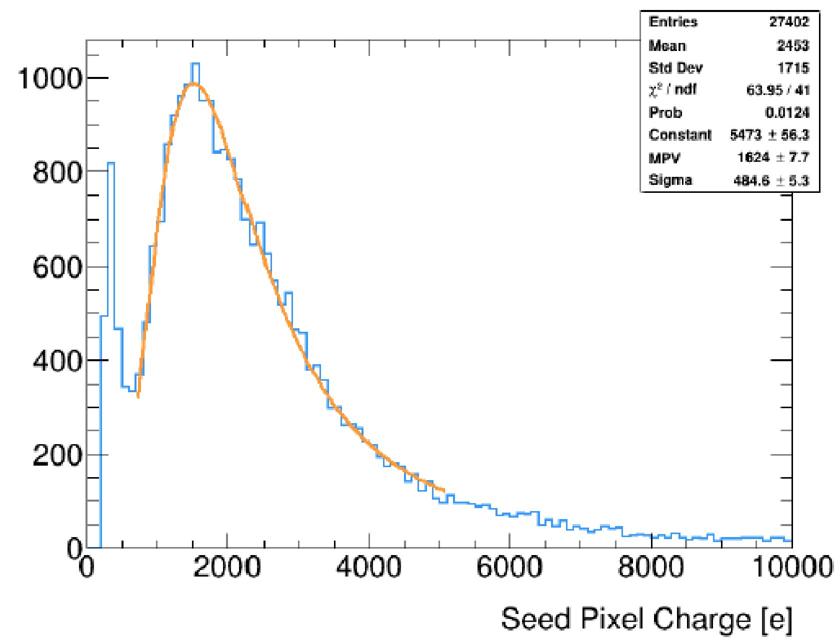




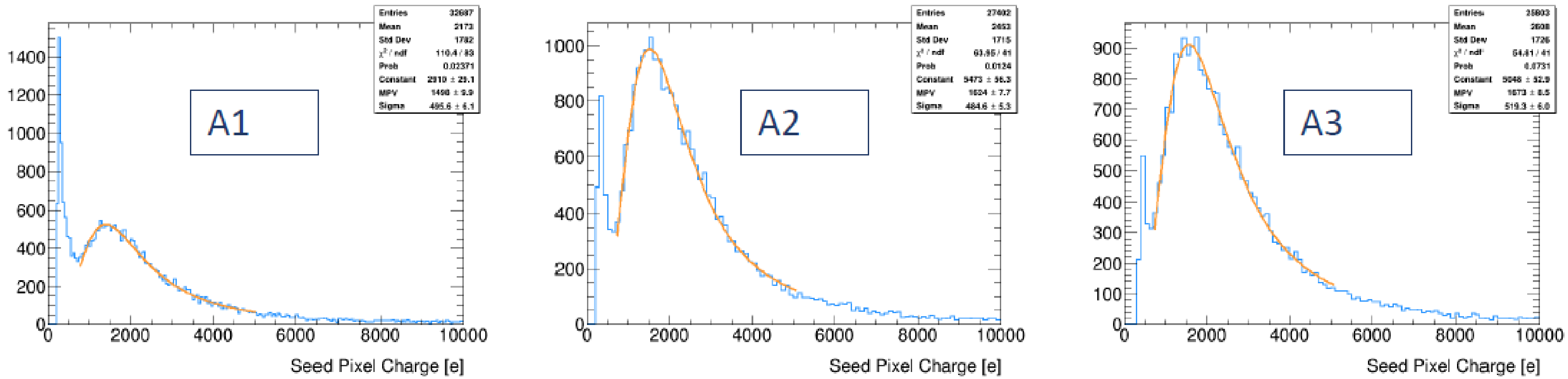
Test with ^{90}Sr

- 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

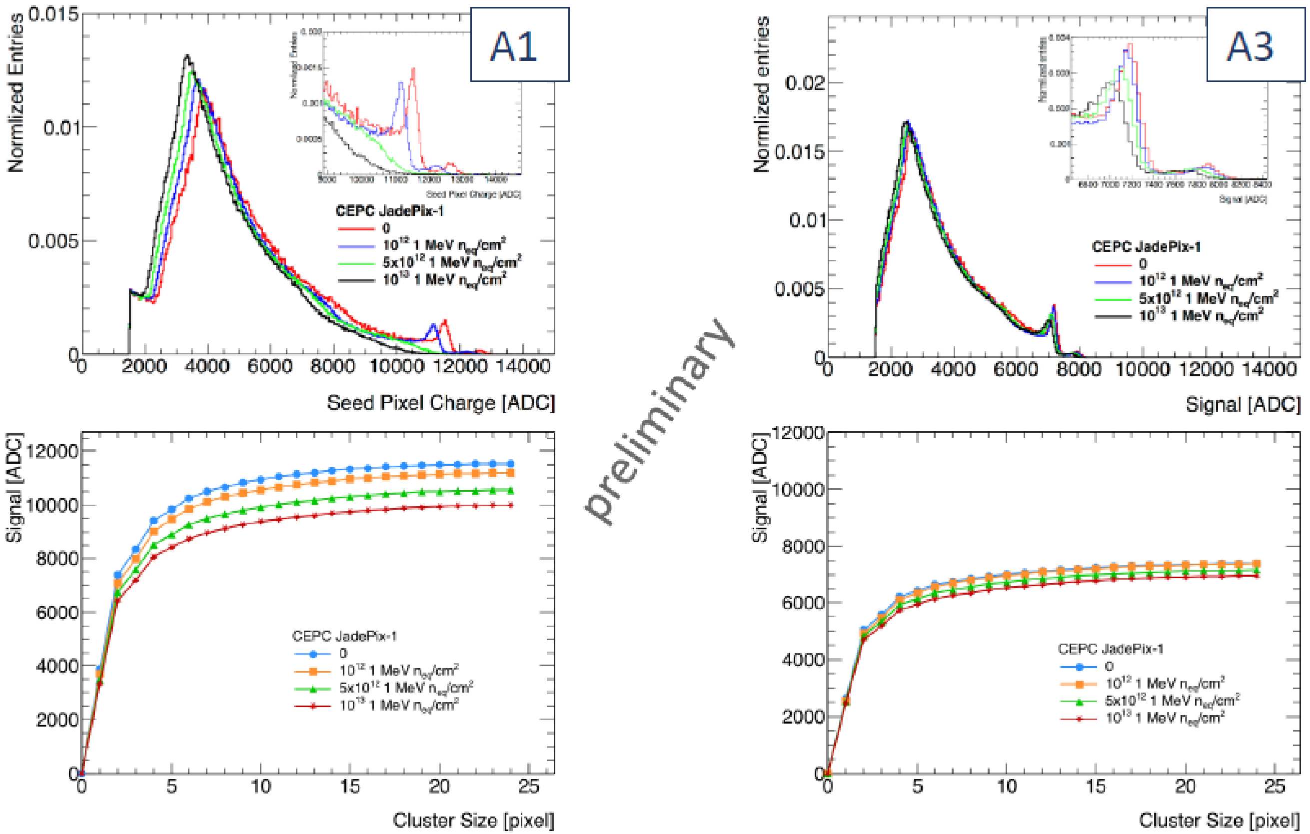


preliminary

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

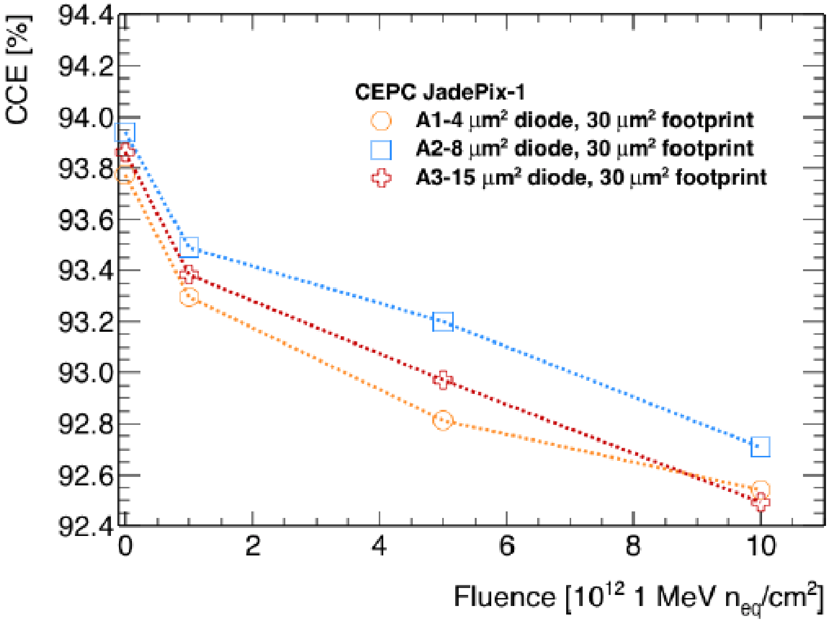
Performance After Irradiation

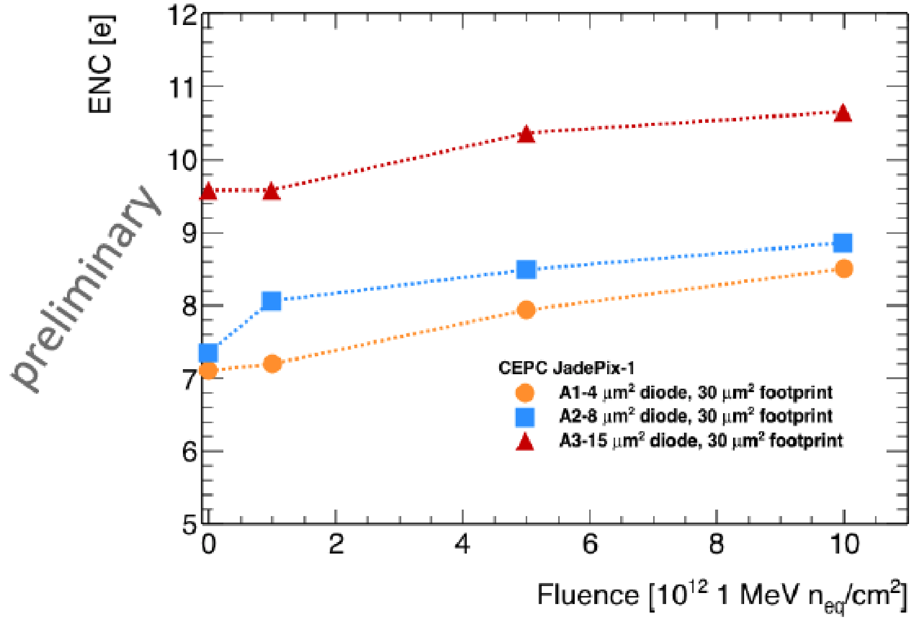
- Samples sent to a pulsed neutron reactors and irradiated to fluences of 10^{12}, 5×10^{12}, and 10^{13} 1 MeV n_{eq}/cm^2
- Larger diode (A3 >A1) more radiation hard as expected



Performance After Irradiation

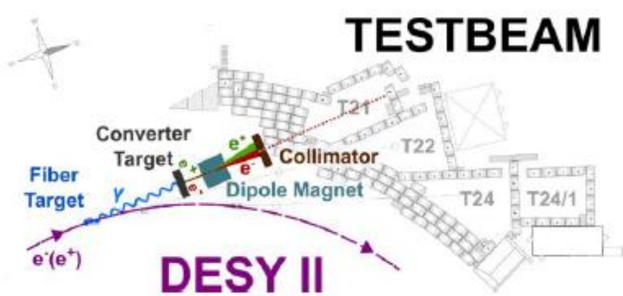
- Charge collection efficiency decreases but noise increases as the neutron fluence goes higher

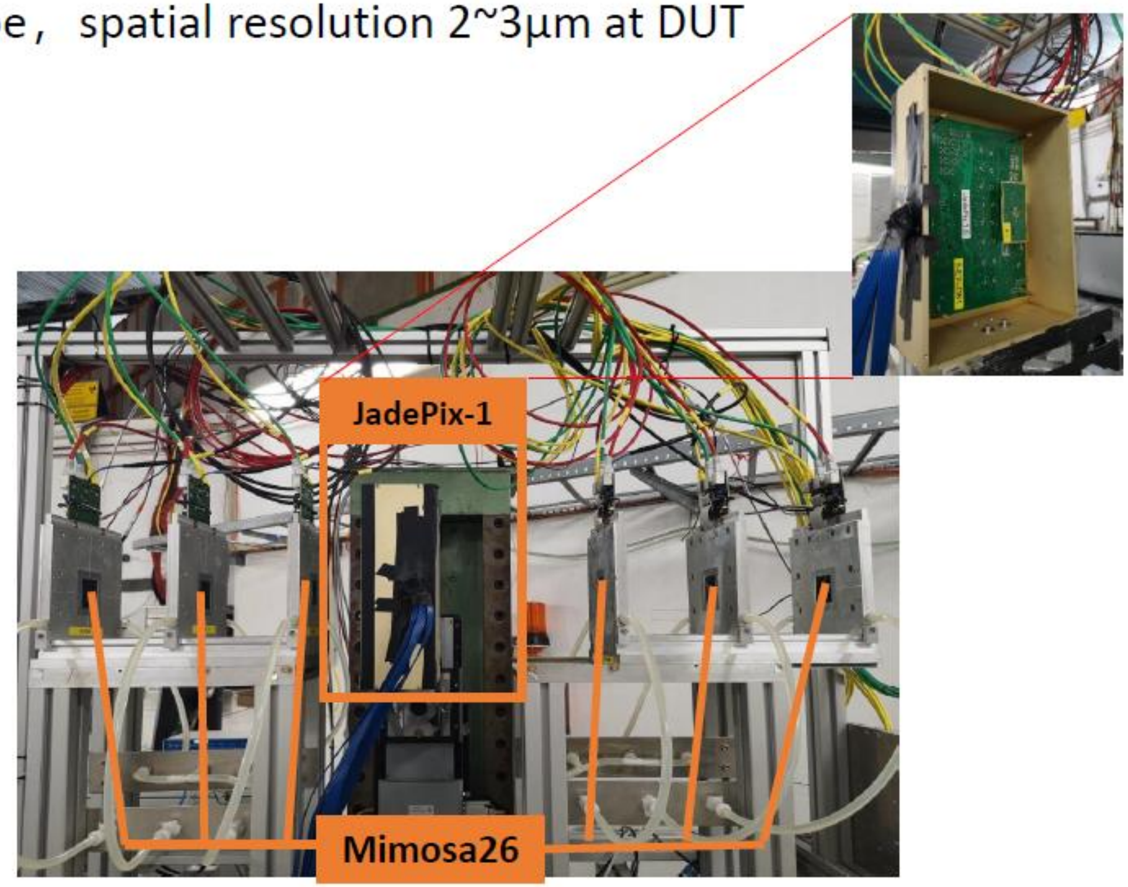




Tests with Electron Beams

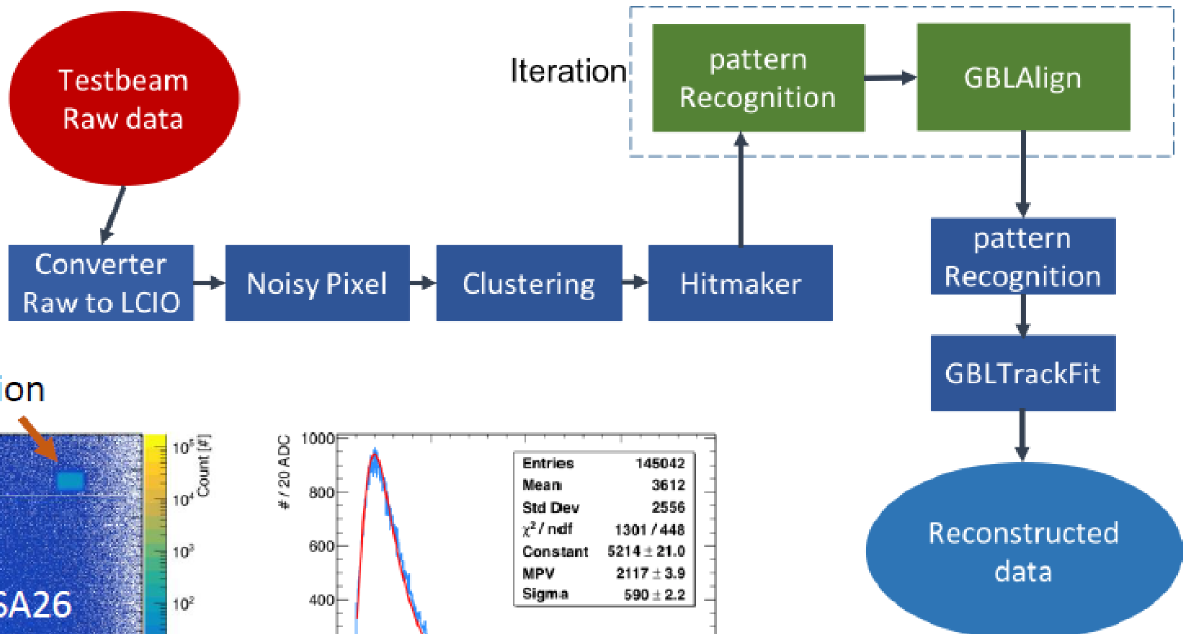
- Sensor characterized with the DESY electron beam in September
  - Beam energy 1-6 GeV, beam size 1x1 cm^2， data taken at 4.4GeV
  - EUDET beam telescope， spatial resolution 2~3μm at DUT

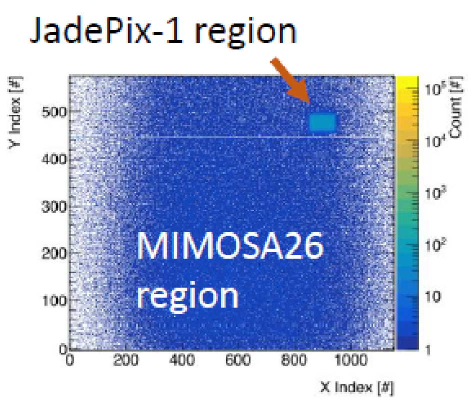


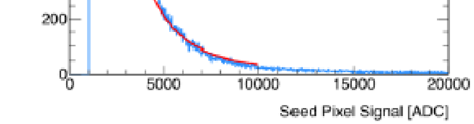


Track Reconstruction

- 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

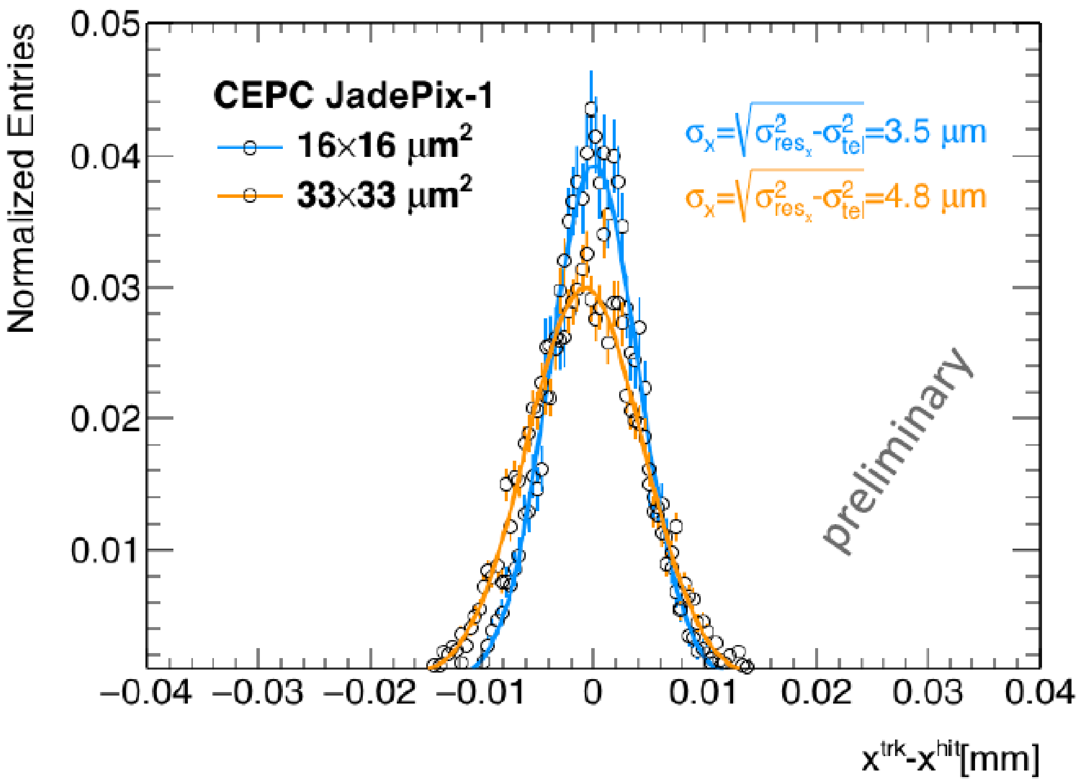




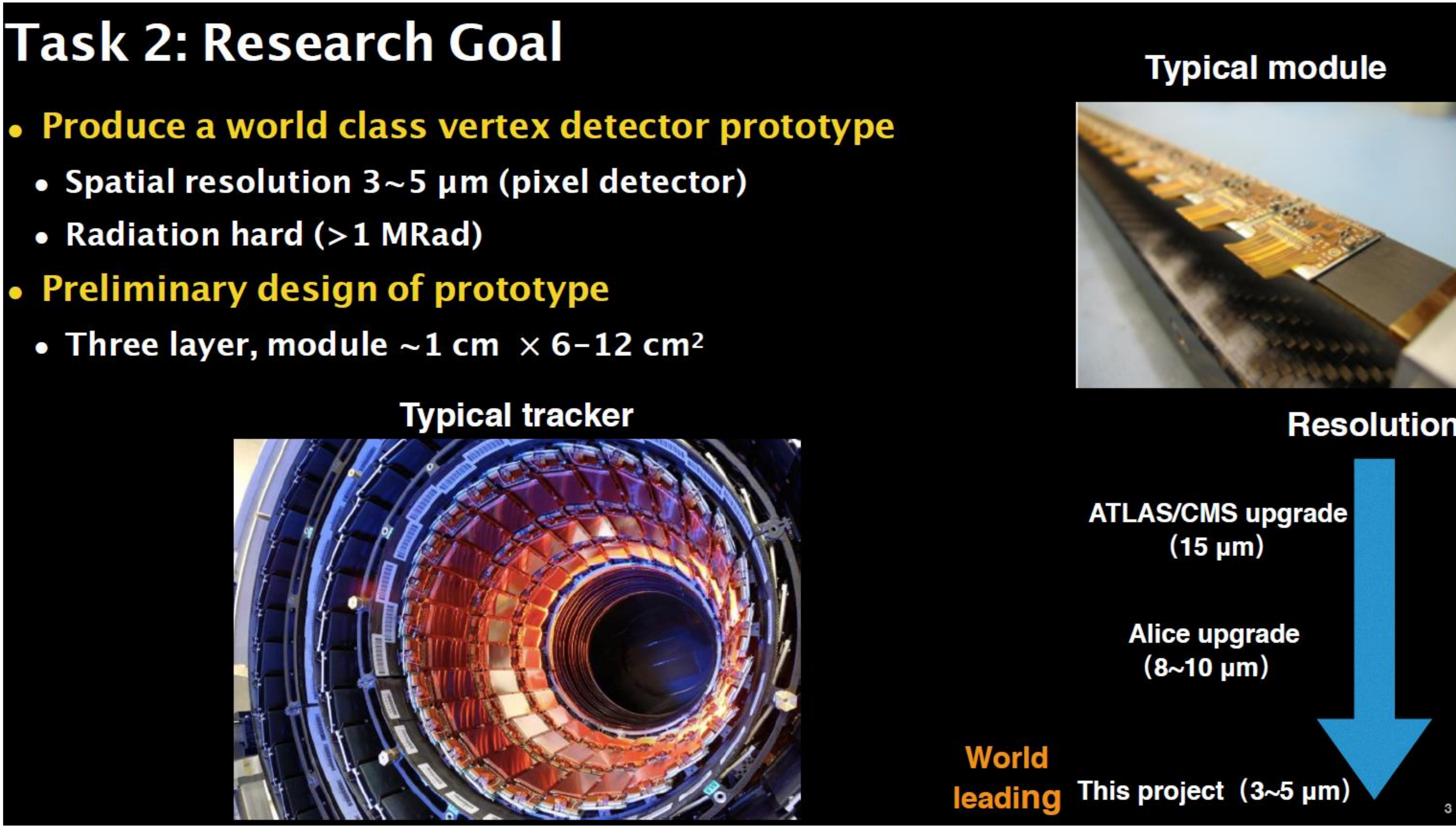


Spatial Resolutions

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



MOST2 -- Pixel Detector Project



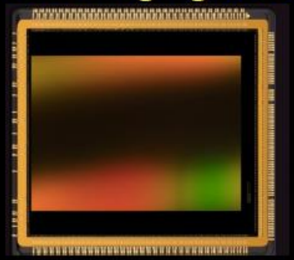
- **Ref: Introduction to the Pixel MOST2 Project, Joao Costa, 2018.6**

MOST2 -- Pixel Detector Project

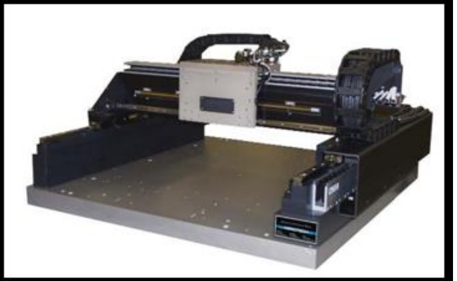
Task 2: Technical route and schedule

- Use CMOS image sensor technology
- Optimize pixel circuitry, reduce size → **High resolution**
- Special design and latest technology → **Radiation hard**
- Use carbon fiber, polyamide, graphene, and other light materials for mechanical structure → **Low mass**
- Robot automatic mechanical assembly → **High accuracy**

CMOS imaging sensor



Gantry



项目启动

Data acquisition R&D

Design of mechanical structure

Sensor design, fabrication

Prototype assembly

Beam testing

第一年 第二年 第三年 第四年 第五年

项目结题

4

- **Ref: Introduction to the Pixel MOST2 Project, Joao Costa, 2018.6**

Summary

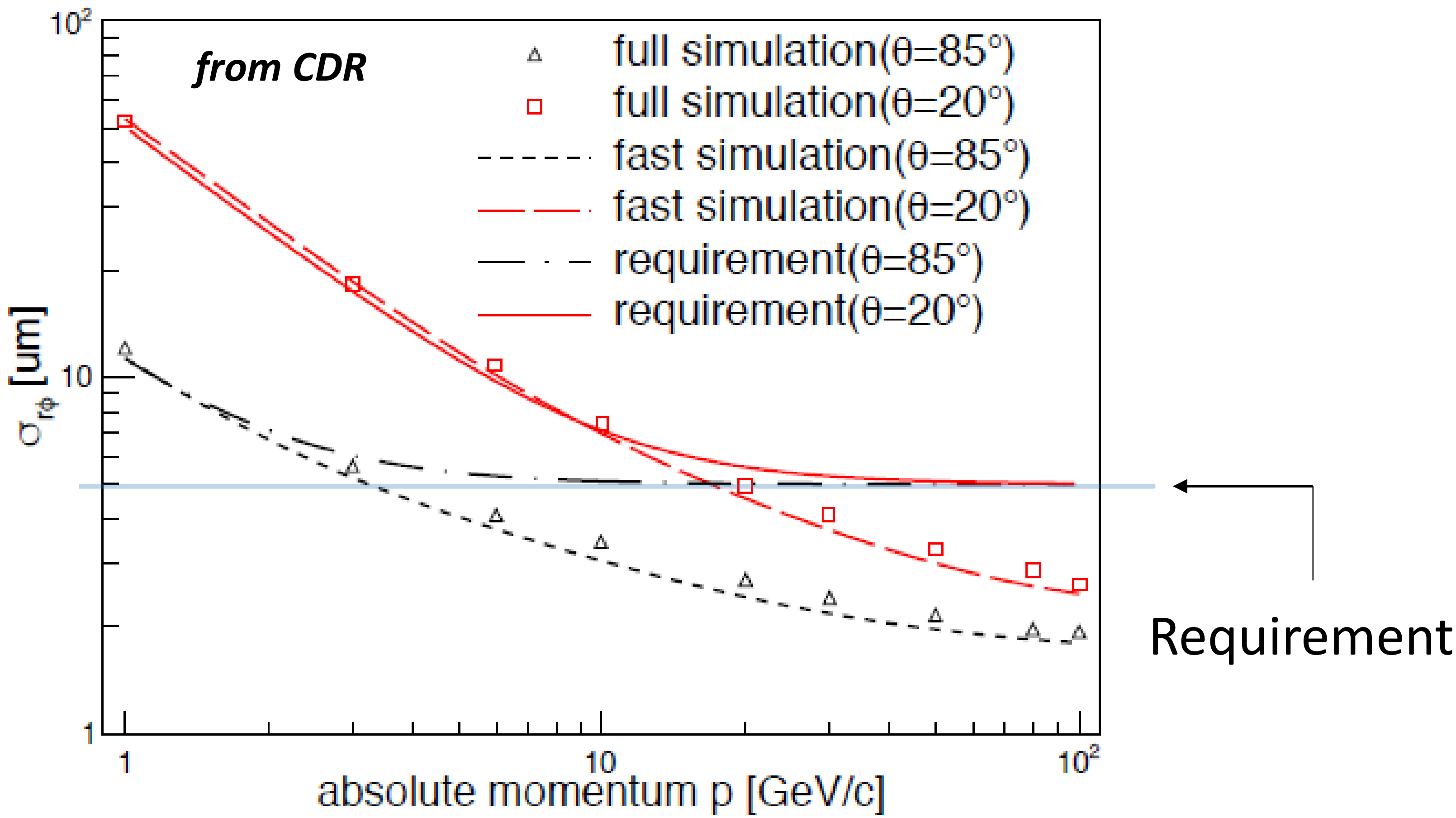
・ Pixel design of high spatial resolution, low power and fast readout is required for the CEPC silicon tracker.

・Several types of prototype pixel sensors for the CEPC are designed. Characterization of the prototype, JadePix1, discussed in this talk as one of example, gives us useful information for future designs.

・All those R&D, including the MOST2 project, are now on-going.

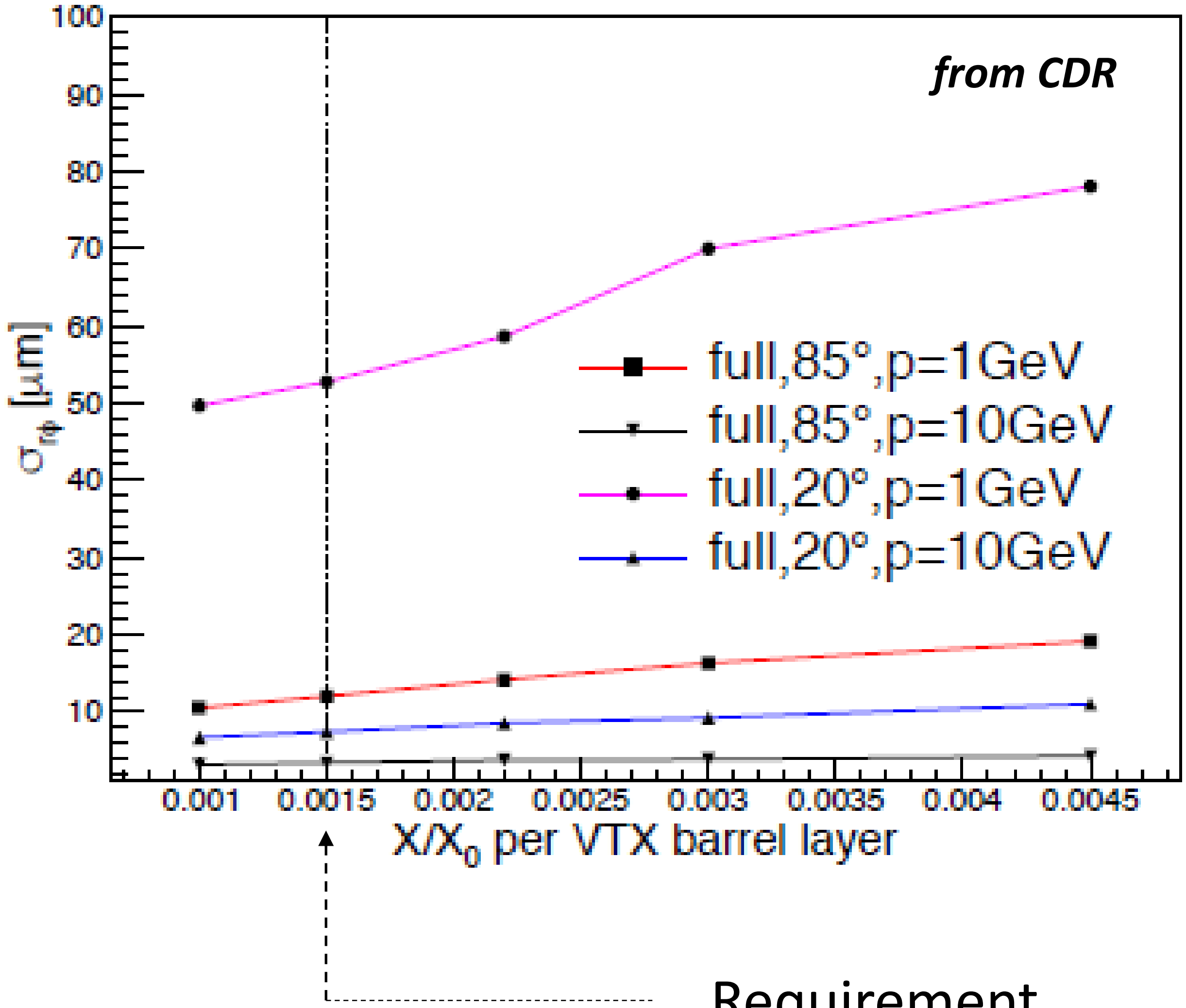
Backup

Performance studies: Impact parameter resolution



Impact parameter resolution goal achievable with current design

Performance studies: Material budget

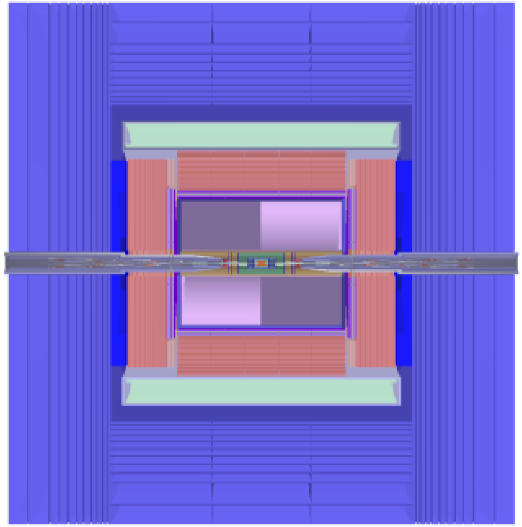


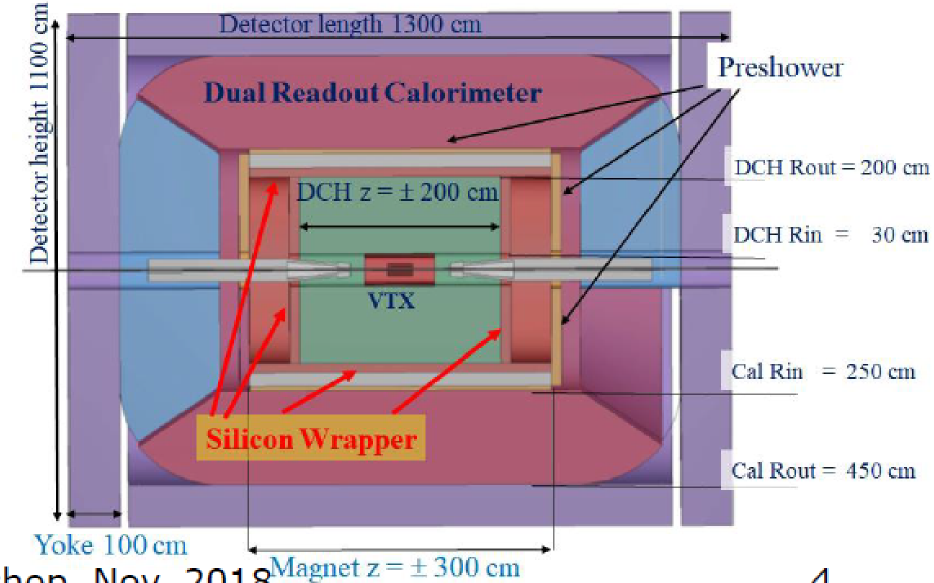
It is studied that the resolution degrades by ~20%, when increasing the material of all detector layers by a factor of two

Two Detector Concepts

- Baseline detector concept
  - Silicon tracker + TPC

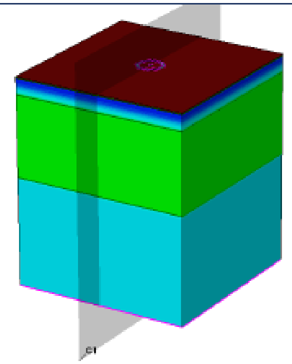
  or Full Silicon Tracker
  - High granular calorimetry system
  - 3 Tesla solenoid
  - Muon detector
- Alternative detector concept, IDEA
  - Silicon pixel + Drift Chamber
  - 2 Tesla solenoid
  - Dual readout calorimeter
  - Muon chamber



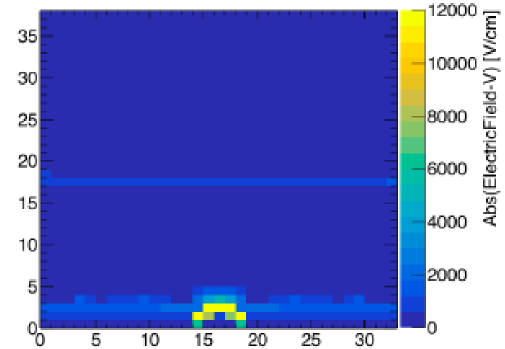


Simulation

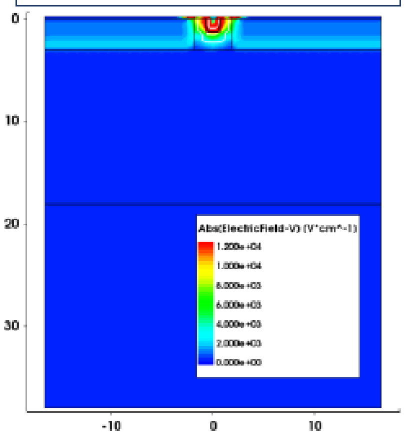
Build Sentaurus TCAD model

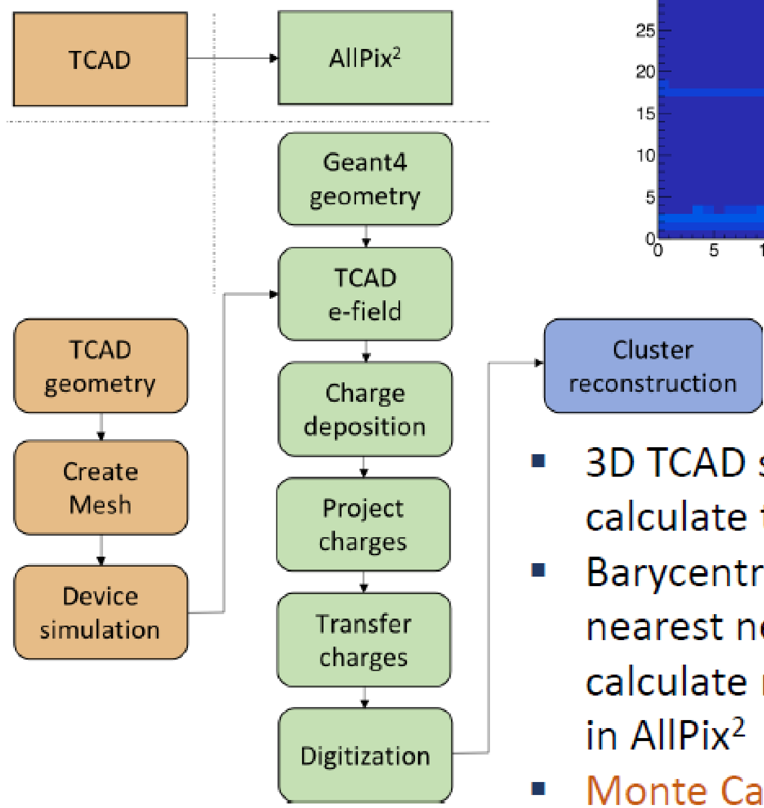


Interpolate on regular mesh



Extract electric field



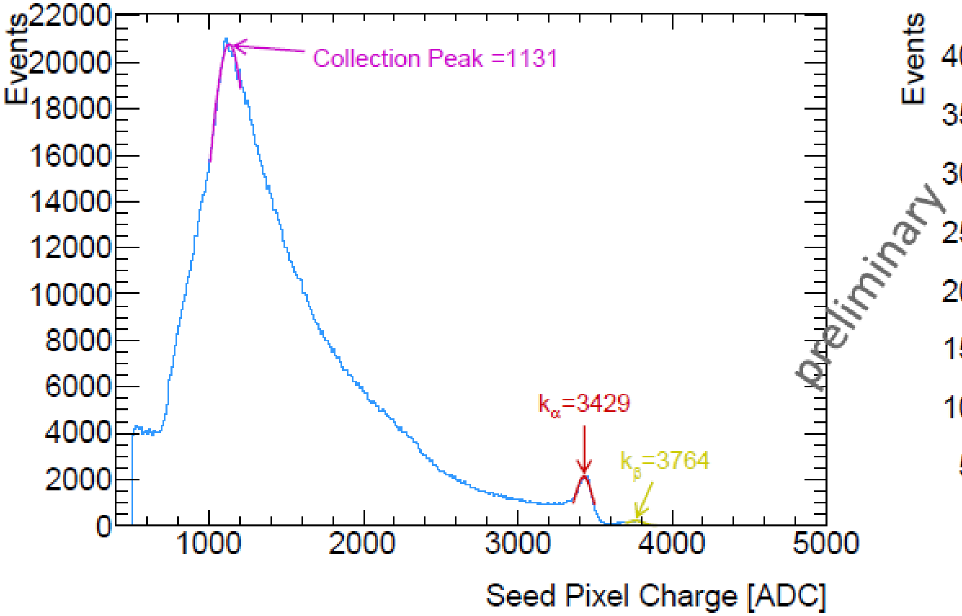


- 3D TCAD simulations are used to calculate the Electric Field Map
- Barycentric interpolation using nearest neighbors is used to calculate results on regular mesh in AllPix^2
- Monte Carlo sampling algorithm used for radioactive source

Simulation vs Measurement

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

Measurement



Simulation（TCAD+AllPix²）