Performance evaluation of an SOI pixel sensor with in-pixel binary counters

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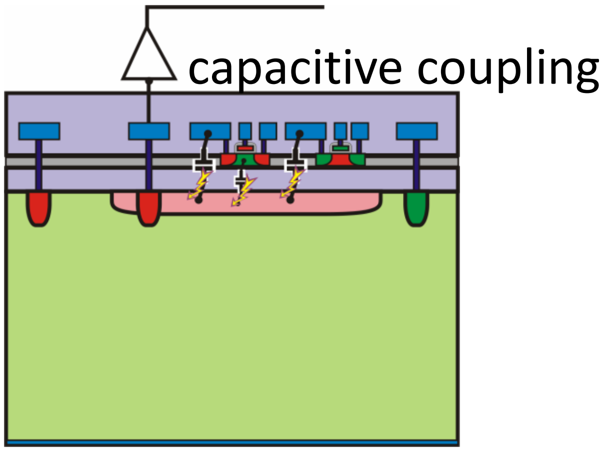
Outline

- Introduction
- Chip concepts
- Noise performance
- Point spread function
- X-ray sensitivity
- Summary and outlook

Introduction

- Merits of SOI pixel detector
  - Monolithic process
  - Full in-pixel CMOS circuitry
  - Small parasitic capacitance
  - High resistive handle wafer with full depletion thickness up to several hundred microns



G. DEPTUCH, SOIPIX 2010

- Digital pickup in SOI sensor

- Motivation of prototype CPIXTEG3b
  - Double-SOI process to solve the pickup issue
  - High resolution low noise detector for X-ray imaging

Introduction

- Design optimization and single pixel test results can be found in
  - Y. Lu et al., Nucl. Instrum. Methods Phys. Res. A 831 44-48 (2016).

- This report mainly focuses on
  - The noise performance of the full matrix
  - Detection of X-ray photons measured on a synchrotron X-ray beam

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  - Pixel circuit
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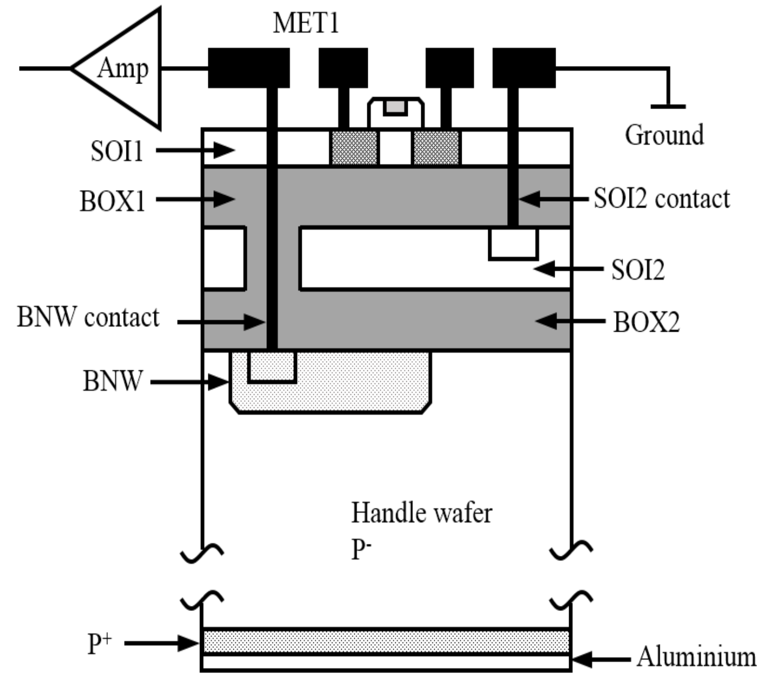
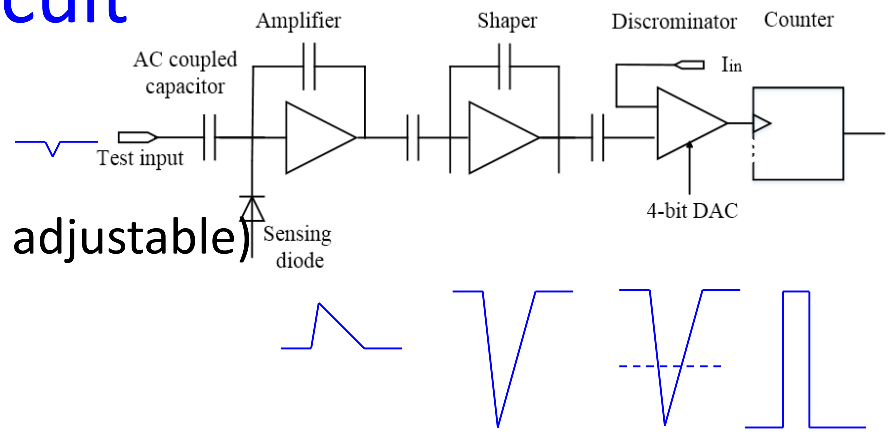
Double-SOI pixel sensor

- 50 µm pixel pitch
- High resistive sensitive layer
  - P type substrate > 1kΩ-cm
  - 300 µm full depletion thickness
- Charge collection electrode
  - Defined by buried n-well (BNW)
  - Octagon with size of 16 µm
- Middle silicon layer (SOI2)
  - Connected to shielding ground, dedicated shielding layer
  - Compensate the trapped charge caused by TID



Pixel circuit



<u>Signal processing chain in pixel</u>

- Charge sensitive preamplifier
  - Cf = 4fF
  - Constant current feedback (0.5 - 10nA adjustable)
- Shaper with inverse polarity
  - AC coupled
  - Voltage gain = 5
- Diode-biased inverter as the discriminator
  - AC coupled
  - 4-bit local DAC dedicated for threshold tuning
- 6-bit ripple counter
  - Register the X-ray photon number
  - Needs further optimization to incorporate more bits
- 6-bit shift register
  - For control of each individual pixel
  - DAC setting, Pixel mask, Calibration enable

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  - Noise count measurement
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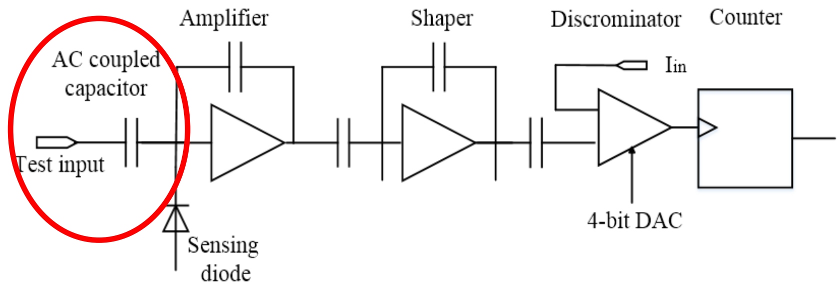
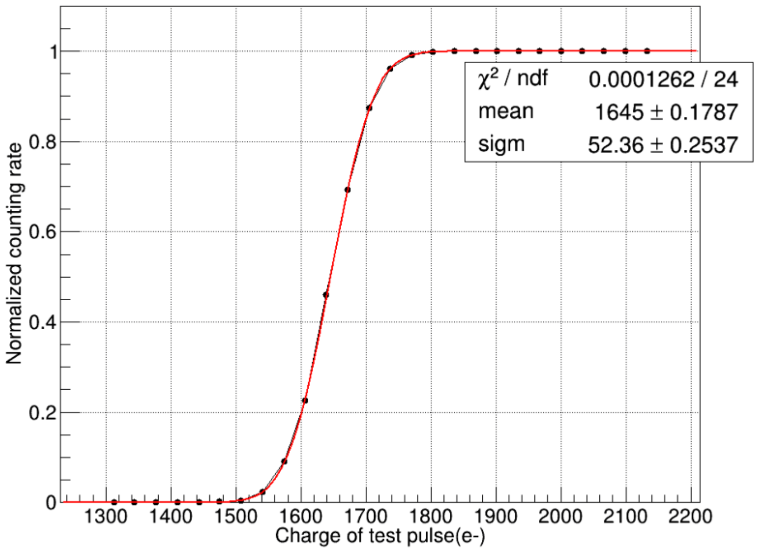
TN and FPN

- Test pulse amplitude scan
  - Based on an AC coupled capacitor



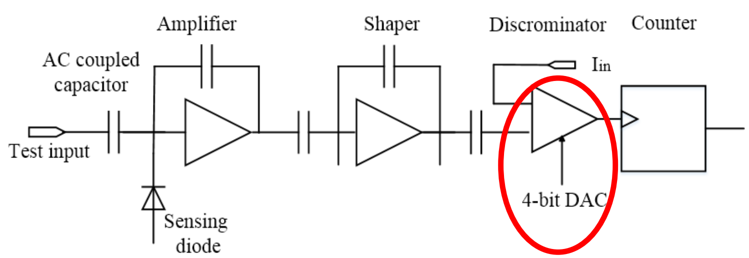
- S-curve fitting
  - Accumulative Gaussian fitting
  - TN, input-referred-threshold ⟷ sigma , mean



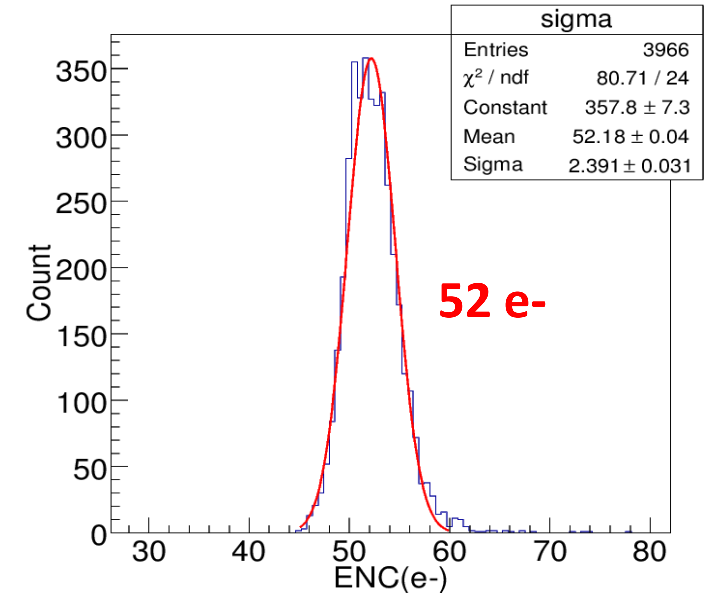
Typical S-curve fitting

TN and FPN

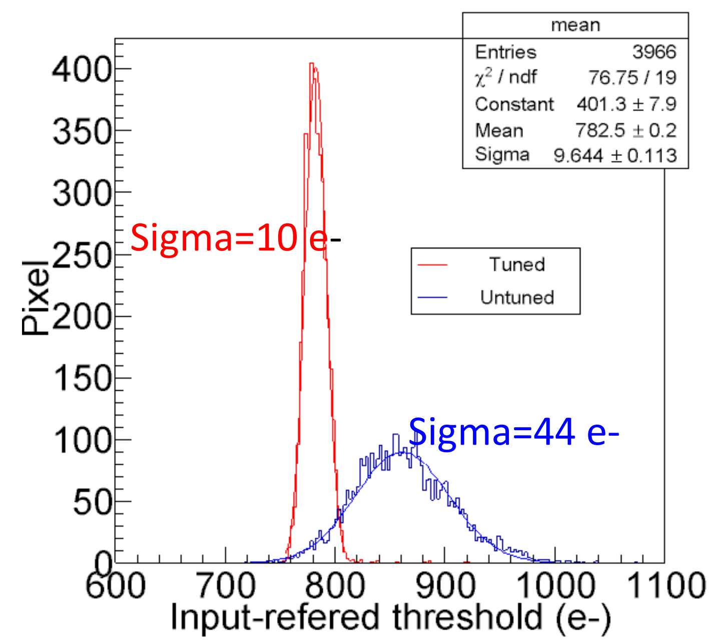
- Temporal noise (TN) : **52 e$^-$**
  – 3966 pixels (special pixels masked)
- Fixed-pattern noise (FPN) : 44 e-
  – 3966 pixels (special pixels masked)
- Threshold tuning
  – Target threshold = 780e$^-$ (2.8keV)
  – The DAC value was added to the global threshold level



- Excellent threshold distribution
  – FPN = 10e- after tuning



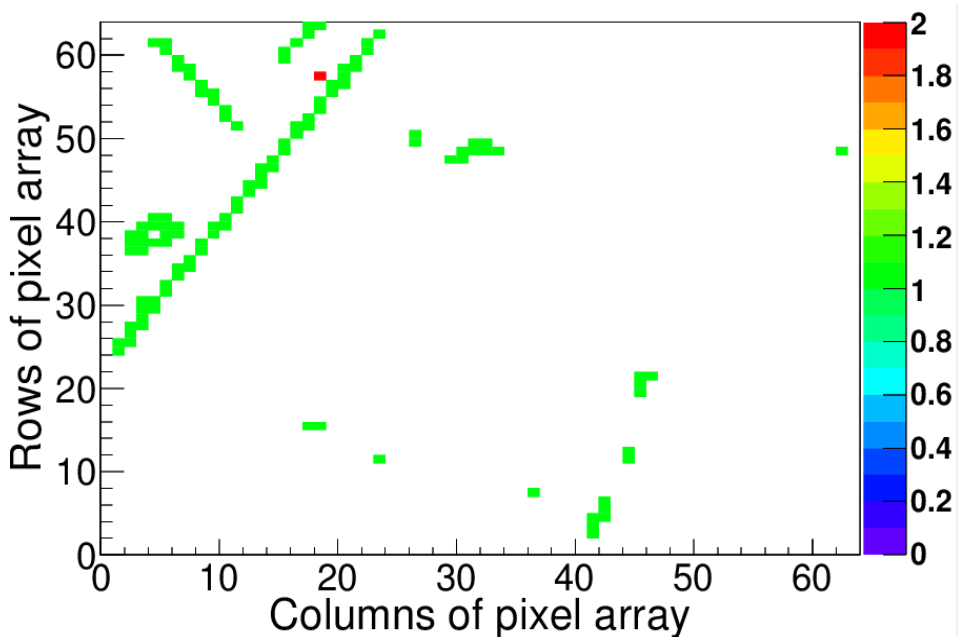
Noise distribution



Threshold distribution

Noise count measurement

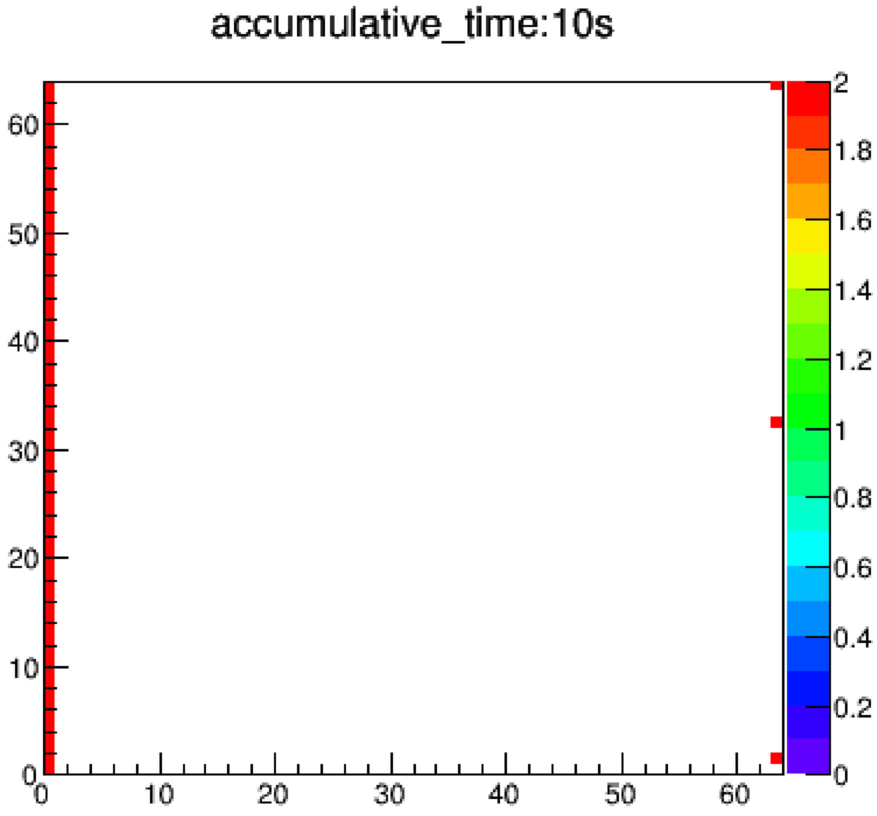
- Zero noise hits
  - set in dark room, perpendicular to horizon
  - Threshold = 830e$^-$ (3keV)
  - 10s ×360 frames (for long exposure time and small data set)
  - Only a few events recorded from environmental radiation



Environmental events accumulated in 1 hour

Noise count measurement

- 10s/frame



Environmental events replay

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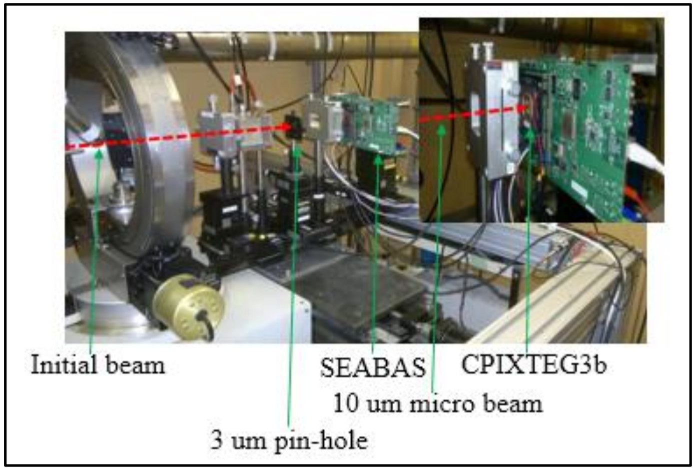
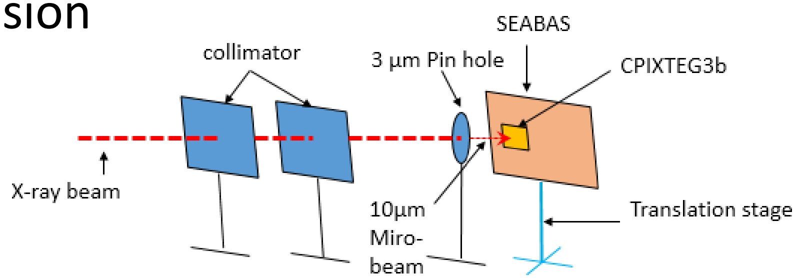
Point spread function

- Micro beam test setup
  - KEK PF BL-14A,
  - Pin hole with 3um in diameter
  - Micro beam with less than 10 μm in diameter
  - Chip and SEABAS mounted on high precision translation stage





- Micro beam measurement
  - For two different energy 6keV and 16 keV
  - Impinged at the center of targeted pixel

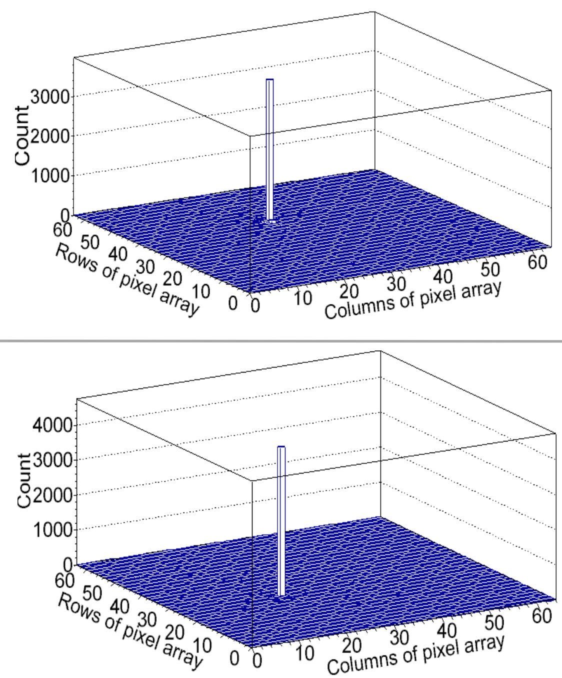
Point spread function

- Micro beam measurement
  - Target pixel dominated almost all of the counts

- The counting ratio of neighboring pixels to the center one is
  - 2.4% and 1.8% for 6keV
  - 1.5% and 0.9% for 16keV

6 keV

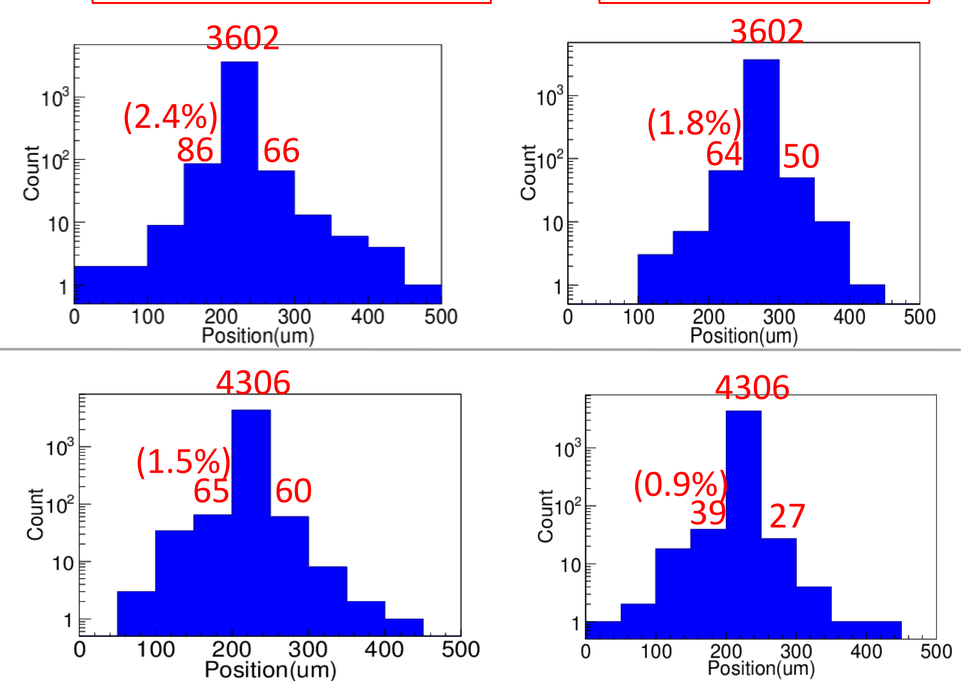
16 keV



Beam profile

Column direction

Row direction



Cross section of hit cluster for 6 keV and 16 keV

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  - Sensor depletion
  - Charge sharing
  - Flat field response
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Sensor depletion

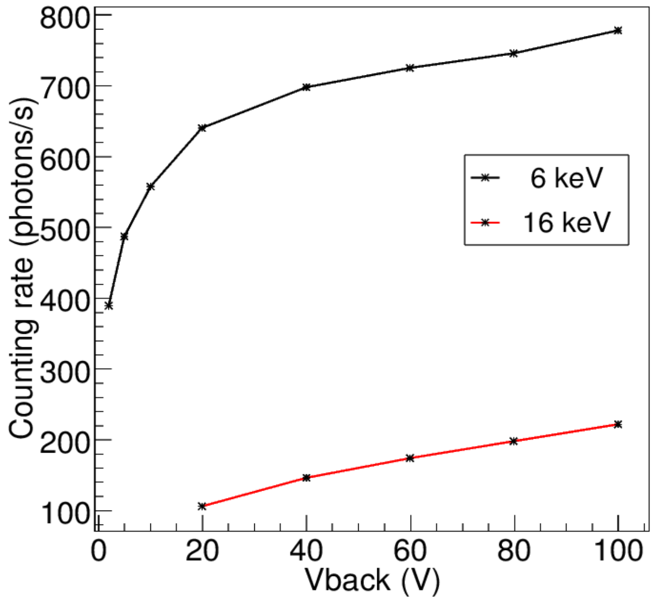
- Measurement
  - Micro beam illuminate from the topside
  - Impinged at the pixel center
  - Bias voltage increasing to -100 V
- Relative quantum efficiency (RQE)
  - Eliminate the effects of various inactive absorption medium

$$RQE = \frac{N(-20V)}{N(-80V)} = \frac{\eta(-20V)}{\eta(-80V)}$$

$$\eta = 1 - e^{-\mu d}$$

$$\mathrm{d} = \xi\sqrt{v}$$

N:counting rate
η:quantum efficiency
μ:attenuation coefficient
d:depletion thickness.
ξ:process-related constant



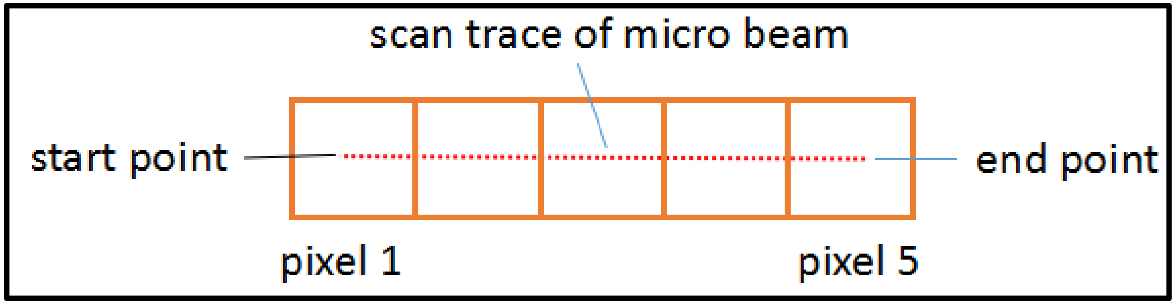
- The depletion thickness
  - ~117 µm at 100 V bias voltage
- High bias voltage leads to significant leakage current in phriphery
  - guard ring need optimization

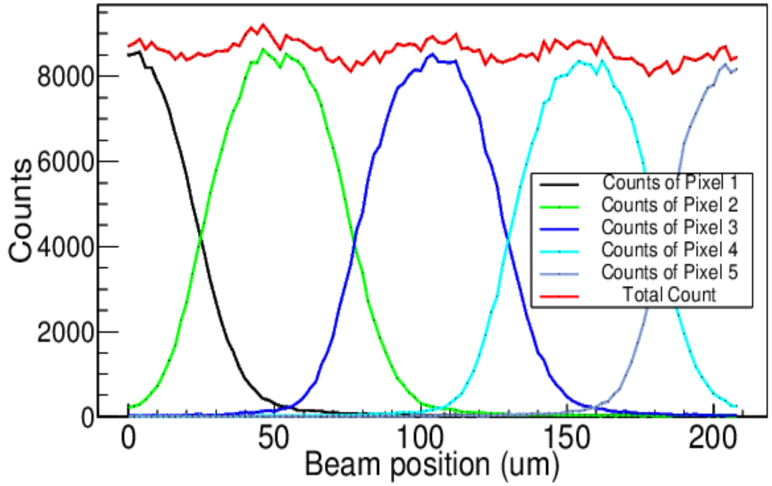
Beam energy (keV)	Bias voltage (V)	Depletion thickness (um)
6	-100	116.9±1.7
16	-100	136.0±21.5

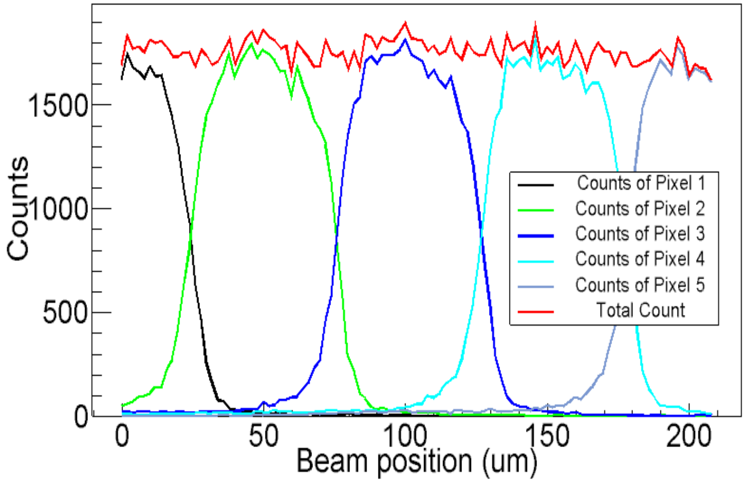
Charge sharing at pixel edge

- Scan across 5 pixels from center to center
  - Step size = 2 µm

- Uniform efficiency can be achieved at pixel edge
  - Threshold = ½ E_{photon}



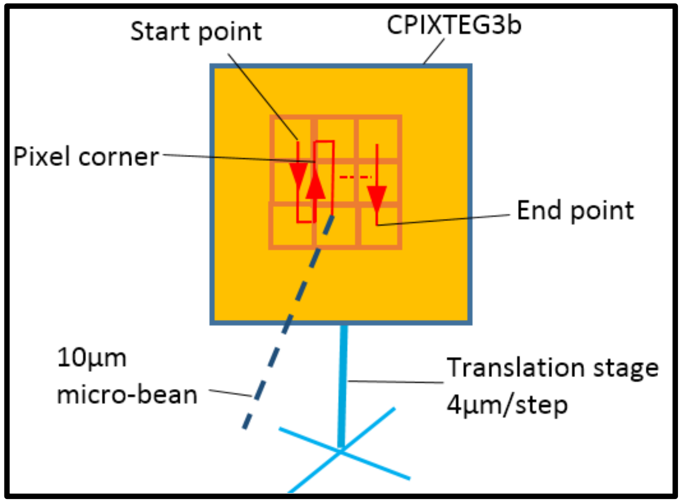




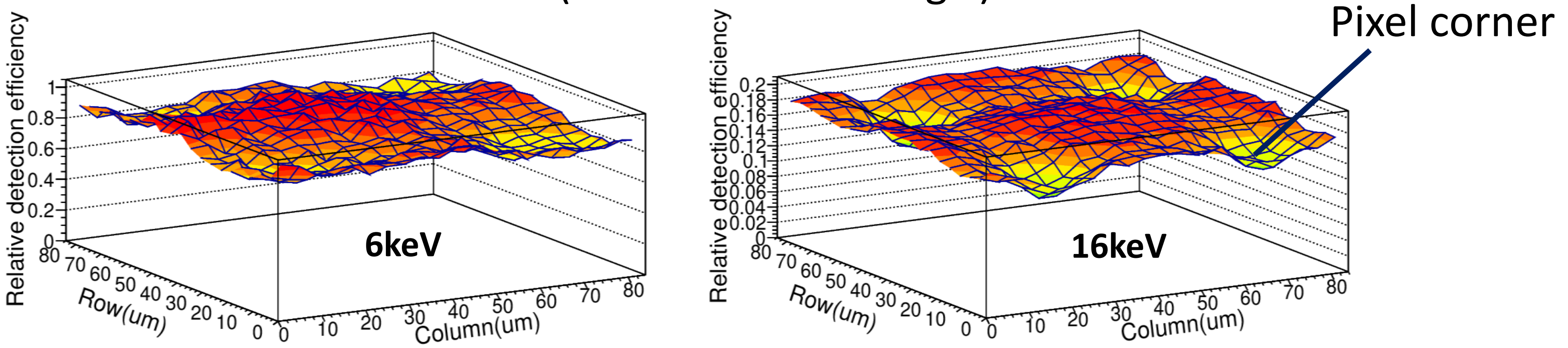
Charge sharing at pixel edge for 6 keV (left) and 16 keV (right) X-ray

Charge sharing at pixel corner

- Across 3×3 pixel-square
  - Step = 4 µm for two direction

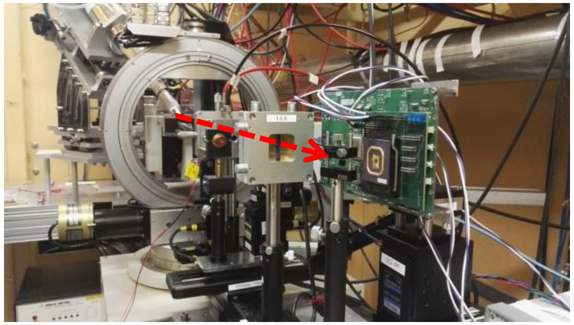


- Inevitable loss of efficiency at the corner
  - Threshold = ½ E_{photon}
  - Charge shared by 4 pixels adjoined
- Considerable effects on pixel sensor with small pixel size
  - Solution: to compare the charge between adjoining pixels and make the winner take the count (winner-takes-all logic)

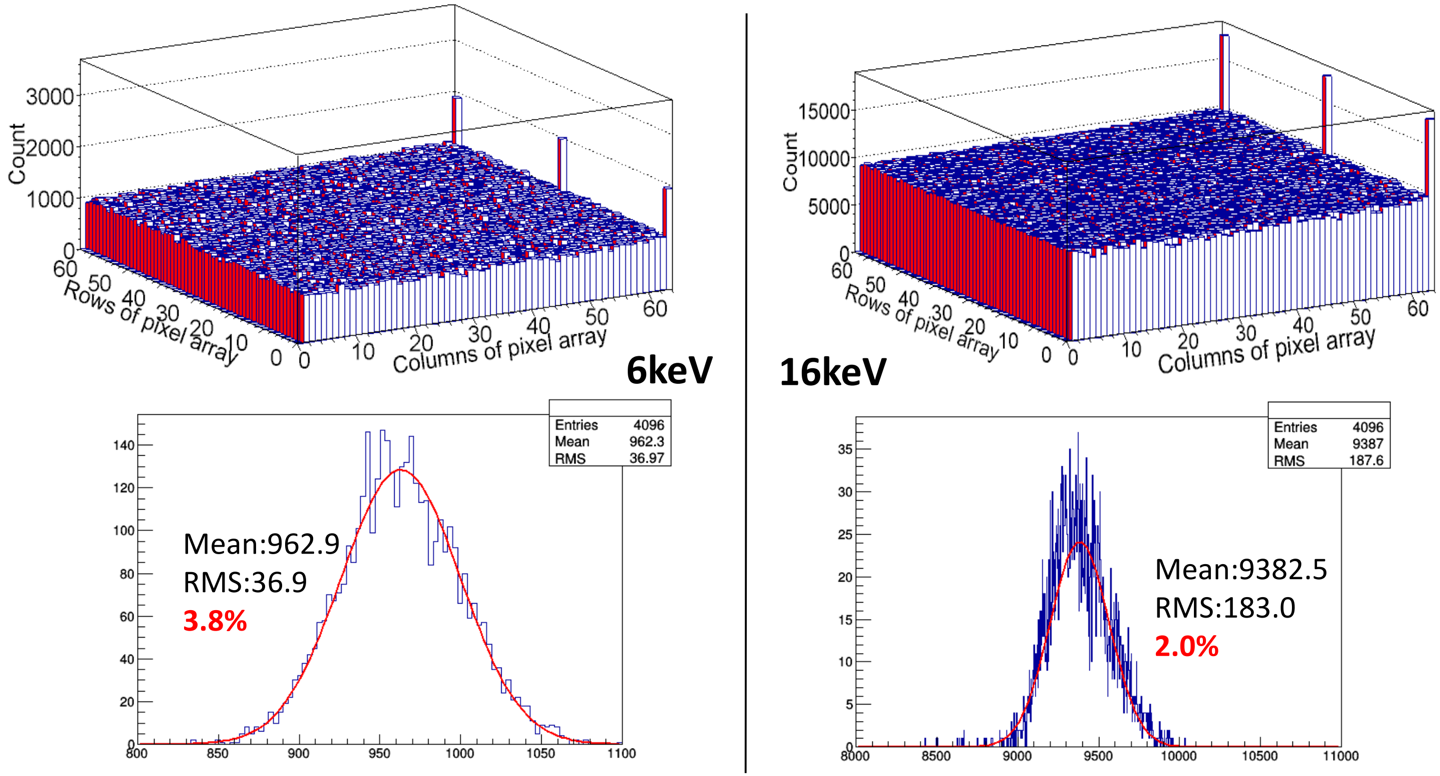


Charge sharing at pixel corner for 6 keV (left) and 16 keV (right) X-ray

Flat field response



- Beam scattered by glassy carbon
  - Sensor placed in 90^{o} with respect to the beam line
- Full pixel array illuminated.
  - inhomogeneity : 3.8% and 2.0%



Count distribution under flat field

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Summary and outlook

- The prototype CPIXTEG3b led to the development of SOI pixel sensors of low noise and high resolution for X-ray imaging.
  - The TN is 52 e^- and FPN is 10 e^- over the full matrix
  - A small pitch of 50μm manifests good PSF as expected
- The depletion of sensor and the impact of charge sharing have been characterized, and provides the insights for further development.
- The uniformity of response to X-ray photons has been obtained in the flat field test.
- Further improvements have been made
  - Charge sharing decision logic equipped in each pixel
  - Compact layout of counter to accommodate 19 bits

Thanks for your attention!