Development of X-ray SOI Pixel Sensors: Investigation of Charge-Collection Efficiency and Quantum Efficiency

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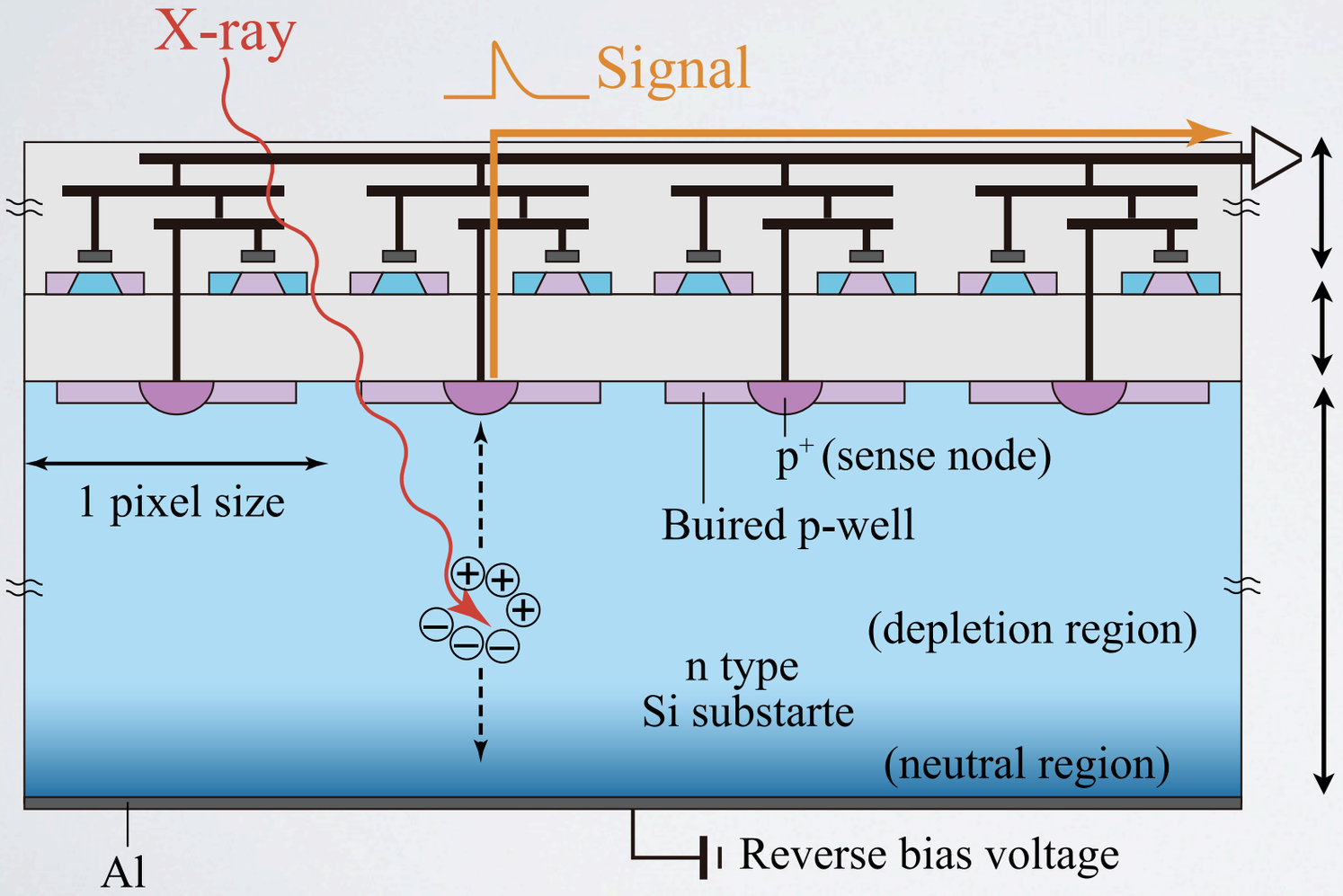
Y. Kohmura, Y. Takei, T. Wagai (RIKEN)

Our SOI Pixel Sensor for X-ray Astronomy

"XRPIX" = Silicon-on-insulator (SOI) pixel sensor for X-ray astronomy



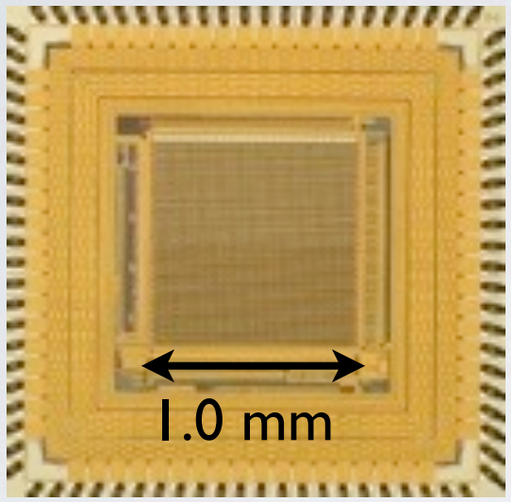
Si circuit layer (5 μm)
··· Low resistivity

A buried oxide (BOX) layer (0.2 μm)

Si sensor layer (250-500 μm)
··· High resistivity

First Prototype Device: XRPIX1

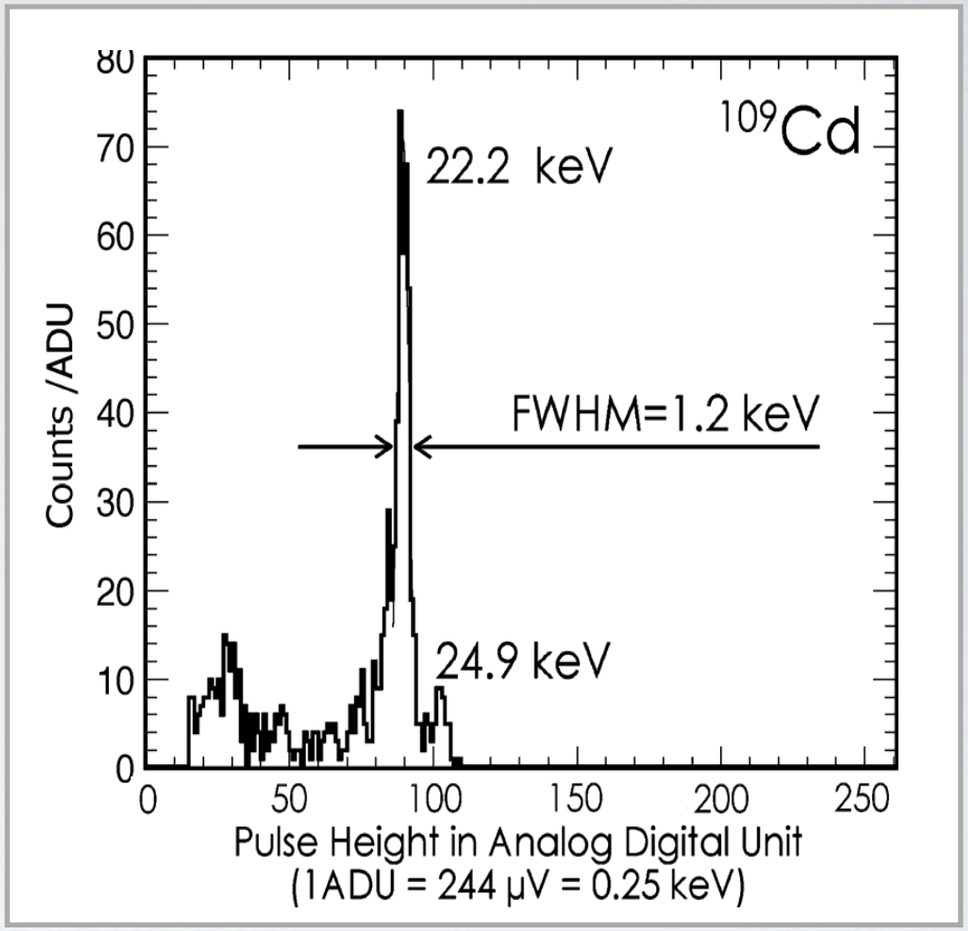
XRPIX1
(first prototype)



Pixel size: 30μm x 30μm

Sensor layer thickness: 250μm

Format: 32 x 32



Ryu+2011 IEEE TNS, 58, 2528

Energy resolution: 5.4% FWHM @ 22.2 keV

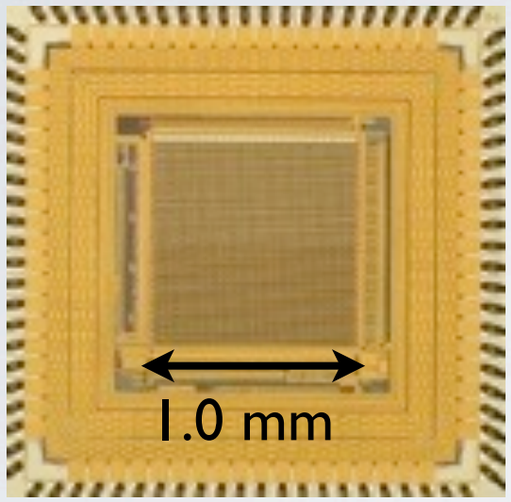
Readout noise: 129 e^- (rms)

Node gain: 3.6 μV/e^-

Node gain is not so high

First Prototype Device: XRPIX1

XRPIX1
(first prototype)



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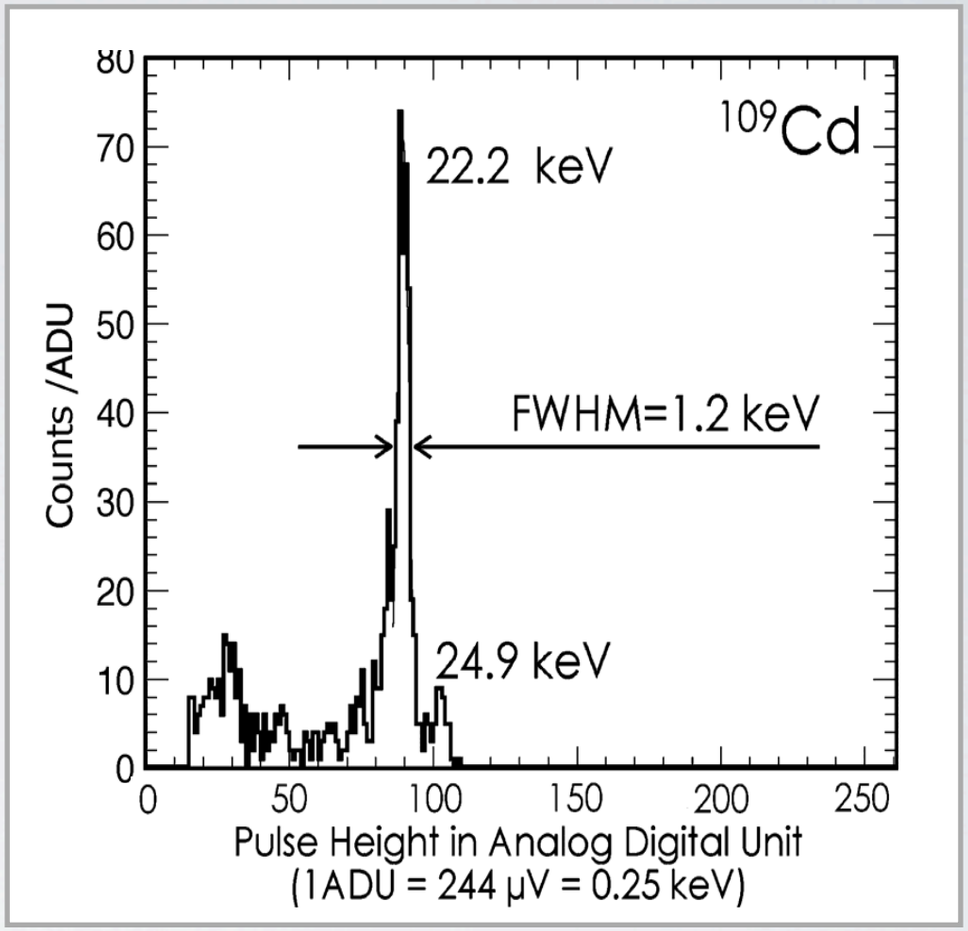

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Energy resolution: 5.4% FWHM @ 22.2 keV

Readout noise: 129 e^- (rms)

Node gain: 3.6 μV/e^-

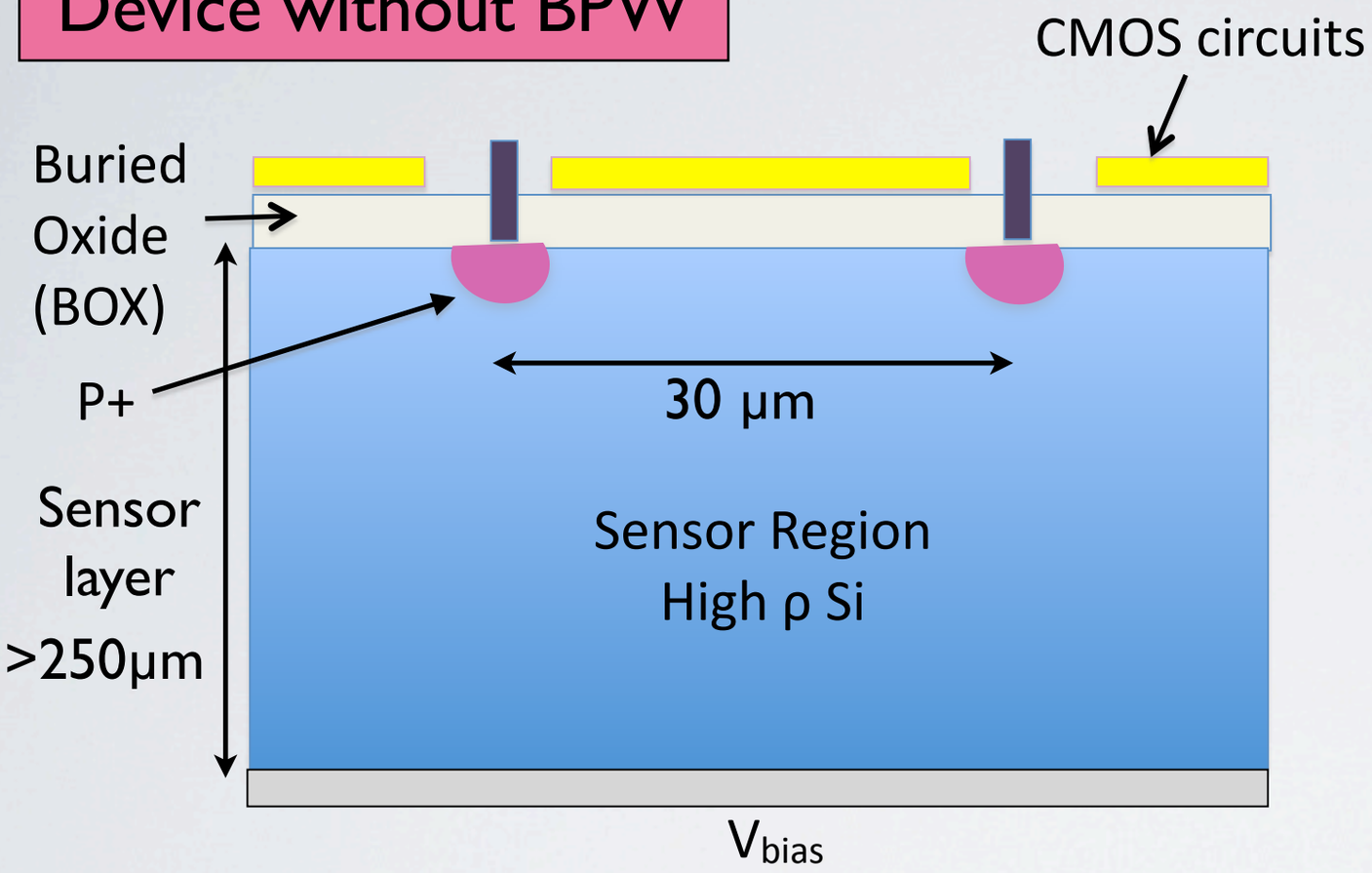
Node gain is not so high

We found the node capacitance is dominated by a structure called BPW

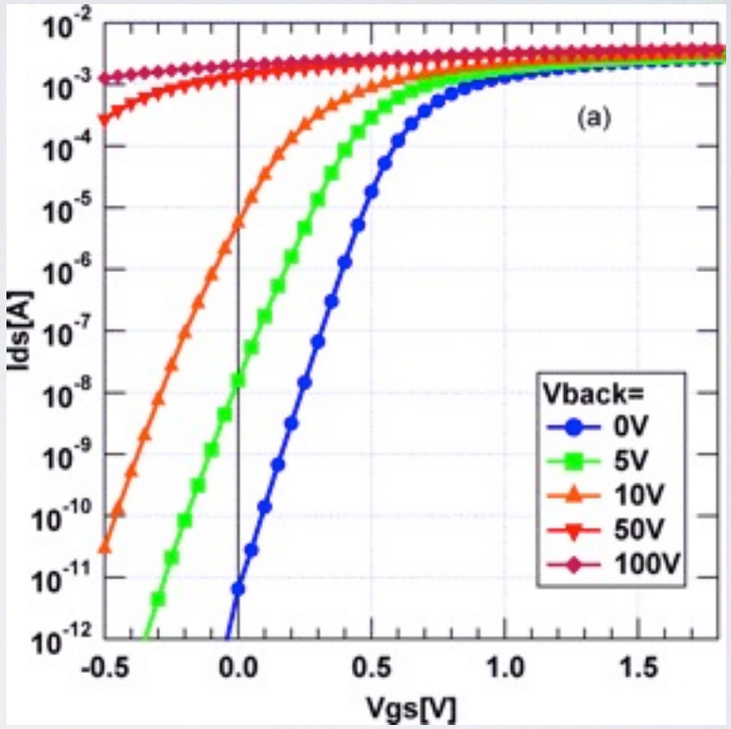
In order to increase the gain, we reduce the size of BPW

Buried P-Well (BPW)

Device without BPW



NMOS w/o BPW

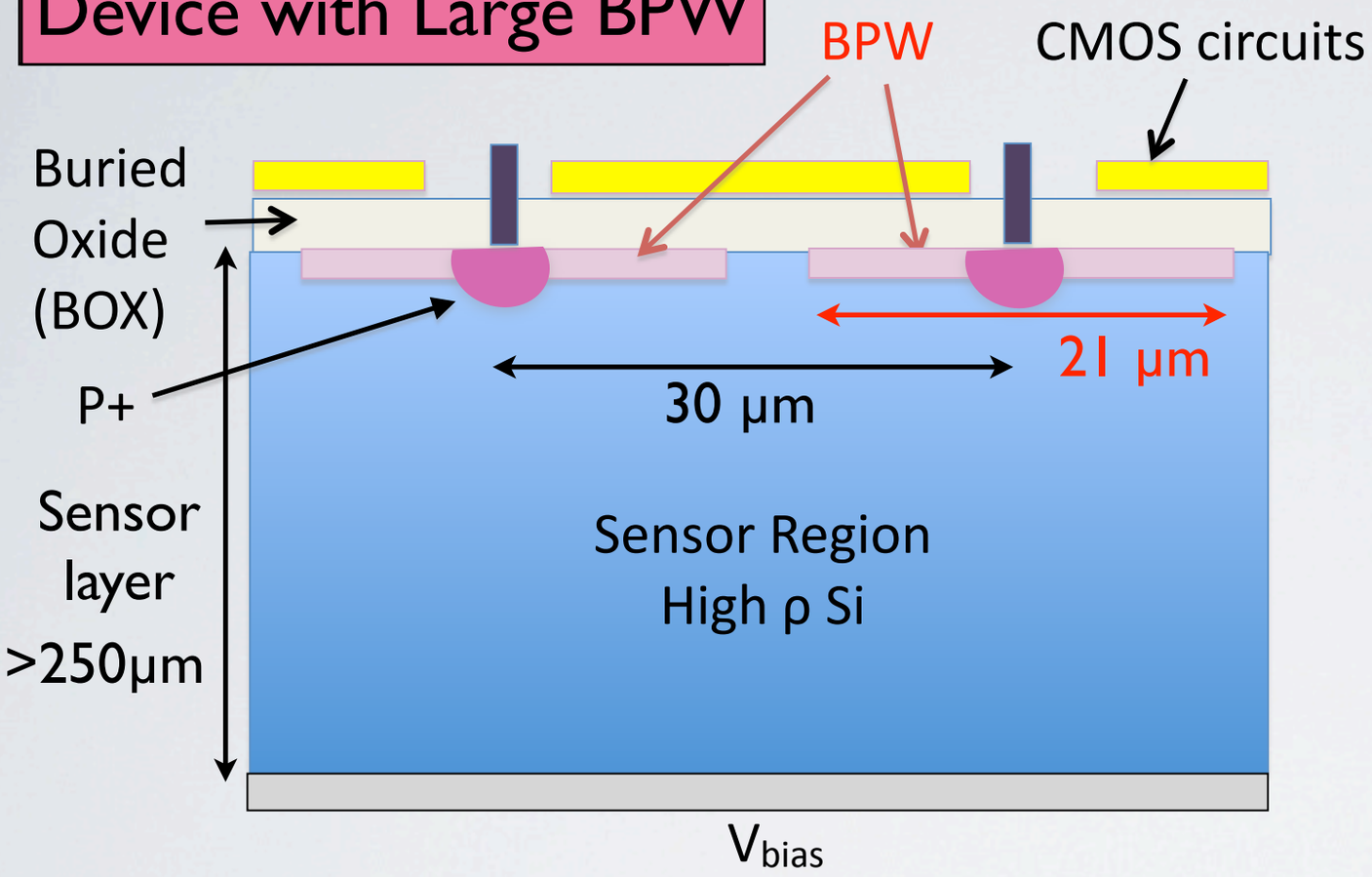


- Need thick depletion layer to detect high energy X-rays.
- High Back Bias Voltage ⇒ Back Gate Effect

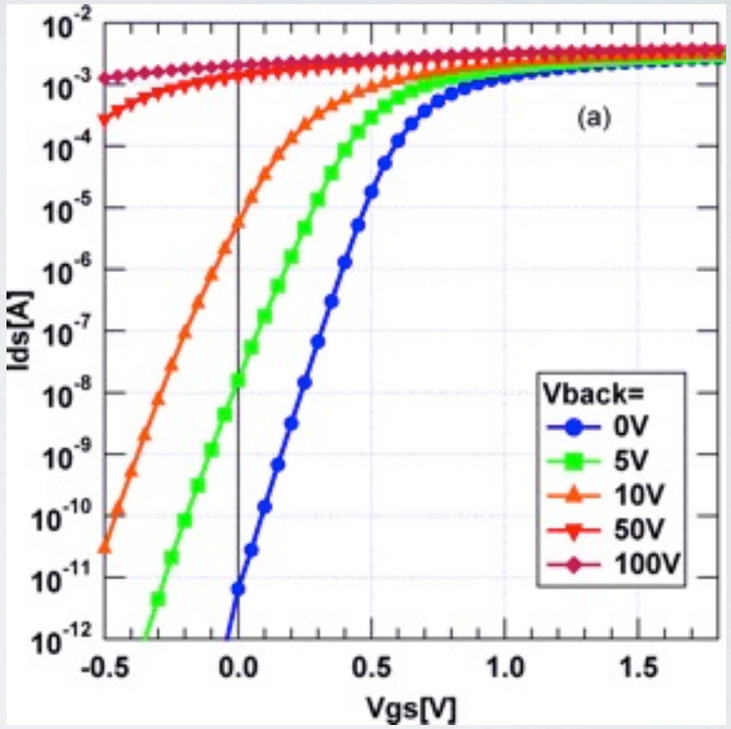
Arai+2011 NIM A, 636, S31

Buried P-Well (BPW)

Device with Large BPW



NMOS w/o BPW

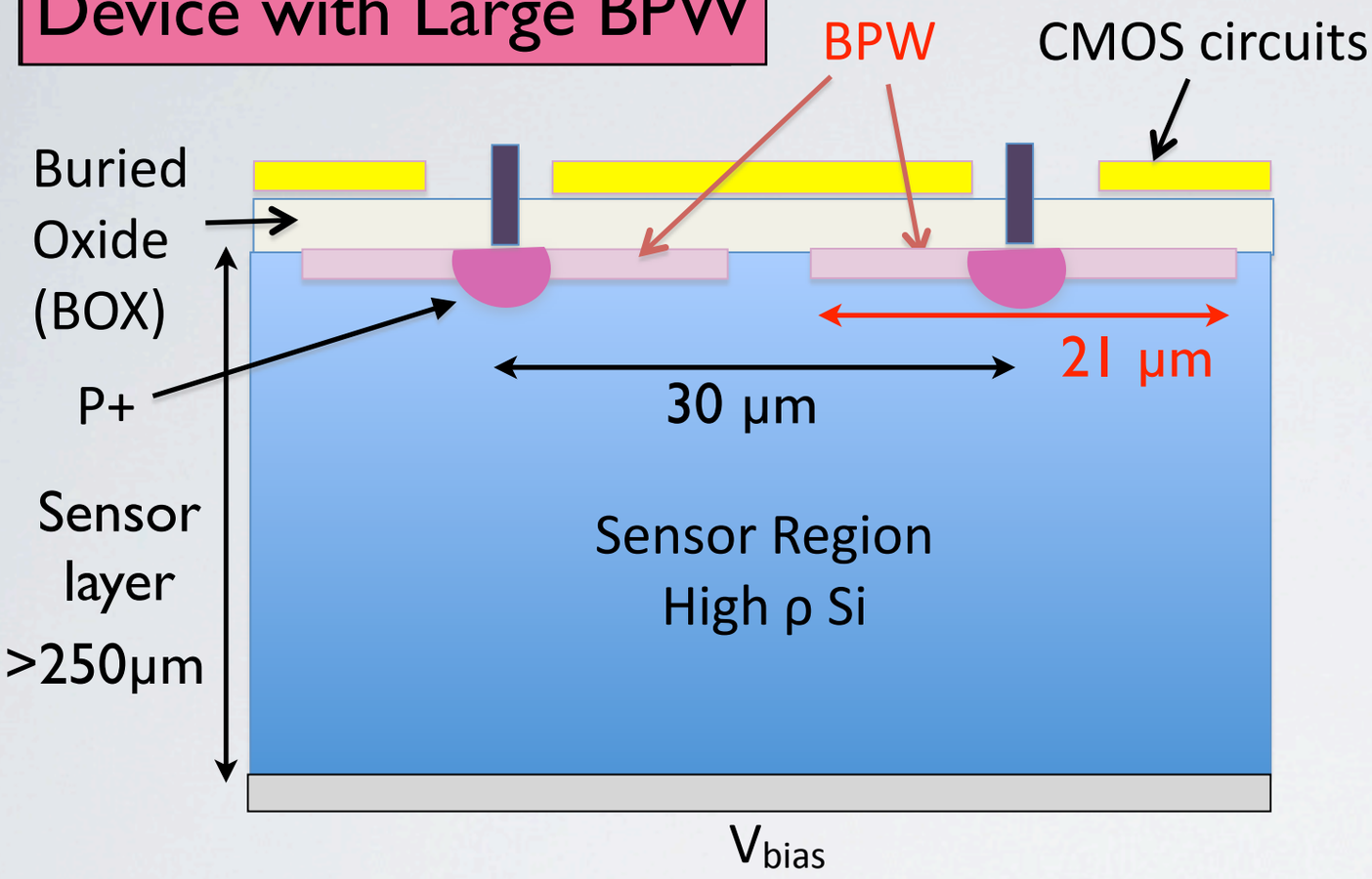


- Need thick depletion layer to detect high energy X-rays.
- High Back Bias Voltage ⇒ Back Gate Effect
- BPW is introduced to suppress the Back Gate Effect.

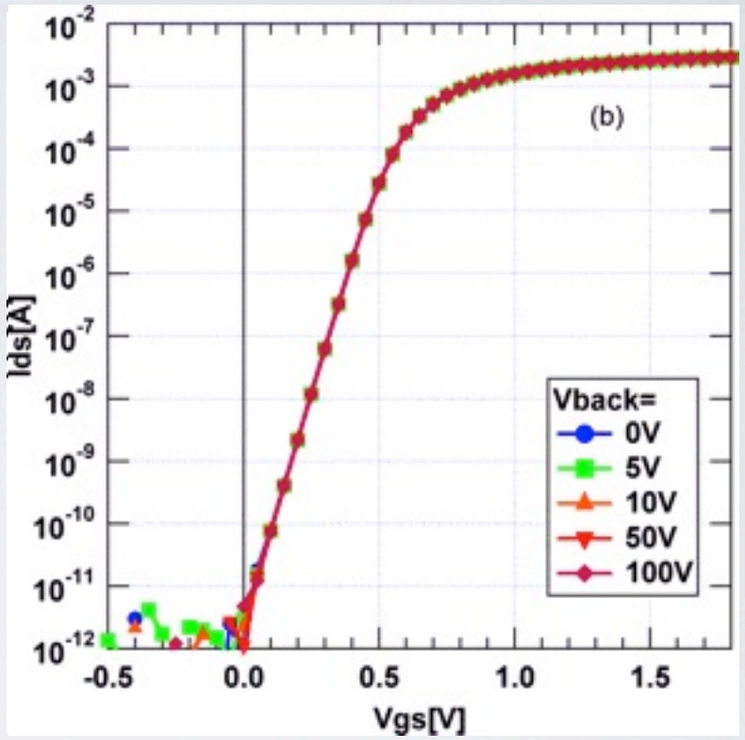
Arai+2011 NIM A, 636, S31

Buried P-Well (BPW)

Device with Large BPW



NMOS with BPW=0V



- Need thick depletion layer to detect high energy X-rays.
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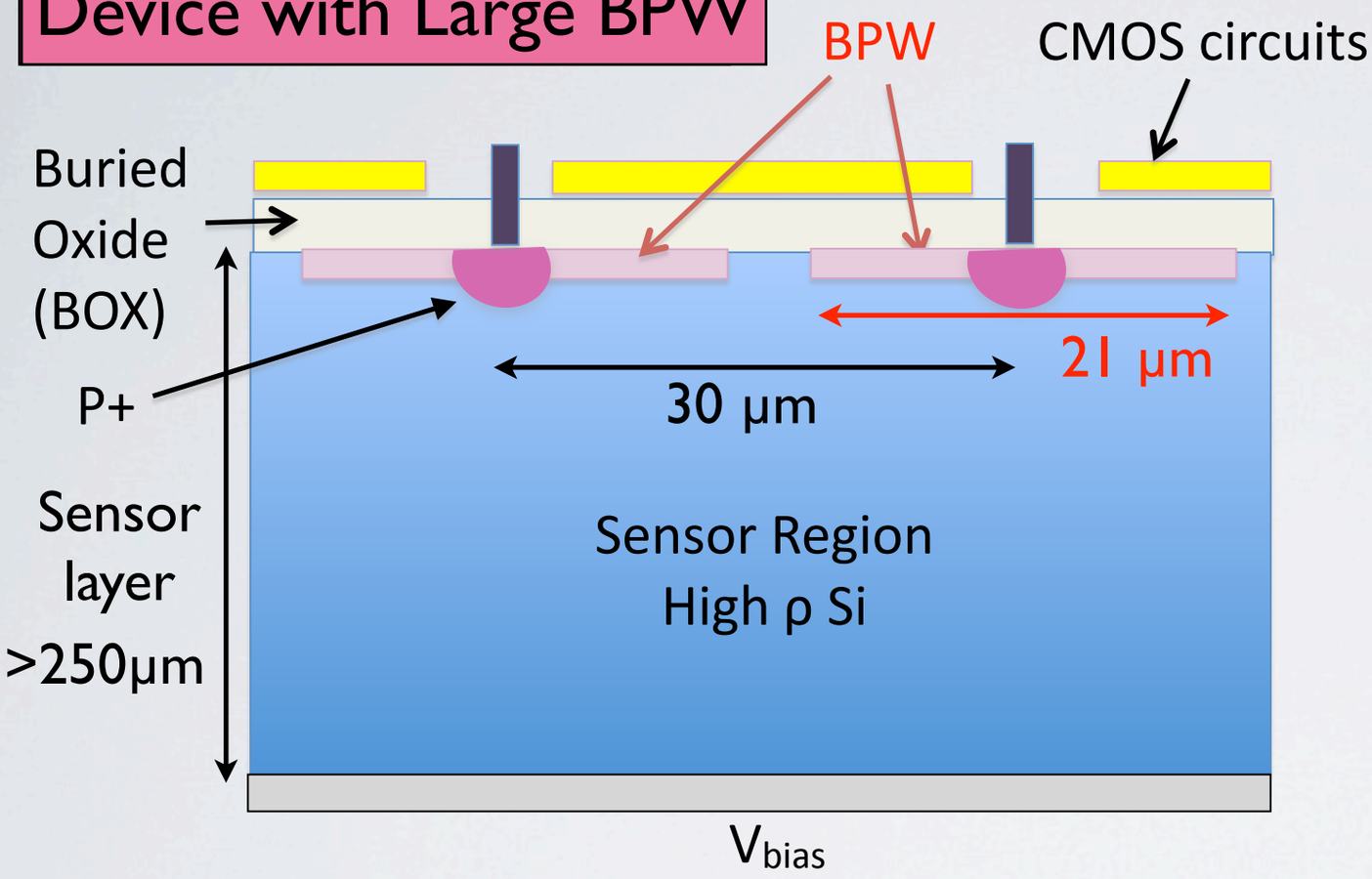
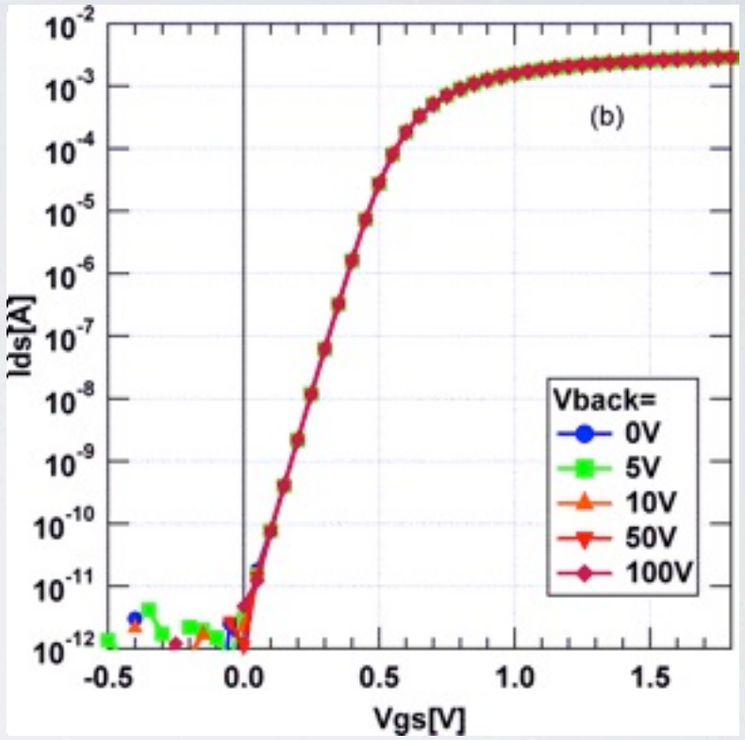
Arai+2011 NIM A, 636, S31

Buried P-Well (BPW)

Device with Large BPW



NMOS with BPW=0V



- Need thick depletion layer to detect high energy X-rays.
- High Back Bias Voltage ⇒ Back Gate Effect
- BPW is introduced to suppress the Back Gate Effect.
- BPW dominates parasitic capacitance of the device.

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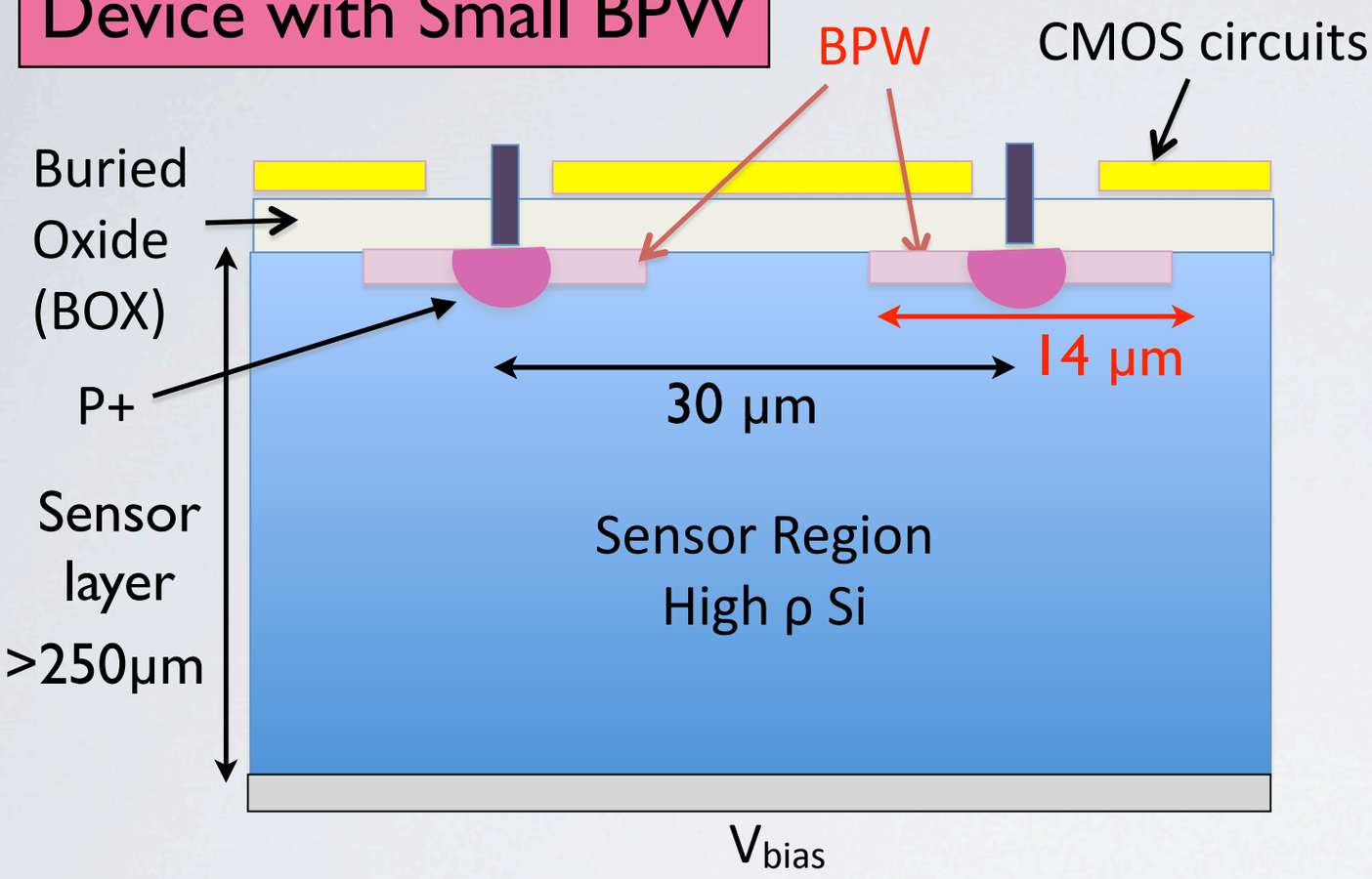
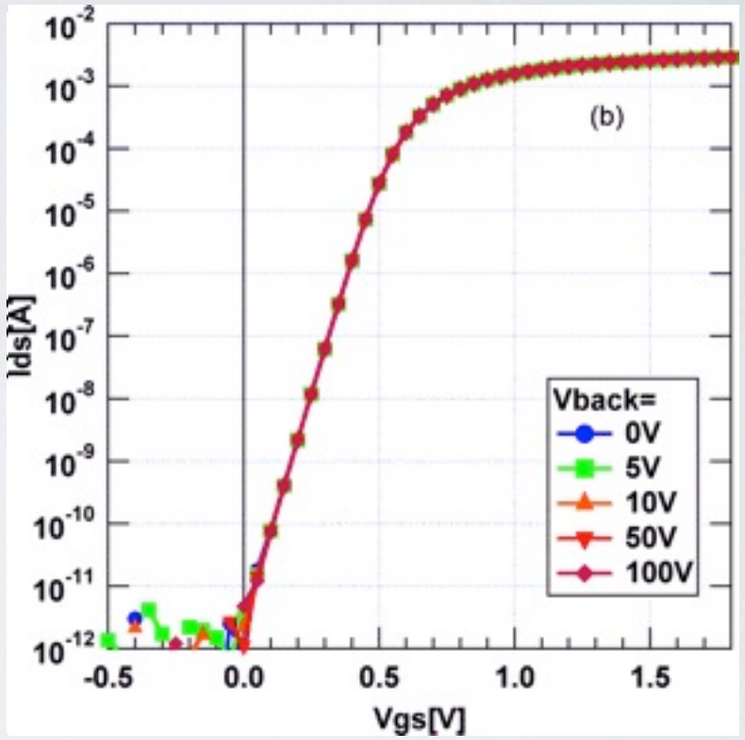
Buried P-Well (BPW)

Device with Small BPW



NMOS with BPW=0V



- Need thick depletion layer to detect high energy X-rays.
- High Back Bias Voltage ⇒ Back Gate Effect
- BPW is introduced to suppress the Back Gate Effect.
- BPW dominates parasitic capacitance of the device.
- In order to increase a gain of the device, we developed new device with small size of BPW

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Ryu+2013 IEEE/TNS 60, 465

Device with Small BPW, XRPIX1b

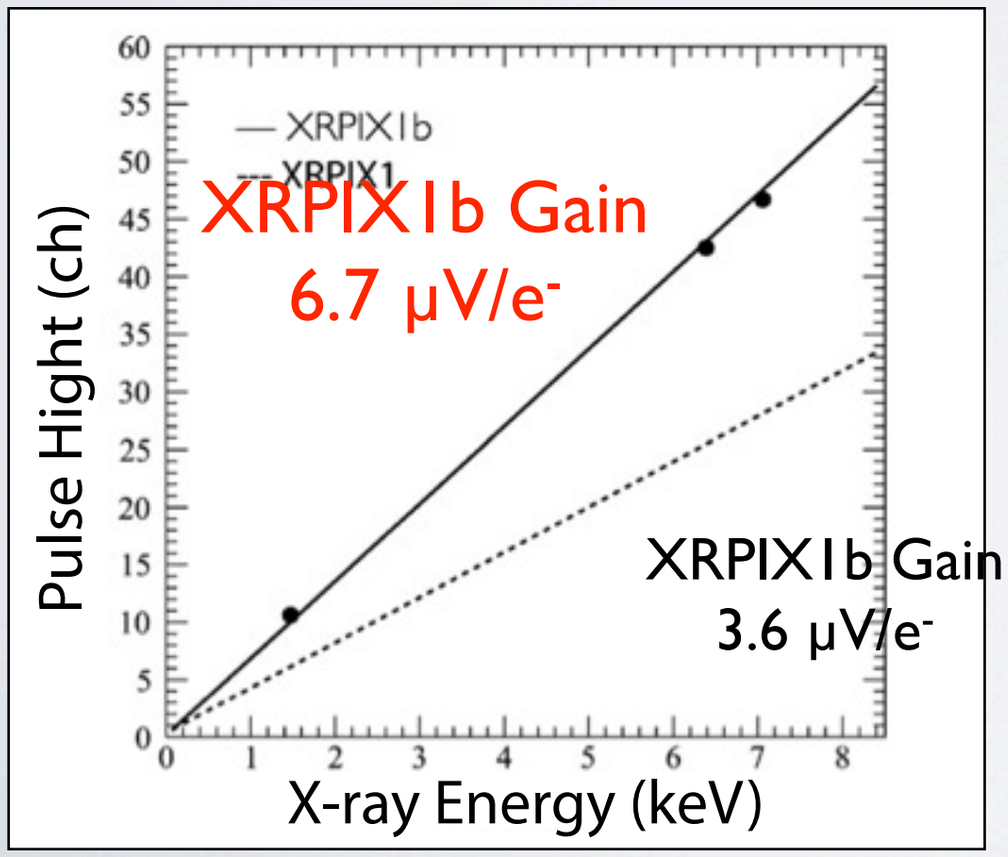
	Pixel size	BPW size	Gain	Energy resolution	Readout noise
XRPIX1 (first prototype)	30μm x 30μm	21μm x 21μm	3.6 μV/e^-	5.4% FWHM @22.2keV	129 e^- (rms)
XRPIX1b (smaller BPW)	30μm x 30μm				

Device with Small BPW, XRPIX1b

	Pixel size	BPW size	Gain	Energy resolution	Readout noise
XRPIX1 (first prototype)	30μm x 30μm	21μm x 21μm	3.6 μV/e$^-$	5.4% FWHM @22.2keV	129 e$^-$ (rms)
		↓ 43%			
XRPIX1b (smaller BPW)	30μm x 30μm	14μm x 14μm			

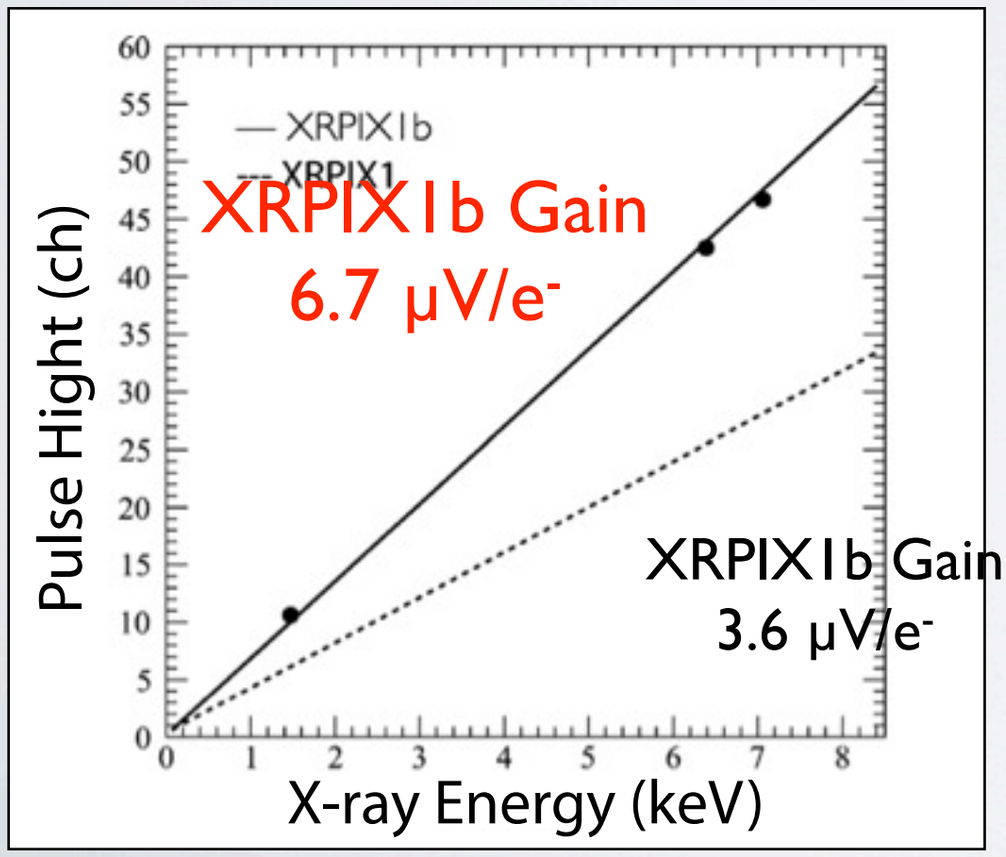
Device with Small BPW, XRPIX1b

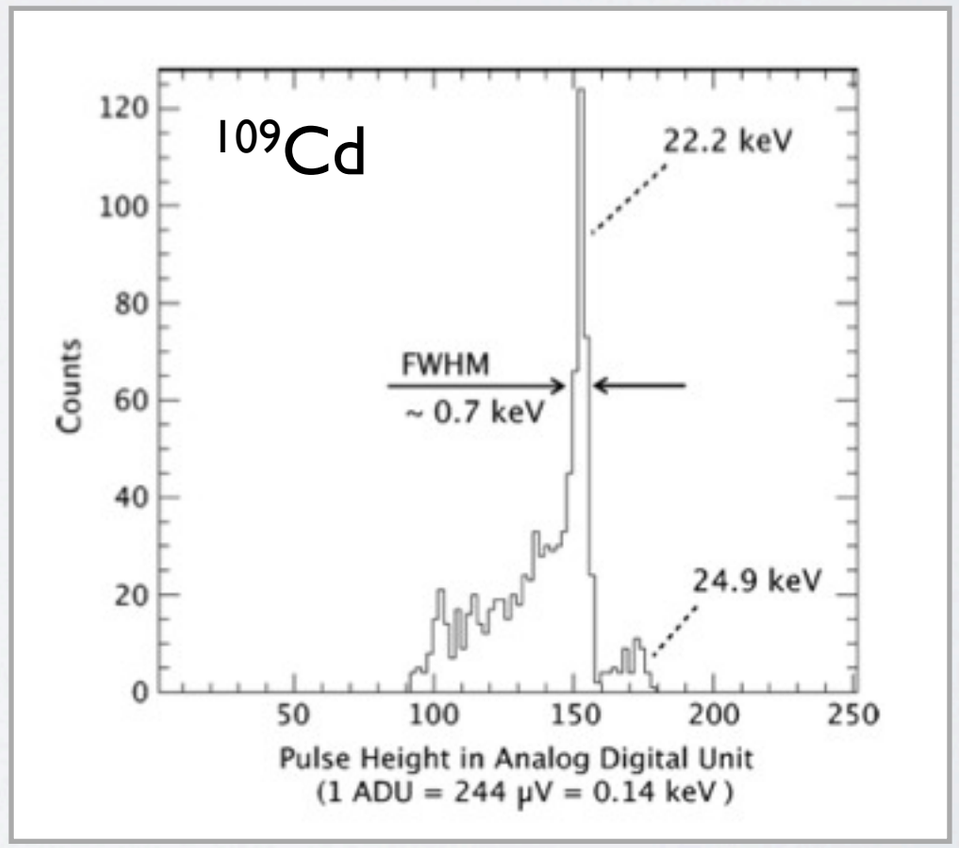
	Pixel size	BPW size	Gain	Energy resolution	Readout noise
XRPIX1 (first prototype)	30μm x 30μm	21μm x 21μm	3.6 μV/e$^-$	5.4% FWHM @22.2keV	129 e$^-$ (rms)
		↓ 43%	↓ 1.9 times		
XRPIX1b (smaller BPW)	30μm x 30μm	14μm x 14μm	6.7 μV/e$^-$		



Device with Small BPW, XRPIX1b

	Pixel size	BPW size	Gain	Energy resolution	Readout noise
XRPIX1 (first prototype)	30μm x 30μm	21μm x 21μm	3.6 μV/e$^-$	5.4% FWHM @22.2keV	129 e$^-$ (rms)
		↓ 43%	↓ 1.9 times	↓	↓
XRPIX1b (smaller BPW)	30μm x 30μm	14μm x 14μm	6.7 μV/e$^-$	3.1% FWHM @22.2keV	70 e$^-$ (rms)

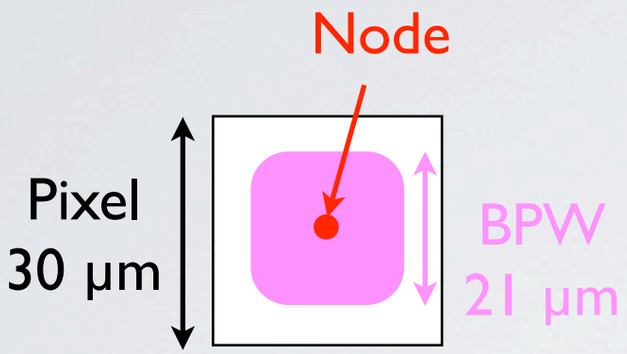




Takeda+2013 IEEE/TNS 60, 586

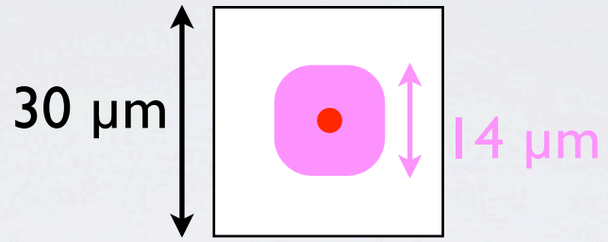
A New Problem of XRPIX

Large BPW



$\frac{\text{BPW size}}{\text{Pixel size}}$: 45%

Small BPW



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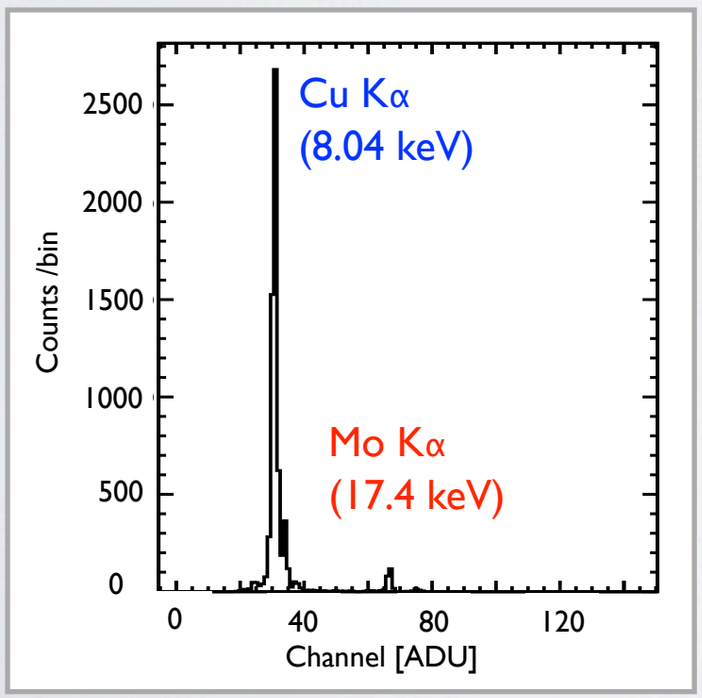

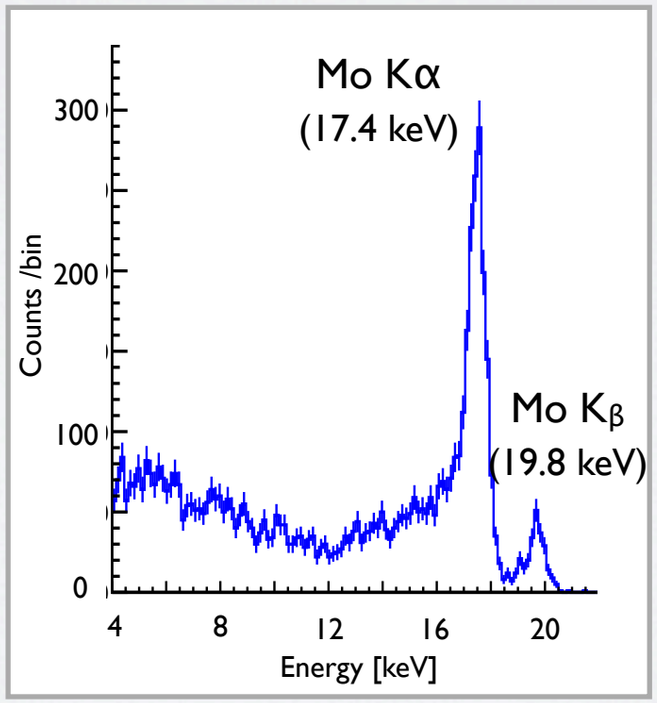

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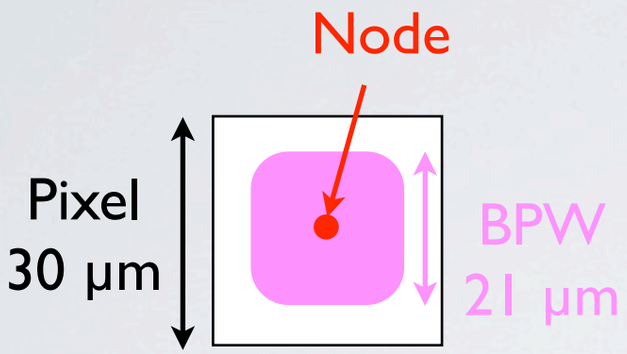

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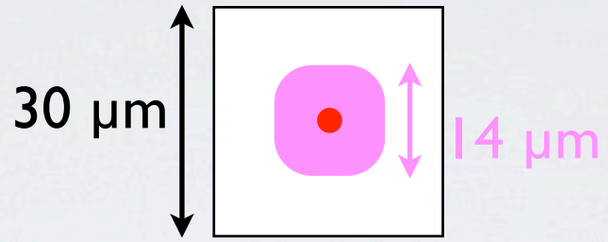

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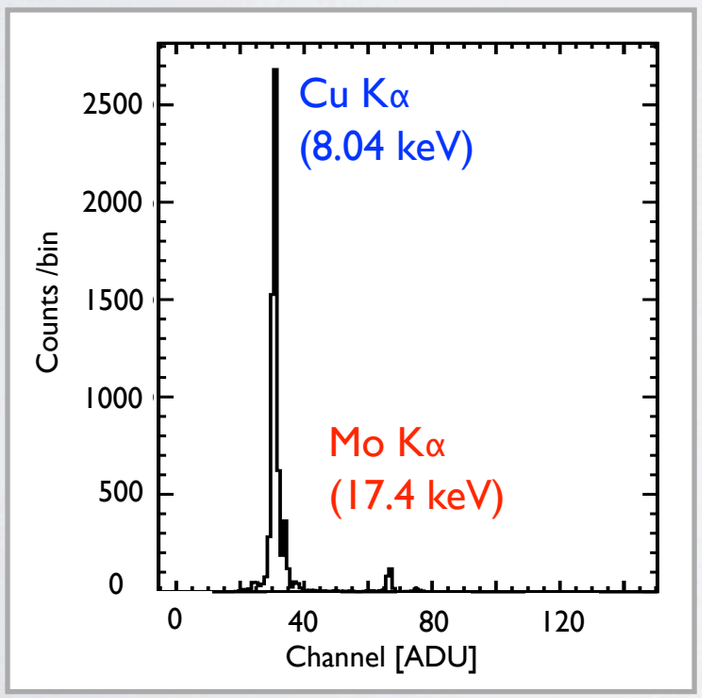

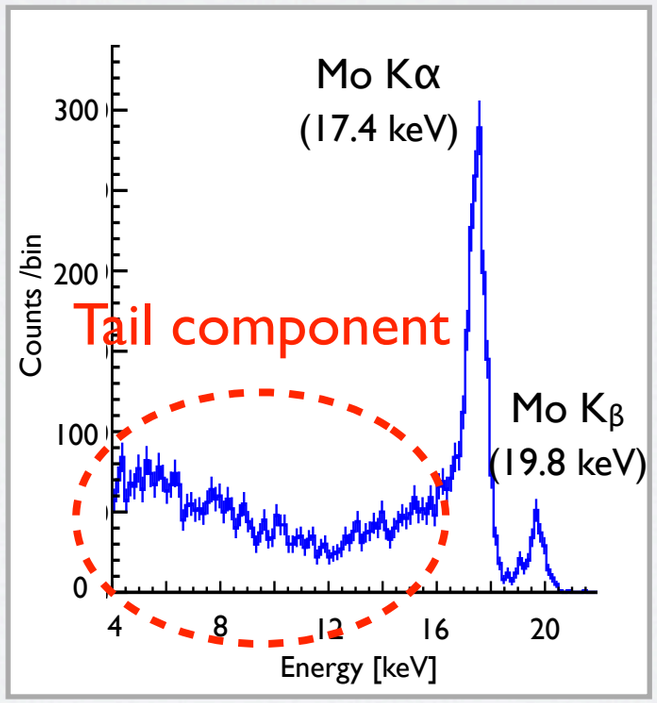

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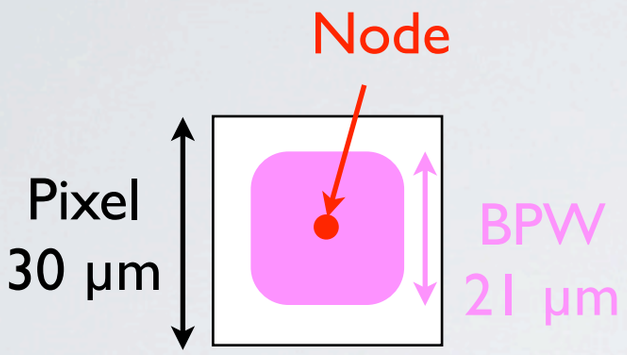

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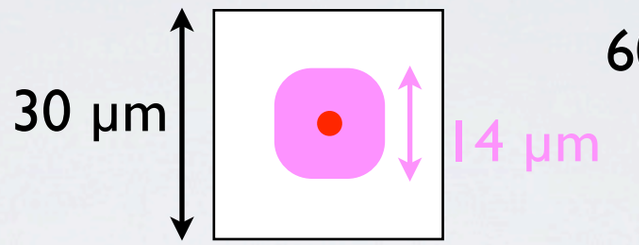
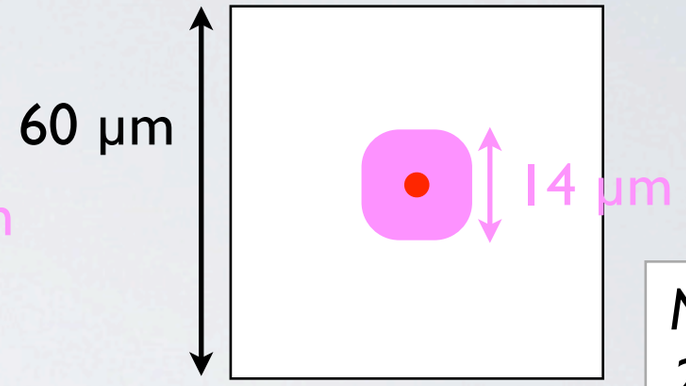


20%

Large Pixel with Small BPW



5%

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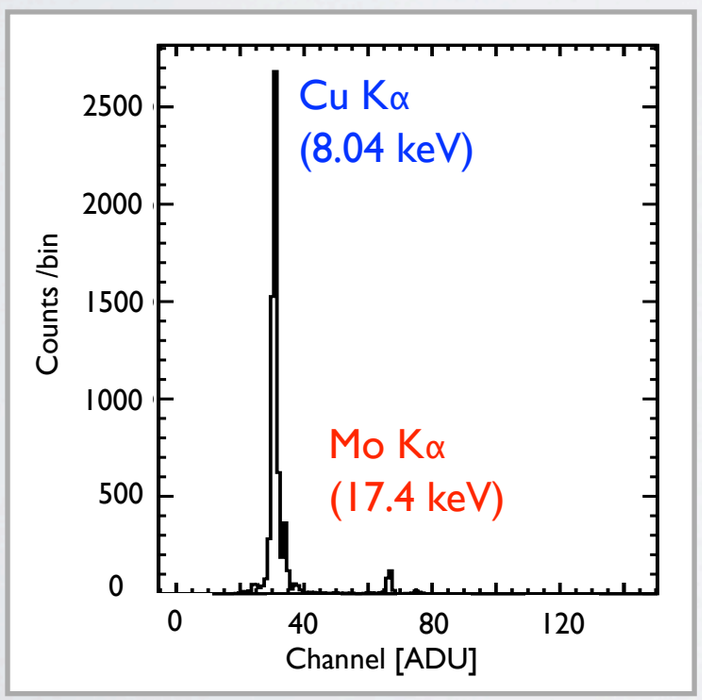

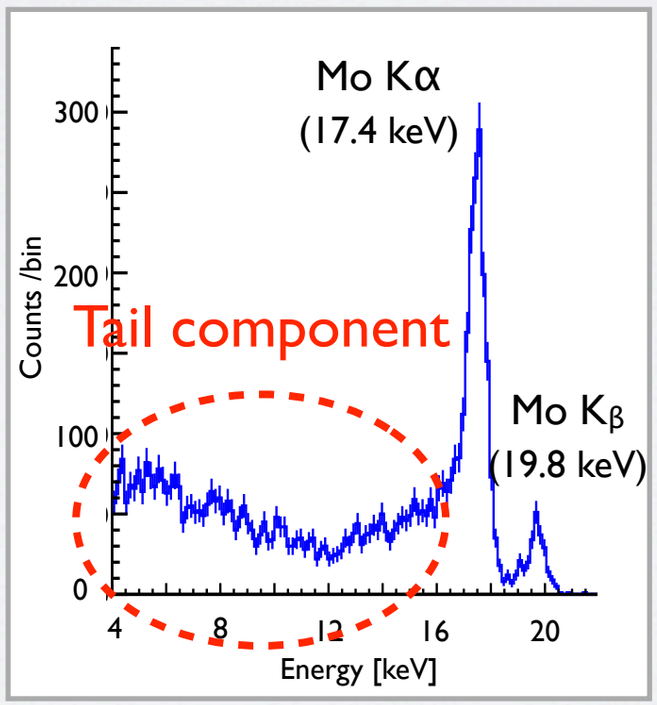

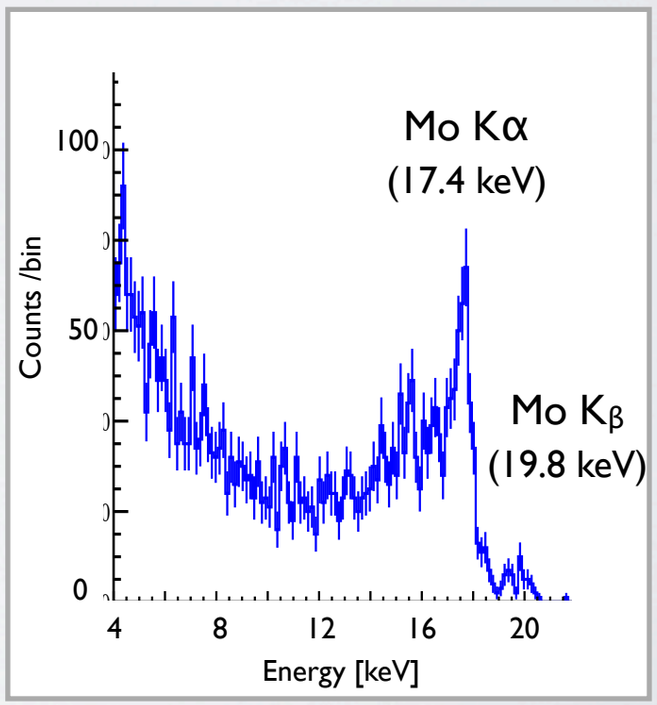

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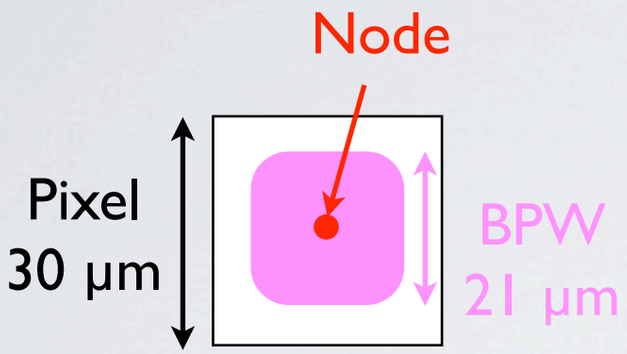

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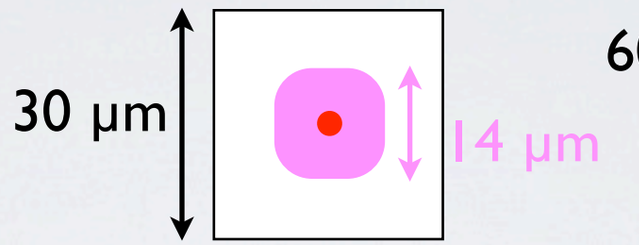
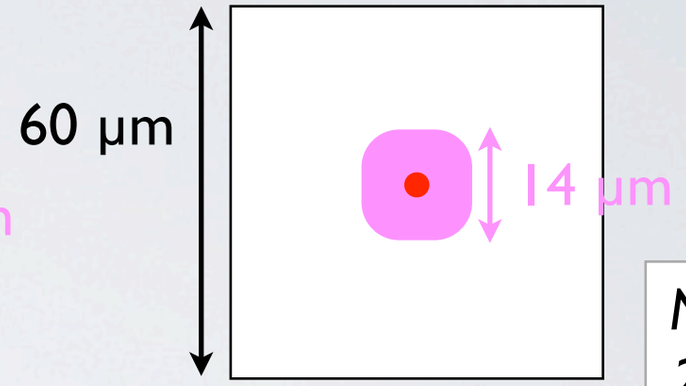


20%

Large Pixel with Small BPW



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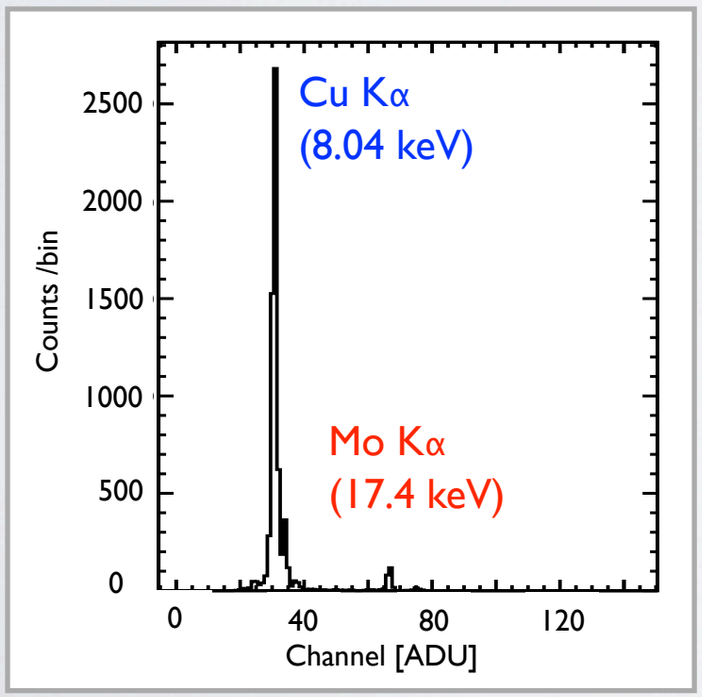
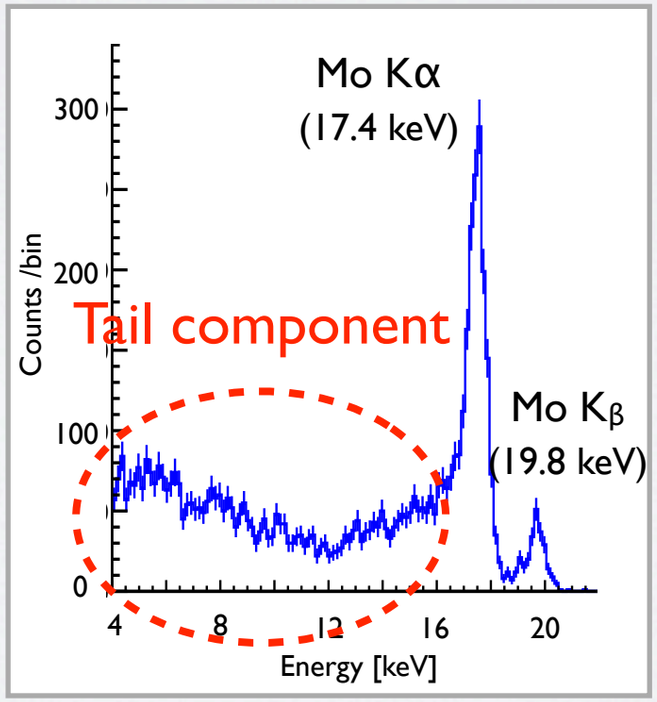
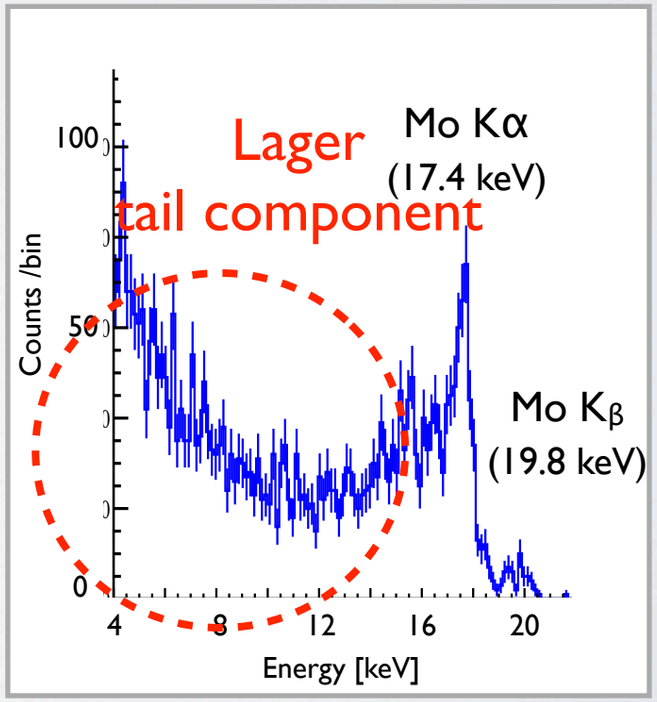
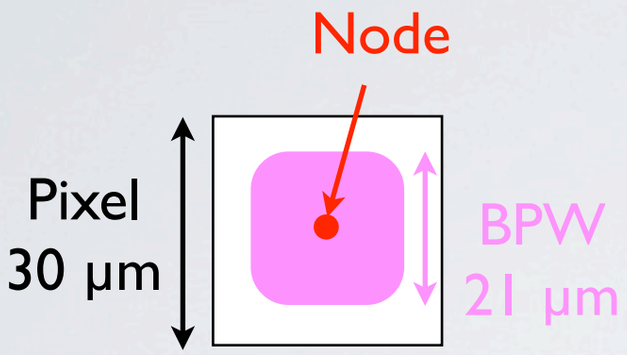






A New Problem of XRPIX

Large BPW



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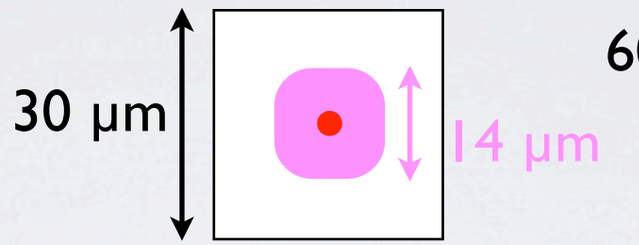

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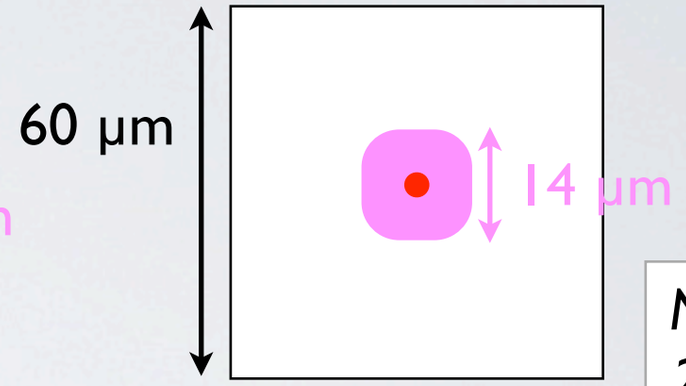
Large Pixel with Small BPW



5%

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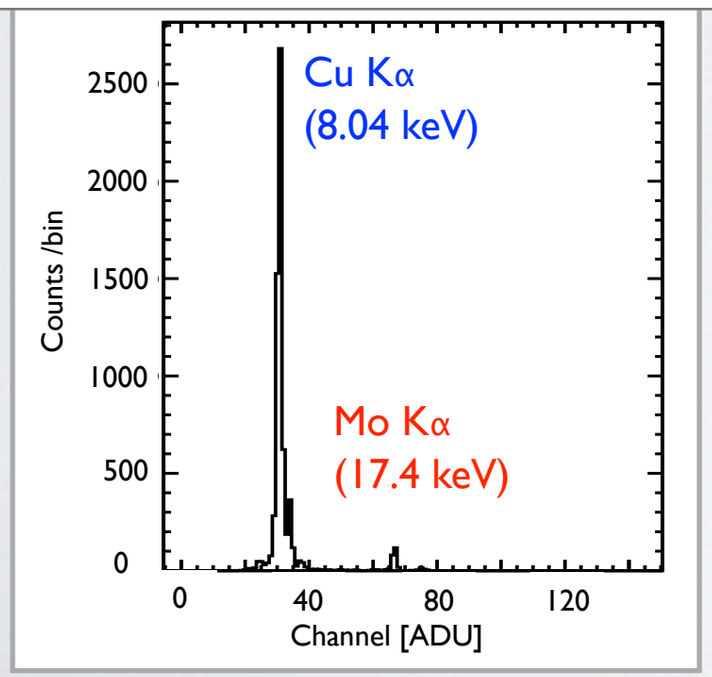
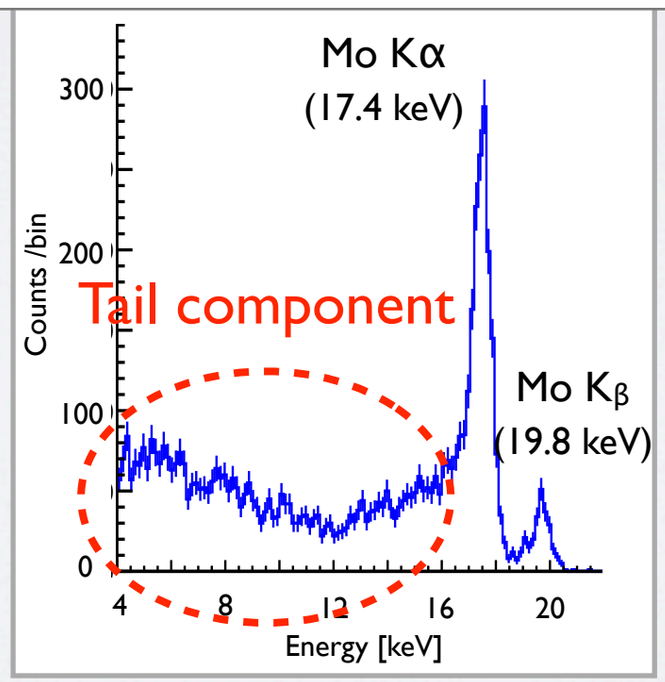
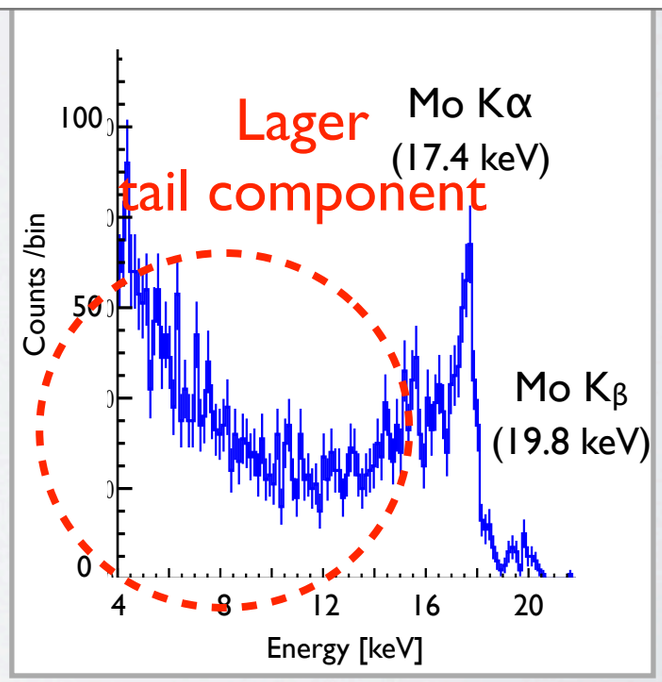
As the area of BPW occupied pixel is decreased, tail component becomes larger







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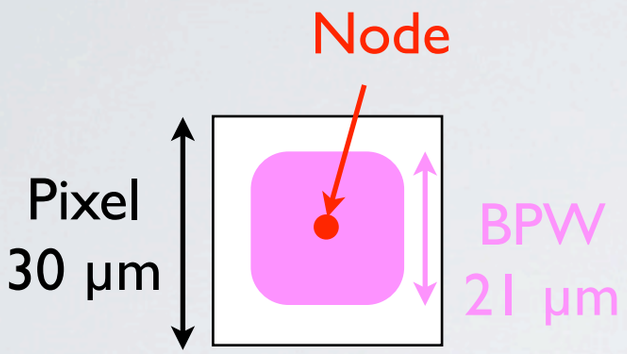

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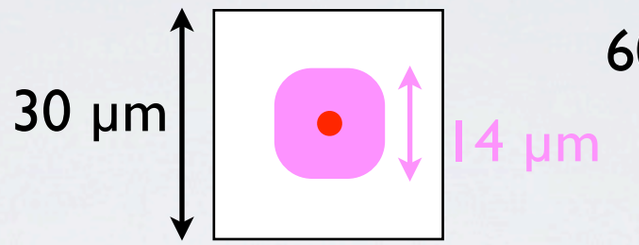
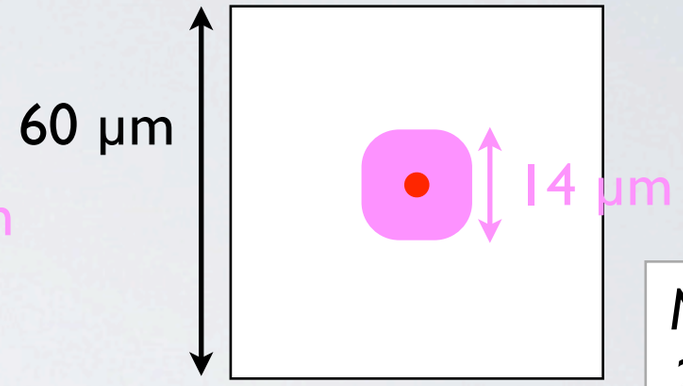


20%

Large Pixel with Small BPW



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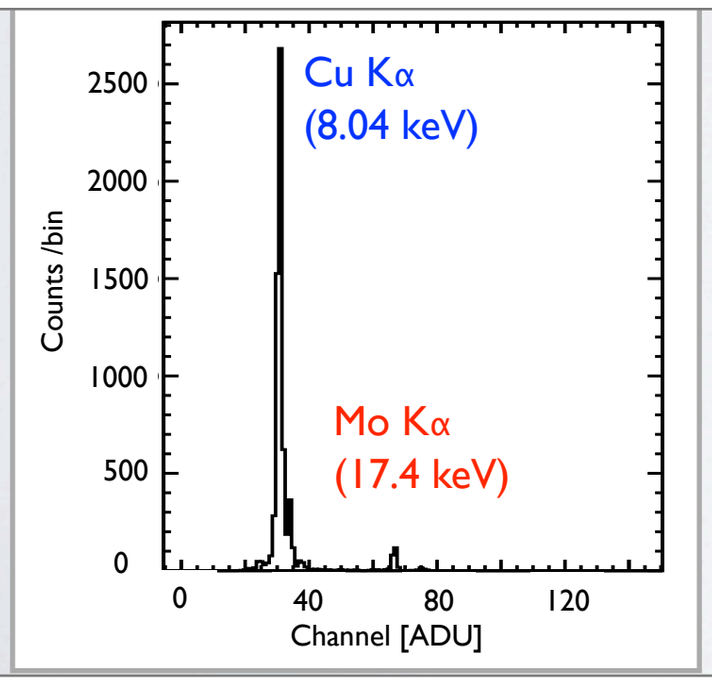
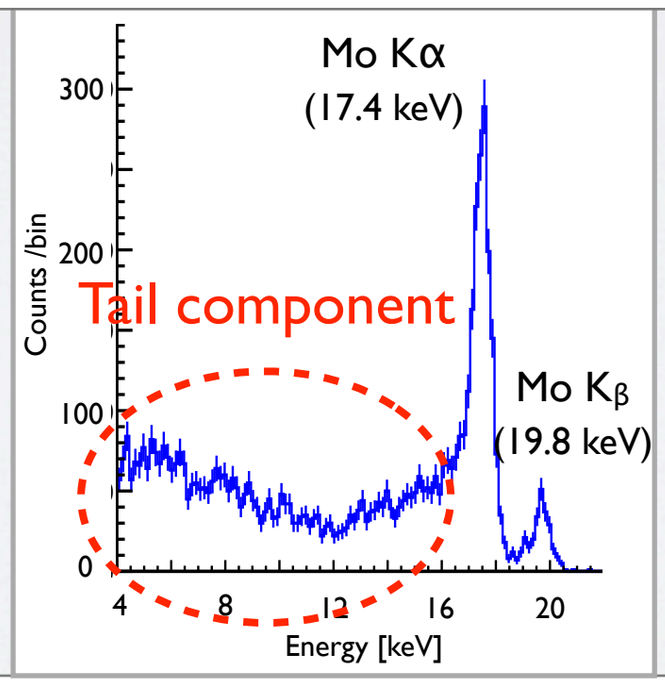
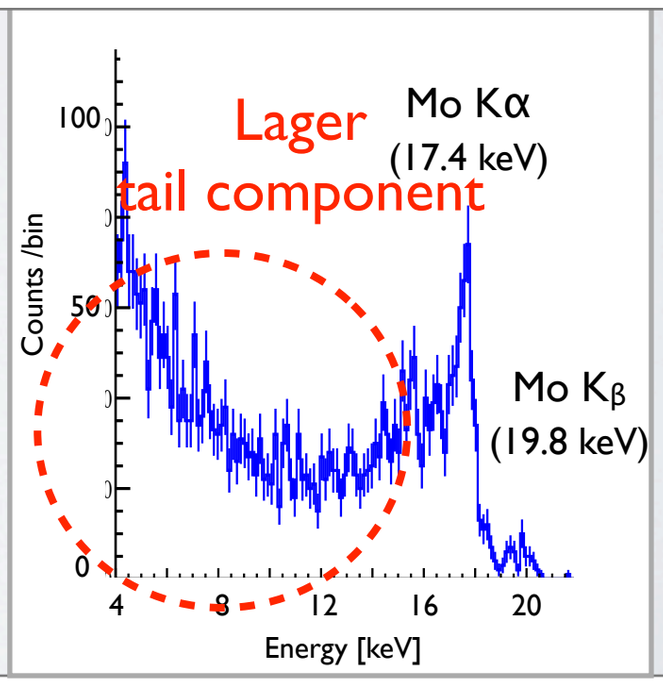
As the area of BPW occupied pixel is decreased, tail component becomes larger

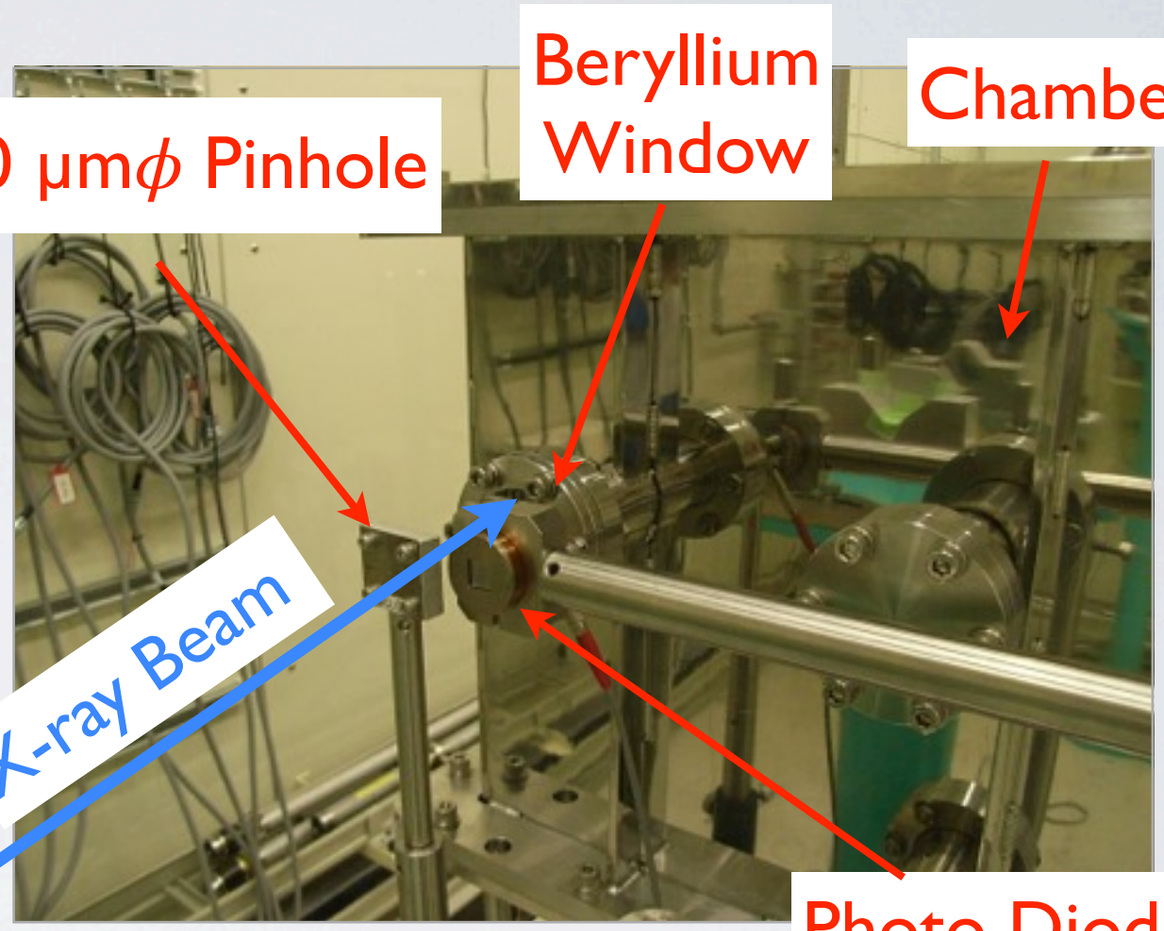


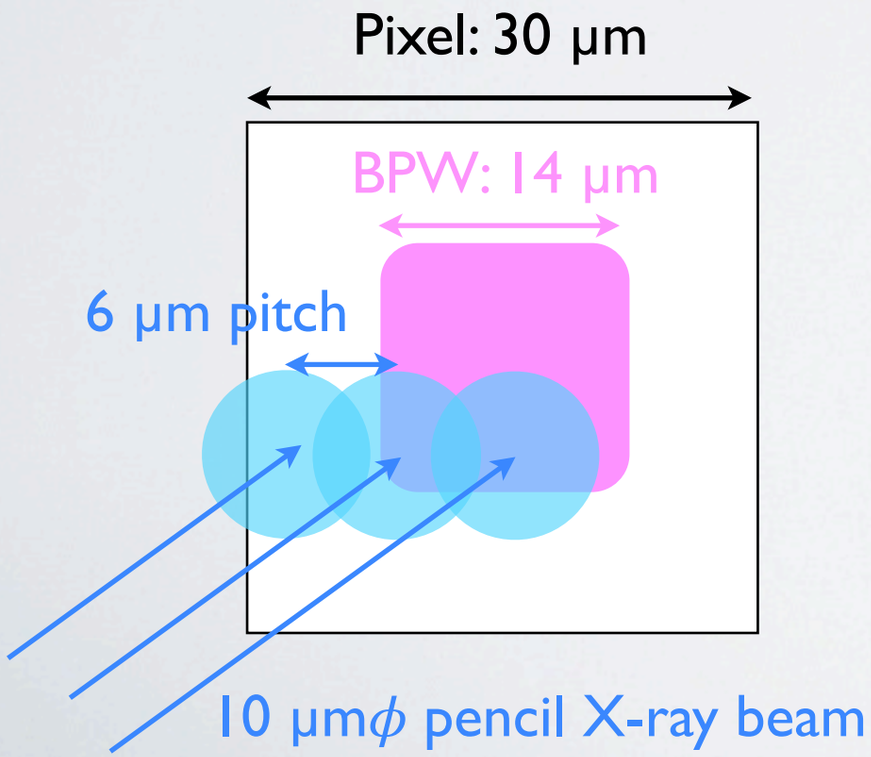




In order to investigate the place where charge is lost, we made beam test in a photon factory

Pencil beam irradiation at SPring-8





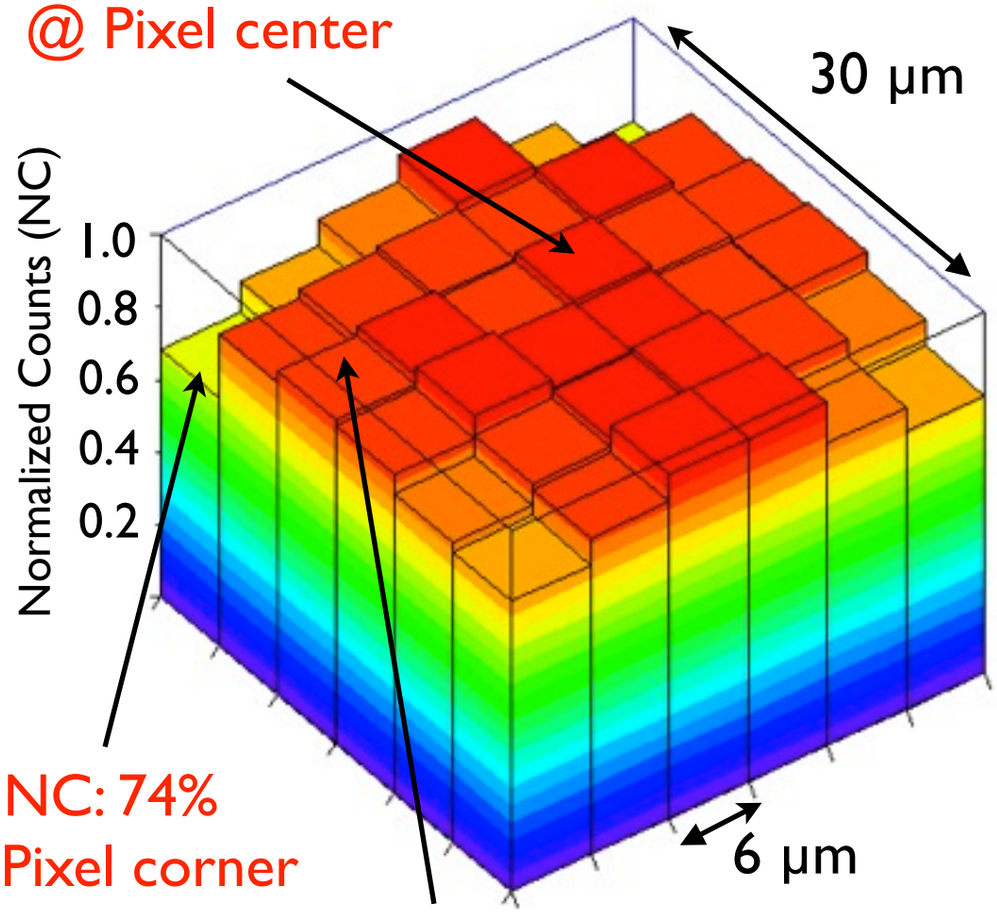
- Irradiate XRPIX1b (Small BPW) with 10 μmϕ pencil beam
- Scan the device with a 6 μm pitch
- Use 8.0 keV and 17.7 keV beams

Measure the sub-pixel response

Relative Quantum Efficiency

17.7 keV Beam

NC : 100%
@ Pixel center

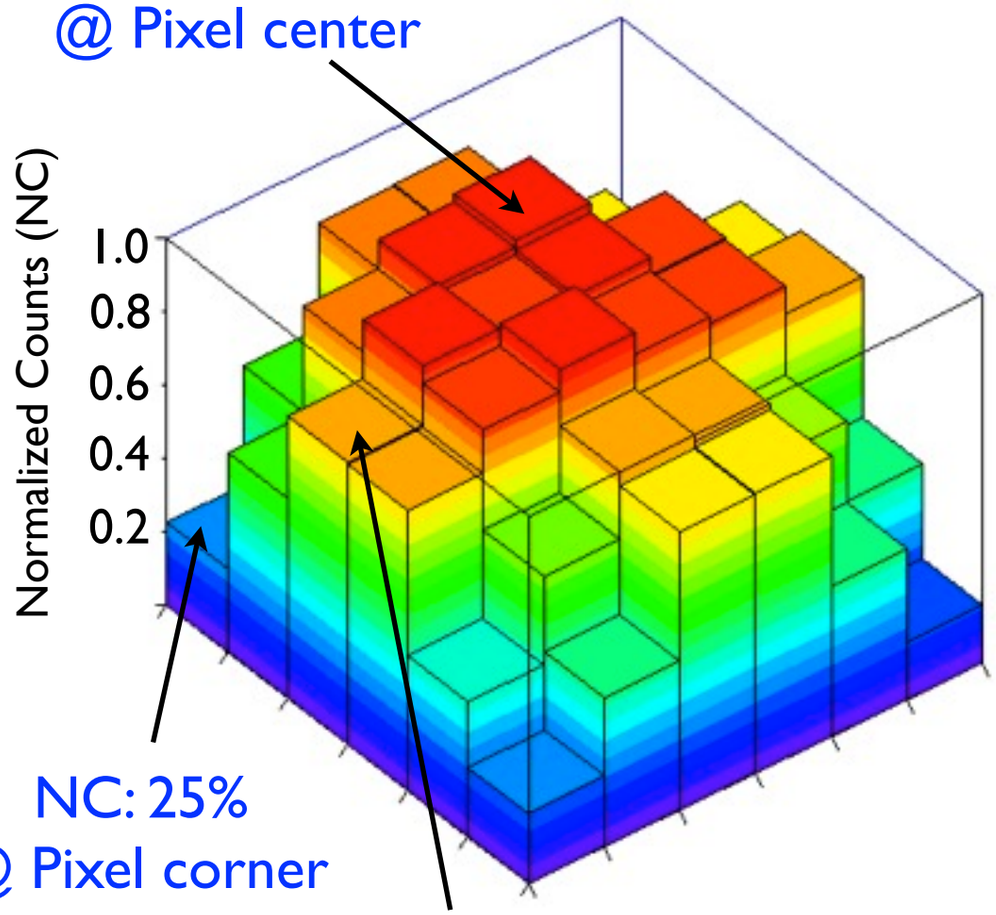


NC: 74%
@ Pixel corner

NC: 97%
@ Pixel boundary

8.0 keV Beam

NC: 100%
@ Pixel center



NC: 25%
@ Pixel corner

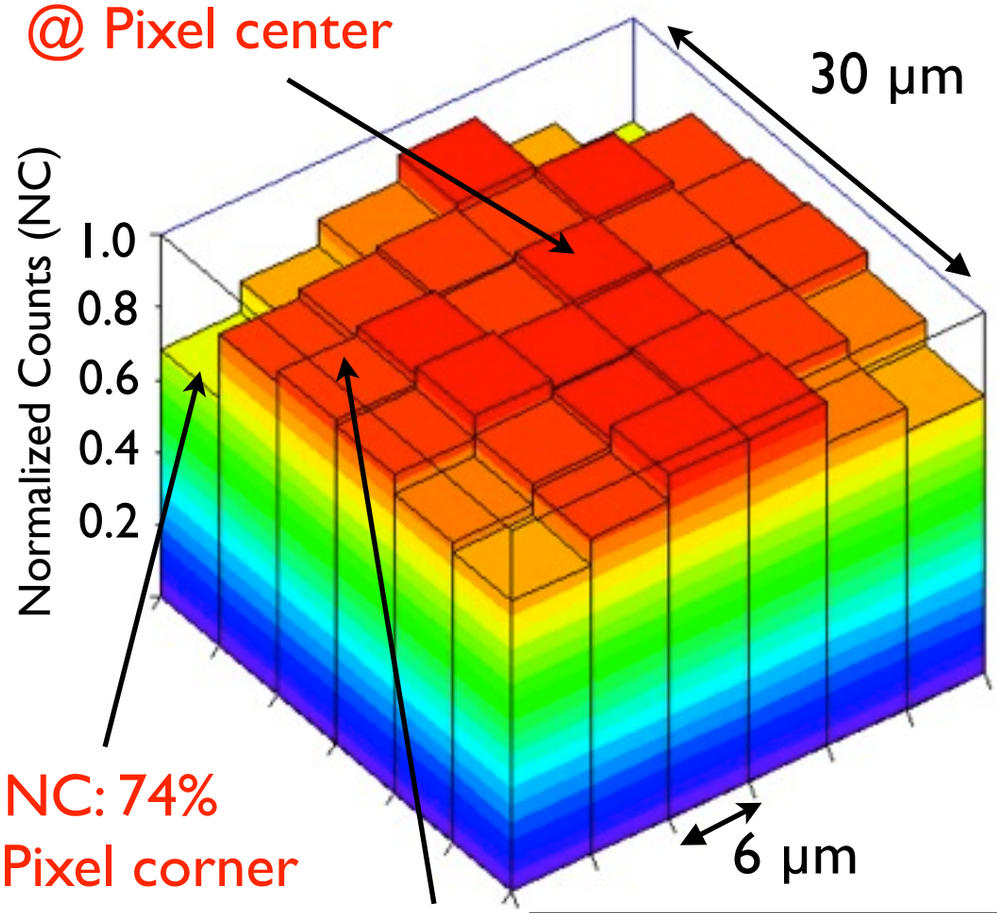
NC 83%
@ Pixel boundary

Relative Quantum Efficiency

17.7 keV Beam

8.0 keV Beam

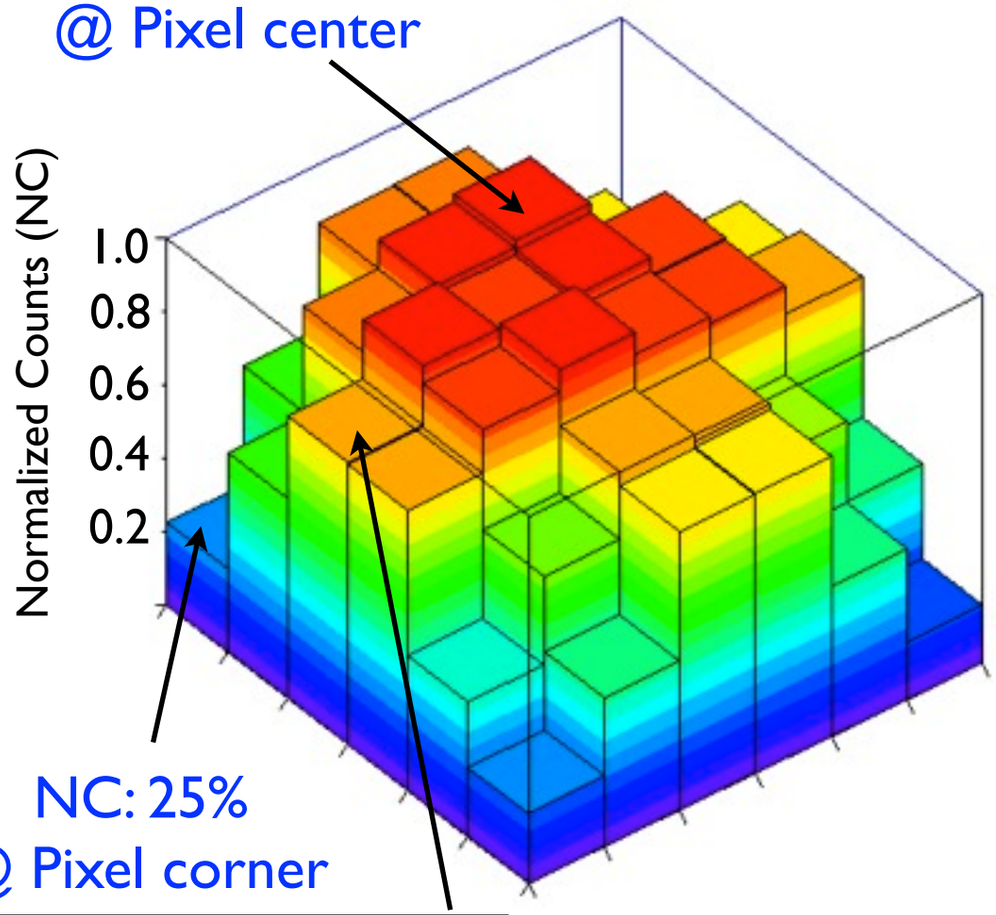
NC : 100%
@ Pixel center



NC: 74%
@ Pixel corner

NC: 97
@ Pixel bou

NC: 100%
@ Pixel center



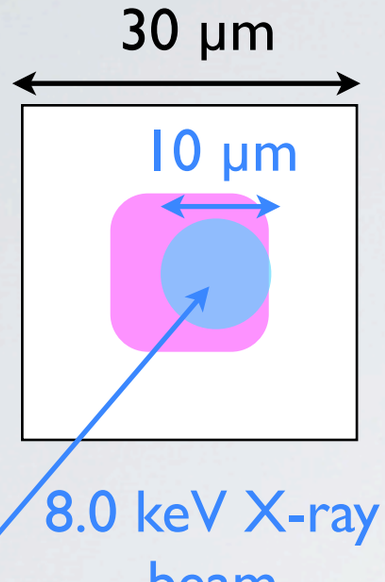
NC: 25%
@ Pixel corner

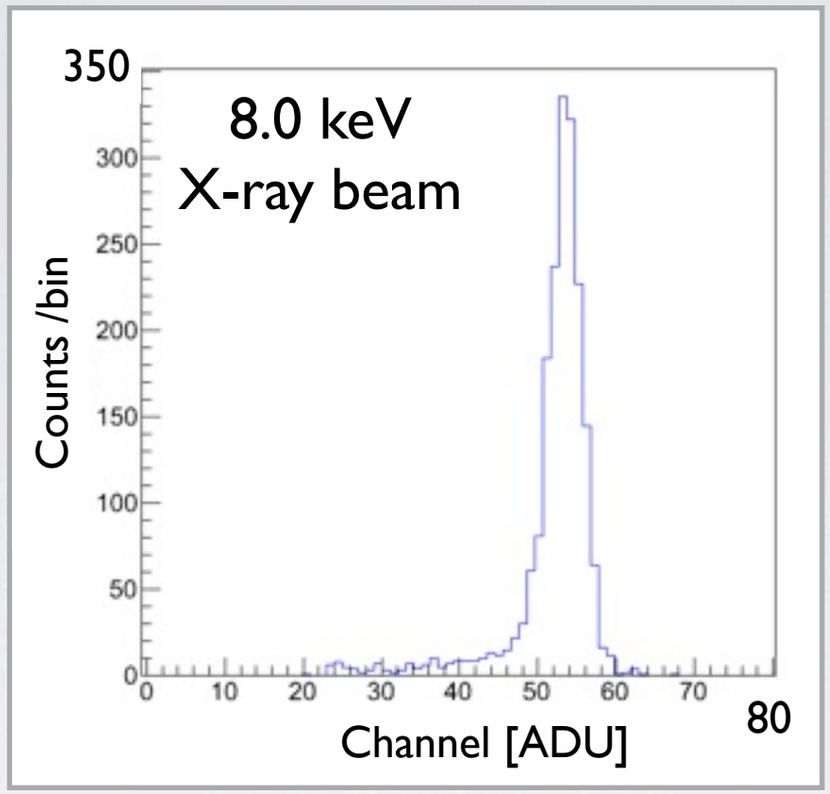
83%
boundary

A thick dead layer reaching
20 μm @ pixel boundary
100 μm @ pixel corner
Depletion layer thickness is 500 μm

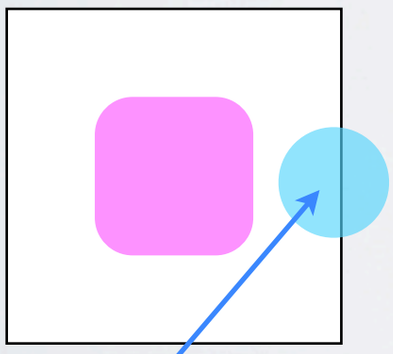
Energy Spectra

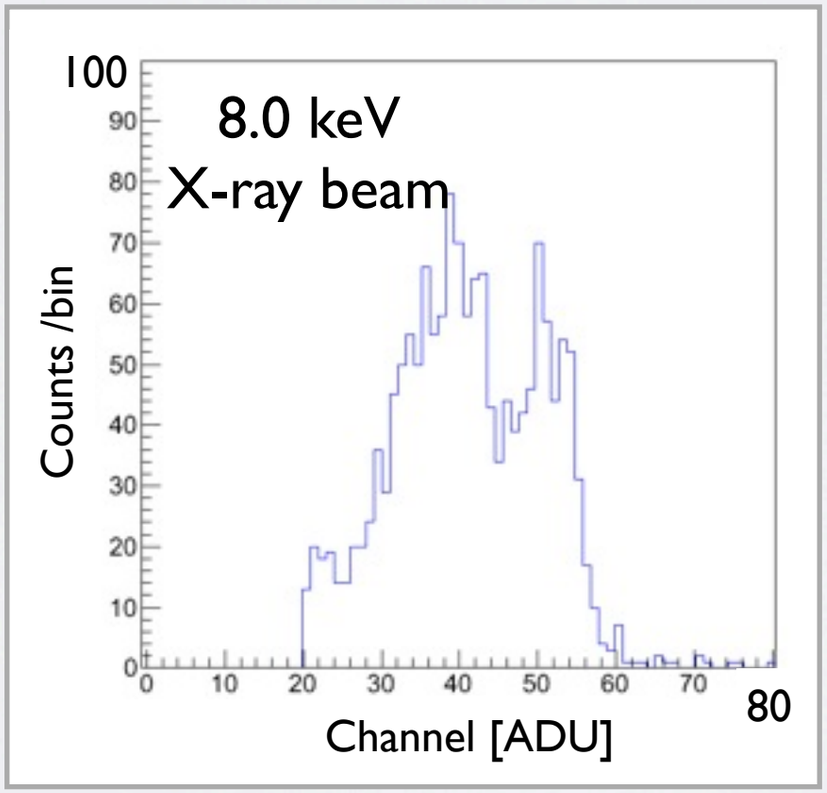
@ Pixel Center





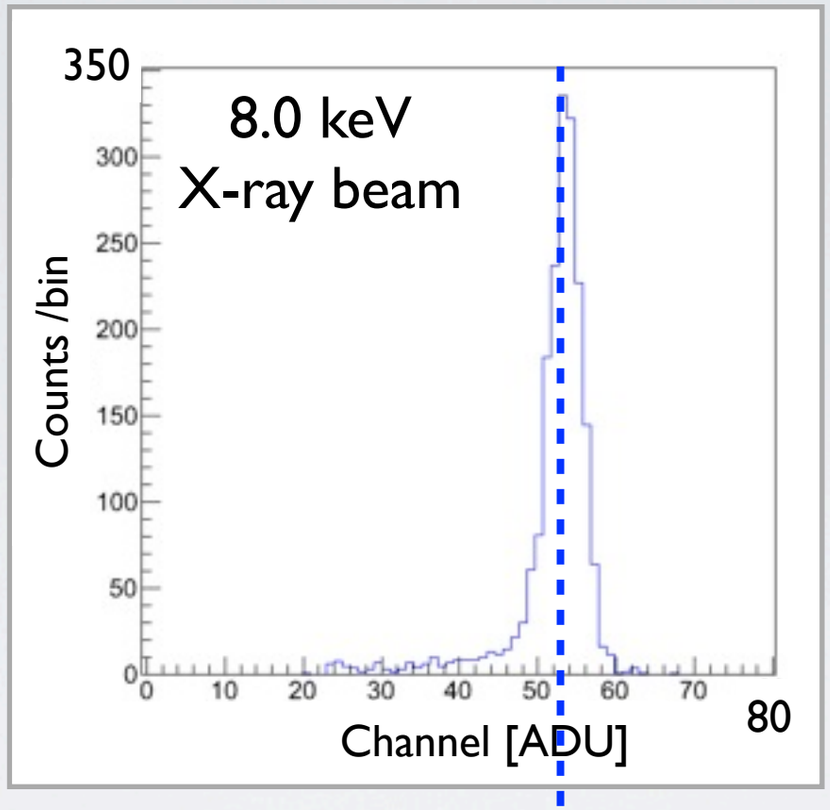
@ Pixel Boundary



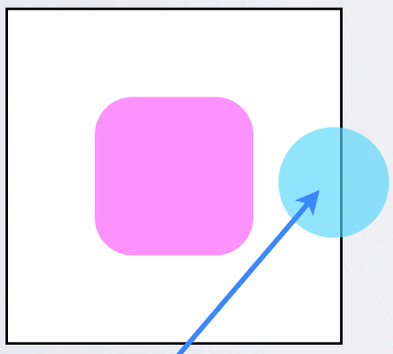


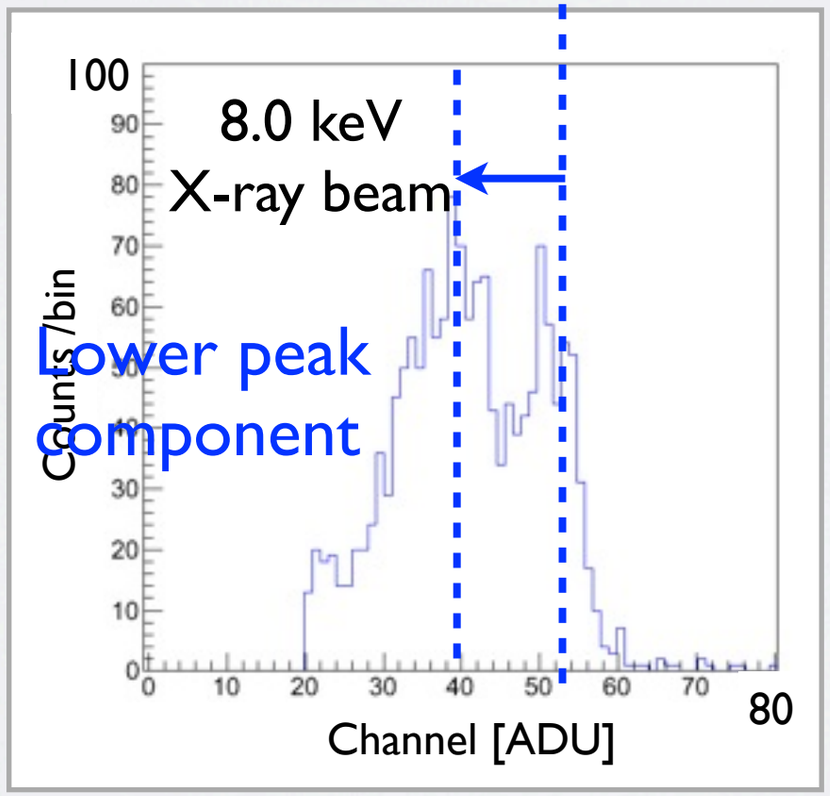
Energy Spectra

@ Pixel Center



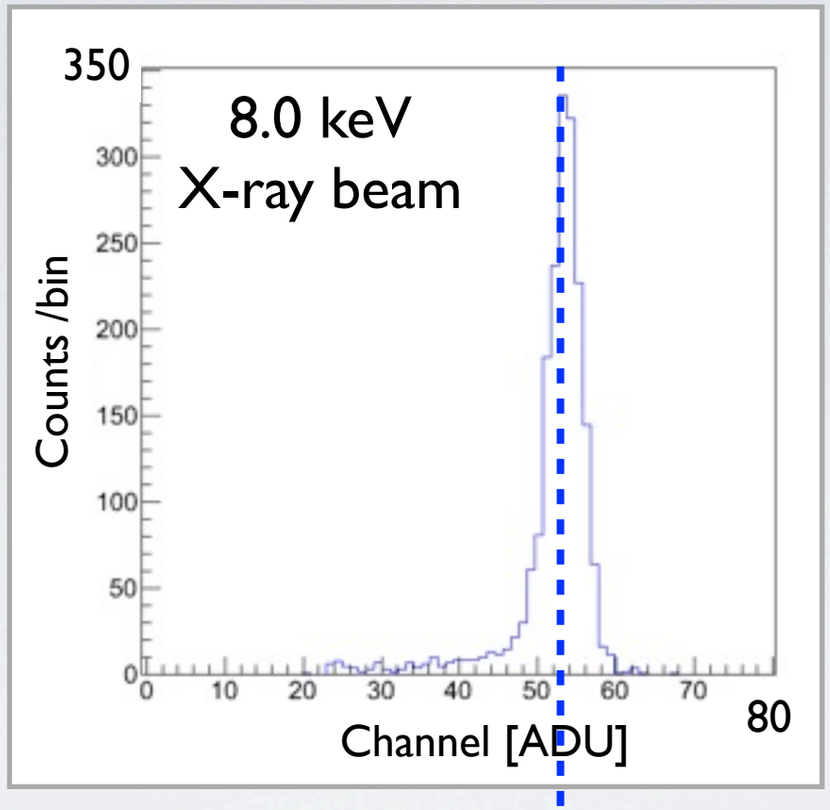
@ Pixel Boundary



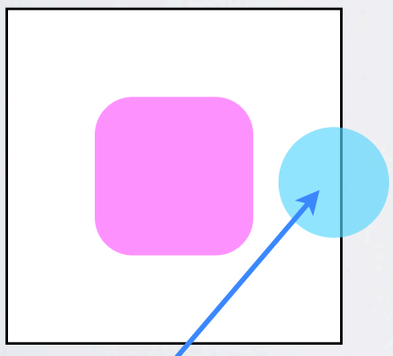


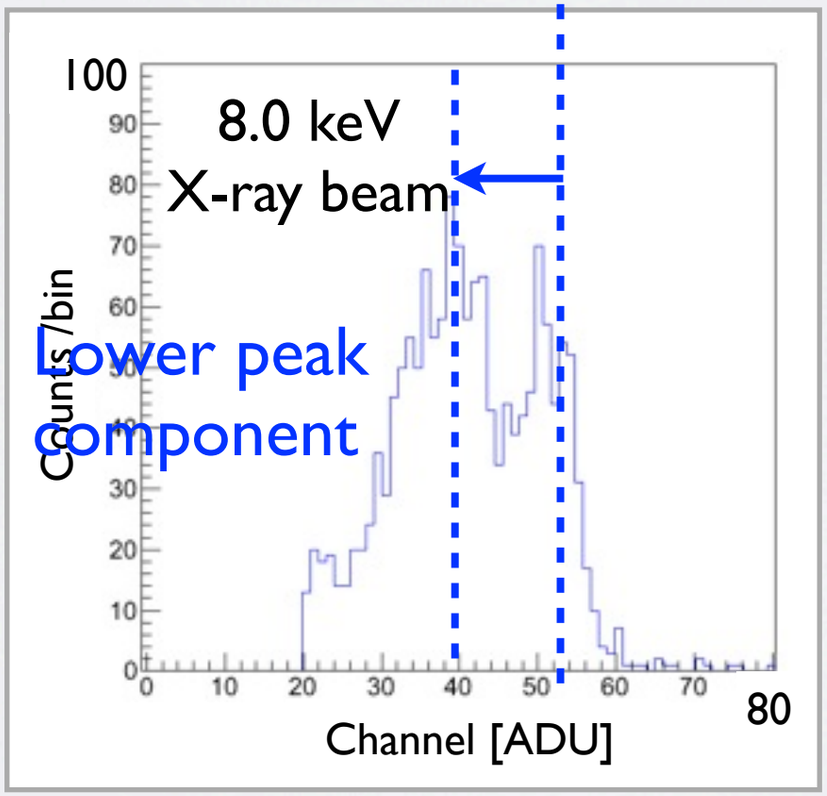
Energy Spectra

@ Pixel Center



@ Pixel Boundary



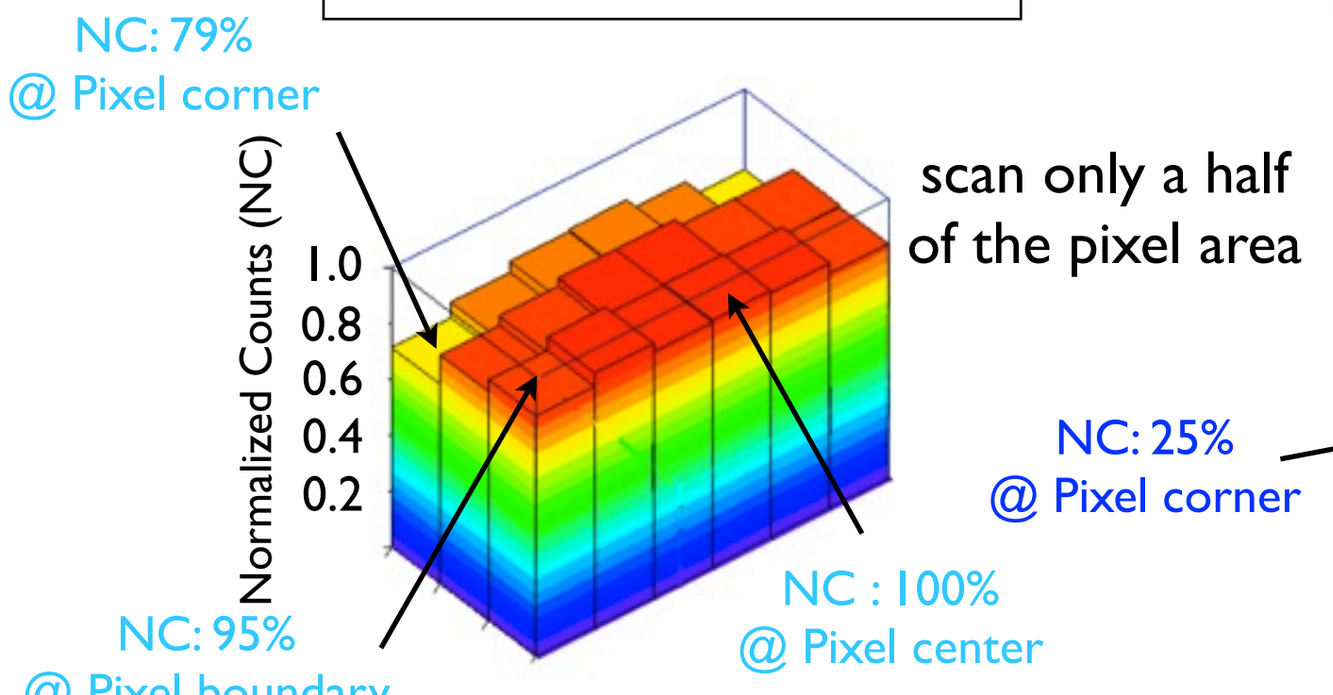


Charge is lost at the pixel boundary

Charge-collection efficiency of charge-shared events is not well

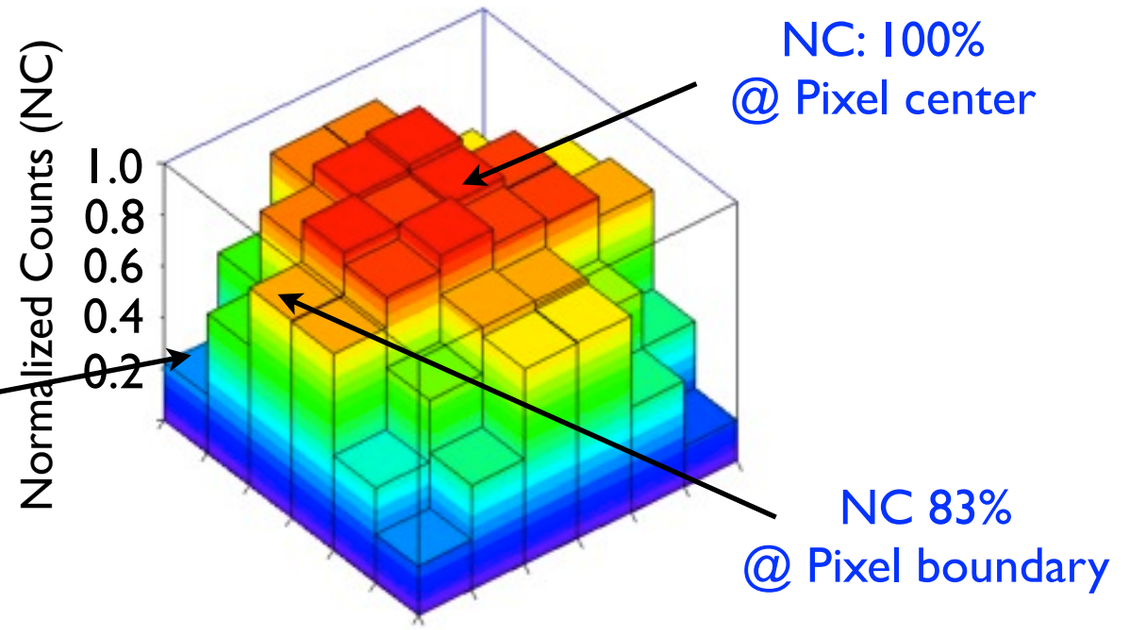
Back Bias Dependence

8keV beam, V_{bias} = 20 V

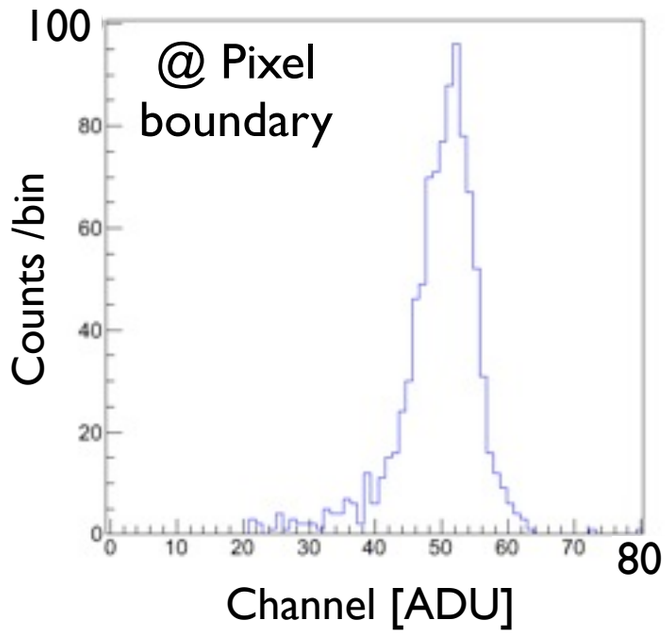


scan only a half of the pixel area

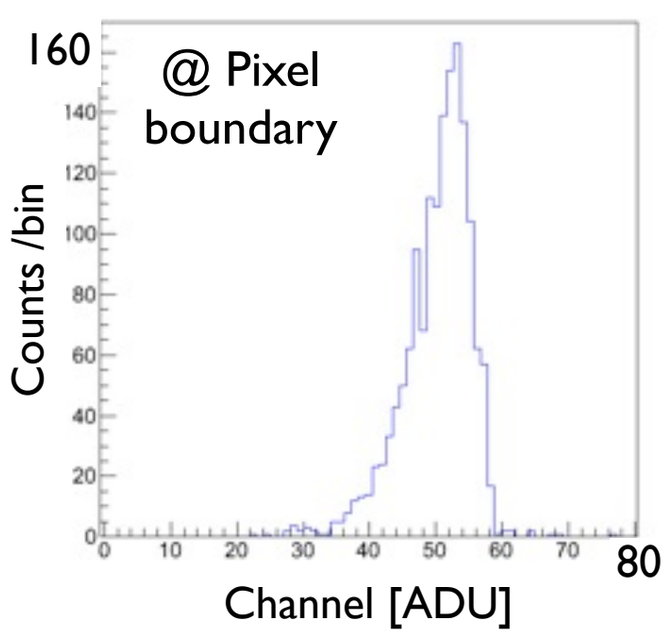
8keV beam, V_{bias} = 200 V



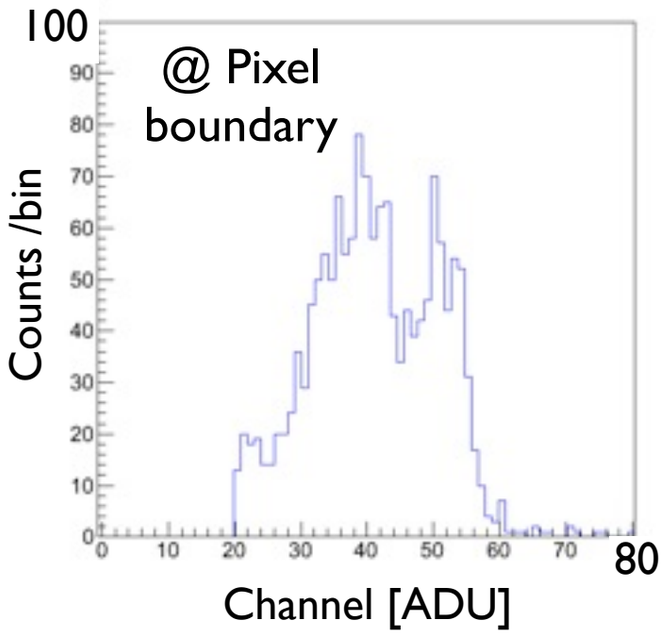
8keV beam, V_{bias} = 5 V



8keV beam, V_{bias} = 20 V



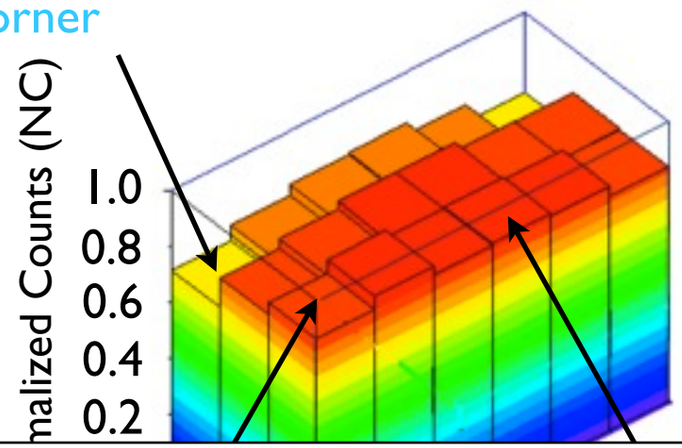
8keV beam, V_{bias} = 200 V



Back Bias Dependence

8keV beam, V_{bias} = 20 V

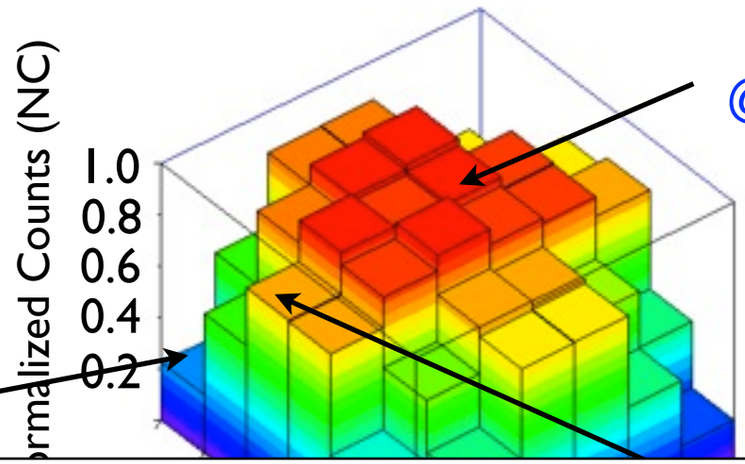
NC: 79%
@ Pixel corner



scan only a half
of the pixel area

8keV beam, V_{bias} = 200 V

NC: 100%
@ Pixel center

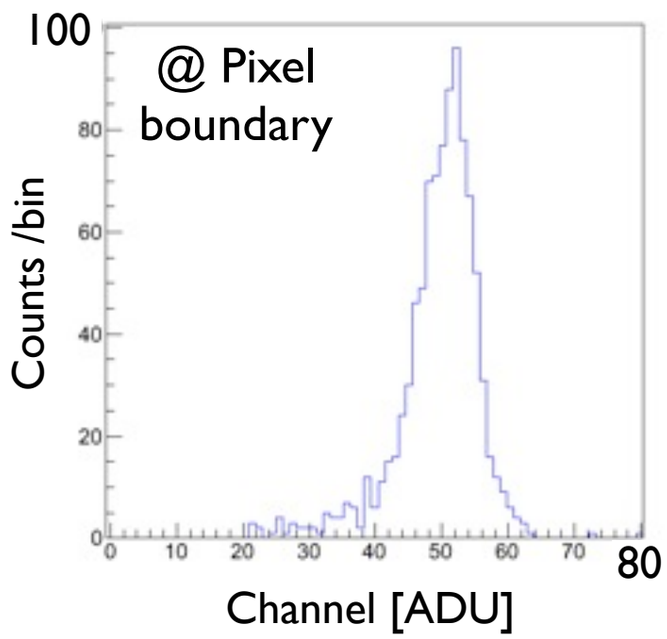


NC: 25%
@ Pixel corner

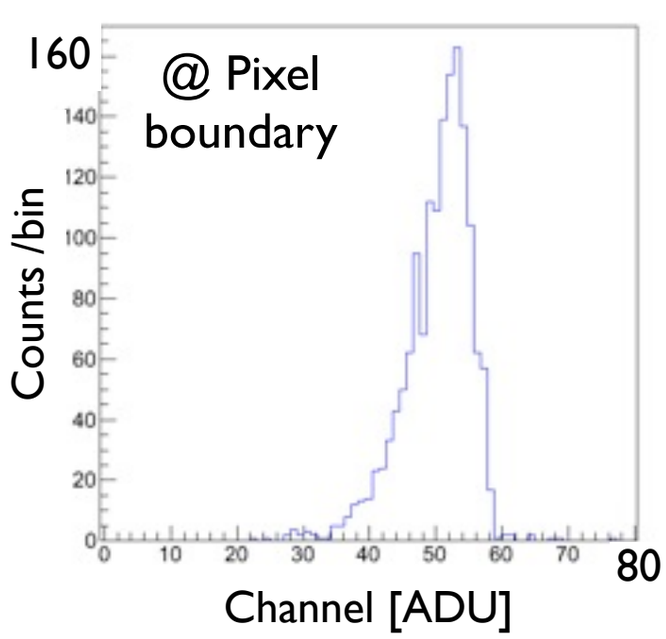
@ dary

The thickness of the dead layer at lower back bias is smaller than that at high back bias

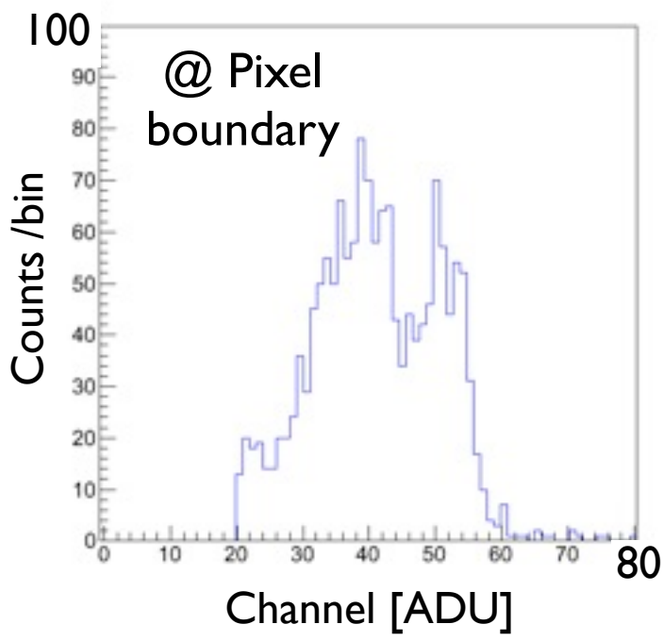
8keV beam, V_{bias} = 5 V



8keV beam, V_{bias} = 20 V



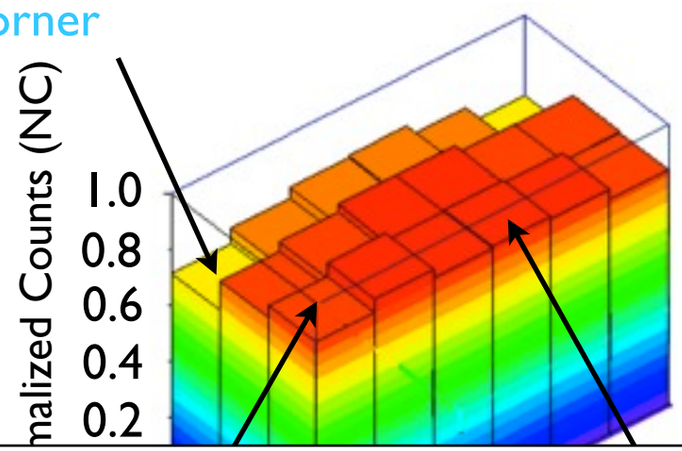
8keV beam, V_{bias} = 200 V



Back Bias Dependence

8keV beam, V_{bias} = 20 V

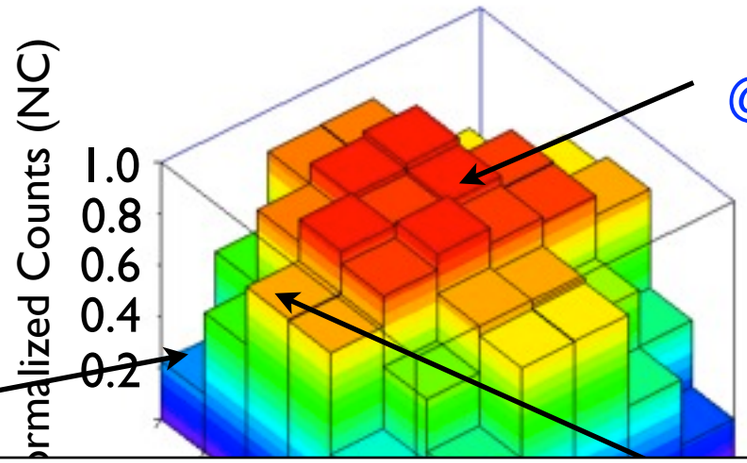
NC: 79%
@ Pixel corner



scan only a half
of the pixel area

8keV beam, V_{bias} = 200 V

NC: 100%
@ Pixel center

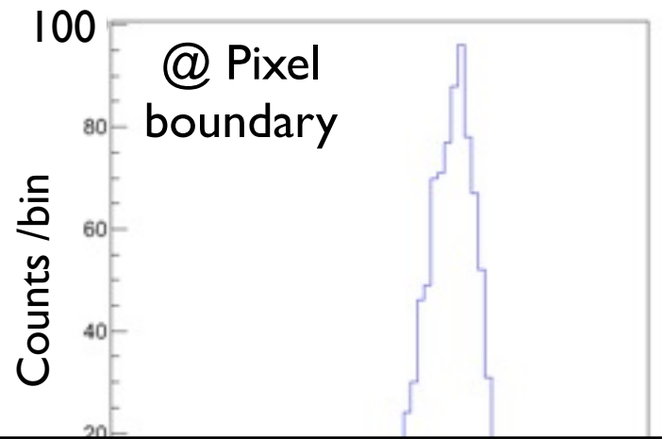


NC: 25%
@ Pixel corner

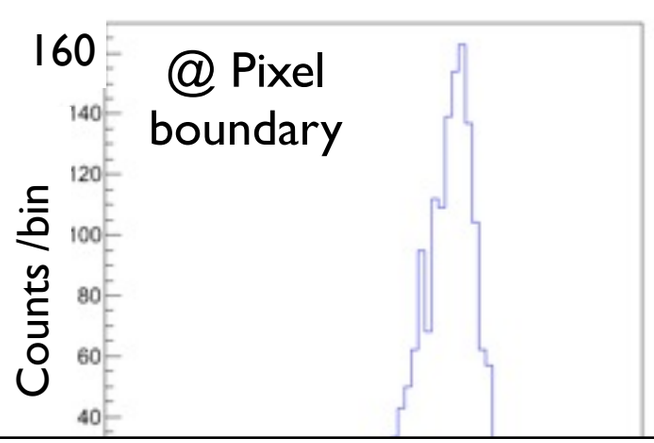
@ dary

The thickness of the dead layer at lower back bias is smaller than that at high back bias

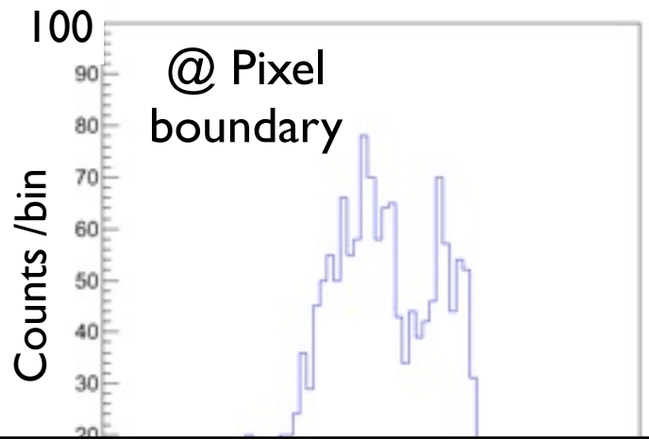
8keV beam, V_{bias} = 5 V



8keV beam, V_{bias} = 20 V



8keV beam, V_{bias} = 200 V

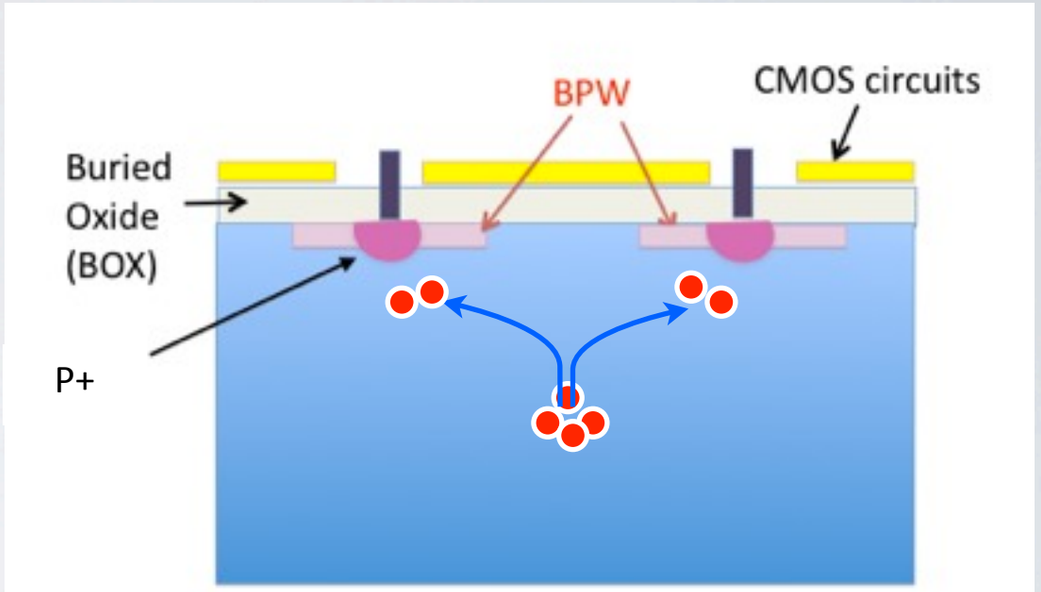


The charge-collection efficiency is better at lower back bias than that at higher back bias

Discussion

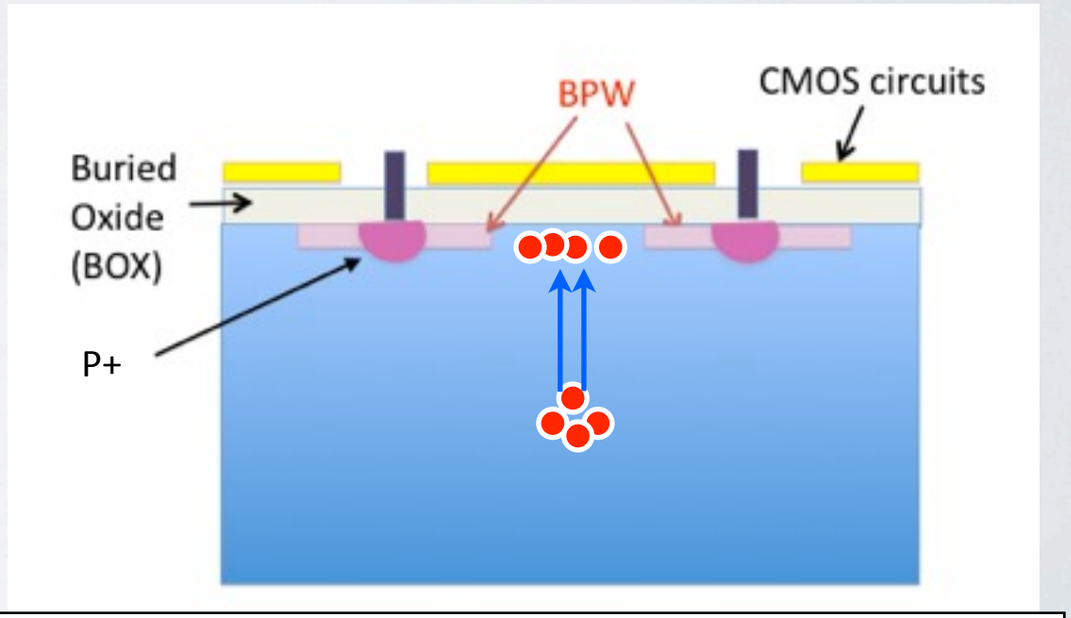
At lower back bias voltage

- Charge generated at the pixel boundary is not lost.
- Charge moves along the electric field in the sensor layer.
- So, we expect that the electric field converge into BPW.



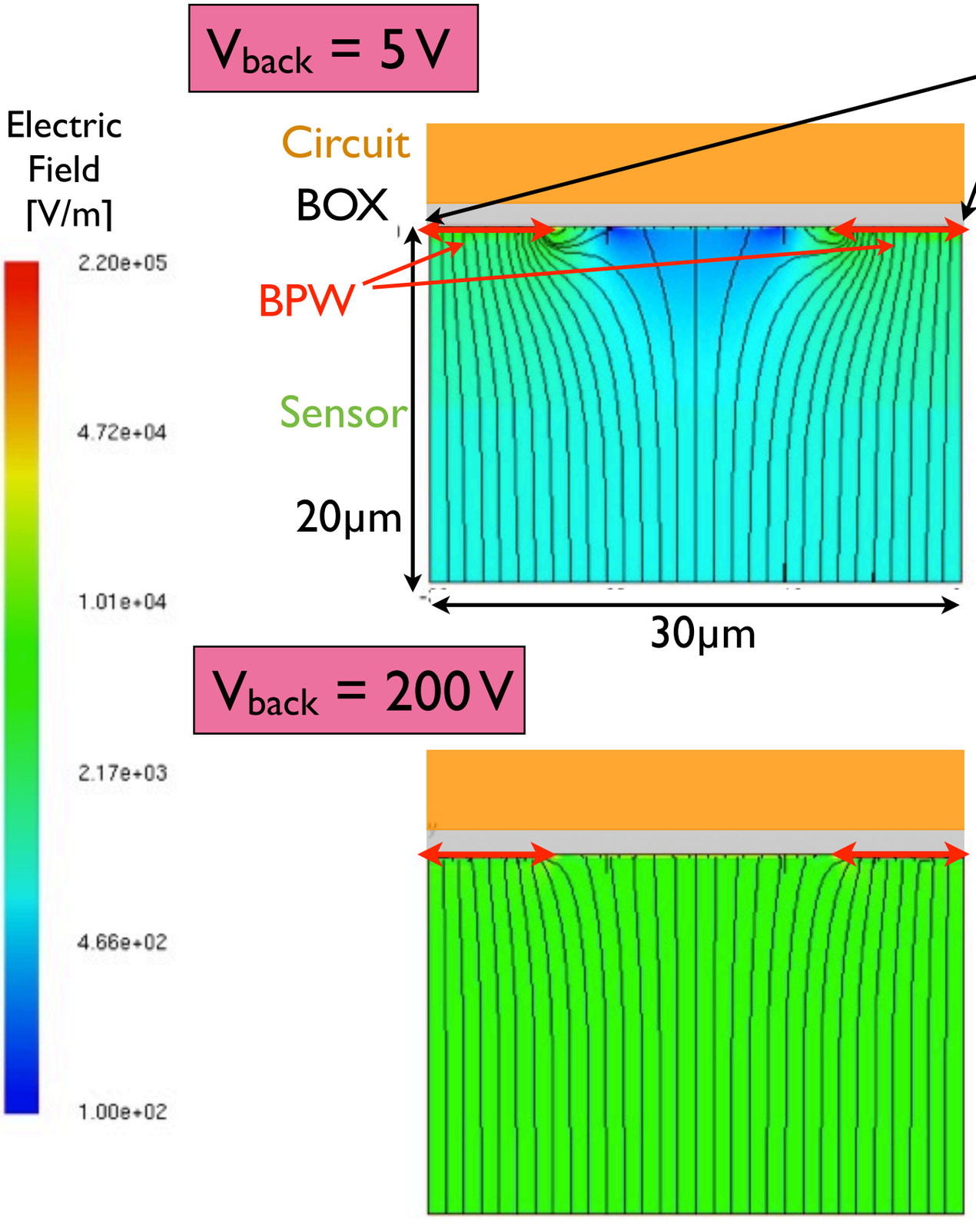
At higher back bias voltage

- We found larger charge loss and larger dead layer
- Charge generated at shallow place does not arrive at BPW.
- Suggesting that the charge is transferred the interface not covered by BPW.
- The electric field will not be converged into BPW.



We simulate the electric field using TCAD simulator

TCAD Simulation of Electric Field



- Electric field converge into BPW.
- Signal charge event at the pixel boundary is collected.

- Electric field penetrates into BOX.
- Signal charge moves to the interface region between Sensor and BOX.
- The signal charge would be trapped and lost at the interface.

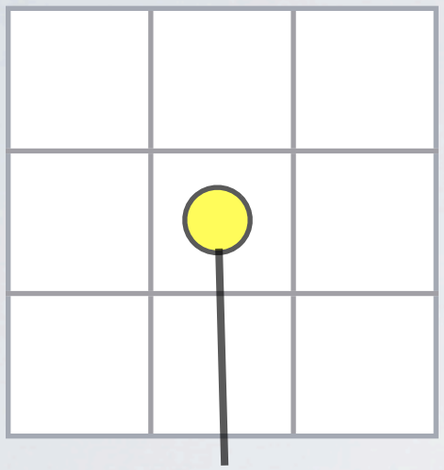
Summary

- We developed the device with small BPW in order to reduce the capacitance and increase the gain.
- We investigate the sub-pixel response by irradiating with pencil X-ray beams.
- Relative quantum efficiency and charge-collection efficiency at the pixel boundary are not well.
- At a high back bias voltage, we found a thick dead layer and lower charge-collection efficiency.
- From TCAD simulation, we found that the electric field penetrates into the BOX layer and charge move to the interface region between Sensor and BOX.

Back Slide

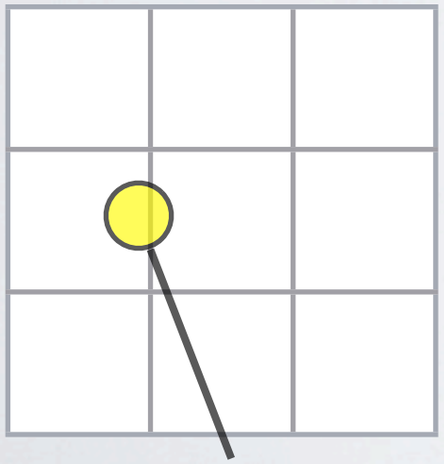
Energy Spectra

Single-pixel event

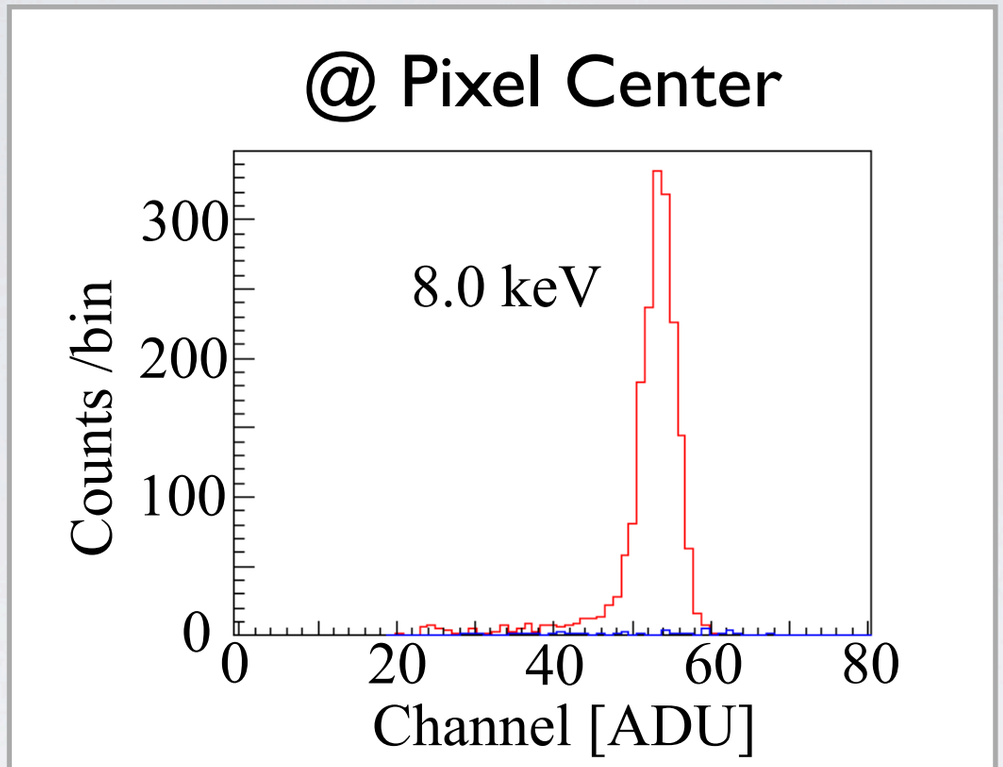


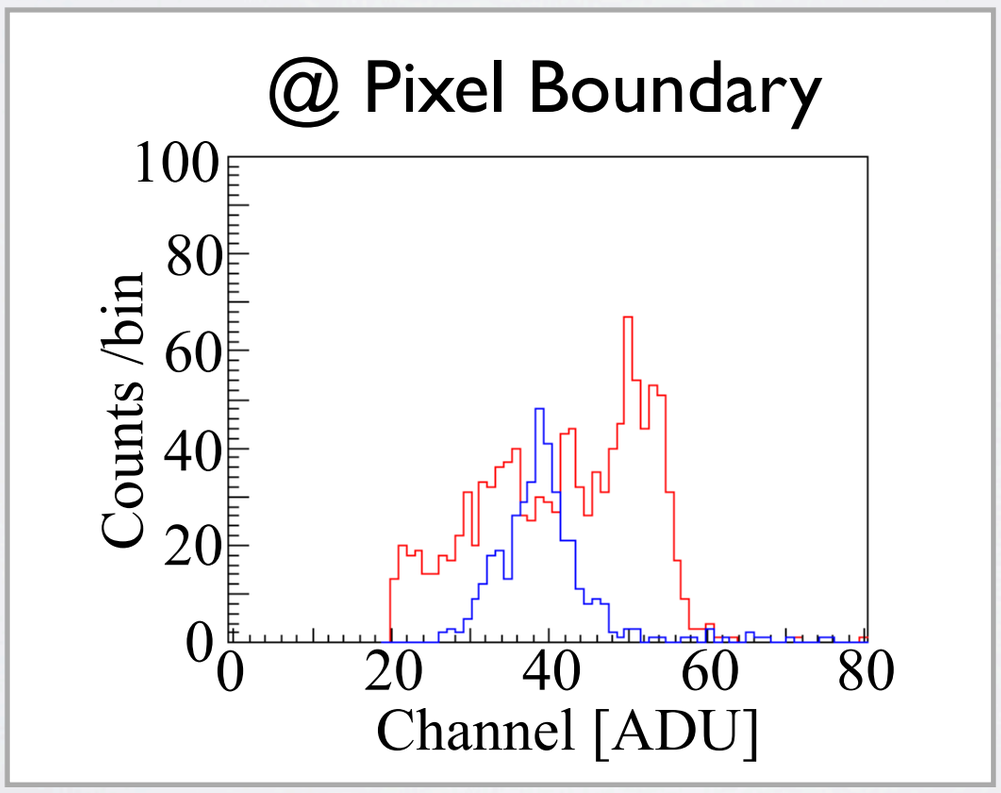
charge cloud
accumulate in a pixel

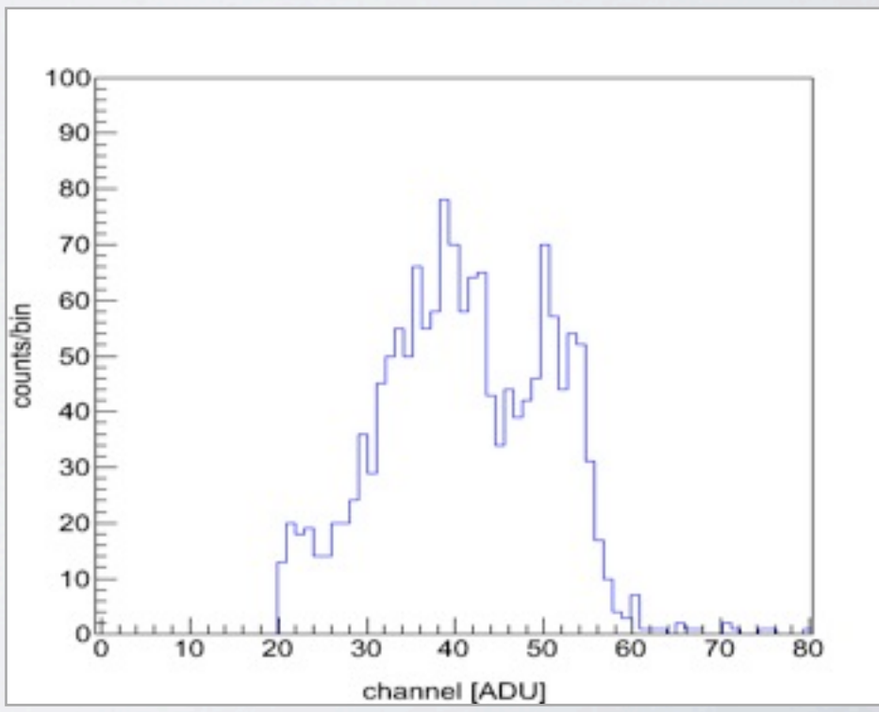
Two-pixel event



charge is shared by
two pixels

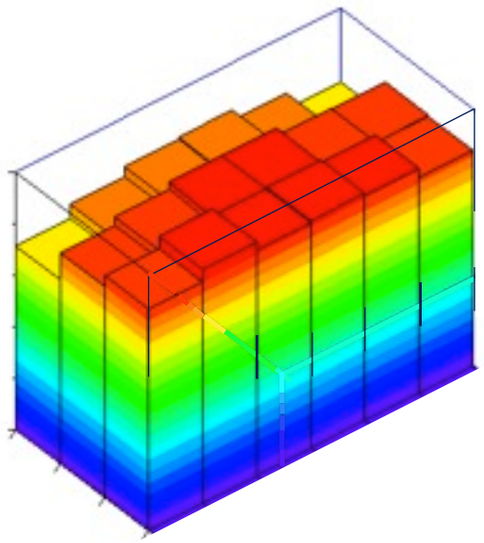




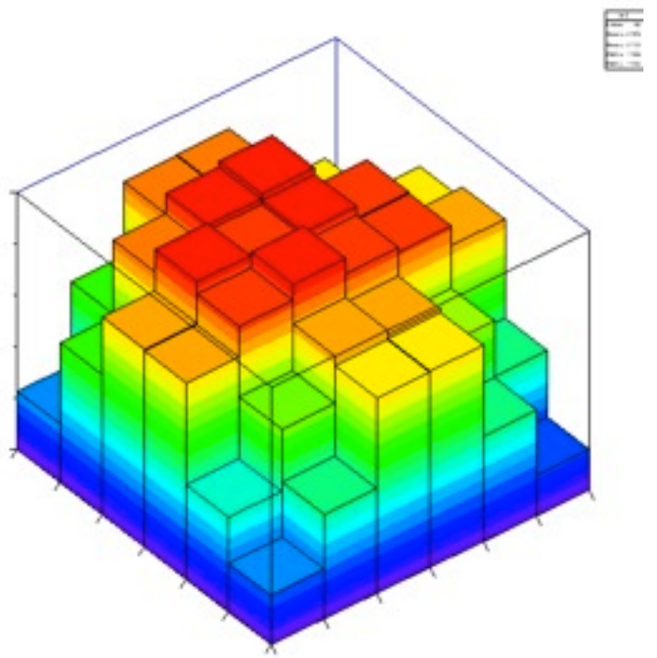


Back Bias Dependence

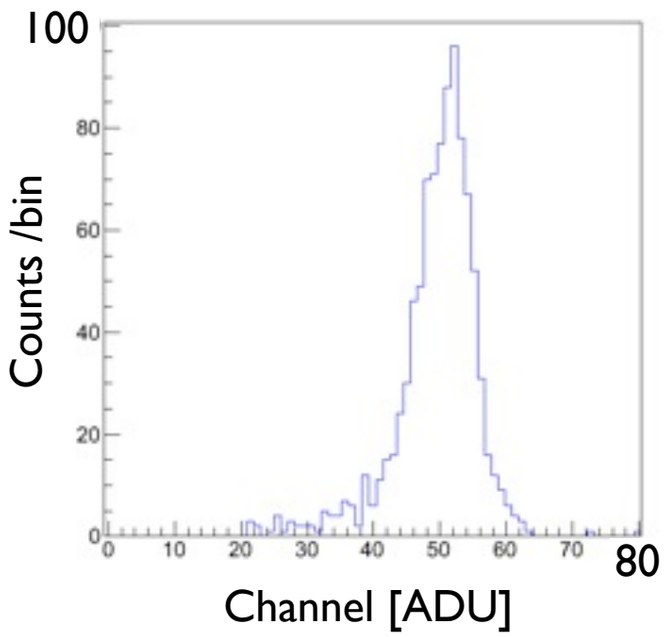
8 keV beam, V_{bias} = 20 V



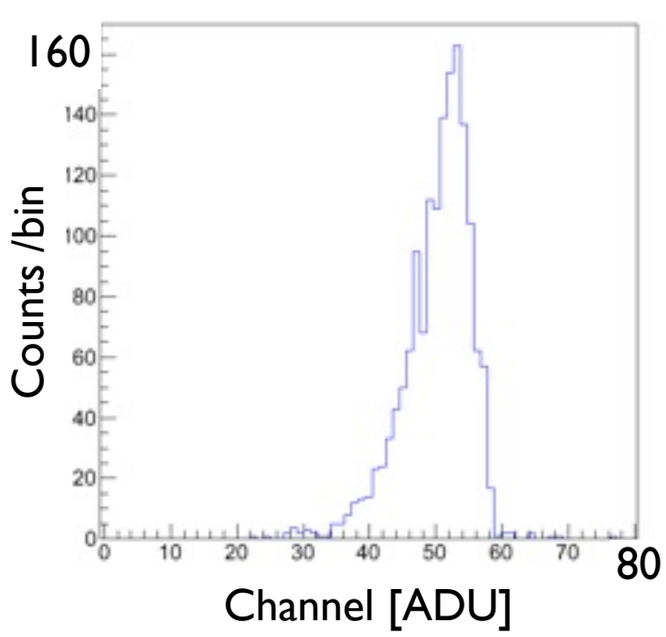
8 keV beam, V_{bias} = 200 V



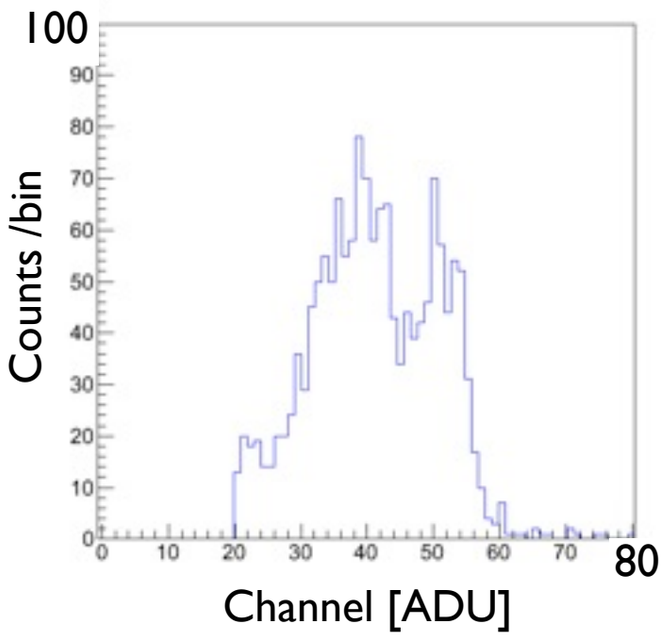
V_{bias} = 5 V



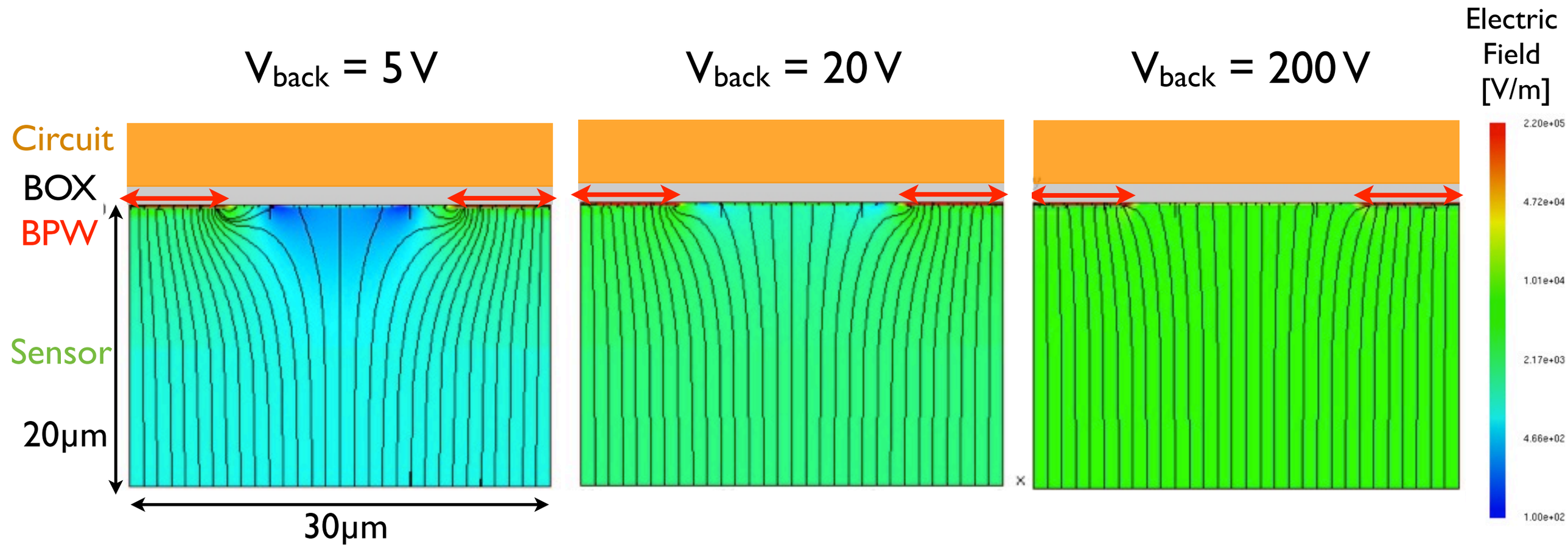
V_{bias} = 20 V



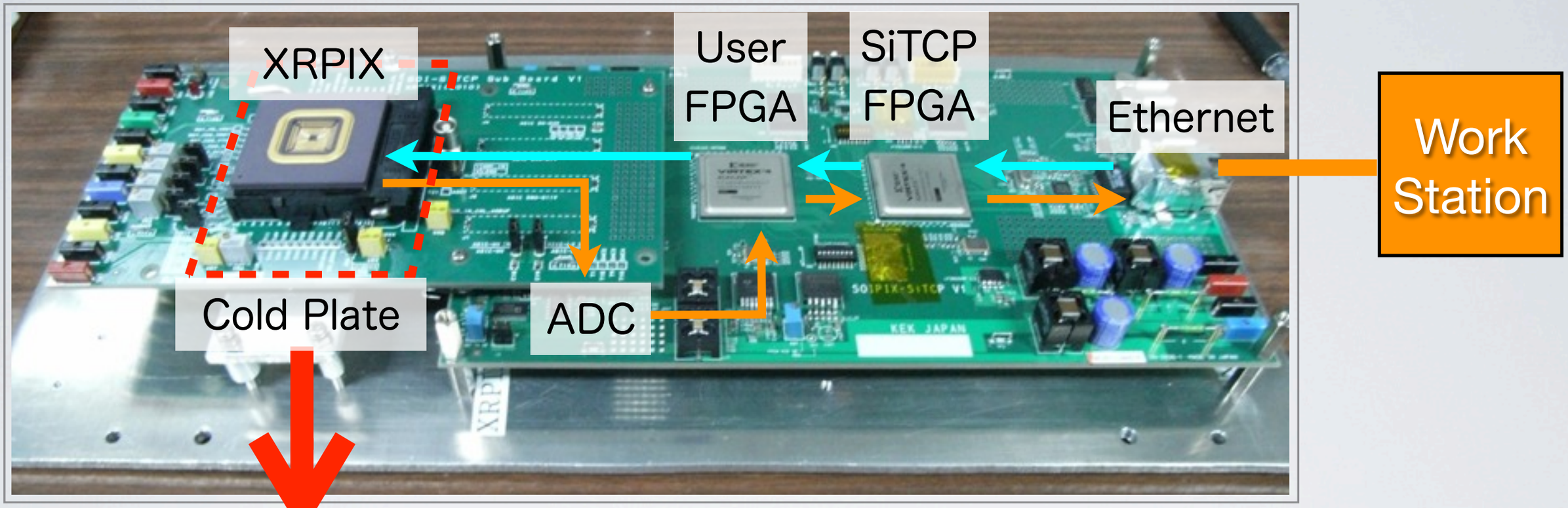
V_{bias} = 200 V

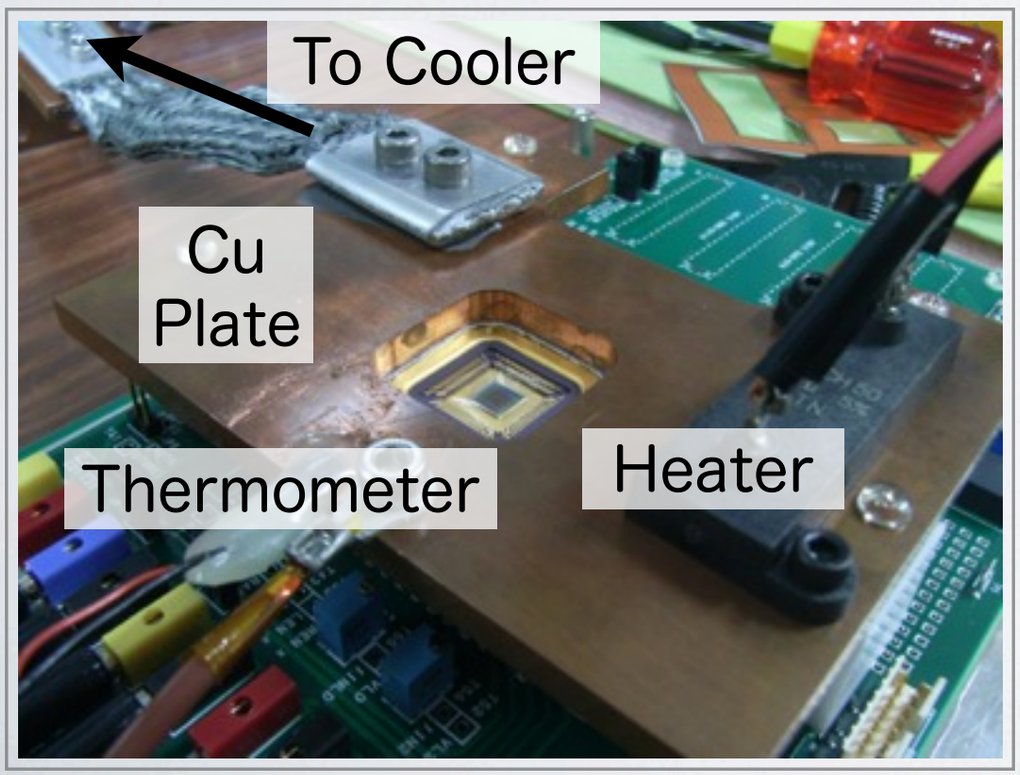


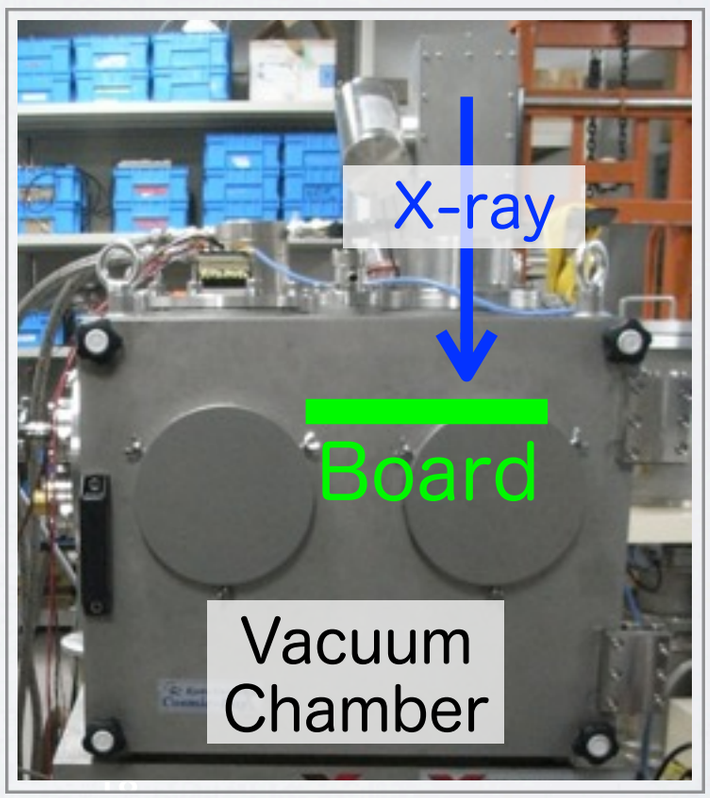
TCAD Simulation of Electric Field



Experimental Setup

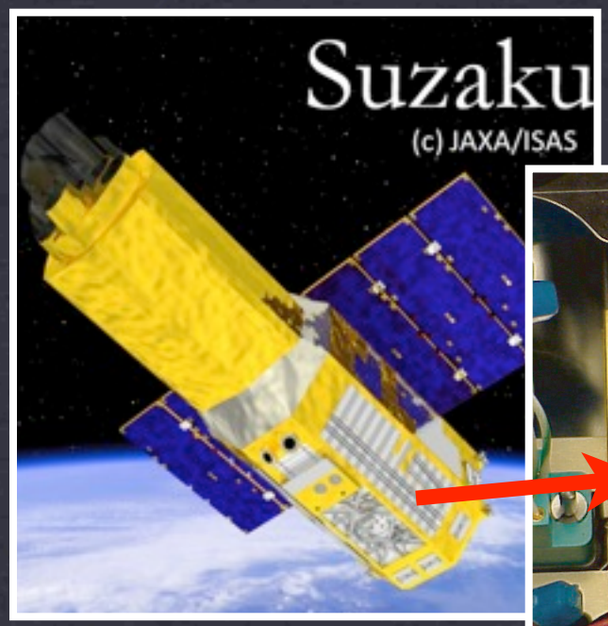




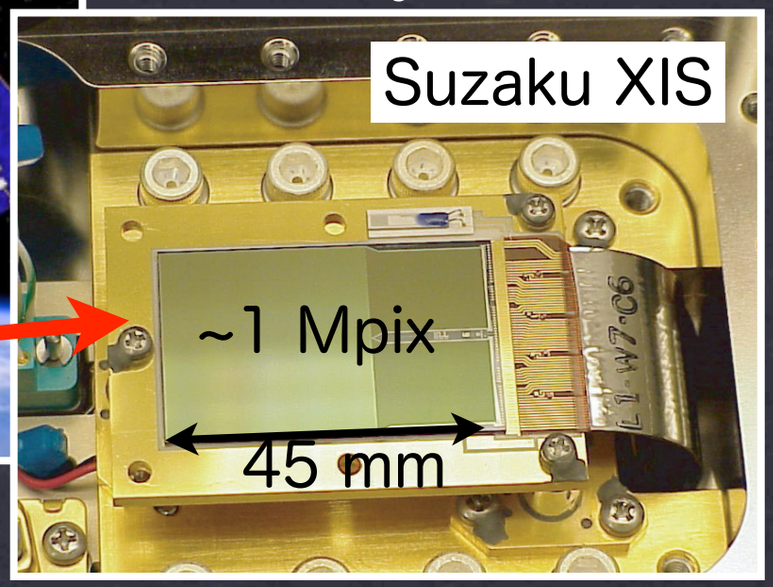


Chip temperature
-> -70℃
Degree of Vacuum
-> 10^{-6} torr

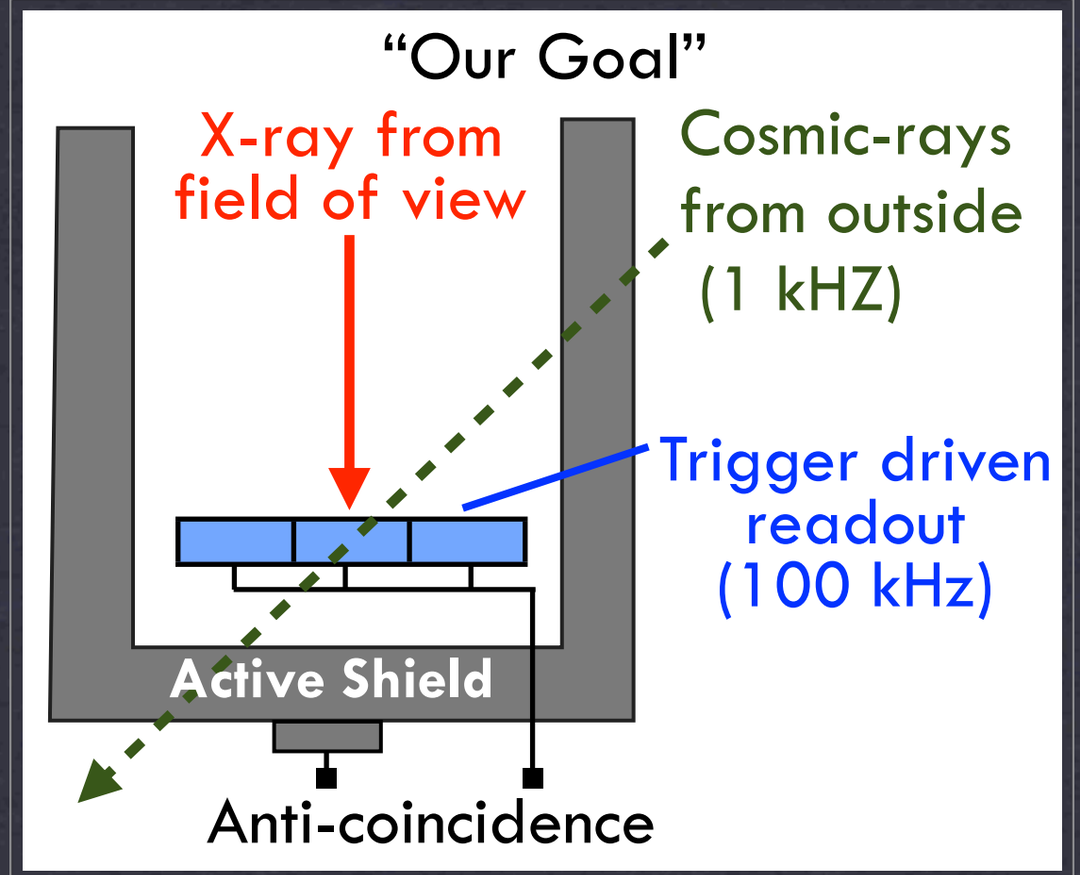
Motivation in X-ray Astronomy



Standard Detector
= X-ray CCDs



new imaging spectrometer
capable of high speed reaout
and low background



Weak Points

- Poor time resolution of ~ sec
- Non X-ray background above 10 keV
  - due to cosmic rays in satellite orbit

	positional resolution	Energy resolution	Timing resolution	observable energy band
CCD	~ 20 μm	2% FWHM@6 keV	~ sec	0.5 - 10 keV
SOI pixel	< 30 μm	2% FWHM@6 keV	< 10 μsec	0.5 - 40 keV