# Evaluation of SOI Pixel Detector with Charge Sensitive Amplifier Circuit for Event-Driven X-ray Readout

**PIXEL2014 @ Niagara Falls, Canada 2014.09.01-05**


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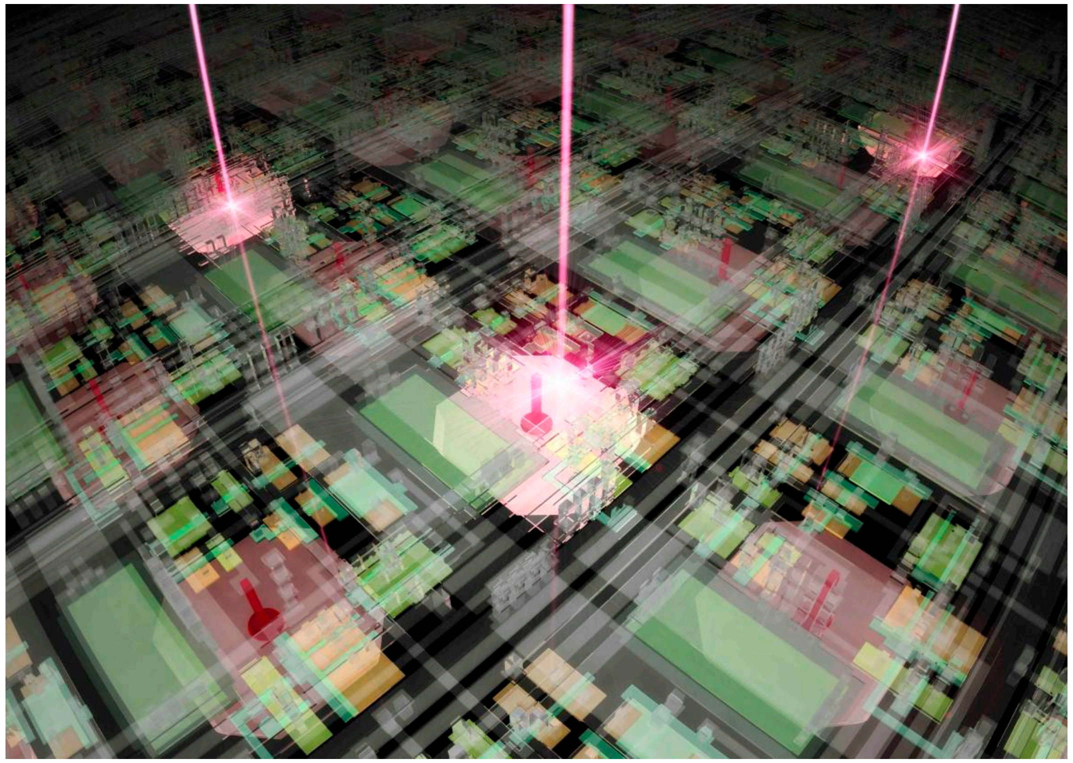
SOIPIX Group.

# Outline

- **Introduction**
  - -> **SOI Pixel Detector for Future X-ray Astronomy (XRPIX)**
- **XRPIX Design Description**
  - -> **XRPIX2b : for Event-Driven Readout**
  - -> **XRPIX3b : for Pixel Circuit with Charge Sensitive Amplifier (CSA)**
- **XRPIX Performance Tests**
  - -> **Evaluation of Event-Driven Readout and CSA Circuit**
- **Summary**



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# Standard Imaging Spectrometer of modern X-ray astronomical satellites ⇒ X-ray CCD

- Fano limited spectroscopy with the readout noise ~3 e- (rms).
- Wide and fine imaging with the sensor size of ~20 - 30 mm, pixel size of ~30 μm sq.
- High QE by BI and thick depletion (200 μm for ASTRO-H).

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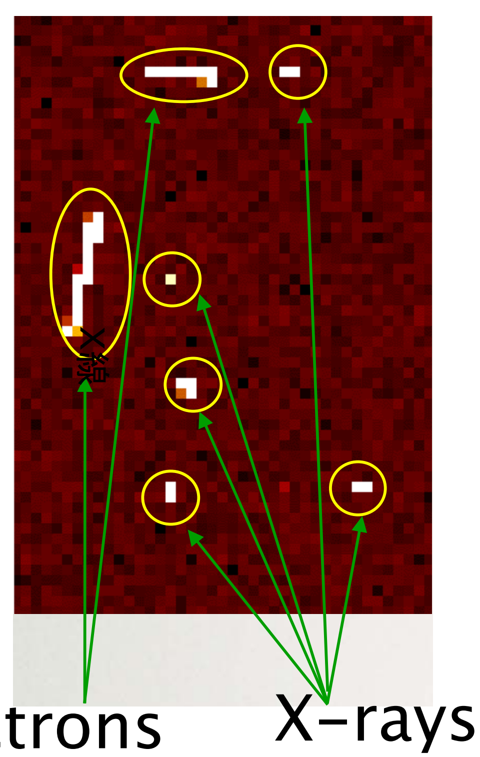
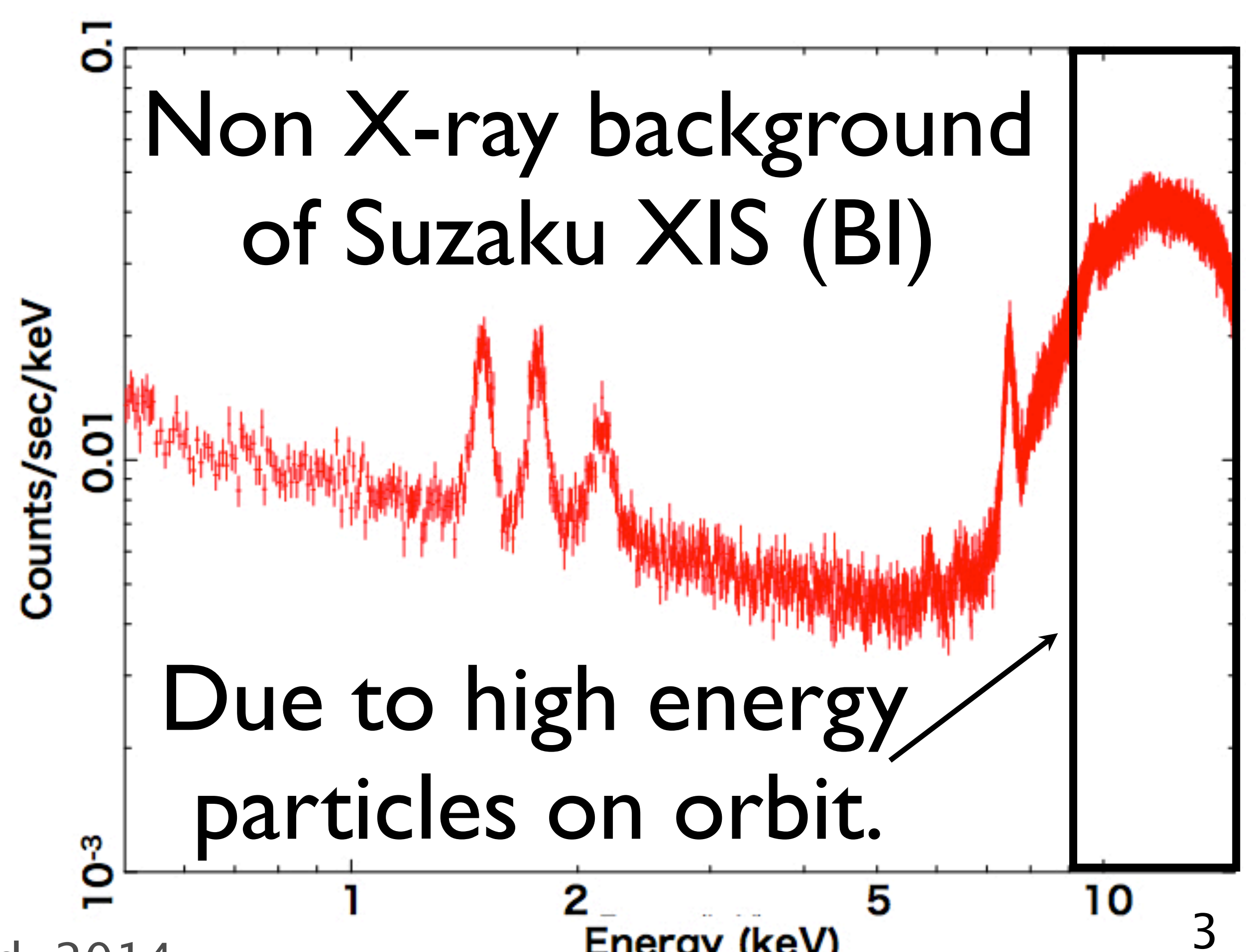
**However …**

- Non X-ray background above 10 keV is too high to study faint sources.
- The time resolution is too poor (~sec) to make fast timing observation of time variable source.

X-ray CCD Raw Image




Particle : Track
X-ray : One or adjacent pixels.



# SOI Pixel Detector for Future X-ray Astronomy

The performance required of a future X-ray astronomical satellite is the following ...

**Target Specification**

(1) FWHM ≤140 eV at 6 keV
Readout Noise :
req. ≤ 10 e-/ goal ≤ 3 e-

(2) <100 μm pitch pixel

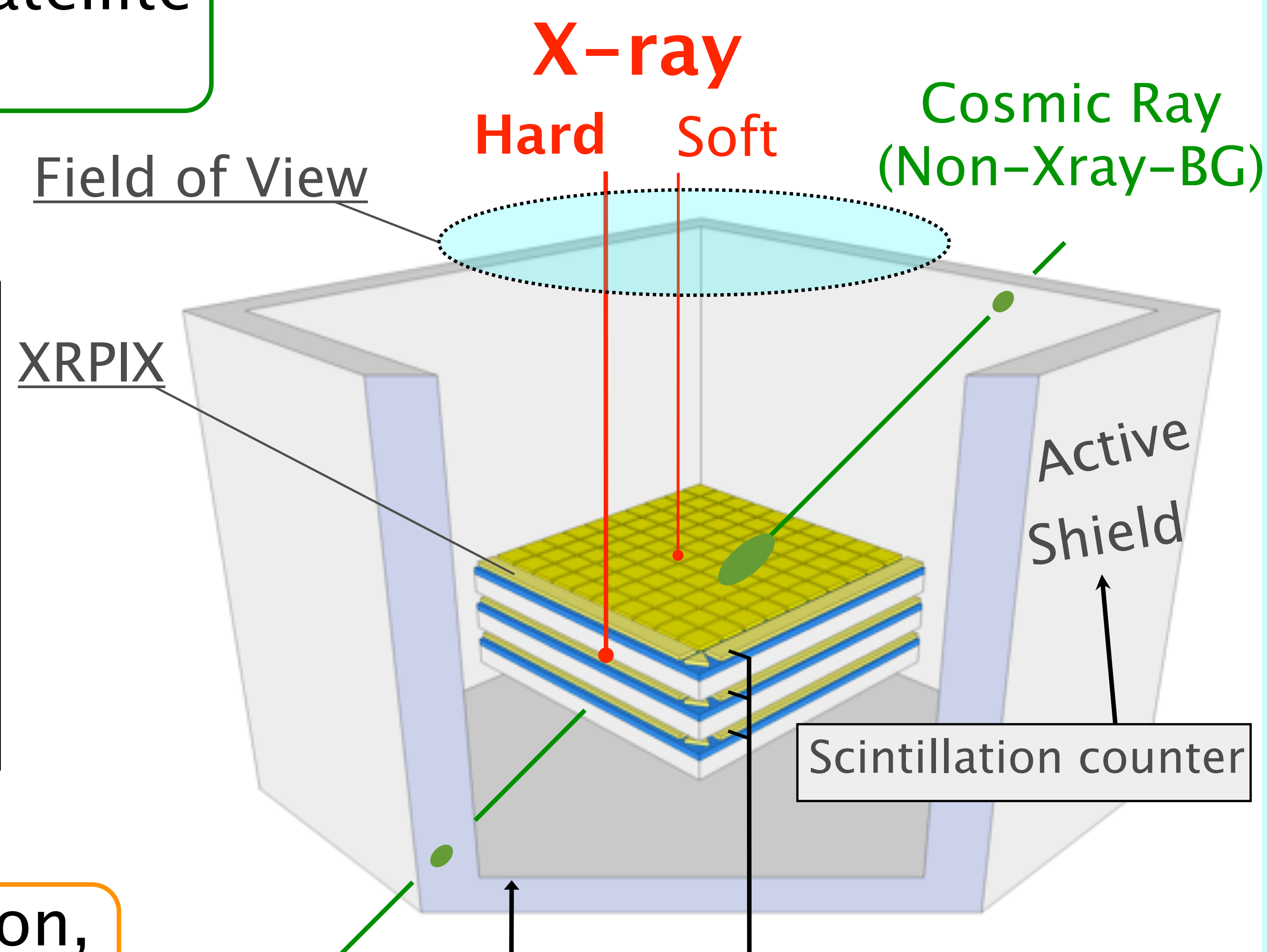
(3) ~10 μs per event readout
(Trigger, Direct Pixel Access)

(4) Wide energy range : 0.3- 40 keV
(Thick Depletion Stacks)

In order to achieve specification, we have been developing X-ray SOI Pixel Detector (XRPIX).

XRPIX has self-trigger function !
-> Realization of Event-Driven

X-ray SOIPIX with Active Shield




**Onboard Processor**

- Anti-coincidence (NXB rejection)
- Hit-pattern Selection (NXB rejection)
- Direct Pixel Access (X-ray Readout)

# Introduction of SOI Pixel Detector

- A monolithic pixel detector with Silicon-on-Insulator (SOI) CMOS Technology -> <u>0.2 μm fully-depleted (FD) - SOI pixel process</u>

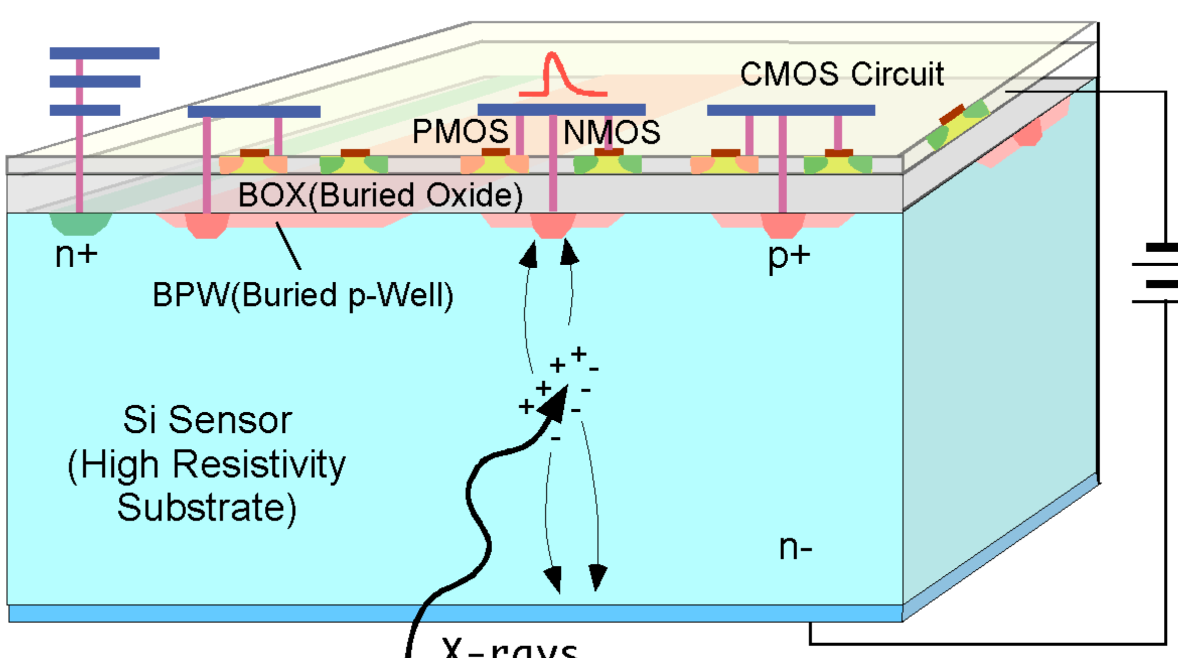
- SOI Pixel Detector (SOIPIX) : Processed by LAPIS Semi. Co., Ltd.

<u>SOIPIX Advantages</u>
- No mechanical bump bonding
  -> High Density, Low Parasitic Capacitance, High Sensitivity
- Standard CMOS circuit can be built
- Based on industrial standard technology

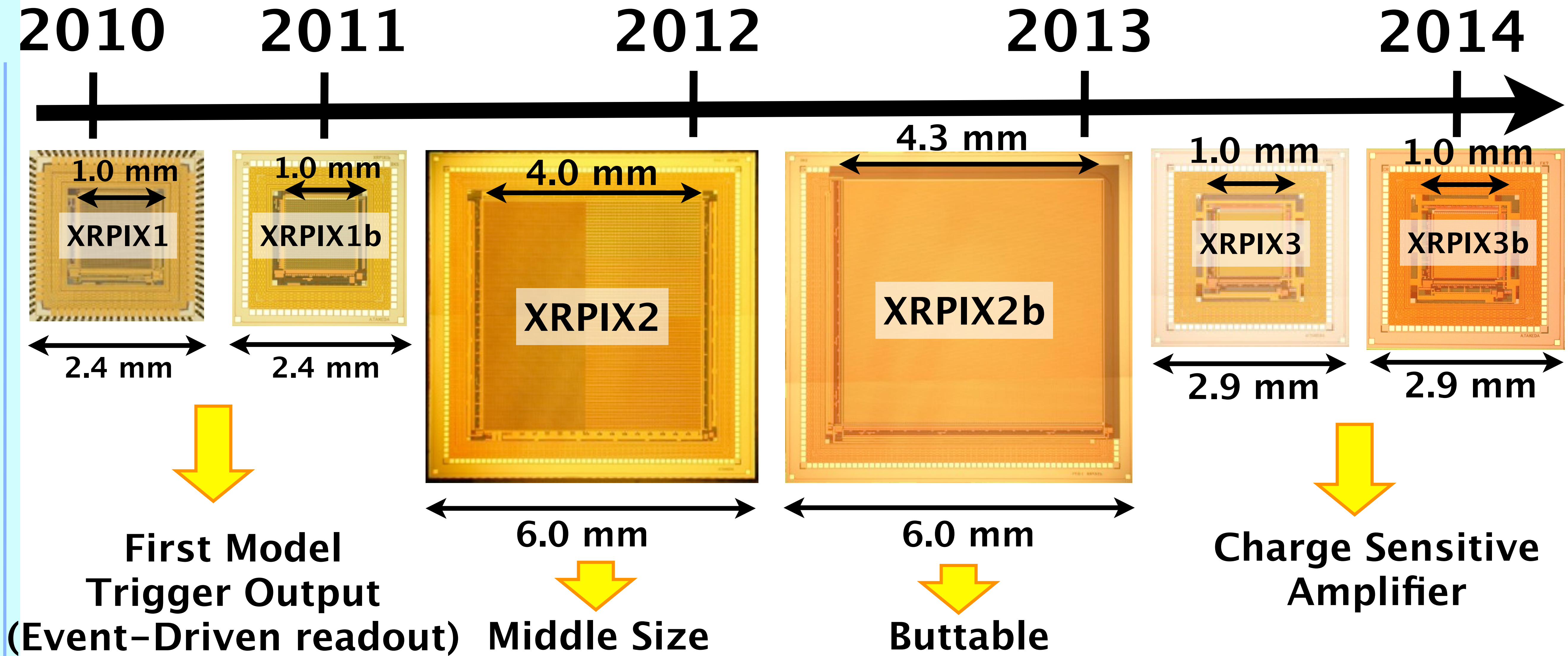
<u>Basic Components</u>
Circuit Layer : ~40 nm
Buried Oxide (BOX) : 200 nm
Sensor Layer : 100 – 725 μm

<u>SOI Pixel Process</u>
New Process to make pixel detector with SOI technology joint development with LAPIS Semi. Co., Ltd.

<u>Our group presentations:</u>
Miho Yamada (1st day),
Makoto Motoyoshi (4th day)

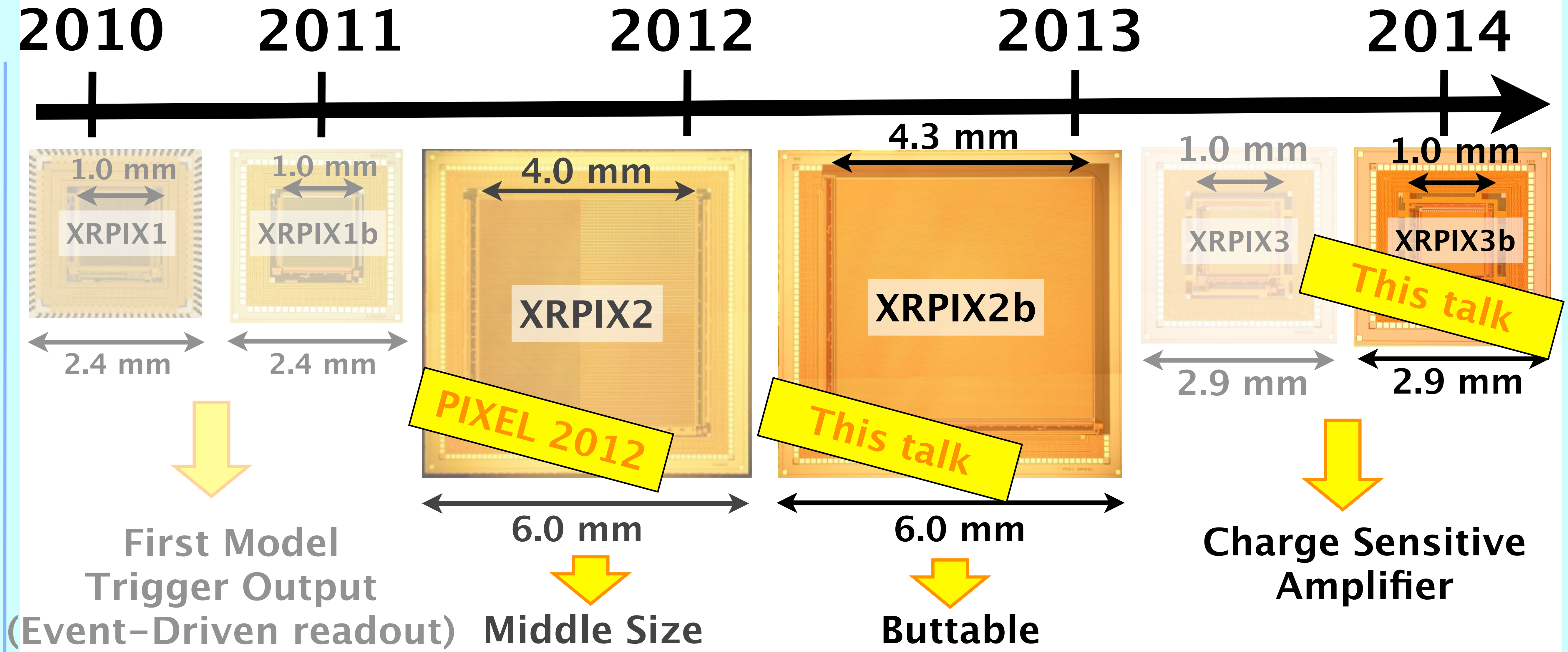


# XRPIX Series




- The XRPIX series has designed six devices: XRPIX1/1b/2/2b/3/3b.
  - -> The spectroscopic performance and event-driven readout are tested and improved.

# XRPIX Series




**PIXEL 2012**

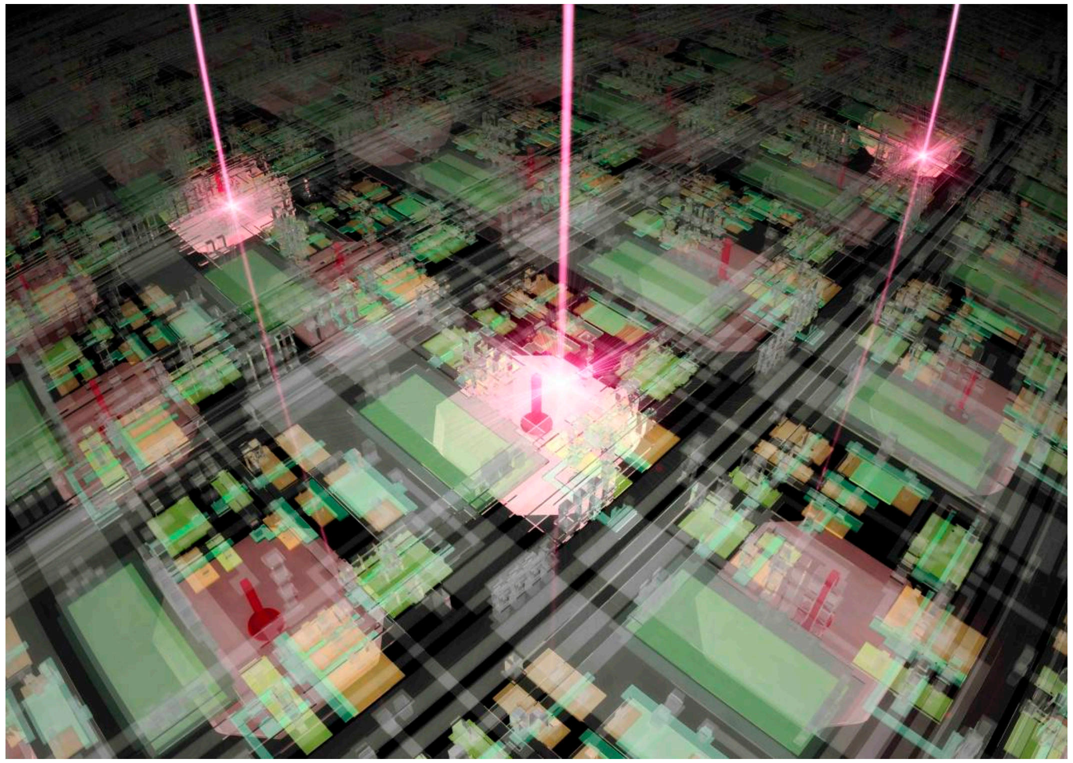
XRPIX2 : Reported by S.Nakashima

**PIXEL 2014**

XRPIX2b : for Event-Driven Readout

XRPIX3b : for CSA pixel circuit

# Evaluation of Event-Driven Readout



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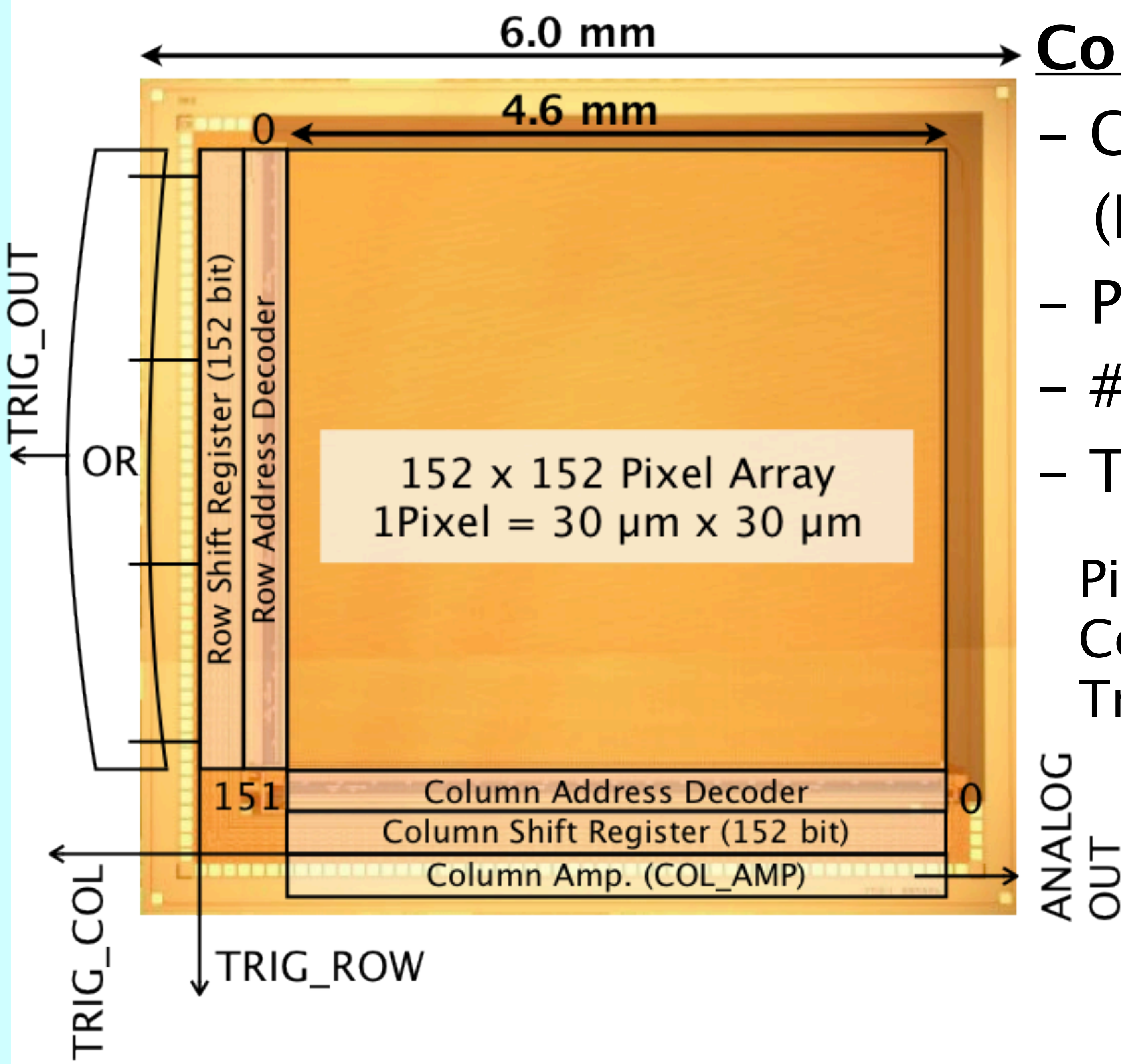
# Design Specification : XRPIX2b

– Optimization of a pixel design / Confirmation of uniformity
  -> It is based on the design of XRPIX1/1b/2.



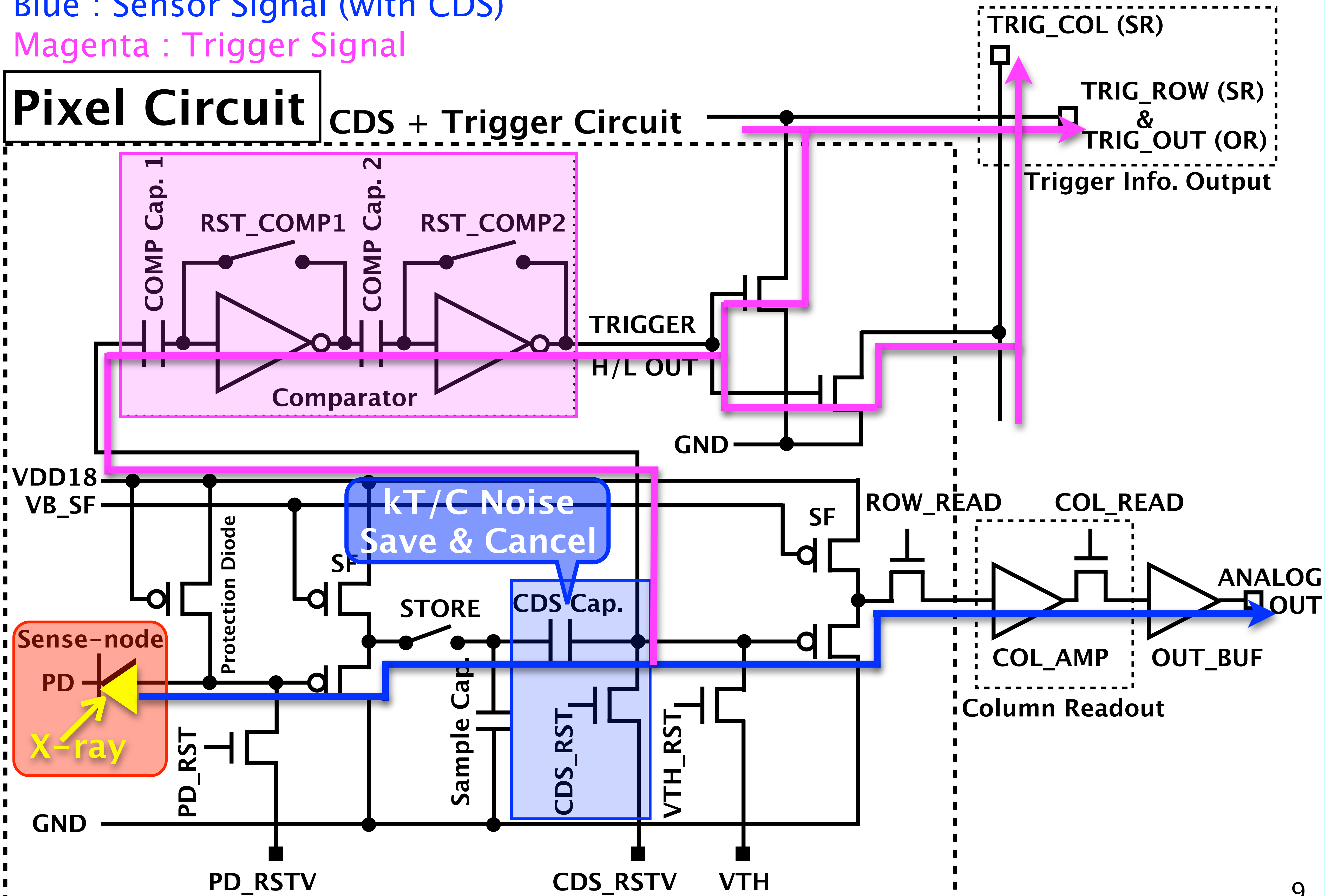

**Components**

– Chip size : 6.0 mm sq.
  (Effective area : ~ 4.6 mm sq.)
– Pixel size : 30 µm sq.
– # of pixel : 152 x 152 (~ 23k)
– Thickness of sensor layer : 260 µm

Pixel Circuit :
Correlated Double Sampling (CDS),
Trigger information output function.

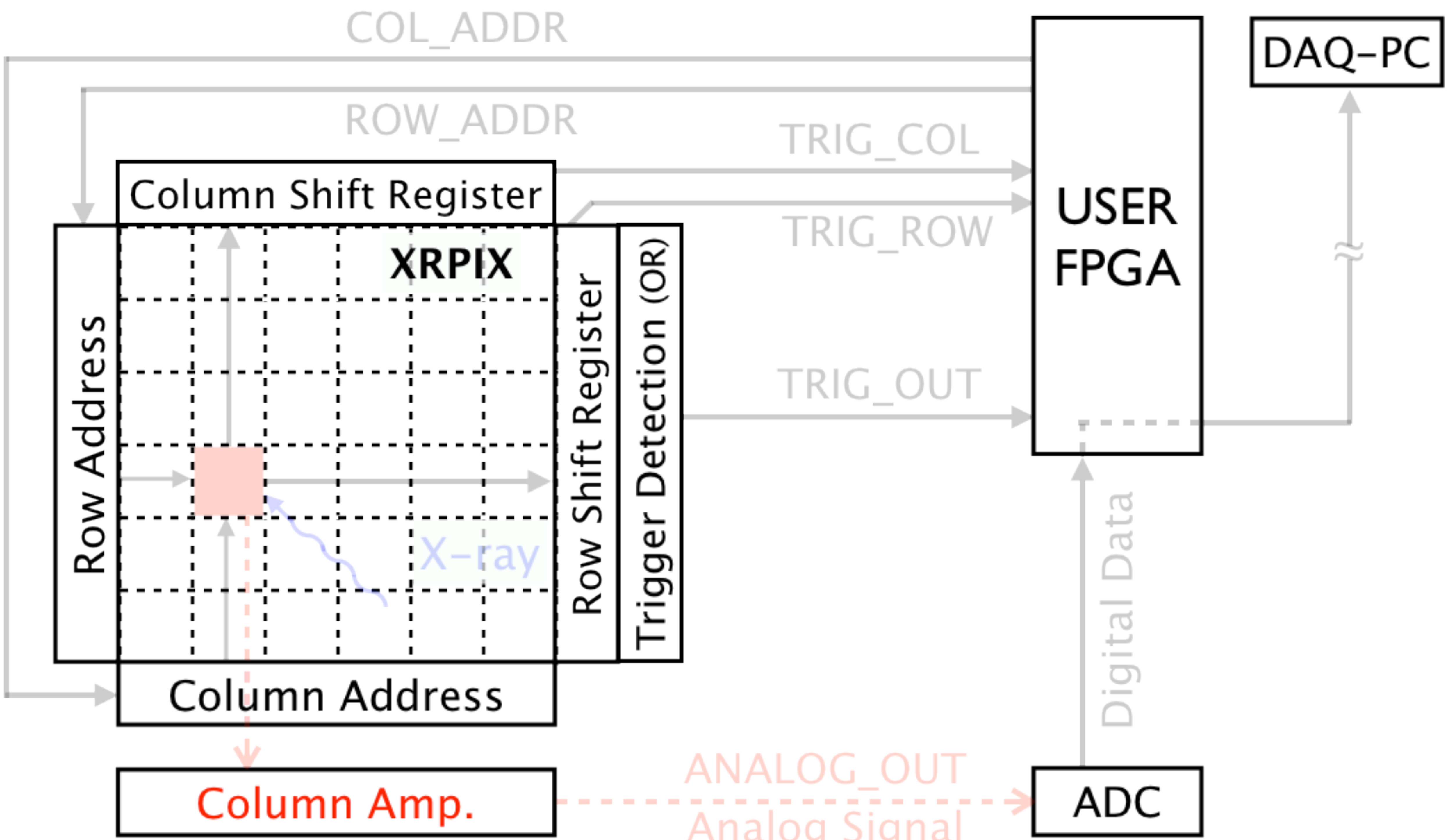
# Design Specification : Pixel Circuit

Blue : Sensor Signal (with CDS)
Magenta : Trigger Signal



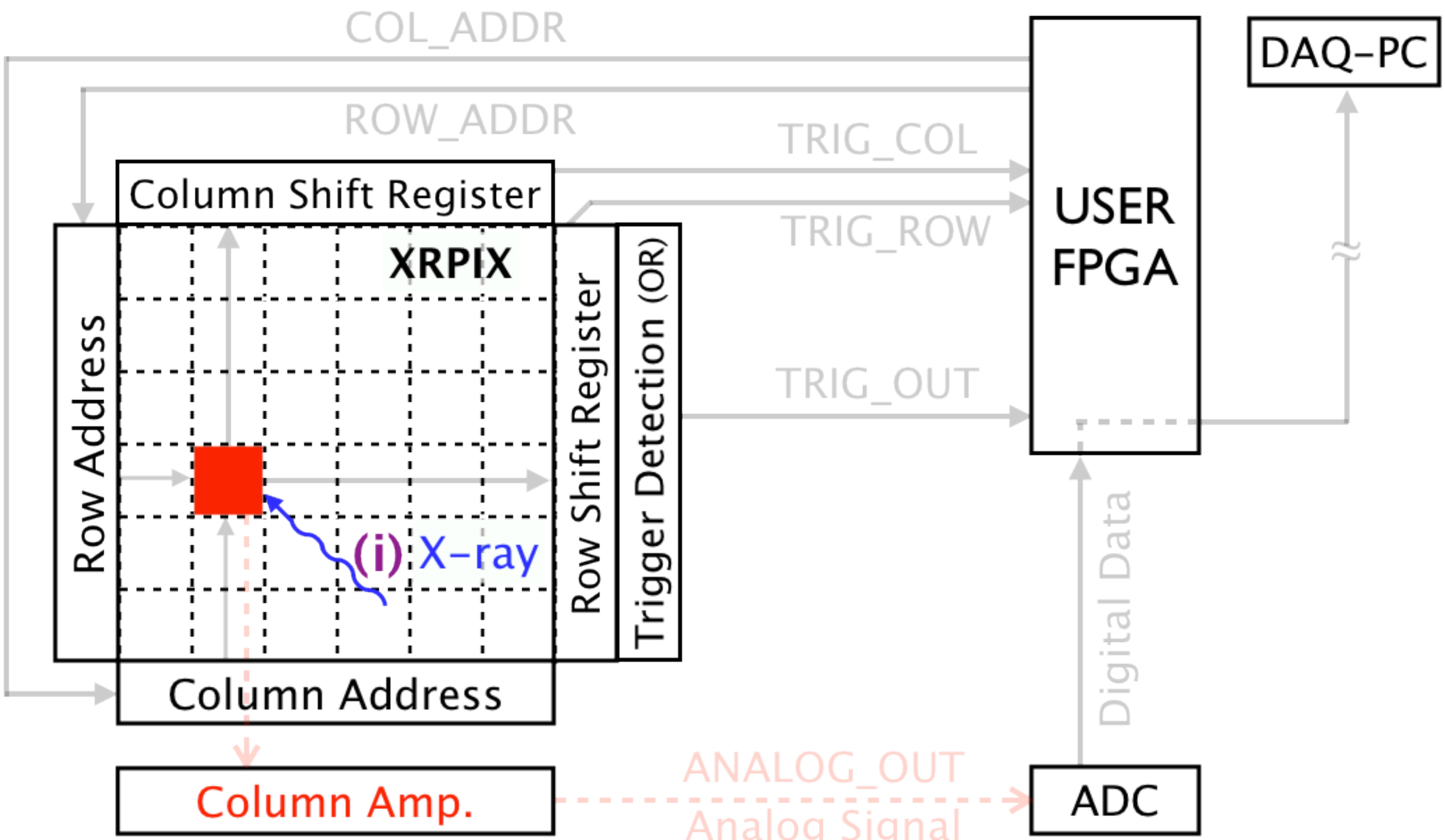
# Event-Driven Readout Mode

- The following figure show the flow chart.



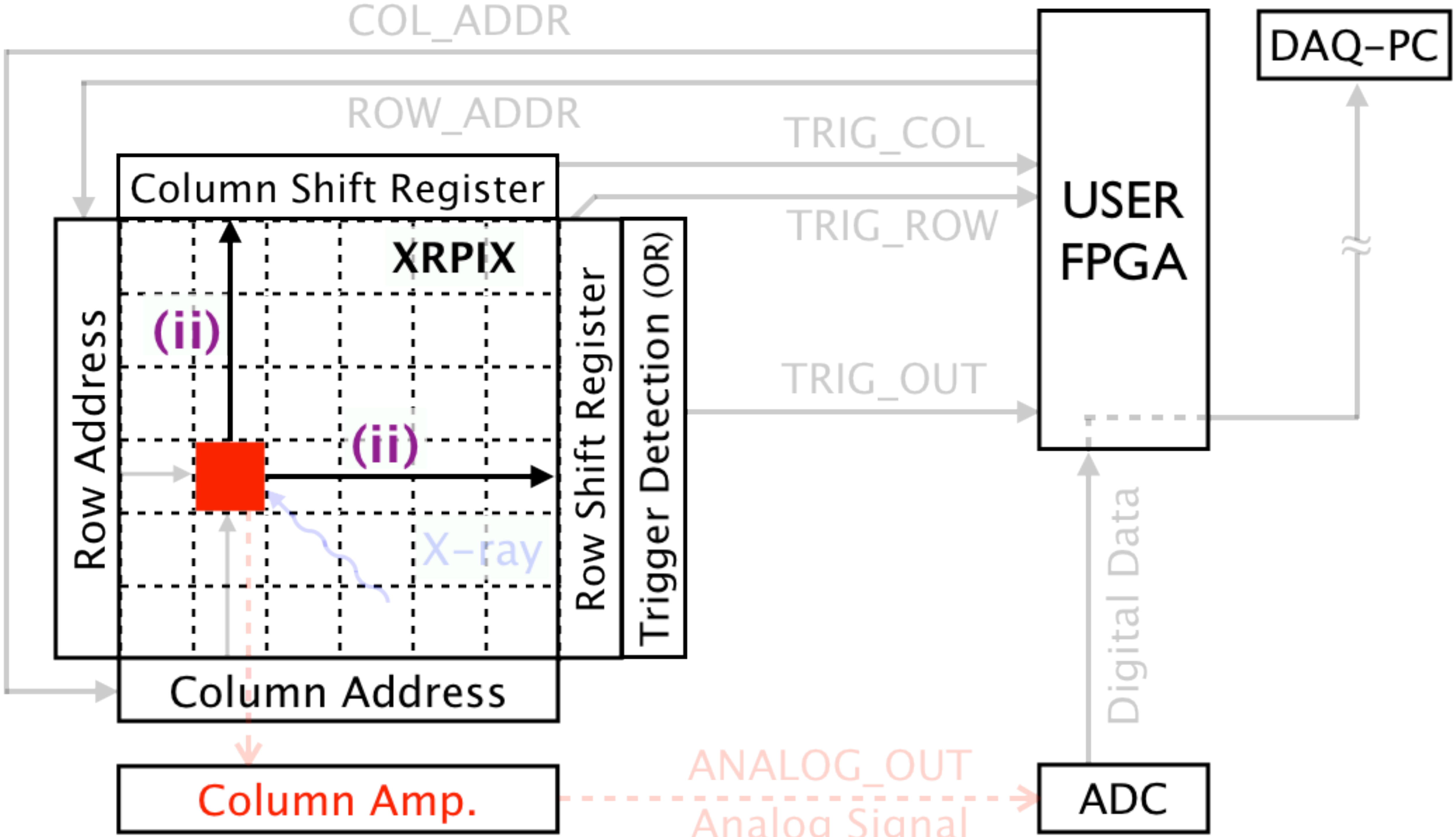
# Event-Driven Readout Mode

( i ) X-ray signal is detected by a pixel.



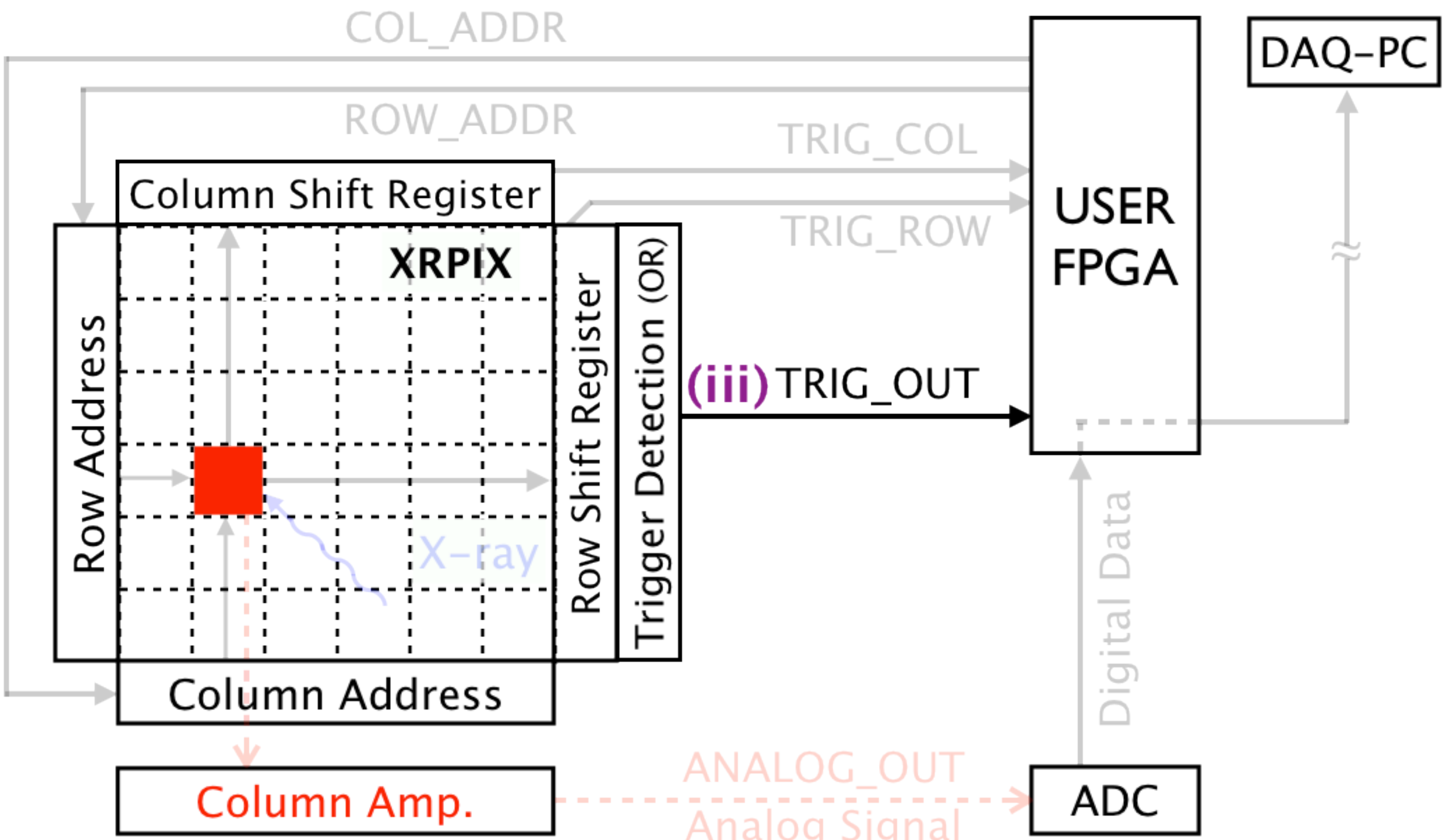
# Event-Driven Readout Mode

( ii ) If the X-ray signal exceeds a threshold voltage, trigger signals are transferred to row and column direction.



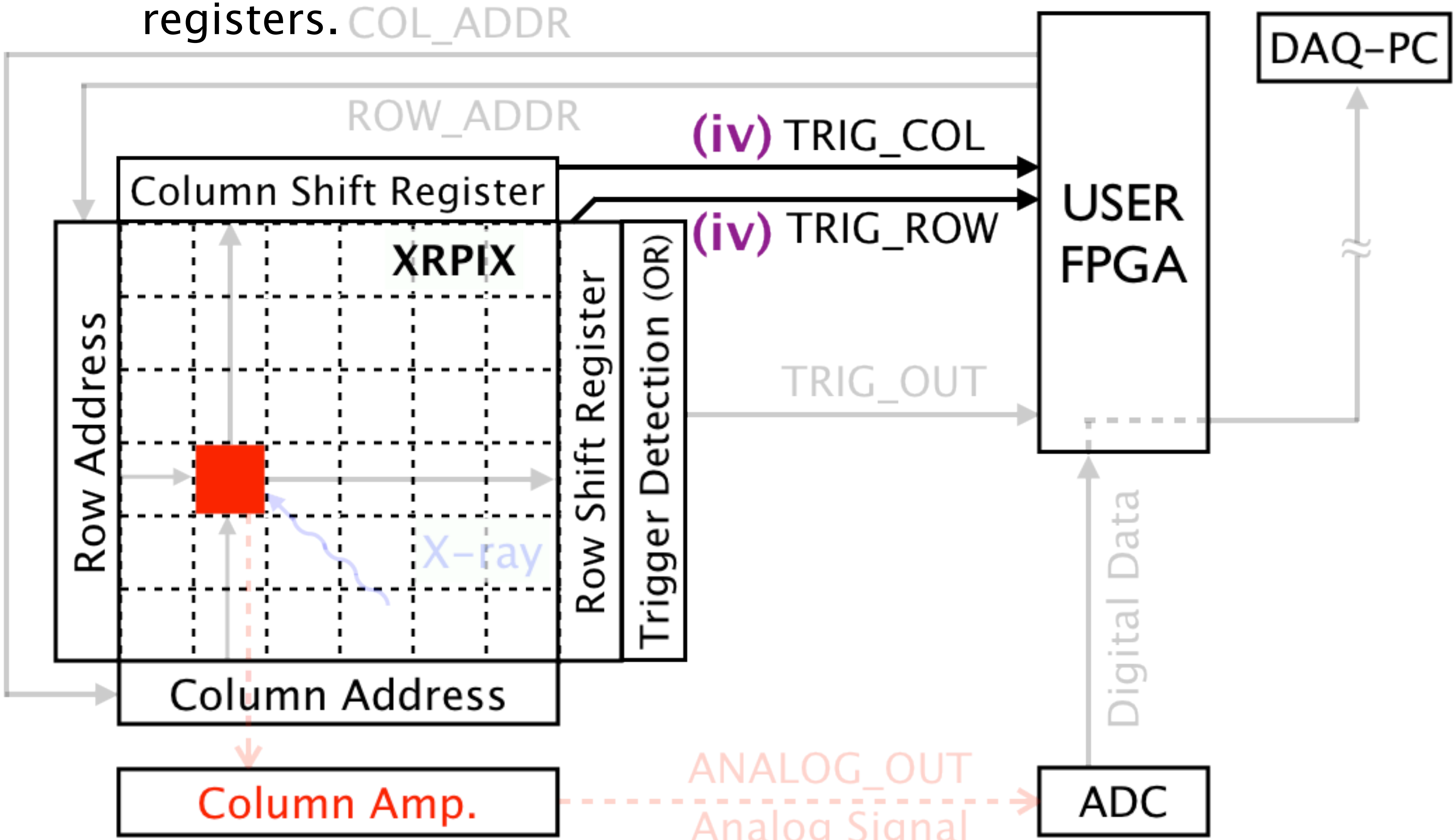
# Event-Driven Readout Mode

( iii ) OR'ed signal (TRIG_OUT) of the trigger is generated.



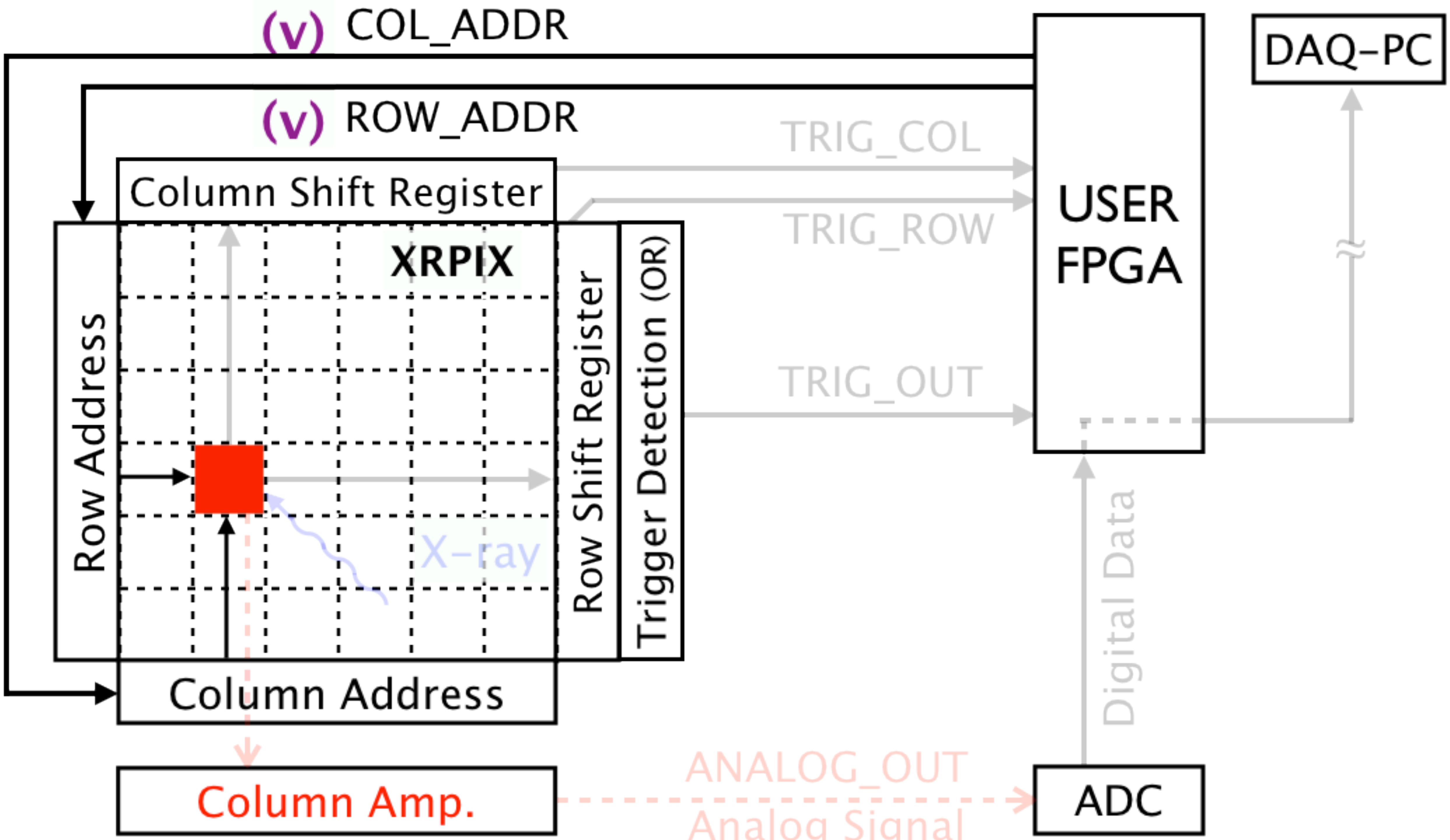
# Event-Driven Readout Mode

( iv ) By receiving the TRIG_OUT signal, USER-FPGA start to read the hit address information from the row and column shift registers.



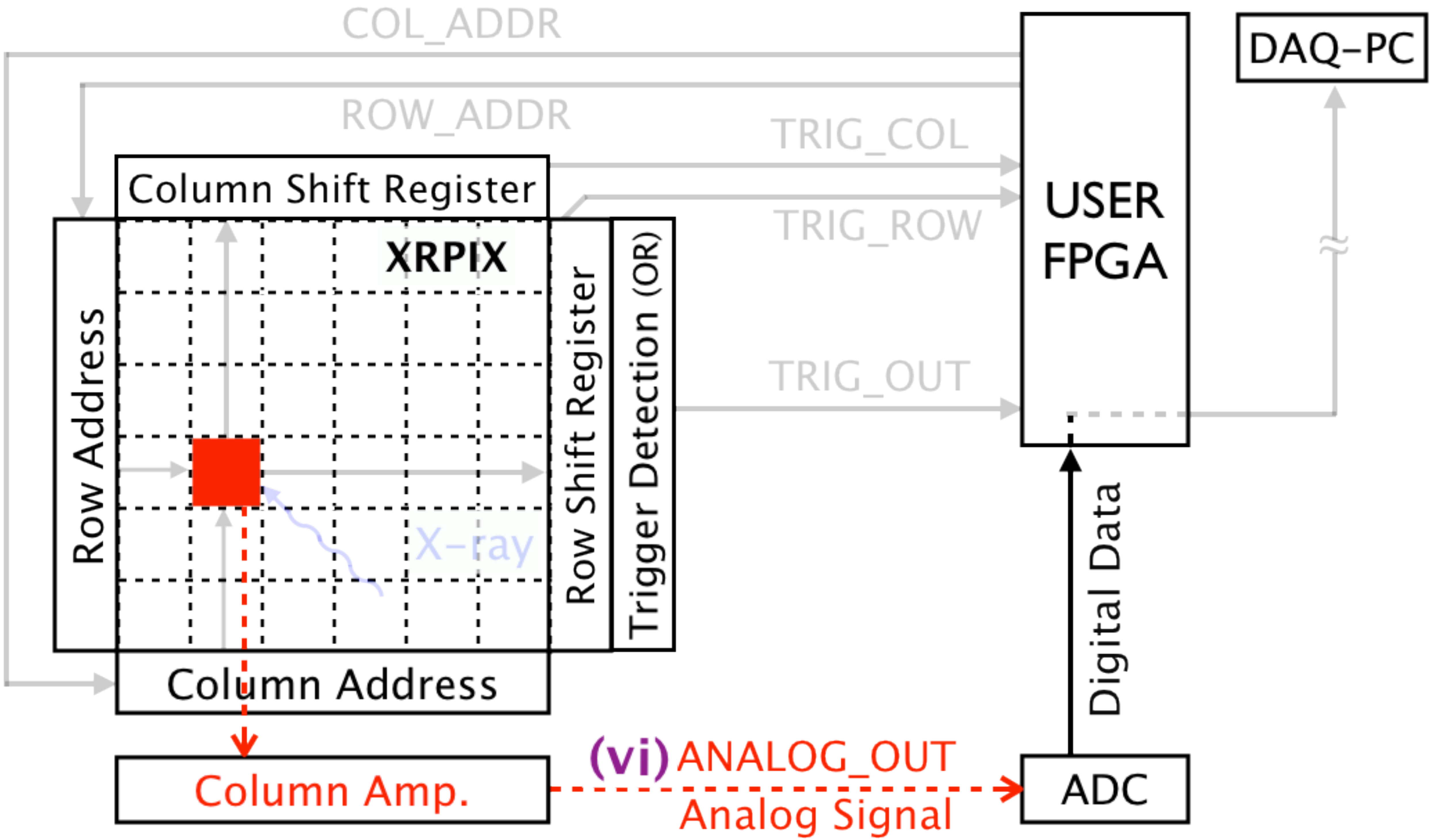
# Event-Driven Readout Mode

( v ) The USER-FPGA accesses the hit pixel directly by asserting the obtained address.



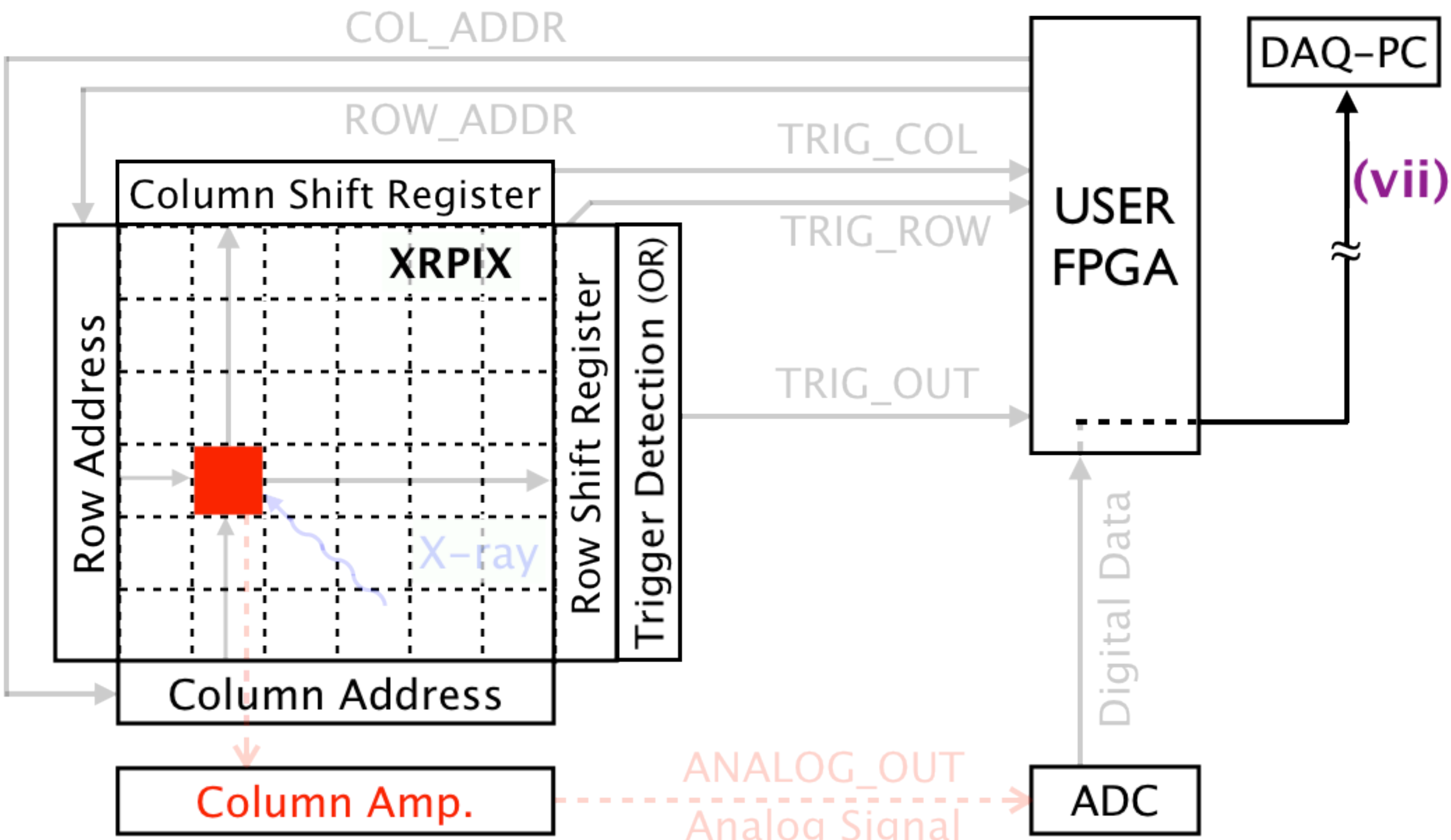
# Event-Driven Readout Mode

( vi ) The USER-FPGA reads out the analog voltage
(signal and pedestal levels) through the ADC.



# Event-Driven Readout Mode

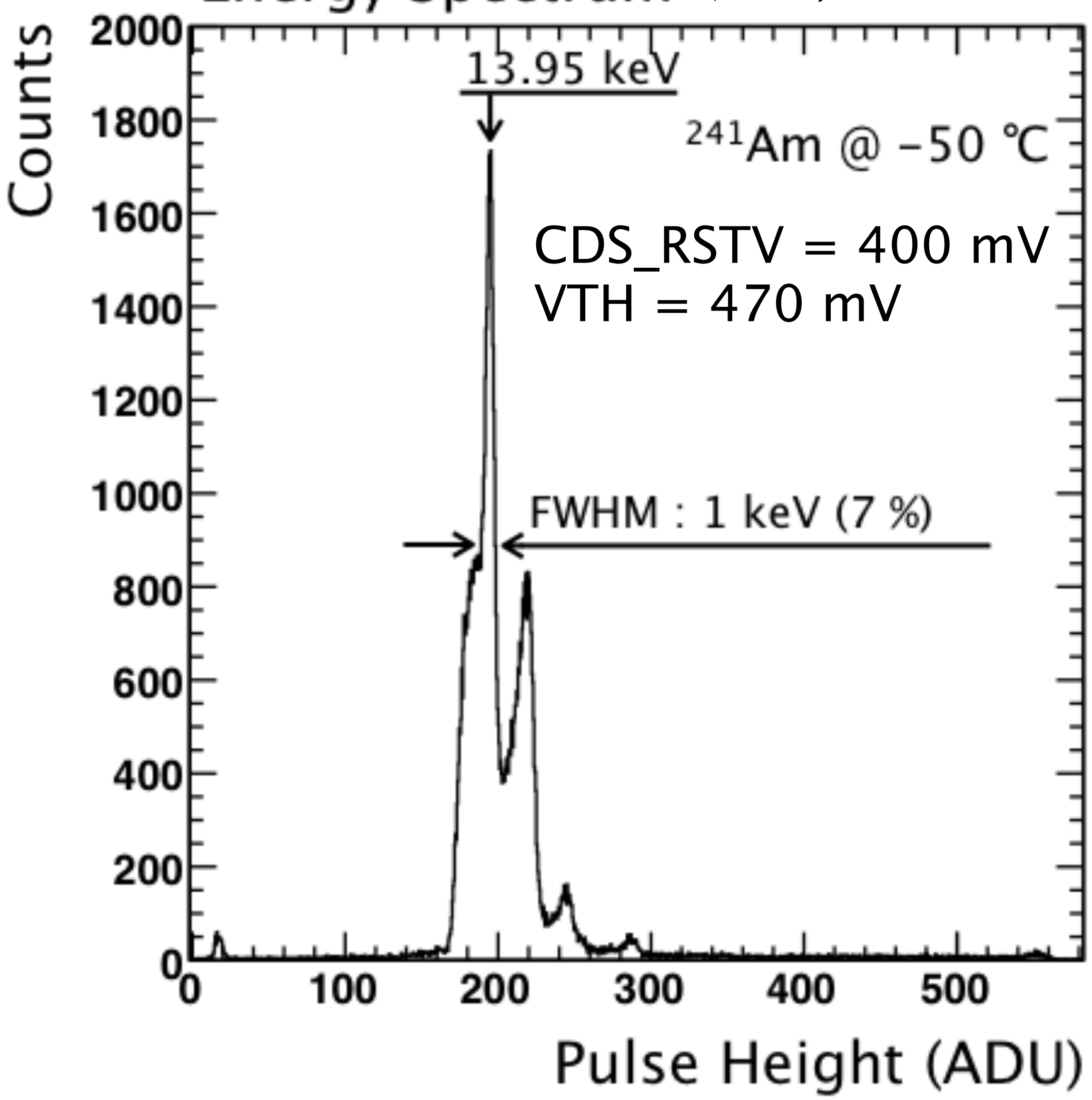
( vii ) Finally, the obtained digital data is transmitted to the DAQ-PC.



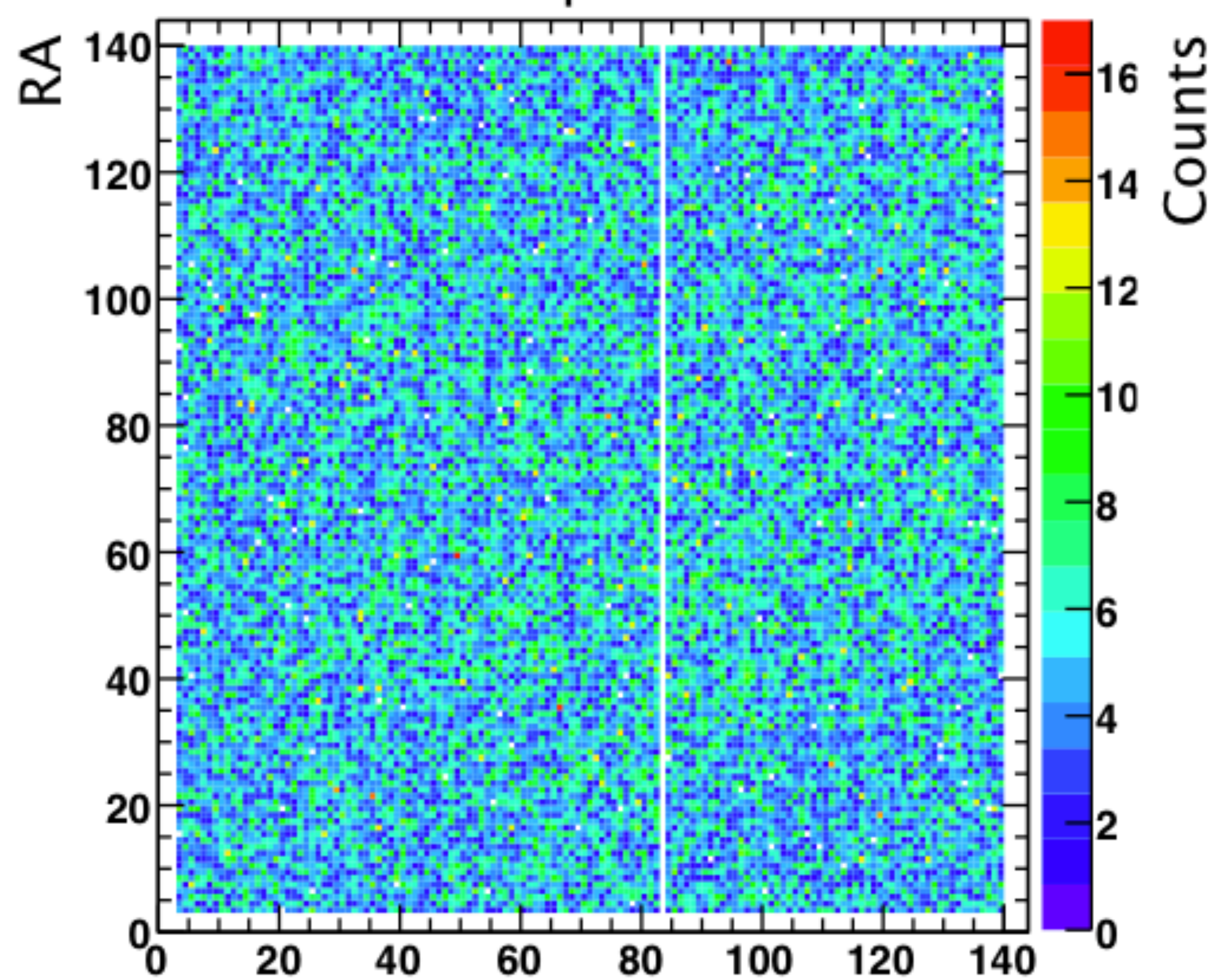
# Event-Driven Spectrum by XRPIX2b

- X-ray spectrum by event-driven readout mode.
  -> Capacity of event rate : ~1 kHz.
- FWHM : 1 keV (7 %) @ 13.95 keV
  -> This is not good compared with the frame readout mode.
  (650 eV at FWHM at the same line)

Energy Spectrum (100,000 events)




2D Counts Map




Bad pixel mask set :
-> 4 pixels of the surround / CA88 line

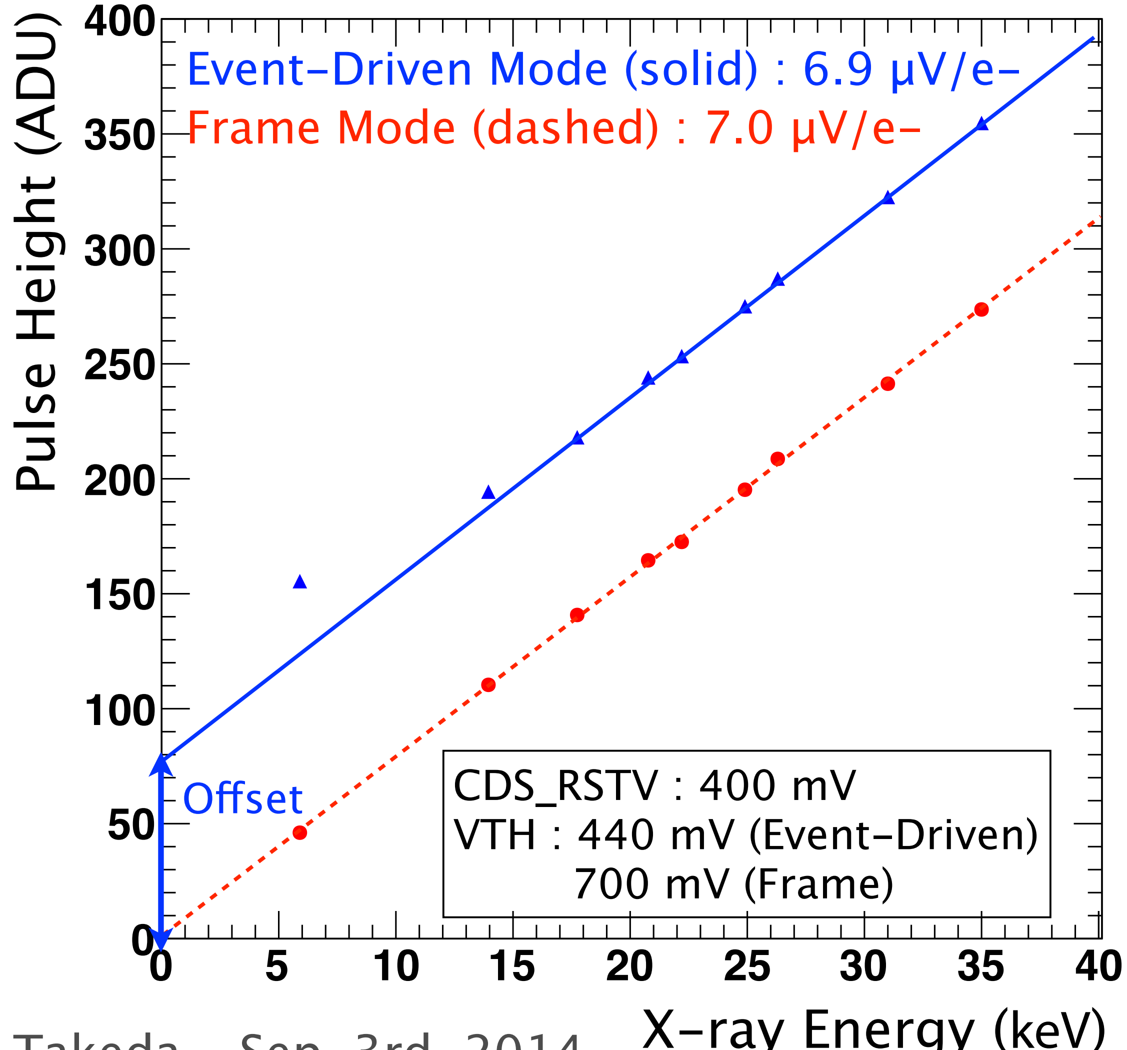
# Event-Driven Calibration

- Calibration plot using the $^{55}$Fe, $^{241}$Am, $^{109}$Cd, and $^{133}$Ba X-ray lines.

**Two problems**

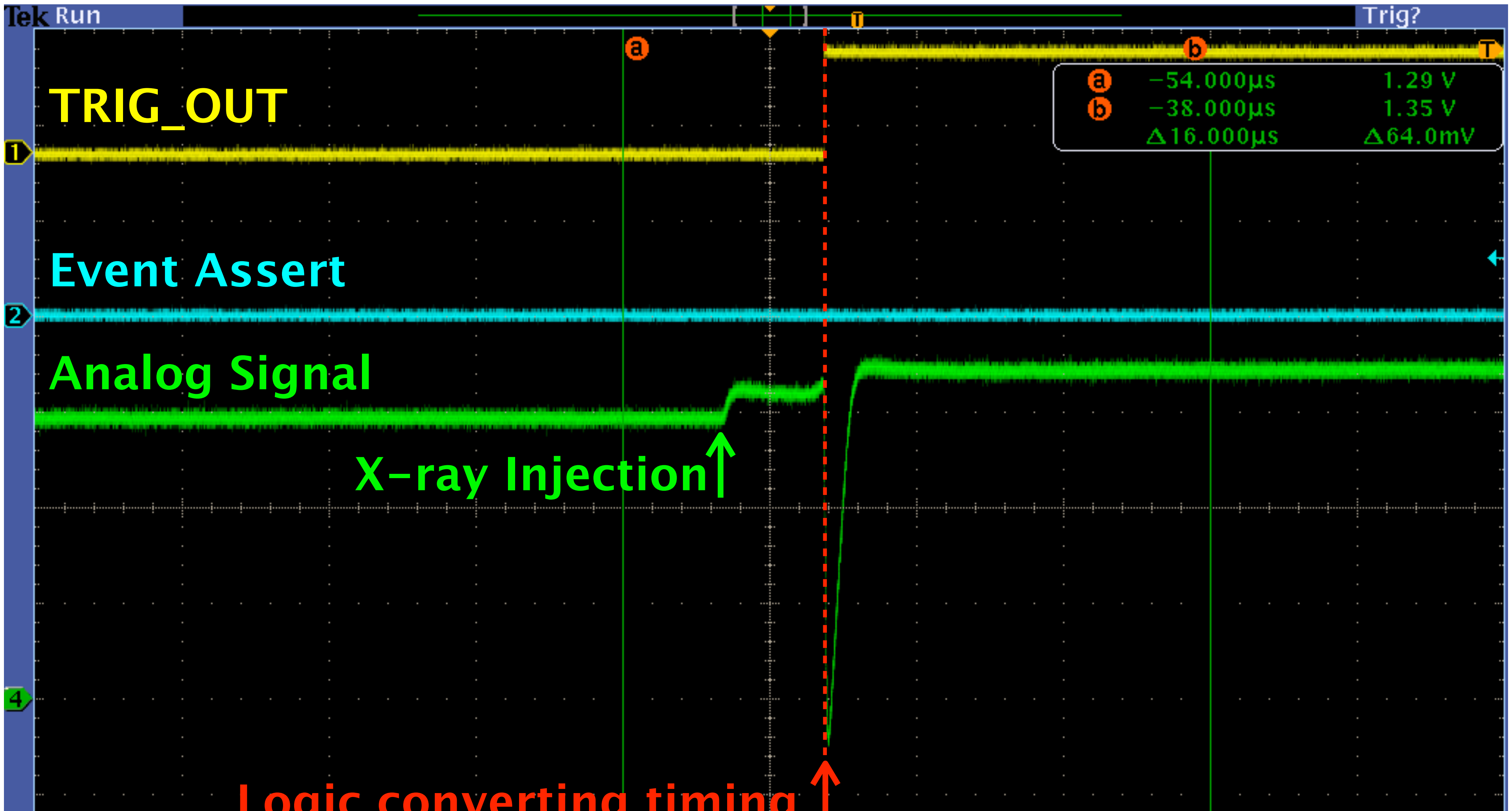
1. The plot has an offset of ~80 ADU (i.e. ~20 mV).
2. The pulse height of the output shifts from linearity at low energy.
   -> In this case, 5.9 keV of $^{55}$Fe line is clearly shifted from the fitting line.

- These differences are caused by the operation of the comparator circuit.
- It is necessary to investigate these causes and to understand the phenomena.



# What happens by X-ray injection?

- The waveform of an oscilloscope when X-rays enter ($^{109}$Cd : 22.2 keV).
  -> The analog signal has 4 problems.




TRIG_OUT : The logic output signal from the comparator circuit.
Event Assert : The fixed signal of the X-ray event by the FPGA.
Analog Signal : The analog signal of the fixed pixel.

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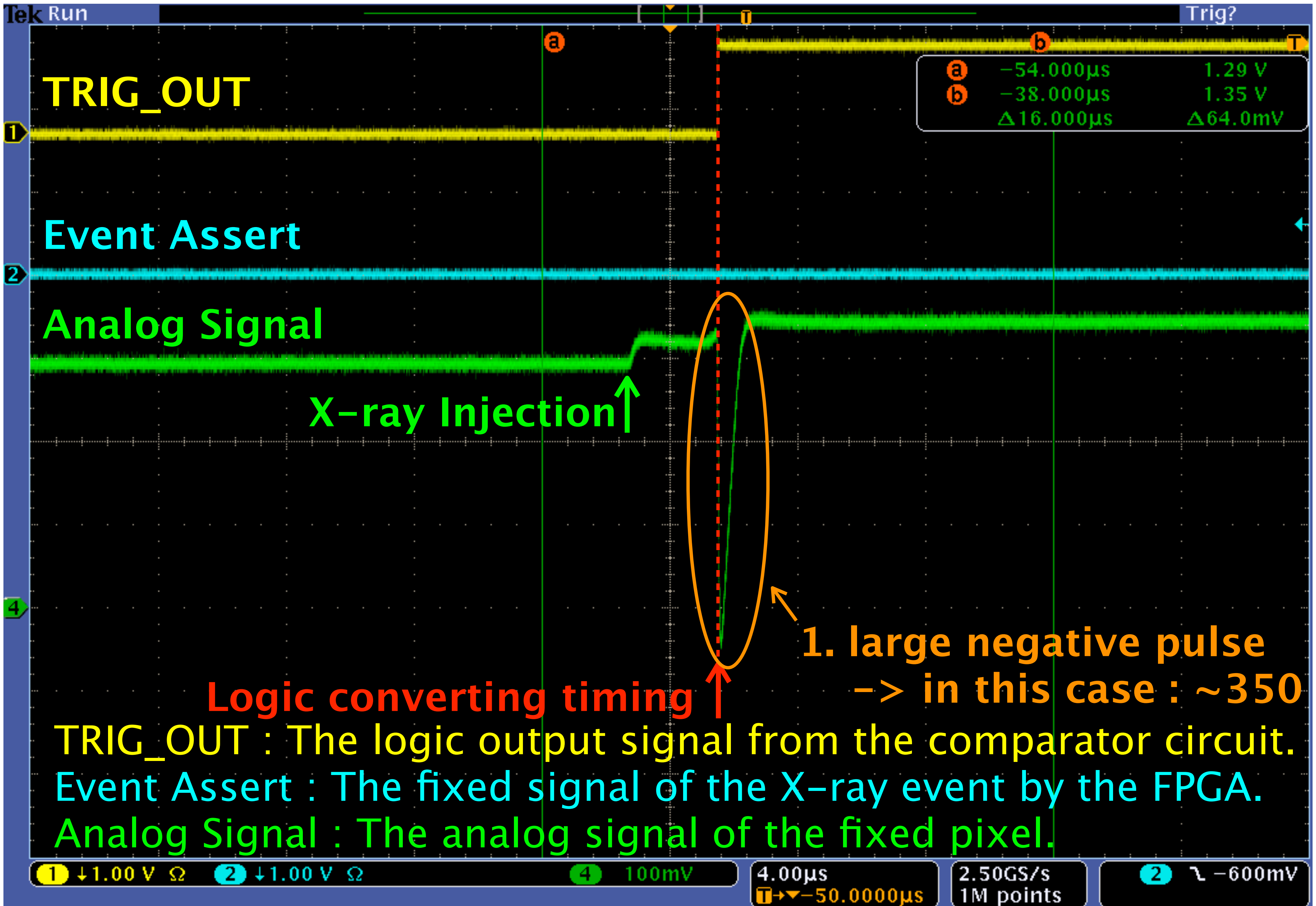

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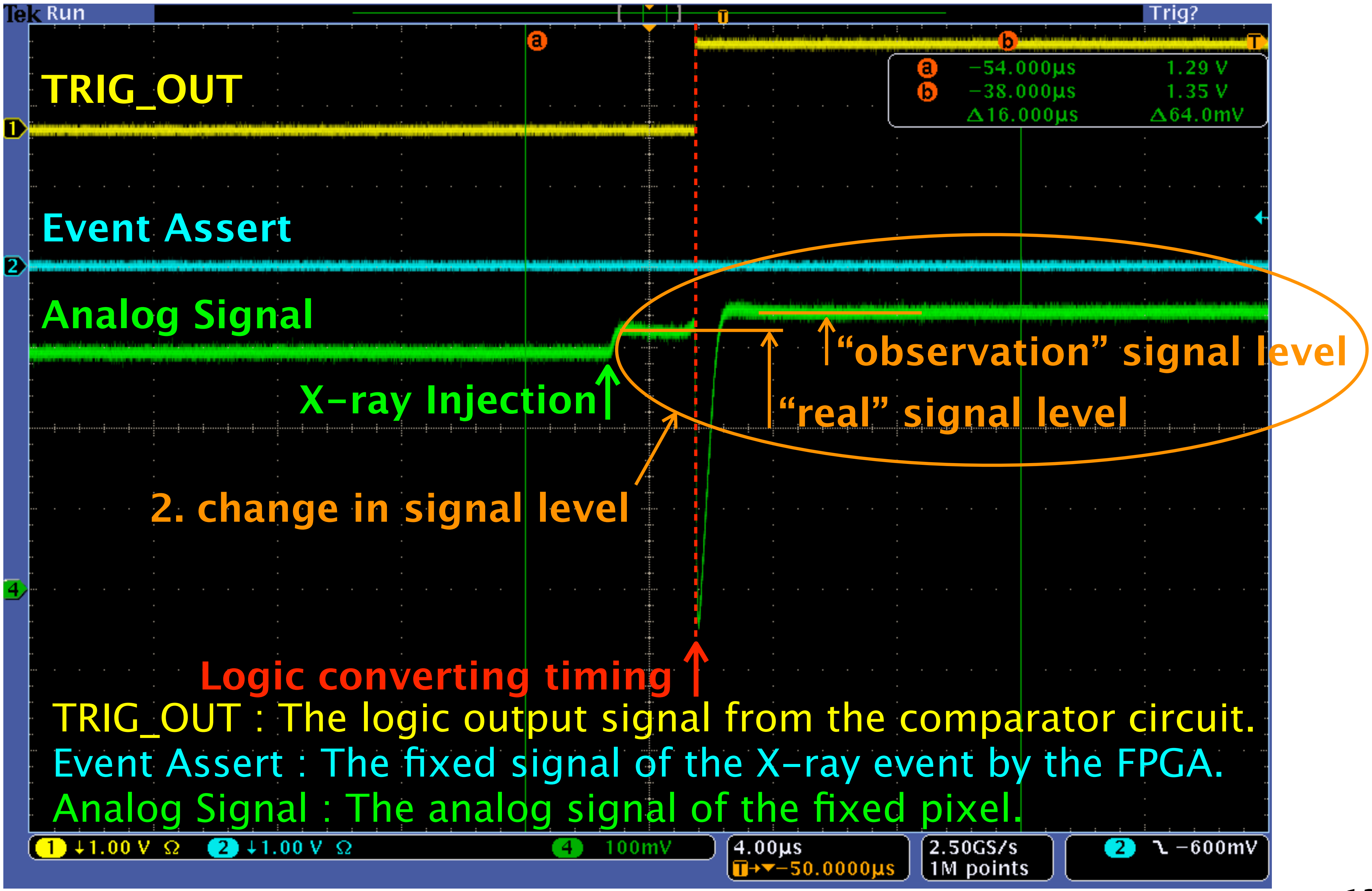

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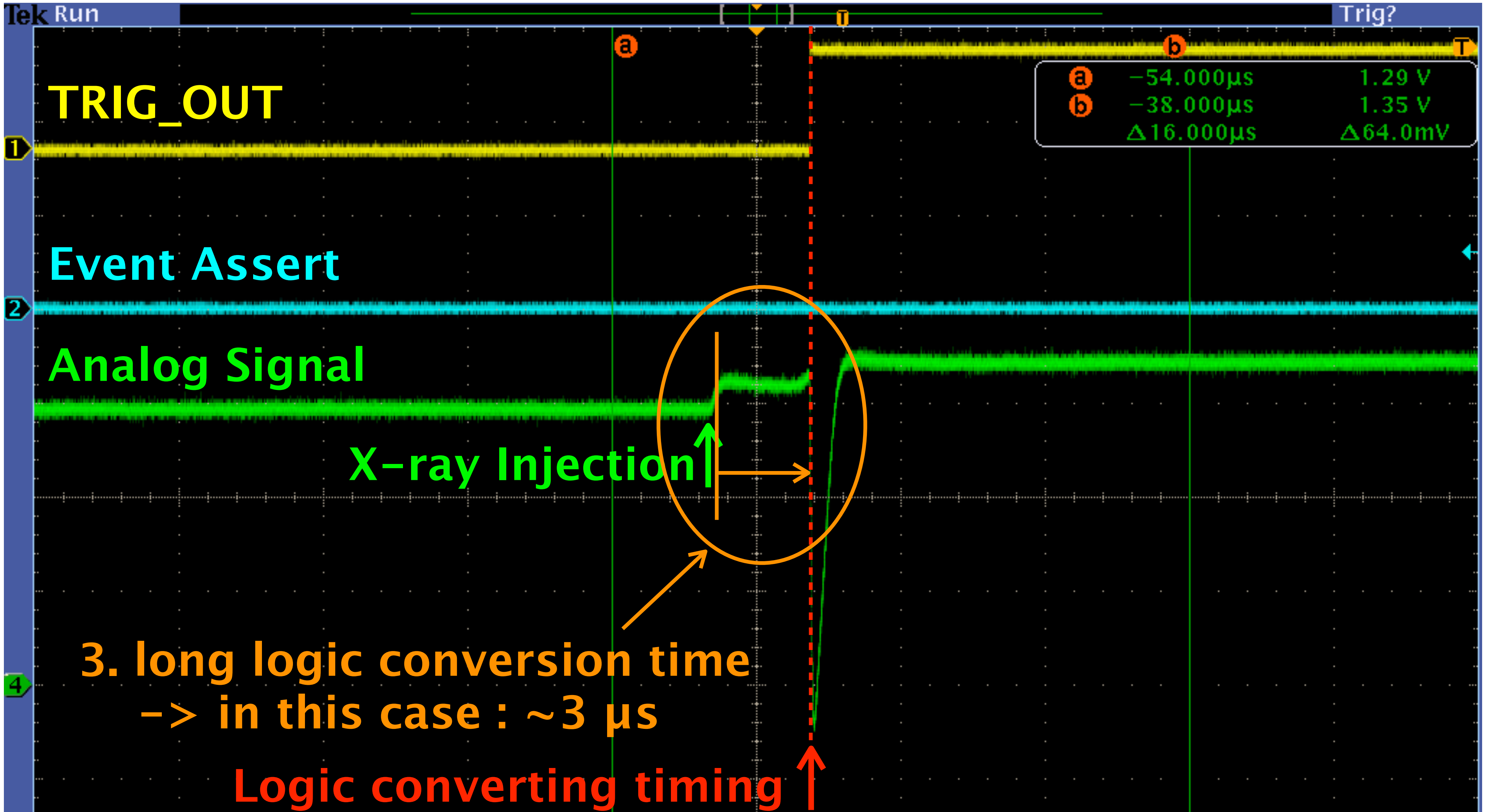


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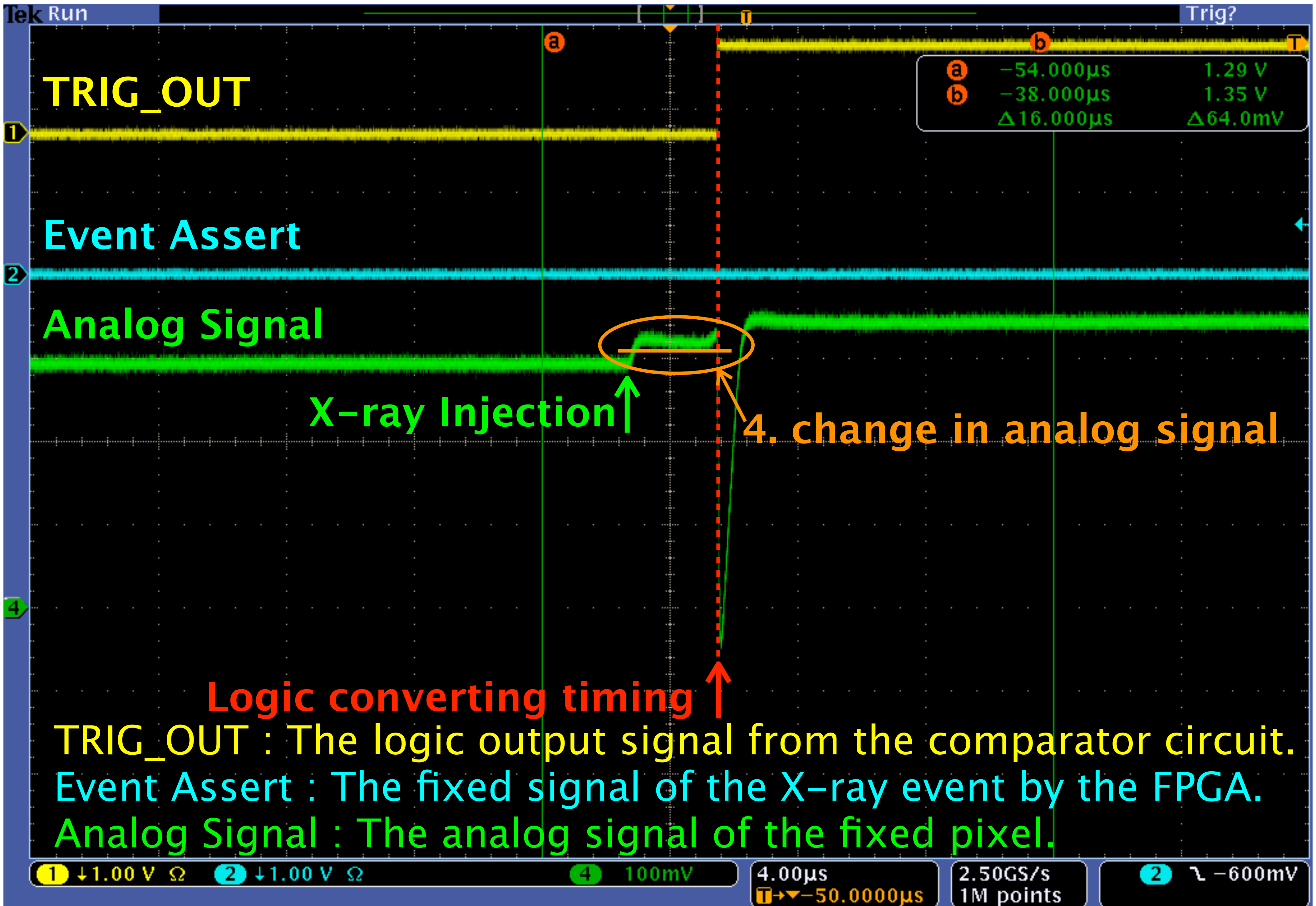
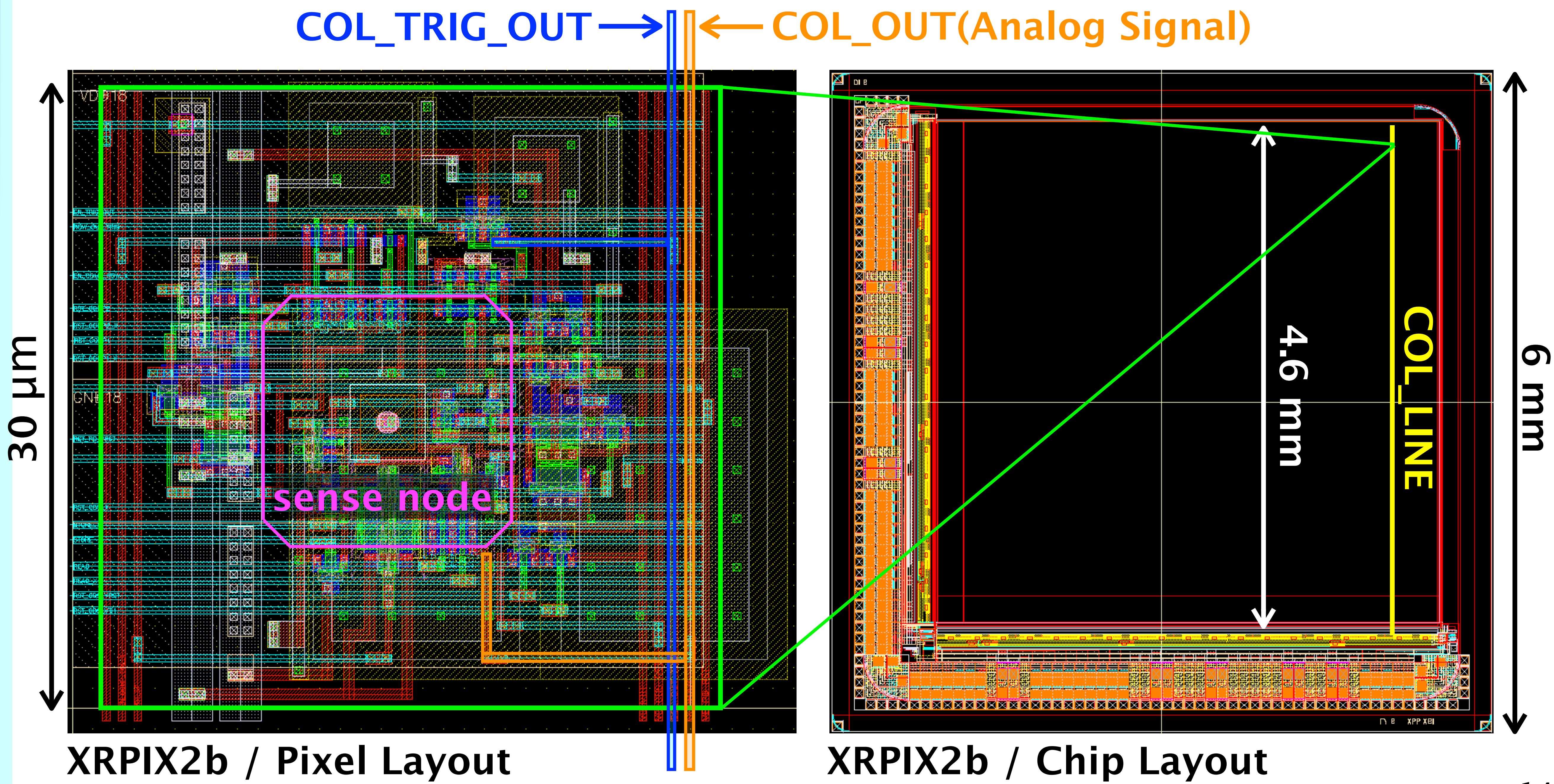


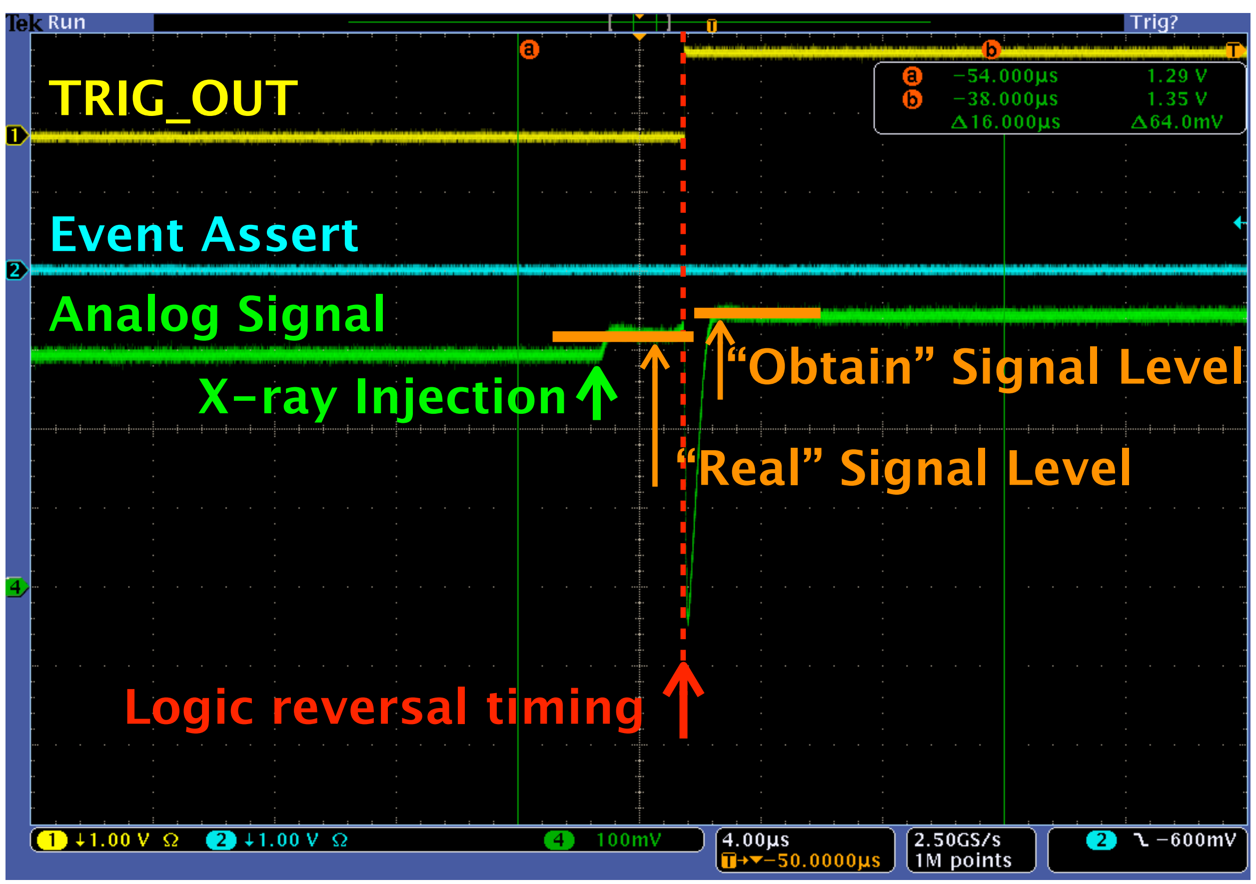
# 1. Reason for Negative Pulse

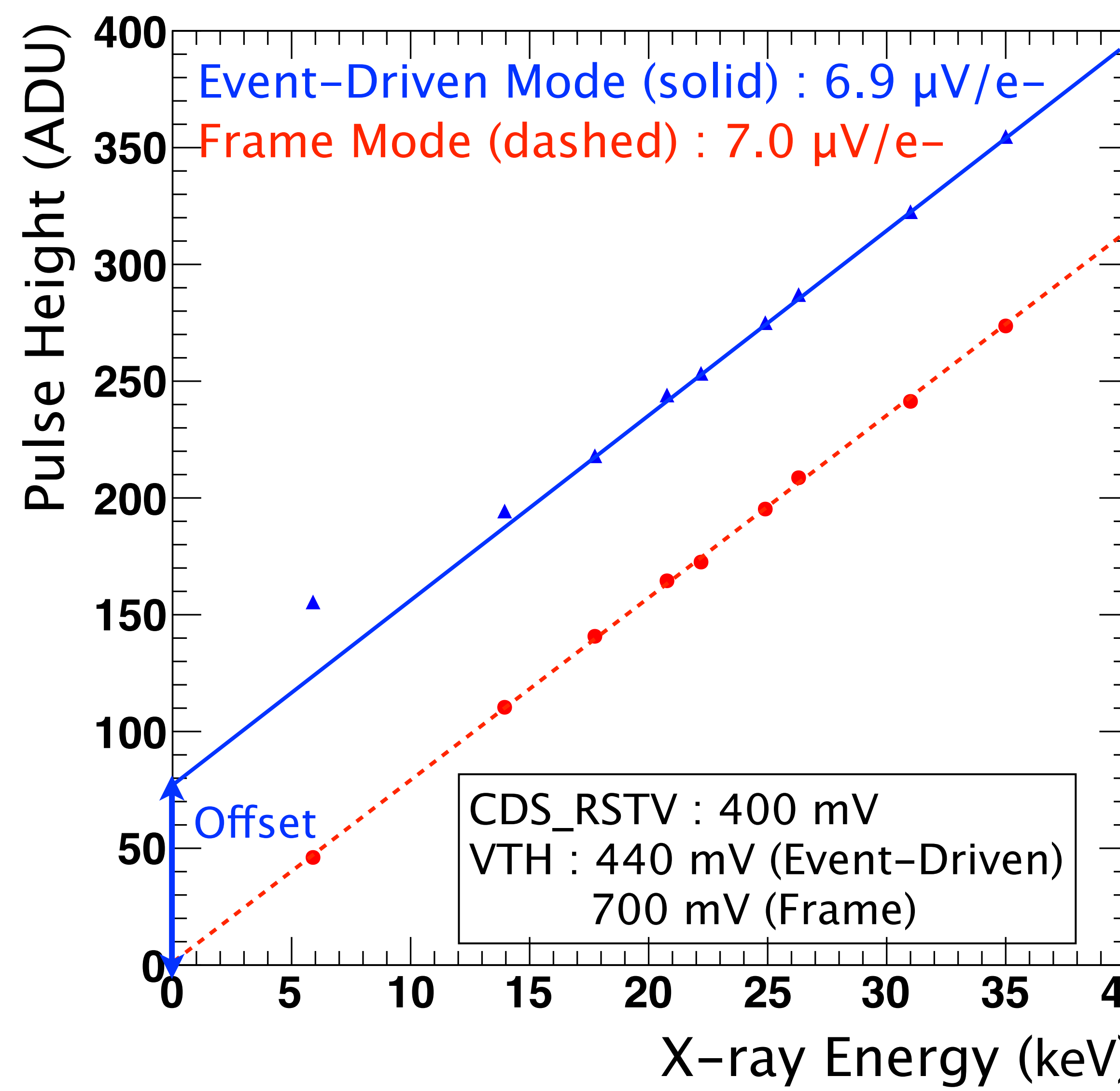
- Wiring of an analog signal line (COL_OUT) and a trigger signal (COL_TRIG_OUT) adjoined each other with the pixel layout. (Distance : 0.4 μm, Length : 4.6 mm)
  -> This has large parasitic capacitance by wiring (~250 fF).
- This is the phenomenon of appearing only when a pixel is specified and observed.
  -> It has checked also by HSpice simulation.



# 2. About the Difference in a Signal Level

- The difference between "real" and "observation" signal levels because of the capacitive coupling of the trigger signal line and sense node.
- This is visualized by abrupt increase in the analog signal level that does not return to the original level.



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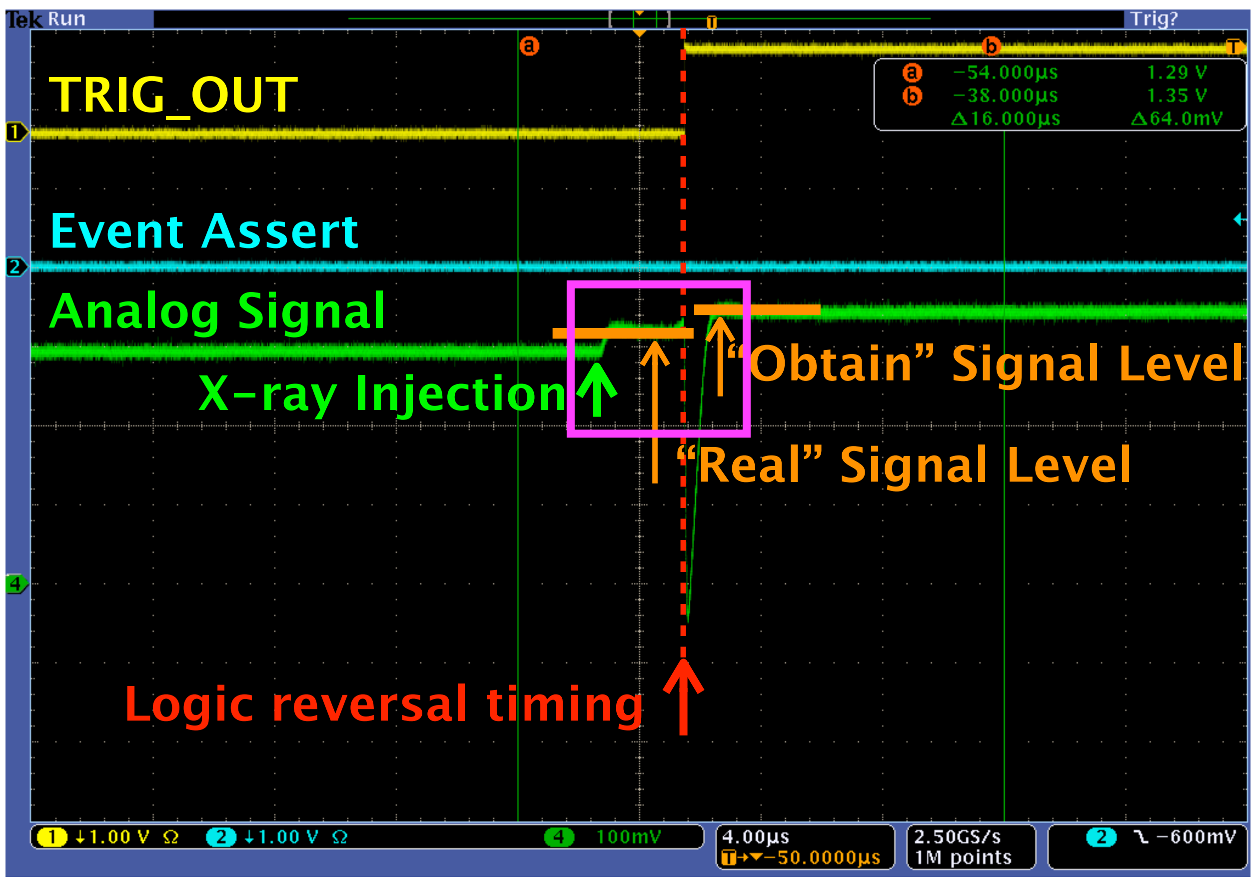


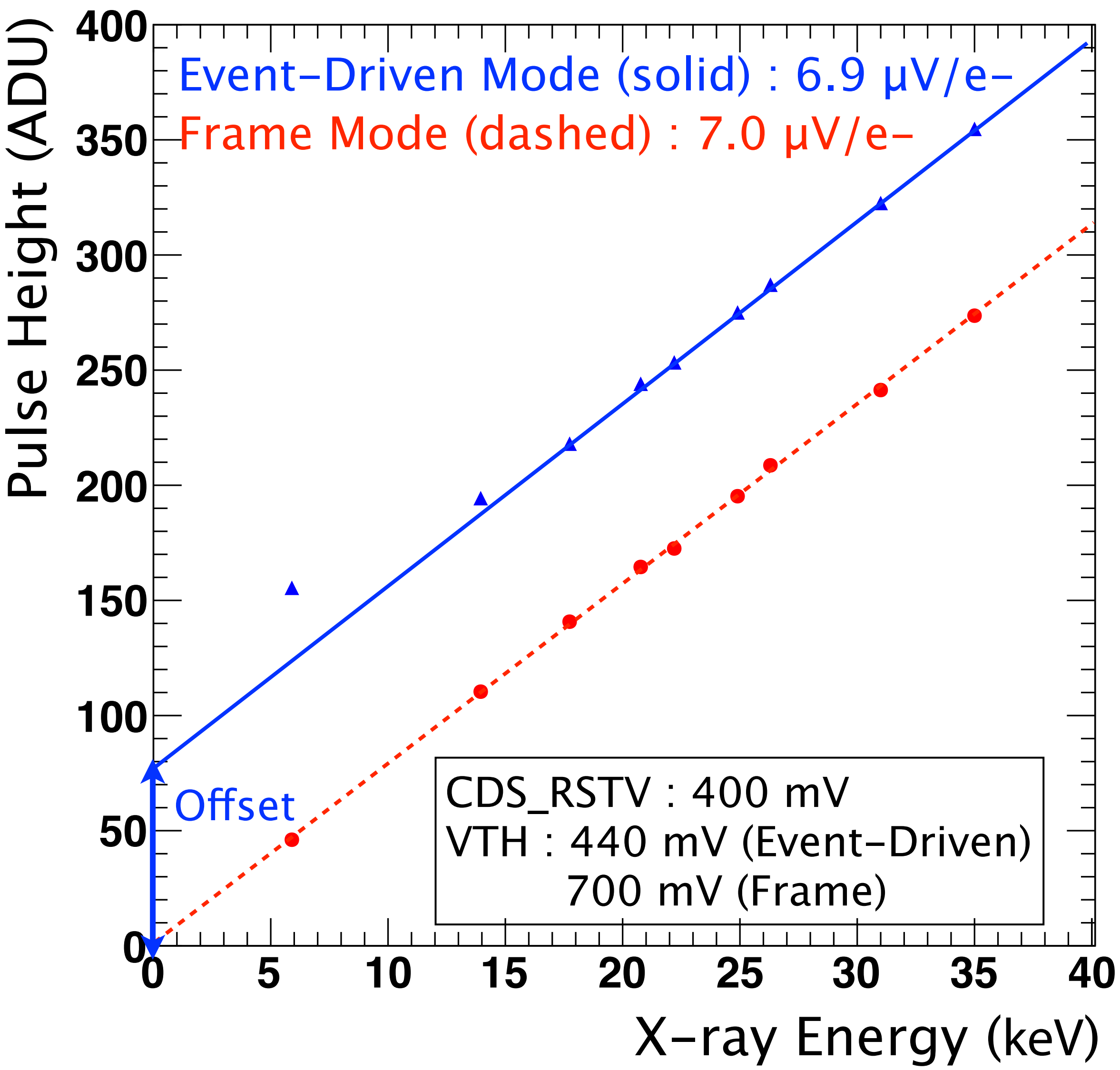

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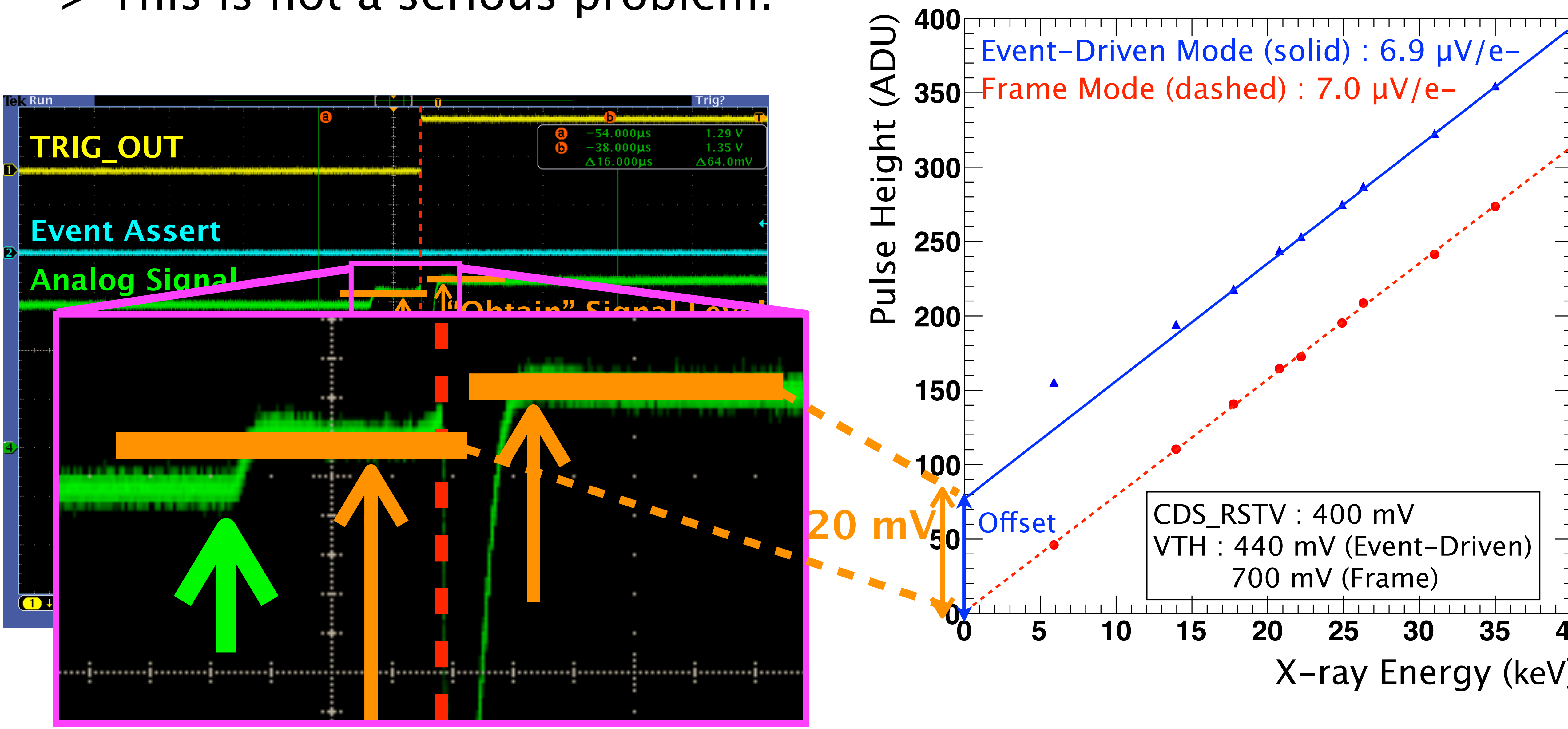
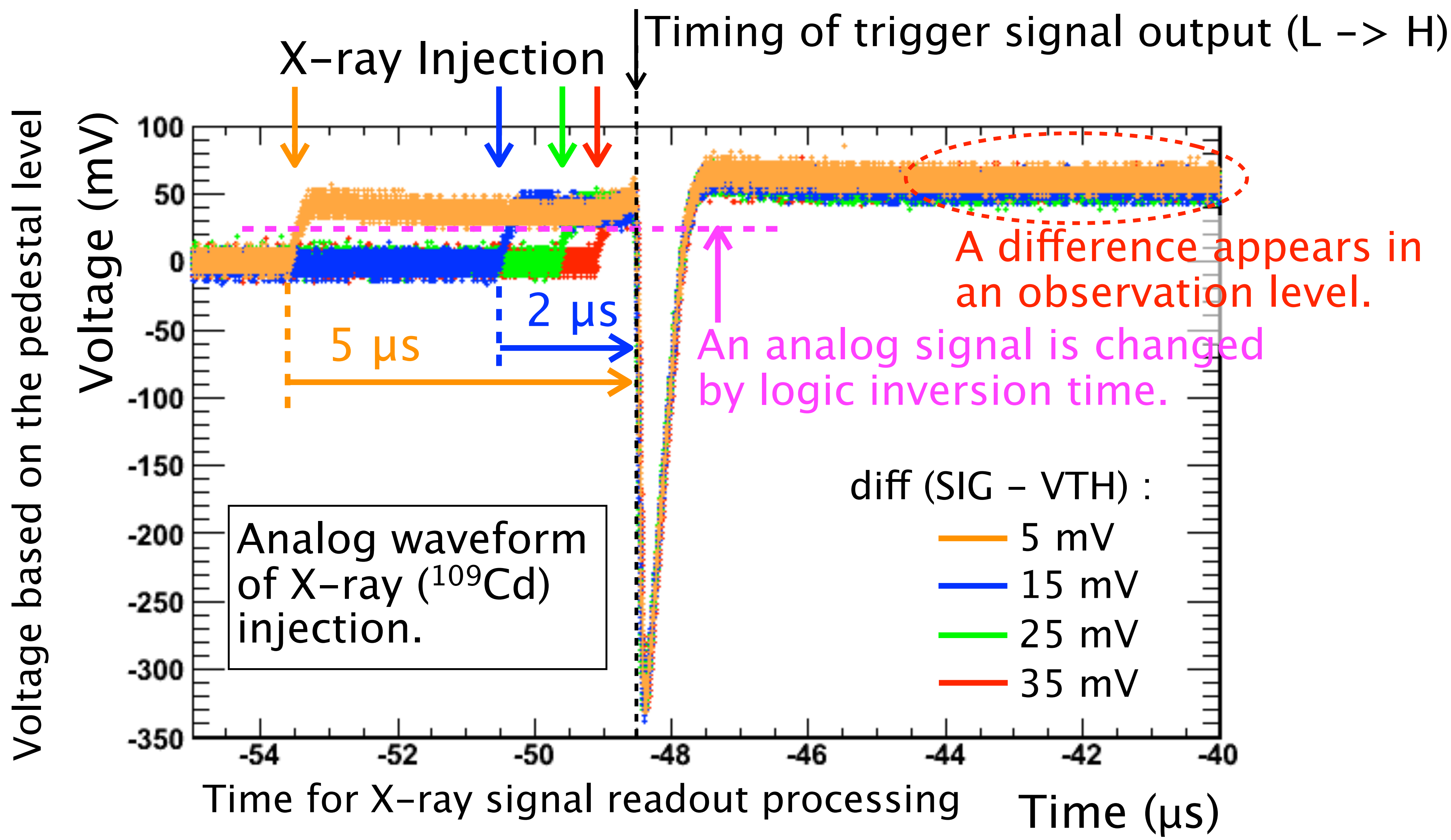
- The difference between “real” and “observation” signal levels because of the capacitive coupling of the trigger signal line and sense node.
- This is visualized by abrupt increase in the analog signal level that does not return to the original level.
- However, it is equivalent to offset of a calibration plot (~20 mV).
  -> This is not a serious problem.



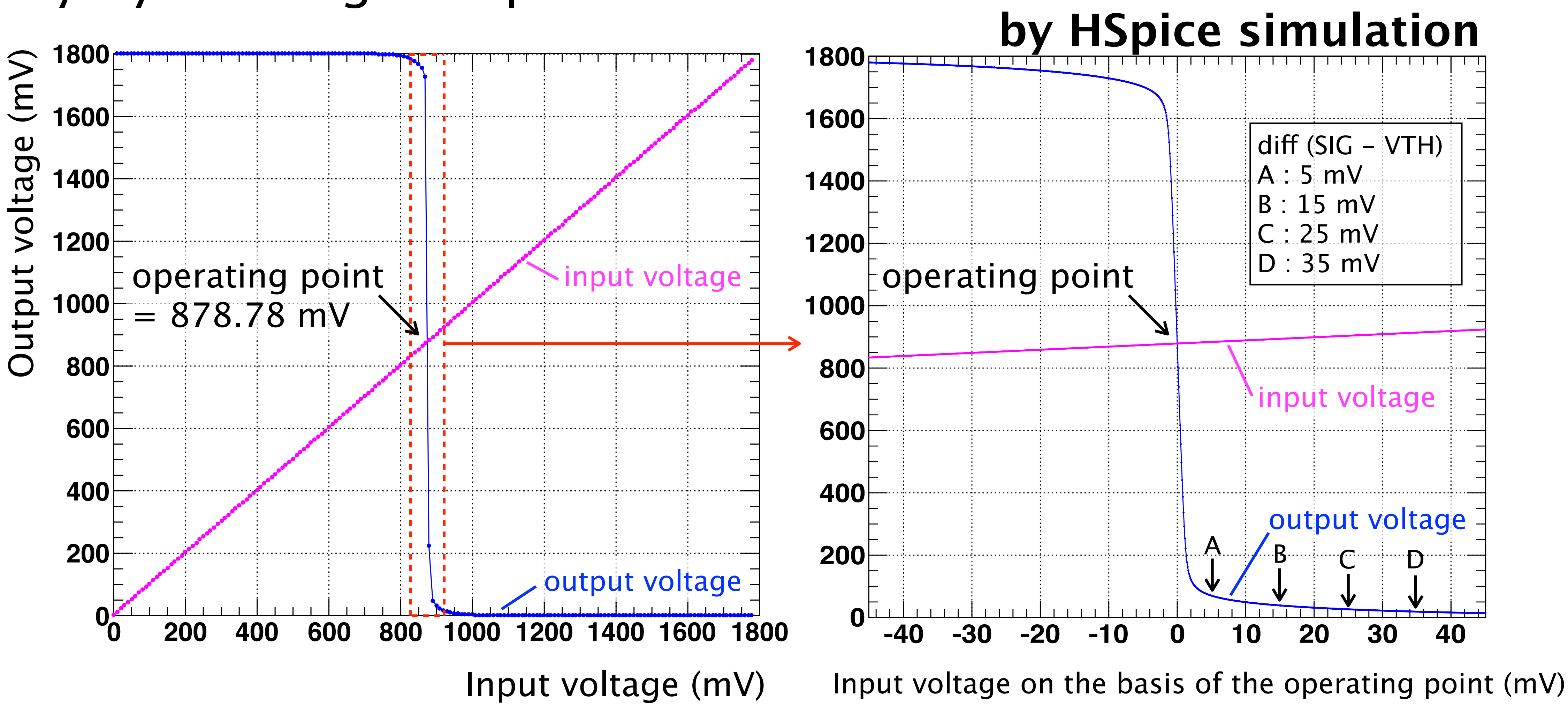
# 3. Long Logic Converting Time

- The long logic conversion time appear with the characteristic of a comparator circuit.
- The time is required for logic reversal such that the difference between the signal level and the VTH is small.
- This is exactly the characteristic of a comparator circuit (i.e., an inverter circuit in this case), as confirmed by HSpice circuit simulation.



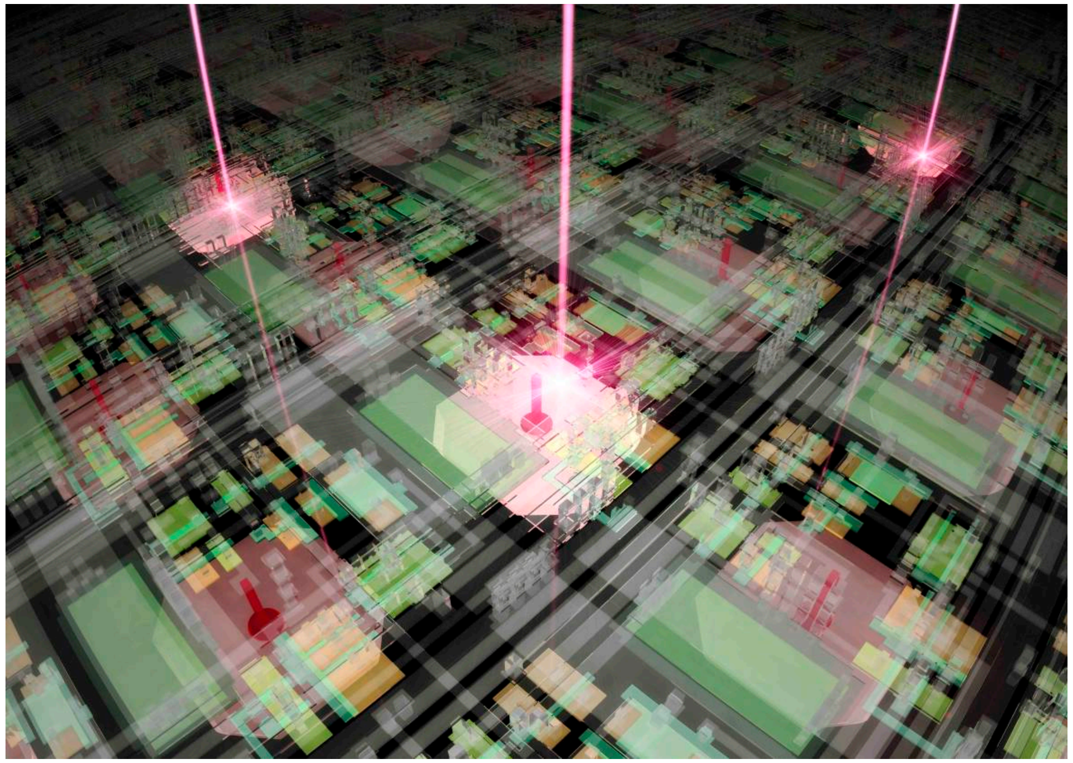
# 4. Change in the Analog Signal

- The change in the analog signal appears from the behavior and wiring composition of a comparator circuit.
- A large through current is obtained for a small value of diff(SIG-VHT).
- Because of the analog and digital power supply lines are not separated in the pixel, the consumption of local current influences the analog circuitry by a voltage drop.




The input-output characteristics of the first stage of the comparator circuit.
The right graph shows a magnified view near the operating point.
In the right graph, the x-axis is re-zeroed at the operating point.

# Evaluation of CSA Pixel Circuit



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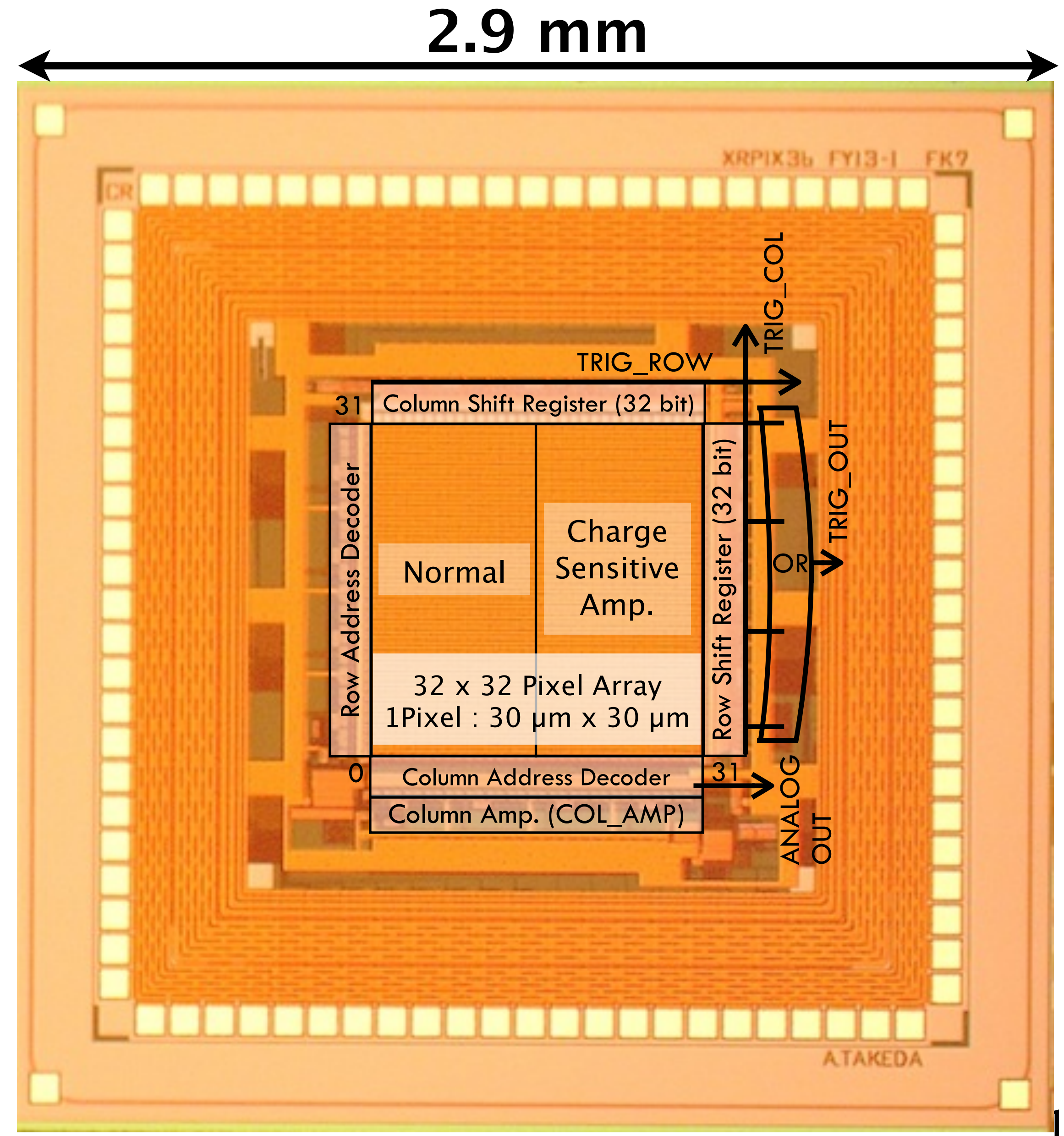
# Design Specification : XRPIX3b

## Components

- Chip Size : 2.9 mm sq. (Effective Area : 1.0 mm sq.)
- Pixel Size : 30 um sq.
- # of Pixel : 32 x 32 (= 1,024)

-> Normal : 32 x 16 (Left) , CSA : 32 x 16 (Right)

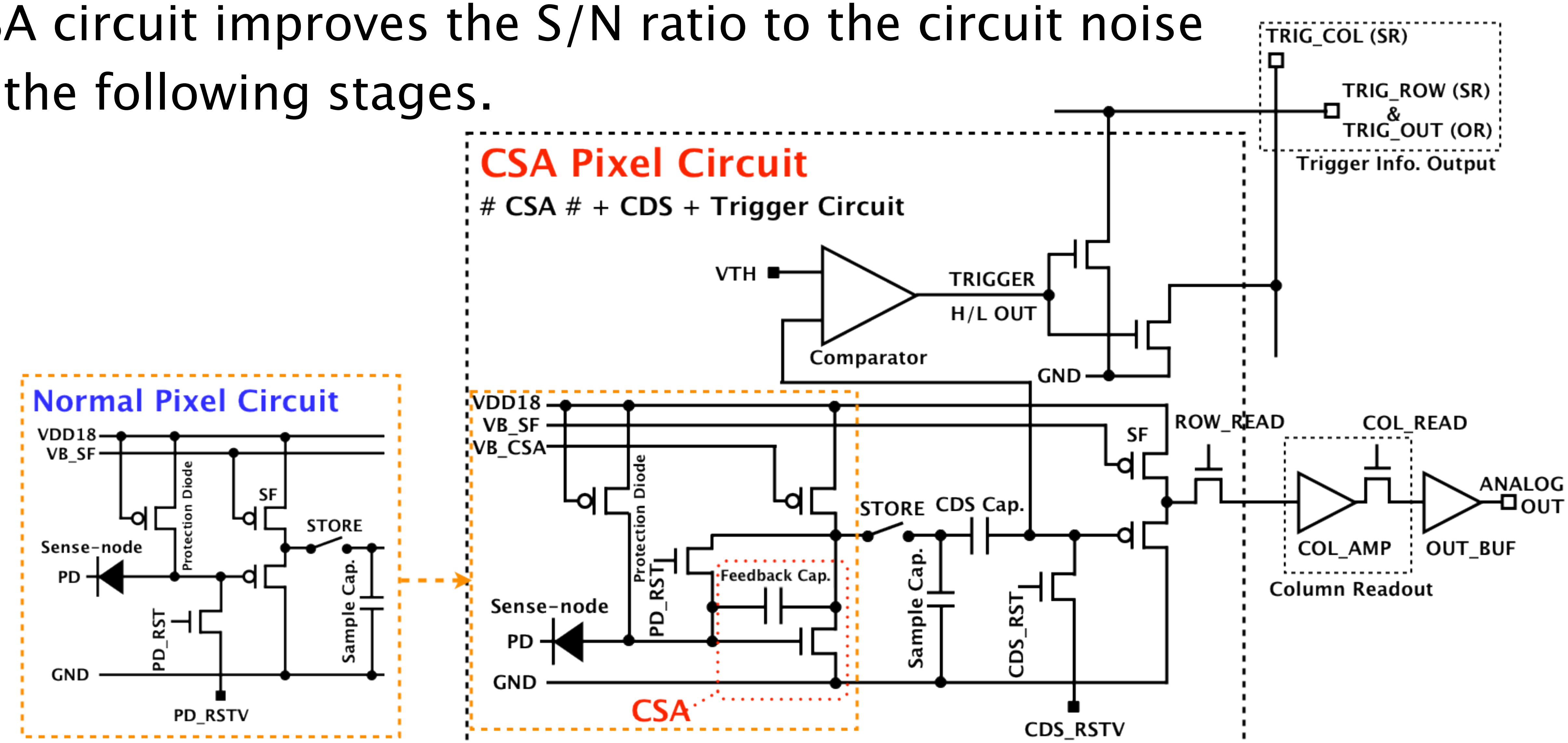
Modification of XRPIX3 which is first prototype of XRPIX CSA circuit.
Comparison of Normal and CSA pixel.
(Fabricated Jun, 2014)



# Pixel Circuit : XRPIX3b

- Normal and CSA pixels have different circuit configuration of preceding stage.
  -> Normal : Source Follower (SF) by Common-Drain of a PMOS transistor (**the same circuit as XRPIX2b**)
  -> CSA : pre-amplifier by Common-Source of a NMOS transistor and a feedback capacitance (1 fF)

  CSA circuit improves the S/N ratio to the circuit noise in the following stages.



# Normal and CSA Circuit Calibration

- Calibration plot by $^{55}Fe$ and $^{241}Am$.
- The pixel circuit with CSA works good. (3.3 times higher gain)

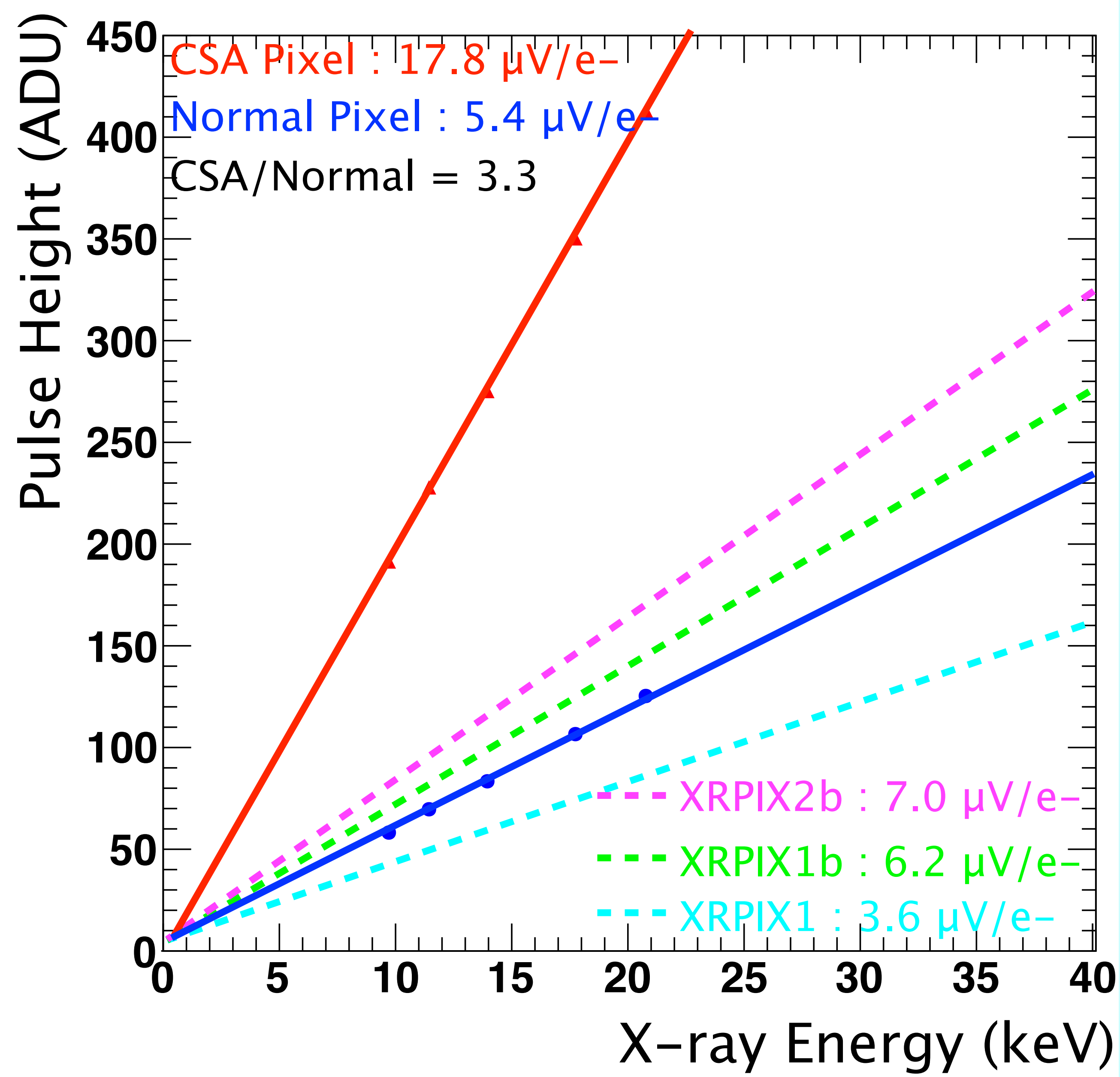
**Gain**

Normal : 5.4 μV/e−

CSA : 17.8 μV/e−

Since parasitic capacitance of sense node increased, the gain fell from XRPIX2b by XRPIX3b.

Observed gain (17.8 μV/e−) is lower than the design (50 μV/e−), which would be due to parasitic capacitance.

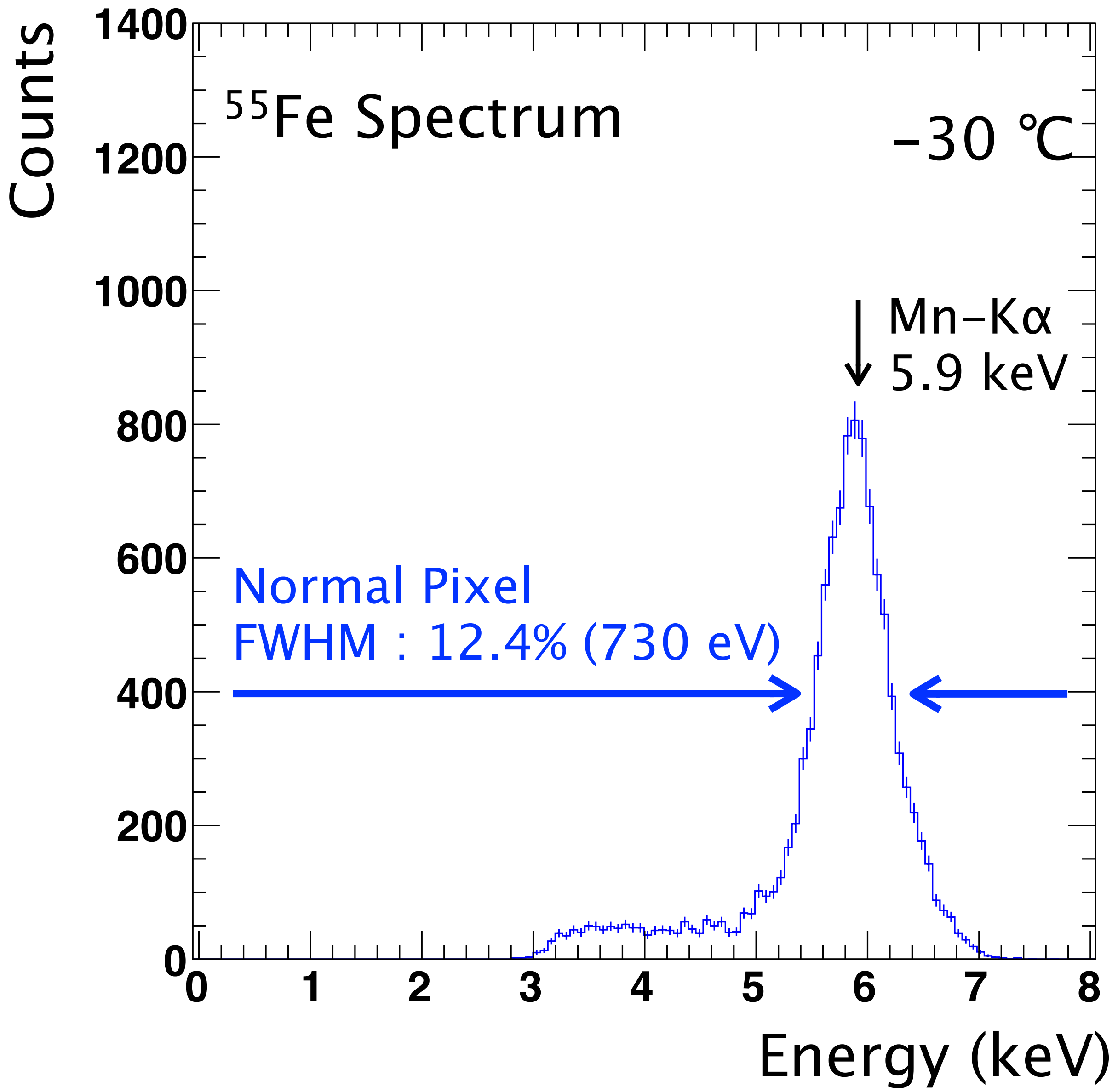



One Analog Digital Unit (ADU) = 244 μV (= 1 V / 12 bit)

# Comparison of Normal and CSA Pixel

- The CSA Pixel succeeded in improvement of energy resolution.
  Comparison of $^{55}Fe$ energy spectrum at Normal and CSA
  (obtain by Frame readout mode, not use Event-Driven)
  -> Readout noise (-> obtained from the pedestal peak)
    Normal : 82 e- (rms)

  -> Mn-Kα @ 5.9 keV
    Normal : 730 eV/12.4% (FWHM)



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Comparison of $^{55}$Fe energy spectrum at Normal and CSA (obtain by Frame readout mode, not use Event-Driven)

-> Readout noise (-> obtained from the pedestal peak)

Normal : 82 e- (rms)

CSA : 35 e- (rms)

-> Mn-Kα @ 5.9 keV

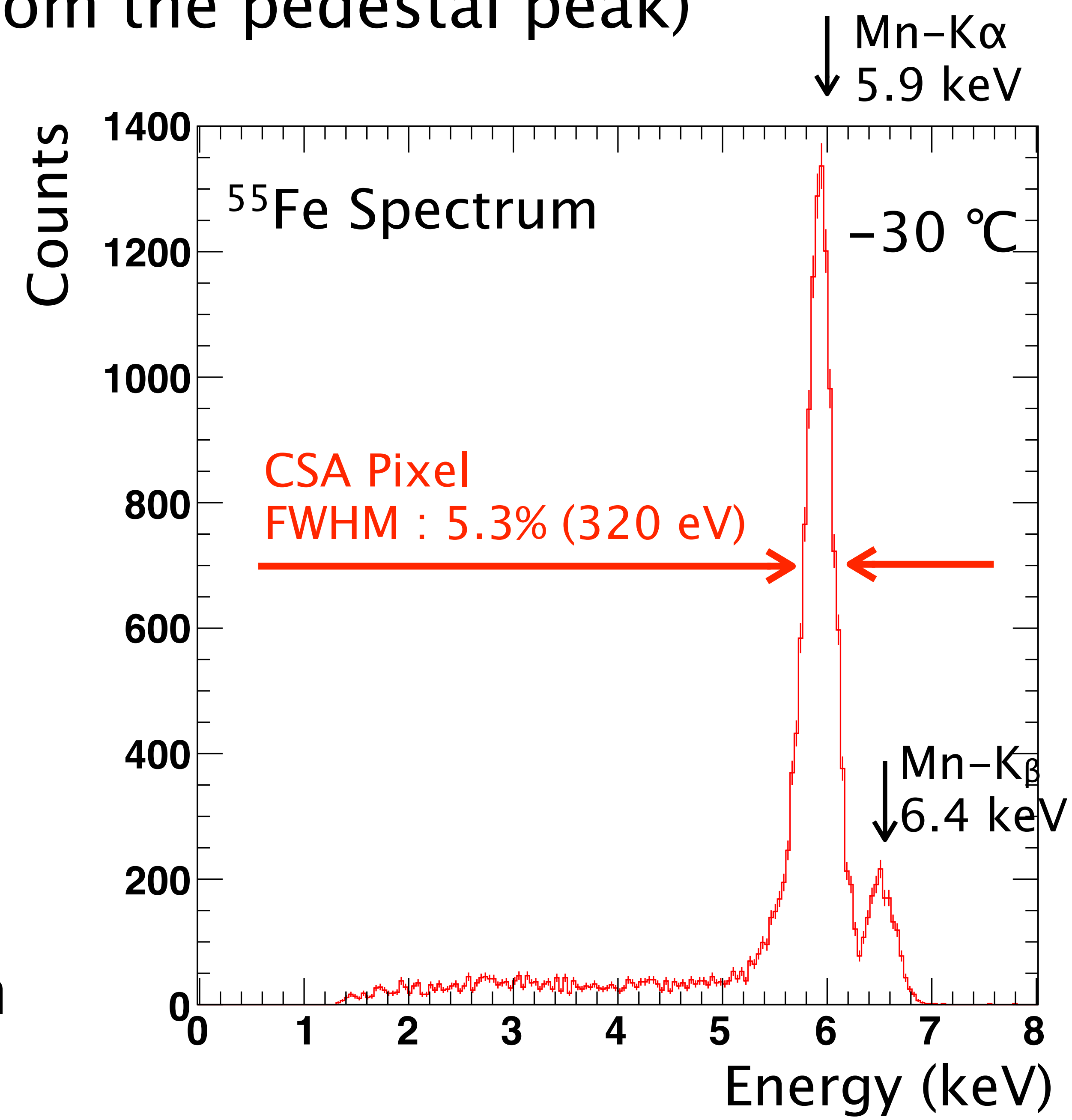
Normal : 730 eV/12.4% (FWHM)

CSA : 320 eV/5.2% (FWHM)

**Resolved Mn-$K_\alpha$ and Mn-$K_\beta$ successfully by CSA circuit !**

**-> Improvement of spectrum performance**

We achieve the target readout noise 10 e- (rms) by optimization of CSA circuit.



# Summary

- We have been developing Event-Driven SOIPIX sensor, “XRPIX”, for future X-ray astronomical satellite mission.
- Realize the Event-Driven readout mode and very low non-X-ray background by the function of the trigger signal output.
- We already successfully obtained X-ray data in Event-Driven mode.
  -> However, it has 4 problems.
  -> It has been understood that these problems were two main causes.
    - The cross talk including the circuit layer and a sense-node.
    - The characteristic of an inverter-chopper-type comparator circuit.
  -> The comparator circuit modification is required.
- By CSA pixel circuit, we improved energy resolution successfully.
  -> The readout noise : 35 e- (rms)
  Mn-Kα @ 5.9 keV : 320 eV / 5.2 % (FWHM)
- We will improve the next design on the basis of these phenomena and optimize the CSA circuit.