Evaluation of the X-ray SOI pixel detector with on-chip ADC

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Outline

Introduction
- X-ray astronomy
- Concepts of future X-ray detector & XRPIX

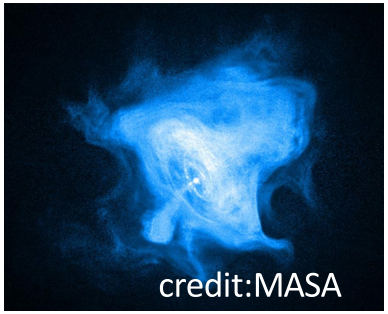
Results of evaluations
- Unit test of the on-chip ADC
  - Integral non-linearity
  - Differential non-linearity
  - Noise from on-chip ADC
- XRPIX end-to end test
  - obtain X-rays spectrum from XRPIX

X-ray astronomy

We can study high-energy physics through X-ray observations

Example : High energy celestial objects

Neutron stars



credit:MASA

Vicinity of Black holes

credit:NASA

Current standard X-ray detector : CCD

Pros : Energy resolution : 150 eV @ 6 keV

Good spatial resolution : 20 ~ 30 um

Cons : Time resolution : several seconds

➤ unsuitable for celestial objects rotating in seconds

Concepts of future X-ray detector

Energy range : 0.5 – 80 keV
adopted Si sensor (<20 keV) and CdTe sensor (>20 keV)
➤ capable of wide-band X-ray research

Observation targets : High energy celestial objects

Low background above 10 keV
➤ Reduce non-X-ray events by active shields
capable of low luminosity celestial objects

Good time resolution ~ a few us

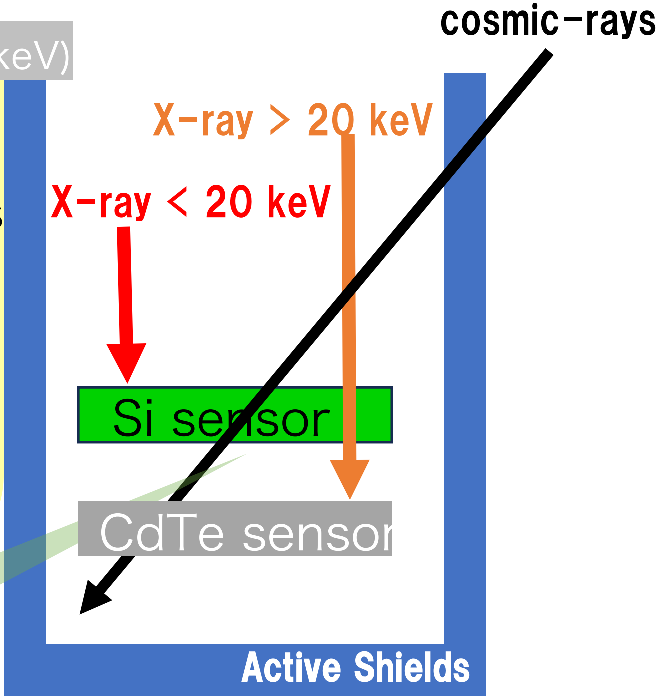


image of Wide-band X-ray Imager

Future Si detector's Requirements

ΔE < 140 eV @ 6 keV
It catches X-rays less than 20 keV
Time resolution ~ a few us

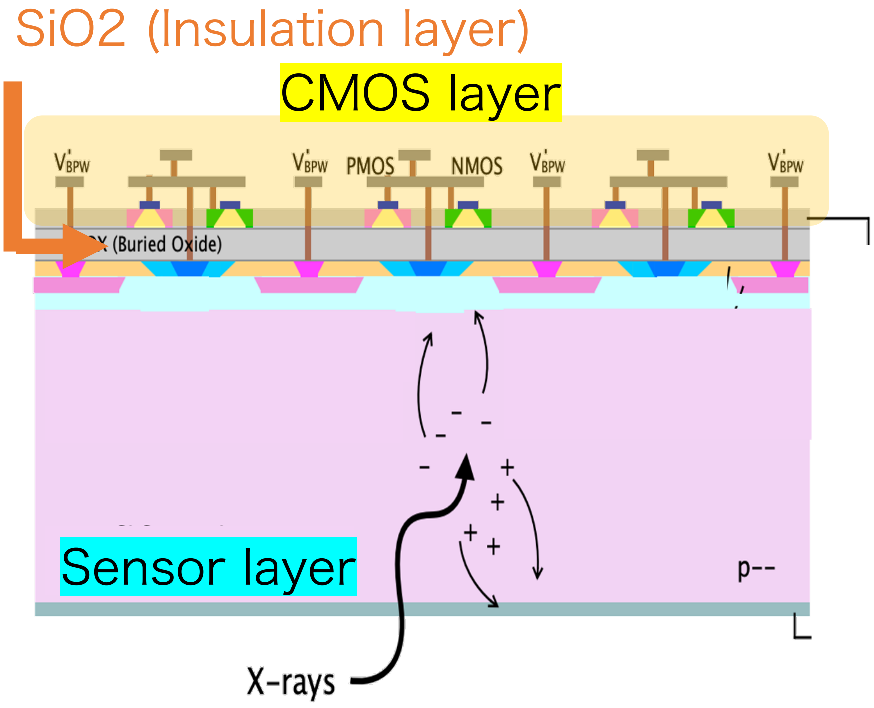
This talk theme
Future Si detector XRPIX

Future X-ray detector : XRPIX

XRPIX is the new X-Ray detector made with SOI technology

trigger function
measure the moment when X-rays hit

➡ Combine CMOS Layer and Sensor



Good time resolution
each pixel has trigger function
▶ Time resolution <10 us

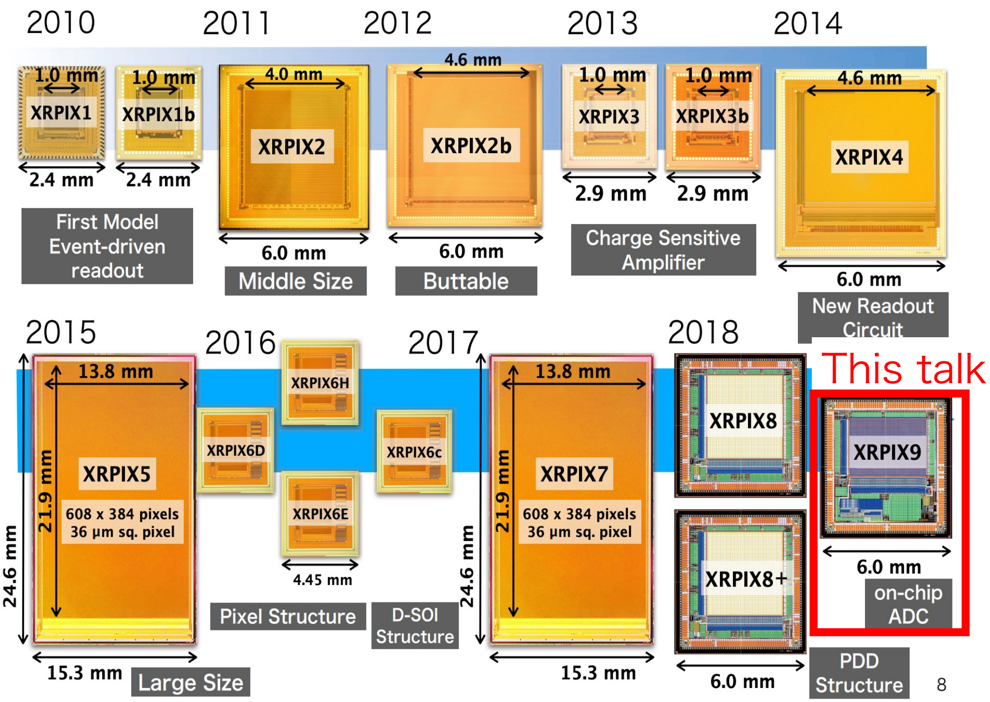
Energy resolution
ΔE < 300 eV at 6 keV
▶ Goal : ΔE < 140 eV at 6 keV

Thick sensor layer
▶ High detection efficiency for X-rays

It will be installed on X-ray satellites

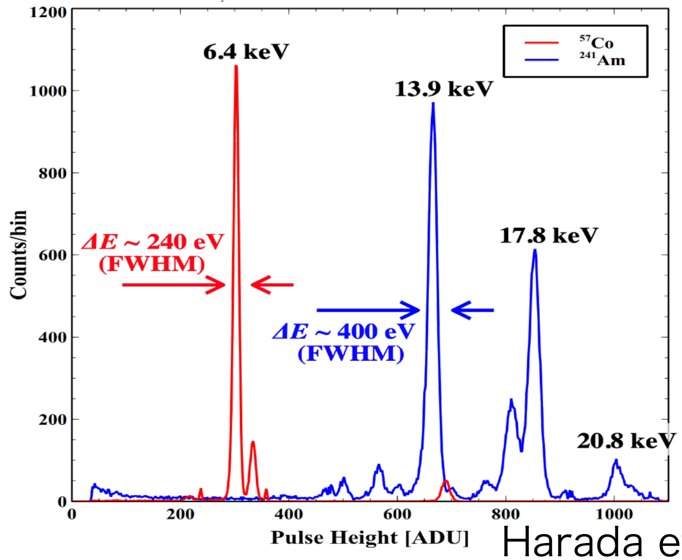
XRPIX's current status

We've been researching and developing



XRPIX6E

FWHM~240 eV at 6.4 keV

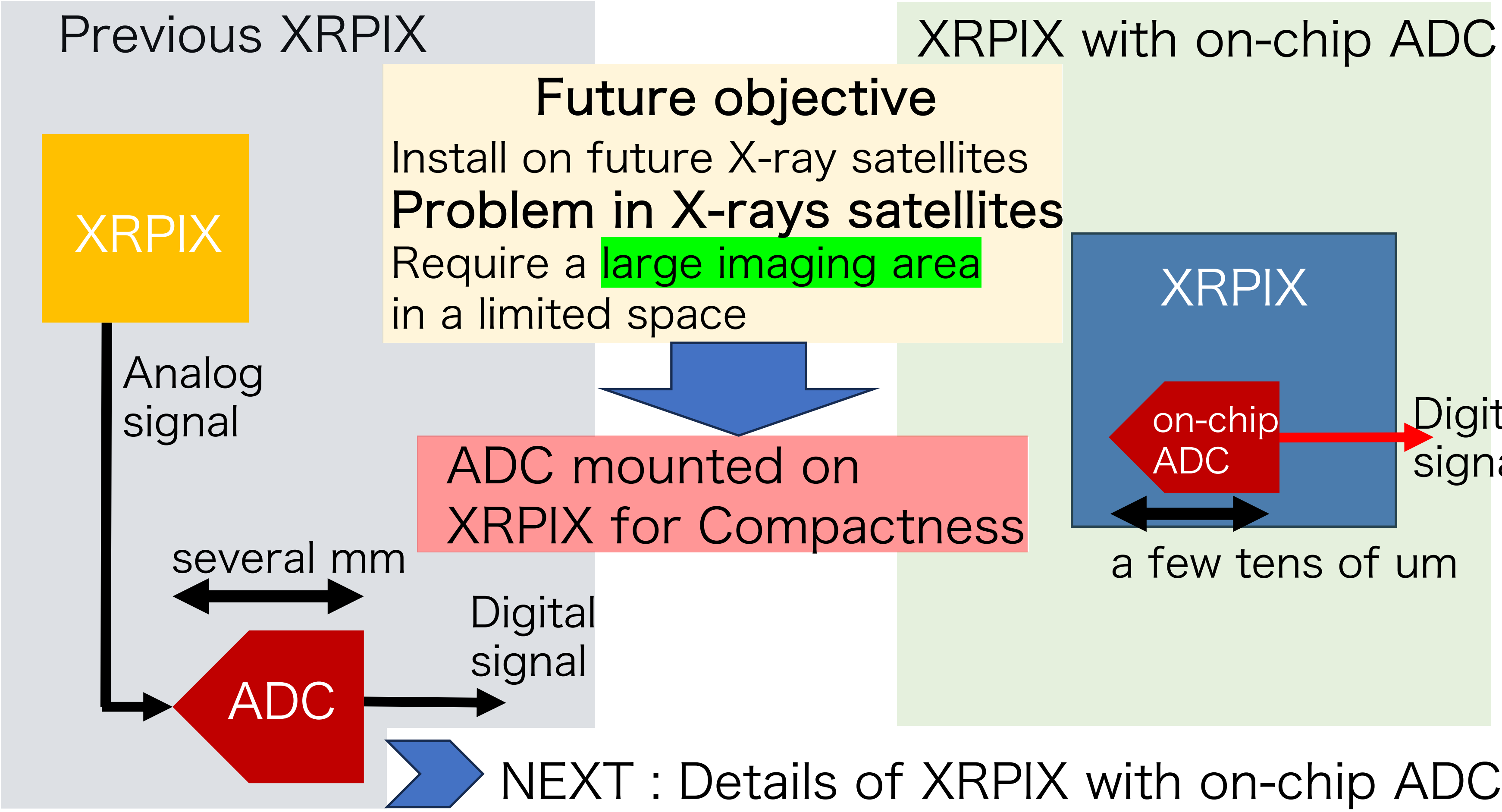


Harada et.al 2019

Sensor : Good spectral performance

We are currently working on digitalization

Previous designs and problems



Previous XRPIX

XRPIX

Analog signal

several mm

ADC

Digital signal

Future objective

Install on future X-ray satellites

Problem in X-rays satellites

Require a large imaging area in a limited space

ADC mounted on XRPIX for Compactness

XRPIX with on-chip ADC

XRPIX

on-chip ADC

Digital signal

a few tens of um

NEXT : Details of XRPIX with on-chip ADC

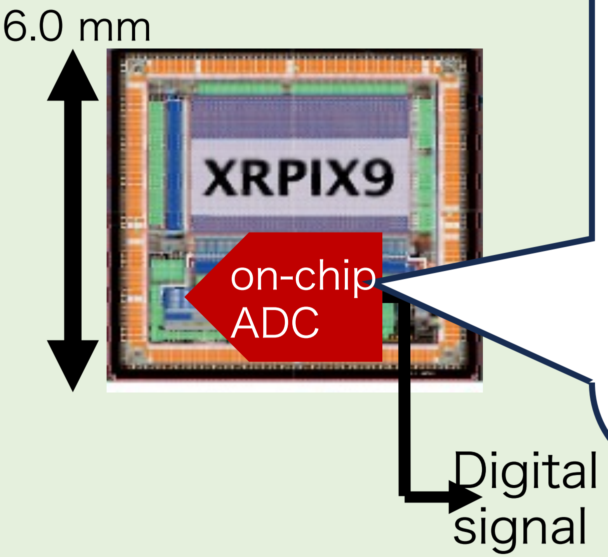
XRPIX with on-chip ADC

XRPIX9
The first XRPIX
to output digital signal

pixel area
36 um × 36 um

Sensor layer ~ 300 um
↓
capable of
wide-band detection
1.0 - 40 keV

XRPIX9 on-chip ADC



Type : Cyclic ADC

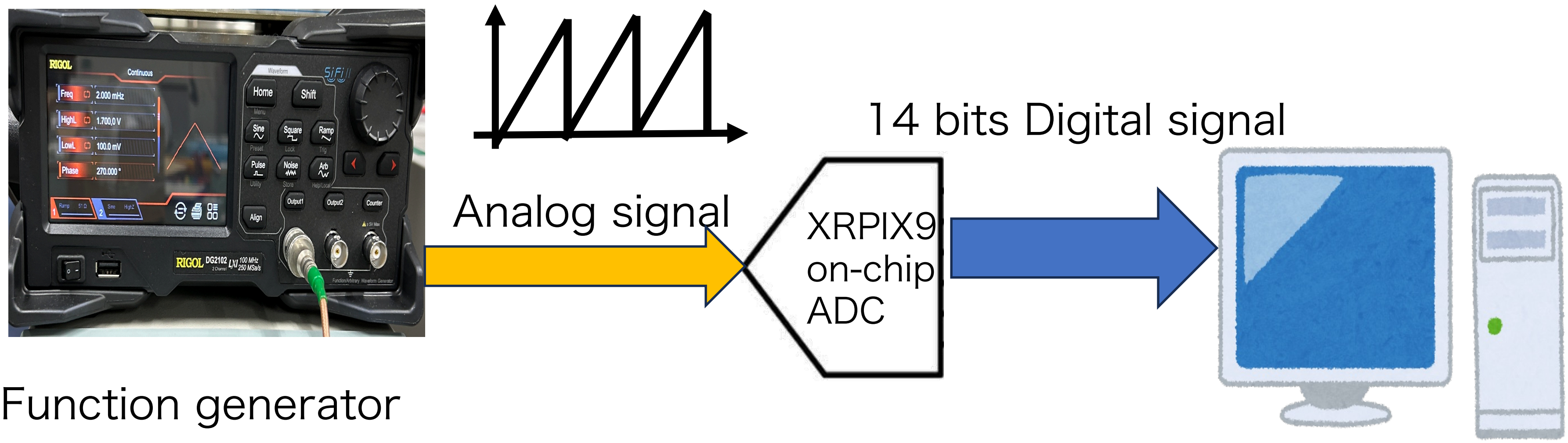
High speed (6 us)
Small size (20 um)
→ Advantages

Number of bits : 14 bits
Voltage range : 0.4-1.5 V
Total units : 16 units
→ 1 column has 2 ADC

Goal :Evaluate the performance of its on-chip ADCs and inspect that XRPIX9 has the same performance of previous XRPIX

Unit test of the on-chip ADC

Input ramp wave or constant voltage into ADC



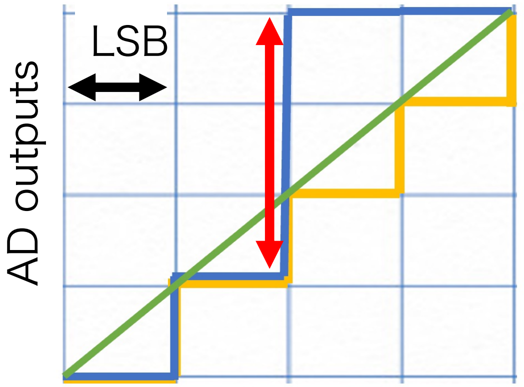
Analog signal

XRPIX9 on-chip ADC

14 bits Digital signal

Function generator

Result1:Integral Non-Linearity (INL)



Input ramp wave into on-chip ADC

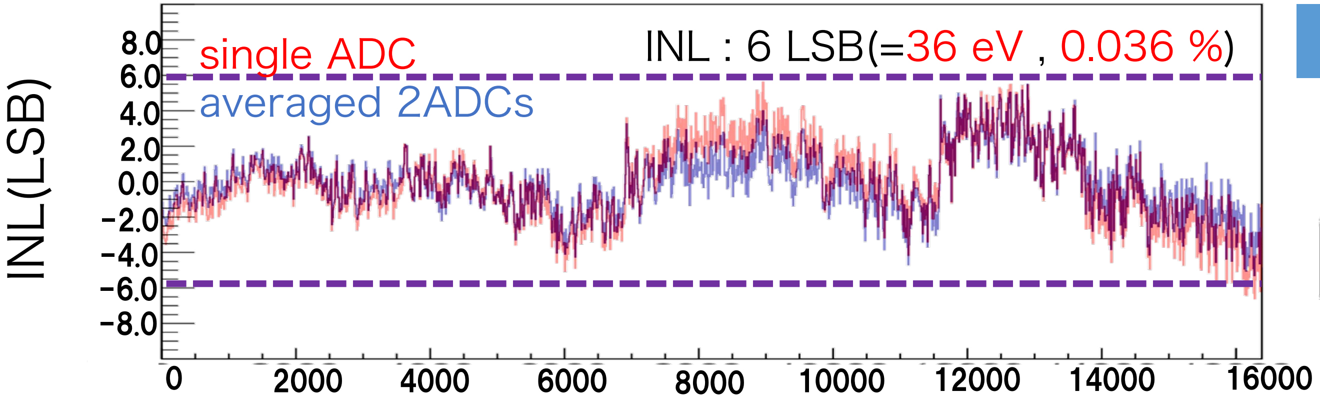
Ideal ADC steps one at a time

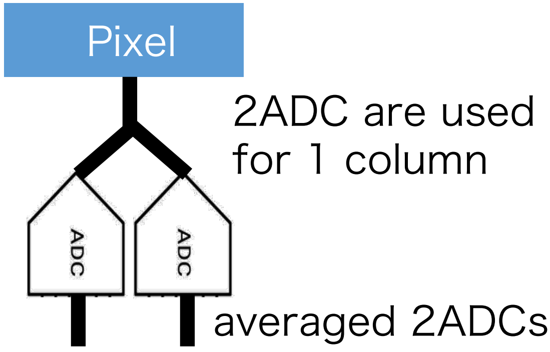
Actual ADC : Vertical deviation occurs

Methods :

Fitted actual ADC outputs with straight line
calculated residuals between the line and ADC outputs

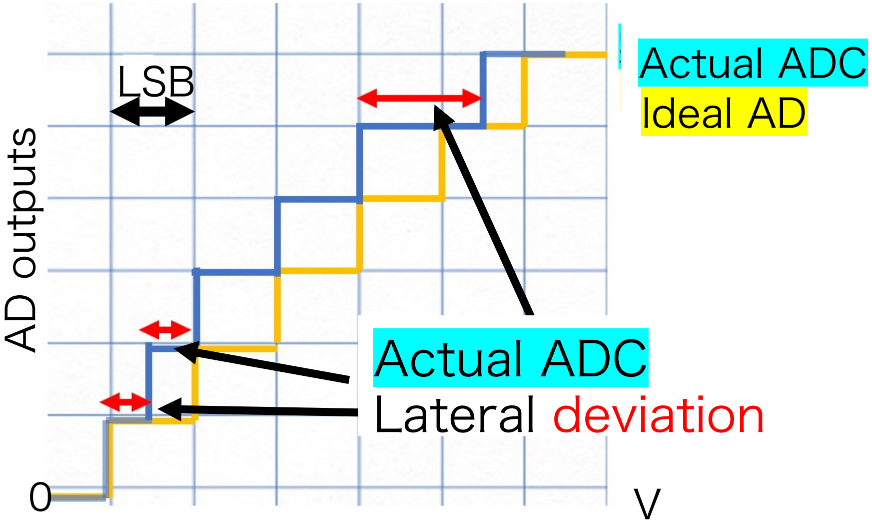
<Result>



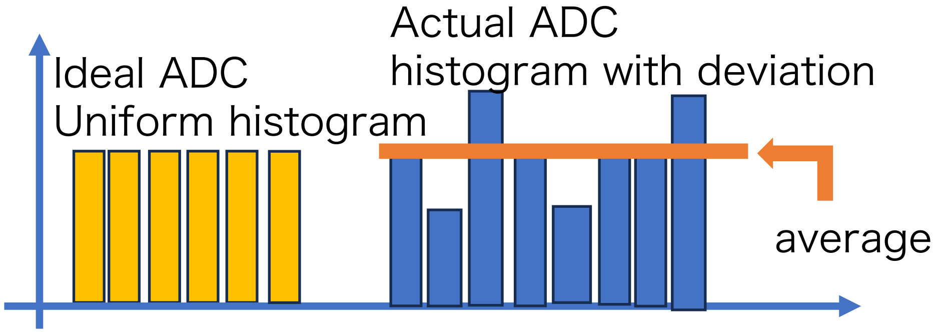


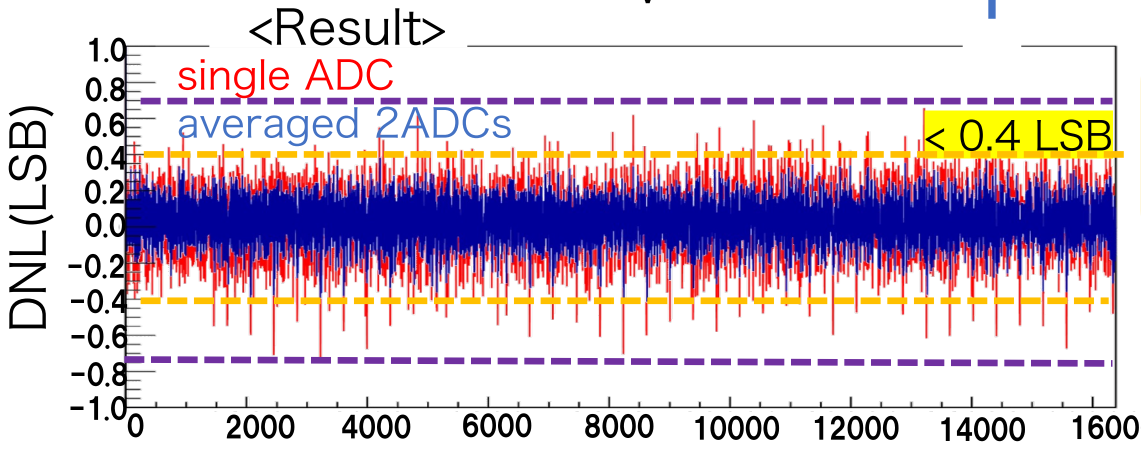
Negligible level for resolution 300 eV

Result2:Differential Non-Linearity (DNL)



Methods :
Histogram the number of AD outputs
Evaluate deviation from ideal ADC

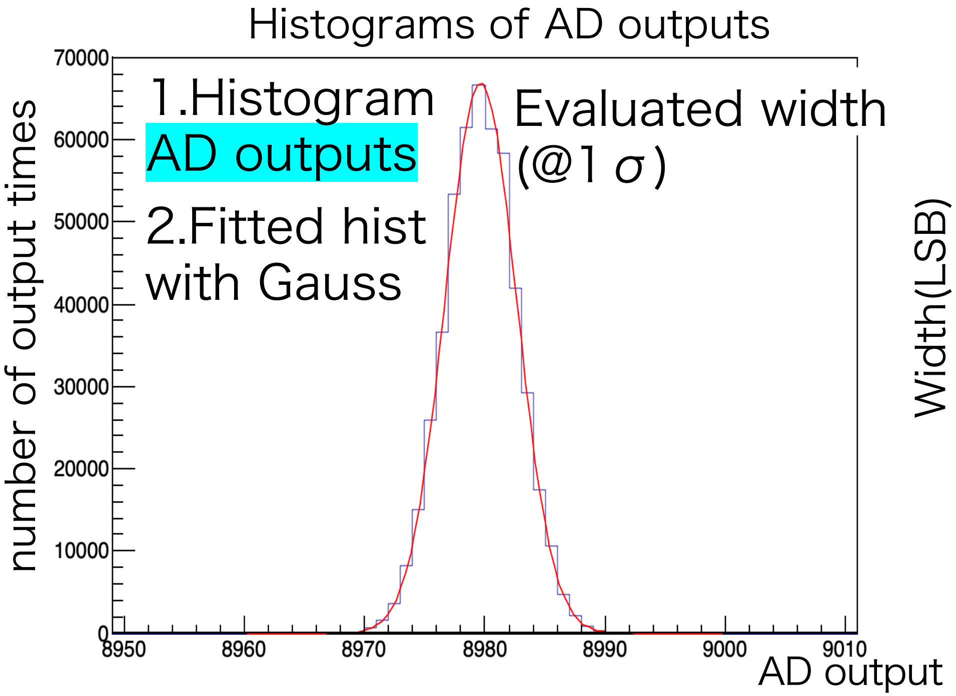


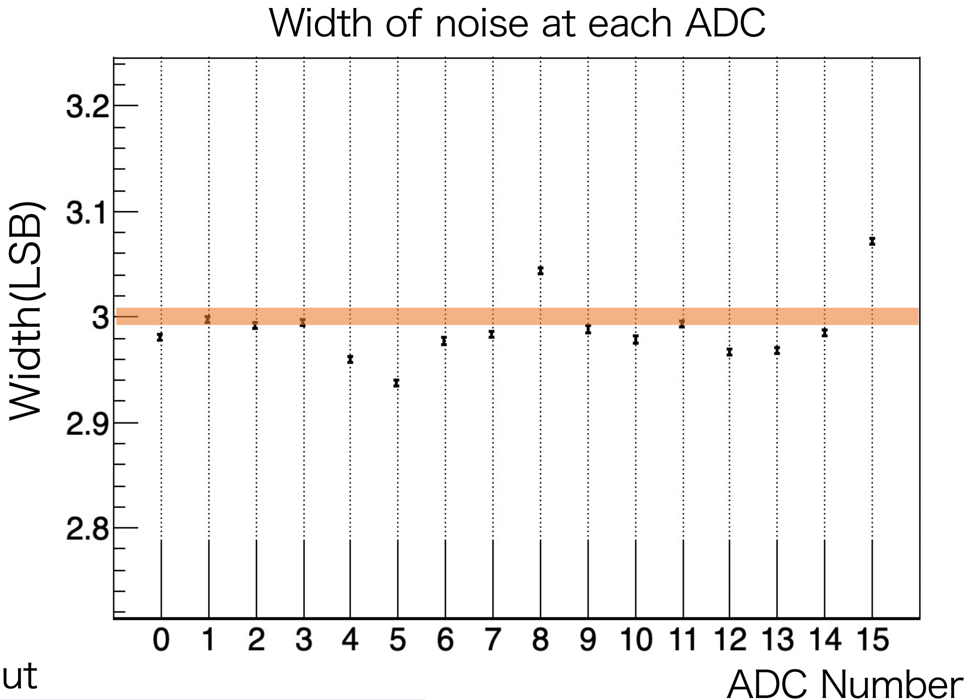


averaged ADC's DNL < 0.4 LSB
single ADC's DNL < 0.7 LSB
→ NO MISSING CODE

Result3:Noise

Methods：Input constant voltage into on-chip ADC



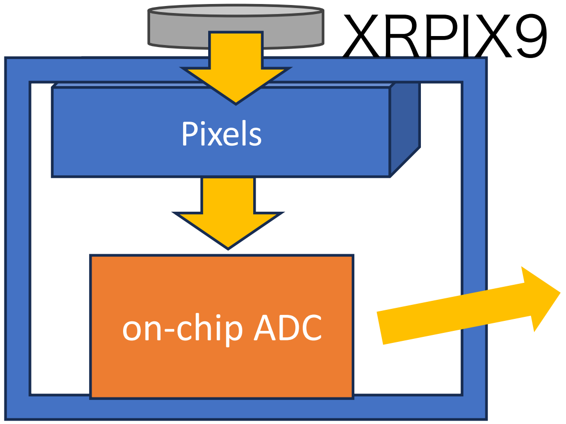


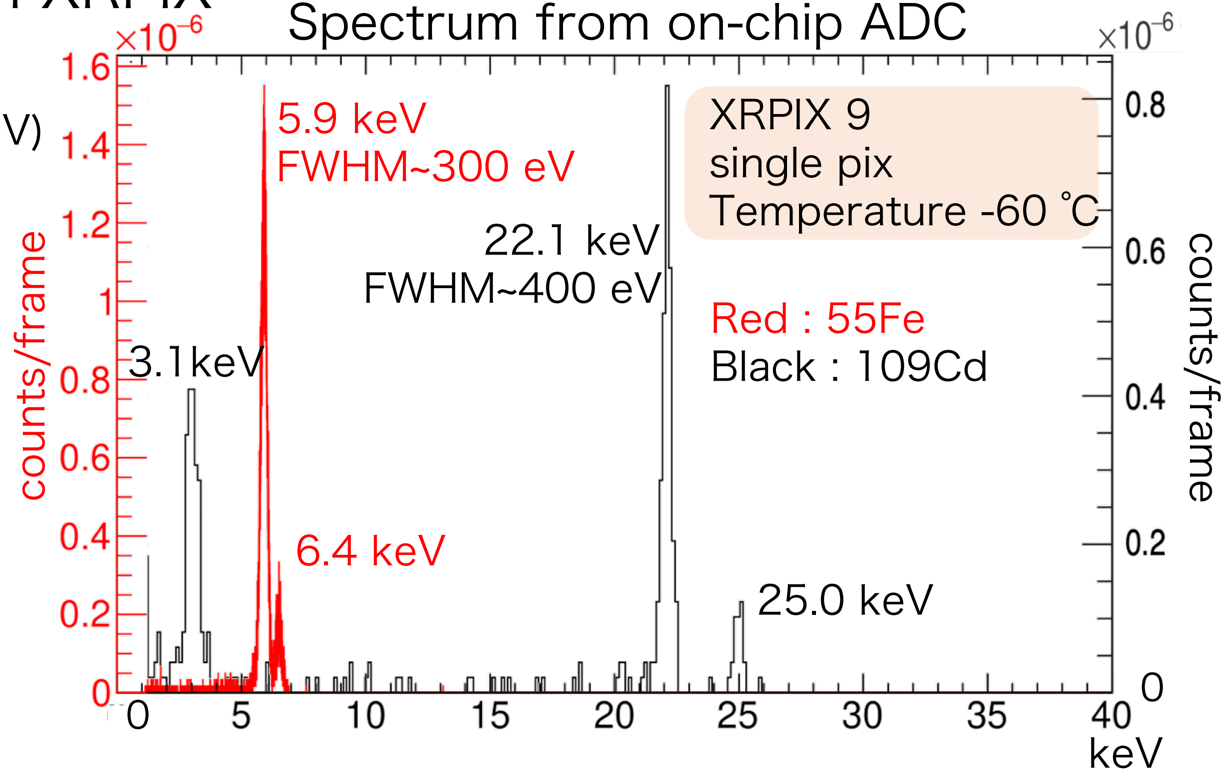
Noise width ~ 3 LSB (= 5 e)
⟹Negligible level for 300 eV

XRPIX9 end-to-end test

- Irradiated X-rays on XRPIX

55Fe(5.9 keV) & 109Cd(22.1 keV)

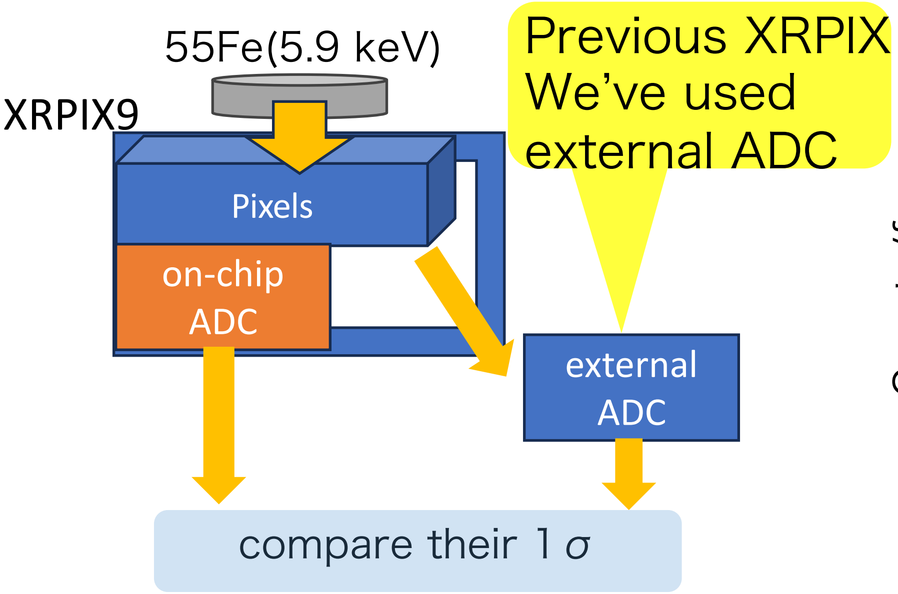




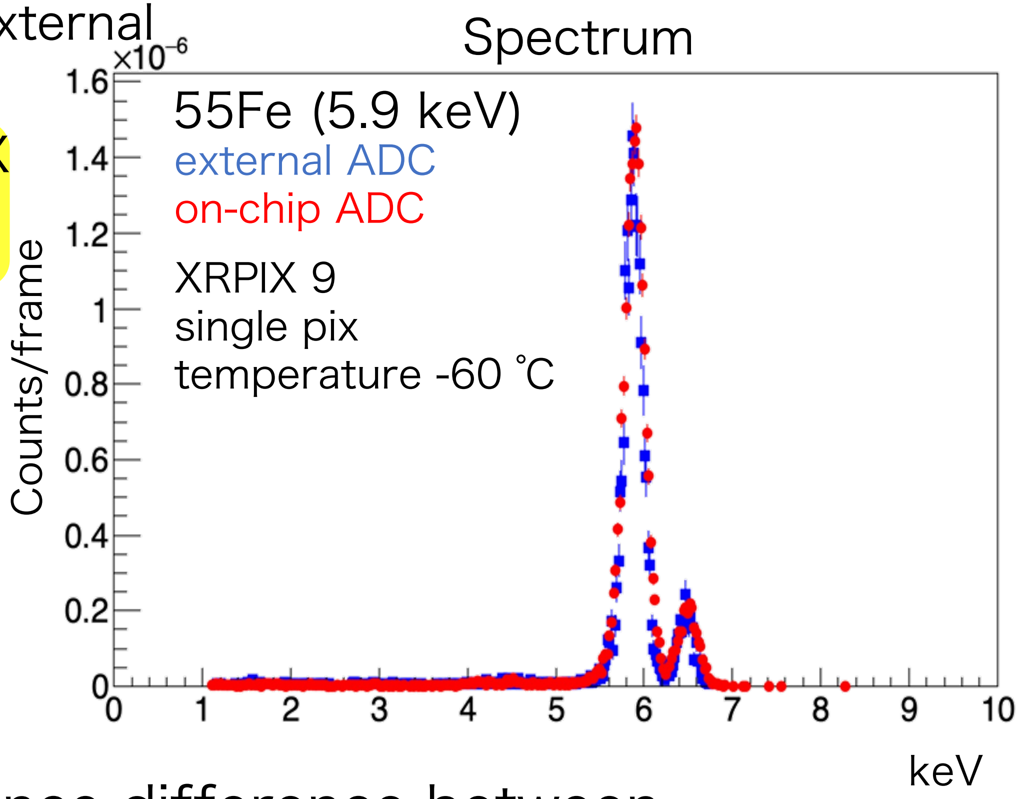
Successfully obtained spectra from on-chip ADC

Comparison with external ADC

- Comparison on-chip ADC with external



Previous XRPIX We've used external ADC



investigate performance difference between external ADC and on-chip ADC

on-chip ADC vs external ADC

Fitted X-ray spectrum with gaussian and compared these width of 1 σ

Most of plots are along

$$\sigma_{\text{on chip}} = \sigma_{\text{external}}$$

Almost the same performance

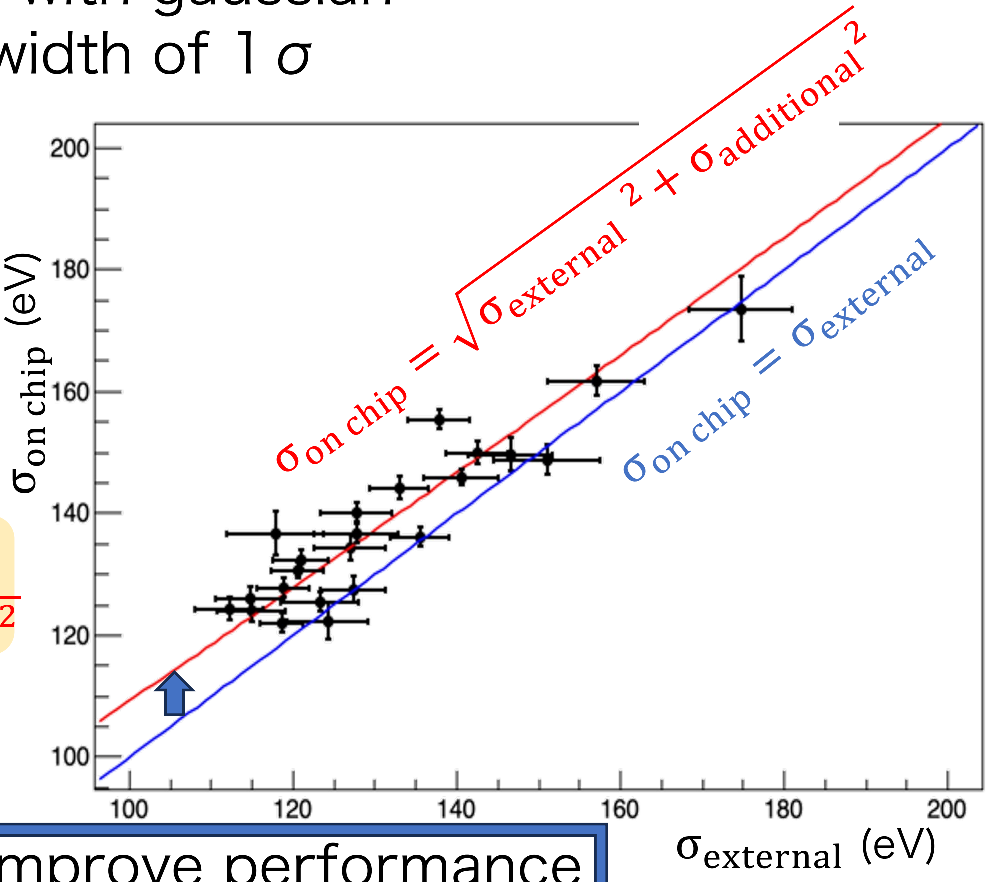
But plots are slightly above it

To go over the noise of on-chip ADC

Fitted plots with $\sqrt{\sigma_{\text{external}}{}^2 + \sigma_{\text{additional}}{}^2}$

Results : contains

unrecognized noise of 45 eV



Future task : Evaluate noise & improve performance

Summary

Objective

XRPIX aims to be installed on future X-ray satellites as detector

→ Future task: Digitalization

Detector needs to be compact → We developed on-chip ADC

Result : Unit test of on-chip ADC

1. Integral Non-Linearity:0.036 % (6 LSB , 36 eV)
2. Differential Non-Linearity: NO MISSING CODE (DNL< 0.7 LSB)
3. Noise : 3 LSB (5 e)

Result : XRPIX9 end to end test

We successfully obtained spectrum from on-chip ADC

(FWHM@5.9 keV ~ 300 eV , FWHM@22.1 keV ~ 400 eV)

No crucial differences between on-chip and external

Problem : Noise(1σ) = 45 eV → Future task & improve it

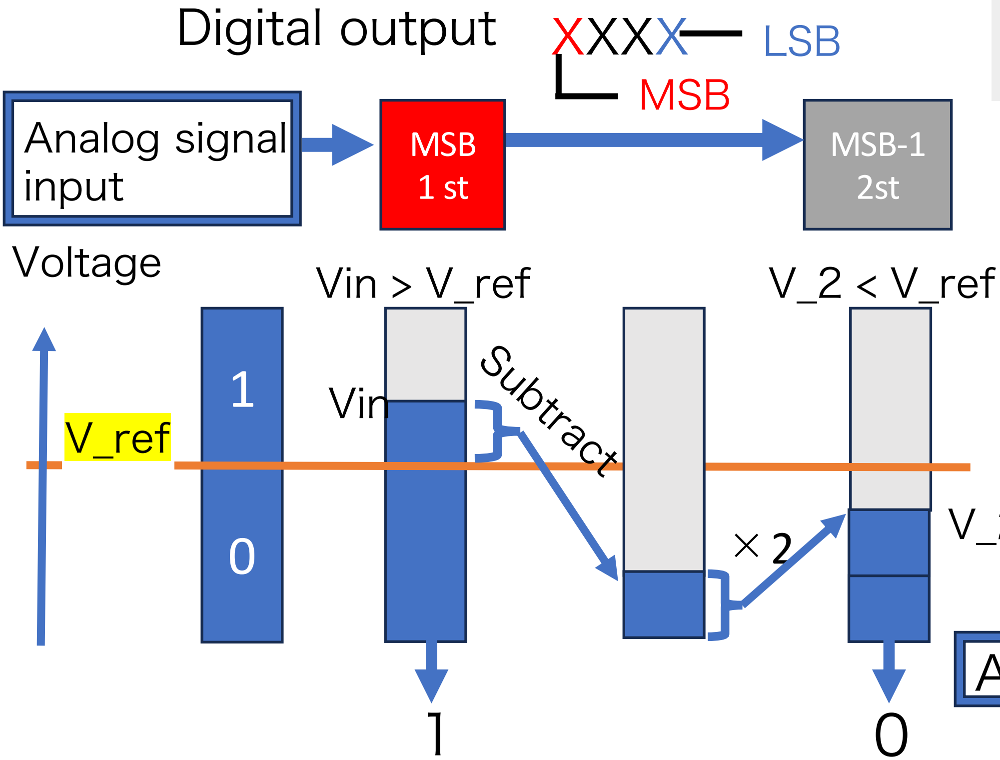
Back up

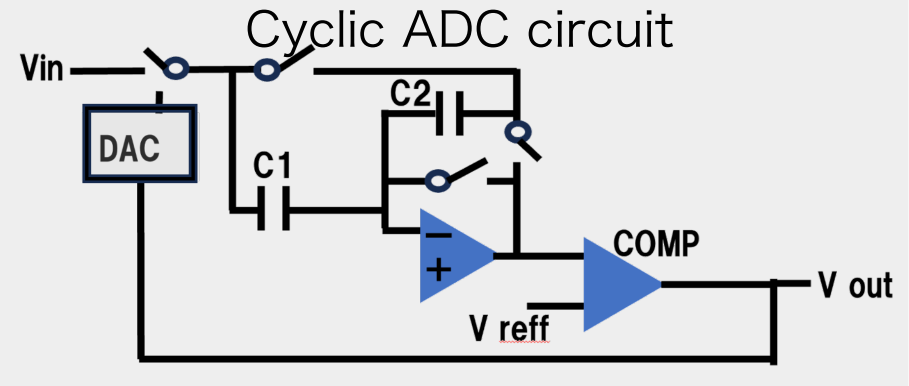
Cyclic ADC

XRPIX9 adopted cyclic ADC

▶ How to work cyclic ADC

Process of AD conversion





1. compare Vin with V_reff
If Vin > V_ref →1 = MSB

2. Subtract V_ref from Vin
& V_2=2×(Vin-V_ref)
compare V_2 with V_reff
If V_2 < V_ref → 0 = MSB-1

3. Repeat process for 14times
→14 bit Cyclic ADC

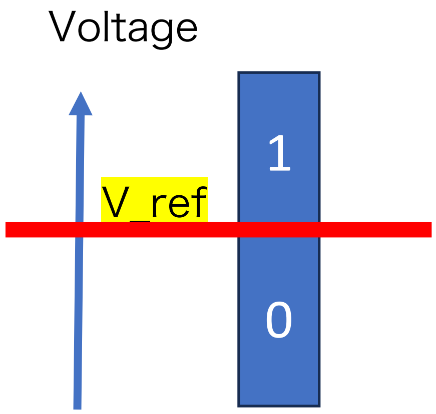
Advantages : small size and high speed

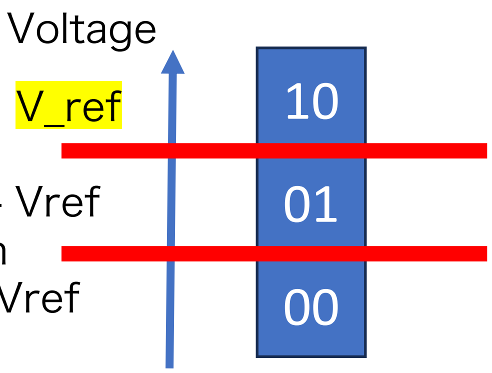
1.5 bit cyclic ADC

Actually, We have used 1.5 bit ADC.

1 bit ADC
So far, ADC to determine 0 or 1

1.5 bit ADC
Bit is determined by 00, 01 or 10



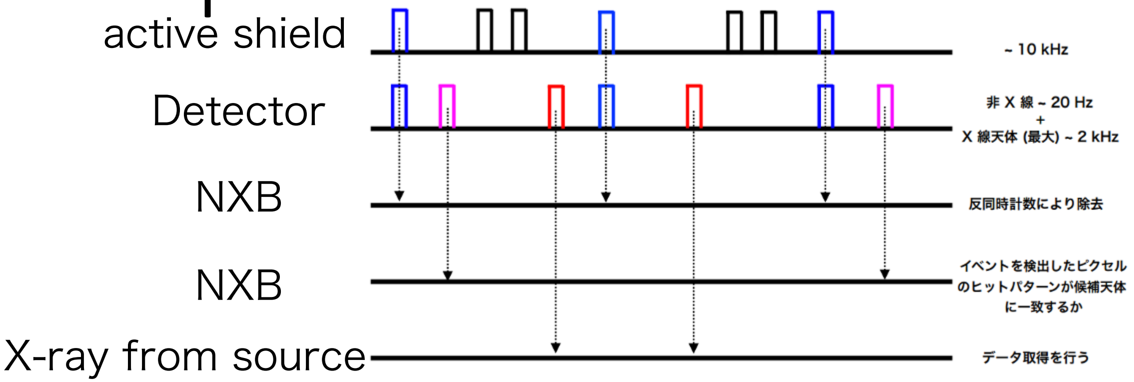


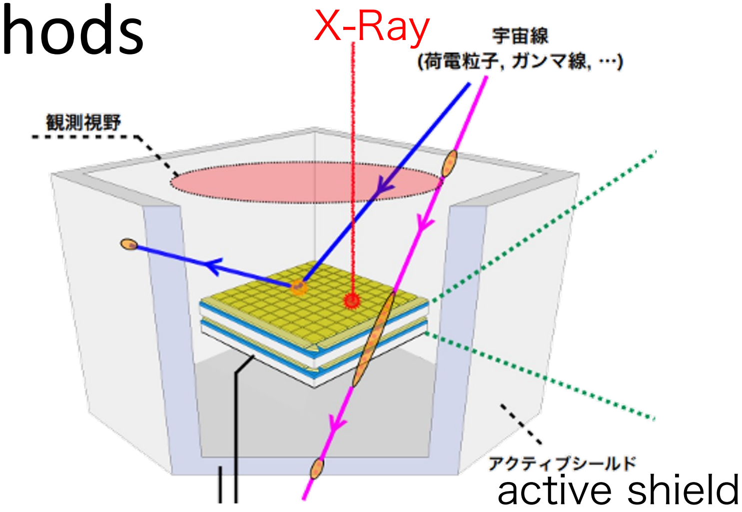
10 → Vin – Vref
01 → 2*Vin
00 → Vin+Vref

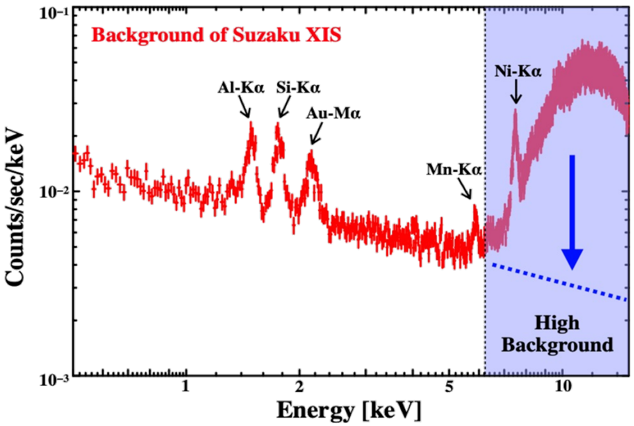
Advantages of Future satellite

1. Low background(from CXB)

▶ introduce anti-coincidence methods





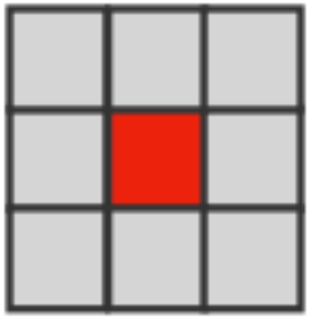


アクティブシールドは10 kHzで反応
時間分解能10 usが必要

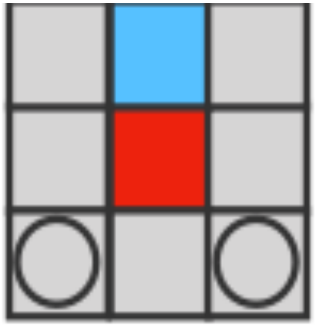
最終的にこの程度まで低減

Pixel pattern

single pixel event

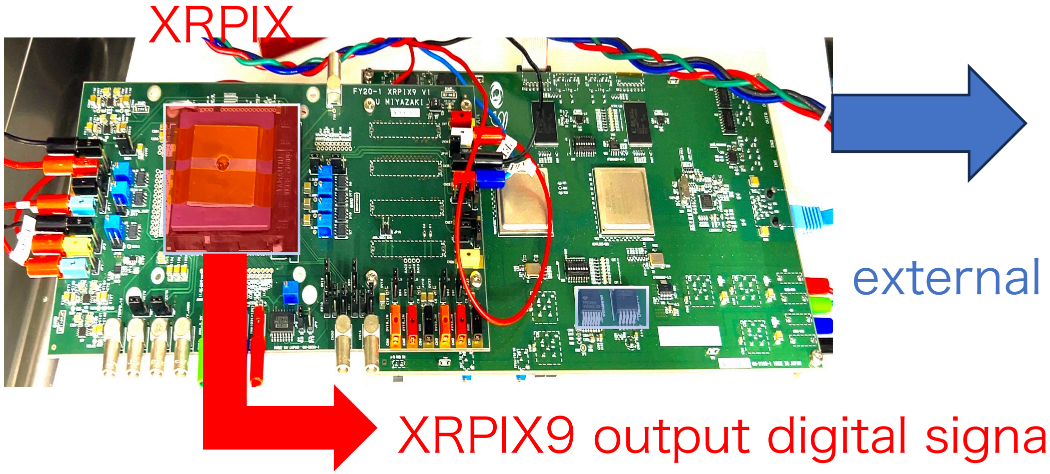


double pixel event



4 pixel event

Purpose of degitalization



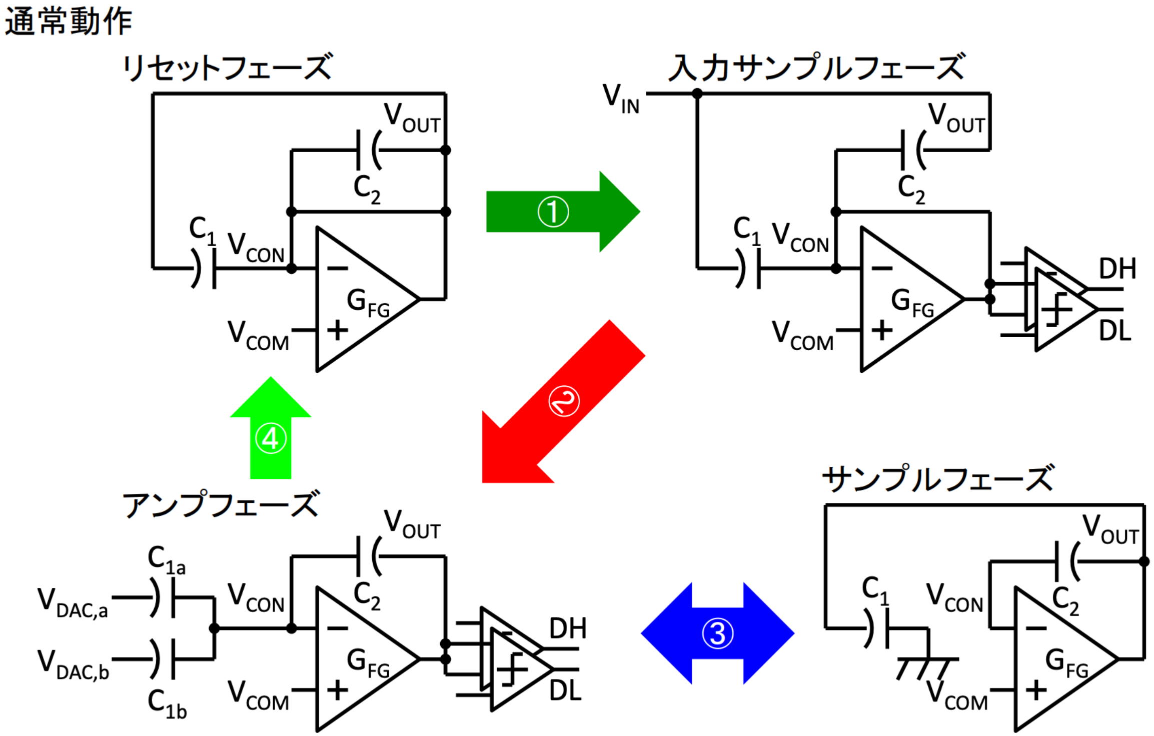
XRPIX

previous version

external ADC

XRPIX9 output digital signals

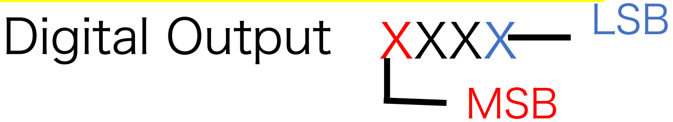
How to work ADC

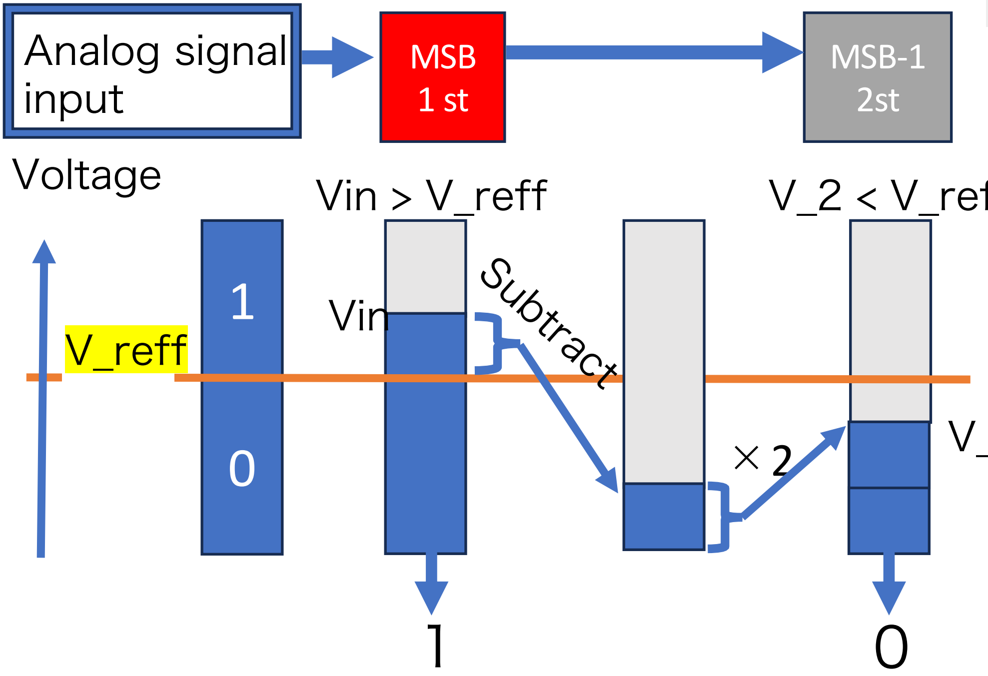


About ADC

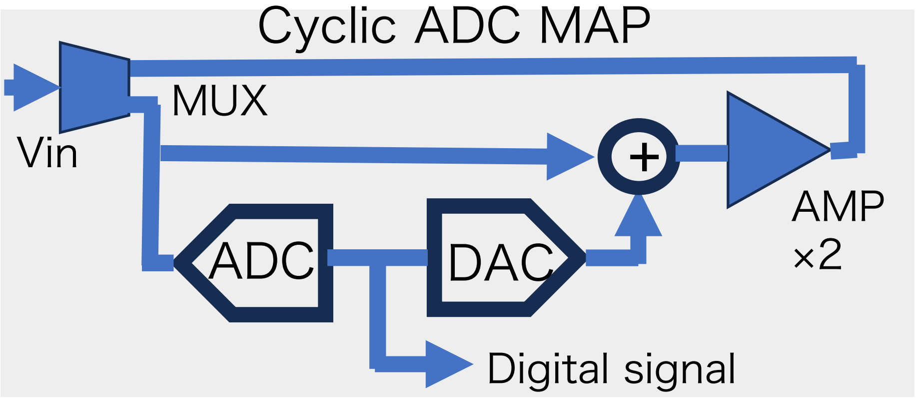
▶ How to work cyclic ADC

Process of AD Conversion





Cyclic ADC MAP



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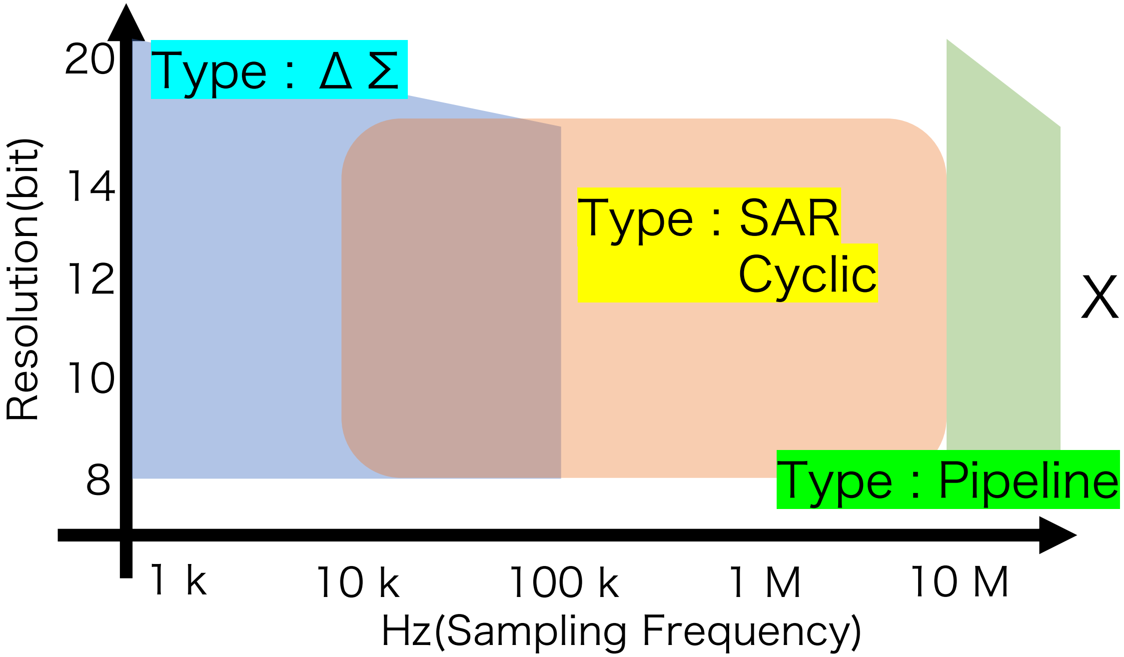
compare V_2 with V_reff
If V_2 < V_reff → = MSB-1

3. Repeat process for 14times
→14 bit Cyclic ADC

Purpose of Digitalization

X-rays create electron pairs
電圧に変換される
しかし、衛星搭載を目指していることや
スペクトル解析などデータ解析にはデジタル化が必須となる→ADCの利用



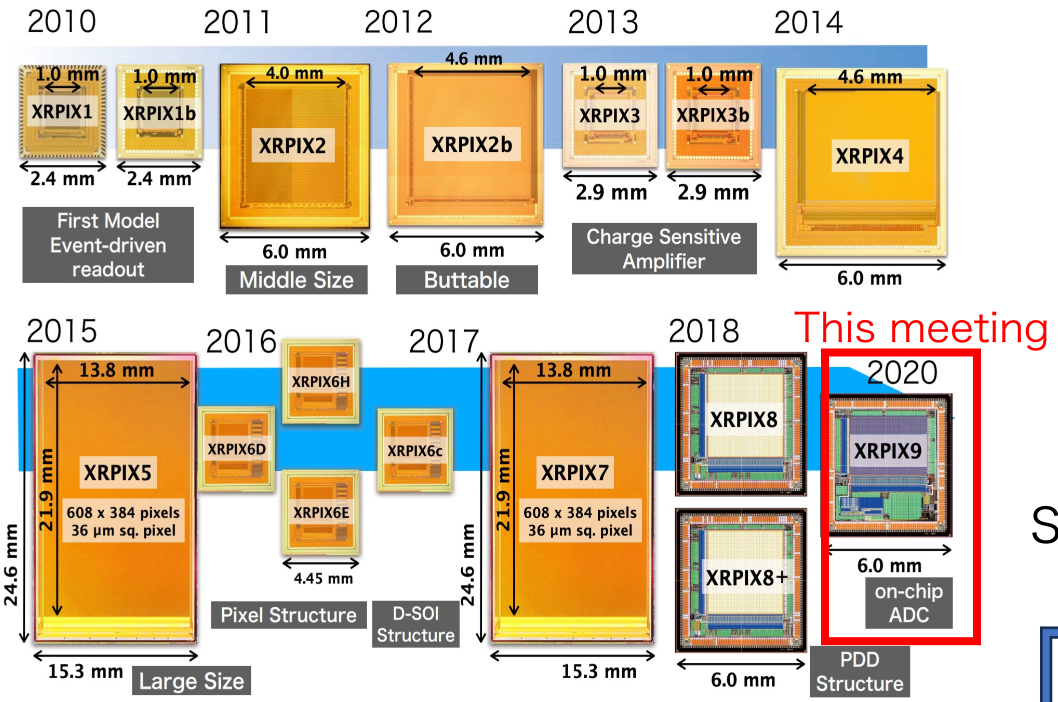
省電力、高速、高分解能

XRPIX9ではCyclic ADCを採用

Cyclic ADC搭載

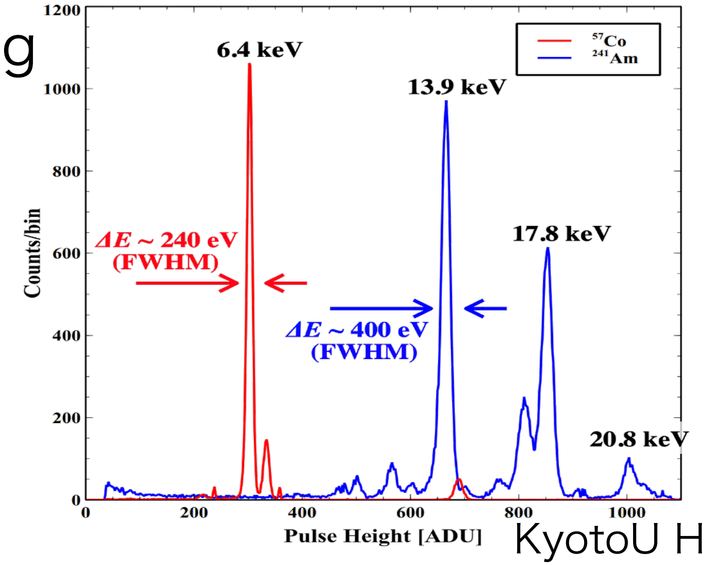
XRPIX's current status

We've been researching and developing



From Ayaki Takeda

XRPIX6E
FWHM~240 eV at 6.4 keV



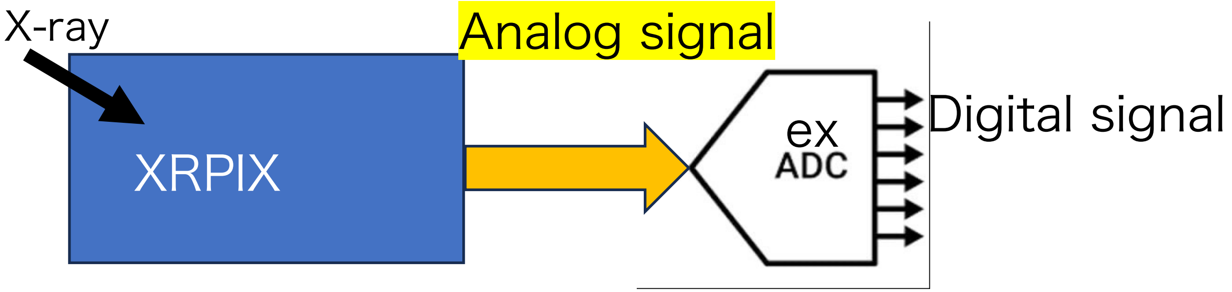
KyotoU Harada

Sensor : Good spectral performance

Future task : Digitalization

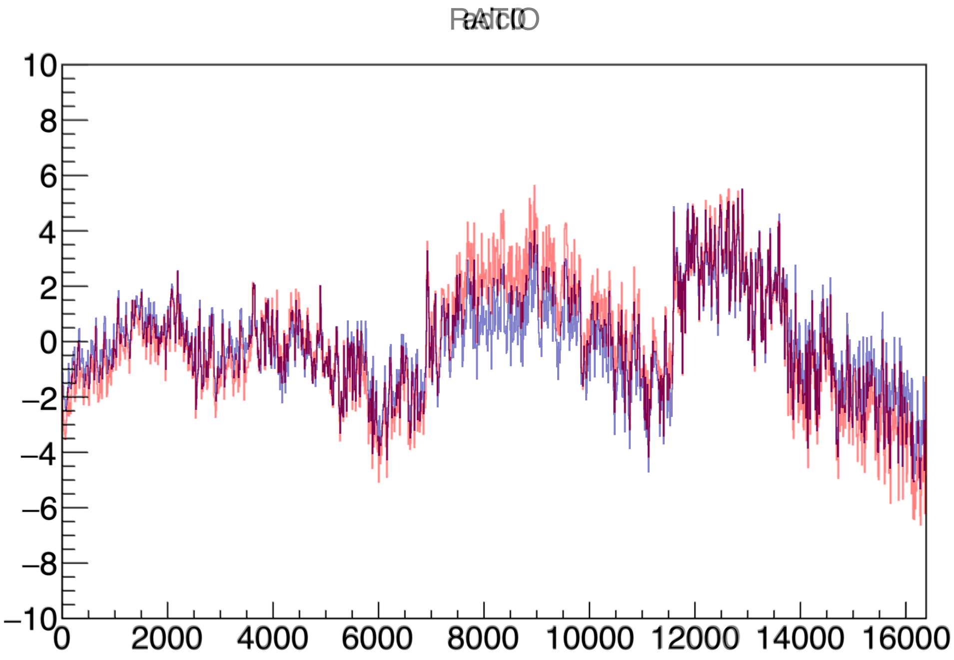
Purpose of on-chip ADC

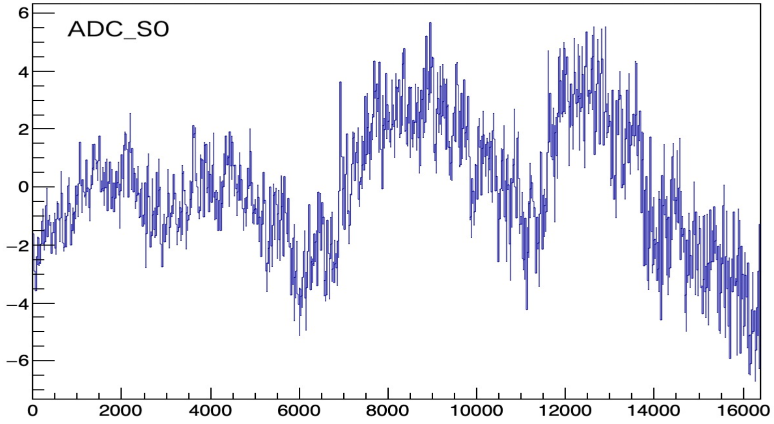
Previous XRPIX： Converts analog signals with external ADC

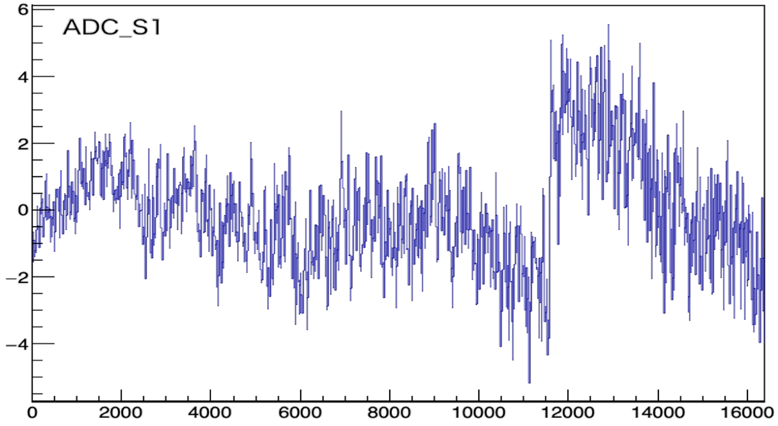


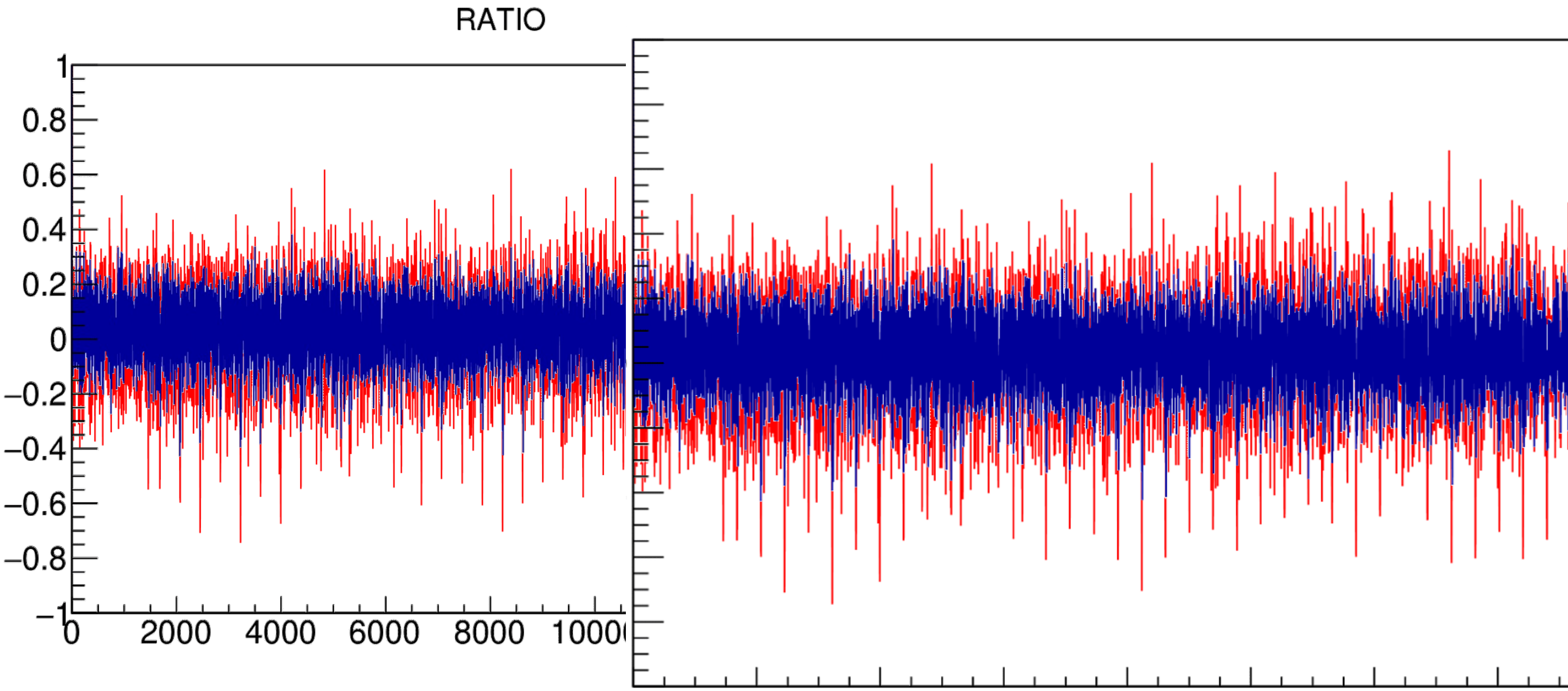
Problem : X-ray satellites require a large imaging area in a limited space

ADC mounted on XRPIX for compactness(on-chip)

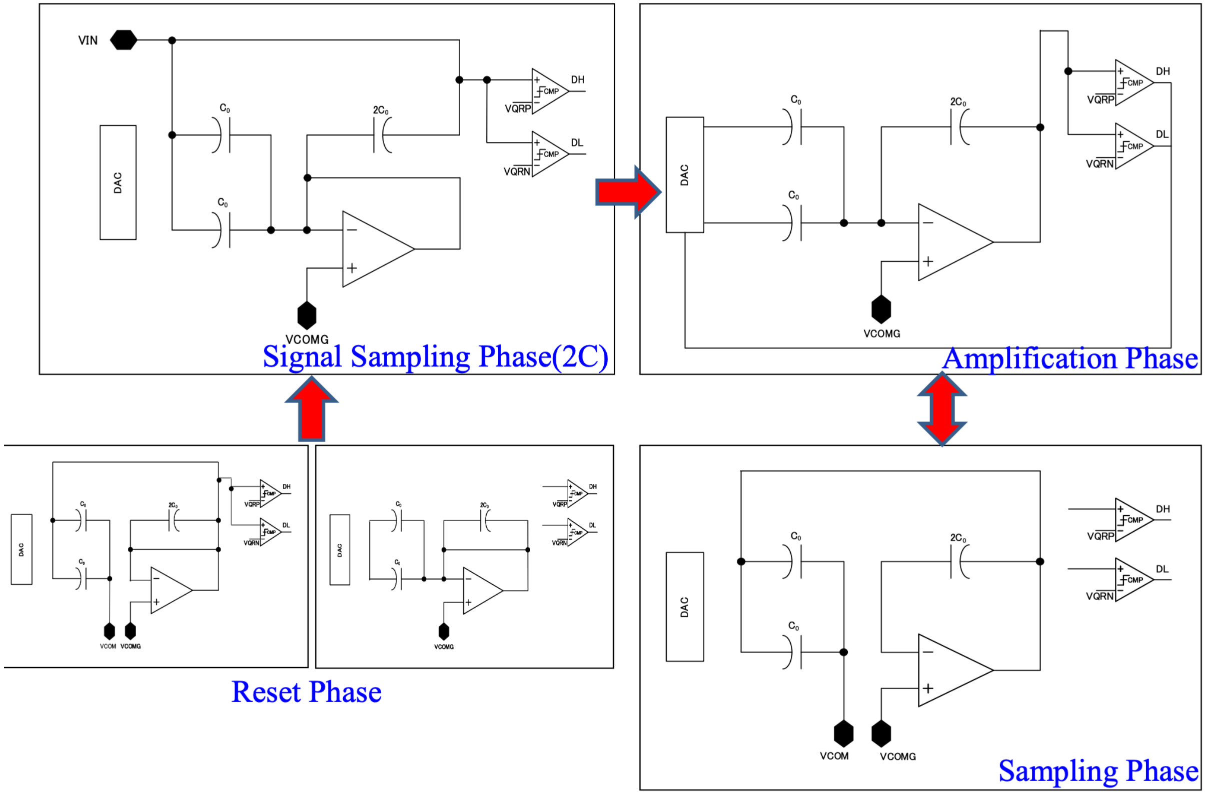

RATIO
10
8
6
4
2
0
−2
−4
−6
−8
−10
0
2000
4000
6000
8000
10000
12000
14000
16000


ADC_S0
6
4
2
0
−2
−4
−6
0
2000
4000
6000
8000
10000
12000
14000
16000


ADC_S1
6
4
2
0
−2
−4
0
2000
4000
6000
8000
10000
12000
14000
16000


RATIO
1
0.8
0.6
0.4
0.2
0
−0.2
−0.4
−0.6
−0.8
−1
0
2000
4000
6000
8000

ADC readout process


Signal Sampling Phase(2C)

Amplification Phase

Reset Phase

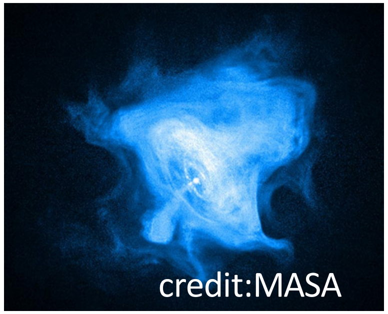
Sampling Phase

X-ray astronomy

We can study high-energy physics through X-ray observations

Example : High energy celestial objects

Neutron Stars

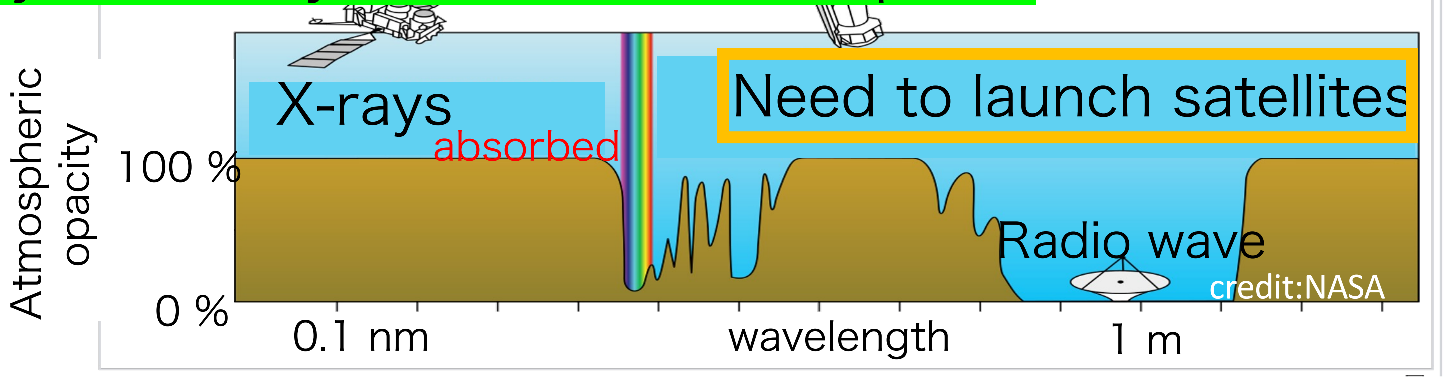


credit:MASA

Vicinity of Black Holes

credit:NASA

X-rays are fairly absorbed in atmosphere

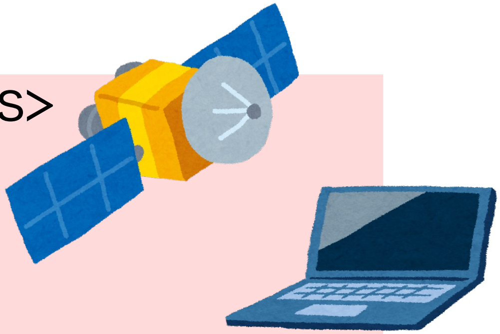


Need to launch satellites

credit:NASA

Purpose of Digitalization

X-ray signals are Analog



<Future Objectives>

Install on Satellite

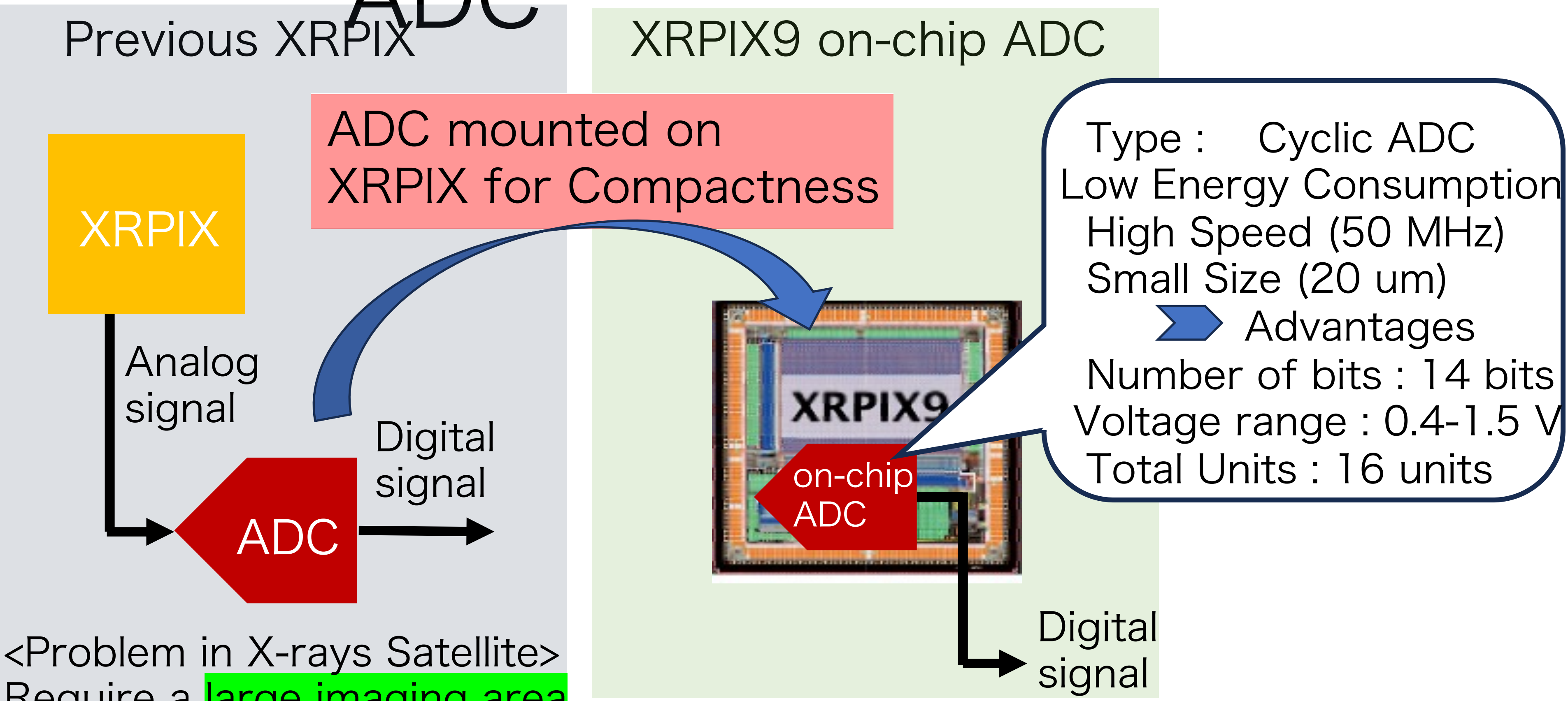
X-ray spectrum Analysis etc…

Digitalization is necessary for these objectives
Also , ADC is necessary for Digitalization

Digital-Analog Converter

NEXT : About ADC & How does it work ?

Purpose of on-chip-ADC



Previous XRPIX

XRPIX9 on-chip ADC

ADC mounted on XRPIX for Compactness

Type : Cyclic ADC
Low Energy Consumption
High Speed (50 MHz)
Small Size (20 um)
➔ Advantages
Number of bits : 14 bits
Voltage range : 0.4-1.5 V
Total Units : 16 units

<Problem in X-rays Satellite>
Require a large imaging area in a Limited space

Goal : Evaluate on-chip ADC

Future X-Ray satellite and detector

<Concepts of future X-ray satellite>

Energy range : 0.5 - 80 keV (Wide band)

Observation targets : Black hole,Neutron star…

Low non-X-ray background above 10 keV

Good time resolution ~ a few us

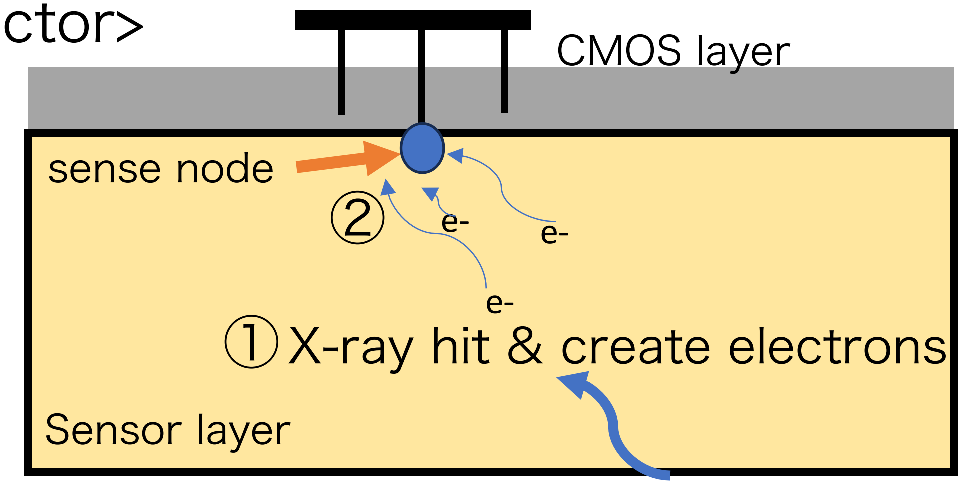

image:FORCE

<How to work CMOS X-ray detector>

1.X-rays create electrons

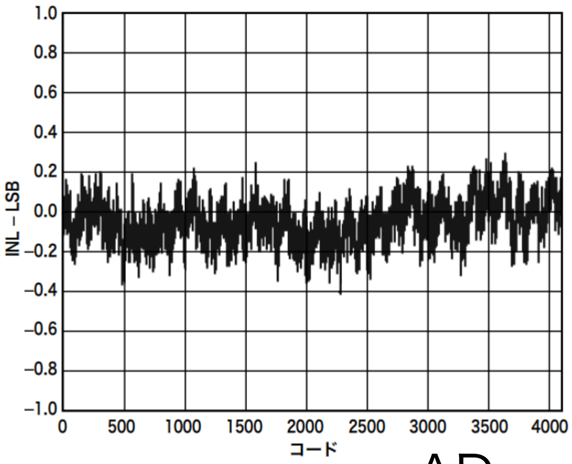
2.Sense nodes catch electrons

This talk theme
Future detector XRPIX

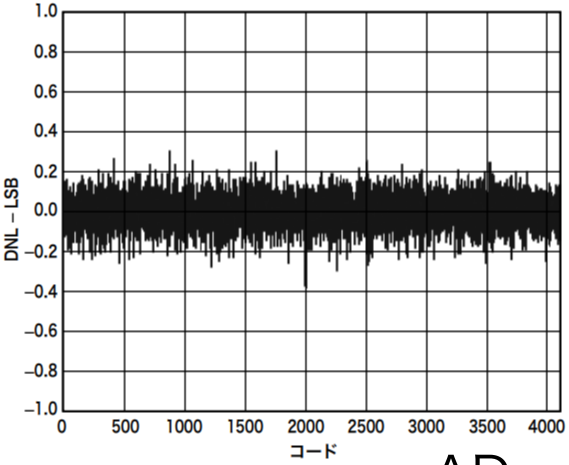


external ADC's INL & DNL

ADC : 12 bits

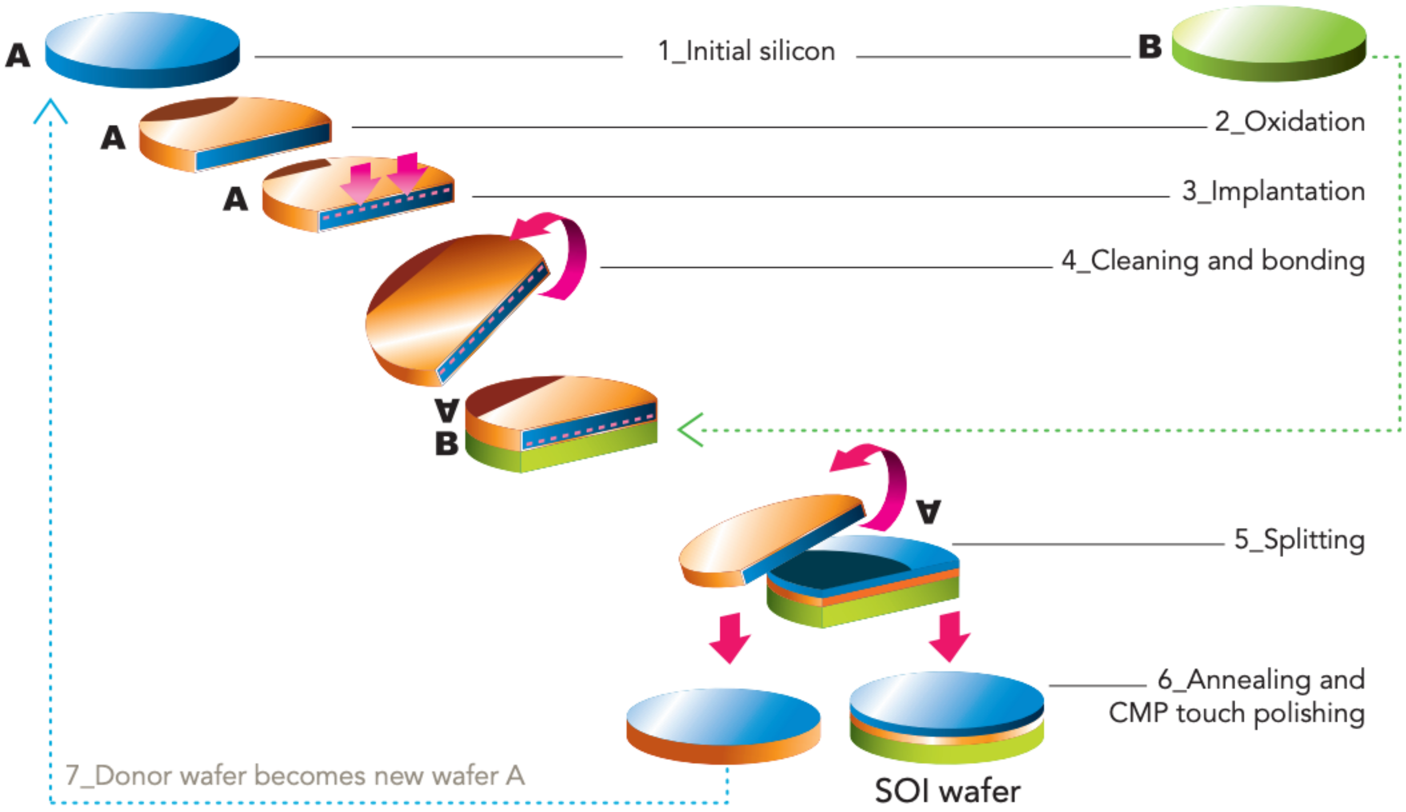


AD output



AD output

How to make SOI wafer



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