X-ray Trigger Telescope (UBAT) of Ultra-Fast Flash Observatory (UFFO) Pathfinder for localizing of Gamma-Ray Bursts

Min-Bin Kim

Center for Underground Physics, Institute of Basic Science

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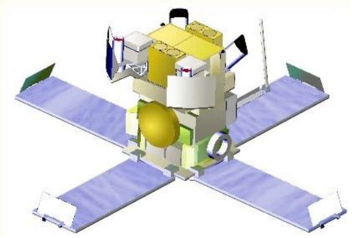
Introduction: Motivation - Gamma Ray Burst

What is Gamma Ray Burst (GRB) ?

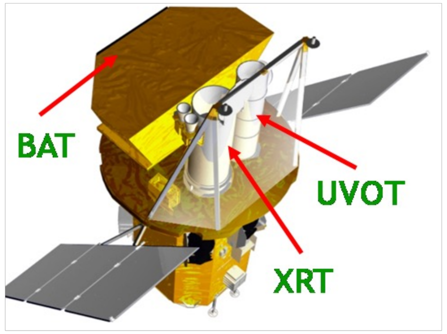
- The most extreme explosion in the universe since the Big Bang
- The brightest phenomena in the universe, emitting ~10^{51} erg energy corresponding to "BILLION YEARS OF SUN RADIATION"
- Flash events lasting seconds ~ minutes,
- Δt ~ msec
- Happening every day: a few / day
- Its origin & mechanism: still unknown yet

Introduction: History of GRB Astrophysics

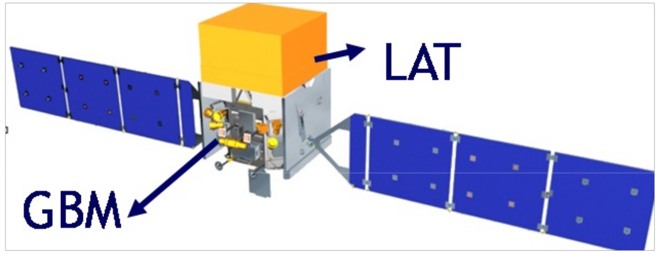
BATSE (1991)
(Burst and Transient Source Experiment)



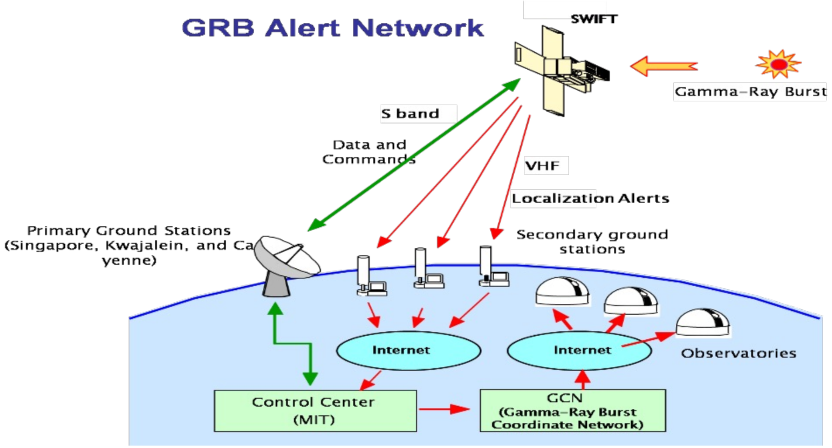
HETE-2 (2000)
(High Energy Transient Explorer-2)



SWIFT (2004)
NASA's MEDEX mission
GRB dedicated mission

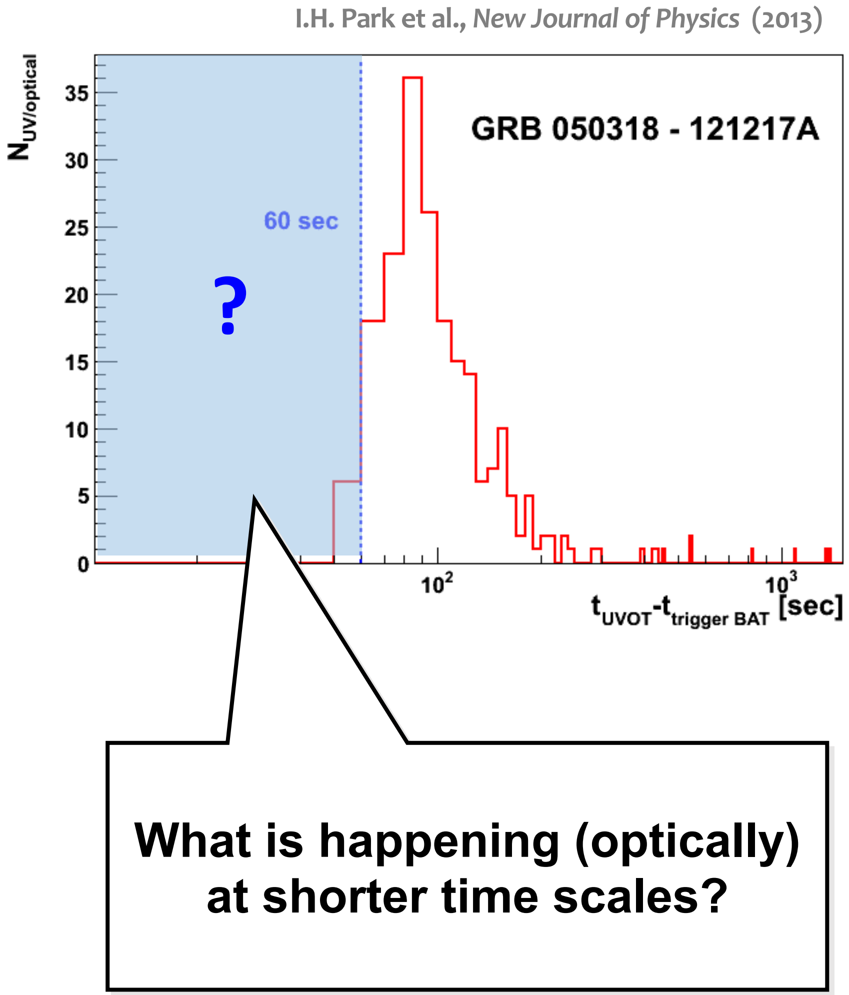


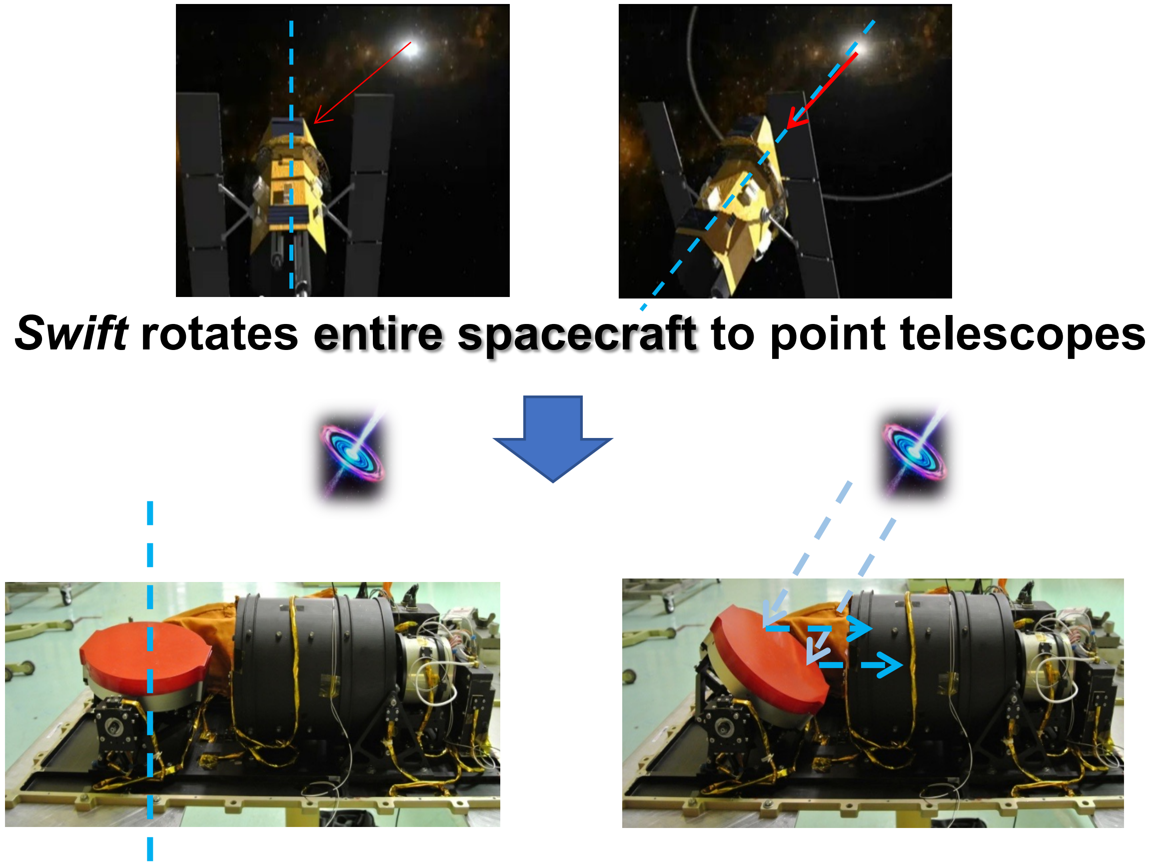
Fermi Gamma-ray Space Telescope (2008)



X-ray missions (BeppoSAX, Integral, MAXI, …), ground telescopes, as well, SVOM, Janus … in near future

Introduction: Present Limit & our New Approach





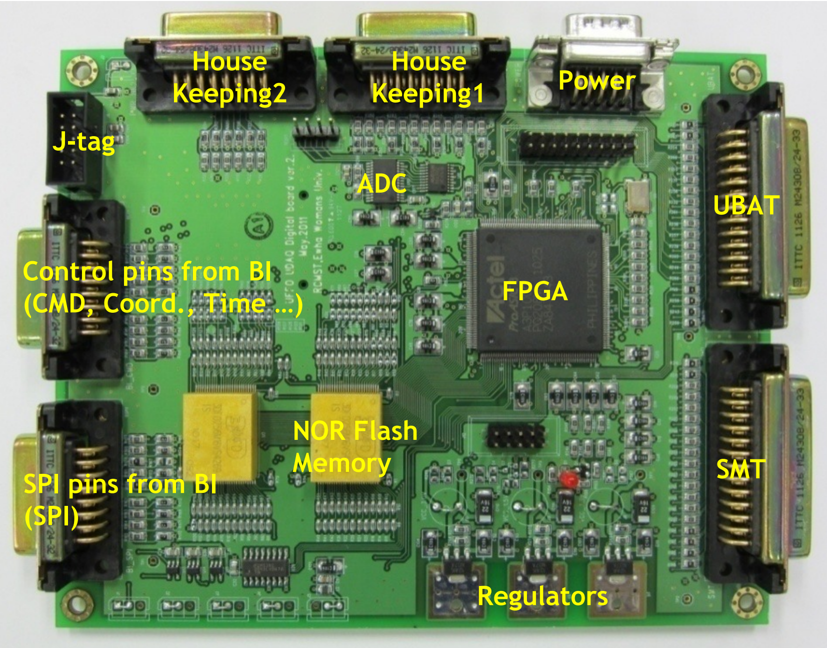
Swift rotates entire spacecraft to point telescopes

We move the optical path with fast slewing mirror system, not the spacecraft

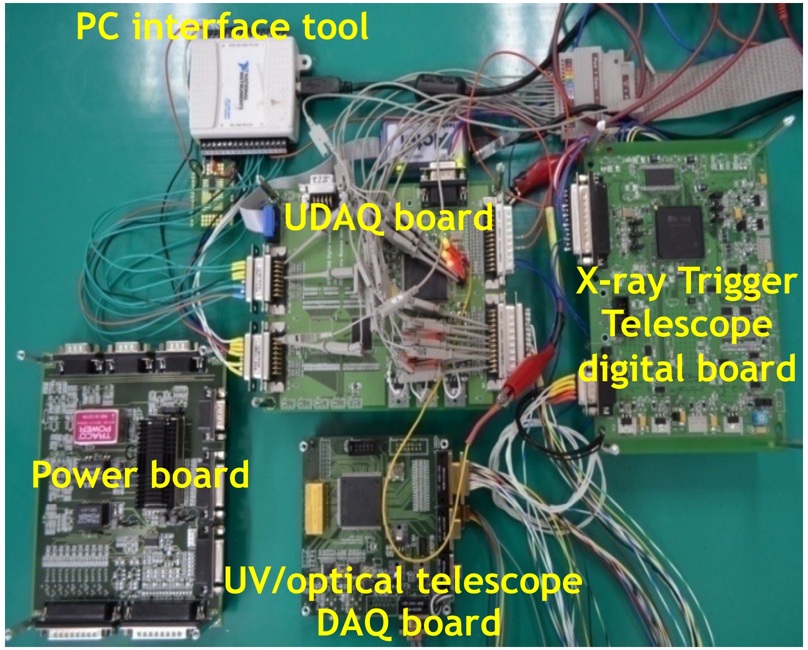
→ **much faster**

Introduction: Present Limit & our New Approach

< UFFO-pathfinder DAQ board - Top view >



< Interface test boards >



Readout, Trigger, DAQ of UFFO only by FPGAs

- In charge of readout/trigger/control/housekeeping/bus-interface
- Implemented into several FPGAs, no CPUs
- Trigger latency in electronics: less than 1 second

X-ray collection for trigger → 1 sec for bright GRB

Trigger calculation → 1 sec

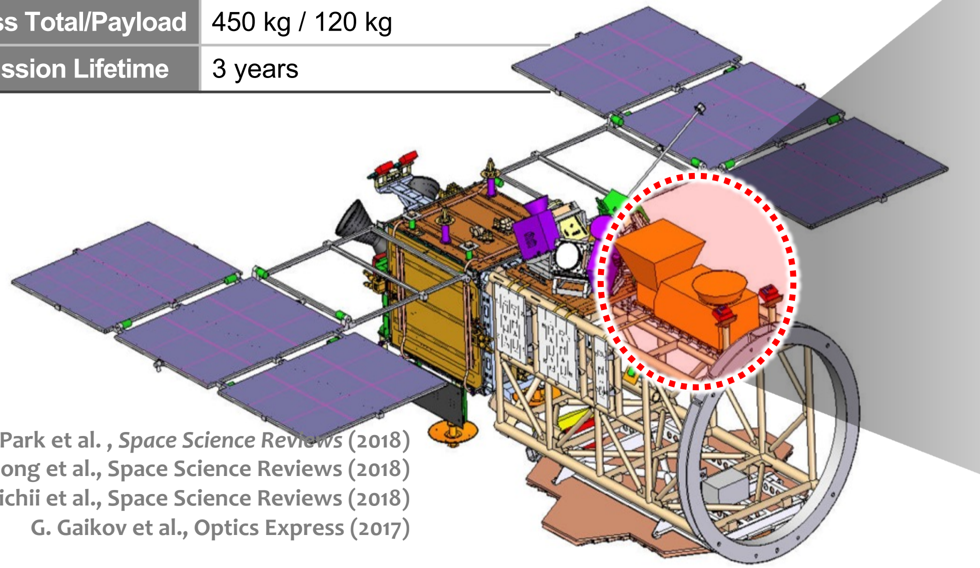
Slewing Mirror → 1 sec

Optical observation →

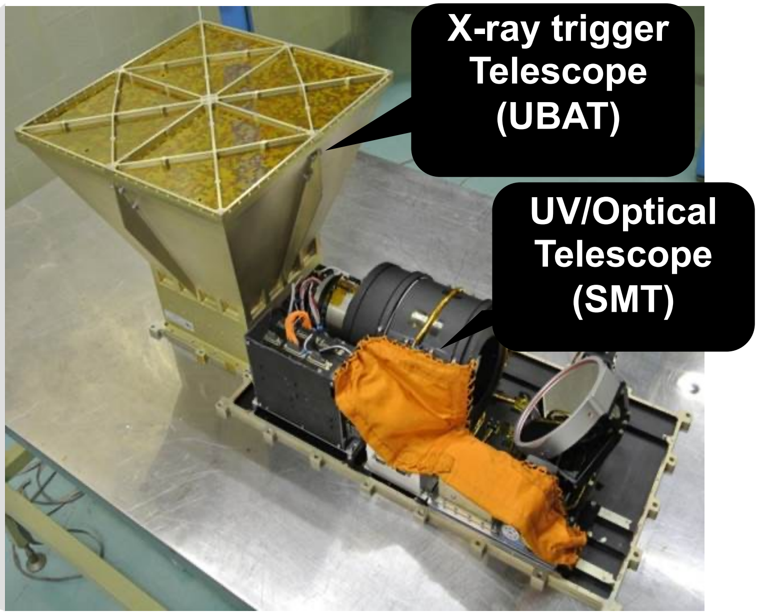
Introduction: UFFO-pathfinder

Lomonosov and UFFO-pathfinder

Launch Date	Apr.28, 2016
Orbit	SSO, Altitude of 550 ± 10 km
Mass Total/Payload	450 kg / 120 kg
Mission Lifetime	3 years



I.H. Park et al. , *Space Science Reviews* (2018)
S. Jeong et al., Space Science Reviews (2018)
V. Sadovnichii et al., Space Science Reviews (2018)
G. Gaikov et al., Optics Express (2017)

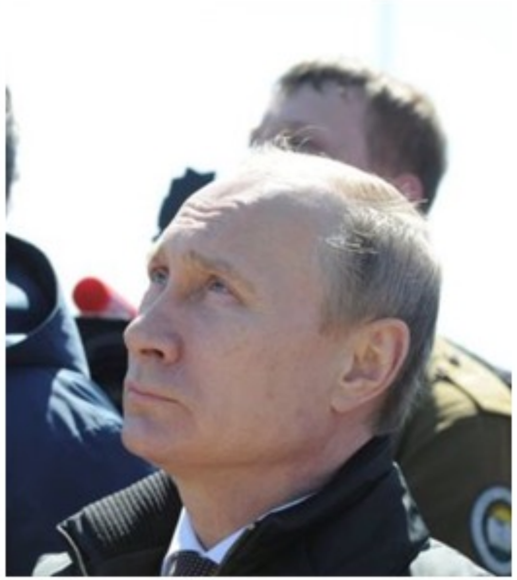


UFFO-pathfinder is made up 2 telescopes and data acquisition system (UDAQ)

1. UFFO Burst Alert & Trigger Telescope (UBAT) : X-ray detection and localization of GRB
→ **“High redshift GRBs observation”**

2. Slewing Mirror Telescope (SMT) : GRB targeting and tracking within a few seconds with slewing mirror
→ **“Early photon observation”**

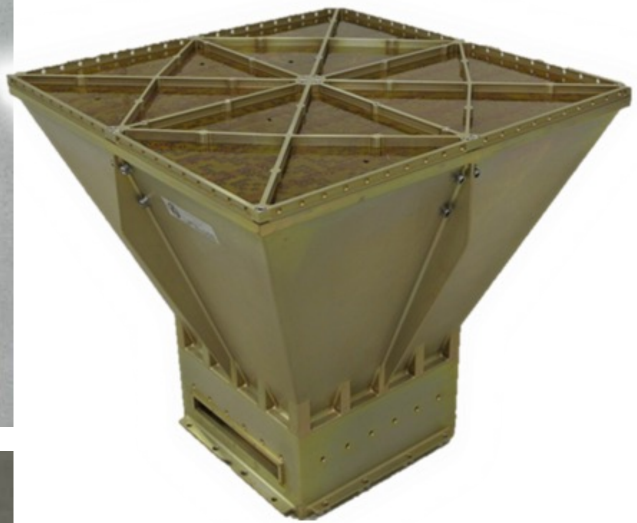
Introduction: UFFO-pathfinder

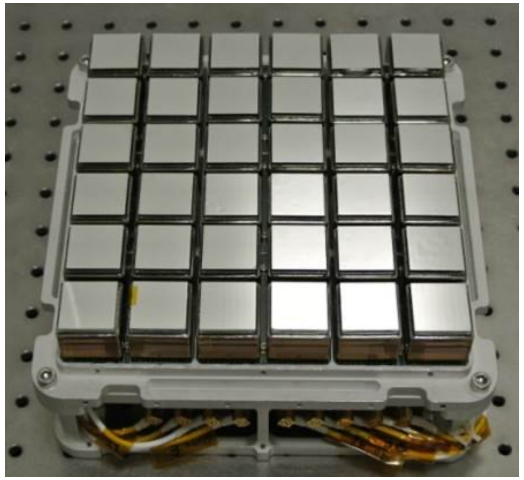


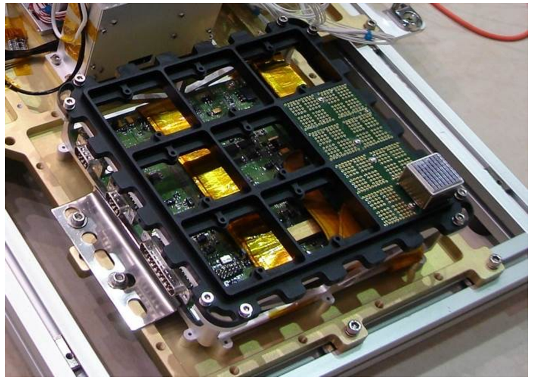
Successfully launched on Apr. 28, 2016

After launch, the satellite was calibrated for 3 months, and the detector was calibrated for 5 months, but unfortunately, before full-scale data collection, the UFFO-pathfinder operation was stopped due to satellite power issue.

UFFO Burst & Alert Trigger Telescope (UBAT)





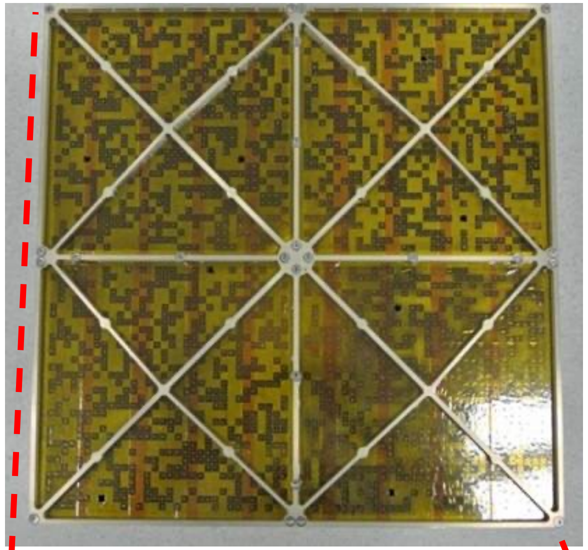


UBAT Parameter	Value
Aperture	Coded mask, random pattern, about 45% open
Field of view	1.35 sr (half – coded)
accuracy	10 arcmin
Detector energy range	5~150 keV
Detection area (Effective area)	191.1 cm^2 (161.5cm^2)
Detector element	36 × 64 pixels YSO + Multi-Anode PMT (Total 2304 pixels)
Pixel size	2.88×2.88 mm^2
Detector operation	Photon Counting

UBAT: the X-ray trigger telescope consisting of the Coded mask technique and the detector using YSO scintillation crystal & MAPMT

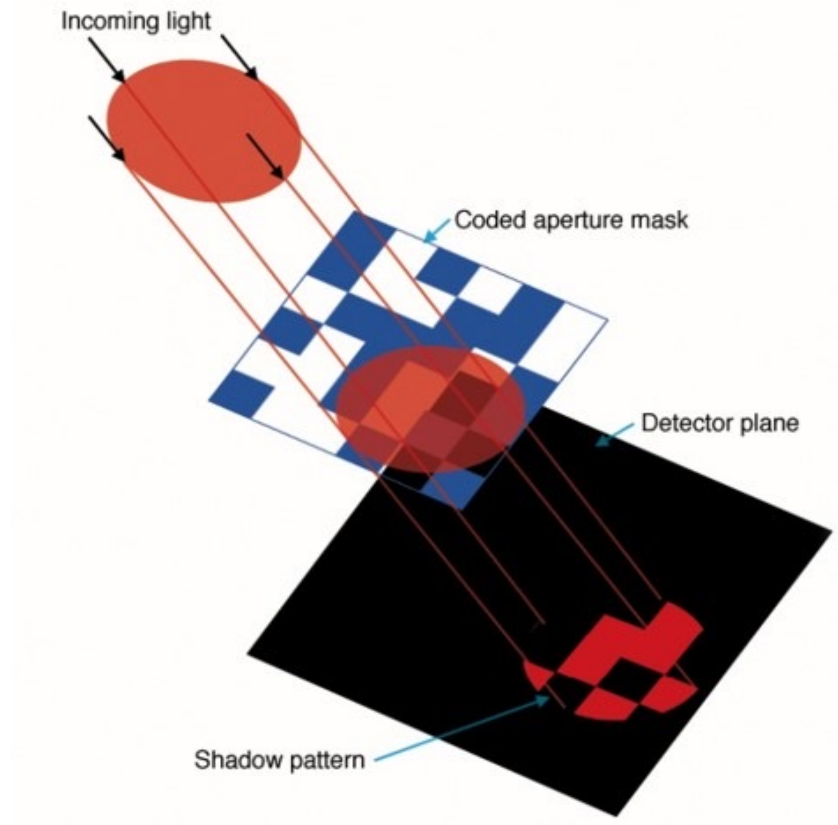
UBAT: Coded mask

Coded mask

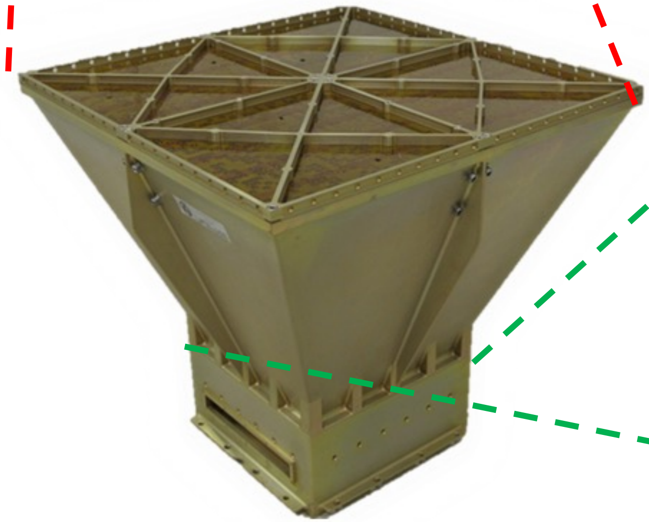


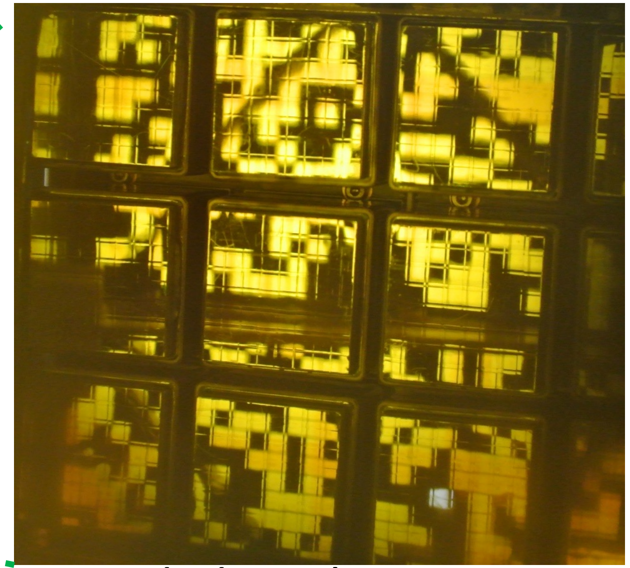
Coded mask pattern

Pixel size: $5.76 \times 5.76\ mm^2$
68×68 pixels



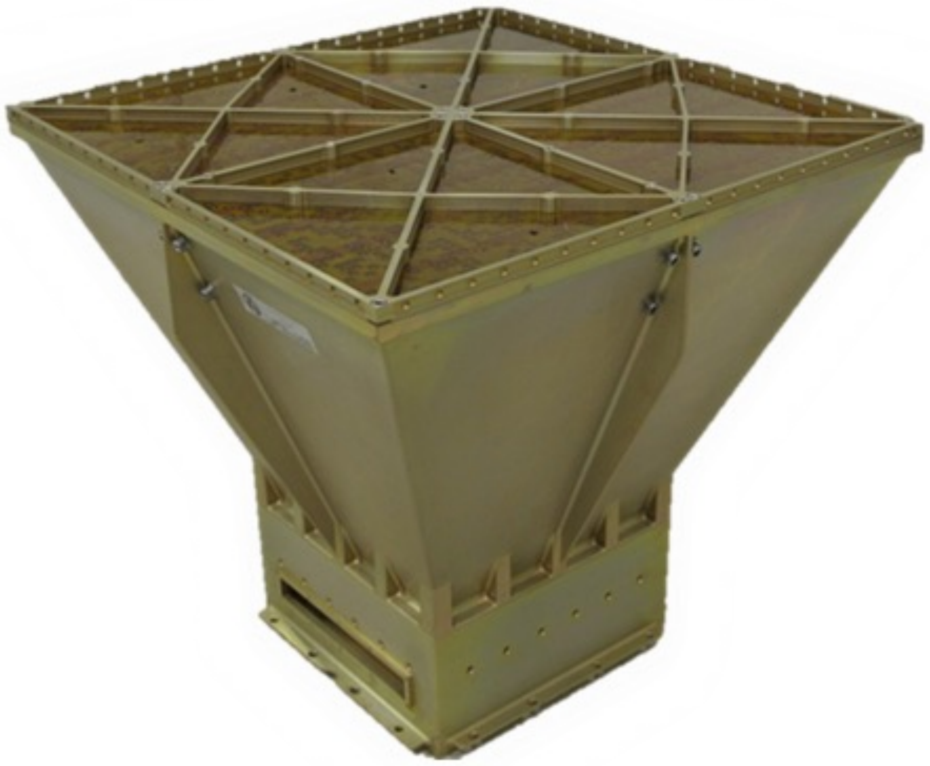
Coded mask technique

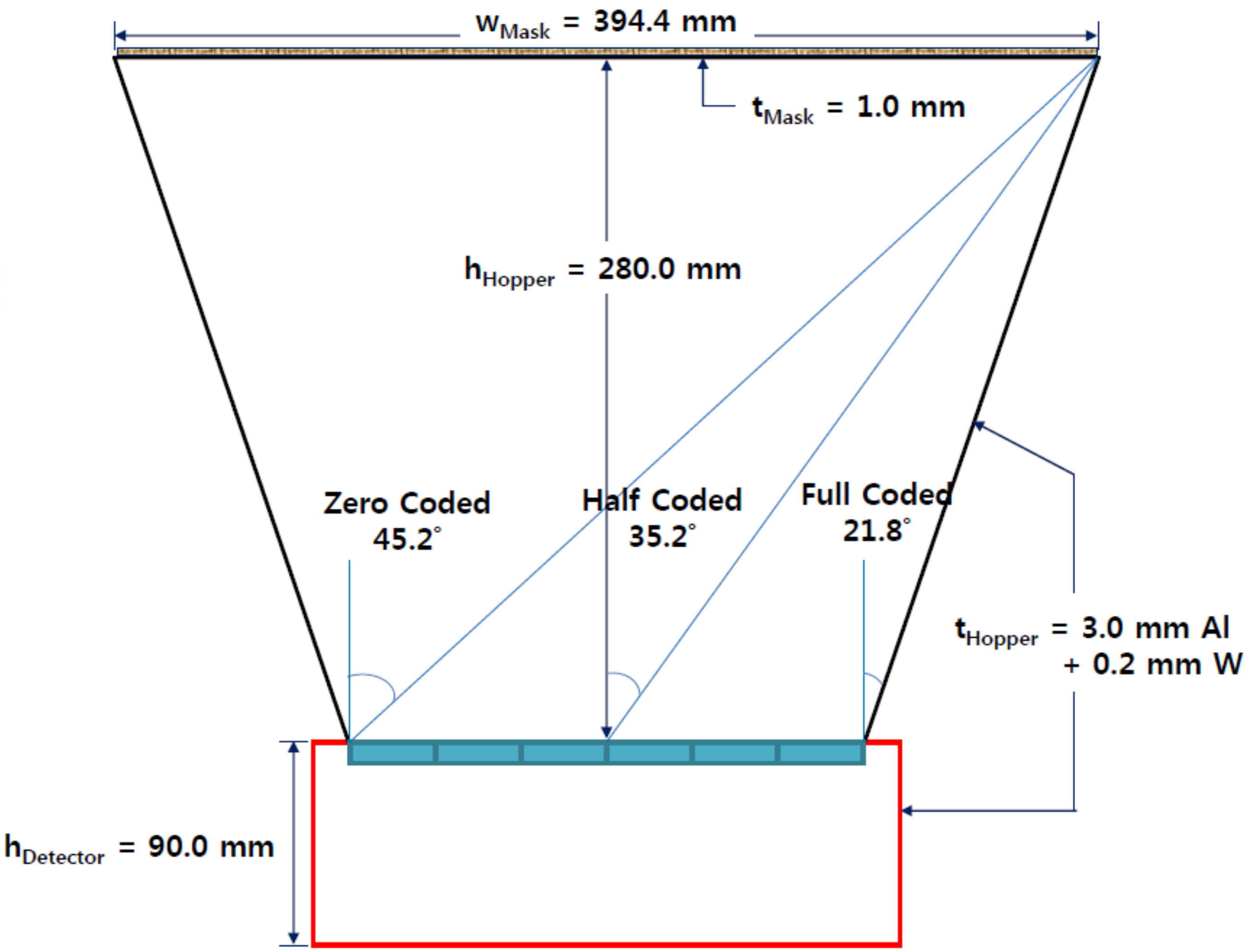




Coded mask pattern
on UBAT detector plane

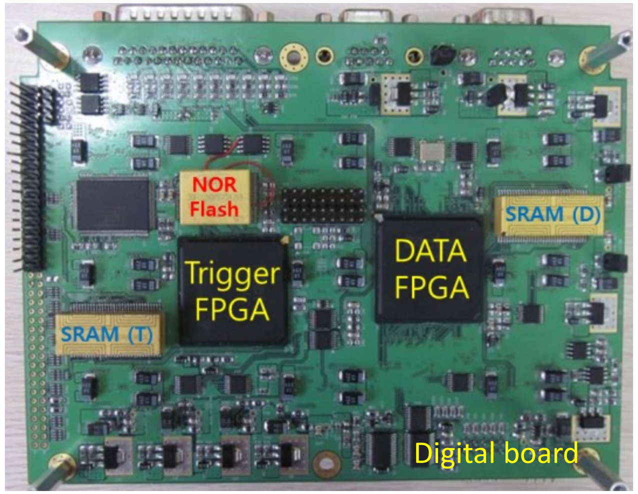
UBAT: Hopper

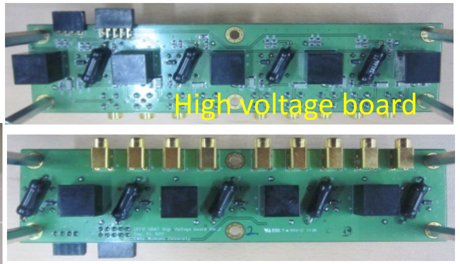


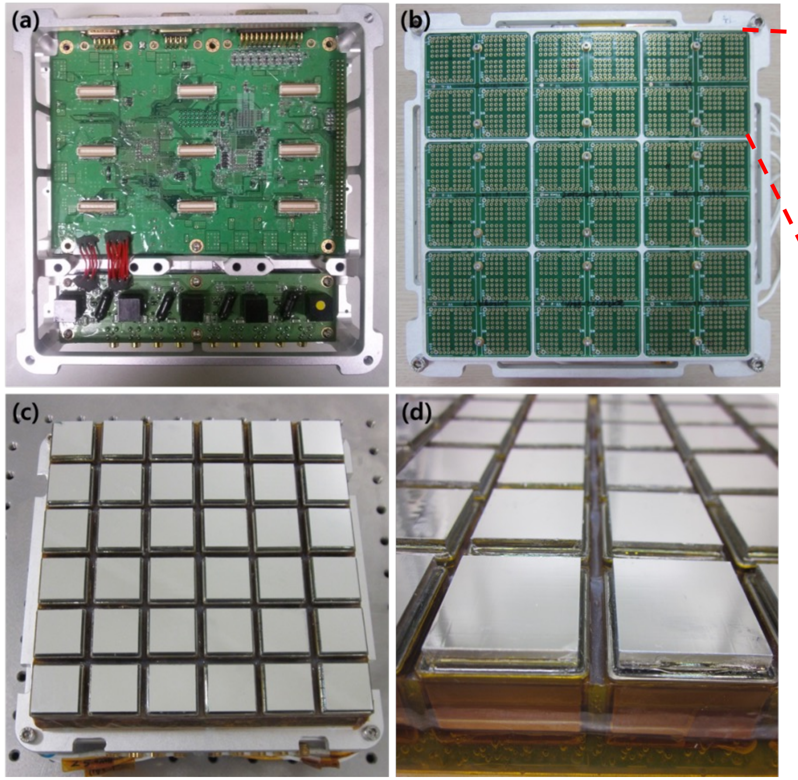


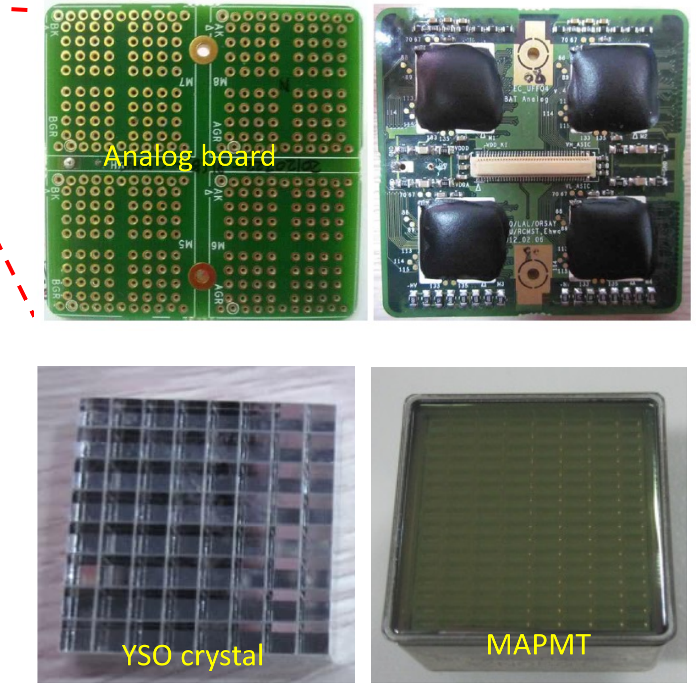
w_{Mask} = 394.4 mm
t_{Mask} = 1.0 mm
h_{Hopper} = 280.0 mm
Zero Coded 45.2°
Half Coded 35.2°
Full Coded 21.8°
t_{Hopper} = 3.0 mm Al + 0.2 mm W
$h_{Detector}$ = 90.0 mm

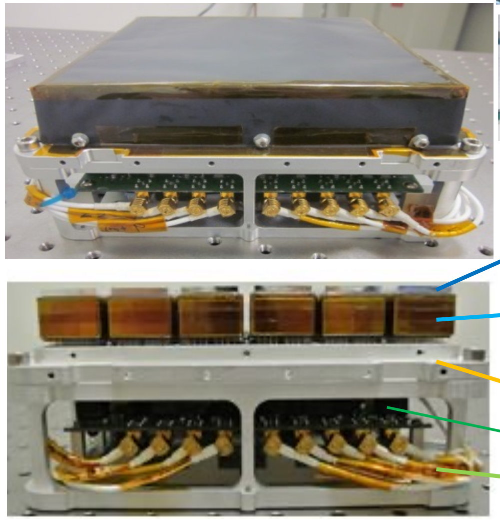
UBAT: Detector

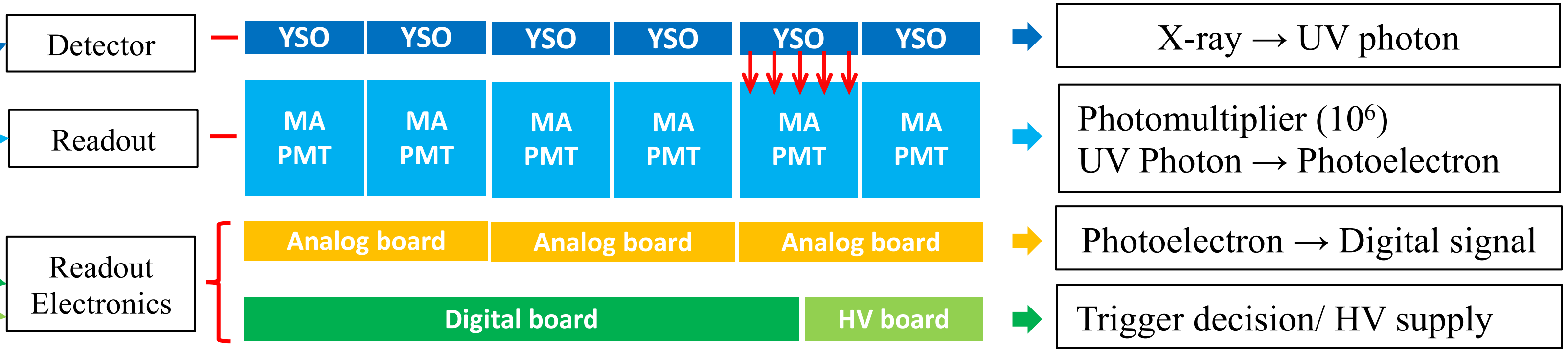












UBAT: Detector

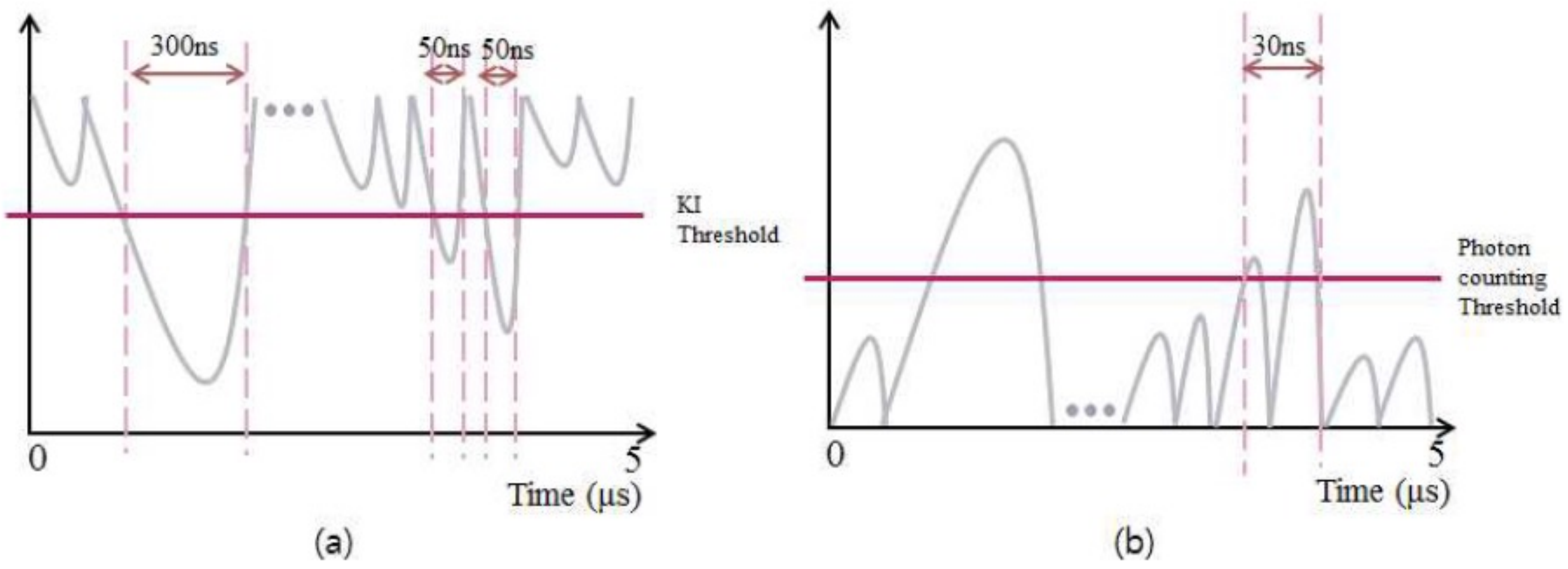
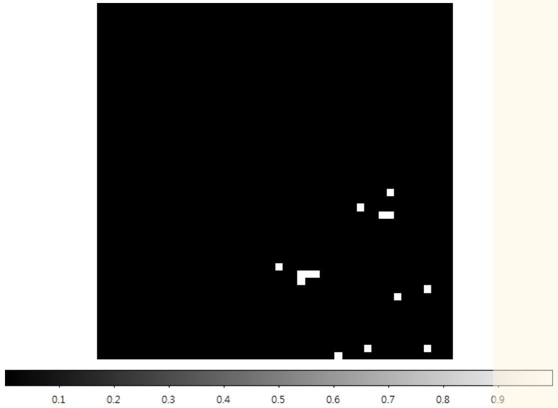
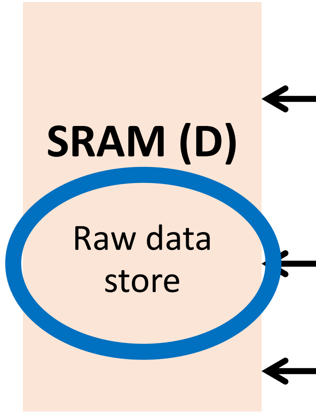


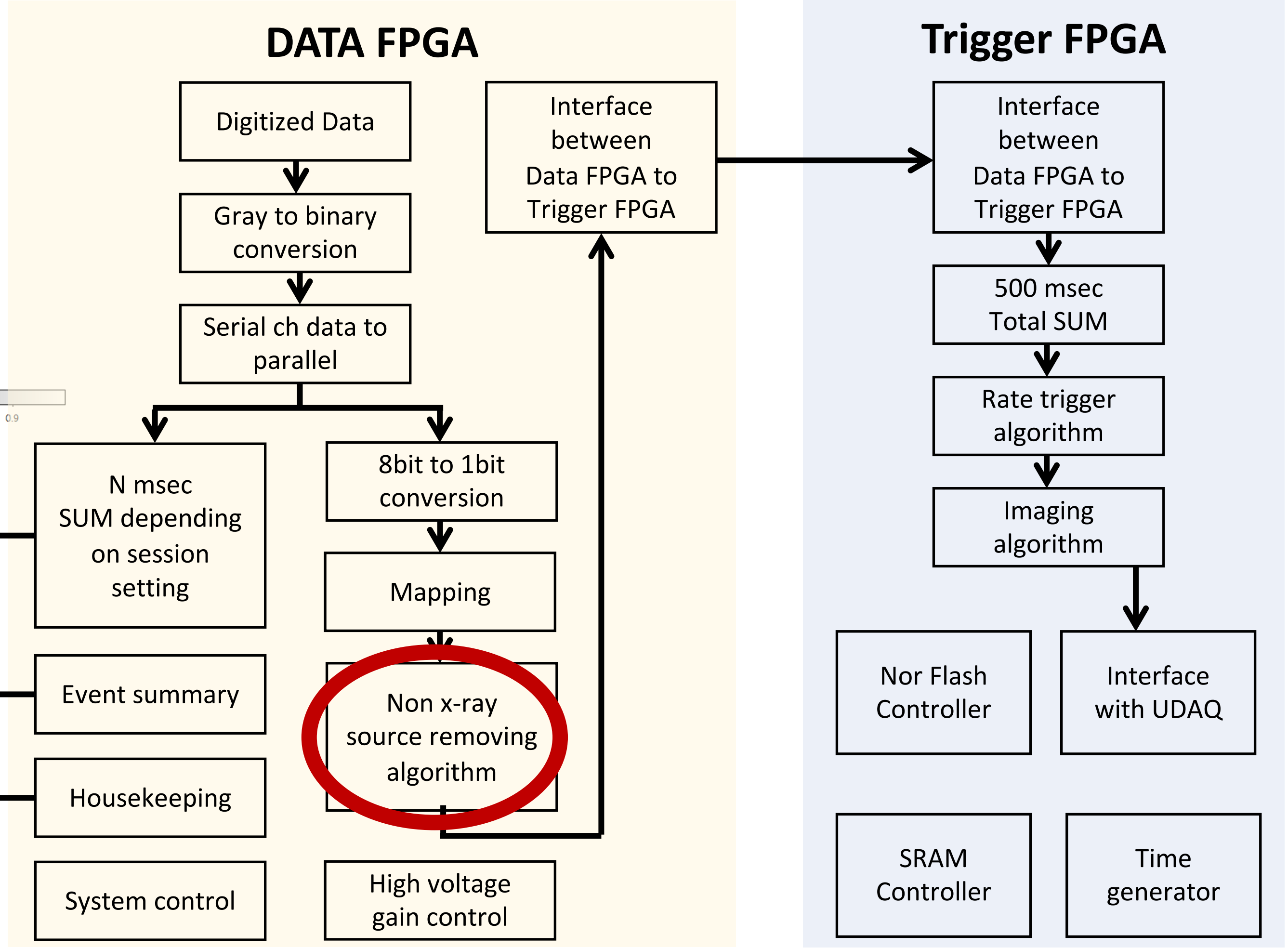
그림 12. (a) 임의의 KI 파형 (b) 임의의 Photon Counting 파형

- KI energy band sum: charge -> time
- calculation: every 50ns

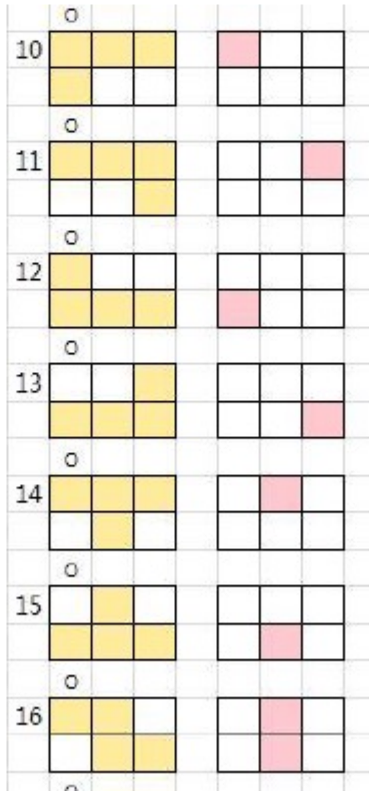
UBAT: Data Flow







Non x-ray source removing algorithm (hit-finding)



	Raw data	Apply non x-ray removing algorithm
RUN 10c	22.5 cnts/cm^2/sec	4.0 cnts/cm^2/sec
RUN 10e	20.9 cnts/cm^2/sec	4.5 cnts/cm^2/sec

Hit count was **reduced approximately 75%.**

UBAT: Data structure

Update date : Jan 22, 2014
Written by : Minbin Kim

UBAT Housekeeping (UBAT Monitoring)

Photon Counting (18342 bit)	KI (2592 bit)		HK (256bit)	

Data structure of 1 frame

255.000000 255.000000 255.000000 255.000000	Frame header	32 bit
15.000000 173.000000	HV9_Monitoring	16 bit
15.000000 155.000000	HV1_Monitoring	16 bit
1.000000 49.000000	1.5V_Voltage3	16 bit
15.000000 177.000000	HV2_Monitoring	16 bit
1.000000 48.000000	1.5V_Voltage2	16 bit
15.000000 172.000000	HV3_Monitoring	16 bit
1.000000 47.000000	1.5V_Voltage1	16 bit
15.000000 178.000000	HV4_Monitoring	16 bit
2.000000 96.000000	3V_Voltage1	16 bit
15.000000 180.000000	HV5_Monitoring	16 bit
2.000000 94.000000	3V_Voltage2	16 bit
15.000000 172.000000	HV6_Monitoring	16 bit
2.000000 100.000000	3V_Voltage3	16 bit
15.000000 169.000000	HV7_Monitoring	16 bit
1.000000 195.000000	Temperature	16 bit
0.000000 74.000000	HV8_Monitoring	16 bit
255.000000 255.000000 255.000000 255.000000	Frame header	32 bit

* Housekeeping data is just an example.

- UBAT House keeping information

1. High voltage monitoring

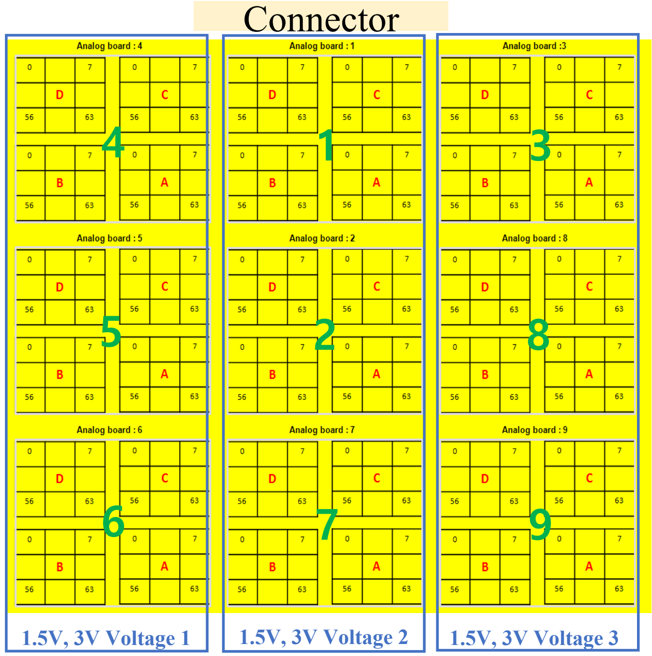
- High voltage board has 9 emco chips.
- HV1_Monitoring ~ HV9_Monitoring : Monitoring voltage of each emco chips.

2. Input voltage of the Analog board

- ASICs of Analog board need 2 input voltage, 1.5V and 3V.
- Following the Fig.1, there are 3 groups.
- Power input lines are divided into 3 parts in the UBAT Digital board.
- The first group including the Analog board No.4,5,6 is named the Voltage1.
- The second group including the Analog board No.1,2,7 is named the Voltage2.
- The third group including the Analog board No.3,8 and 9 is named the Voltage3.

3. Temperature monitoring

- UBAT Digital board has 1 temperature sensor.



<Fig 1. Input power division of Analog board. >

✓ **Data Analysis method**

1. Read the data
ex) 15.000000
173.000000

2. Convert the decimal to the binary
00001111
10101101

3. Combine the 2 values.
0000111110101101

4. Convert the binary to the decimal
4013

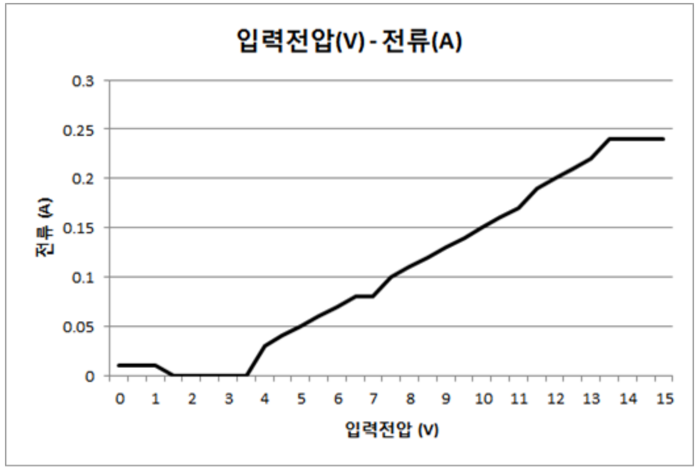
UBAT: Data structure

UBAT Frame and Session Default

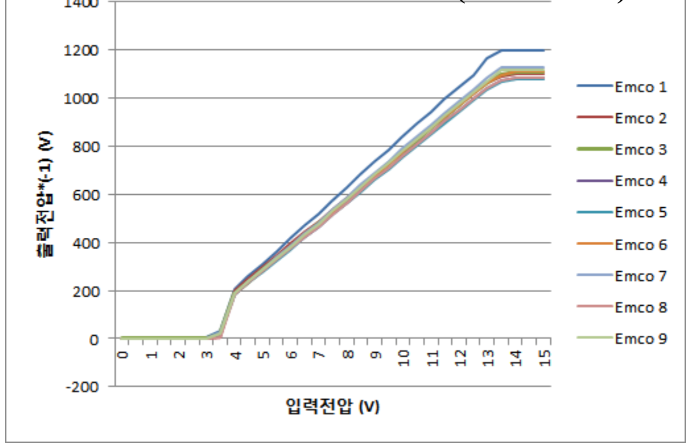
Session No.	Trigger	Exposure time /1 frame	# of frame	Duration time
0	Before imaging Trigger	100ms	200	20s
1	After imaging Trigger	100ms	300	30s
2		500ms	100	50s
3		500ms	50	25s
4		500ms	50	25s
Total			**700**	**150s**

High voltage supply board test results

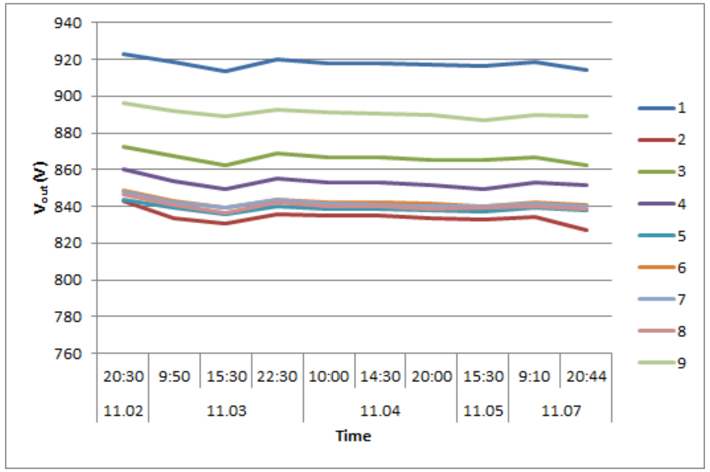
- 입력전압변화에 따른 전류변화



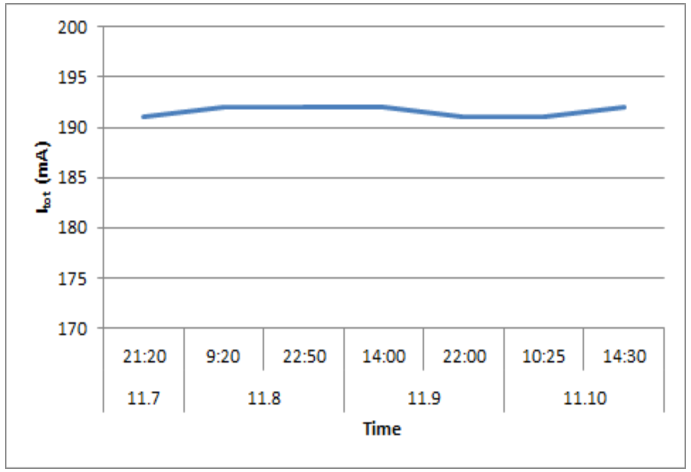
- 입력전압변화에 고전압 출력전압변화 (9개의 출력)



- 장기간 테스트 (5일간 고전압 출력전압변화)



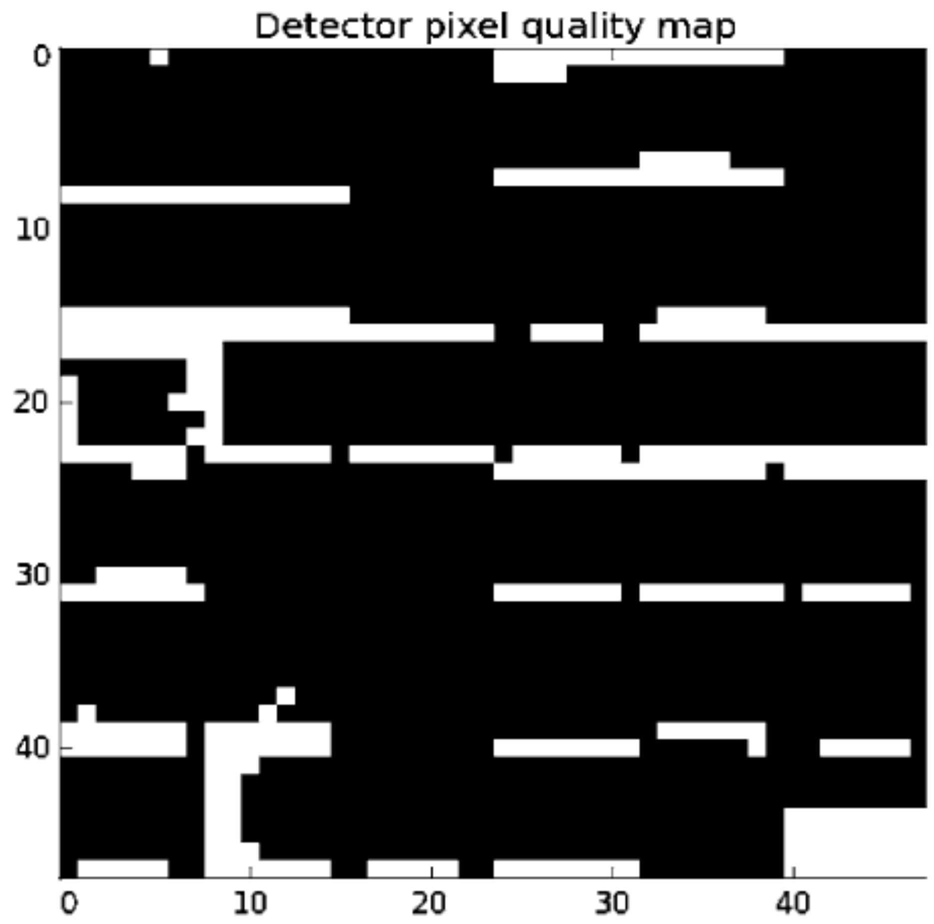
- 장기간 테스트 (3일간 전류변화)



- ✓ Available input voltage value: 0~15V
- ✓ Input voltage to high voltage supply board of UFFO: 12V
- ✓ Output voltage of high voltage supply board: about 960V
- ✓ 9 output voltage have maximum 10% difference
- ✓ Long-term test results: both output voltage and current are stable

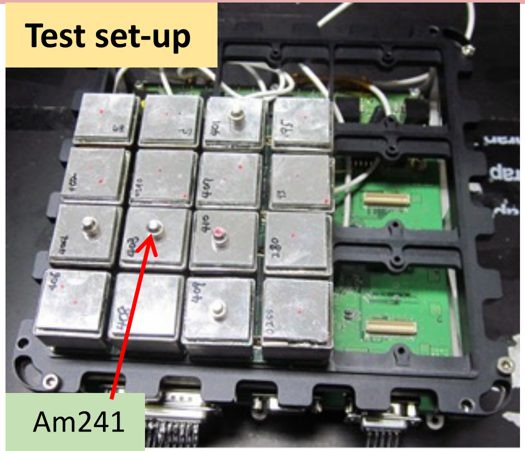
UBAT: Performance test

Fig. 13 UBAT detector pixel quality map for the flight model. Noise pixels at the edges of MAPMT are seen as hot channels, and blocked out for the imaging algorithm calculation. Active channels are indicated in black and the masked-out channels of hot pixels are indicated by white. 1931 channels, or ∼83.8% of 2304 channels, are found to be active



UBAT: Performance test

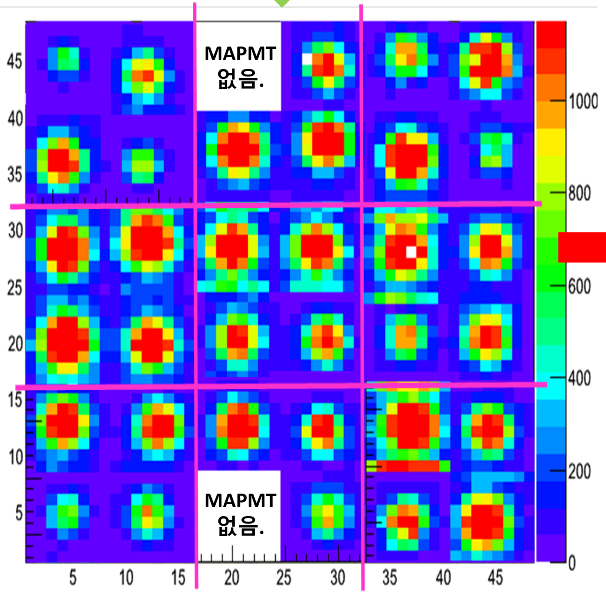
Detector calibration



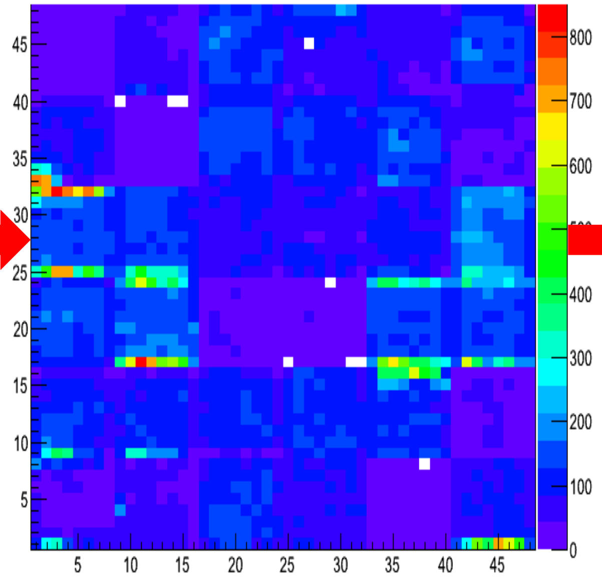
아날로그 보드의 ASIC 별로 다른 gain을 가짐.
고전압 공급 보드의 9개 출력전압은 각각 다른 값을 가짐.

idea : 아날로그 보드와 고전압 출력의 매칭을 조절해가면서
검출기를 좀 더 균일하게 만들어 줄 수 있을 것.

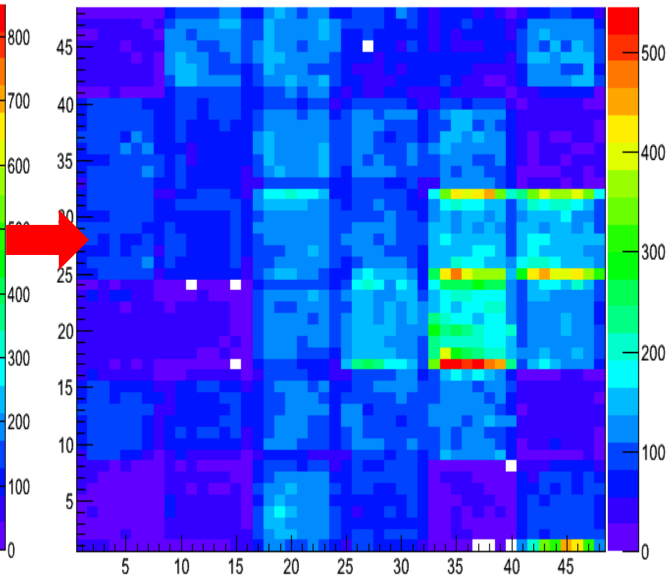
→ 하드웨어 위치와 매칭의 변경으로 검출기 전체 반응이 가능한 균일하게, 검출기의 중심에 좋은 세트가 가도록 조절.



하드웨어 셋팅 ver.1
(Am241 source , 성균관대)



하드웨어 셋팅 ver.1
(X-선 튜브 , 러시아)



하드웨어 셋팅 ver.2
(X-선 튜브 , 러시아)

UBAT: Performance test

Detector calibration

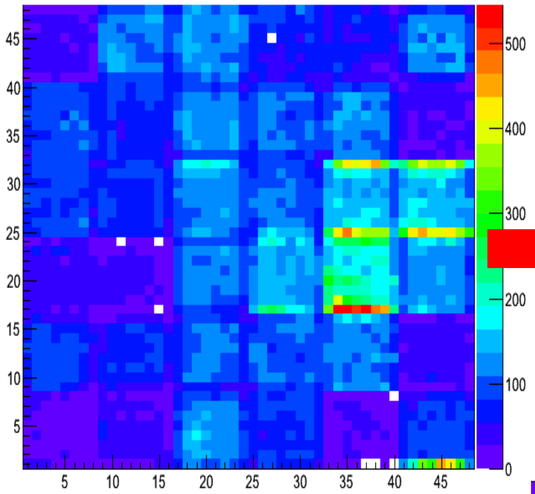
✓ **ASIC 번호**

1	2	3	4	5	6
7	8	9	10	11	12
13	14	15	16	17	18
19	20	21	22	23	24
25	26	27	28	29	30
31	32	33	34	35	36

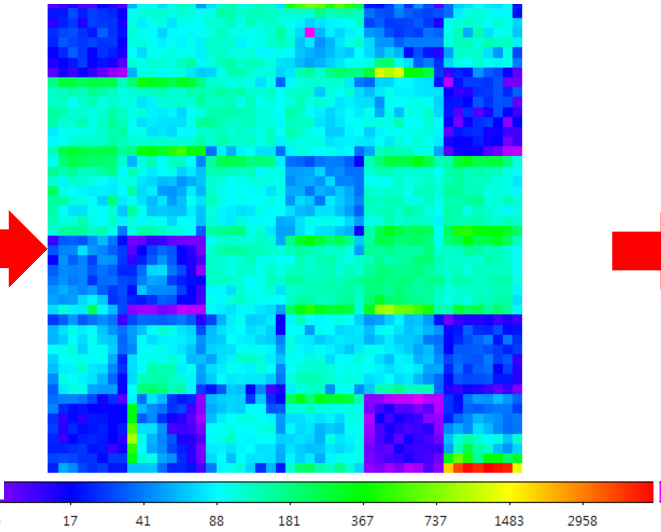
하드웨어를 이용해 검출기 반응을 균일하게 만드는 것은 한계가 있으므로, ASIC 내부의 parameter인 Photon Counting threshold를 조절해가면서 검출기를 보다 균일하게 만들어줌.

→ Ver. FM2014와 FM2013을 비교했을 때, ASIC 16, 19, 20, 25, 26 등의 ASIC이 좀 더 평균적인 값과 비슷한 값을 나타냄.

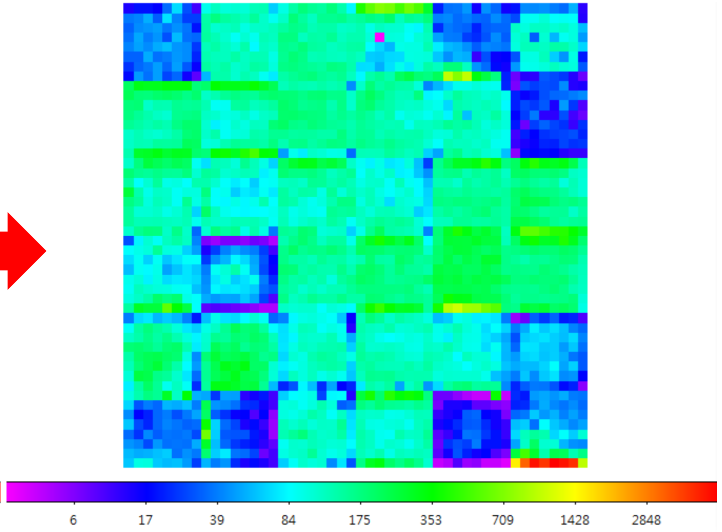
※ 입력 에너지 : X-선 튜브 소스 9keV가 평행하게 들어감. (Ver. FM2013 / Ver. FM2014)
X-선 튜브 소스 47keV가 평행하게 들어감 (같은 Threshold setting)



같은 Threshold (450)



Ver. FM2013

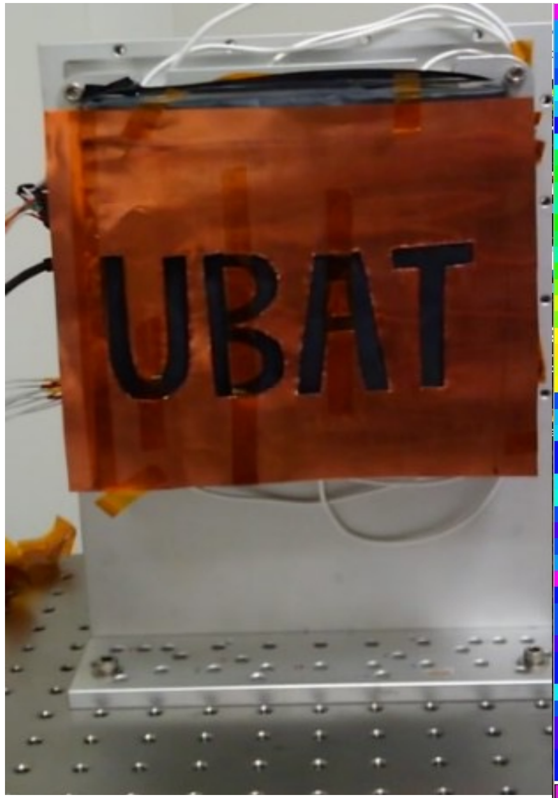


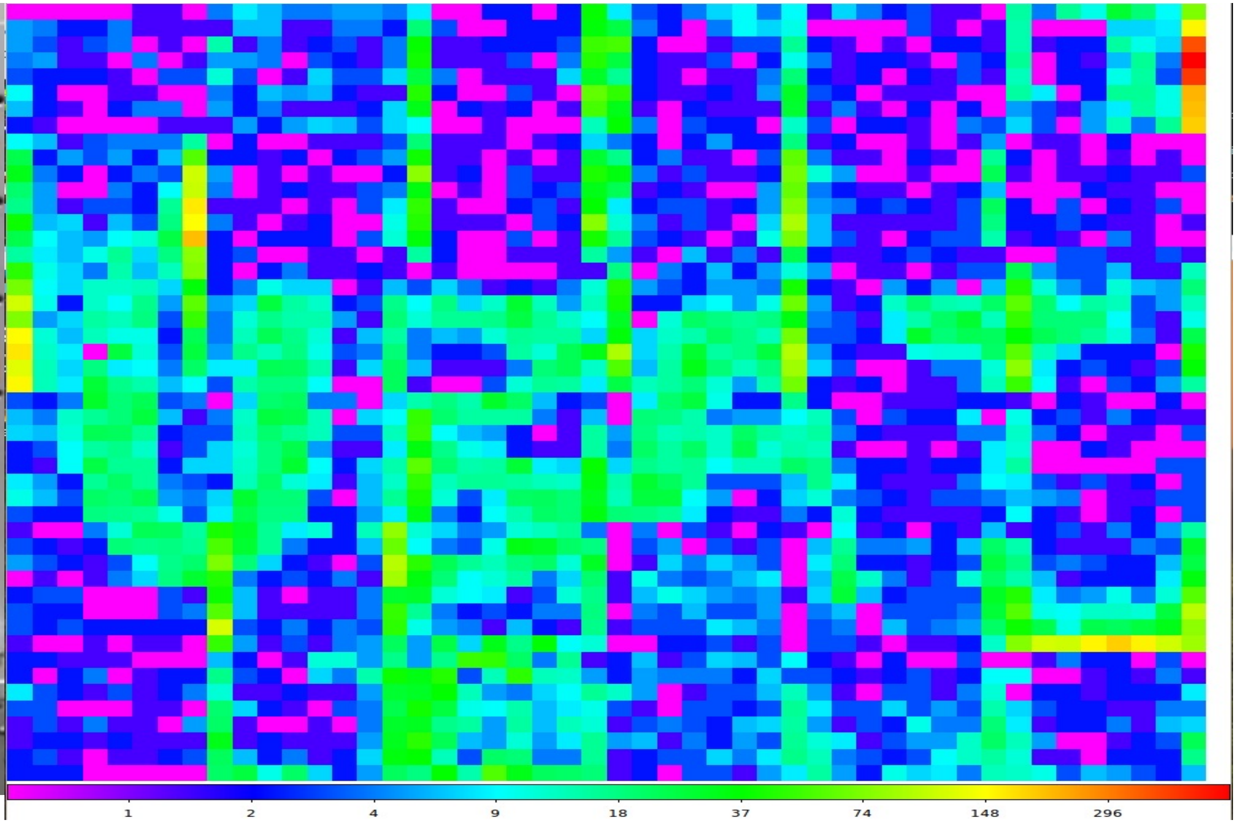
Ver. FM2014

UBAT: Performance test

Detector calibration

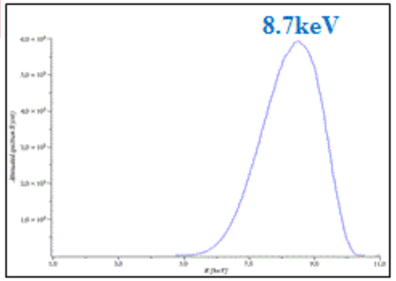
X-ray energy: 8.7keV
Exposure time: 12 sec
Copper plate mask



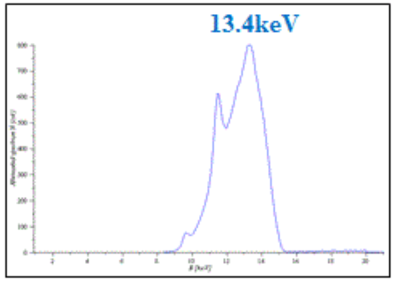


UBAT: Performance test

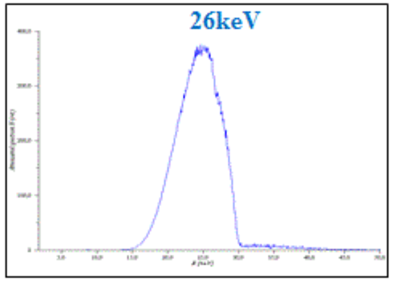
Input energy



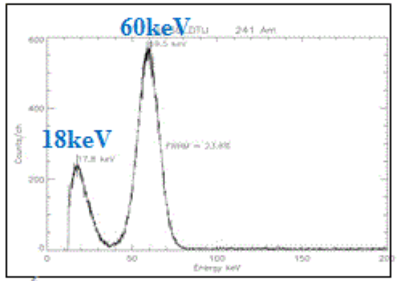
(a) X-ray Tube 10kV



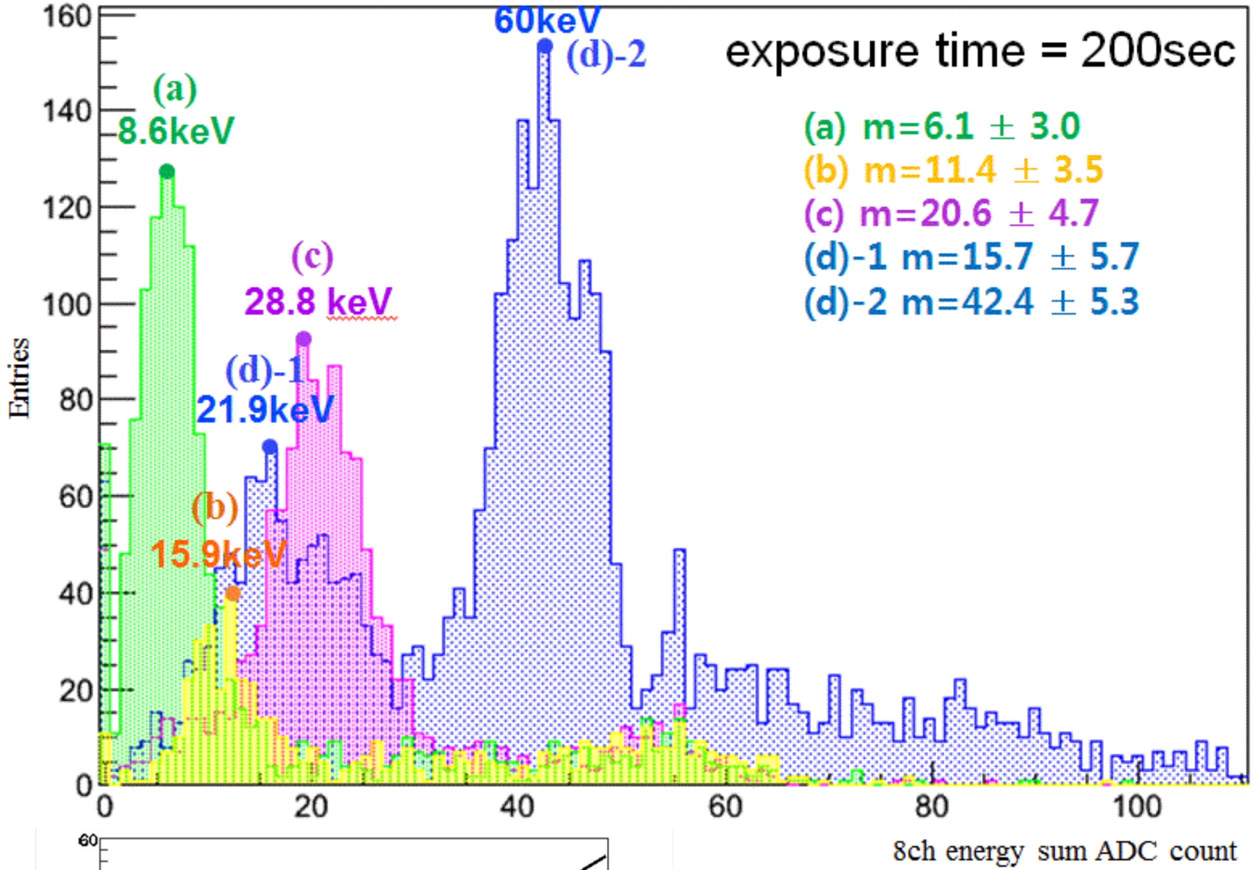
(b) X-ray Tube 15kV + Mo filter

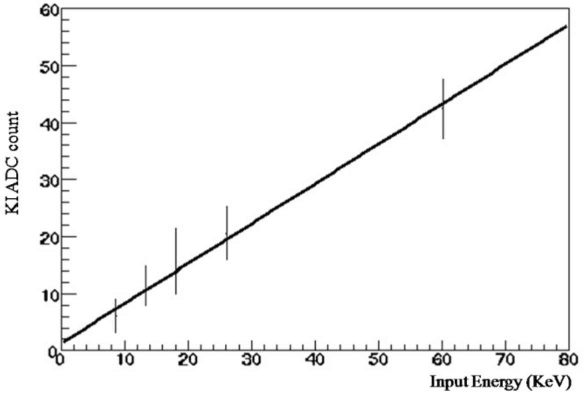


(c) X-ray Tube 30kV + Cu filter



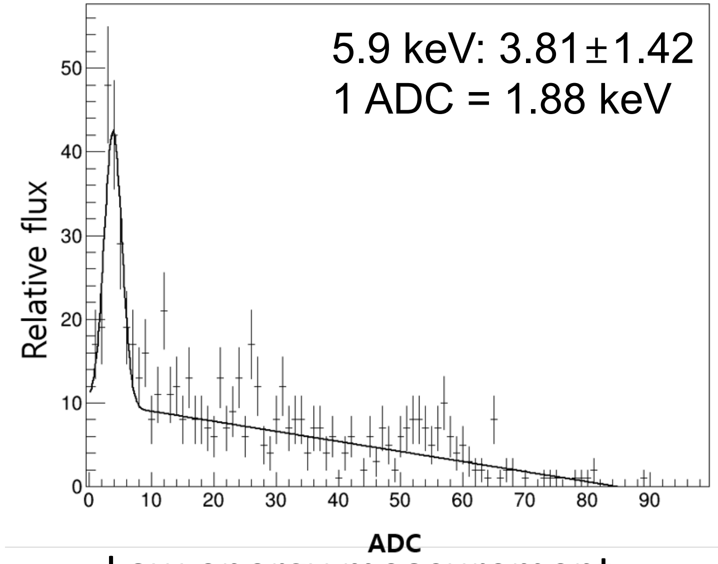
(d) Am241 source





1 KI ADC Count = 약 1.4 keV

Low energy X-ray measurement

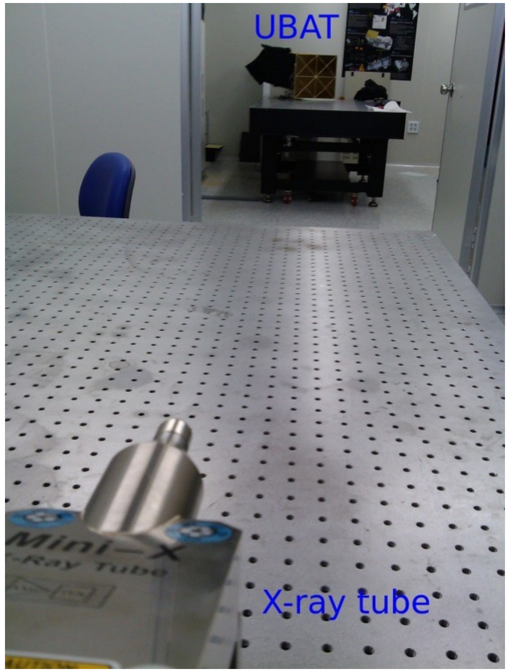


Low energy measurement
5.9 keV (Fe55)

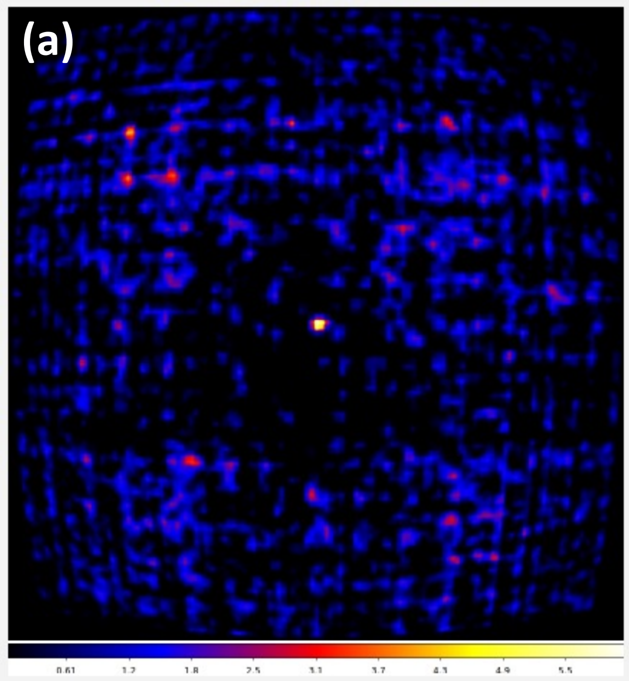
The X-ray detector can measure less than 5.9 keV well enough.

UBAT: Performance test

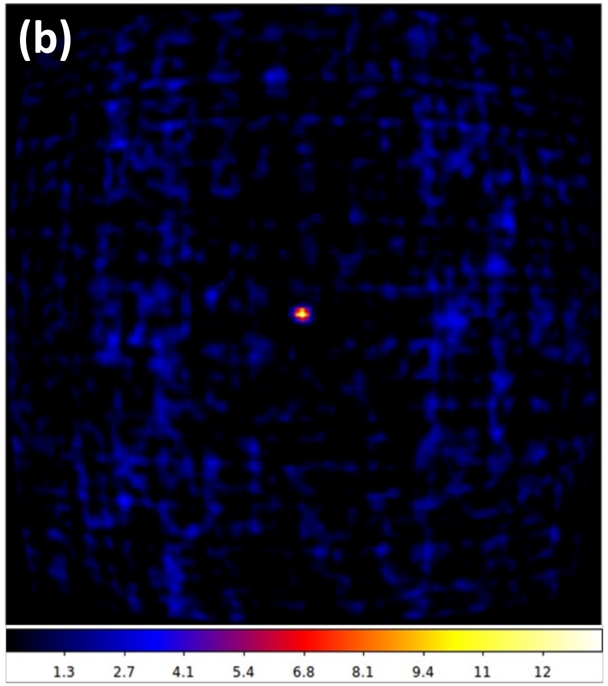
Confirmation of X-ray position finding



TEST setting



8.7keV



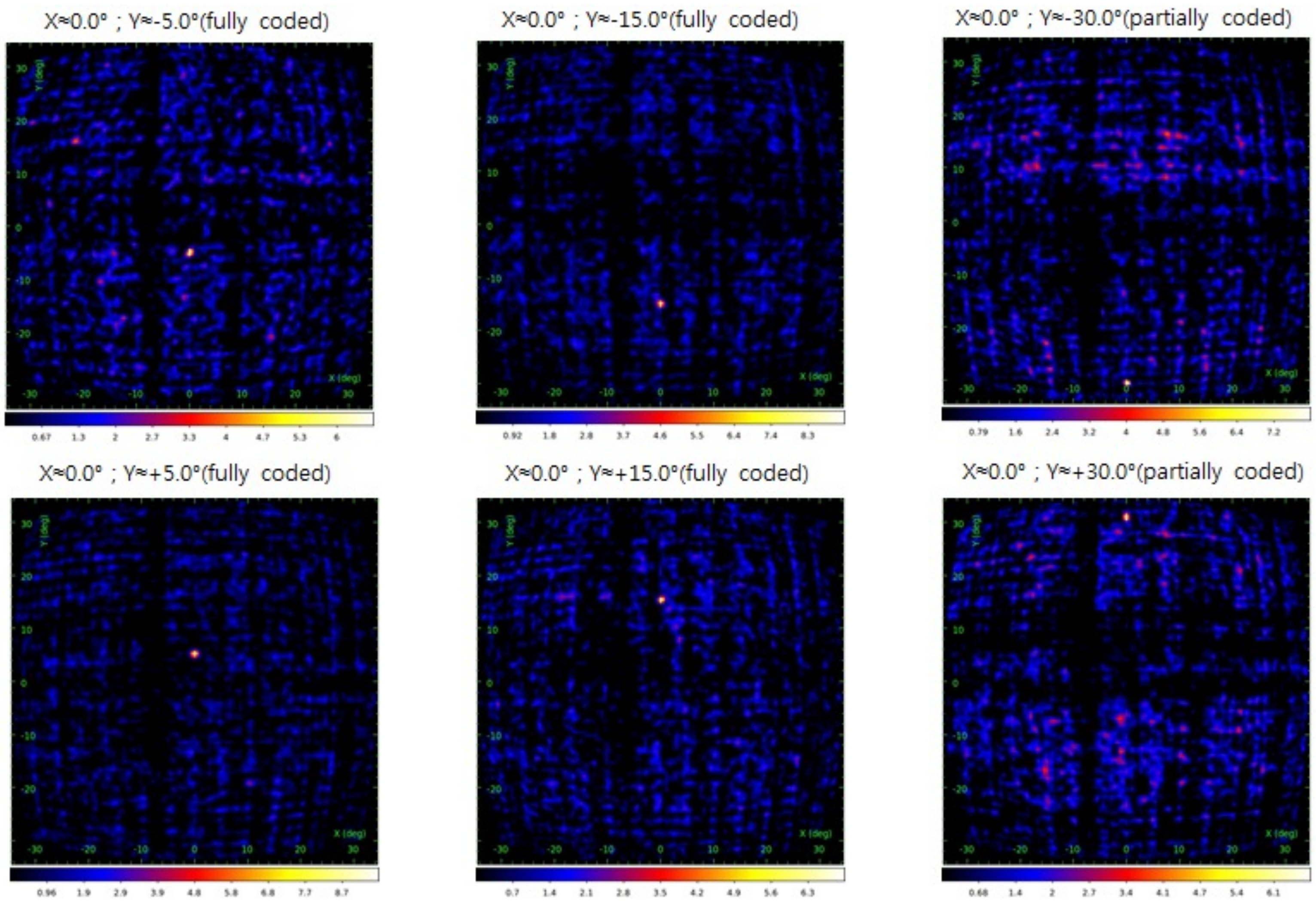
47keV

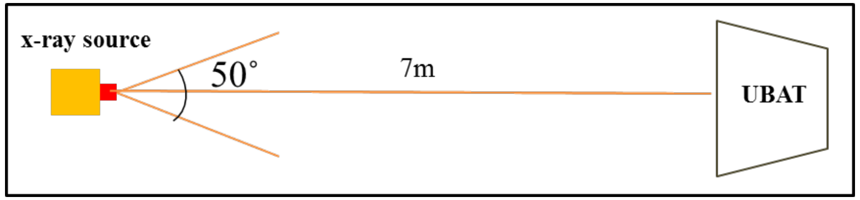
We can find X-ray source location @8.7 keV (low energy)

UBAT: Performance test

Confirmation of X-ray position finding

Input energy: 47keV (using X-ray tube)

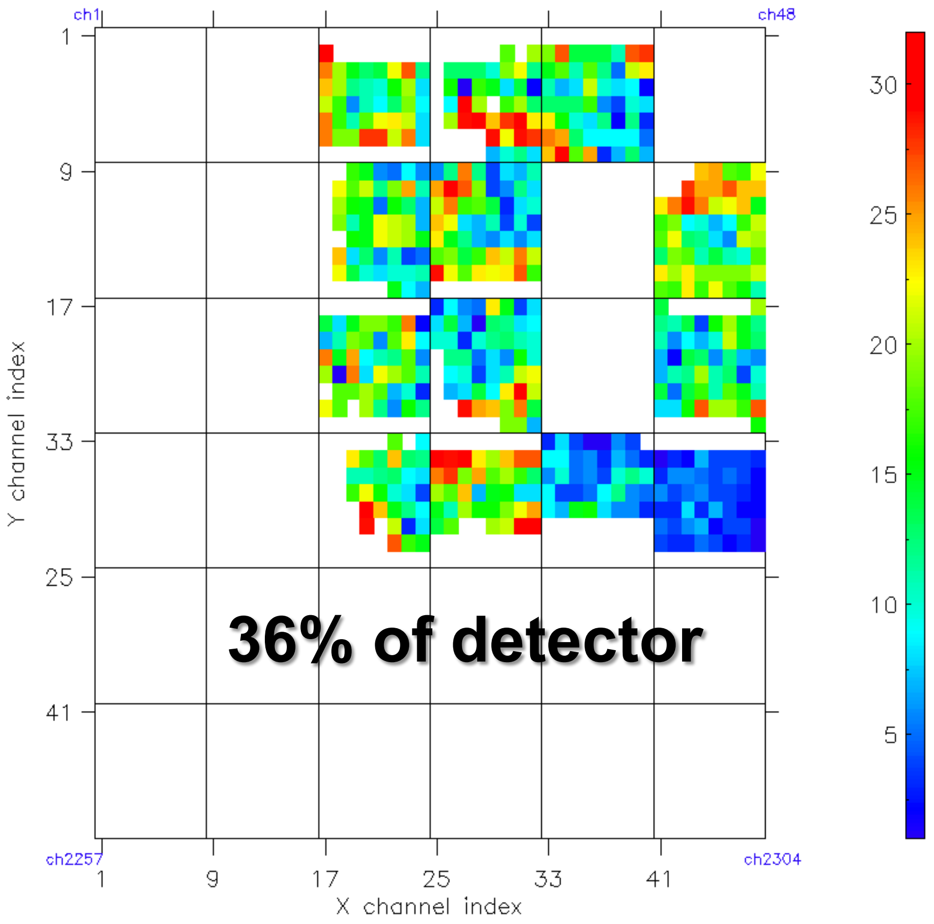


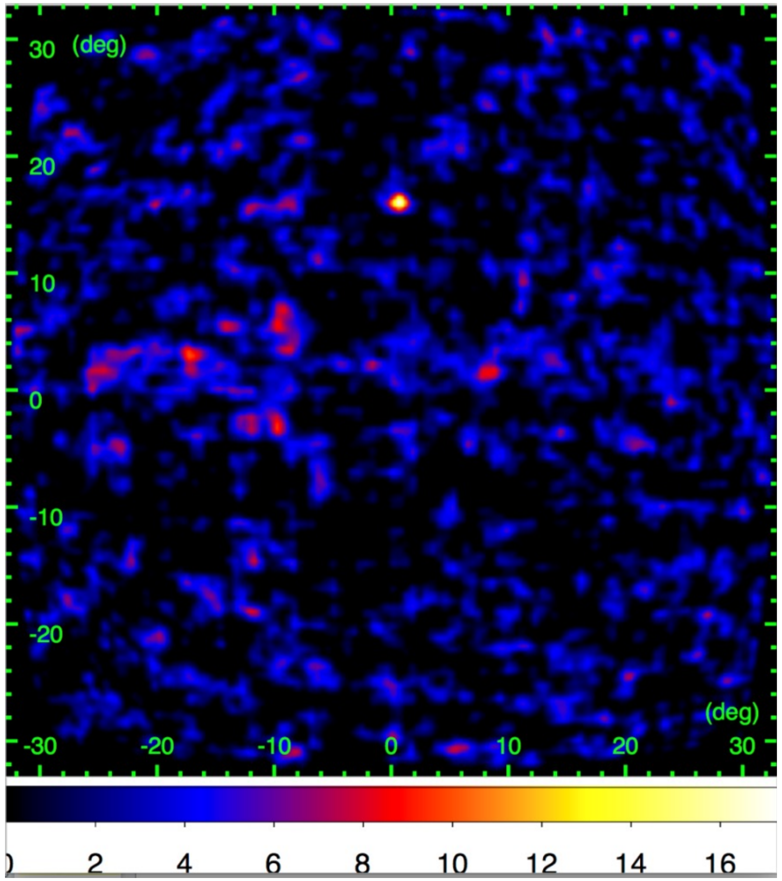


I confirmed X-ray localizing of UBAT by laboratory test with X-ray tube source.

UBAT: Performance test

We lost several analog boards during robustness test because of aging effect and unknown effect.

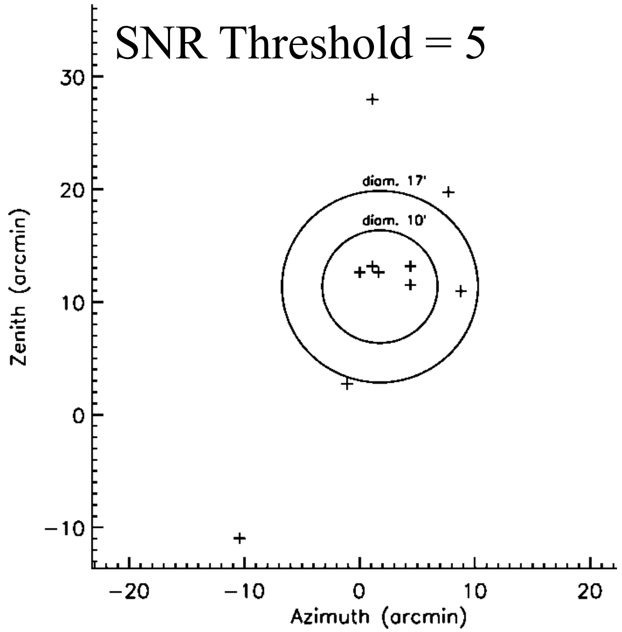




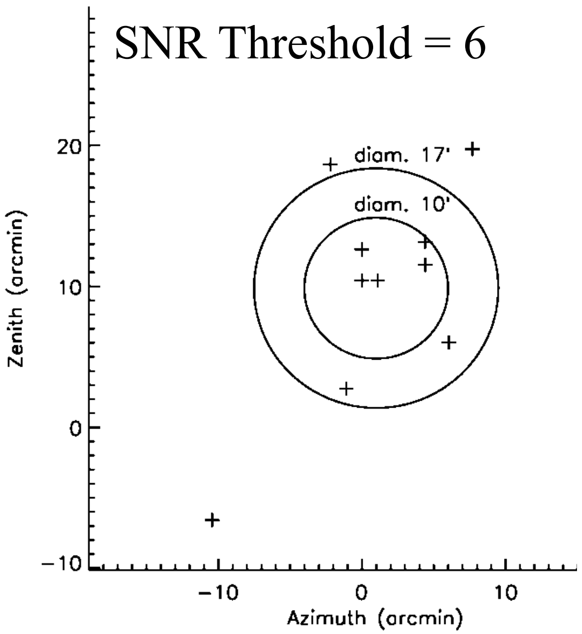
✓ **Even if 2/3 of the detector is lost, localization is possible.**

UBAT: Performance test

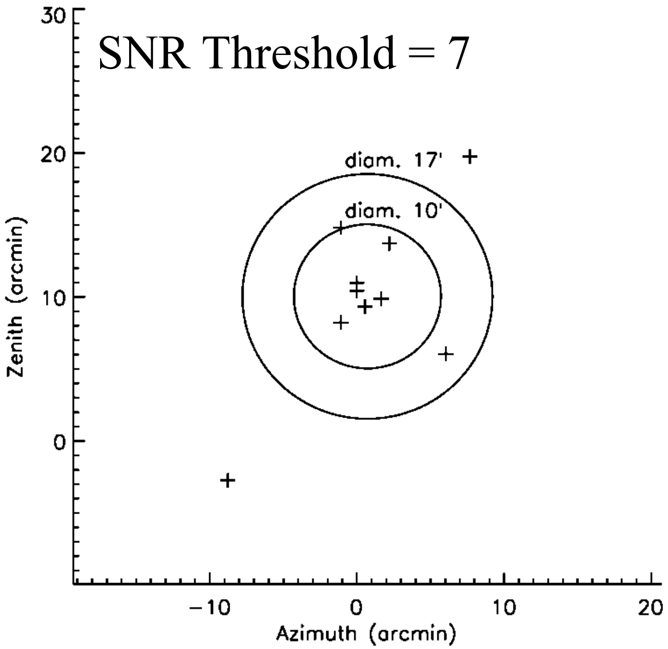
- ✓ X-선 튜브 소스와 X-선 우주선의 위치 고정 (On-axis)
- ✓ 10개의 샘플
- ✓ 신호 대 잡음비(Signal to Noise, SNR)에 따른 소스 위치 확인



5/10 이 UBAT accuracy 내에 들어감.
SNR = 5.3 ~ 7.4



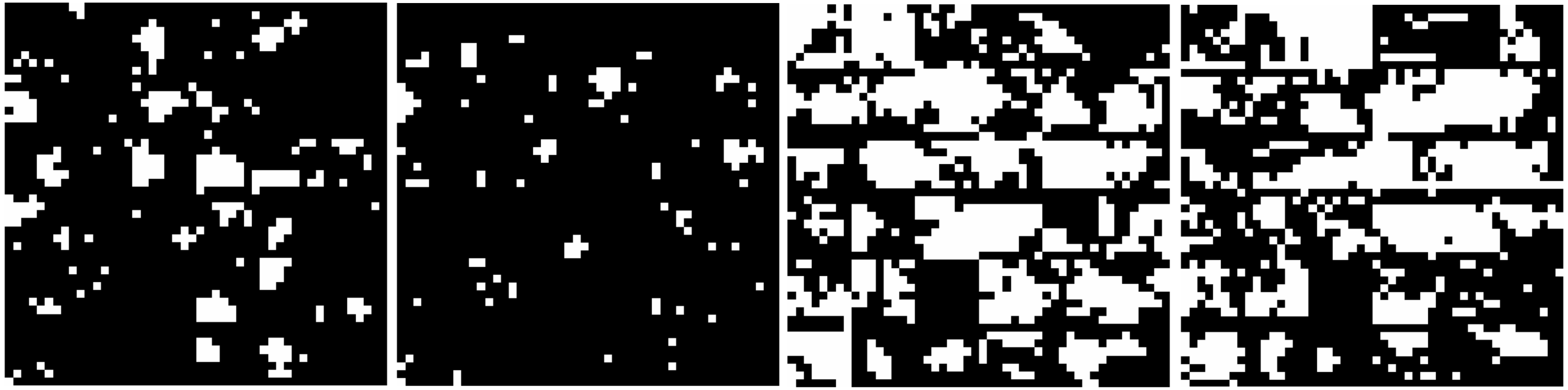
5/10 이 UBAT accuracy 내에 들어감.
SNR = 6.2 ~ 7.7



7/10 이 UBAT accuracy 내에 들어감.
SNR = 7.1~8.0

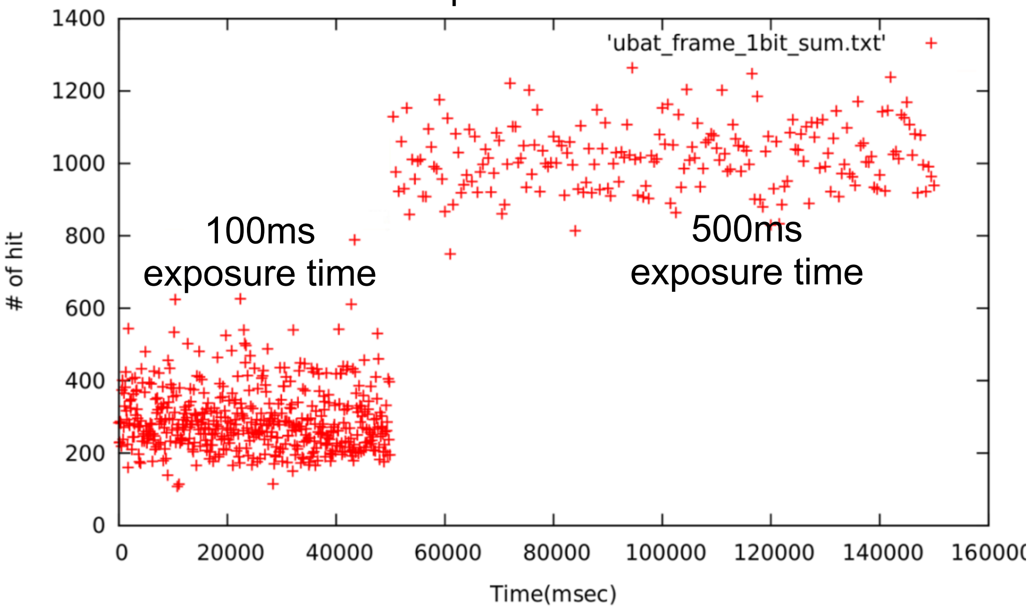
UBAT: Performance in space

X-ray telescope (UBAT) detector hitmap – 48ch ×48ch **Alive and working in space!!**



100ms exposure time

500ms exposure time



High X-ray counts

Count rate : 21.3 counts/cm^2/sec
Counts of diffused x-ray background :
2~3 cnts/cm^2/sec (up to 15keV, by *swift*)

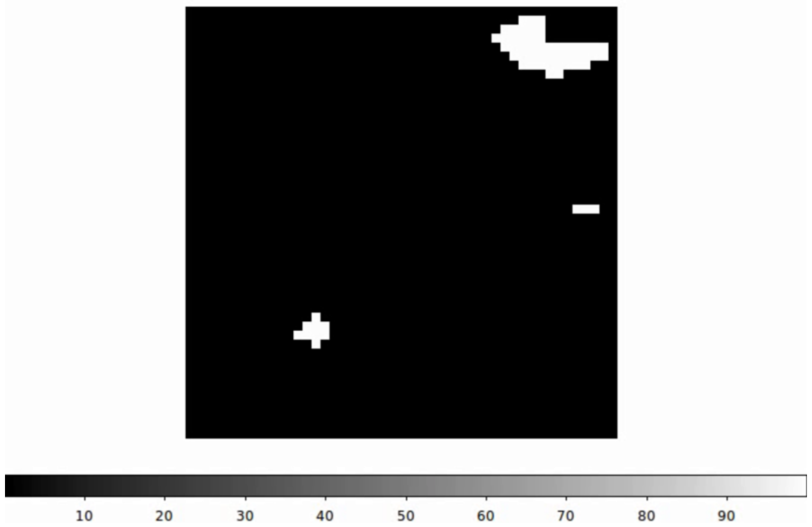
Why our value is about 7 times bigger than well known value?
→ Candidates are

1. Other particles effect
2. Crosstalk effect
3. Others?

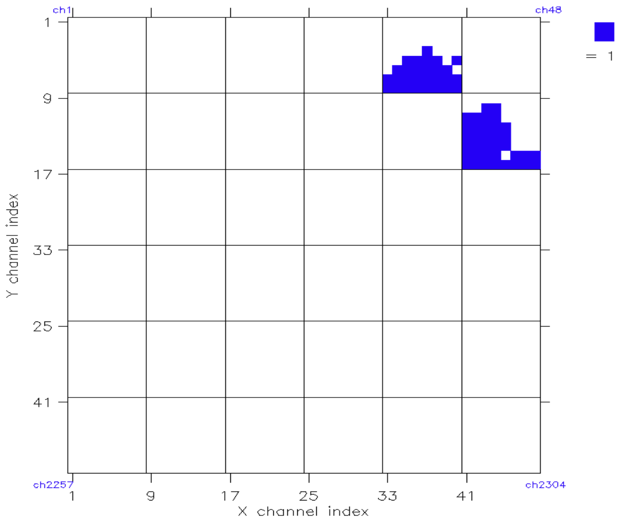
UBAT: High x-ray count issue

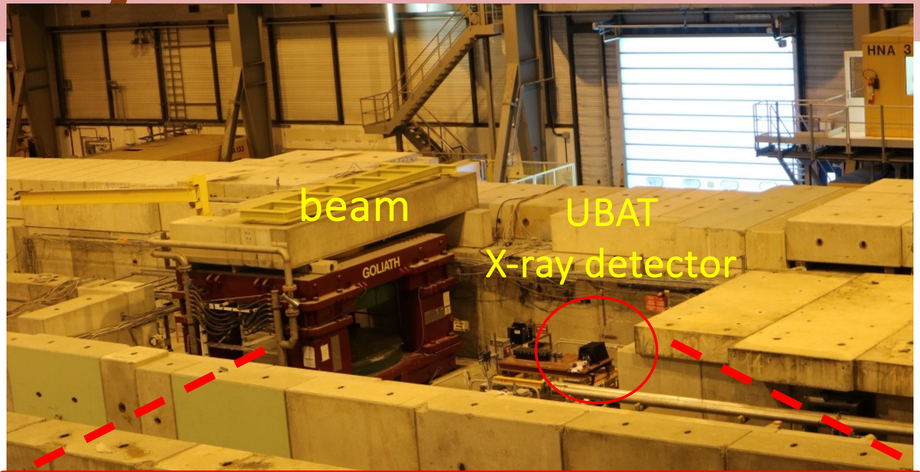
1. Other particles effect

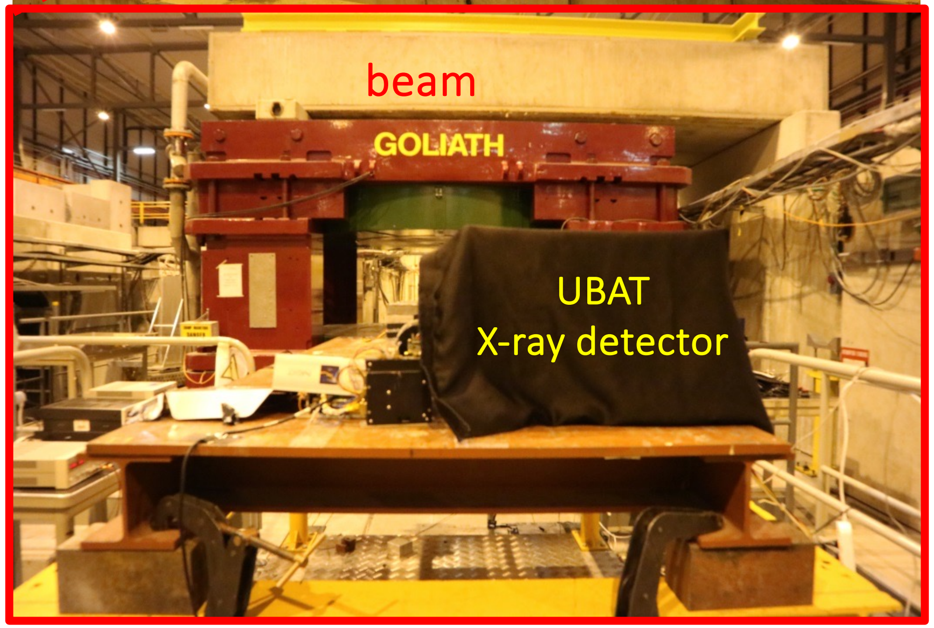
<Space data RUN14 >



<CERN beam test data>



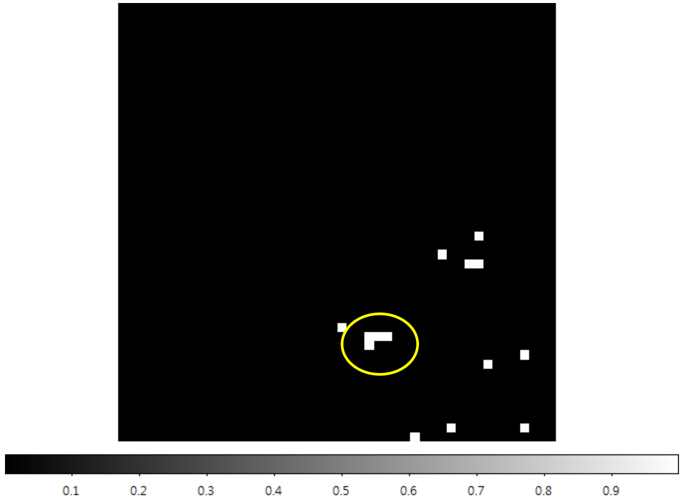


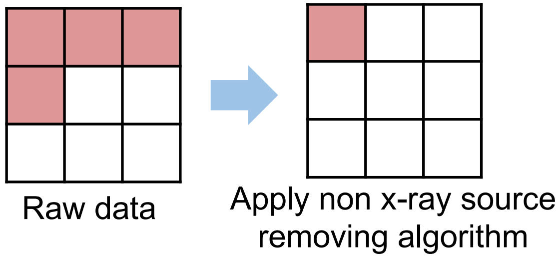


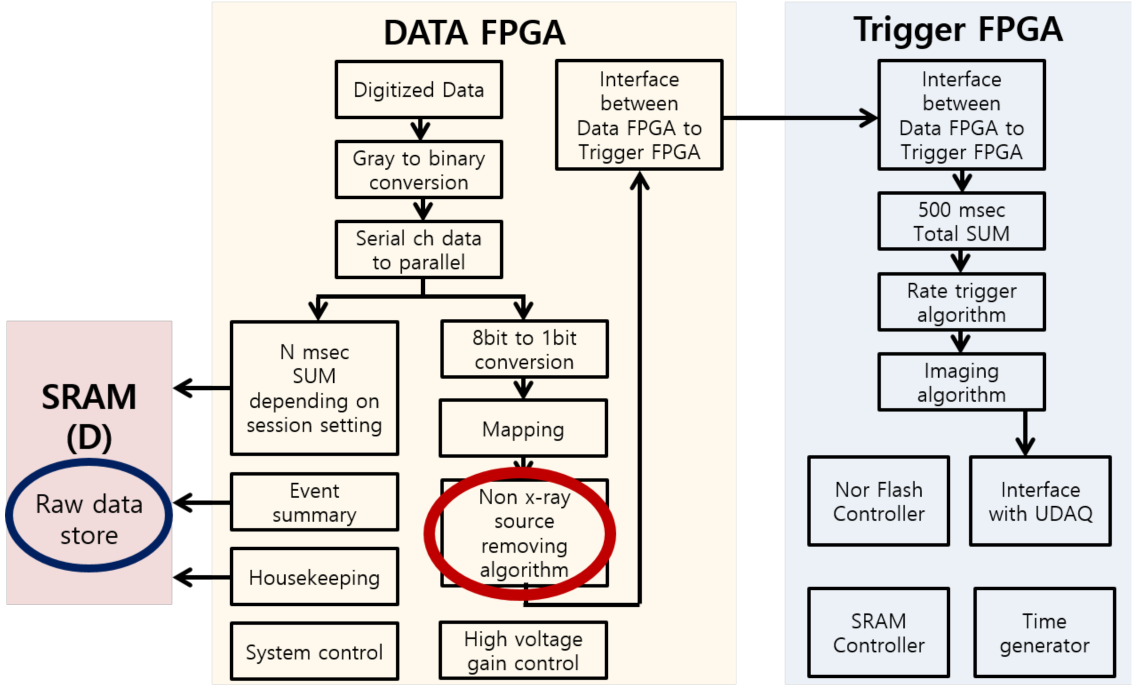
We tested our X-ray telescope detector at CERN(European Organization for Nuclear Research) to confirm cosmic ray effect on our detector.

UBAT: High x-ray count issue

2. Crosstalk effect







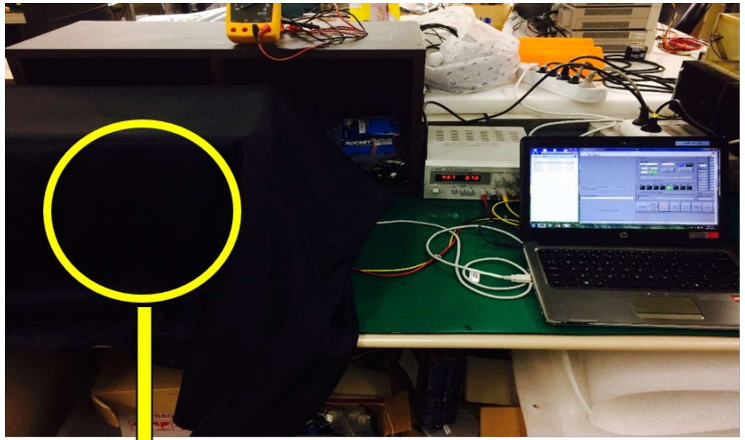
	Raw data	Apply non x-ray removing algorithm
RUN 10c	22.5 cnts/cm^2/sec	4.0 cnts/cm^2/sec
RUN 10e	20.9 cnts/cm^2/sec	4.5 cnts/cm^2/sec

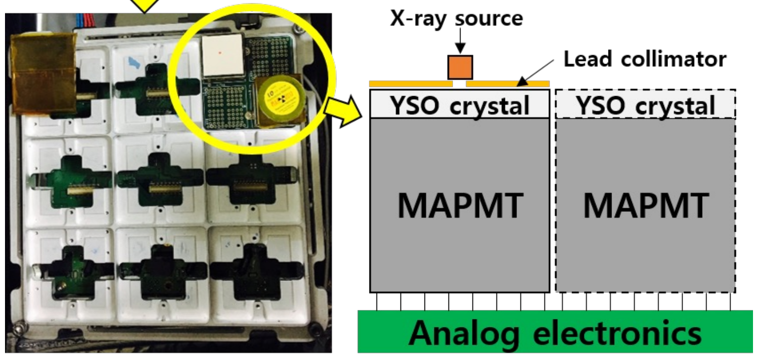
✓ When I applied non x-ray source removing algorithm in space data, hit count was **reduced approximately 75%.**

UBAT: High x-ray count issue

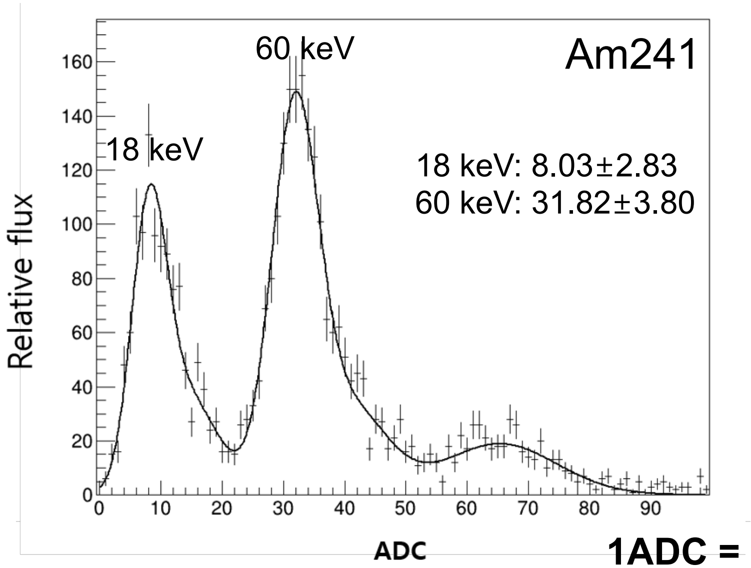
3. Others -> Low energy effect

Test set-up using UBAT 2nd set

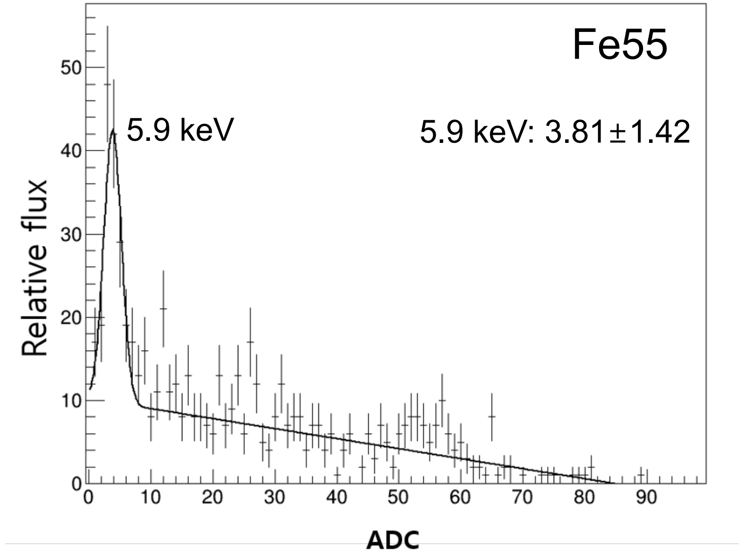




- X-ray source: Am241 (18keV, 60keV), Fe55(5.9keV)
- Exposure time: 70sec



1ADC = about 1.88 keV



⇒ UBAT can detect X-ray energy 5.9keV even lower than 5keV !!