Solar Neutron and Gamma-ray Spectroscopy Mission: SONGS

Kazutaka Yamaoka*a, Hiroyasu Tajima*a, Daiki Nobashi*a, Masaki Usami*a, Kikuko Miyata*b, Takaya Inamori*a, Ji Hyun Park*a, Kazuya Ito*a, Koji Matsushita*a, Kazuhiro Nakazawa*a, Satoshi Masuda*a, Hiromitsu Takahashi*c, Kyoko Watanabe*d

*a: Nagoya University, *b: Meijyo University, *c: Hiroshima University, *d: National Defense Academy of Japan

Abstract: Fast neutrons generated by the interaction between ions and the solar atmosphere are important observation probles to clarify the ion acceleration mechanism in the Sun, but so far neutrons have been detected from only 12 X-class solar flares in the highland on the ground due to the influence of atmospheric absorption. As for observations in space, SEDA-AP at the International Space Station continued to operate until 2018 and succeeded in neutron detections from 52 solar flares, but there are currently no dedicated space missions. In order to overcome this situation, we have been designing and developing a 3U CubeSat and a novel neutron / gamma ray sensor since 2018 with the aim of performing satellite observations from space. The sensor consists of the multi-layered plastic scintillator bars readout with Si photo-multipliers(PMs), and detects fast neutrons from the tracks of recoiled protons via elastic scattering. Furthermore, by placing a GAGG scintillator array at the bottom, it is designed to be sensitive to gamma-rays based on the principle of the Compton camera. In this presentation, we will report on the scientific purpose and the development status of CubeSat and neutron / gamma-ray sensors.

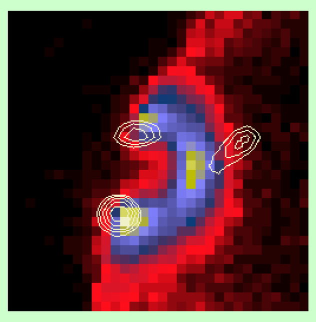
1. Solar Neutron Observation

1.1 Scientific Motivation

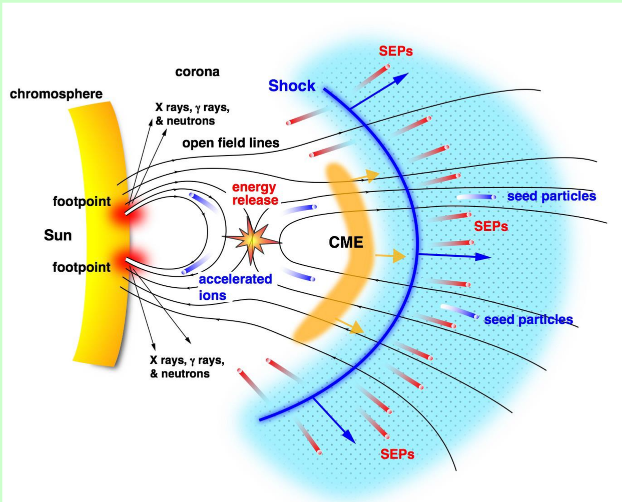
Clarify two scientific problems in solar flares

1. When, where and how are protons (ions) accelerated?
   Trigger: magnetic reconnection
   → magnetic loop
   & Coronal Mass Ejection(CME)
2. Difference between electrons and protons in acceleration
   Electrons → Electro-magnetic waves (Micro-wave、X-rays, Soft gamma-rays)
   Protons, Ions→Neutrons・Nuclear gamma-rays・High energy gamma-rays (>100 MeV)

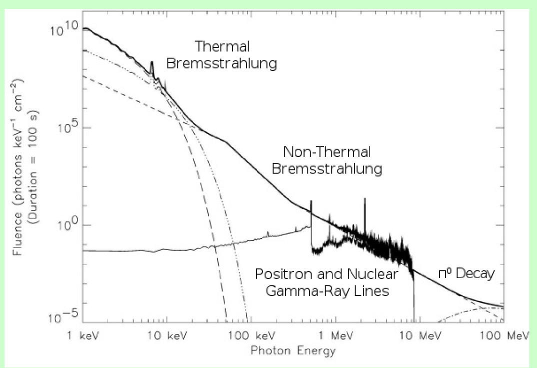
→ We will focus on neutrons because **neutrons are generated by only hadronic process, and observations have not been in progress in compared to GeV gamma-rays (Fermi).**



Soft and hard X-ray image of coronal loop structure (Masuda et al. 1994)



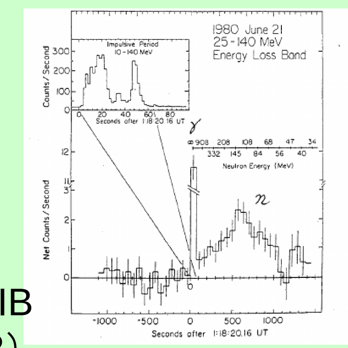
Picture of magnetic reconnection and CME n in solar flare



X-ray and gamma-ray spectrum from typical bright solar flare.. This is contributed both from ions and electrons (Lin et al. 2003)

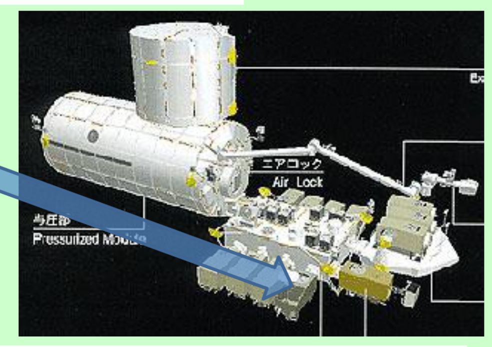
1.2 Previous solar neutron observations and their problems

① Insufficient detection with low detection sensitivity
Since discovery in 1980 (Chupp et al. 1982)
Only 12 sample by ground-based observations over 40 years
The SEDA-AP FIB observed on the International Space Station (ISS) since 2009 (Muraki et al. 2012)
Operation ended in 2018,
and detected neutrons from more than 40 solar flares..
→ No space mission dedicated for solar neutron observations in a near future.



Neutron event observed by SMM on June 21, 1980 (Chupp et al. 1982)

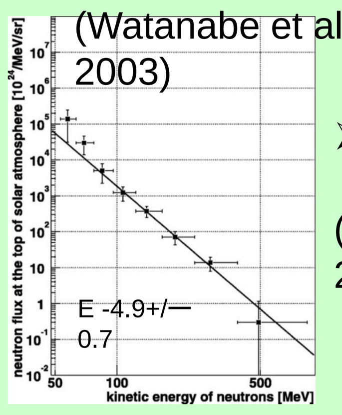
Engineering model Of the SEDA-AP FIB（Muraki et al, 2012）



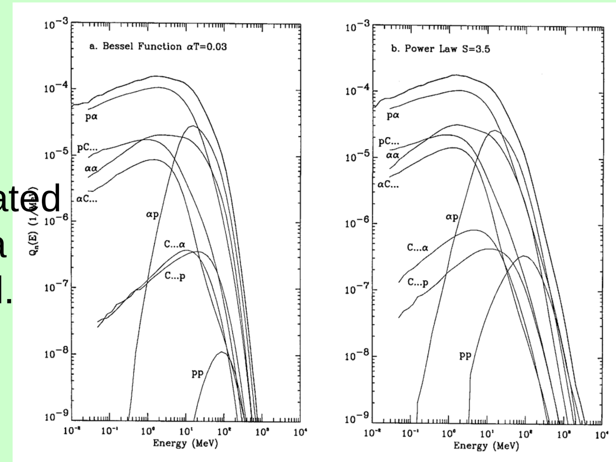
② Insufficient energy determination capability for ground-based detectors.
→ Inaccurate Time-Of-Flight method
Precise measurement is necessary
→ acceleration mechanisms
e.g. Stochastic VS Shock

To overcome this situation, we have designed and developed neutron sensors for microsatellites.

➢ Neutron spectrum of SF 031124 (Watanabe et al. 2003)



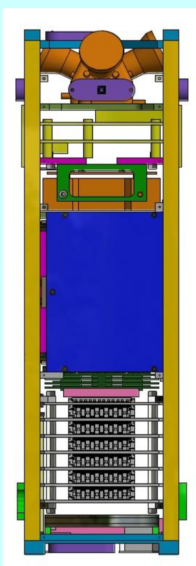
➢ Calculated spectra (Hua et al. 2002)



2. SONGS mission and Solar Neutron/Gamma-ray Detector

2.1 Mission Requirement

Item	Values	Requirements to the bus system
Size	100 x 100 x 120 [mm]	
Mass	2 kg	
Power	4 W	Deployable solar paddle
Attitude Determination & Pointing accuracy	~1 deg. (Does not affect energy resolution) & ~10 deg.	Earth-edge sensor
Data downlink（neutron+background）	~15 Mbyte/day (with no sel.) ~1 Mbyte/day (with selections)	S-band comm. system
Absolute Timing accuracy	1 sec (neutron)、1 msec (gamma)	GPS synchronization
Storage temperature	-20～60℃	
Operation temperature	<20℃	Thermal control
Others	No light leakages	Shields solar light



2.2 Novel Neutron/Gamma-ray Sensor

★Geometry & Structure
- Laminated scintillator＋Silicon photo-sensor MPPC
  → Can track cosmic-ray interaction in three dimensions.

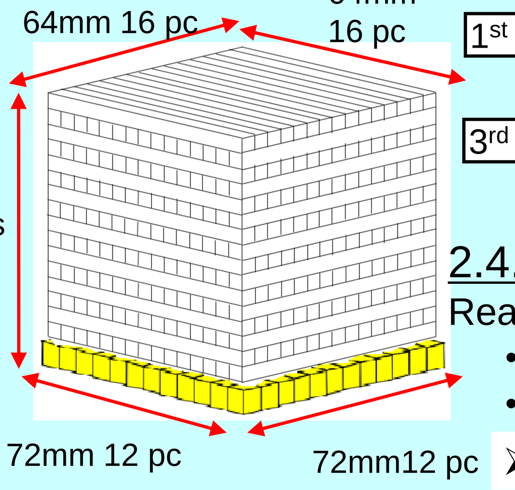
★Uniqueness
- Sensitive to both neutron and gamma-rays
  - Neutron: 30-100 MeV
  - Gamma-rays 100 keV-3 MeV
- Can determine energy and incident direction of both neutron and gamma-rays (in principle)

Light weight (2 kg), Compact (~1.2 U), Low power(4 W), and scalable

★Required technology
- High dense implementation and lamination
- Multi-channel readout system e.g. ASIC

Sun

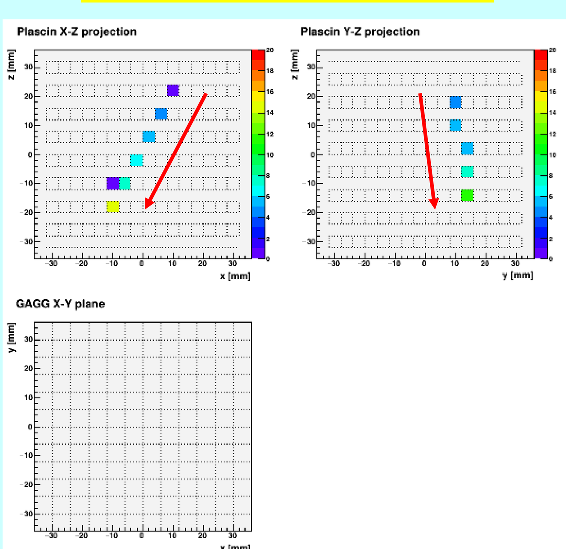
Plastic Scintillator Array（＋anti-scintillator）



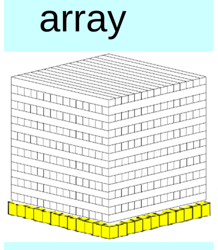
GAGG(Ce) 12x12 array

Example of tracks for neutrons and gamma-rays
- Neutrons
  → Via elastic scattering
  Neutron Energy (E_n) can be calculated as $E_n = E_p/\cos^2\theta$ using total energy deposits (E_p) of recoiled protons and recoil angle (θ).
- Gamma-rays
  → Via Compton scattering in Plastic and Photo-absorption in GAGG
  Compton camera techniques

100 MeV Neutron

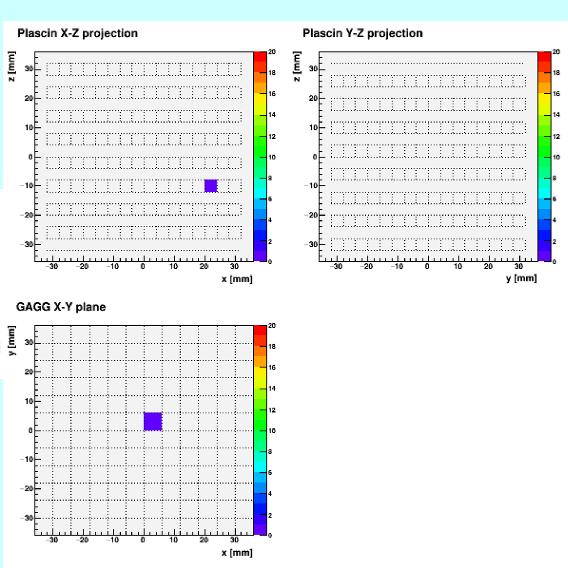


Plastic scintillator array



GAGG array

1 MeV Gamma-ray



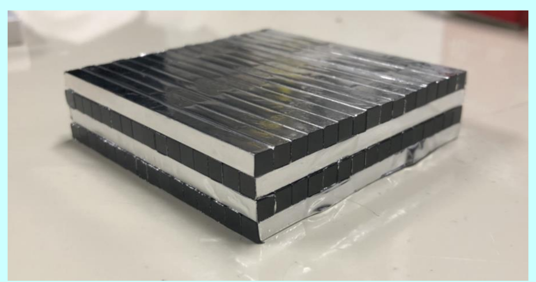
Based on Geant4 simulation of flight model sensors.

2.4 Results from Bread-Board Model (BBM)

2.4.1 Evaluation of Plastic Scintillator Array

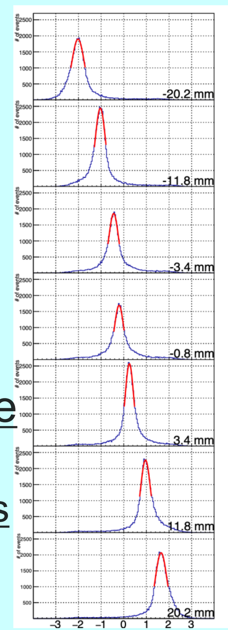
Readout from both sides of bar(4 x 4 x 64 mm) with MPPC
- Can determine 1D position by using the difference of light outputs $\ln\frac{E_1}{E_2} \propto x$
- The 1σ position resolution is 2-3 mm@<478 keV ^{137}Cs

4-layer Model

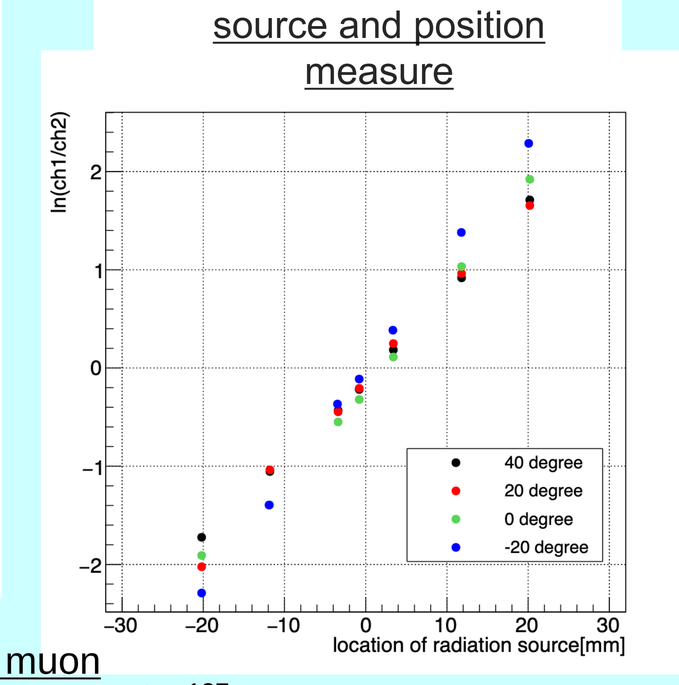


Constructed plastic scintillator array with 4 layers

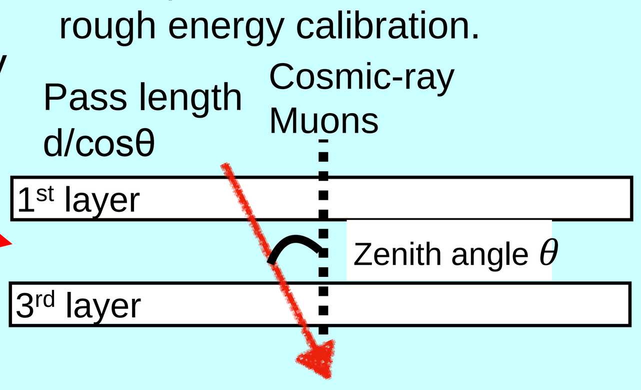
➢ Position measure distribution at various positions



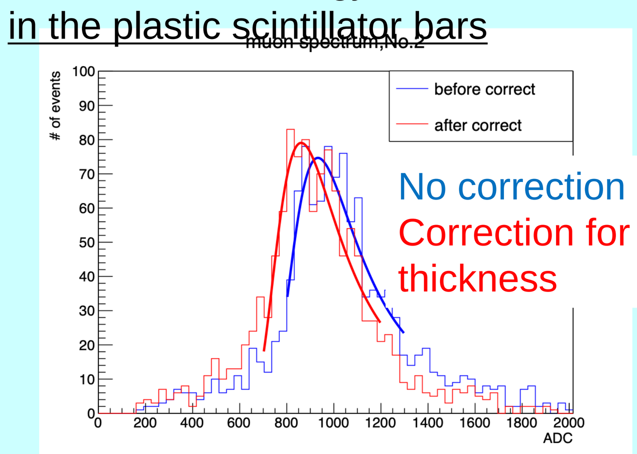
➢ Relation between real position of the radiation source and position measure



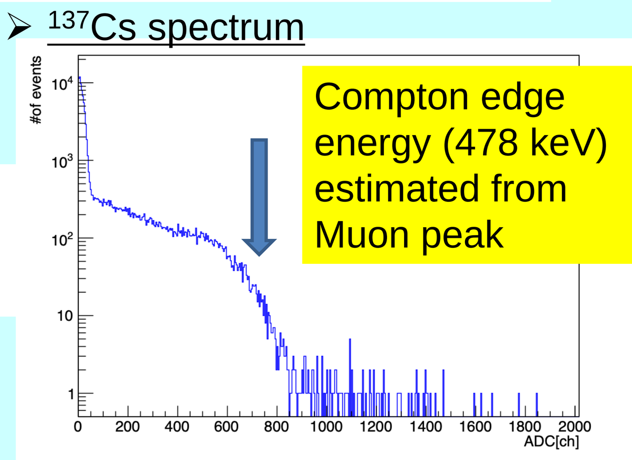
➢ Muon tracking in plastic scintillator bars
- Muon peak can be used for rough energy calibration.



➢ Distribution of energy loss of muon in the plastic scintillator bars



➢ ^{137}Cs spectrum

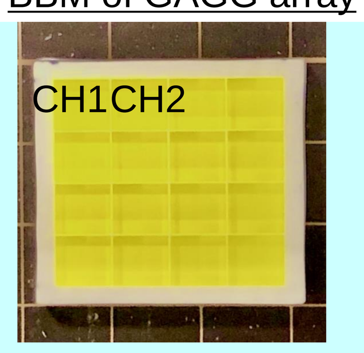


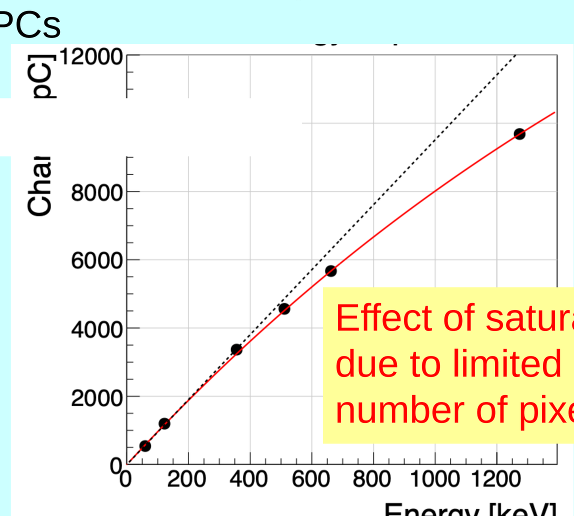
The peak of the Landau distribution is estimated to be 0.538 MeV for 2 GeV muons.

2.4.2 Evaluation of GAGG(Ce) Scintillator Array

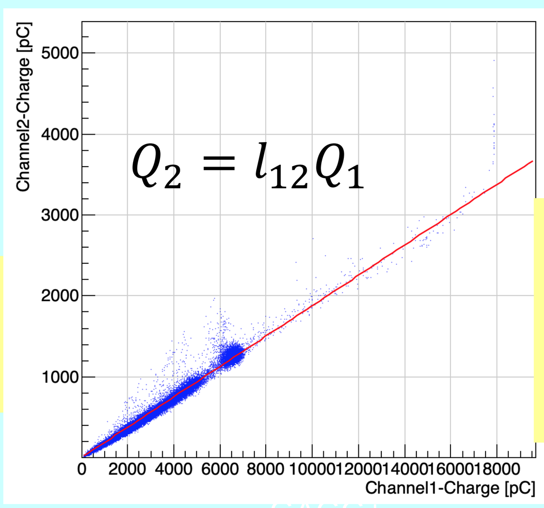
Readout 4x4 GAGG array with MPPC 4x4 array
- Saturation effect in MPPCs
- Light leak effect among

➢ BBM of GAGG array



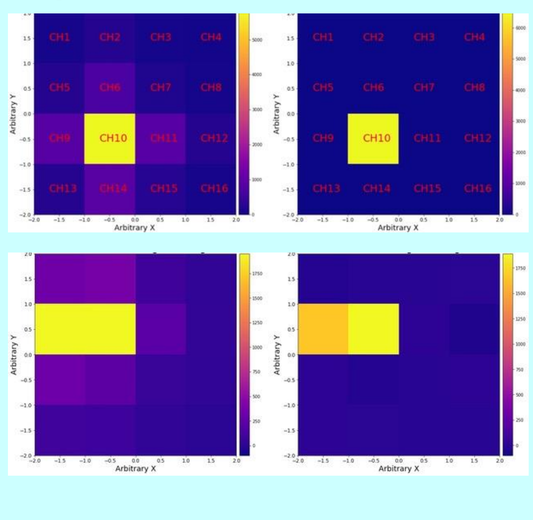


➢ Relation between CH1 and CH2

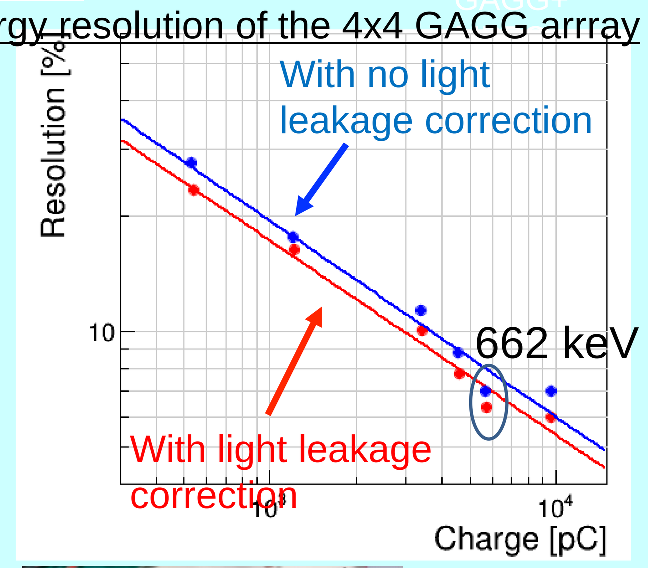


Effect of light leakage
→ Estimate this factor for every combination

➢ Pixel distributions in 4x4 GAGG array



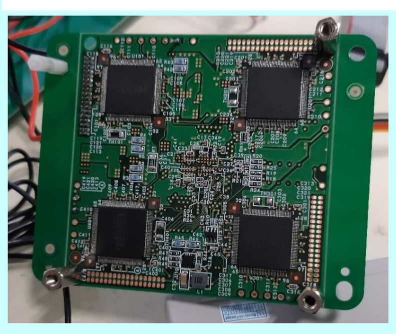
➢ Energy resolution of the 4x4 GAGG arrray



The energy resolution is roughly proportional to Q$^{-1/2}$ (Q:charge), which follows statistical distribution of photo-electrons.

☐ Current Status
- Testing and constructing blead-board model (BBM) is still underway. The readout test from multi-ASICs is also in progress.
- Plan to start production of the flight model In FY 2023, and launch the CubeSat in FY 2024.

➢ ASIC IDE3380 + FPGA board



Questions & comments: yamaoka@isee.nagoya-u.ac.jp