Single Event Effect Characterization of the Analog ASIC Developed for CCD Camera in Astronomical Use

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contents

- Introduction to analog ASIC for onboard CCD cameras
  - Specification
  - Target missions
  - Performance as front-end electronics
- Radiation tolerance for space applications
  - Radiation damage to space ICs
  - Spec. of the experiment
  - Results and prospects

ASICs for CCD camera

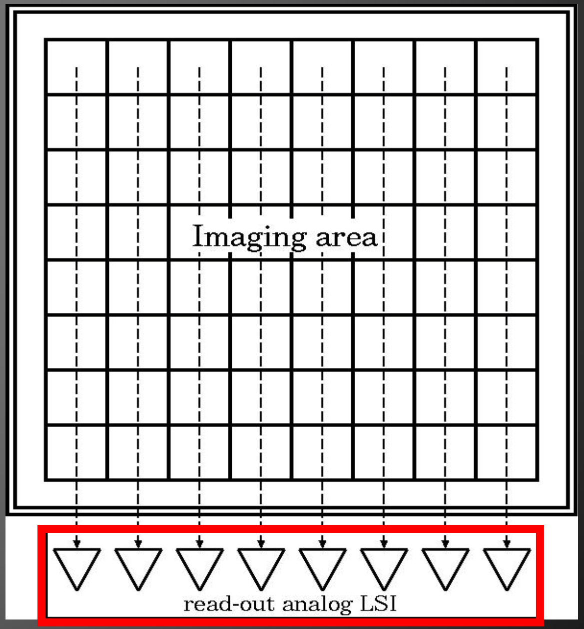
➢X-ray astronomy

- spectroscopy: almost Fano limit
- imaging: up to 0.5arcsec thanks to X-ray telescope
- timing: typically from ～100msec to several sec

  future mission require better time resolution because the telescope with larger EA and superior imaging capability cause photon pile-up

➢Optical land observing satellite

- spacial resoltion depends on CCD readout speed



- Scale down the signal processing electronics
- High-speed low-noise AD conversion
- Increase readout nodes and locate many ASICs

Target missions

ASTRO-H/SXI (2014-)

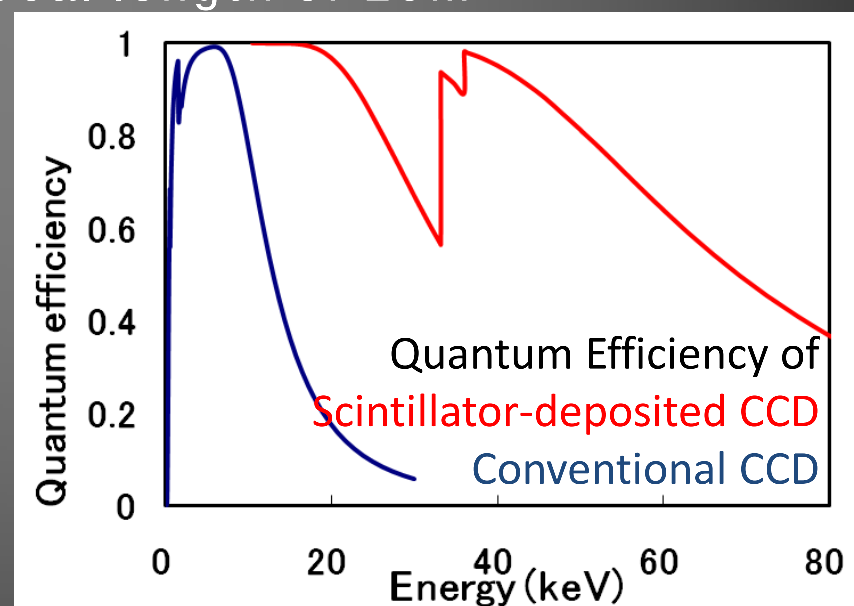
◆Soft X-ray imaging with large FOV of 38’

FFAST (201?-)

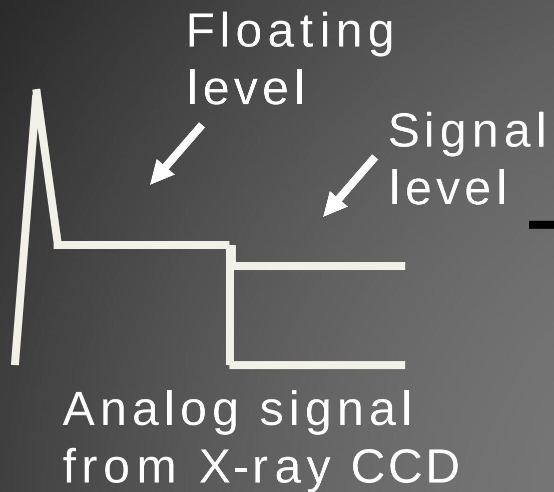
◆First wild-field sky survey at hard X-ray band up to 80keV.
→search for compton-thick AGN and discover the cosmological history of star formation

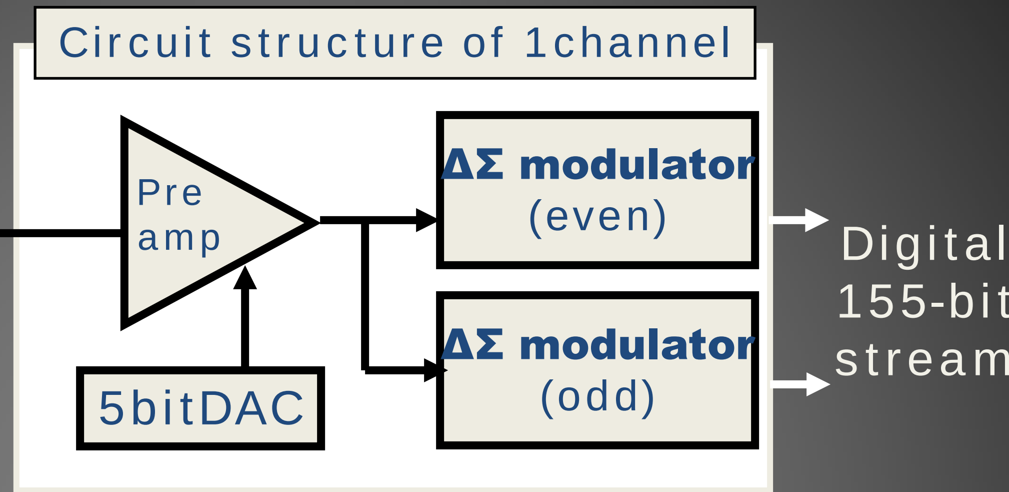
◆Two satellites fly in formation realizing long focal length of 20m

Scintillator-deposited CCD
15μm^2, 2048x4096 pixels



Circuit structure of our ASIC

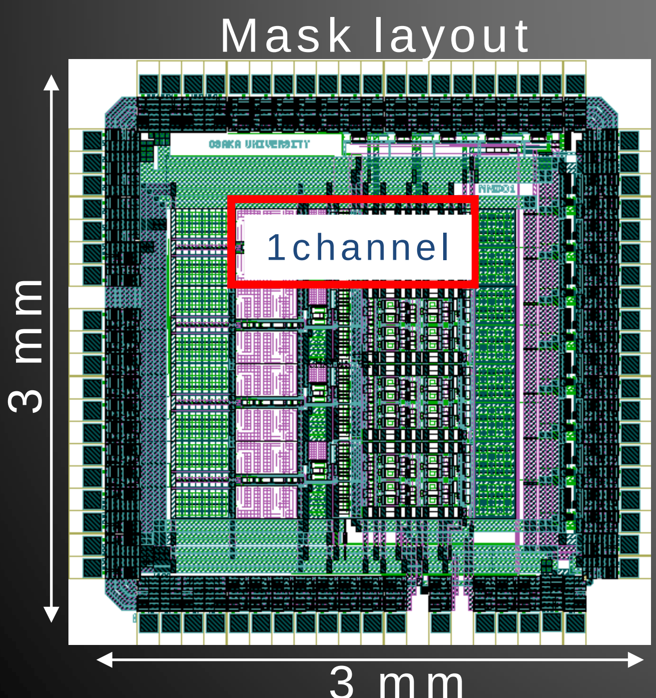




Pre-amp multiply signal 10 times

DAC gives offset to signal level

ΔΣ AD conversion of voltage gap

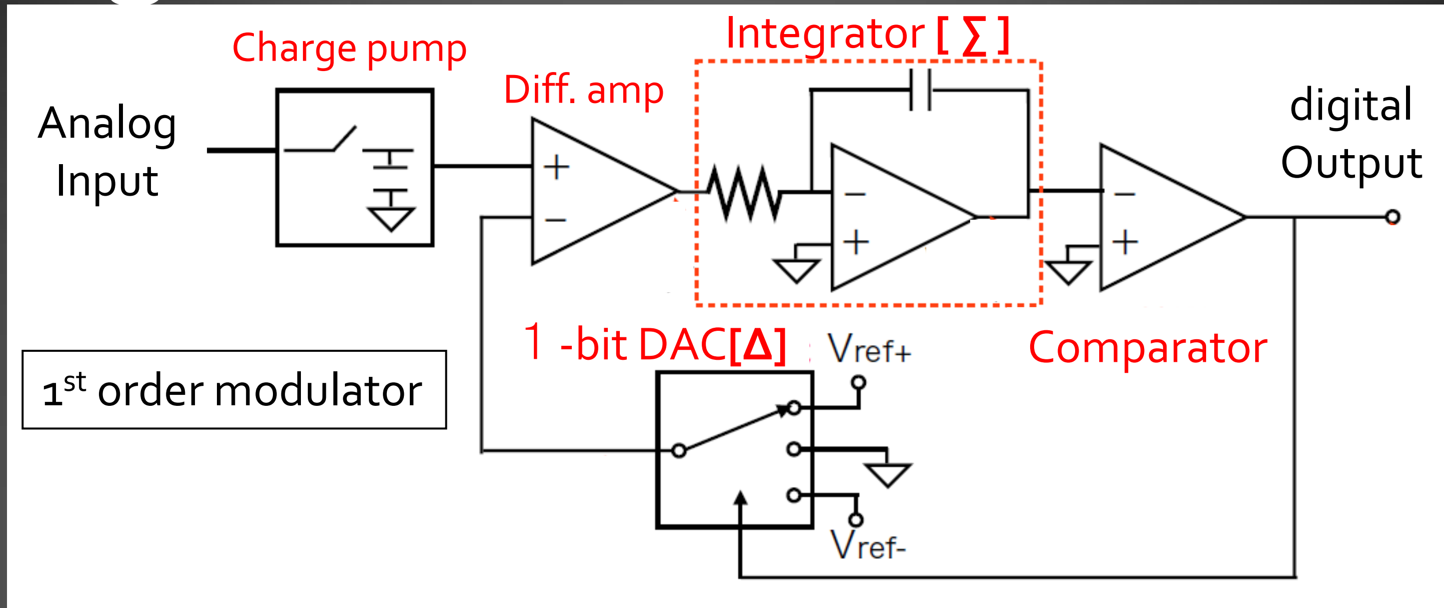


Bare chip size	3 mm X 3 mm
Num. of ch	4
Power supply	3.3 V
process	TSMC 0.35 **μm** CMOS

※made by TSMC via MOSIS service

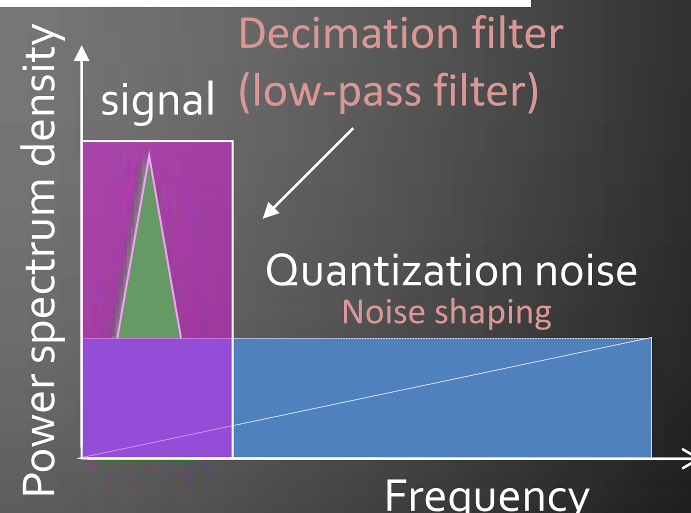
QFP package of 15mmX15mm

Configuration of ΔΣ modulator



$$O(f) \approx e^{-j2\pi f T_{clk}} I(f) + 2\pi f T_{clk} N(f)$$

Filter in order to cut the high-frequency quantization noise



x(n) : n-th output
w(n): filter coeff.

ASIC output
00101010010
111010111…

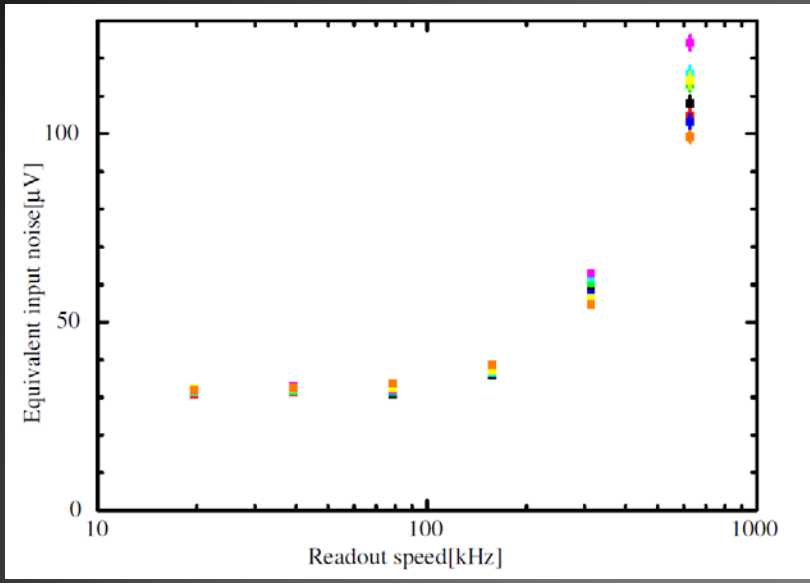
Decimation filter

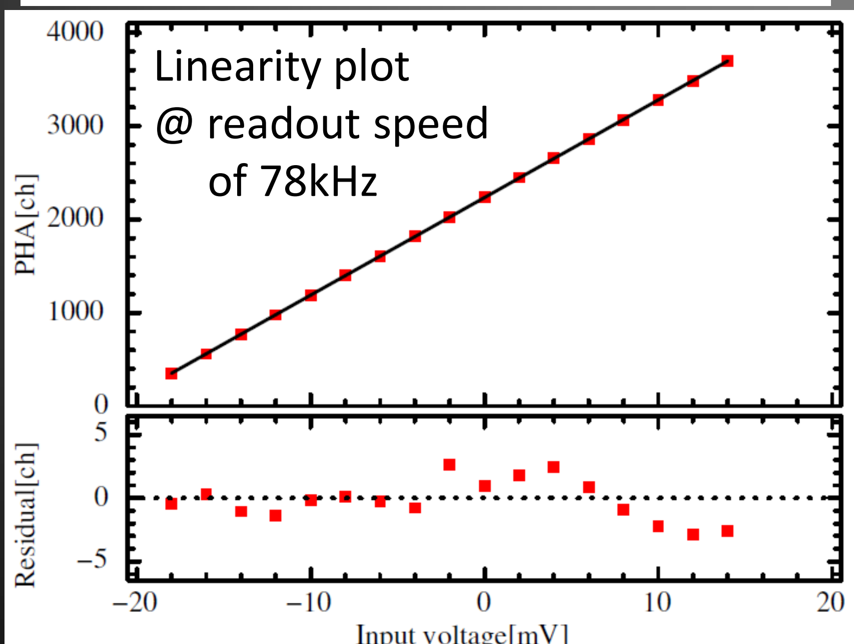
$$\sum_{n=1}^{n=155} (2 \times x(n) - 1) \times w(n)$$

$$= -w(1) - w(2) + w(3) - w(4) \cdots$$

decimal value

Performances as FE (1/2)





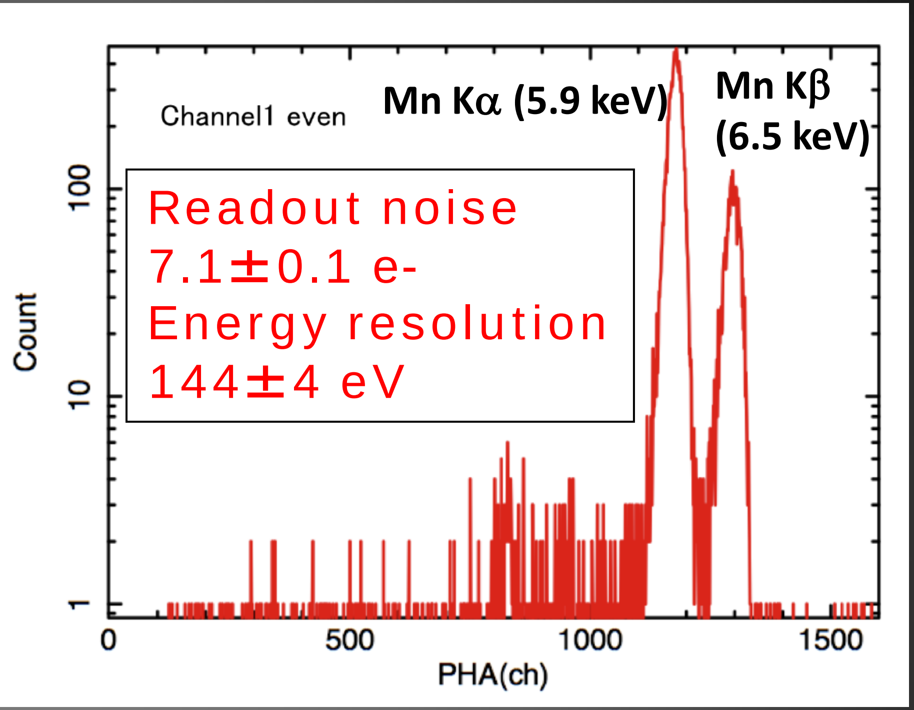
✓Power consumption : <170mW per chip @ <500kHz assuming standard LVDS output of 3.5mA/pair

✓Input equivalent noise : 29～34μV @ <100kHz (expected noise level is 6e- **if we use CCD of 5μV/e**-)

✓Integral non-linearity : ≦0.3% in the input signal range of ～35 mV (corresponding to X-ray energy of 0 - 30keV) @ ≦ 100 kHz

Performances as FE (2/2)

✓Spectroscopic performance measured with prototype CCD of ASTRO-H exhibited almost the same energy resolution as that of the X-ray CCD camera currently in orbit (note that it is for single pixel events).



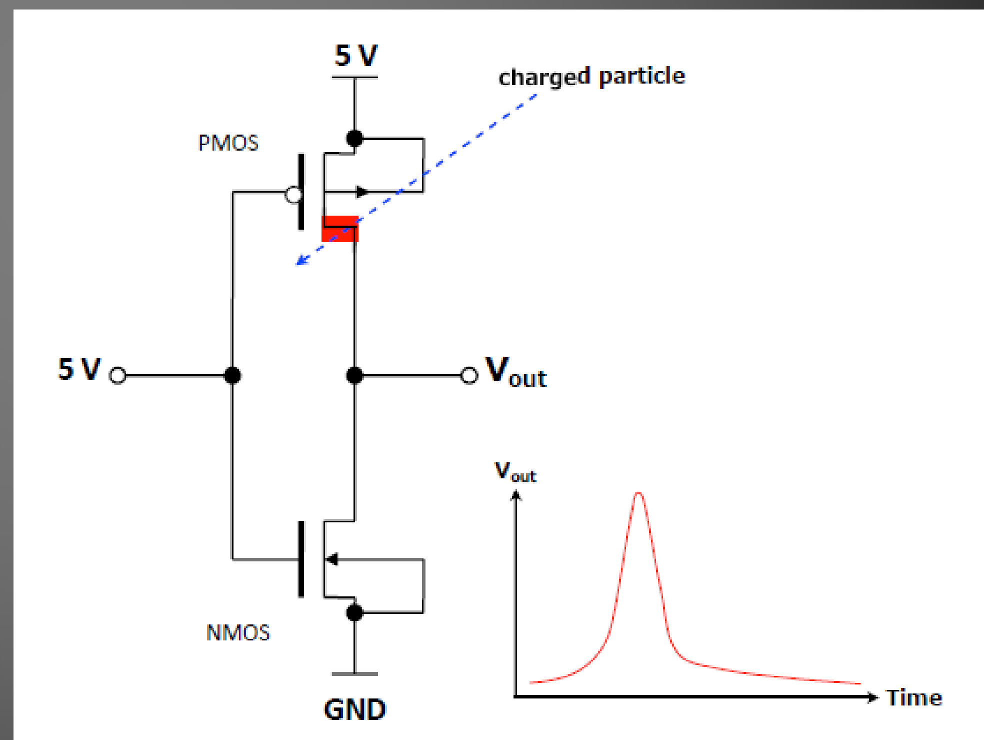
$$\sqrt{\mathrm{Re}\,adOutNoise(CCD)^2 - ASICUnitNoise^2} = NoiseFromOthers$$

$$\sqrt{\left(7.1(e^-)\right)^2 - \left(\frac{32(uV)}{6(uV/e^-)}\right)^2} \approx 4.7(e^-)$$

✓Now the noise from other than ASIC is almost the same as that from ASIC.

Radiation damage to ICs in satellites

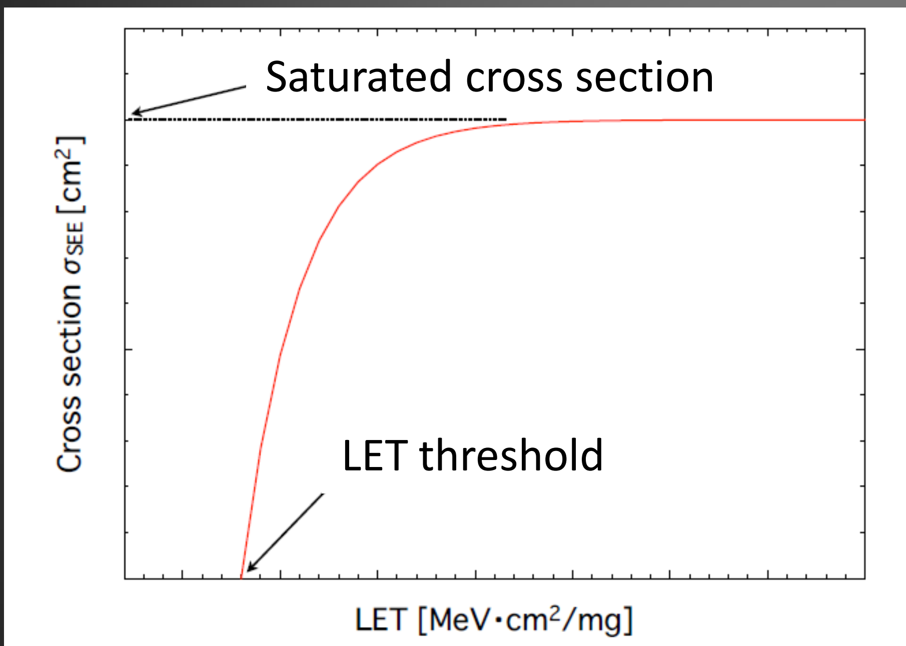
- Total Ionizing Doze(TID)
  - Integral damage primarily due to solar protons • electrons and trapped protons in the SAA cause increase of leak current.
  - Our ASIC has already proved its sufficiently high TID tolerance (x10 of requirement, Nakajima et al. 2011)
- Single Event Effect (SEE)
  - Stochastic events primarily due to a large amount of electron/hole-pairs created by galactic cosmic rays and heavy ions from the sun It caues Single Event Upset(SEU) that turn over bits in memories and latch-up (SEL).



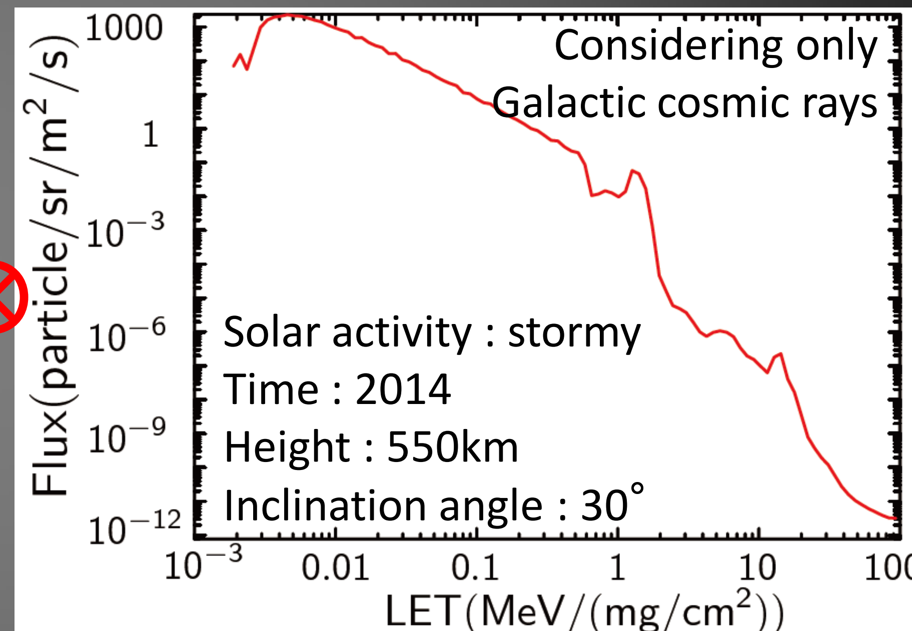
Estimation of SEE tolerance

The cross section for SEE is generally expressed as a function of linear energy transfer (LET : MeV・cm^2/mg). Parameters are Saturated cross section and LET threshold (Weibull curve).

Weibull curve



Integral LET flux spectrum in an LEO



The cross section must be multiplied with LET spectrum in the orbit. Our target missions (ASTRO-H and FFAST) will be put in similar Low Earth Orbits (LEOs) with height of 550 km and the inclination of 30°

p/Heavy ion irradiation test

Species	Energy (MeV/u)	LET (MeV/(mg/cm^2))
H	100	5.9×10^{-3}
Si	400	4.9×10^{-1}
Fe	400	1.7
Kr	200	4.7
Xe	400	7.2
Xe	200	1.1×10^{1}
Fe	6	2.2×10^{1}
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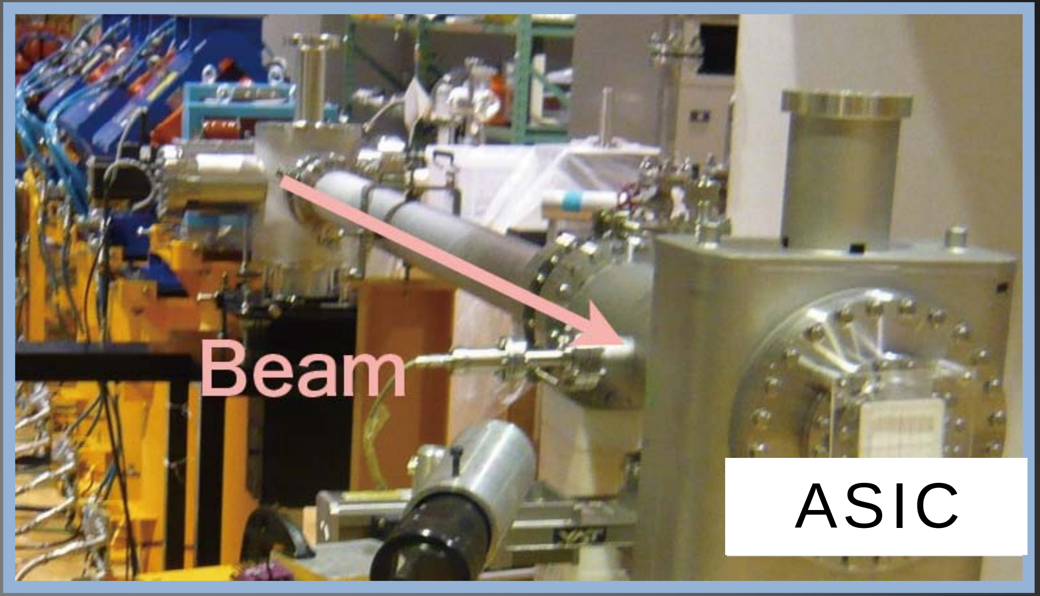
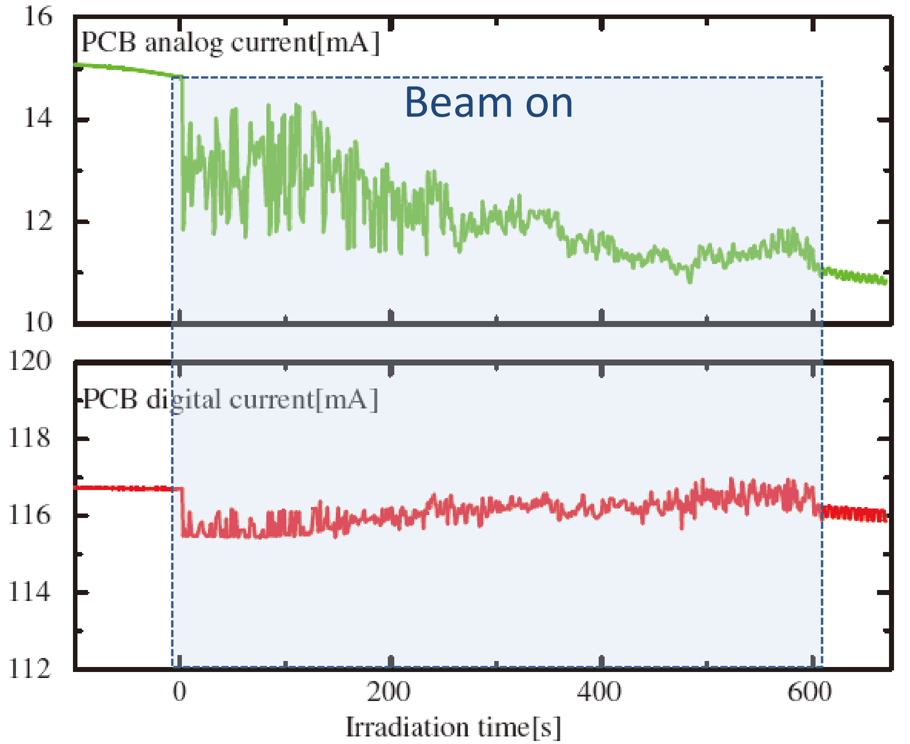


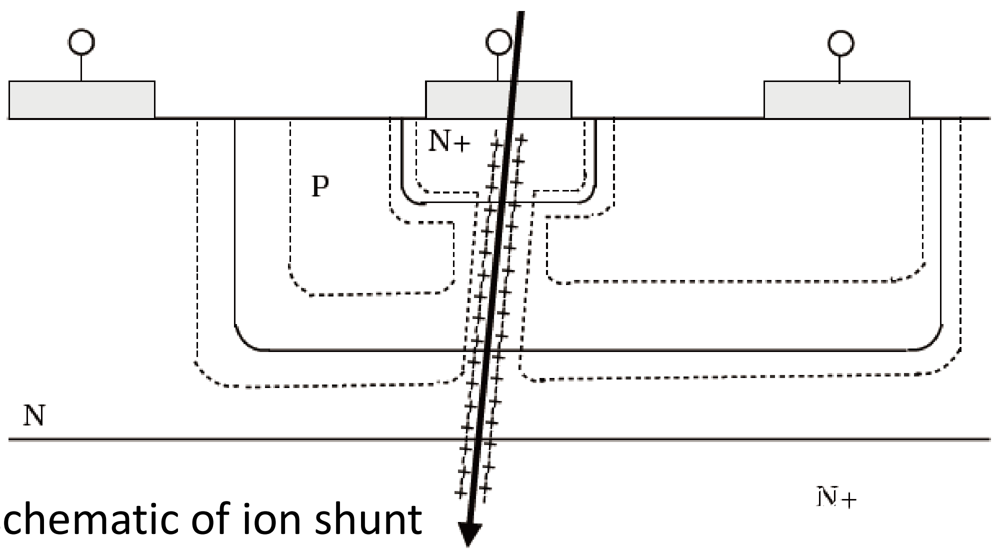
Beam line @ NIRS/HIMAC

- ✓ASIC bare chip was directly irradiated with heavy ions.
- ✓For lower energy beams, heavy ions are extracted before they were put into the synchrotron and DUT were put in a vacuum.

✓Current in the test board and noise performance were monitored during irradiation.

SEL tolerance





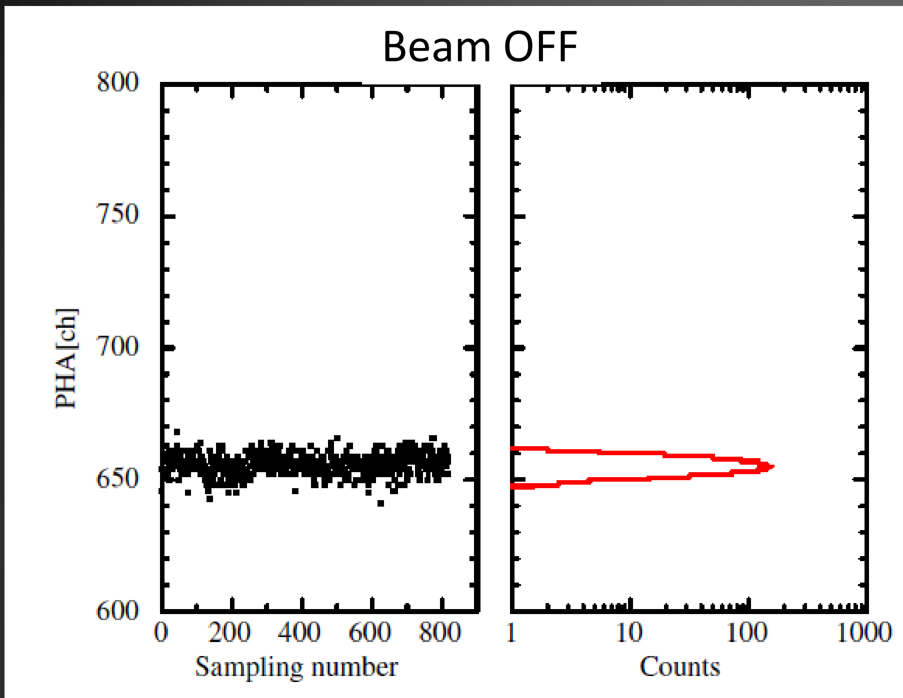
schematic of ion shunt

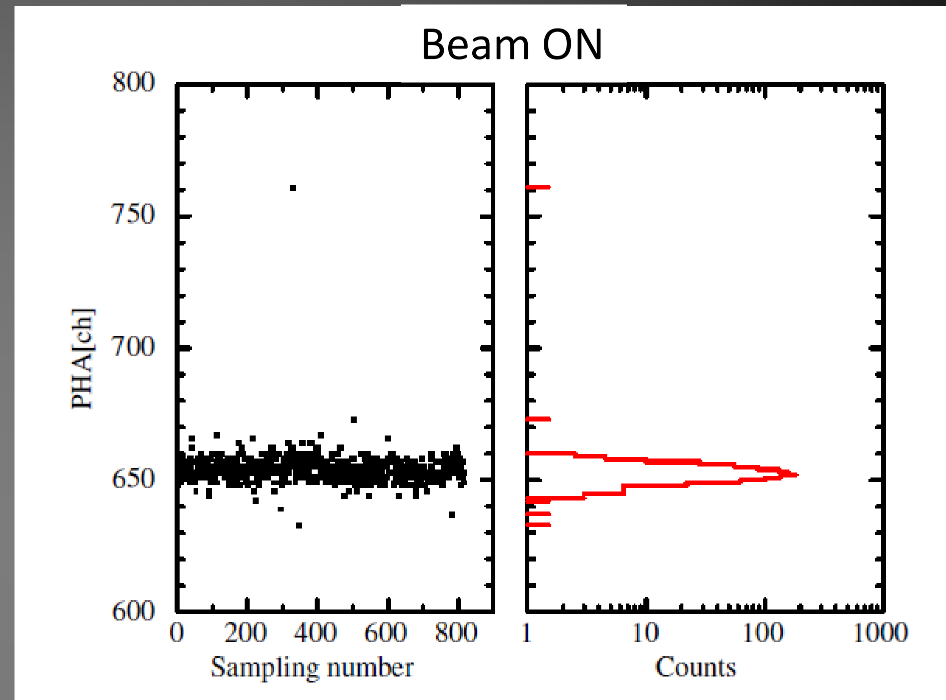
✓There's no latch-up throughout the test. Some time variability in the PCB current was seen, which might be due to "ion shunt" in the MOS-Tr.

✓The cross-section against SEL is derived with 95% confidence level to be
< 2.7×10^{-11} cm²/(IonxASIC)

✓The expected SEL rate in the orbit is once per 6700 years.

SEU tolerance (1/2)

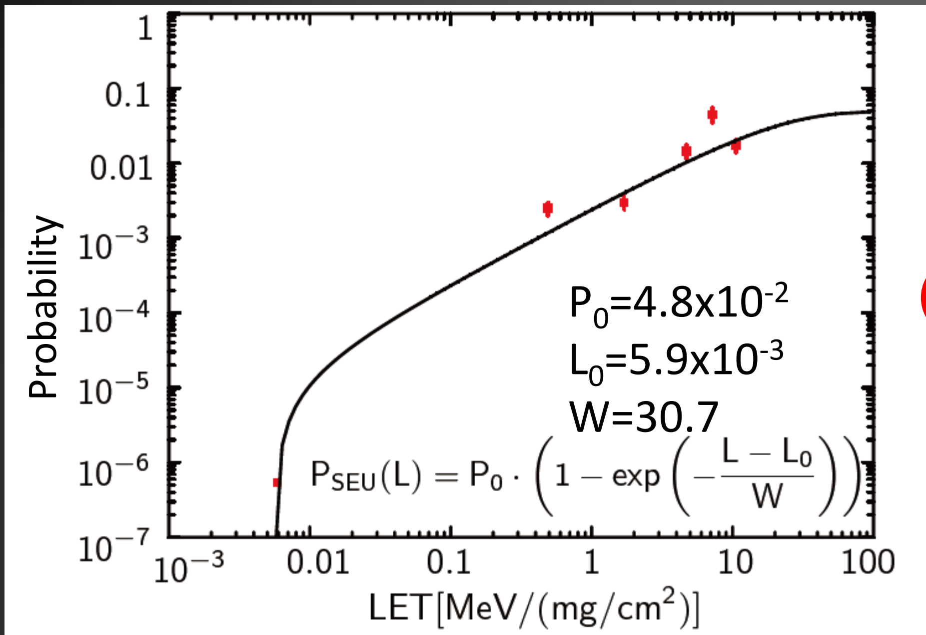




✓Some of the decimated pulse heights showed deviated values during irradiation in spite of the constant input voltage.

✓Those peculiar events are supposed to be due to any of the SEU in the digital circuit or charge injection into analog circuits. Regardless of the origin that cannot be identified, we call the events SEU and estimate the event rate in the LEO.

SEU tolerance (2/2)



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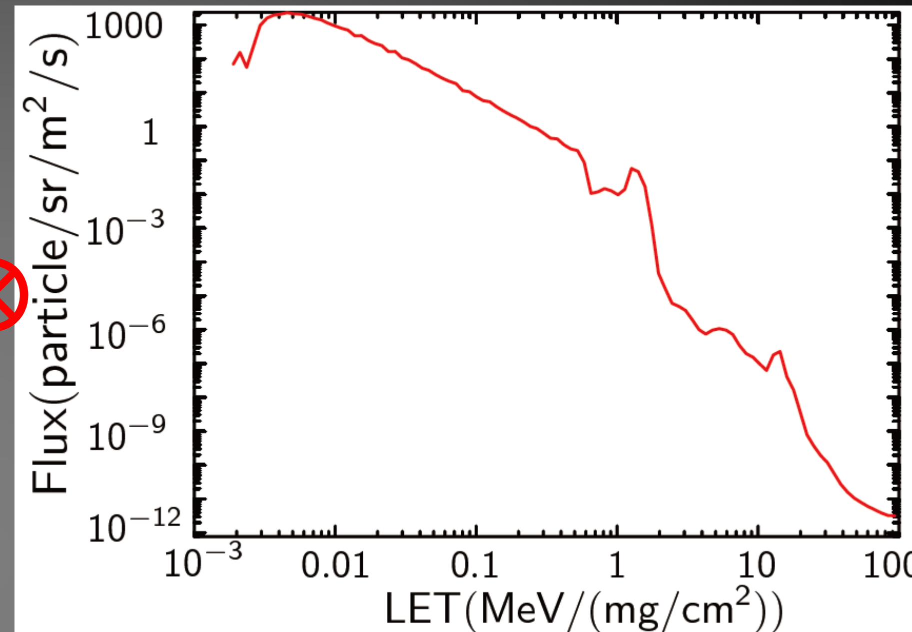


$$R_{SEU} = \int_{L_{th}}^{\infty} \underbrace{F(L)}_{\text{Flux}} \times P_{SEU} \times \underbrace{S}_{\text{Area}} \times \underbrace{\Omega}_{\text{Solid angle}} dL$$

Estimated SEU event rate in the LEO :
2.4×10^{-6} (1.4×10^{-8} – 6.6×10^{-4}) events/sec
Smaller than 5% of CCD origin Non X-ray background rate of ASTRO-H/SXI. Sufficiently low, sufficient SEE tolerance

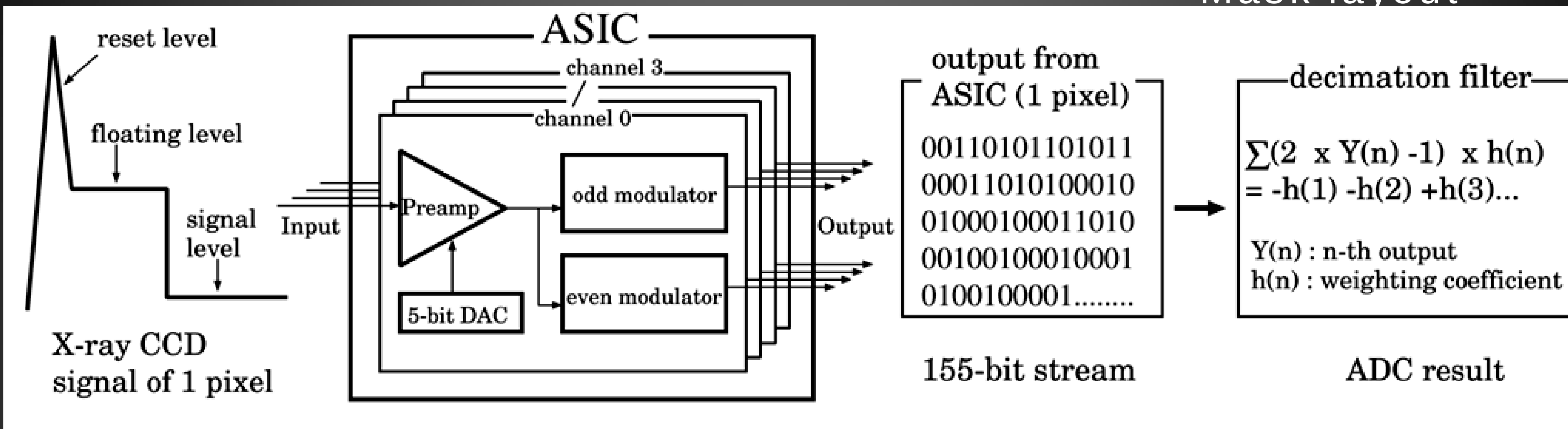
Summary

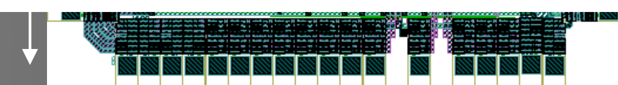
- Analog ASIC developed as front-end electronics of onboard CCD cameras for astronomical use
  - Proper function up to pixel rate of 625kHz
  - Input equivalent noise of 29-34μV
  - INL of 0.3% in the range of 0 - 30 keV X-rays
  - Package for space use already developed
- Radiation tolerance against SEE
  - Very high SEL threshold (> 58.9 MeV · cm^2/mg)
  - Estimate SEU rate in the LEO is sufficiently lower than that of NXB for ASTRO-H/SXI
  - Fabrication of the flight model front-end electronics are undregoing

Followings are backup slides

Circuit structure of ASIC

Mask layout





Pre-amp multiply signal 10 times

DAC gives offset to signal level

ΔΣ AD conversion of voltage gap

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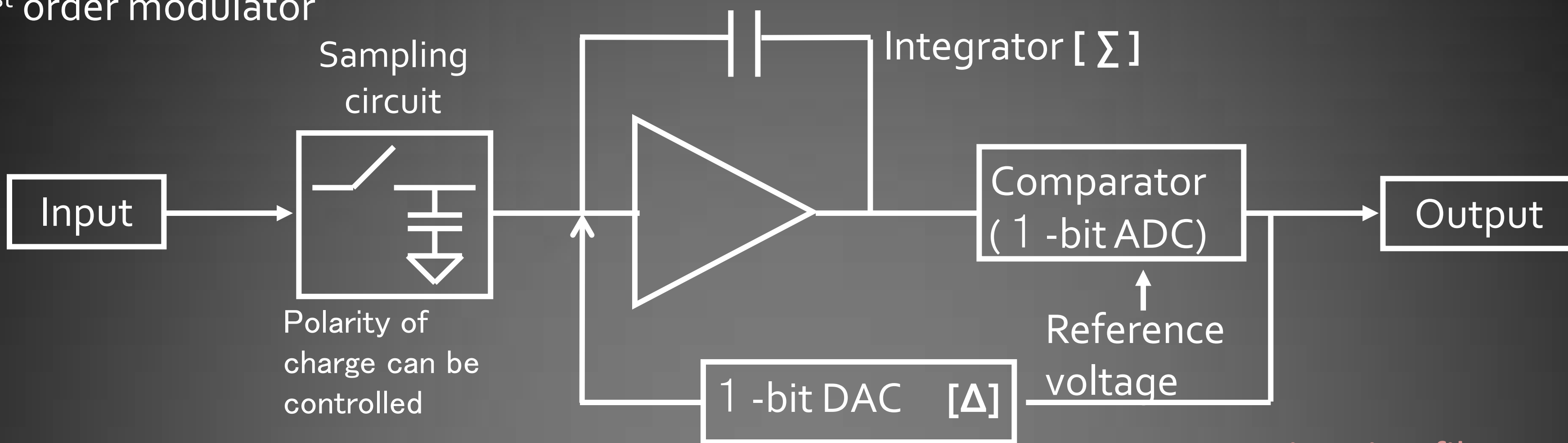
Num. of ch	4
Power supply	3.3 V
process	TSMC 0.35 **μm** CMOS

※made by TSMC via MOSIS service

QFP package of 15mmX15mm

Configuration of ΔΣ modulator

1st order modulator



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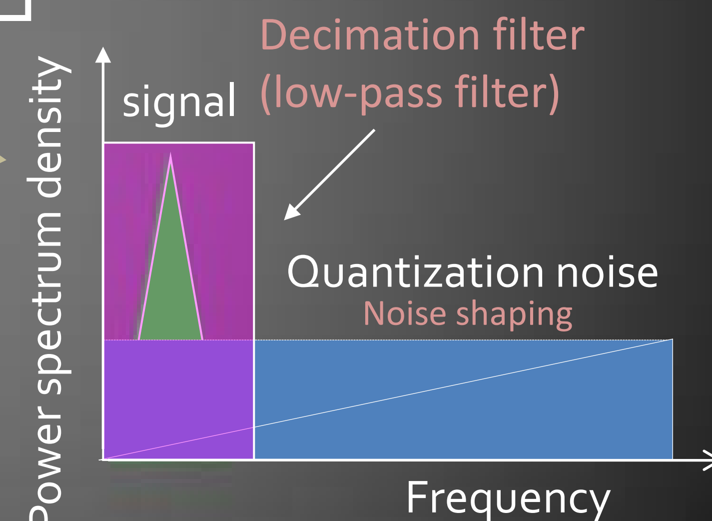
Filter in order to cut the high-frequency quantization noise



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Decimation filter

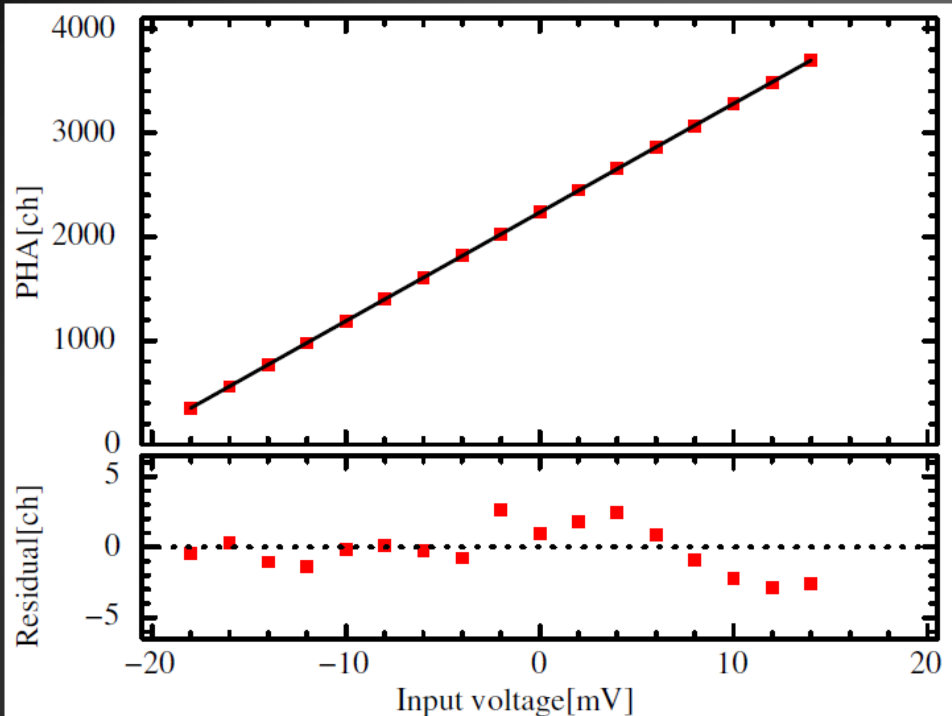
$$\sum_{n=1}^{n=155} (2 \times x(n) - 1) \times w(n)$$

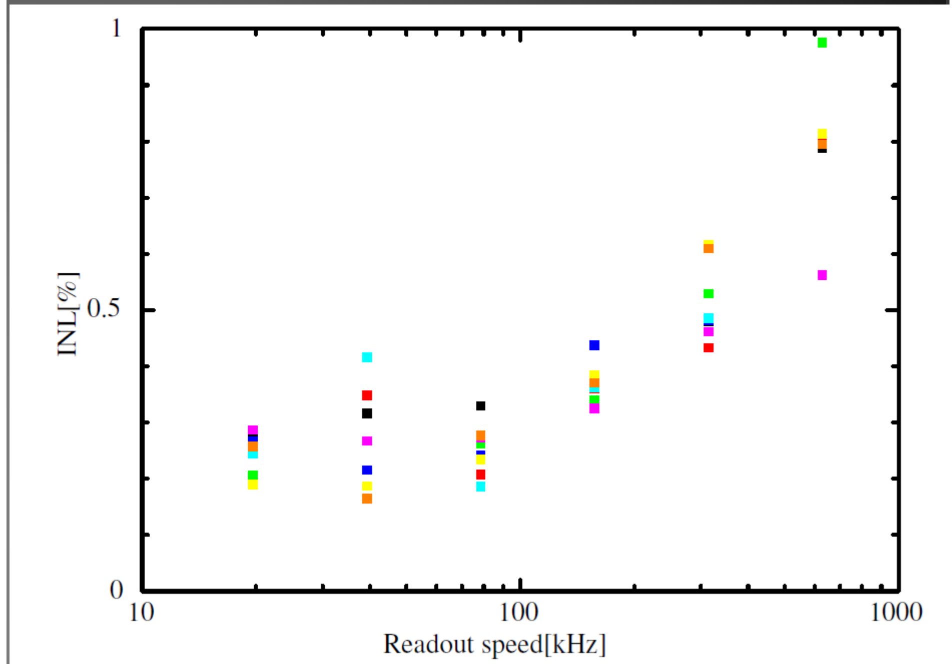
$$= -w(1) - w(2) + w(3) - w(4) \cdots$$

decimal value

Coefficient and num. of sample determine the resolution of ADC

Performances as FE (2/2)

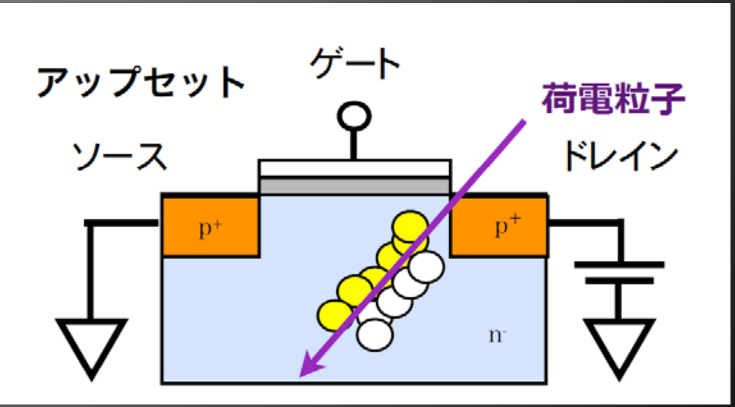




✓INL of ≦0.3% in the input signal range of ∼35 mV (corresponding to X-ray energy of 0 - 30keV) @ ≦ 100 kHz

Radiation damage to ICs in satellites

- Total Ionizing Doze(TID)
  - Integral damage primarily due to solar protons • electrons and trapped protons in the SAA cause increase of leak current.
  - Trapped holes in the gate oxide layer prevents MOS-Tr to close and hence they lead the current from power to ground.
  - Change in Vth and decrease of career mobility are also seen.
- Single Event Effect (SEE)
  - 主に系内起源宇宙線や太陽からの重イオンが多量に生成するelectron/hole-pairが及ぼす確率的現象。　レジスタやメモリのデータを反転させるSingle Event Upset(SEU)や、ラッチアップ(SEL)などがある。



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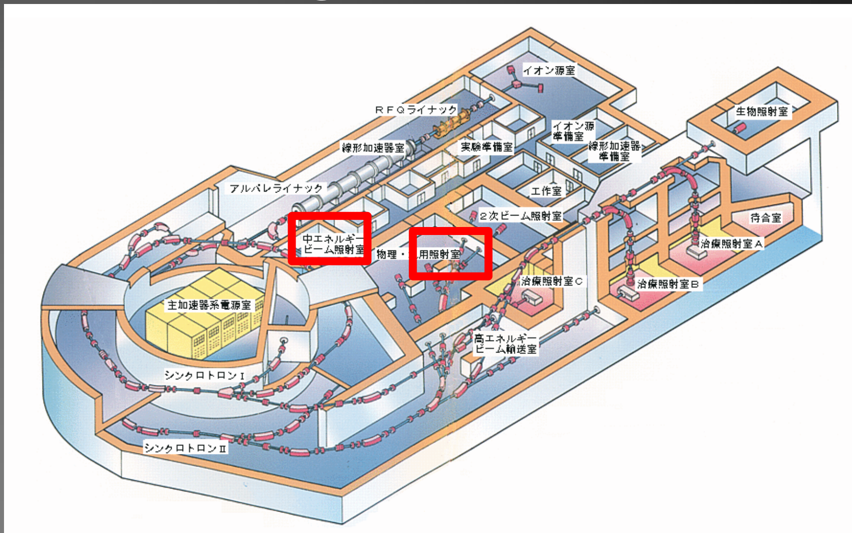

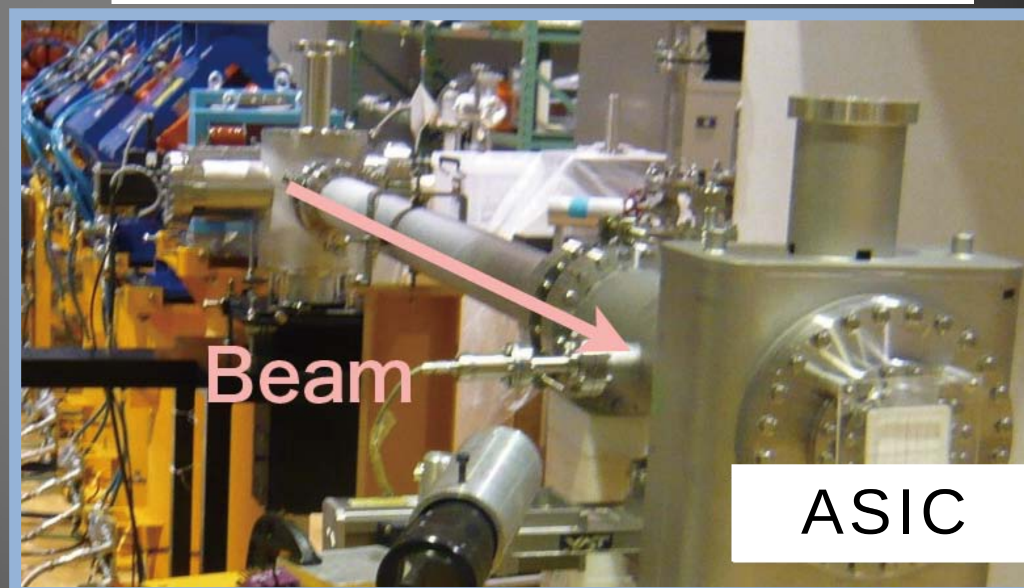

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