Wide band-gap semiconductor sensors and front-ends for harsh environments

KEK Electronics-system group
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Outline

- SiC sensors for MIP detectors at COMET muon experiment @ J-PARC (Japan Proton Accelerator Research Complex)
    - Application to muon beam monitor and proton extinction monitor
    - Characteristics of the PN-sensors
- Diamond sensors for neutron detection at Fukushima nuclear power plant
    - Device fabrication and characteristics
    - Detector system and prototype performance

Introduction

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- SiC and diamond are more radiation-hard than standard n-type Si, 10^{14} n_{eq}/cm^2 for SiC and 10^{15} n_{eq}/cm^2 for diamond.
- Uniform device characteristics and productivity are still challenging.

Property	Diamond	GaN	4H-SiC	Si	Ge	CdTe	CdZnTe
E_g [eV]	5.5	3.39	3.26	1.12	0.67	1.44	1.60
$E_{breakdown}$[V/cm]	10^7	$4x10^6$	$2.2x10^6$	$3x10^5$	10^5	TBD	TBD
μ_e [cm²/Vs]	1800	100	800	1450	<3900*[2]	1090*[1]	906*[3]
μ_h [cm²/Vs]	1200	30	115	450	<1900	110	-
v_{sat} [cm/s]	$2.2x10^7$	-	$2x10^7$	$0.8x10^7$	$0.74x10^7$*[5]	10^7	10^7
Z	6	31/7	14/6	14	32	48/52	48/52/30
ε_r (dielectric const.)	5.7	9.6	9.7	11.7	TBD	TBD	TBD
e-h energy [eV]	13	8.9	7.6-8.4	3.6	2.9	4.5	5.0
Density	3.515	6.15	3.22	2.33	5.3	5.9	5.8
Displacem. [eV]	43	20	25	13-20	15-18	5.3-6.2*[4]	-

low leakage current

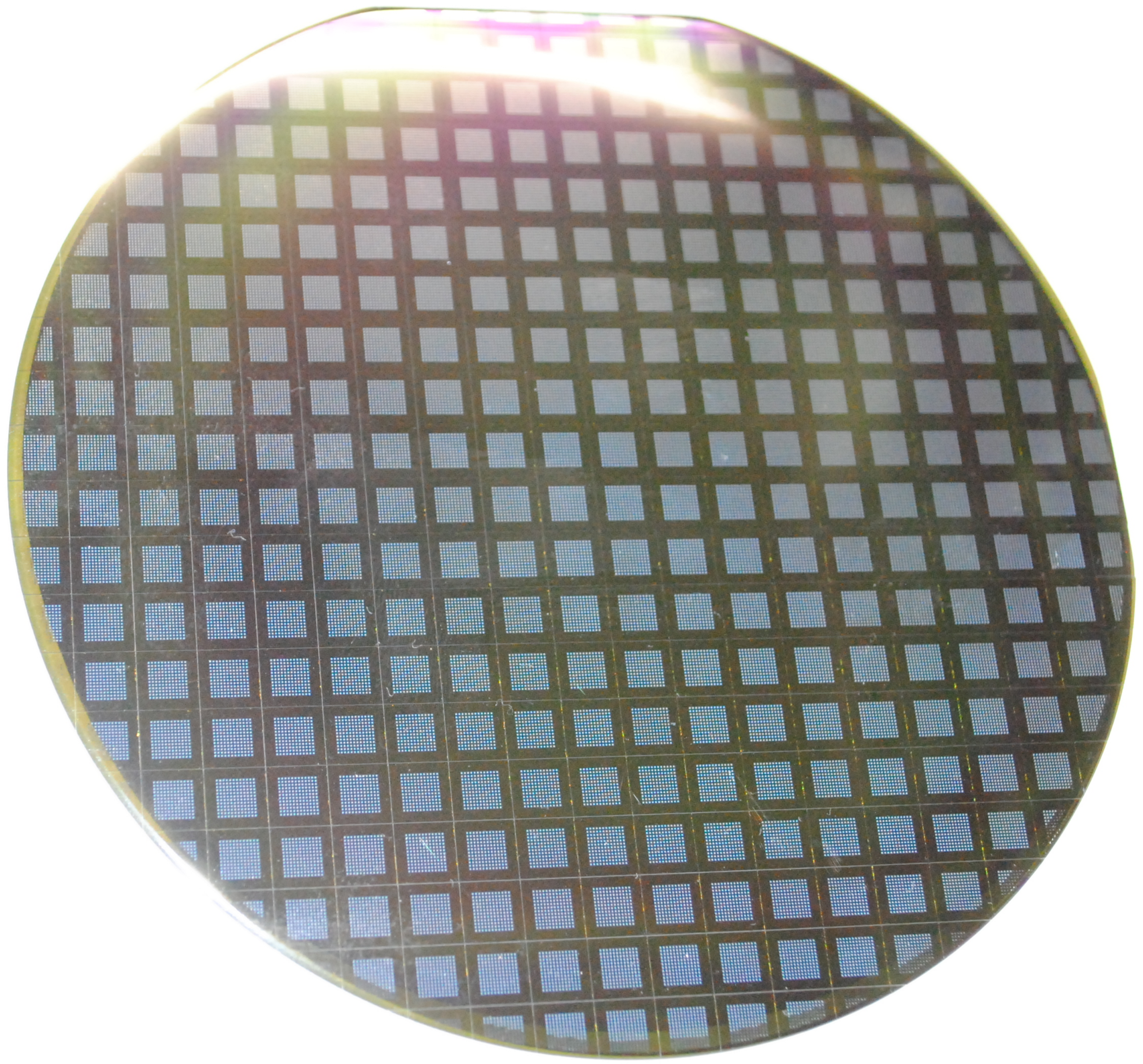
high radiation-tolerance

small signal charges

For stable device production, KEK-Esys collaborates with AIST power device group from 2019.

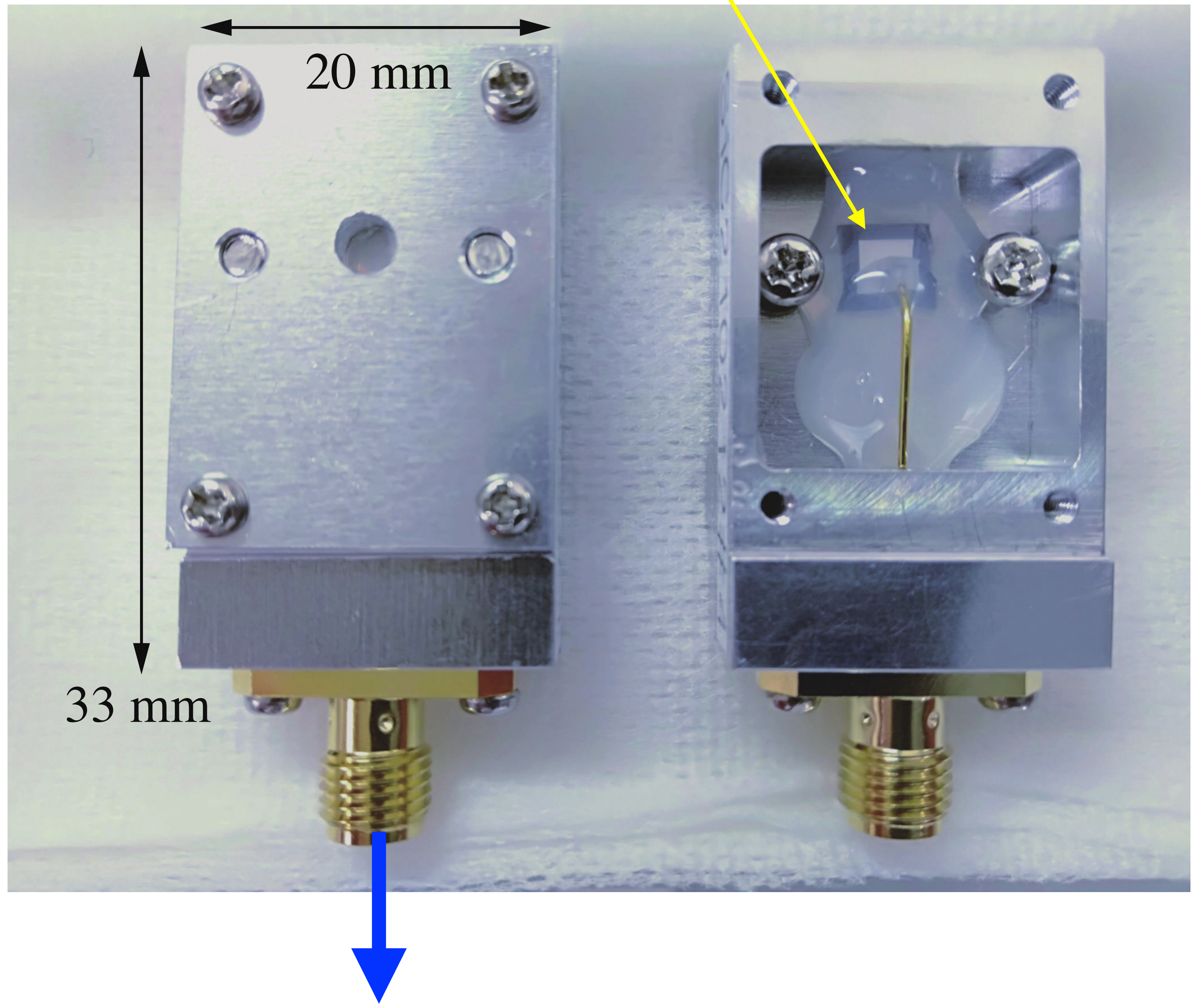
SiC device fabrication

- PN diodes in wafer process
- Reverse bias tolerance of 3 kV
- 50 um epi grown on (0001) 4H-SiC n-type substrate @AIST
- Nd-Na: 4.7 x 10^{14} cm^{-3}
- Thickness: 350 um
- 260 dies with 5 x 5 mm^2 from 4-inch wafer, 4 x 4 mm^2 active area



Schottky diode	PN diode
- Easy process	- Difficult process (High temperature annealing)
- Sensitive to surface conditions	- Less sensitive to surface conditions

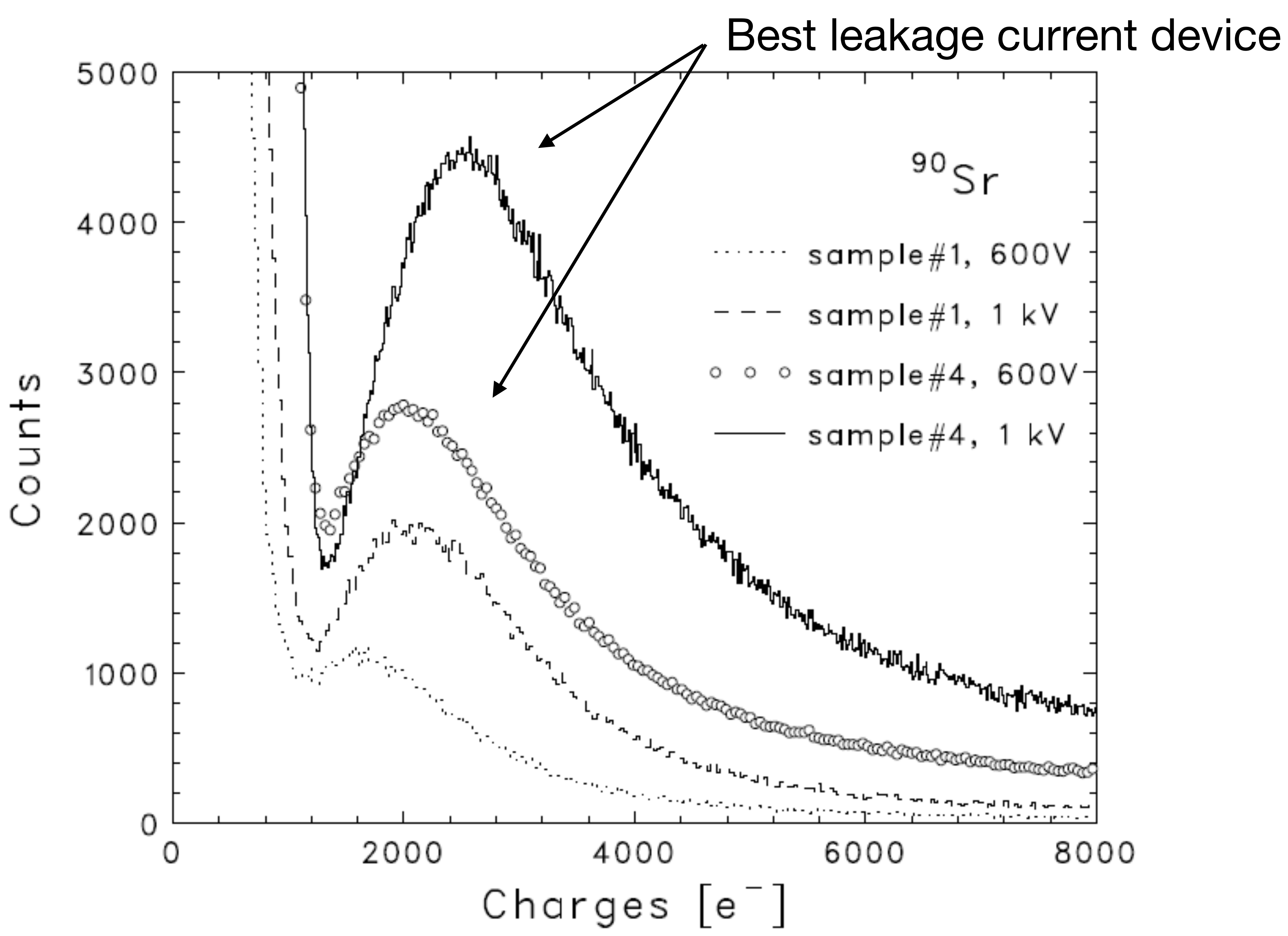
Silicone rubber for preventing electric discharges



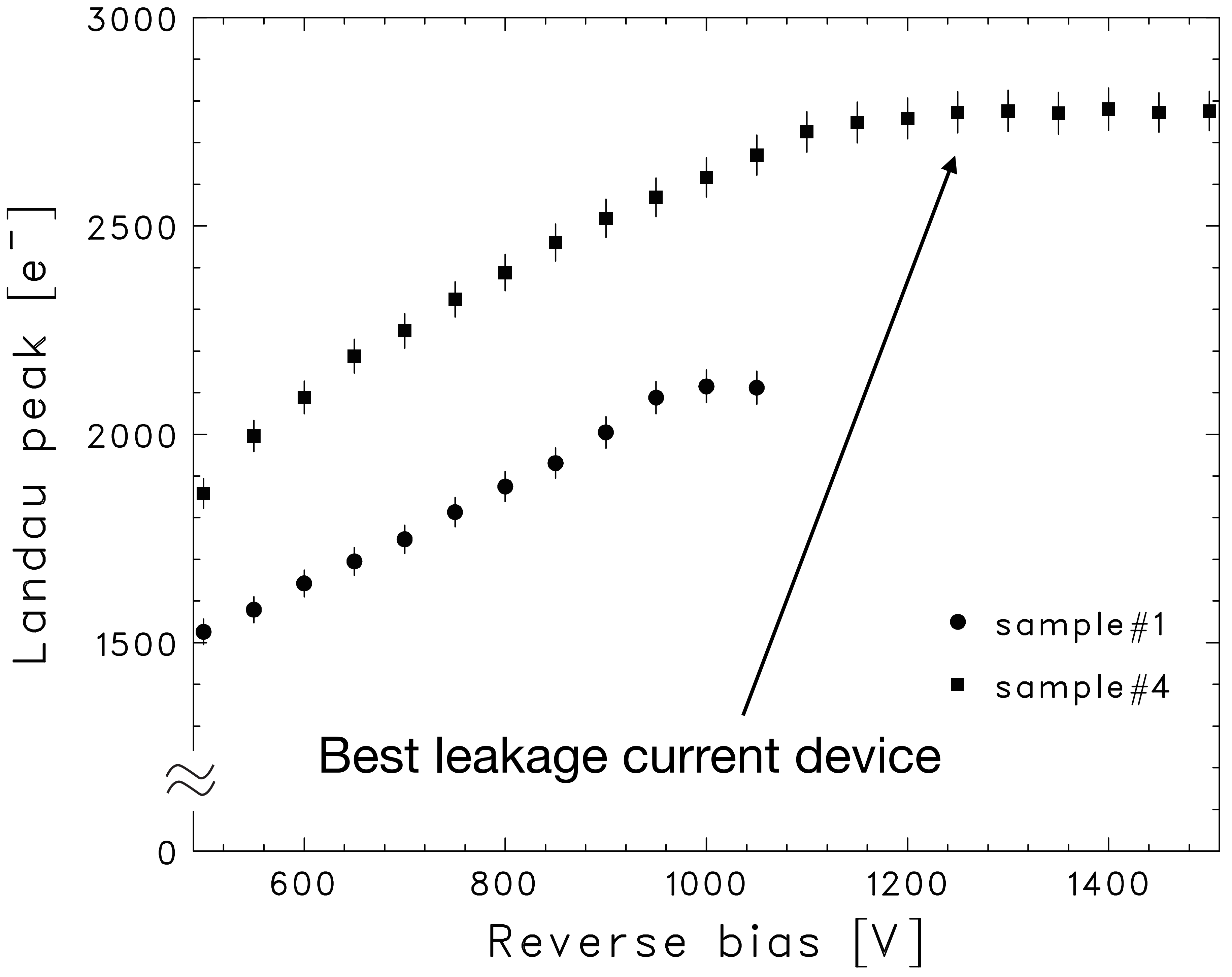
commercial CSA (AC-coupling)+shaper

Device characteristics

- Leakage current <10 nA (26 samples from 260 dies), uniform within one order of magnitude
- Stable Landau peak position (no polarization/charge-up)
- Full depletion voltage 1000 V for 50 um epi (TCAD).



Landau peak is separated from pedestal in worst leakage device.



Full-depletion voltage is consistent with TCAD simulation.

What can we do with these devices?

Needs for SiC sensor: COMET at J-PARC

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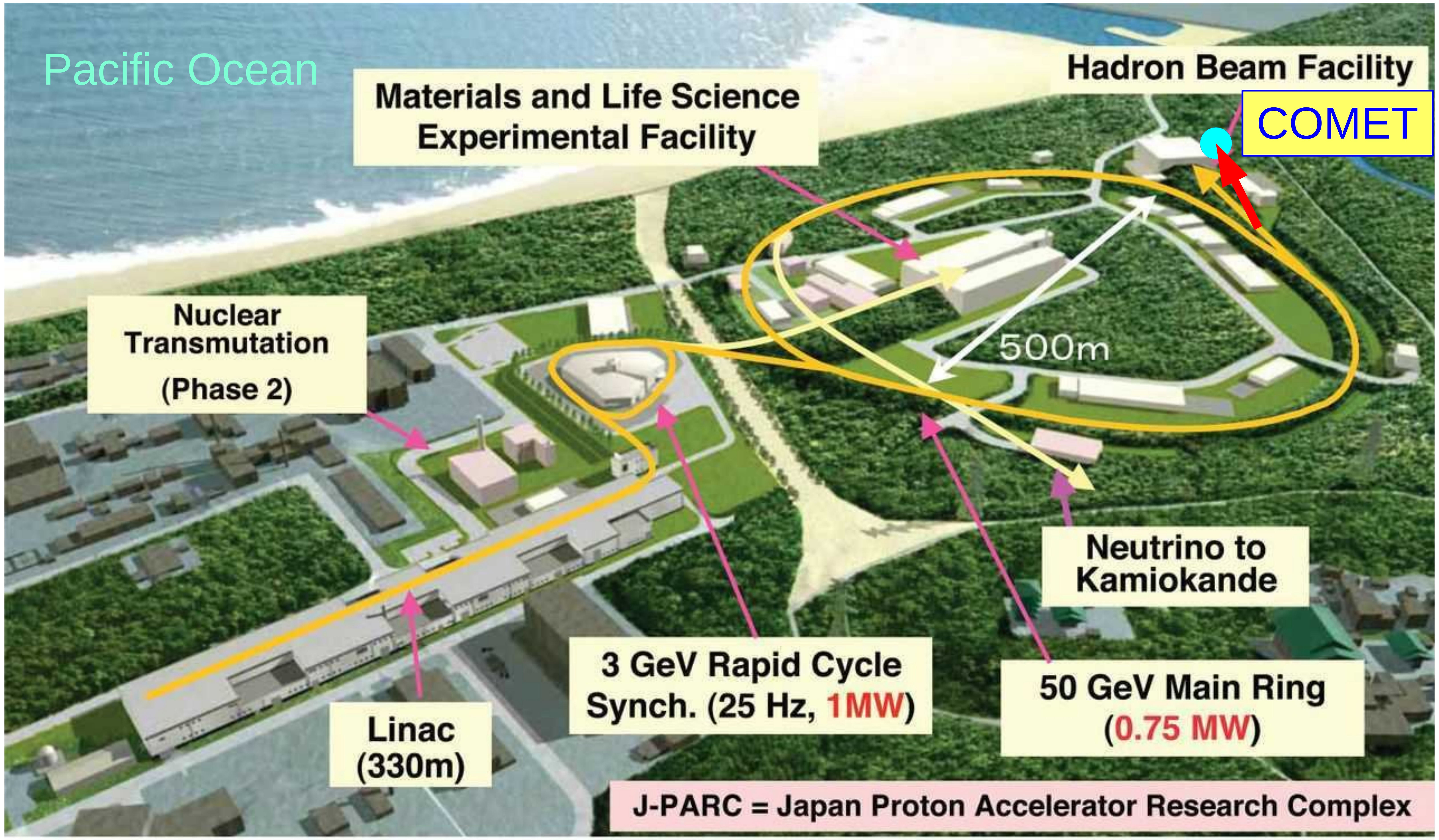
- COMET (COherent Muon to Electron Transition) starts from 2027 (one of the KEK core projects).
- They require rad-hard beam monitors for high-intensity 8 GeV protons / secondary particles.



What do we do in COMET: Muon to Electron Transition

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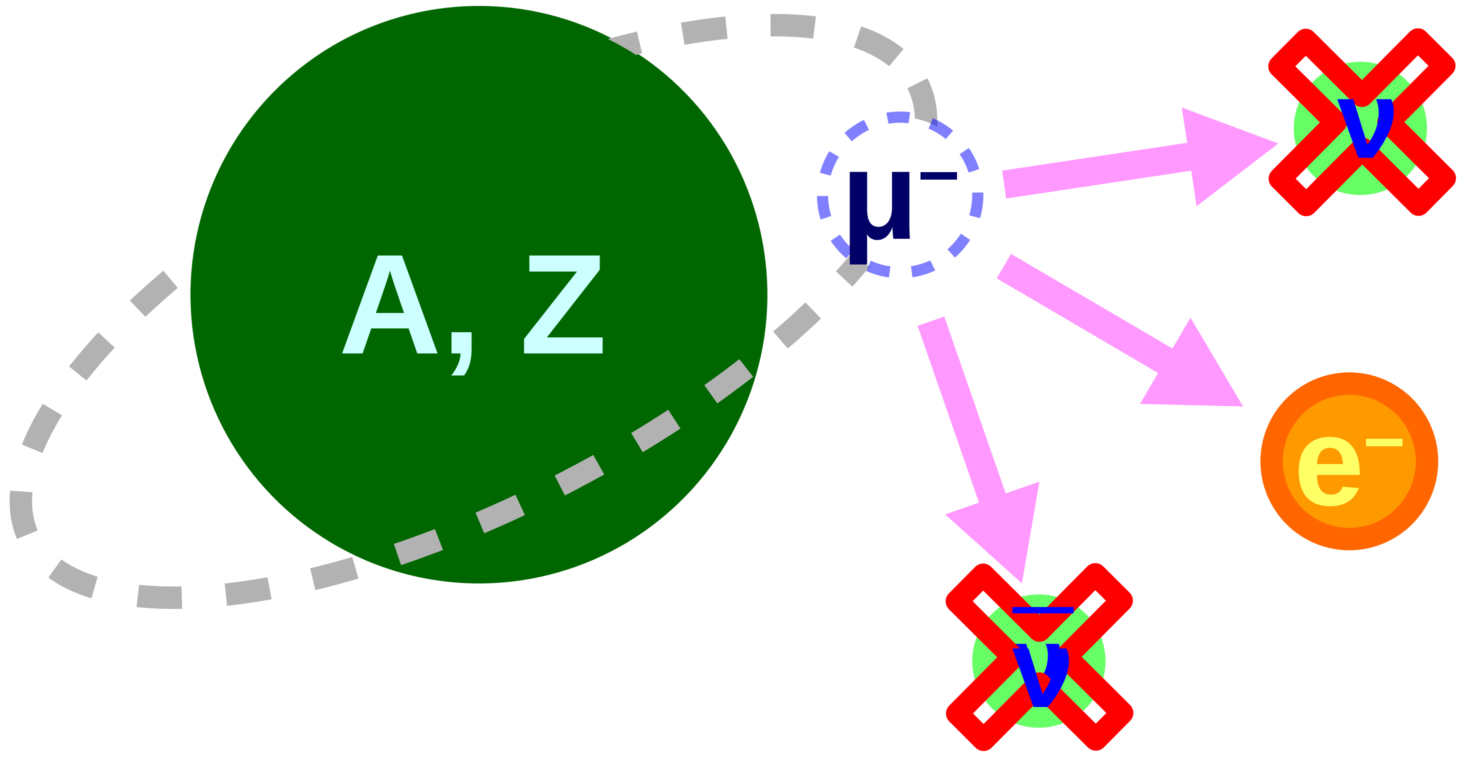
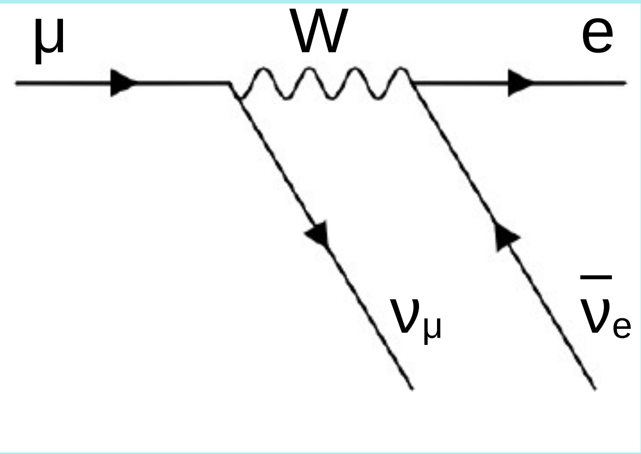
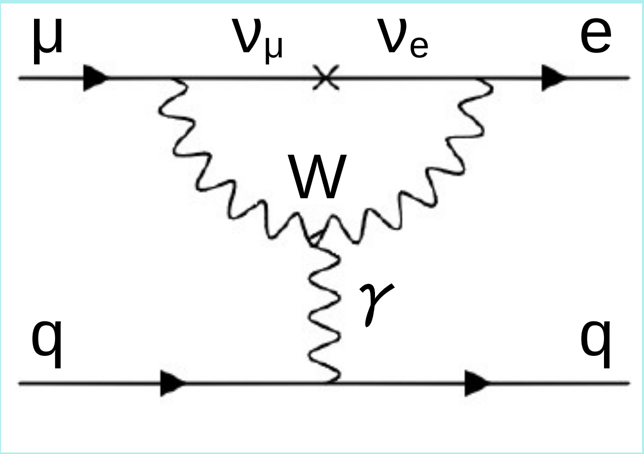


- Conversion of a muon to an electron is "Charged Lepton Flavor Violation" process and strongly prohibited in the Standard Model.
- Its discovery is an evidence of the new physics.

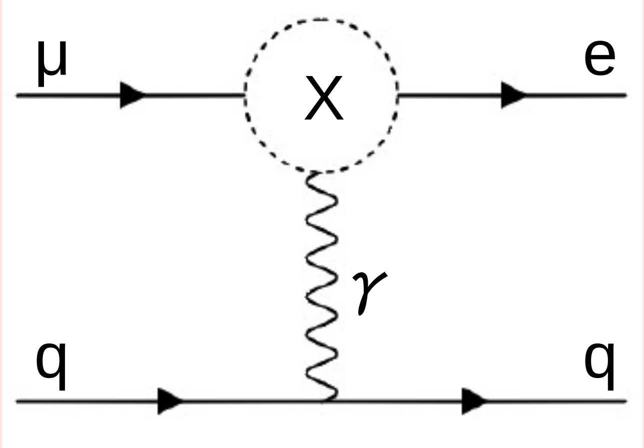
Standard Model

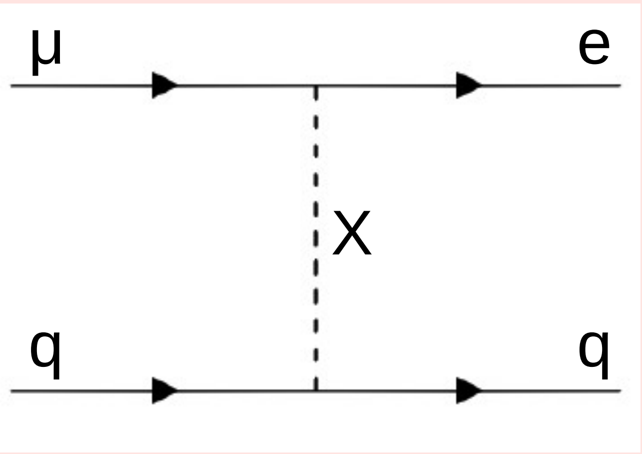




- ✓ Muon can decay to electron with neutrinos.
- ✓ μ-e conversion via neutrino oscillation is $<O(10^{-54})$.

New Physics



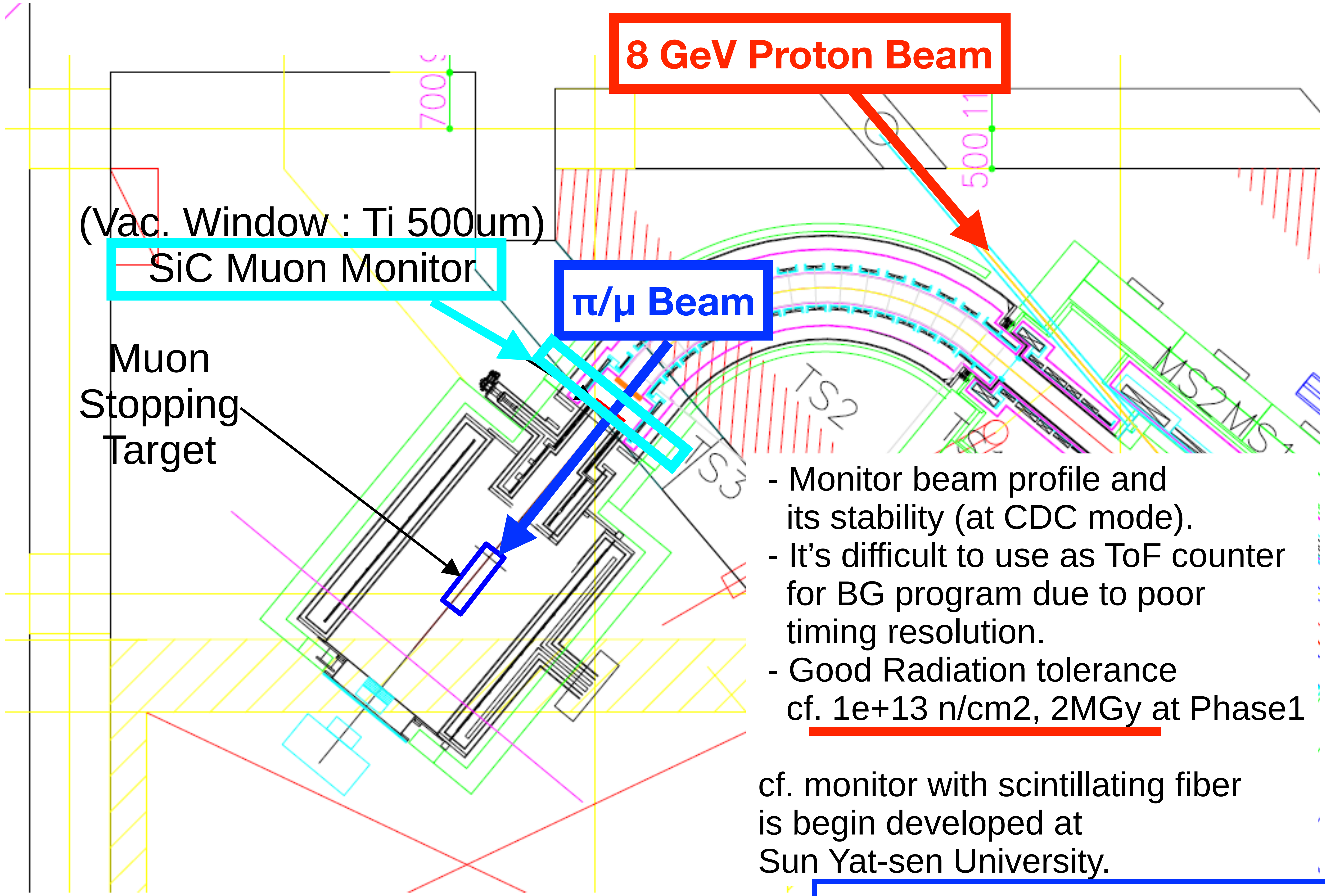


- ✓ Sensitivity for the new physics scale is >1000TeV.
- ✓ μ-e conversion has sensitivity to both photonic and non-photonic interaction.

It's good opportunity to install "own" detectors to contribute to new physics!

COMET Phase-1

- 8 GeV proton beam is injected to Pion production target.
- Pions decay to muons during transportation in Solenoid magnet.



- Monitor beam profile and its stability (at CDC mode).
- It's difficult to use as ToF counter for BG program due to poor timing resolution.
- Good Radiation tolerance cf. 1e+13 n/cm2, 2MGy at Phase1

cf. monitor with scintillating fiber is begin developed at Sun Yat-sen University.

Radiation-tolerance is the key to the muon beam monitor.

Concept of SiC Muon Beam Monitor

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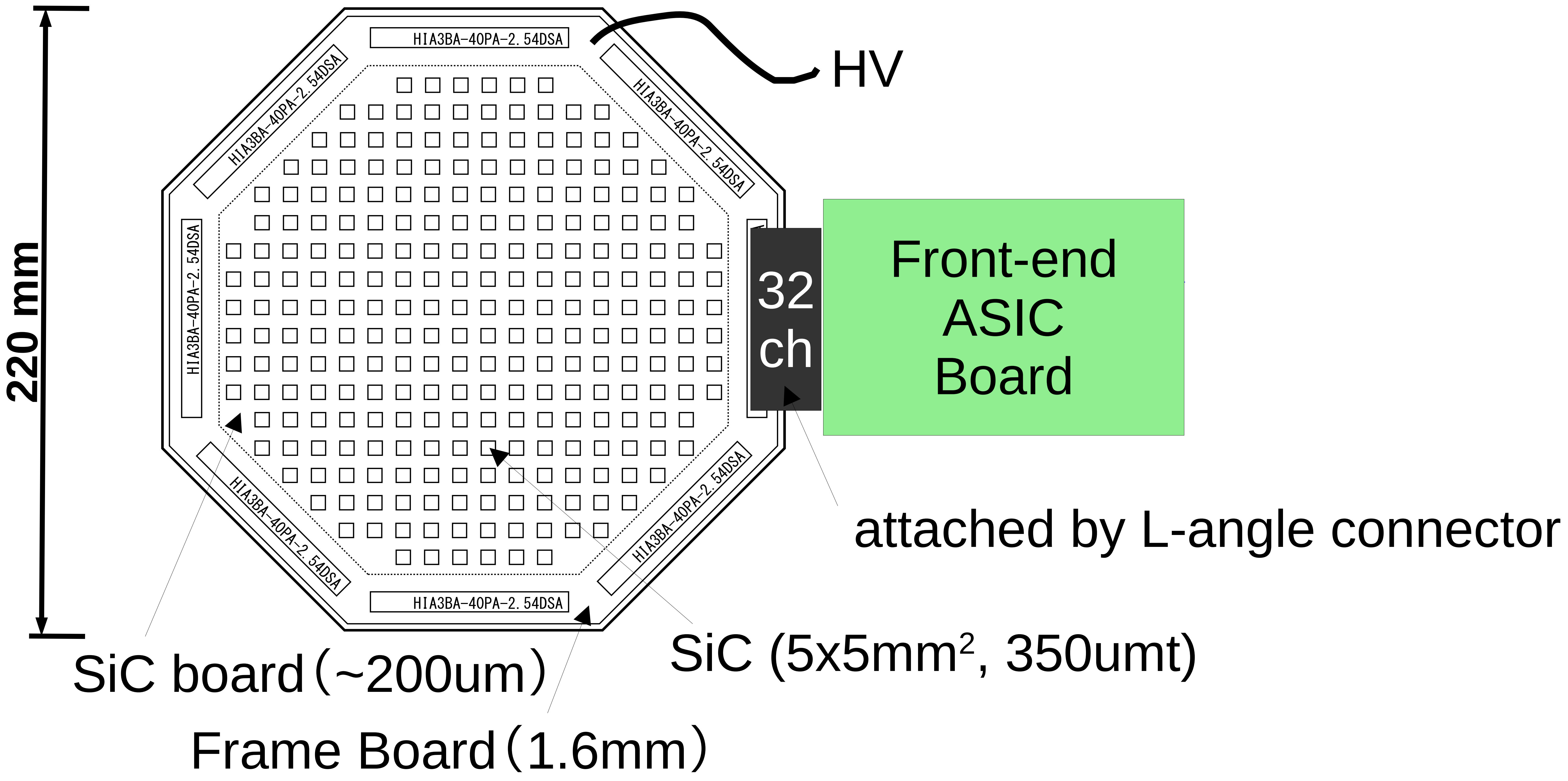
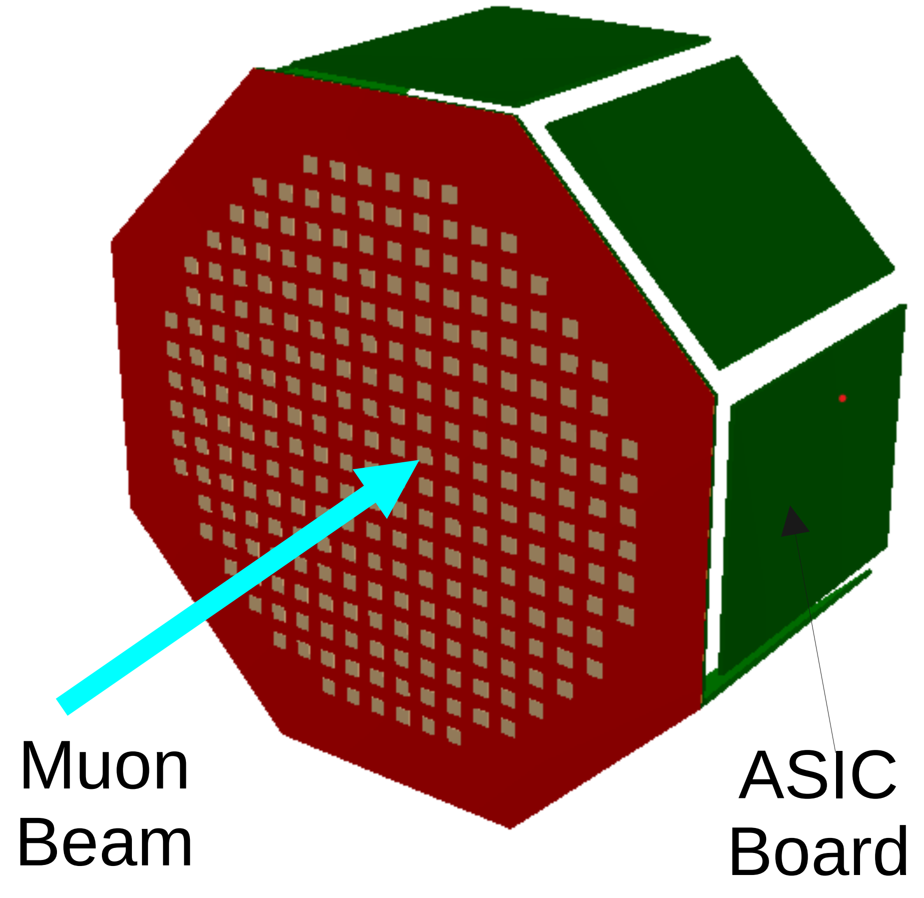
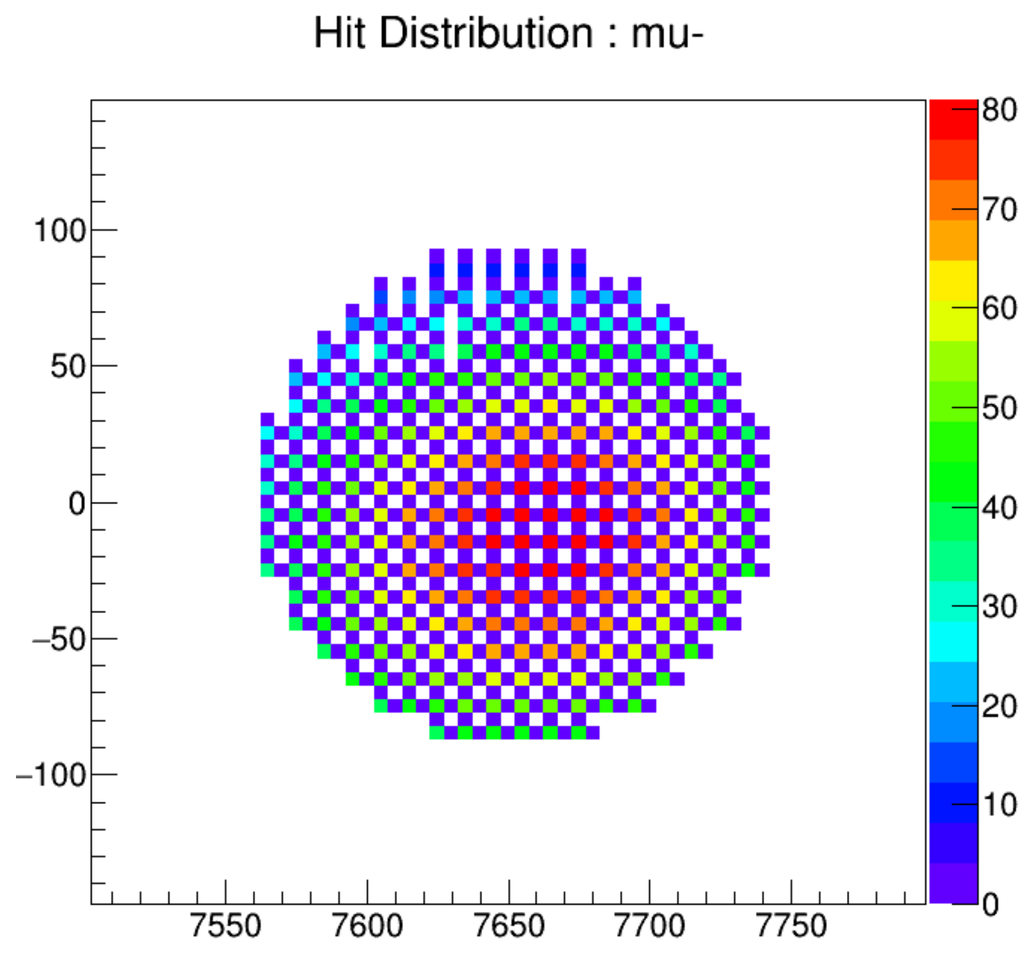






- Center region is thin Kapton board. Edge region is normal board to support the center region.
- Signal wires run between SiC sensors.

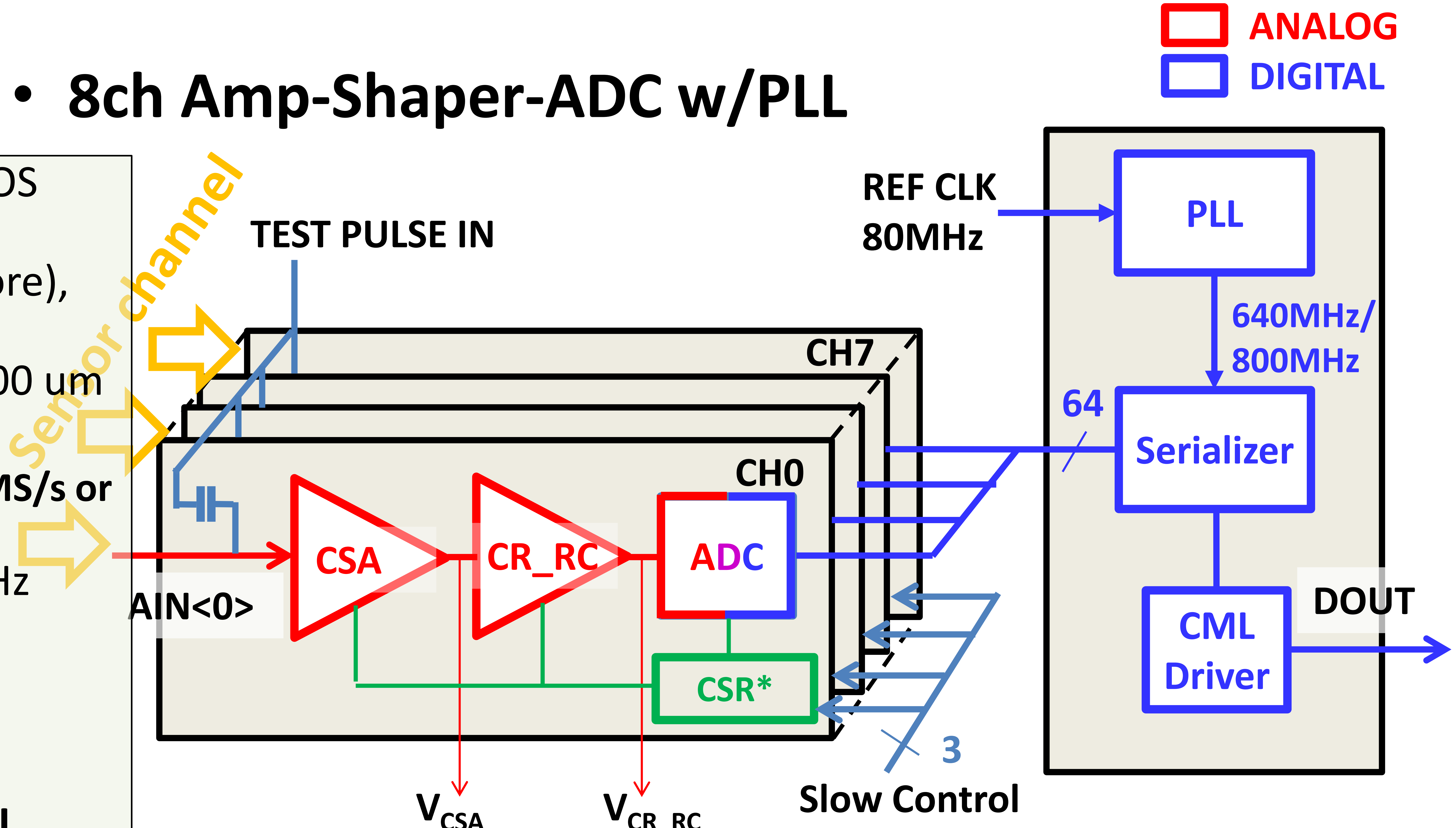
Q_{sig}: 75 MIPs (11 ke-/MIP), continuous waveform digitizing in 10 MHz.

Readout electronics (SCIBER-1, Silicon Carbide IC for beam monitor)

- 8ch Amp-Shaper-ADC w/PLL

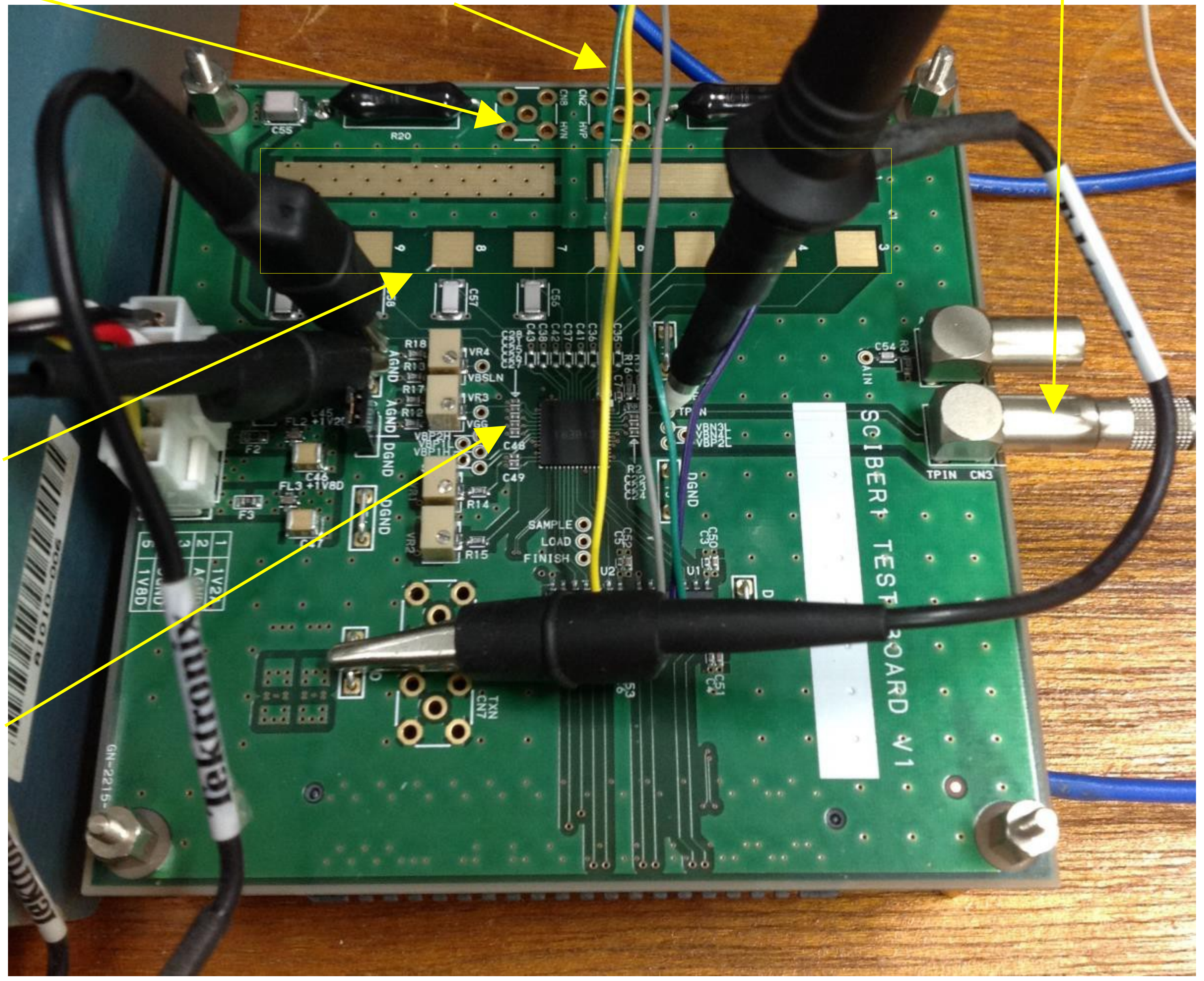
Jakub's talk→

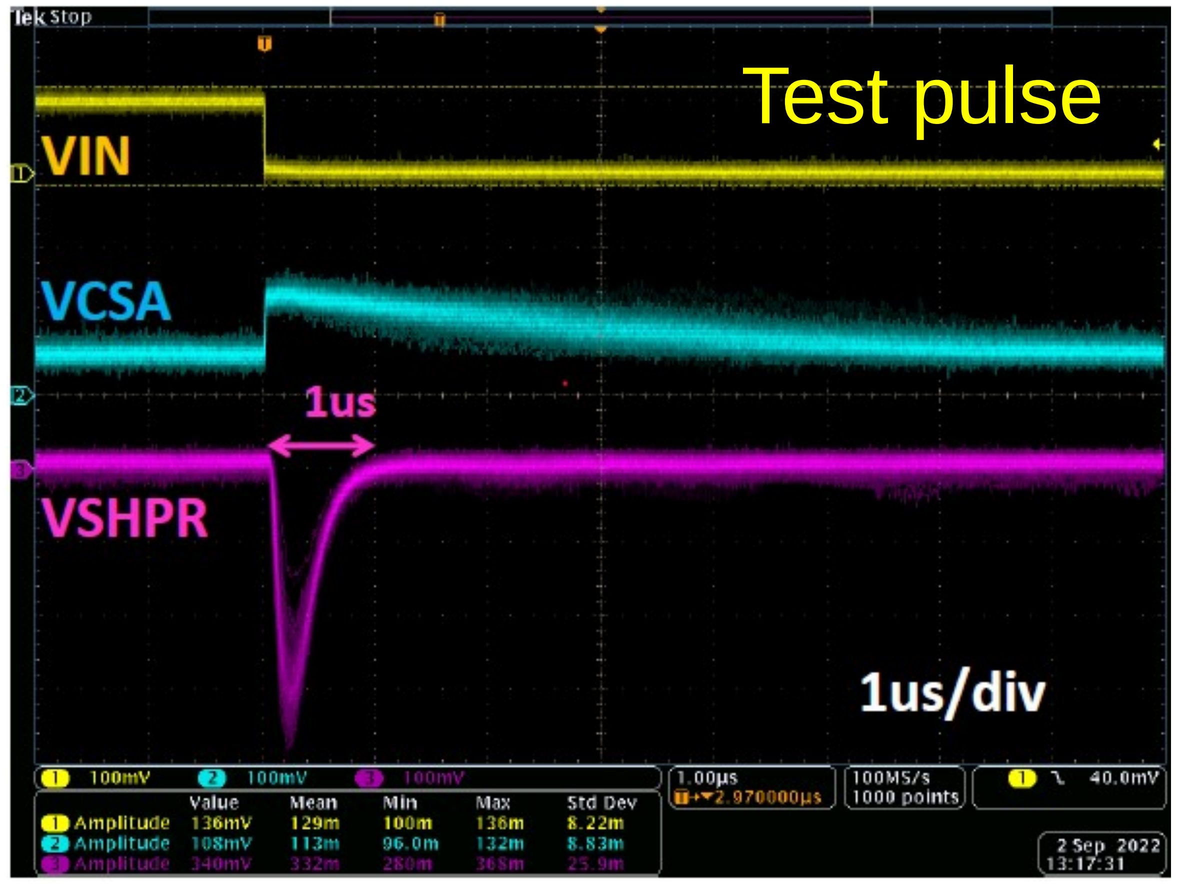
- Technology: TSMC CMOS 65nm LP
- Supply Power: 1.2V (Core), 1.8V (I/O)
- Chip size: 960um x 2,000 um
- 8-bit SAR ADC
  - Sampling Rate: **12.5MS/s or 10MS/s**
- PLL: 800MHz or 640MHz (w/80MHz REF CLK)
- Inputs: 8 channels to connect sensors
- Outputs: Digitized differential signals, **CML**



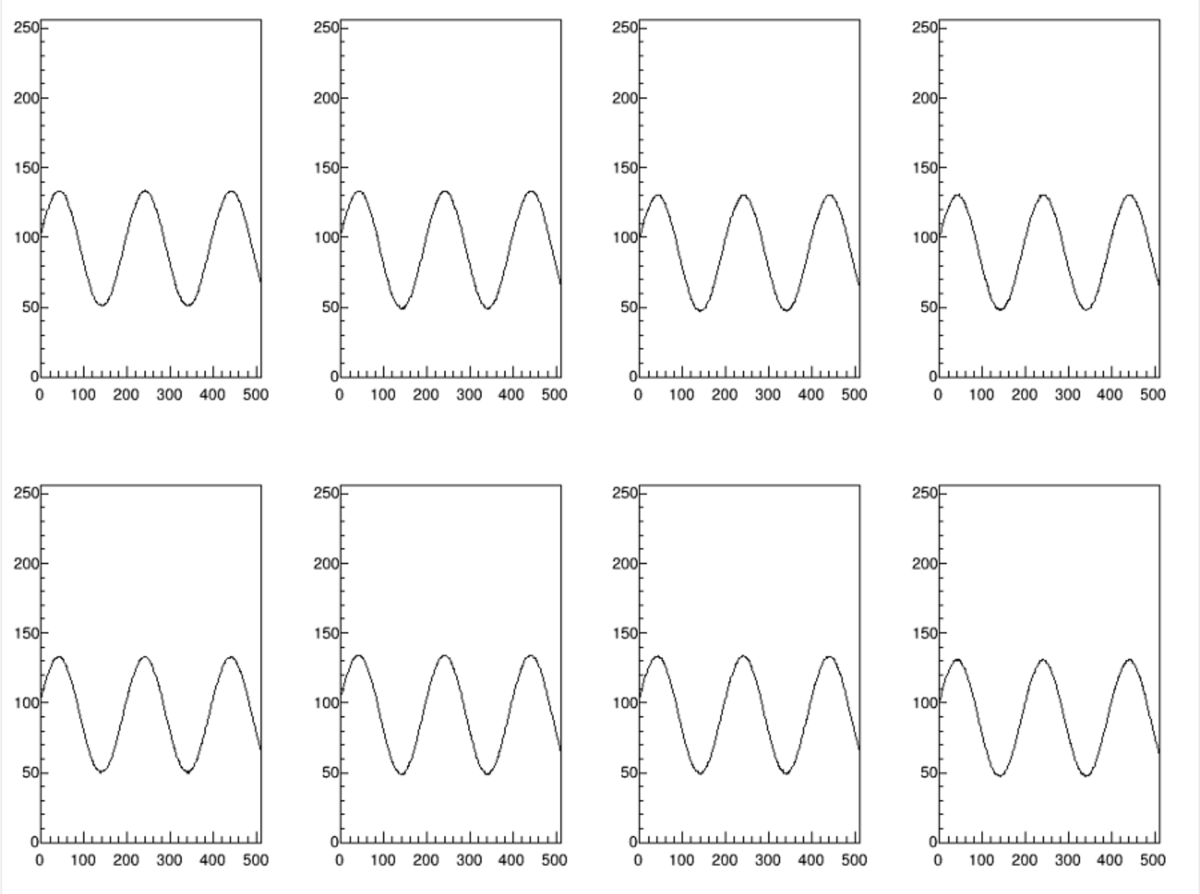
ADC Sampling Rate: 10MS/s or 12.5MS/s

Preliminary test results

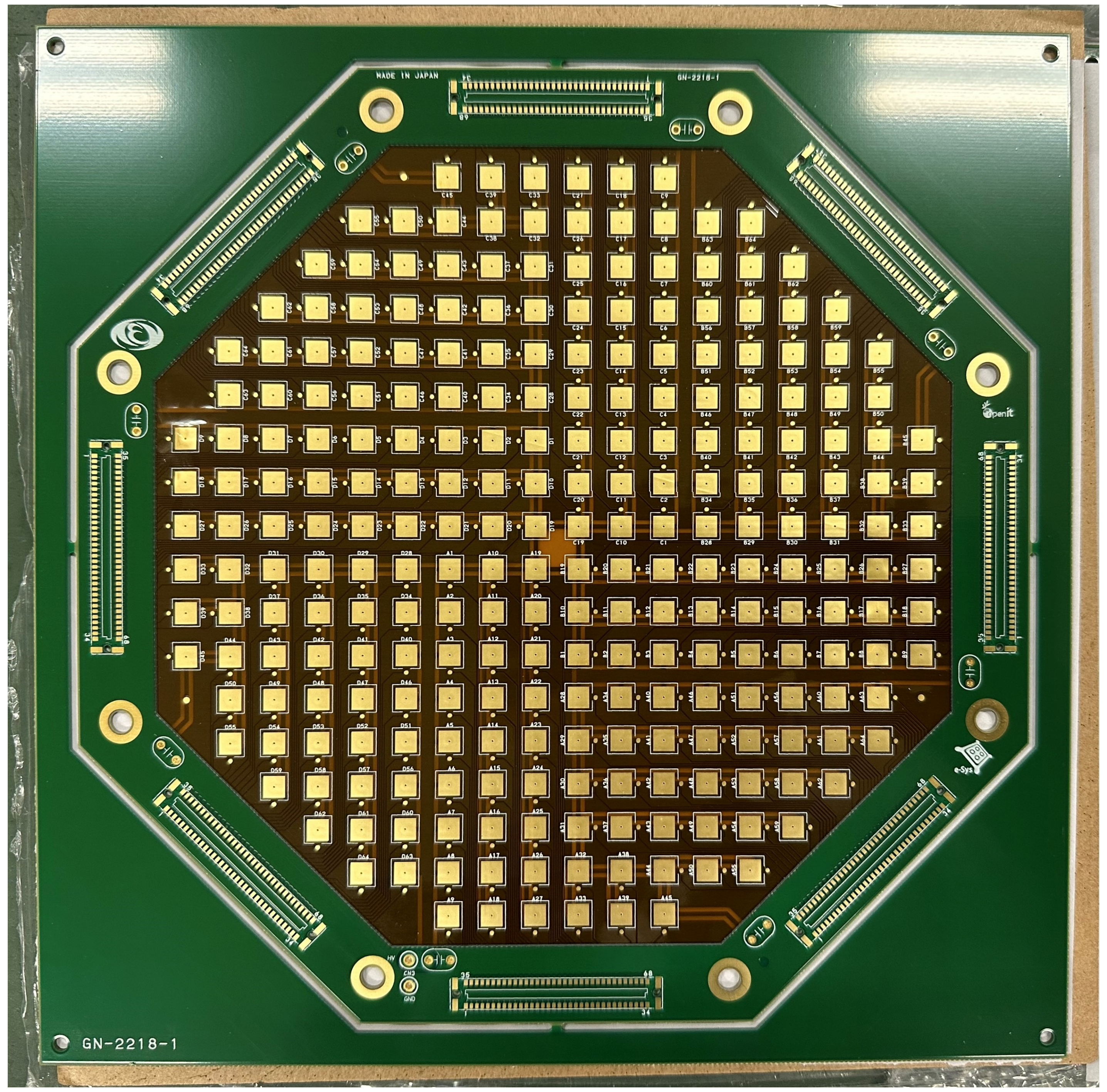




ADC outputs from 50 kHz sin-wave



Prototype of the SiC matrix board



We can make the muon beam monitor on time before the COMET Phase-1.

*Commercial SiC epi-wafer is another option. (6k euros/wafer).

Further Needs for SiC sensors (more challenging)

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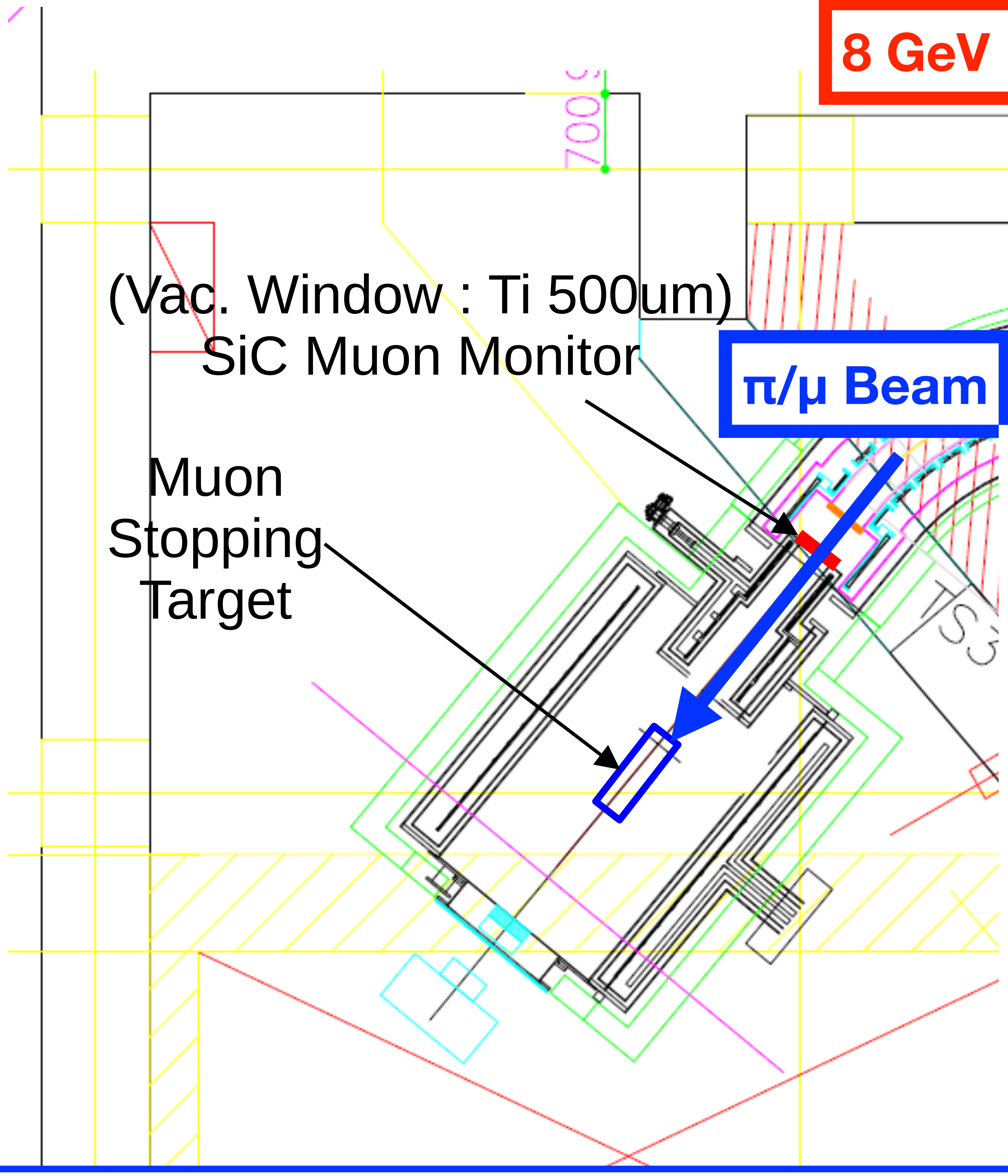
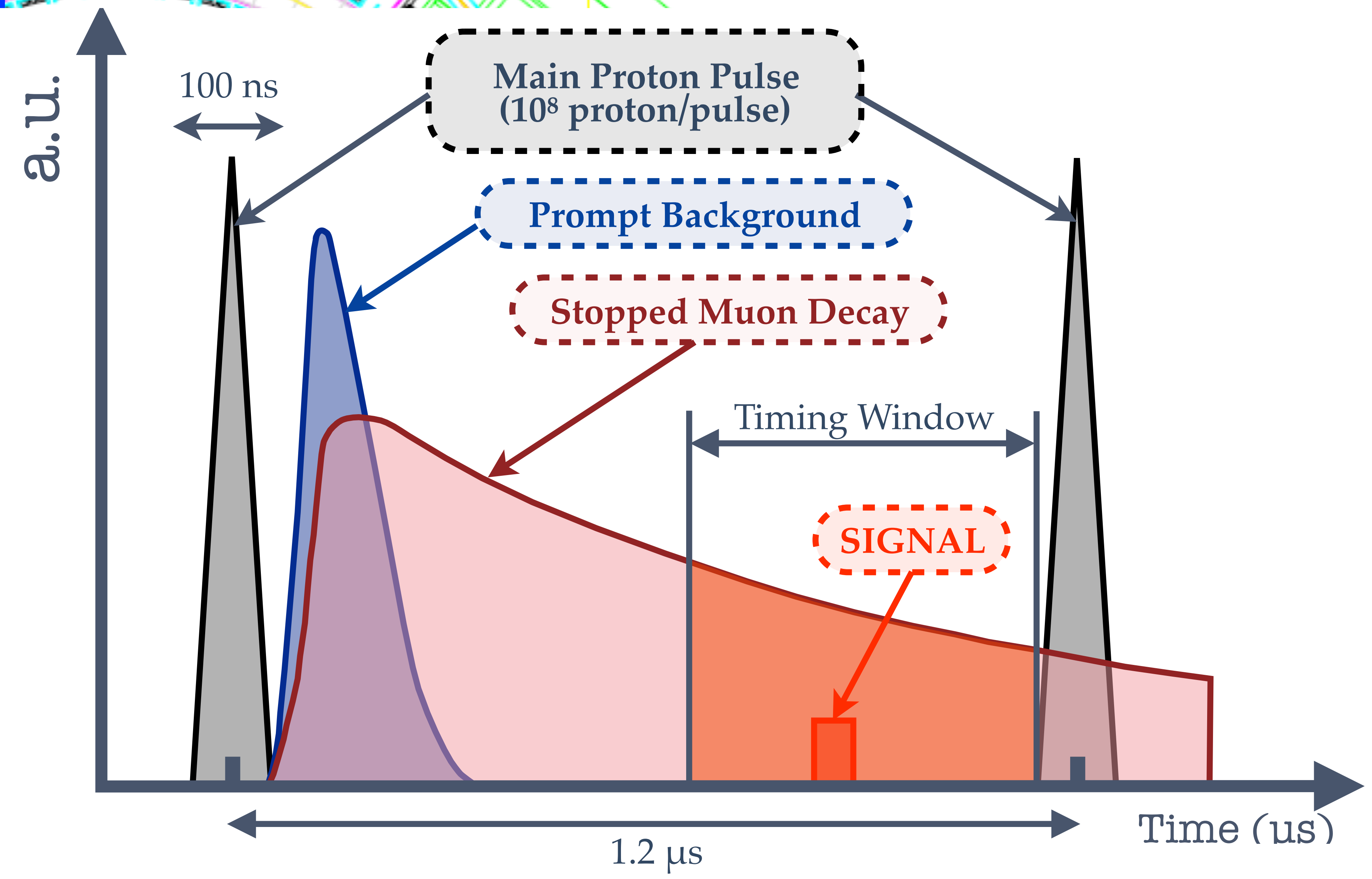
- 8 GeV proton beam is bunched in every 1.2us.
- Pion is BGD. Select muon events by timing difference.





Want to confirm no leaky protons (extinction) between bunches. → On-axis beam monitor with SiC!

Requirements for Extinction Monitor

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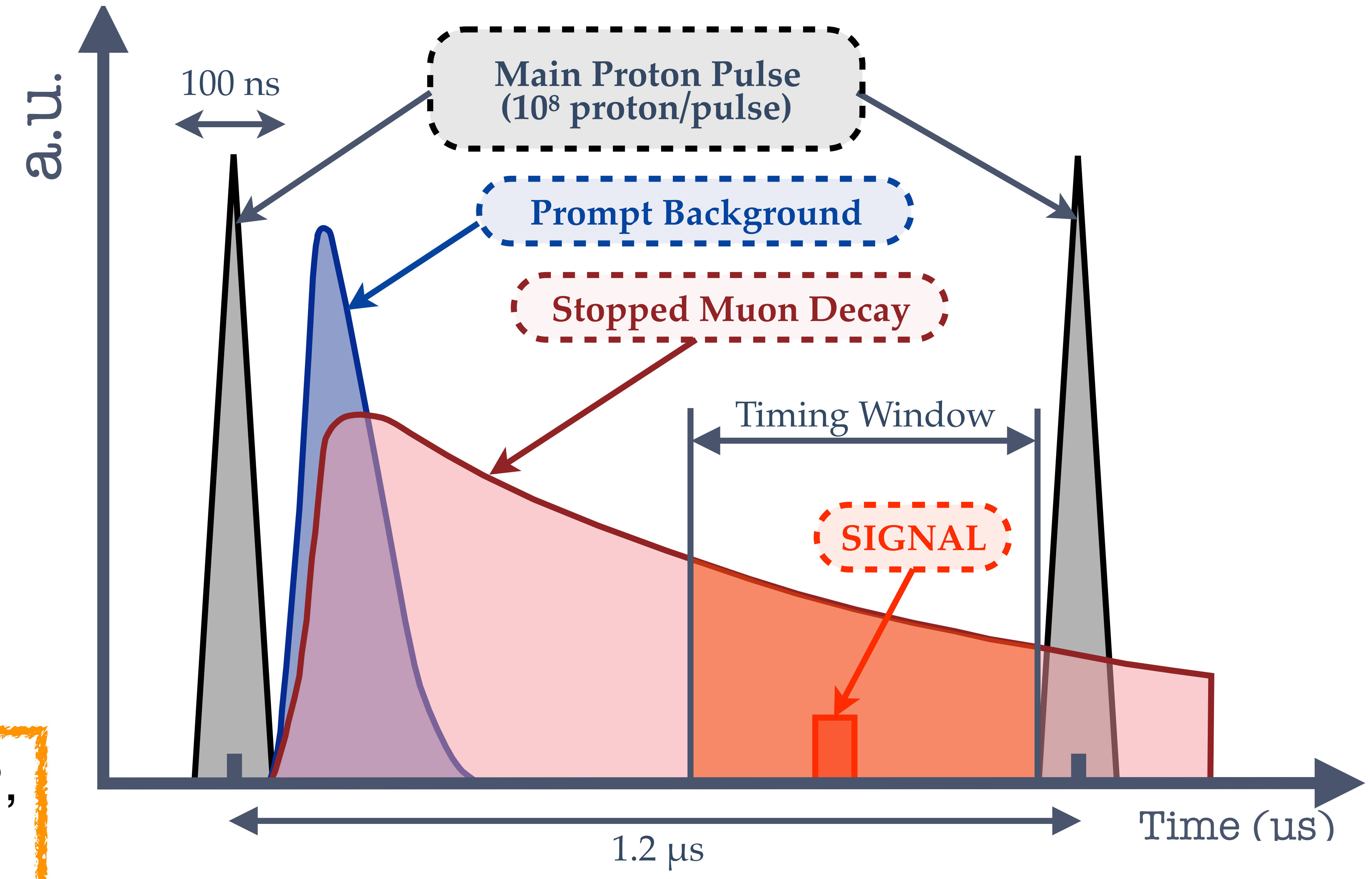
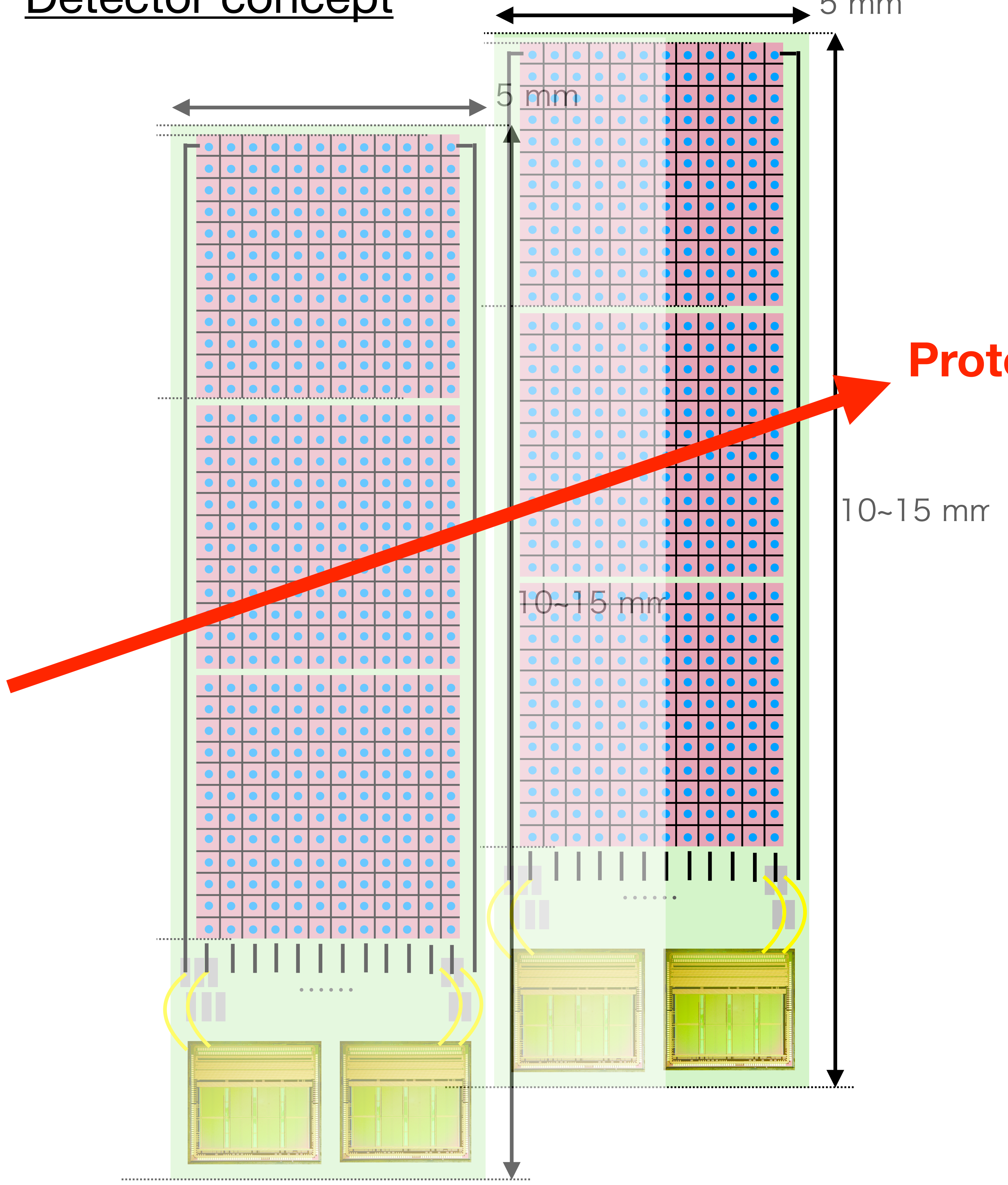
- Want to detect 1 proton after the main bunch
- Max. 1.6 x 10^7 proton/bunch with beam spot of ϕ~1 cm (TBD)
- Neutron fluence of 2.1 x 10^{14} n_{eq}/cm^2 during Phase-1



Detector concept



Why SiC?, realistic?

1. Relatively large-area devices can be fabricated in wafer process.→many detectors
2. Machine maintenance period is available every week.→ We replace the detector!

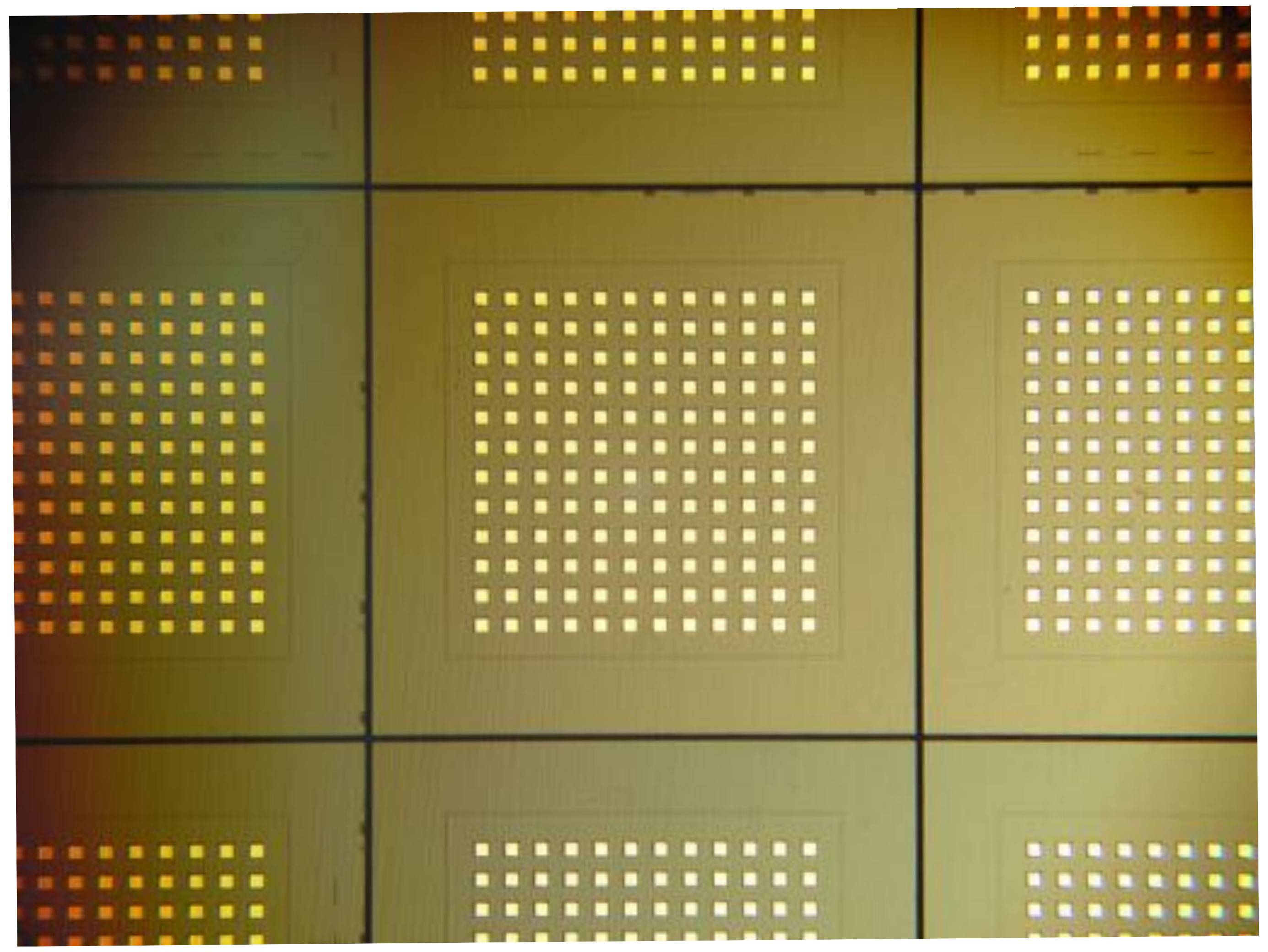
- Electrodes should be segmented (pixel/strips) to reduce the event rates.
- Readout electronics placed sidewards to avoid proton beam spot for radiation reason.

To prove the concept, we investigated the sensor segmentation and performance uniformity.

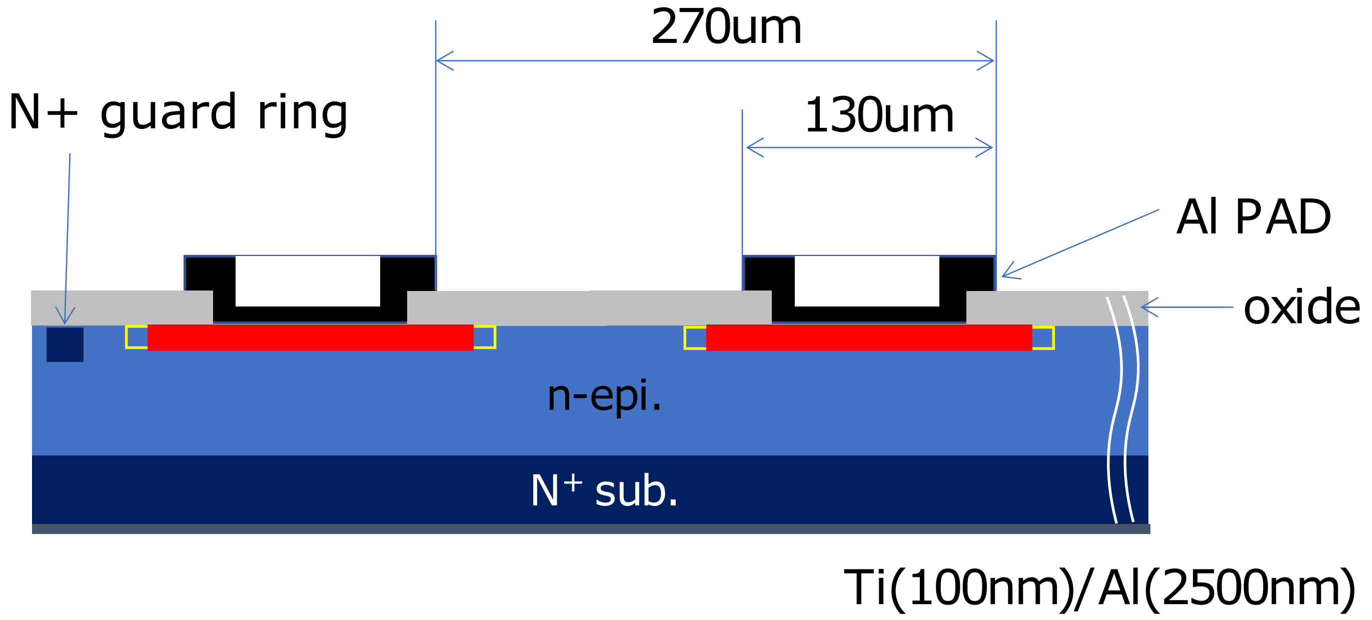
Sensor segmentation (hybrid pixel detector)

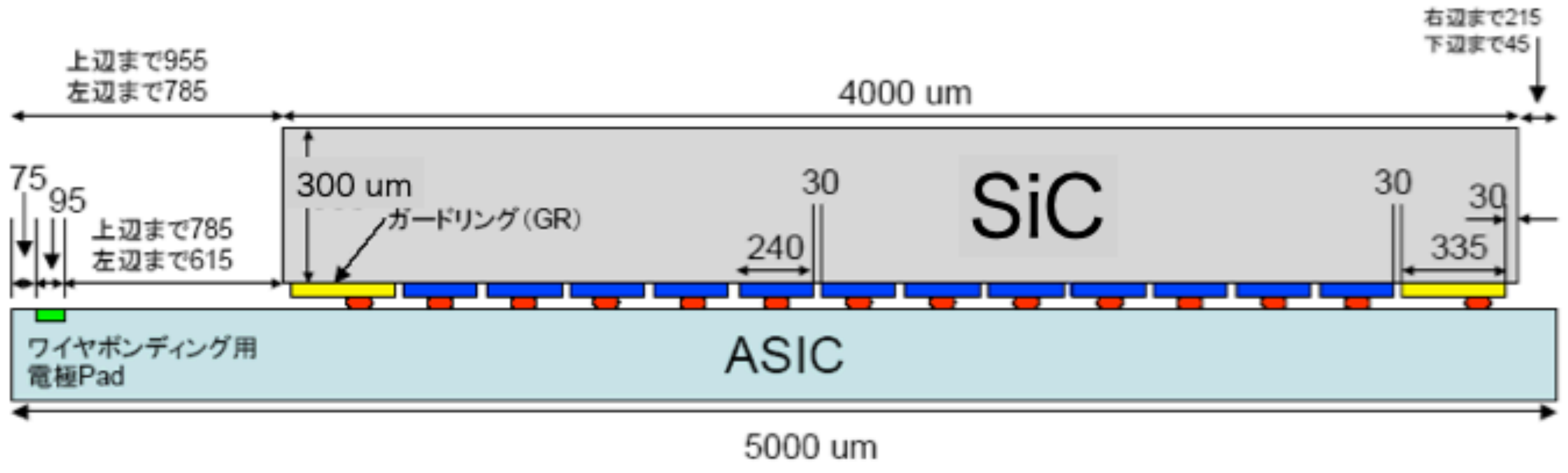
- 5 mm x 5 mm with 12 x 12 electrodes, 270 um pitch
- readout with low-noise ASIC
- Au/In stud bump technology

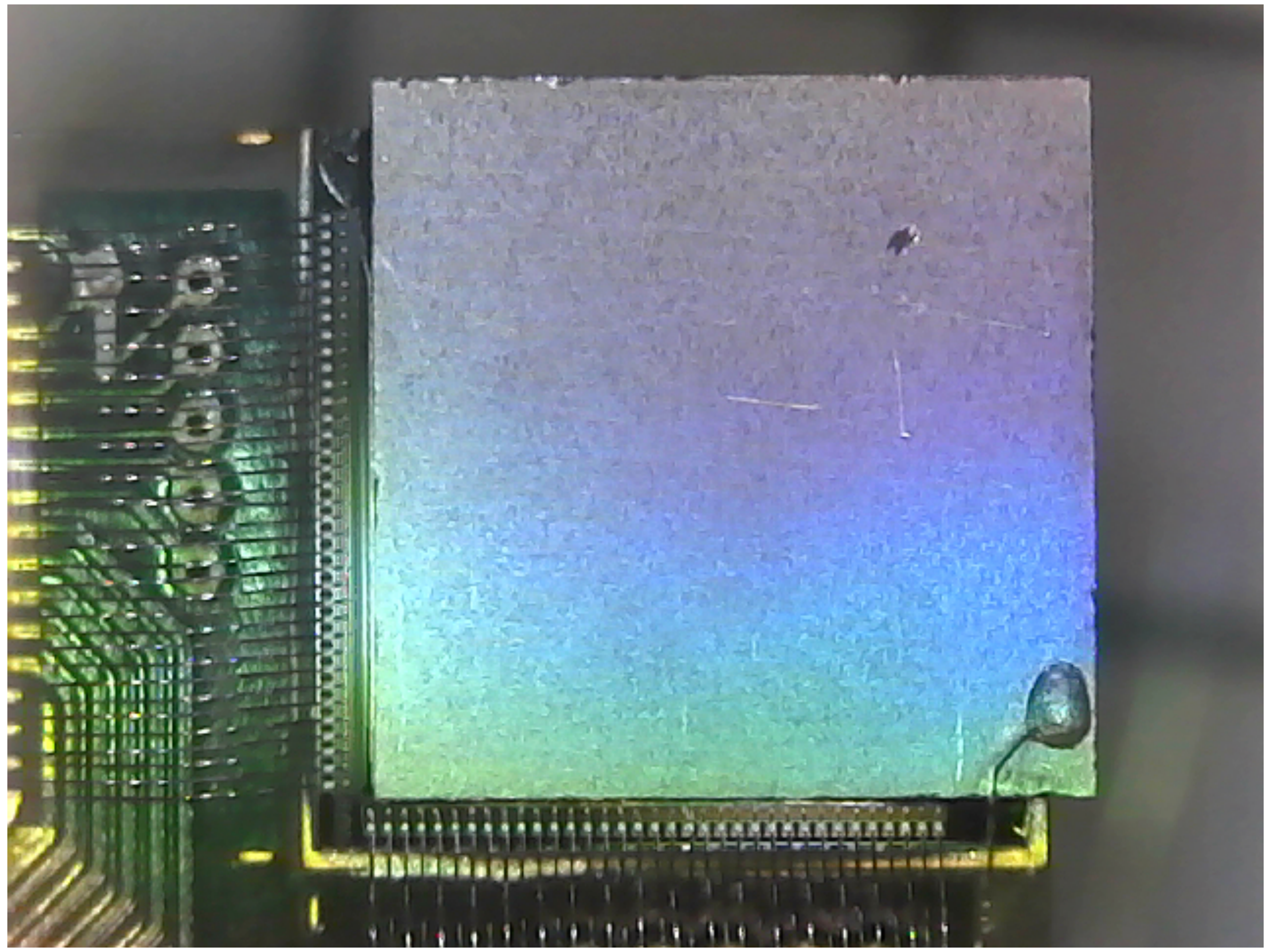
(a)



(b)



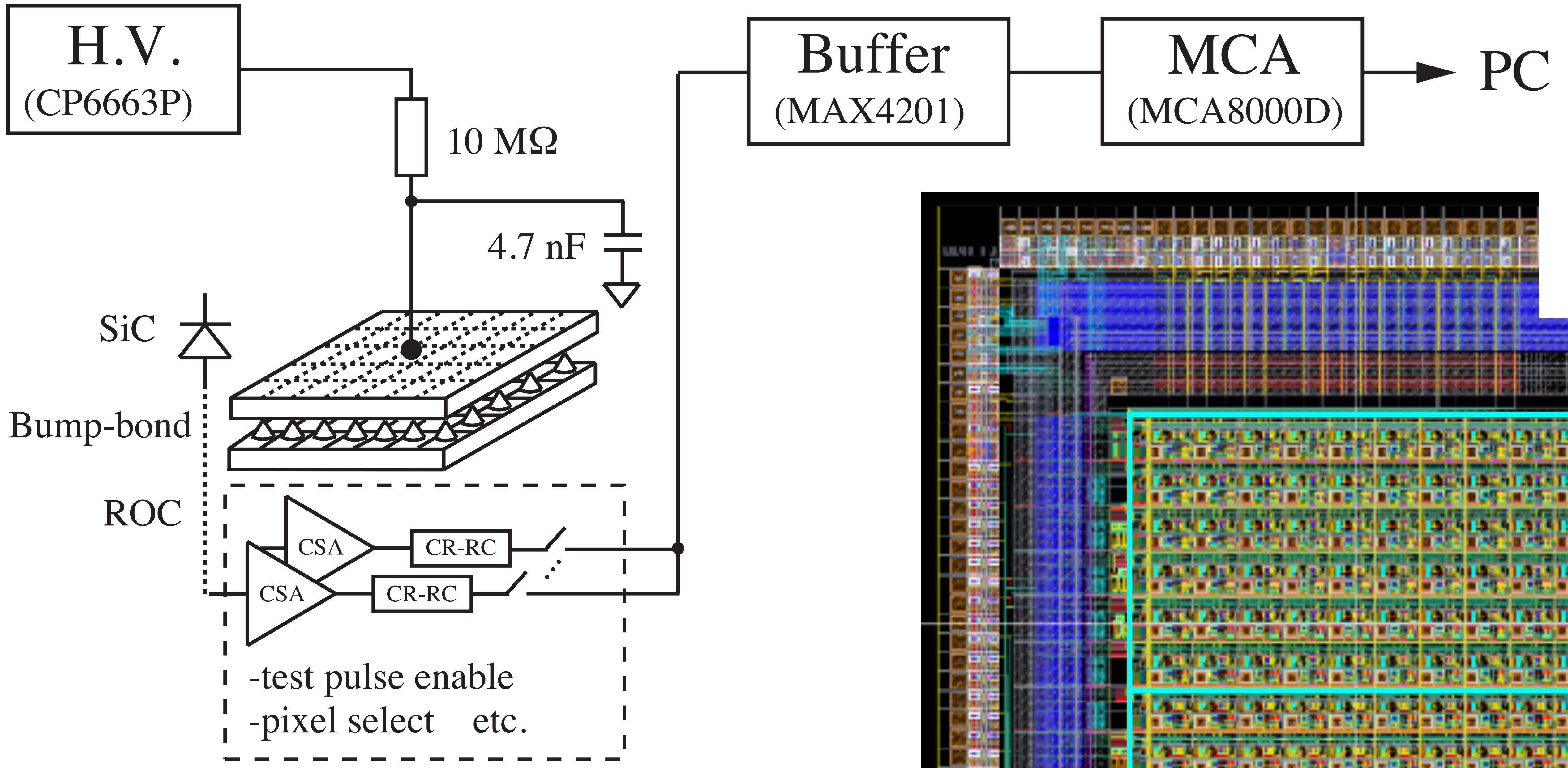


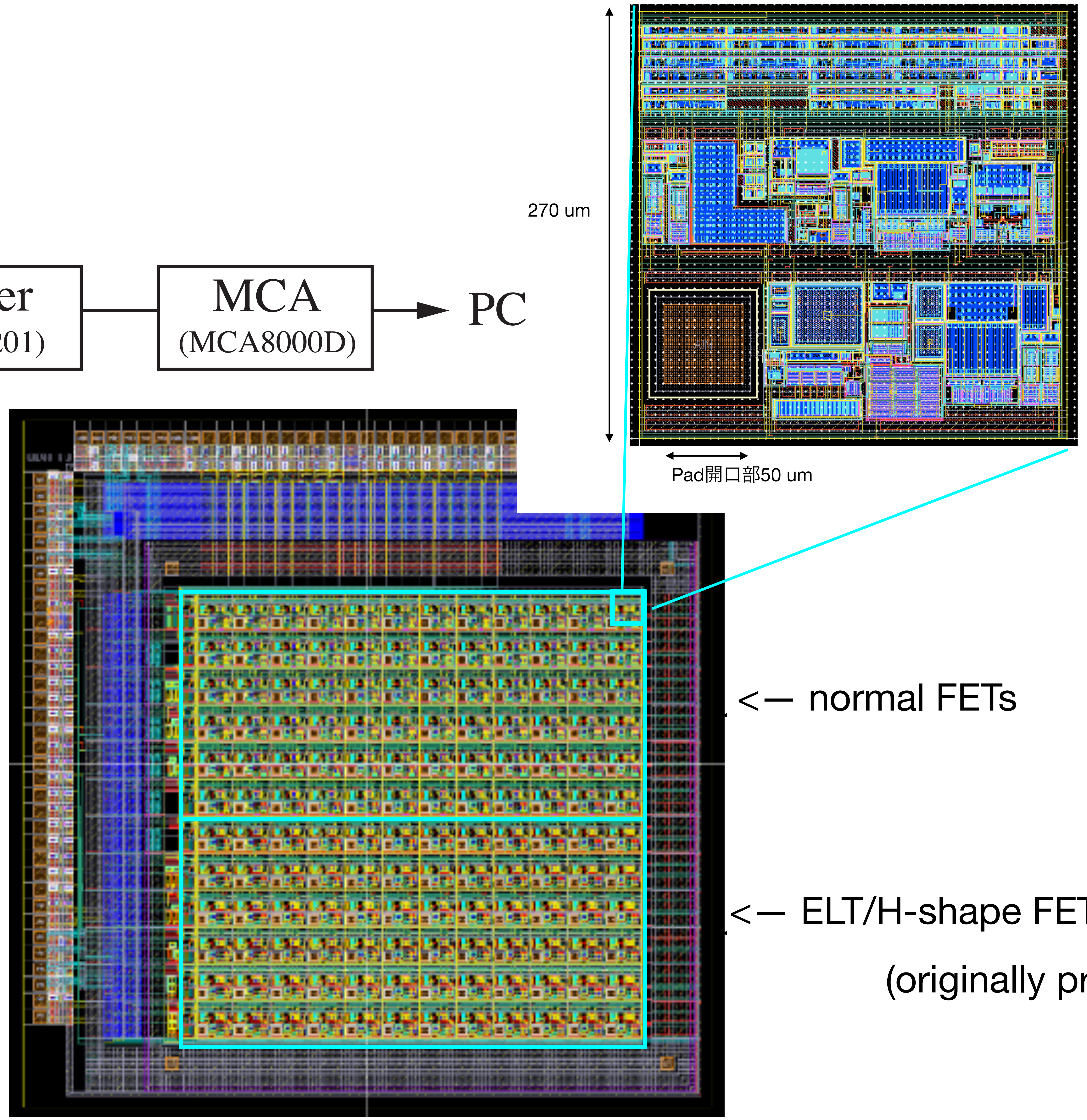


Passivation (Parylen or Silicone rubber) is necessary to prevent electric discharges @1 kV.

Readout ASIC

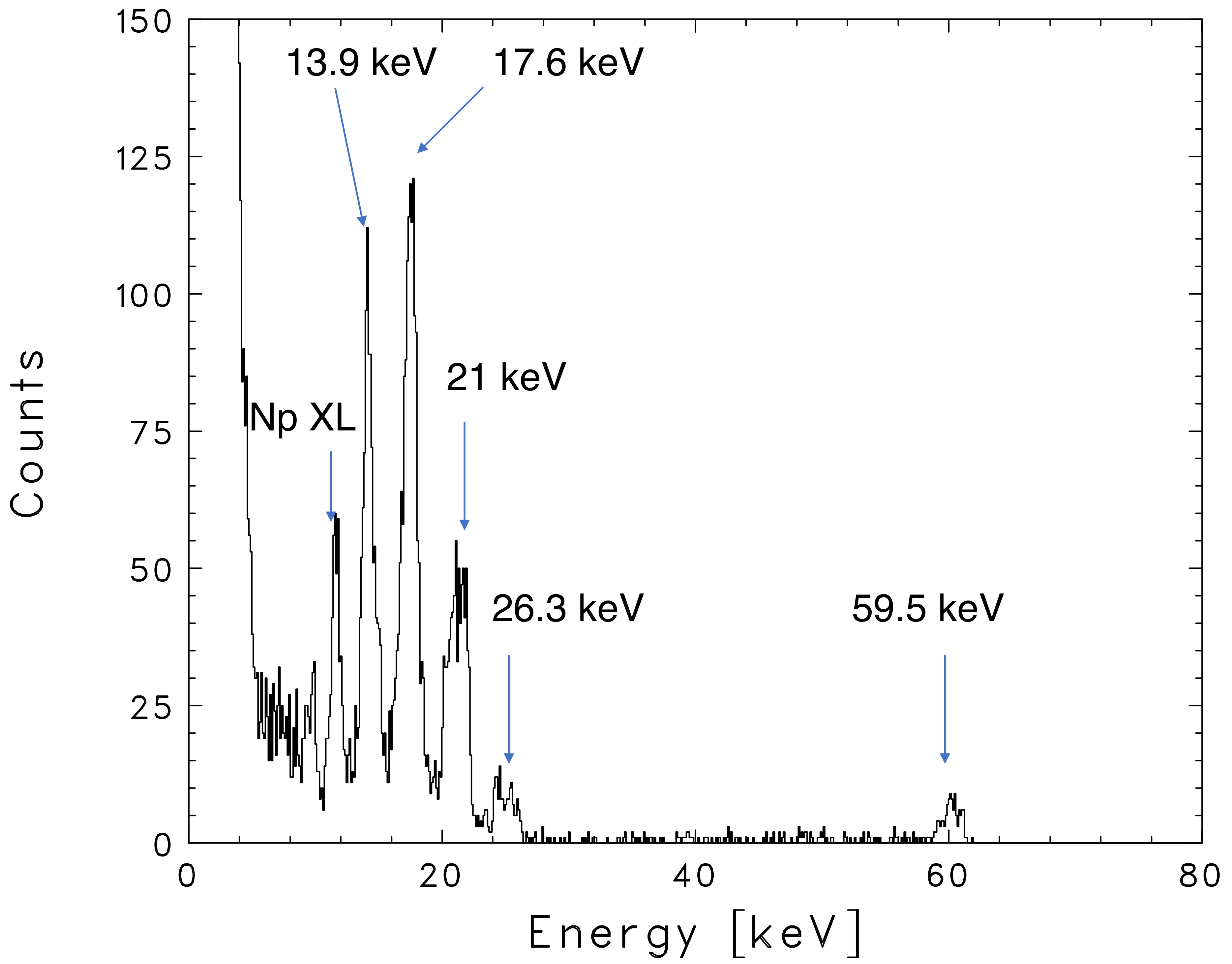
- TSMC 0.35 um CMOS
- 270 um x 270 um pixel size, 12 x 12 pixel cells
- CSA (DC-coupling to SiC)+Shaper with 5 us shaping time
- Used wirebonding for DC-power supply/control signals





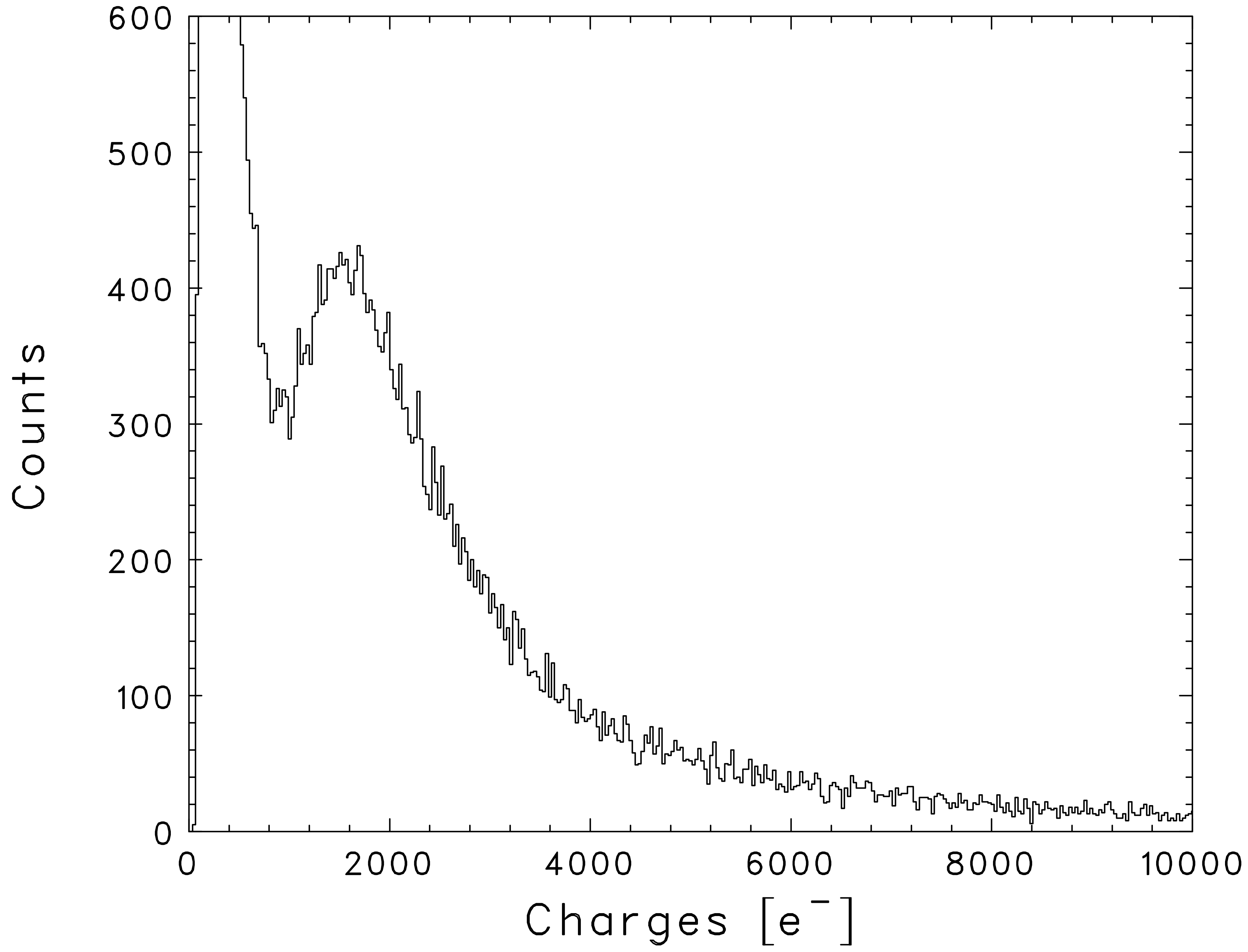
Spectral performance

- HV: +600 V
- Exposure: 3 days
- Mode: HG



FWHM: 1.72 keV @17.6 keV

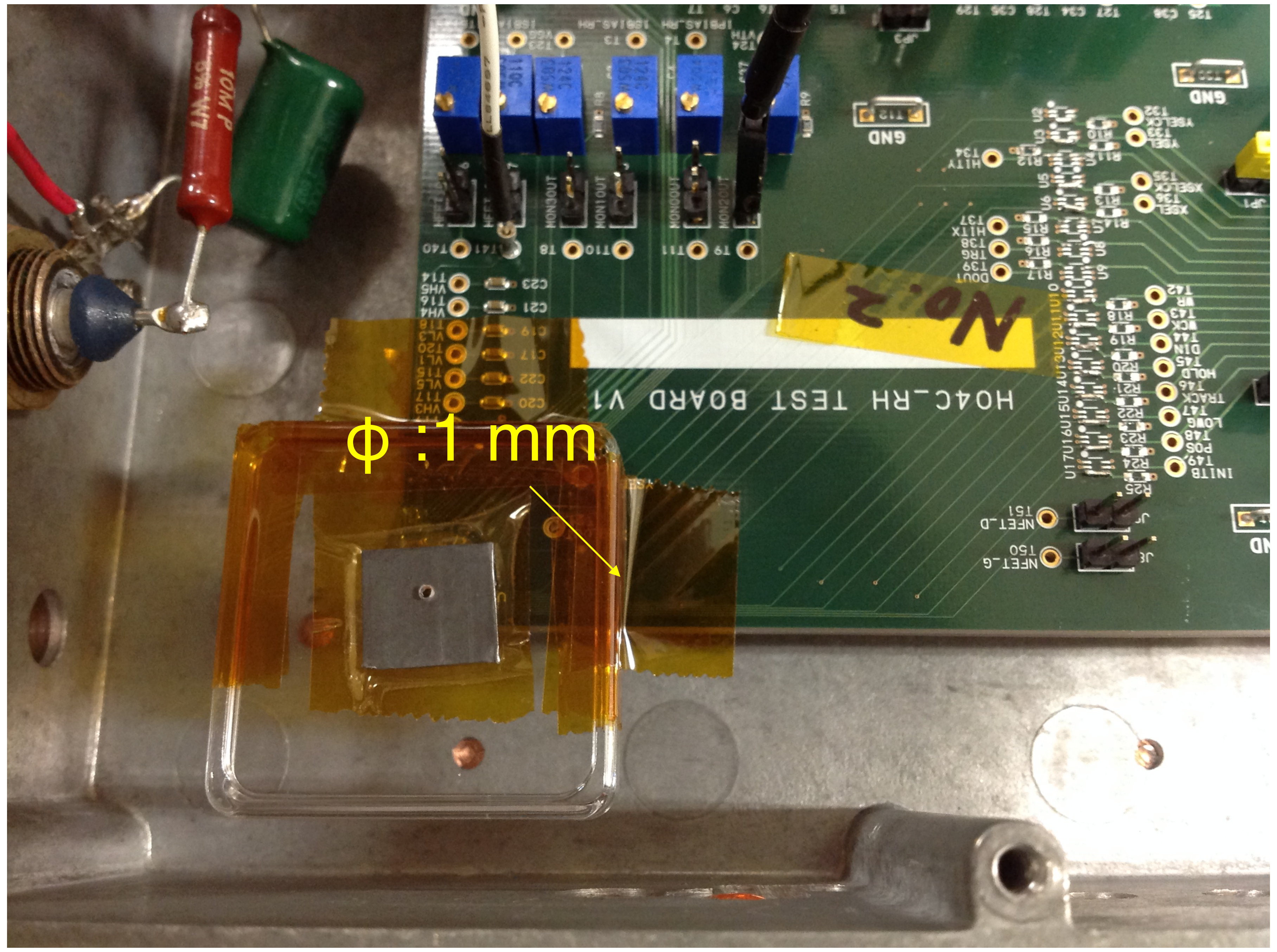
- HV: +600 V
- Exposure: 0.5 days
- Mode: HG

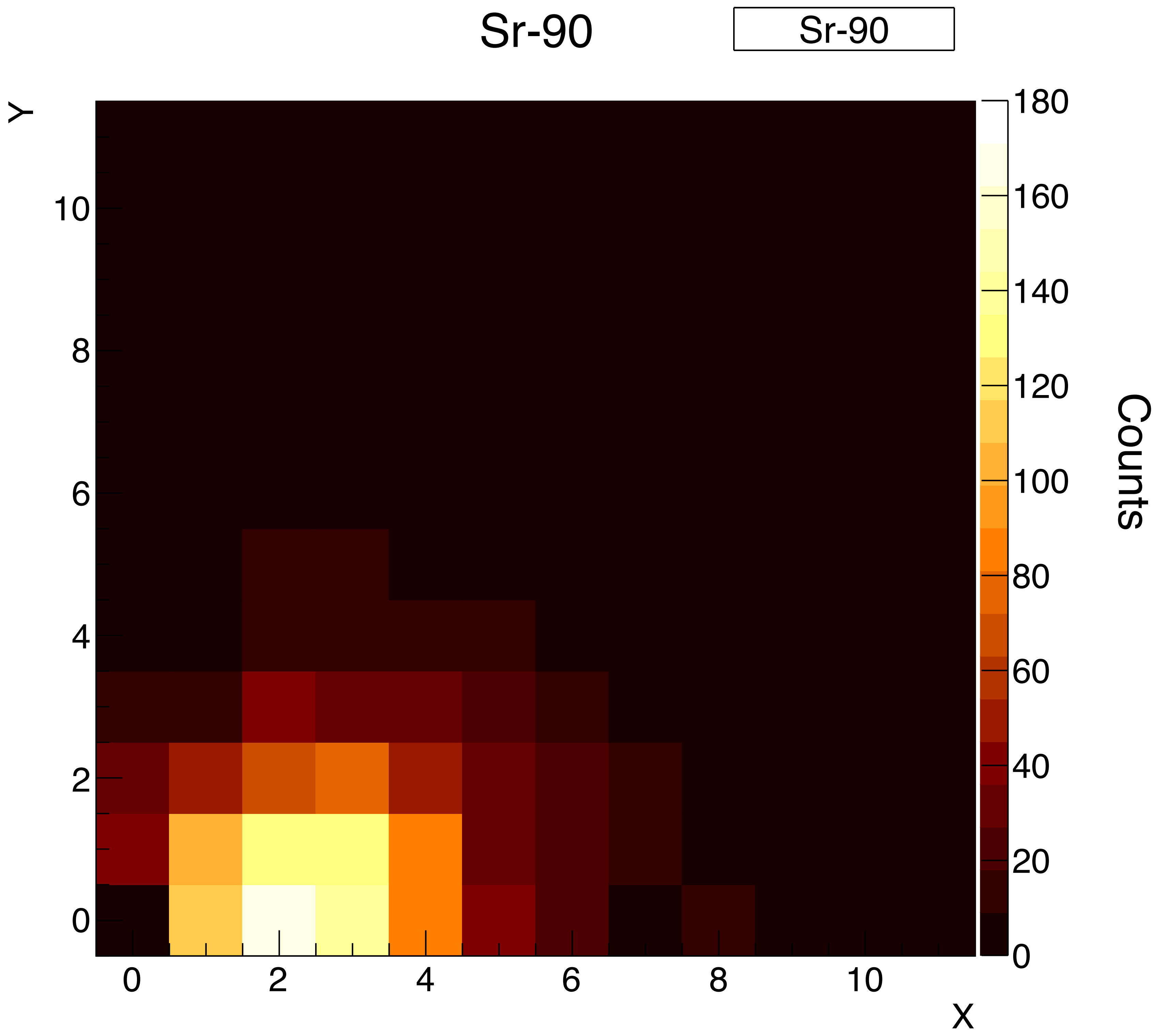


Confirmed β-ray events from all pixels.

Imaging performance

- Blind search of pinhole position in Pb sheet
- Count Sr-90 events between 1000-6000 e-, 1 min for each pixel





- Finer segmentation is realistic and nice uniformity expectable in larger devices
- SiC performance is closing to silicon.
- Still long way to reach the proton extinction monitor, but SiC is an important candidate.

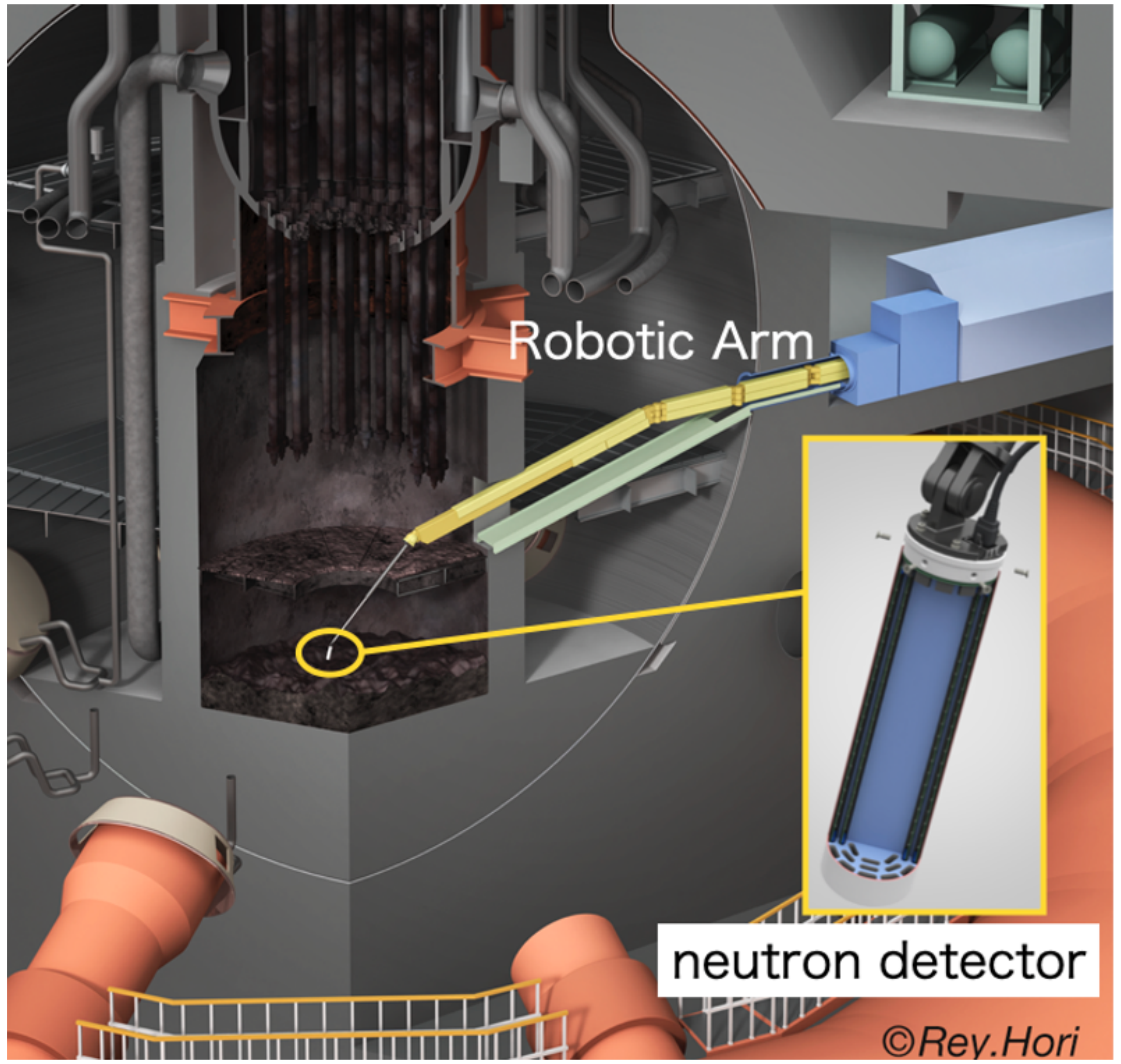
Needs of Diamond sensors

- Nuclear decommission is on-going at Fukushima Nuclear Power Plant.
- Need "eye" to know exact locations of nuclear debris for robotic arms (at least monitor the neutron flux to protect workers).
- No data of radiation environment yet.
  Gamma-rays from Cs every direction: max. 1 kGy/h (100 krad/h)

Site of the Fukushima Nuclear Power Plant

Pacific ocean

Concept of the neutron detector

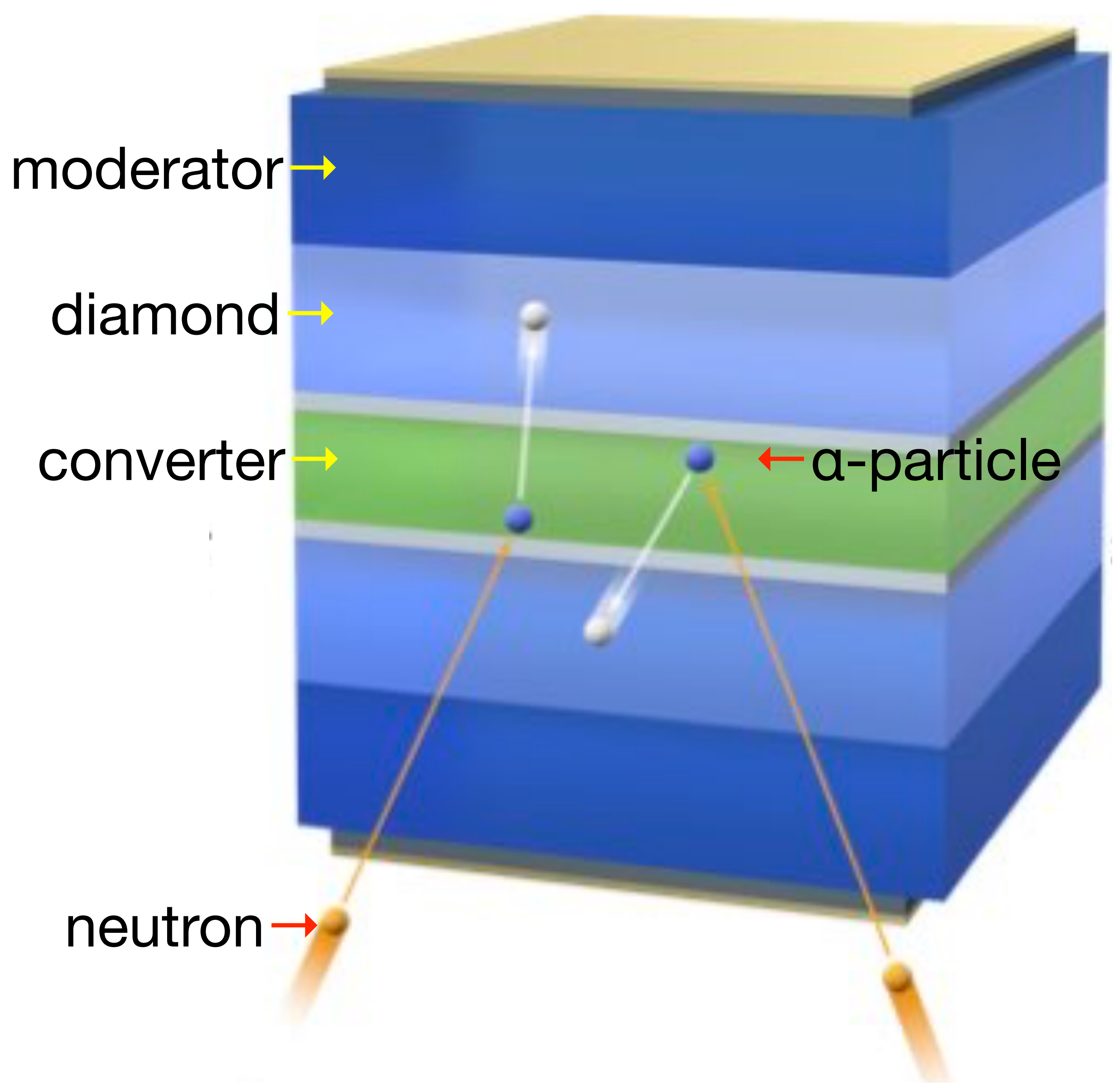


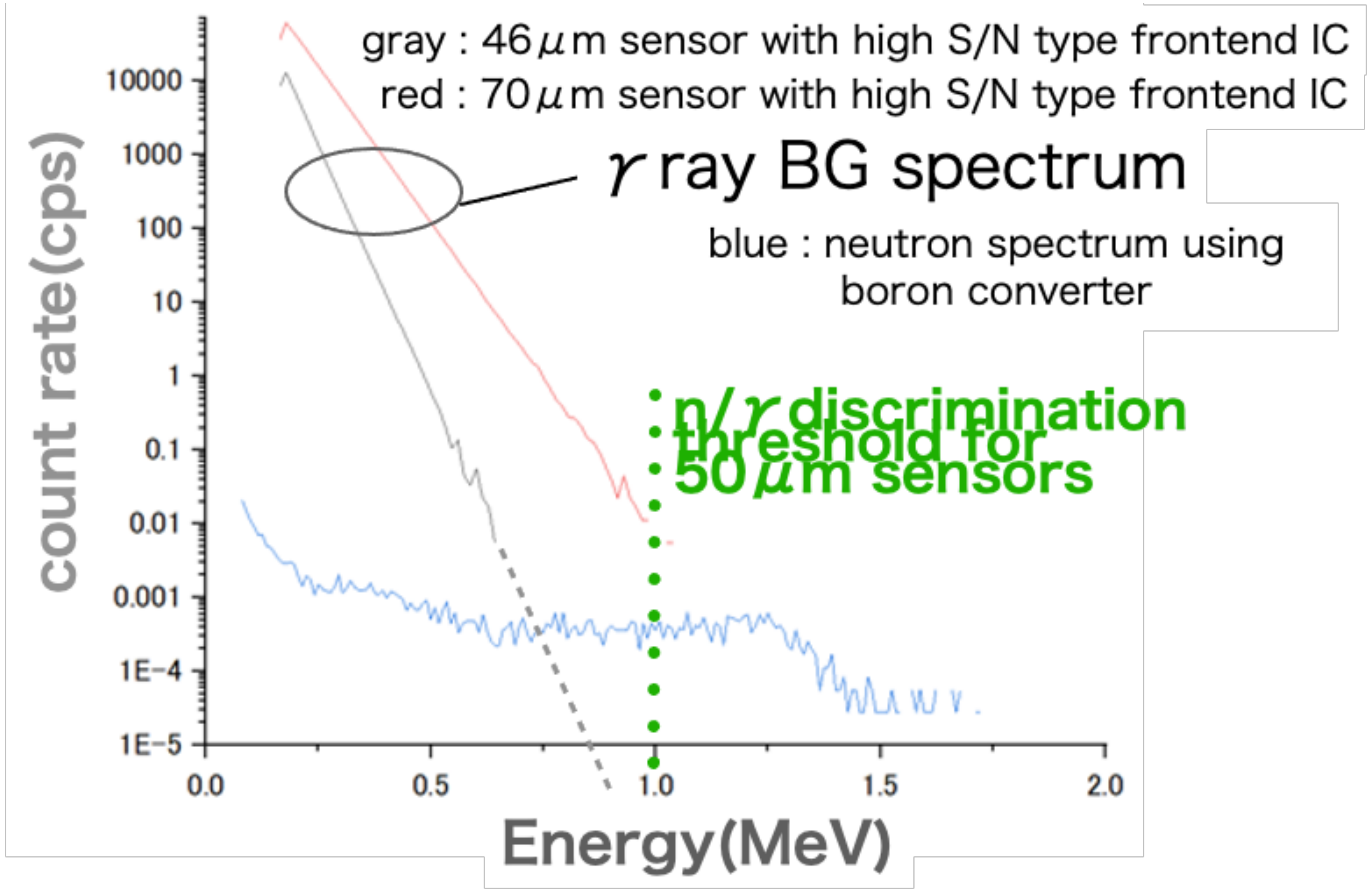
Under high γ-BGD, thin sensors are required for neutron detection.→Diamond!

Concept of neutron detector

- Use neutron converters ($^6LiF/^{10}B_4C$) and detect alpha-particles
- Detect neutrons (~1 Hz) under high gamma-ray BGD (~1 MHz)
- Sandwich configuration to increase detection efficiency

Concept of the neutron detector





To detect neutrons with 1 Hz, we need more than 1000 diamonds!   How to realize such number?

Device fabrication: self-supported diamond

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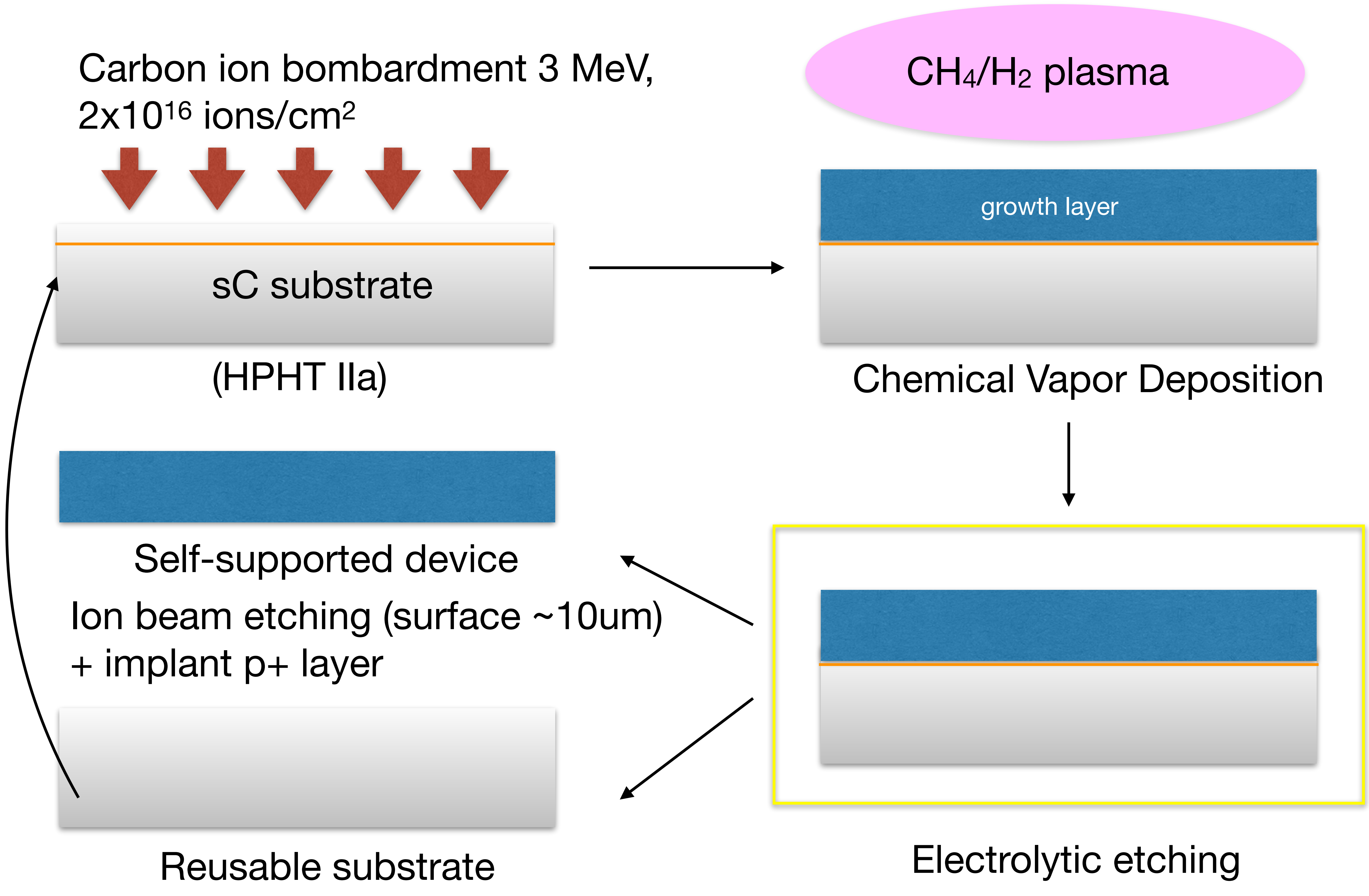
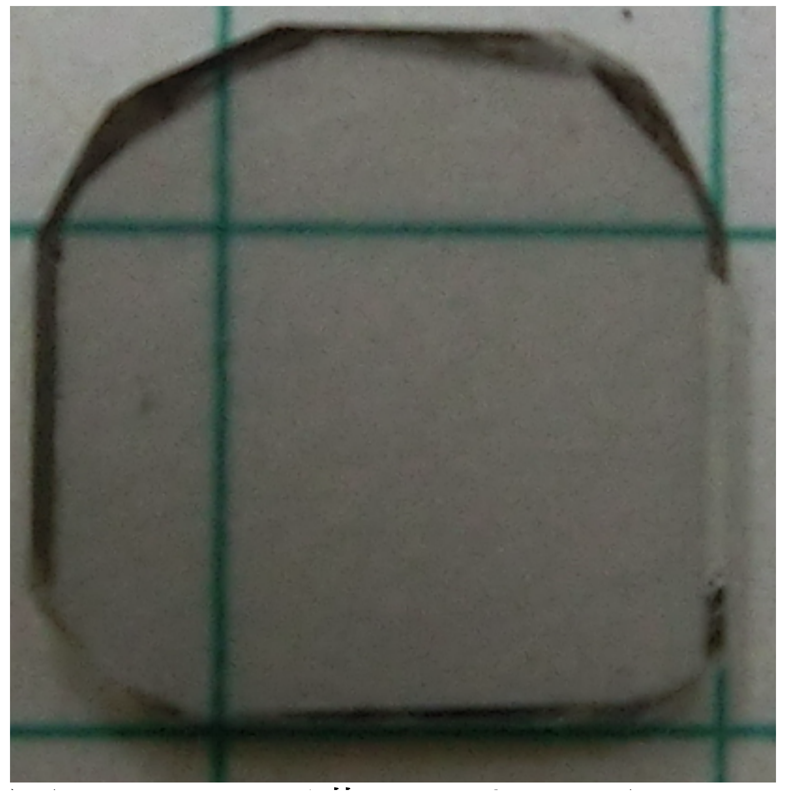
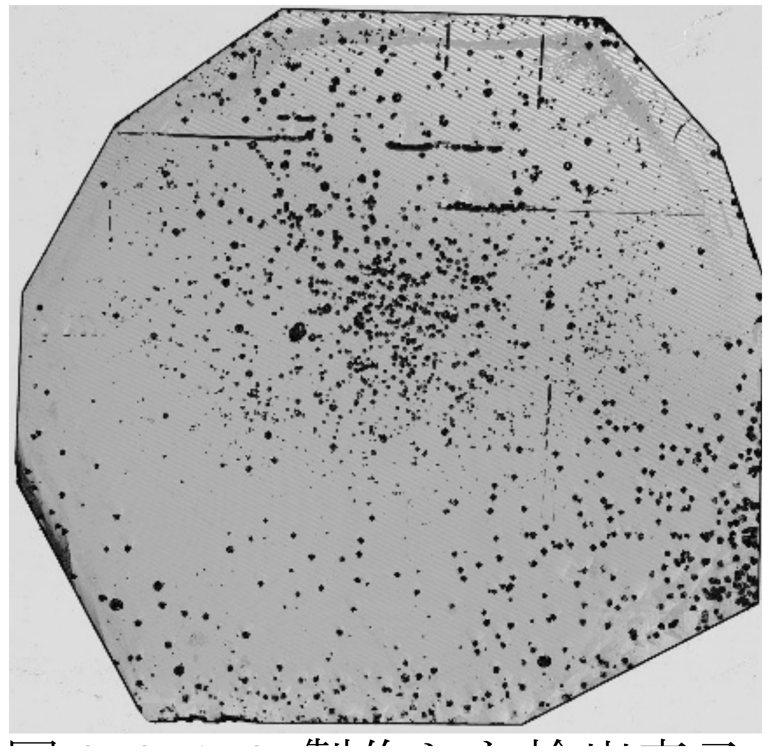
- Self-supported diamond with reusable substrate
- 30-50 um thickness to avoid cracking
- Na-Nd: 10^{11}-10^{12} cm^{-3}
- Long process time (>2 weeks), yield issues, wire-boning etc.



Single-crystal substrate



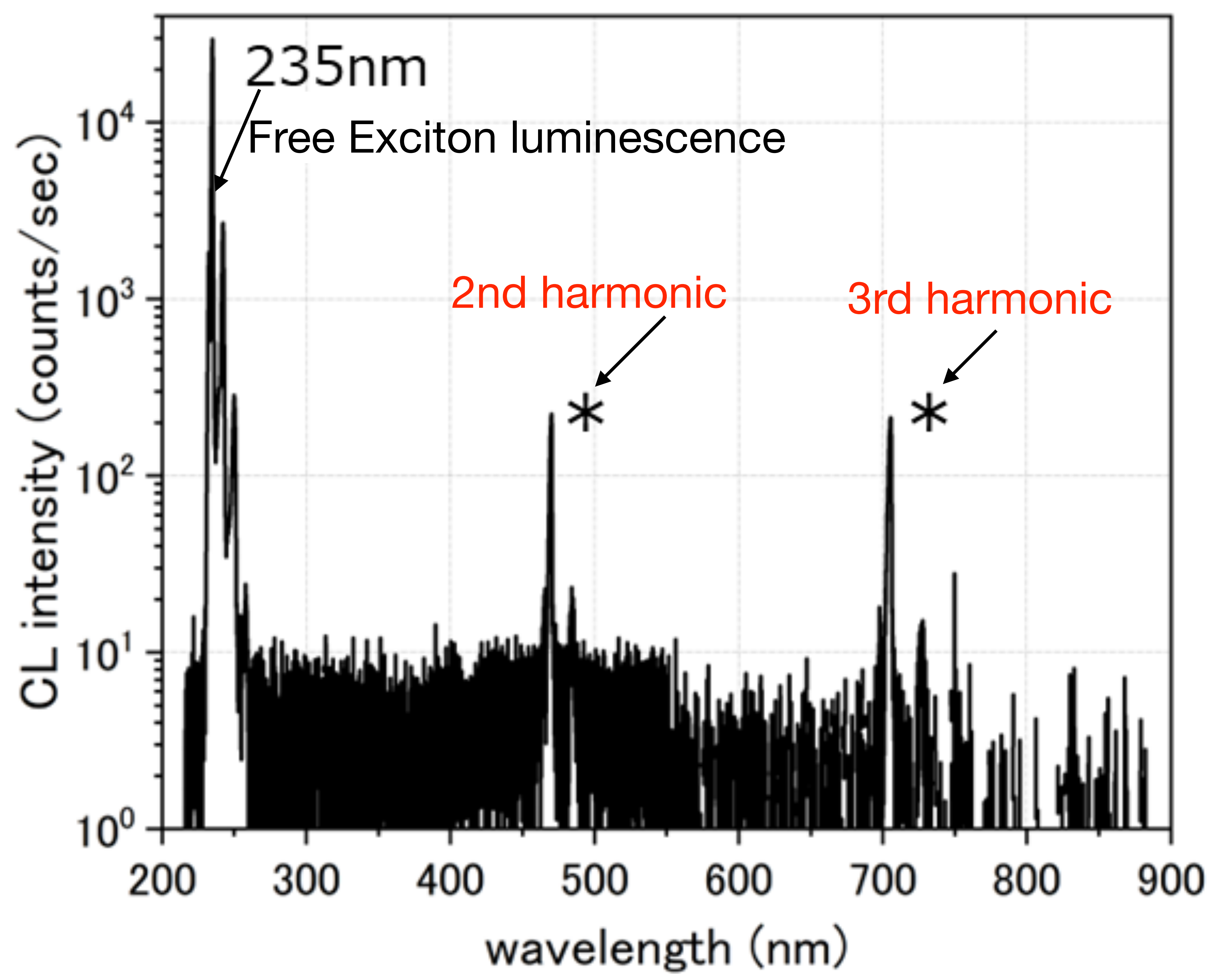
Self-supported diamond



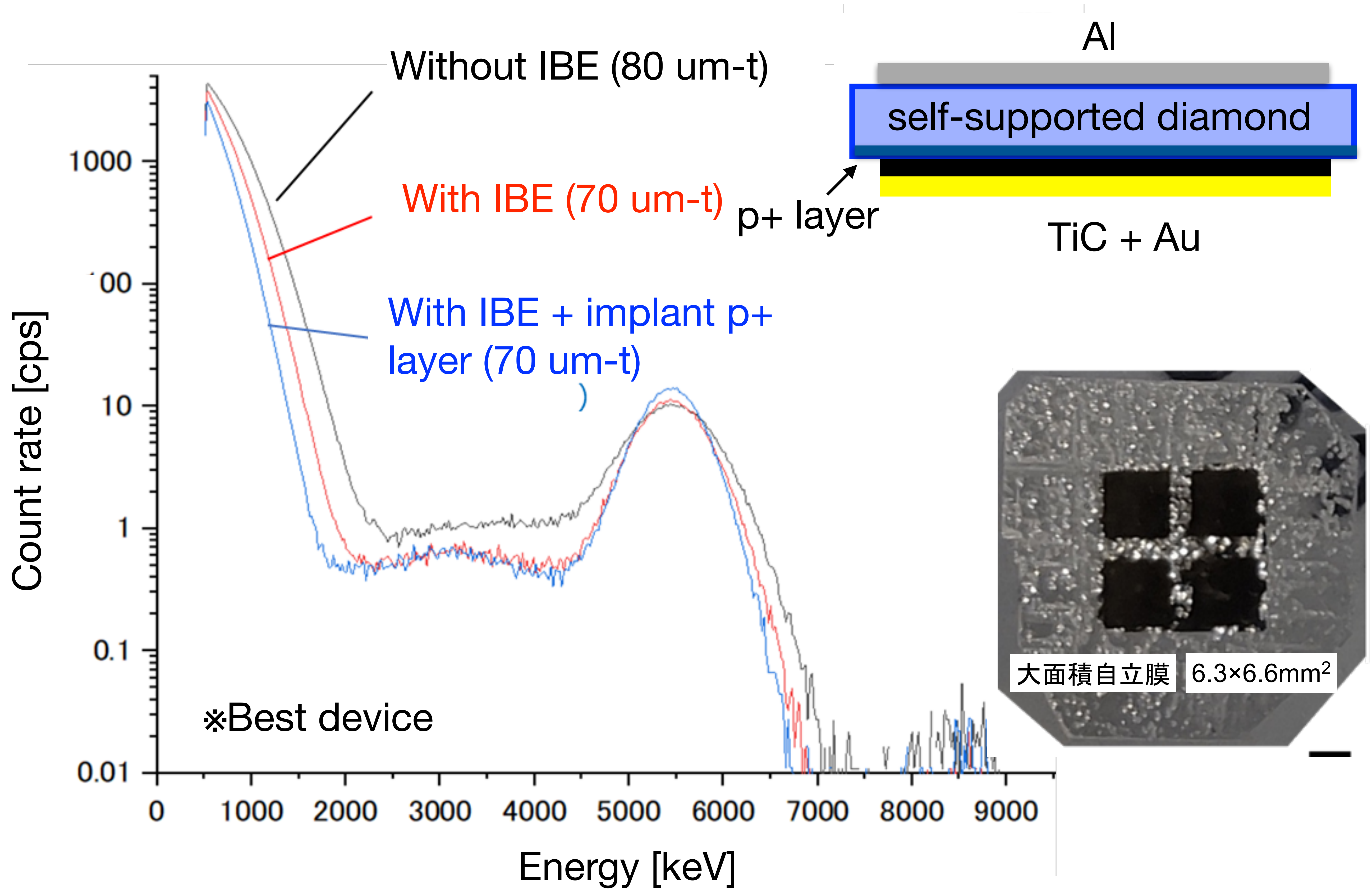
Long process time is covered by parallel CVD machines by venture company.

Characteristics of the diamond device

- Cathode luminescence method, free-exciton recombination line@ 235nm
- IBE (Ion Beam Etching) on 10 um surface to mitigate roughness
- Implant p+ layer on Ohmic side



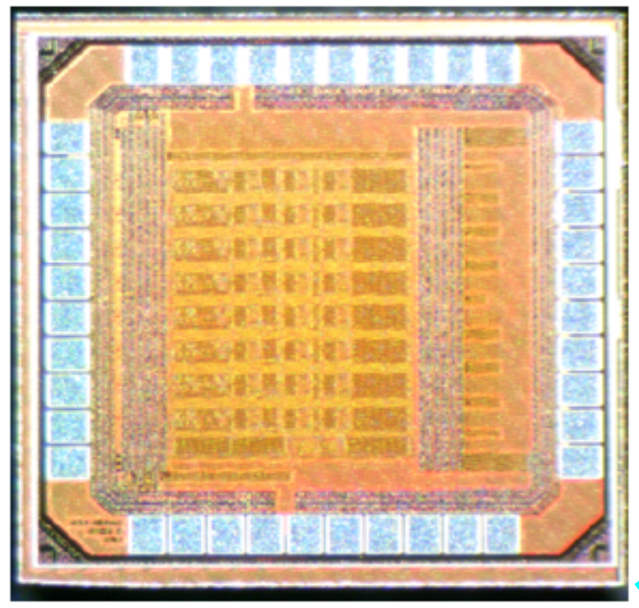
Am-241 spectrum under γ-BGD (260 Gy/h)



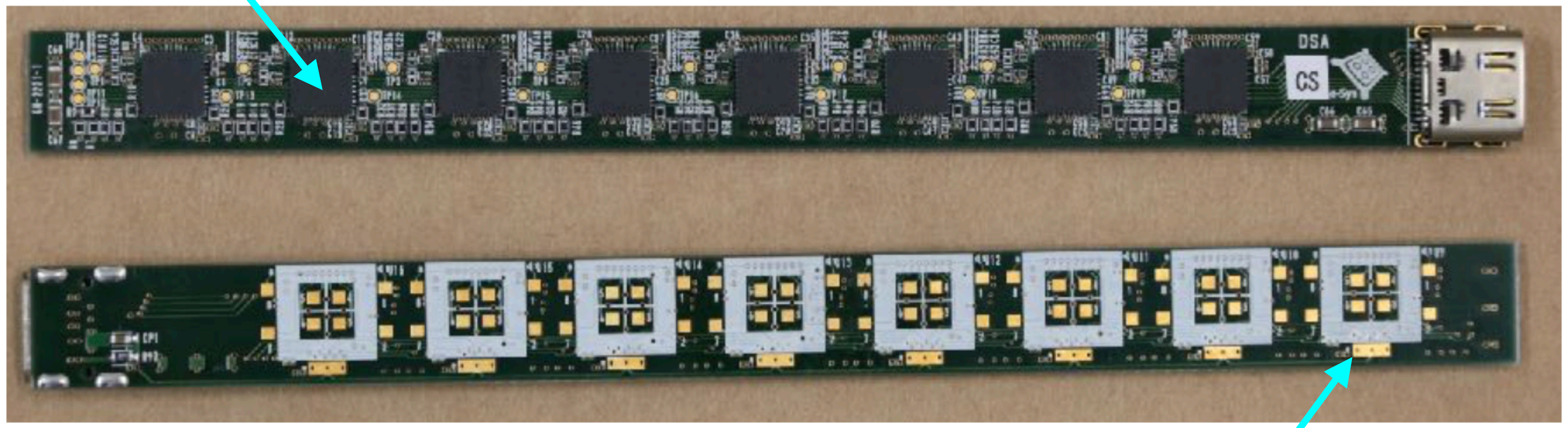
γ-rejection capability increased by IBE and p+ layer.

Analog front-ends & prototype

- TSMC 65 nm LP process, 1 mm x 1 mm
- 8 channels, CSA+CR-RC+Disc.+counter
- No ENC degradation confirmed @ 1 MGy

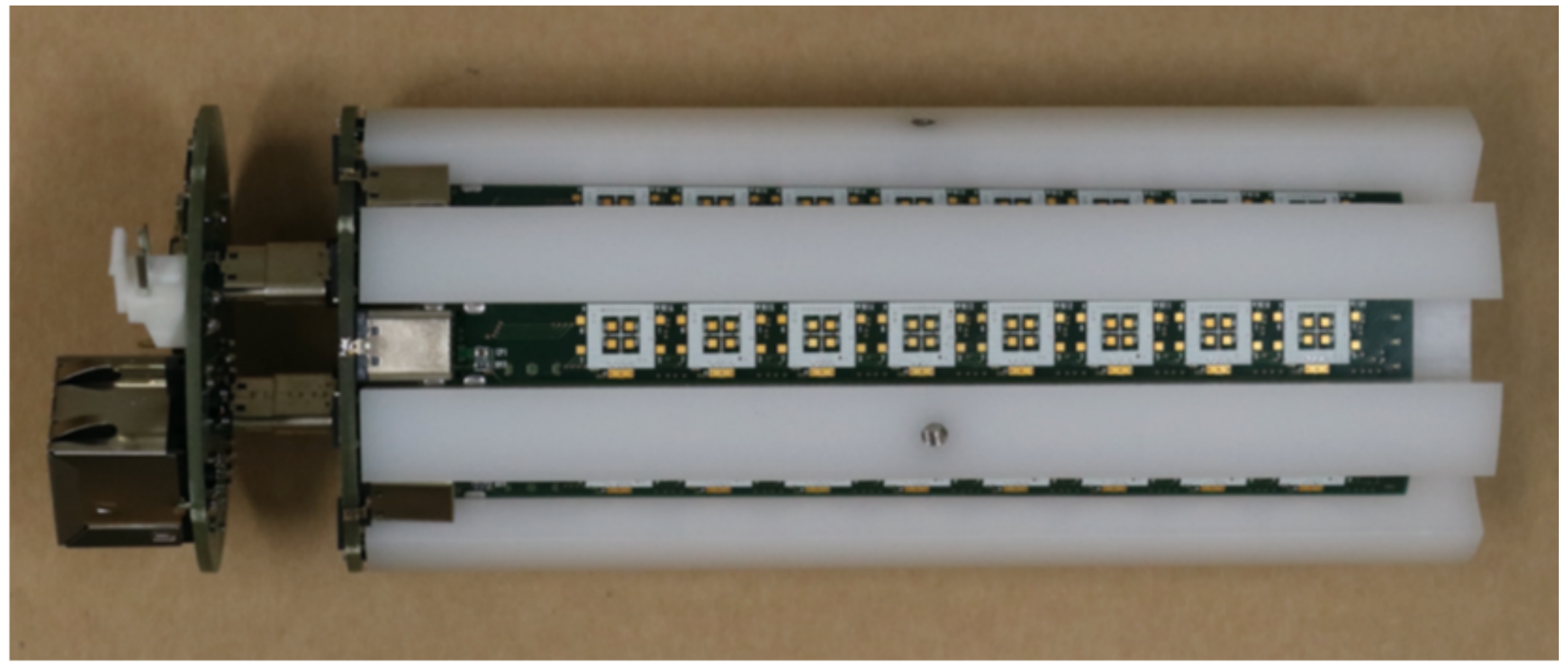


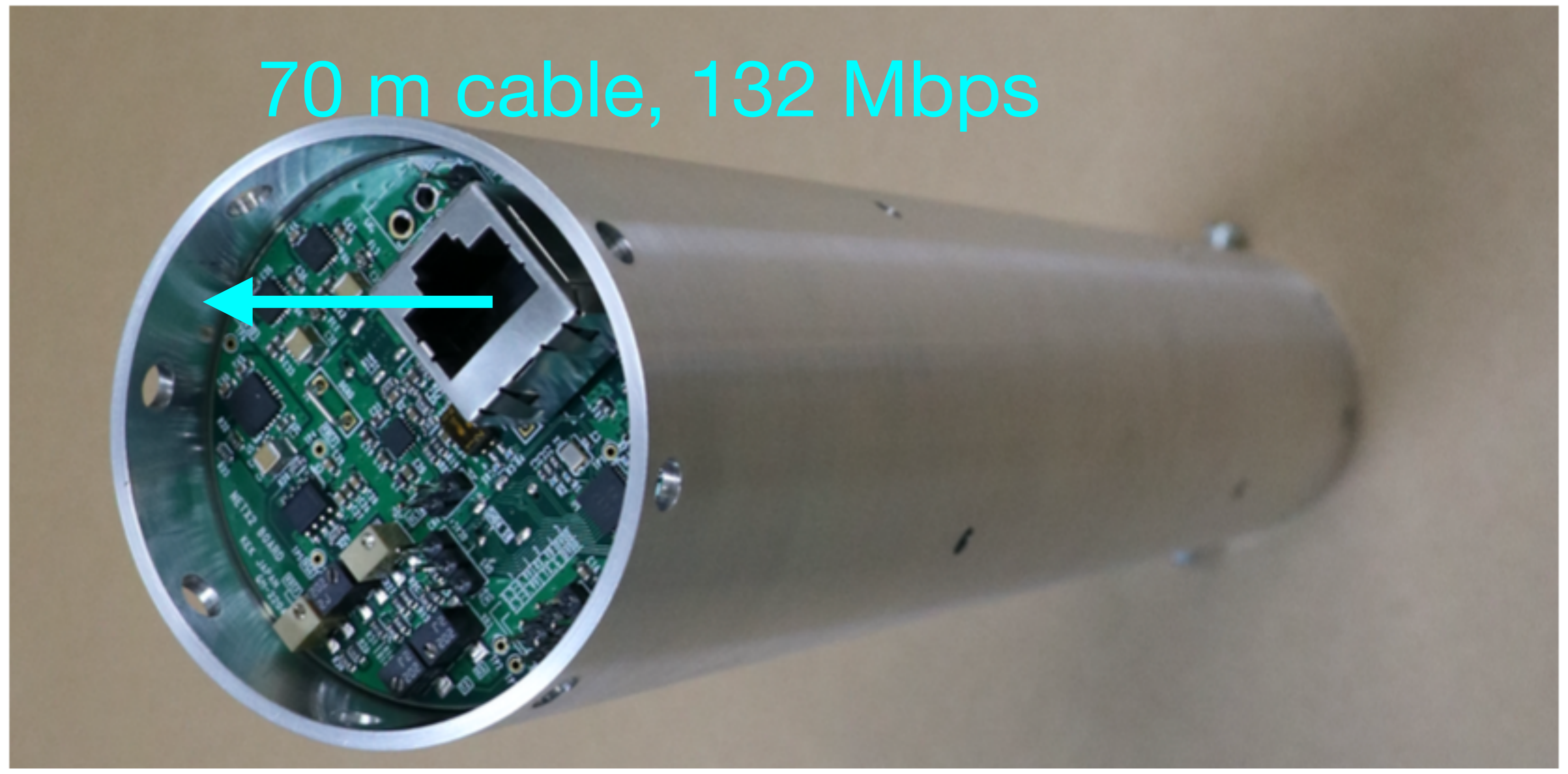
Nu-K_CSA (0.5 mW/ch)	
Type	charge sensitive
Peaking time	50nsec(t_w~100nsec)
Noise	~1500e @Cdet=5pF
S/N	~350@Cdet=5pF



Sensor pads (4ch x 600 chips!)

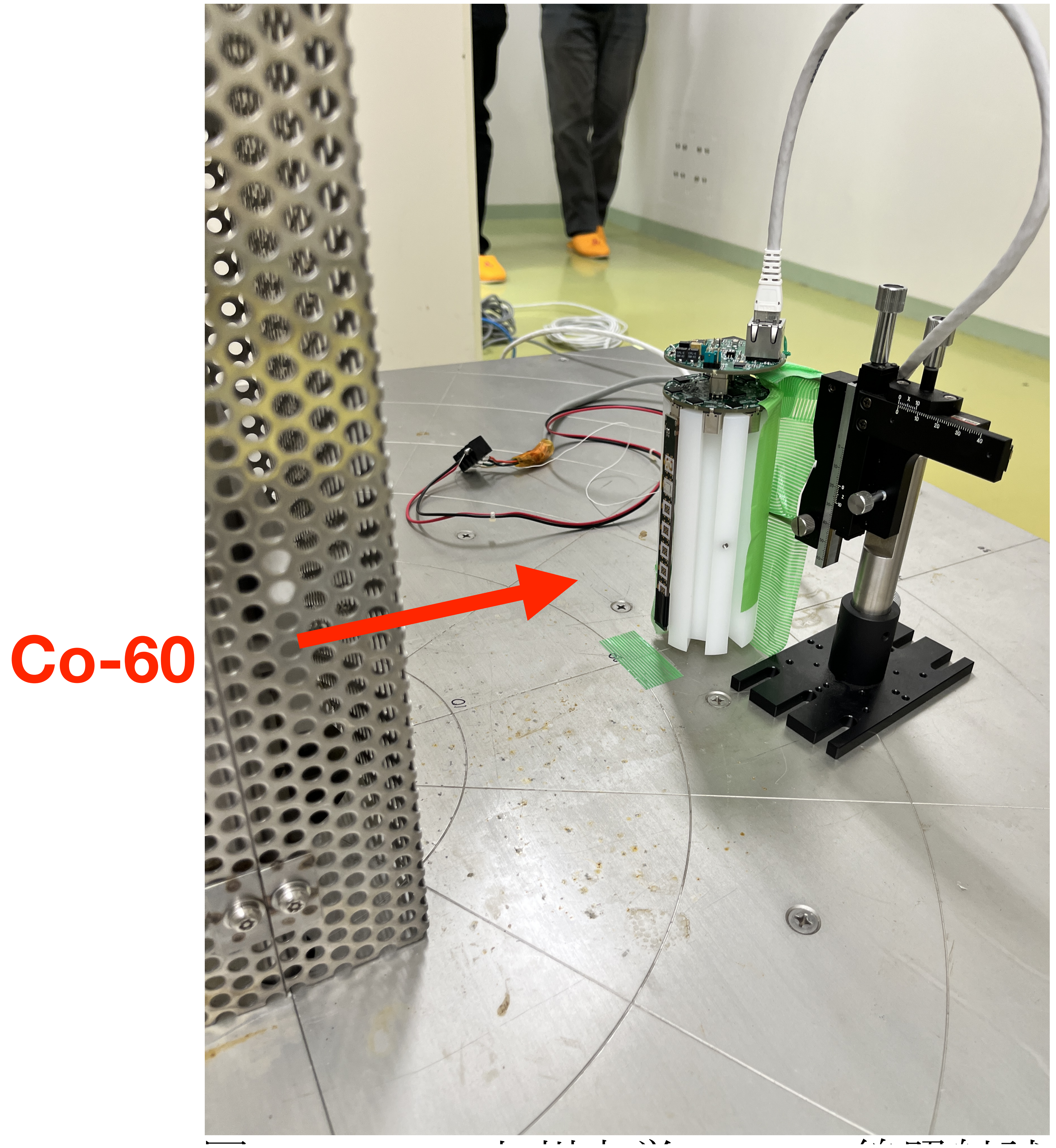
Prototype of the neutron detector



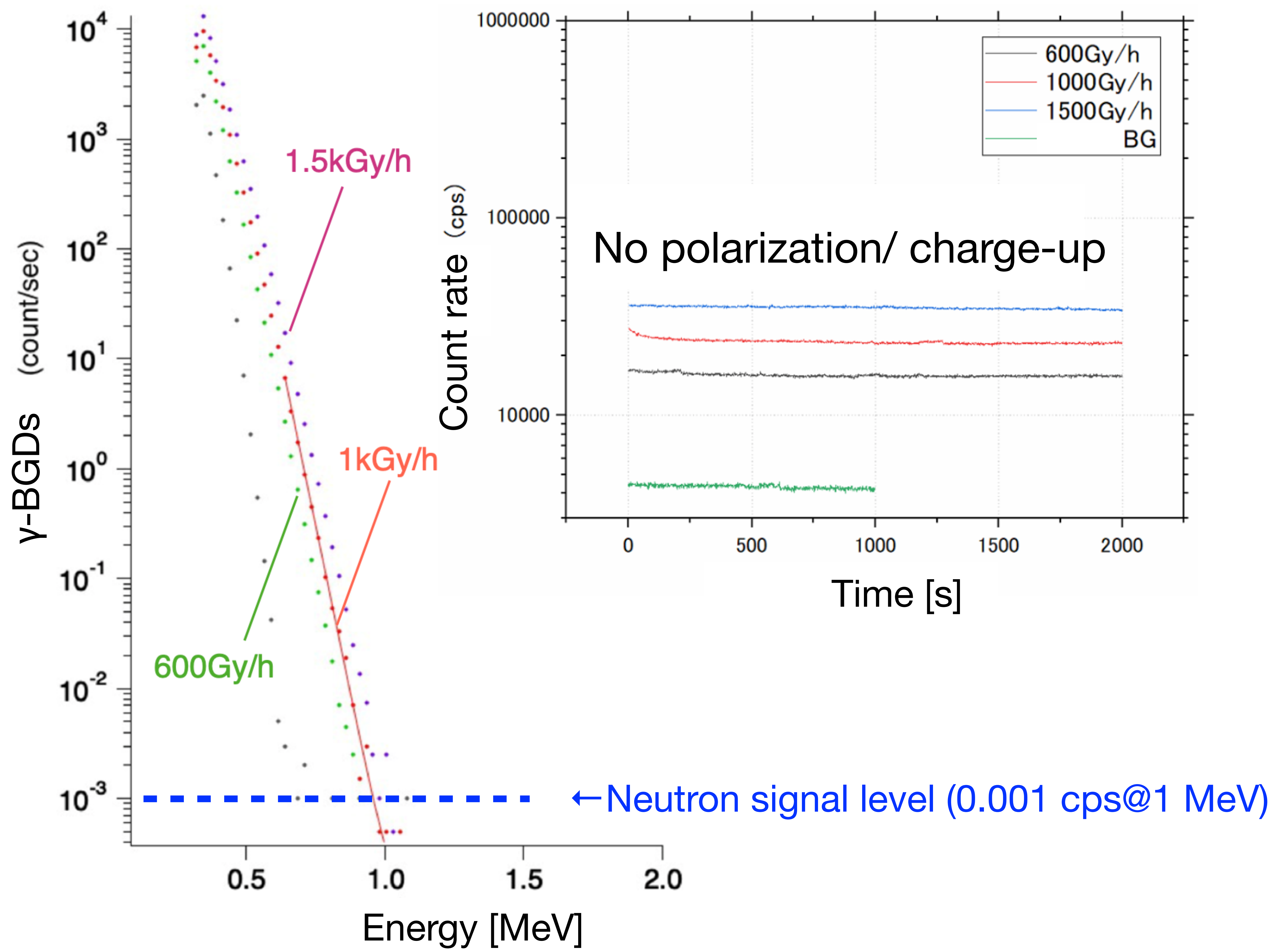


System test @ γ-facility

- Tested best device under γ-BGDs, 1 kGy/h is the requirement
- Neutron converters under preparation



γ-ray response of the AFF (CSA)



Readout system meets all requirement and we start to develop actual detector from this October.

Thank you very much for your attention.