Prototype of SiC beam monitor for the COMET experiment at J-PARC

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)

    - Basic properties of the PN-devices
    - Overview of the COMET experiment
    - Concept of muon beam monitor based on SiC
    - Test beam results
    - Future prospect

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 [cm^2/Vs]	1800	100	800	1450	<3900*[2]	1090*[1]	906*[3]
μ_h [cm^2/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 since 2019.

SiC device fabrication

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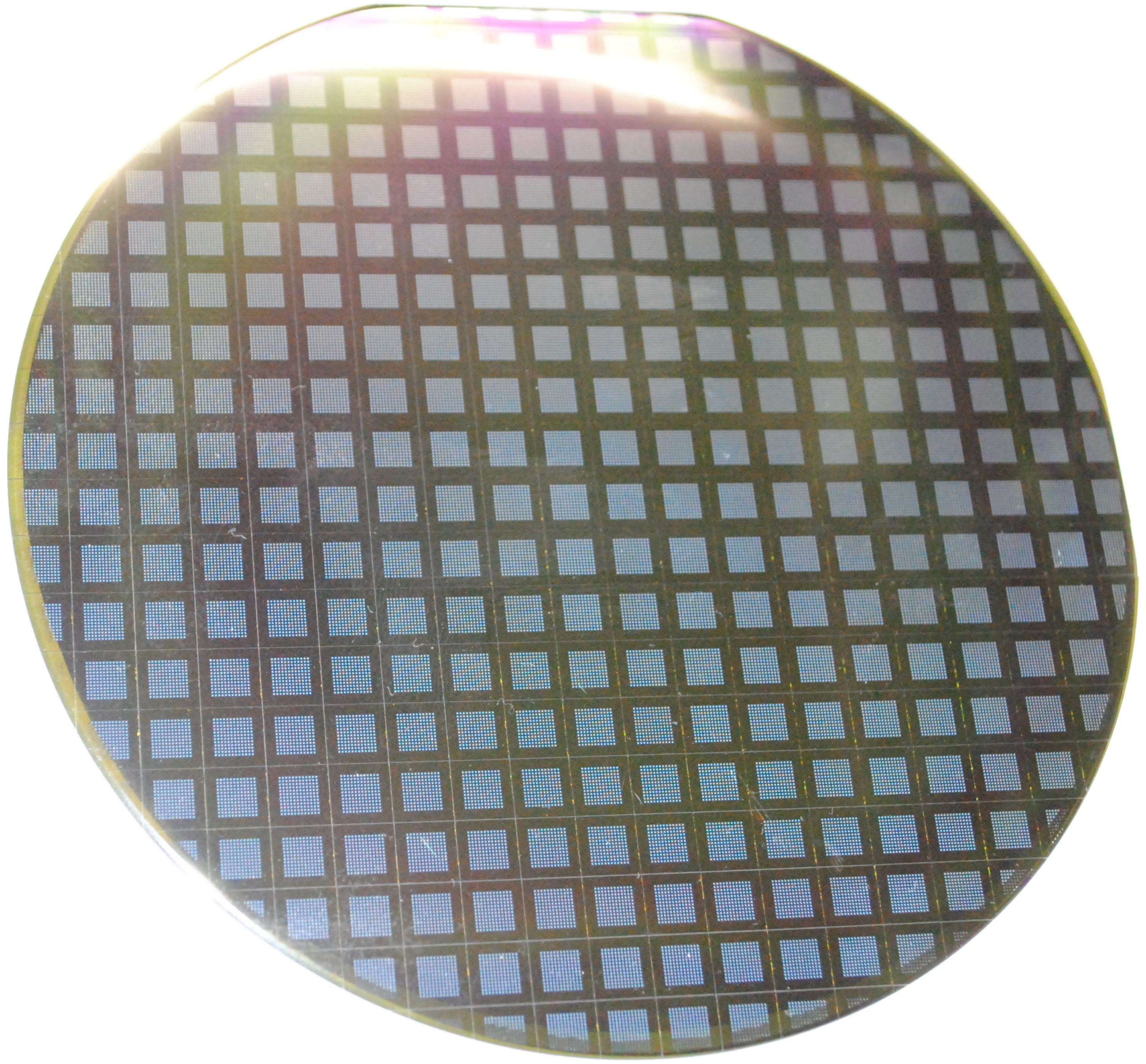
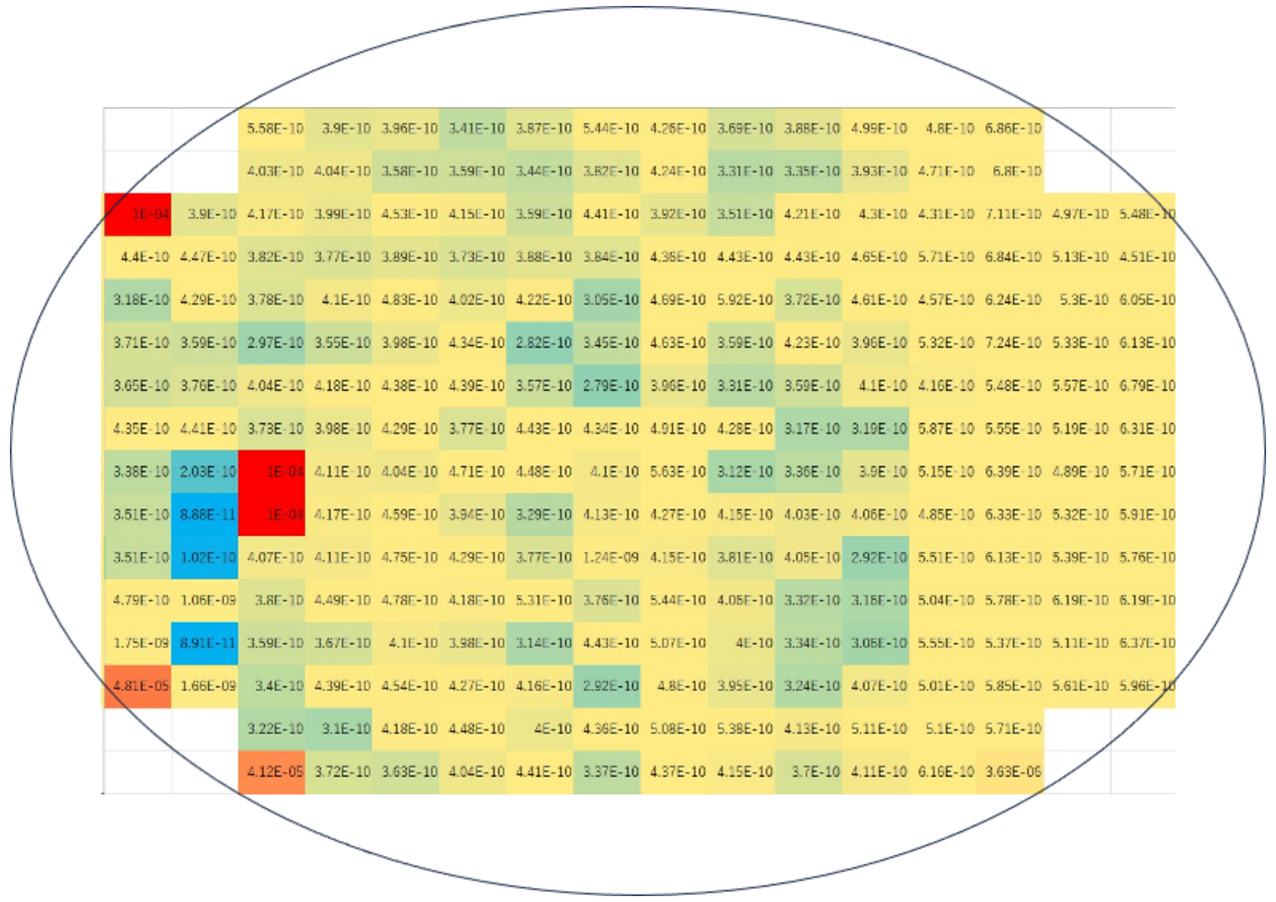
- PN diodes in wafer process, 5 mm x 5 mm simple diode
- Reverse bias tolerance of 3 kV
- 50 um epi grown on (0001) 4H-SiC n-type substrate @AIST
- Nd-Na: 4.7 x 10^{14} cm^{-3}
- Thickness: 350 um
- 260 dies with 5 x 5 mm^2 from 4-inch wafer, 4 x 4 mm^2 active area

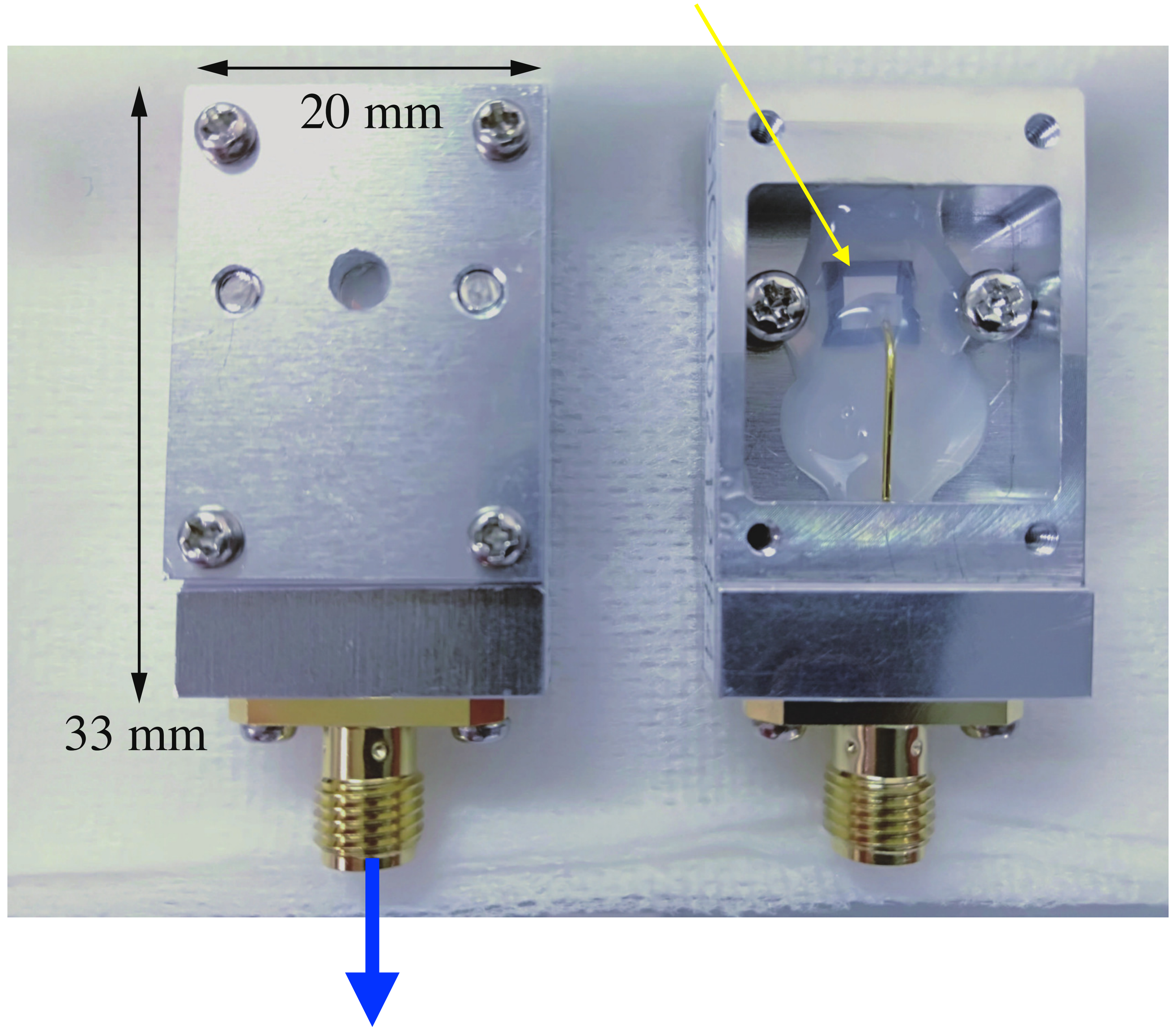
Schottky diode	PN diode
- Easy process	- Difficult process (High temperature annealing)
- Sensitive to surface conditions	- Less sensitive to surface conditions



Color map of leakage currents



Silicone rubber for preventing electric discharges

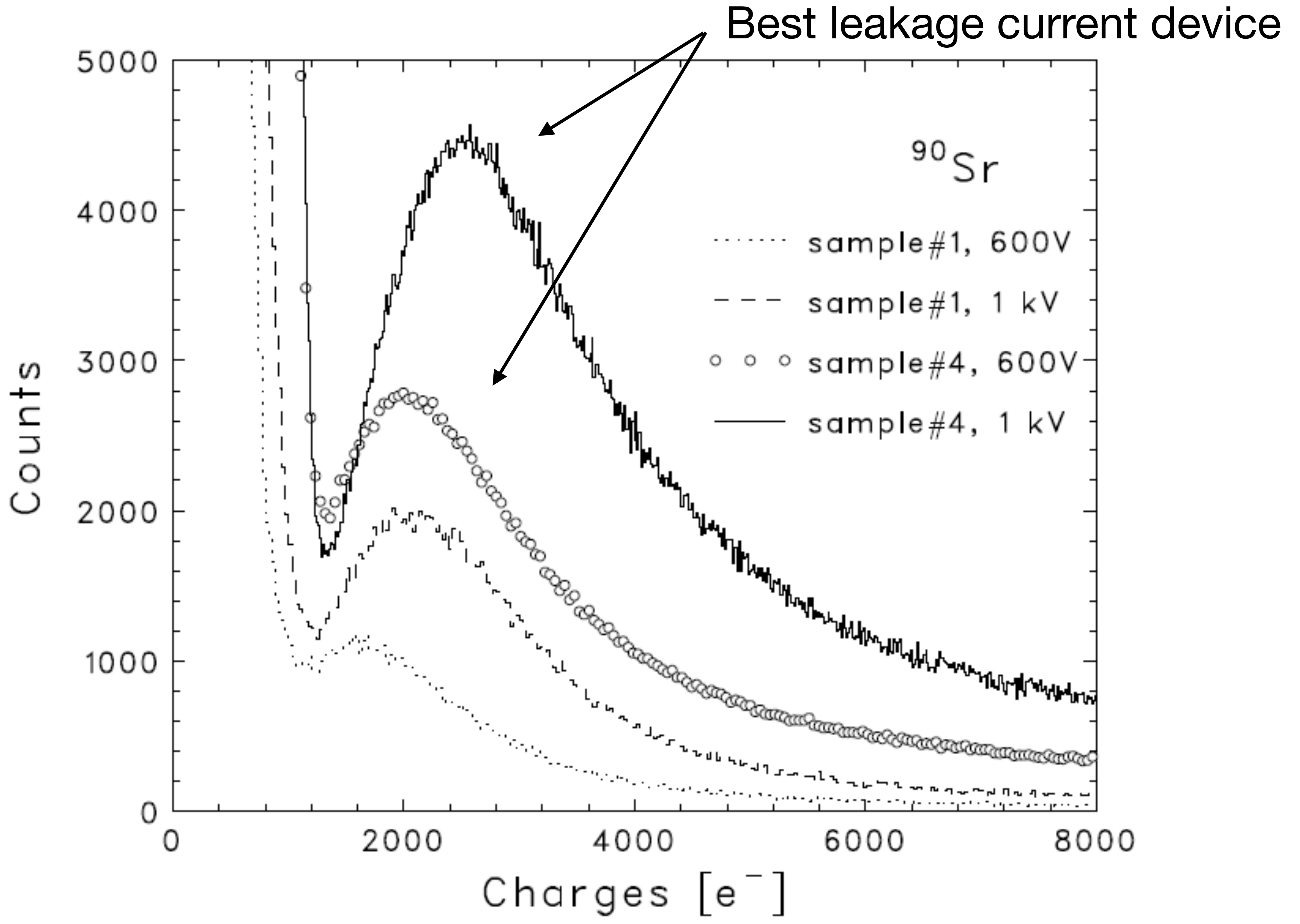


commercial CSA (AC-coupling)+shaper

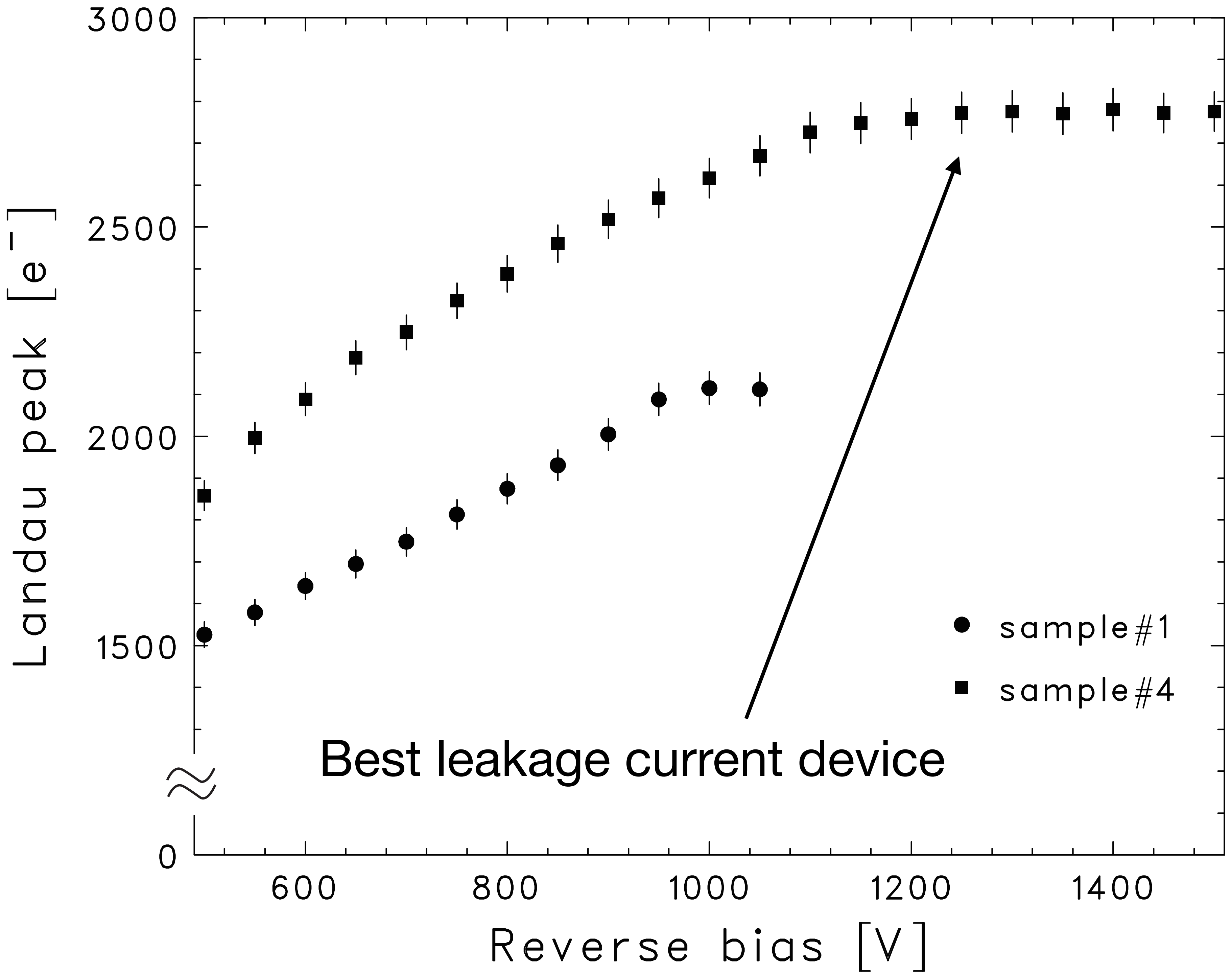
Device characteristics

- Leakage current <10 nA, uniform within one order of magnitude
- Stable Landau peak position (no polarization/charge-up)
- Full depletion voltage 1000 V for 50 um epi (TCAD)
- No signal / leakage current degradation, even after 10e+13 n_{1MeV}/cm^2, even with biasing

IEEE TNS, vol.68, p.2787, 2021.



Landau peak is separated from pedestal in worst leakage device.



Full-depletion voltage is consistent with TCAD simulation.

How can we play with these devices?

Demand for SiC sensor: COMET at J-PARC

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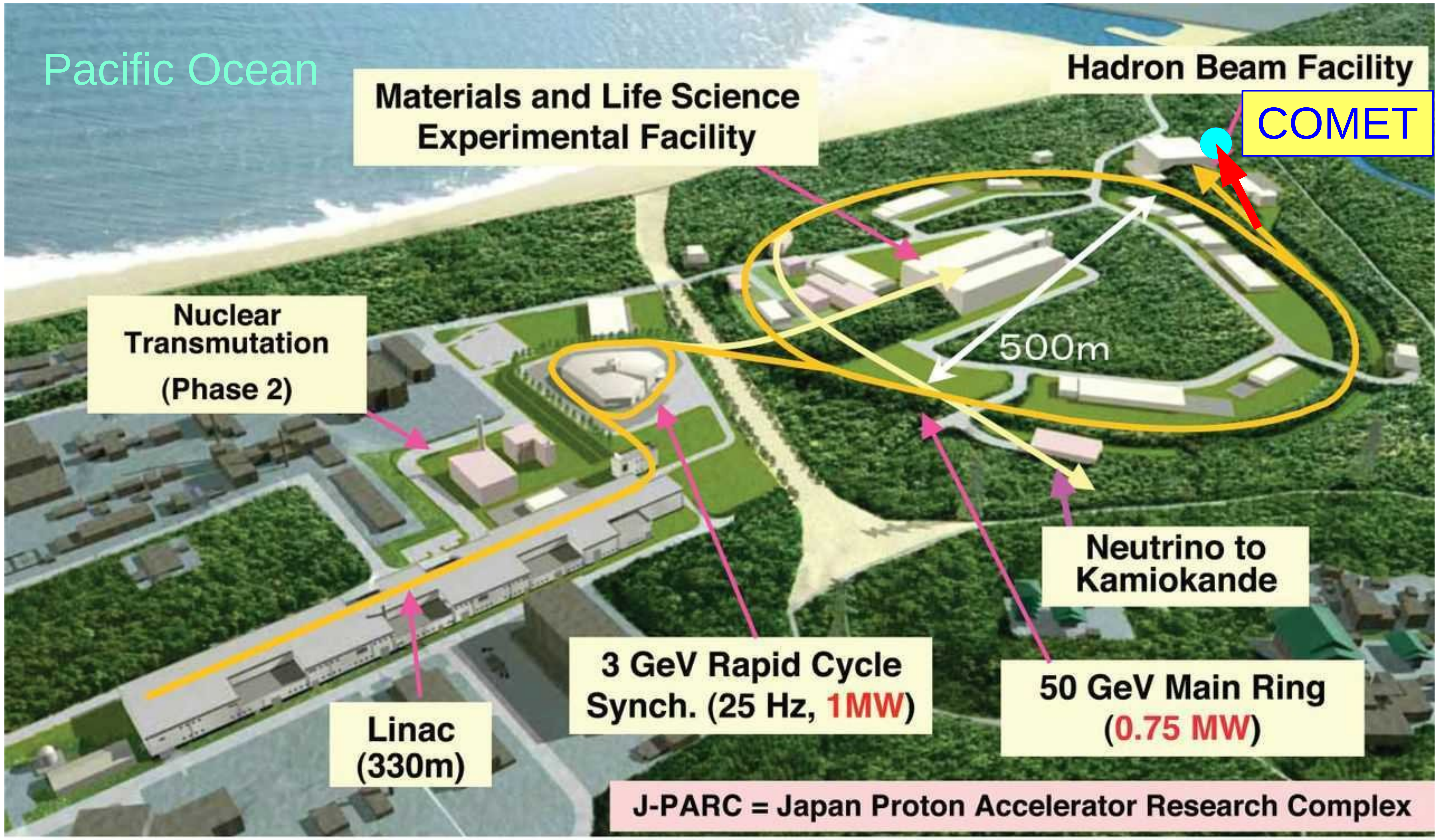
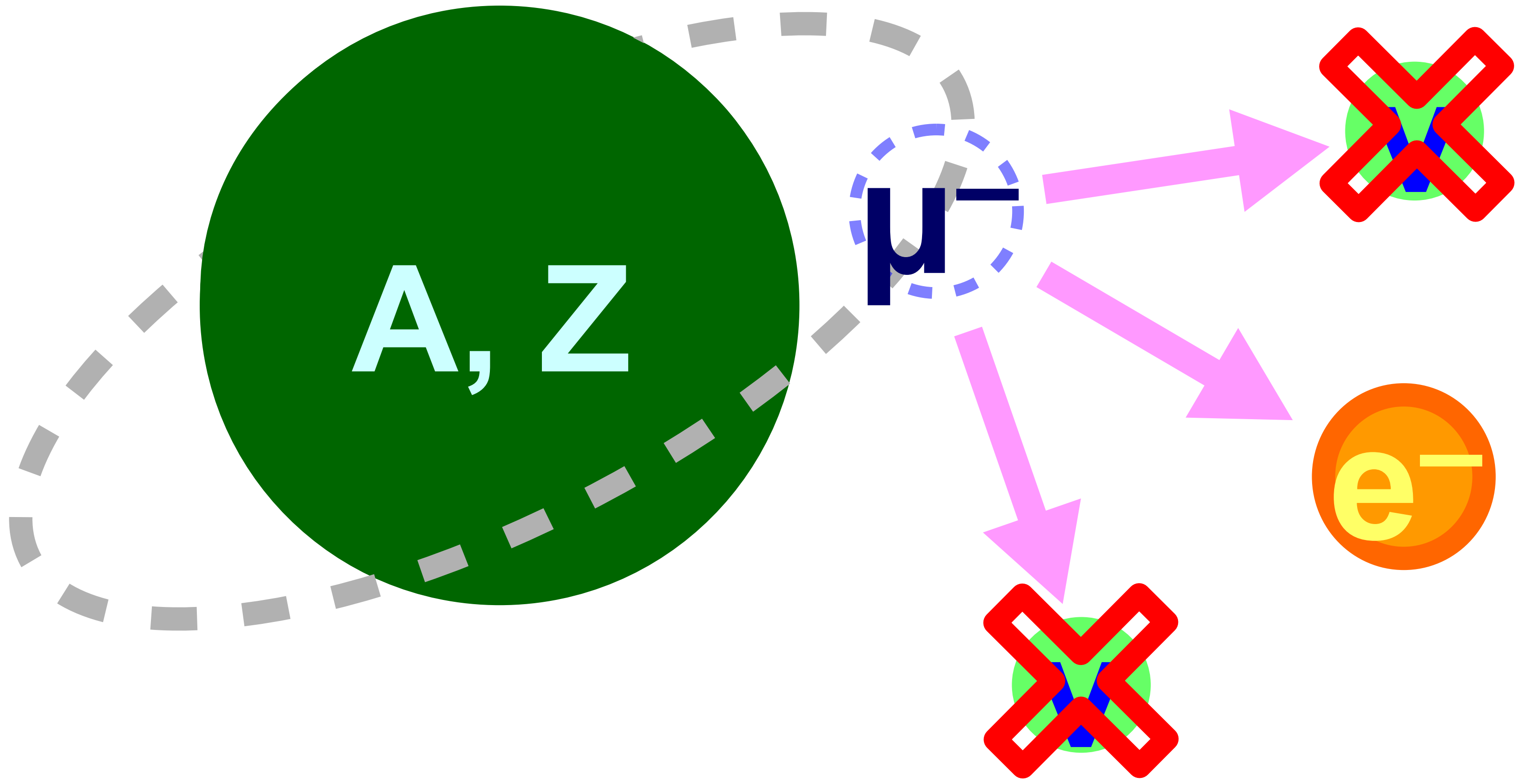
- COMET (COherent Muon to Electron Transition) starts from 2027 (one of the KEK core projects)
- They require rad-hard beam monitors for high-intensity 8 GeV protons / secondary particles

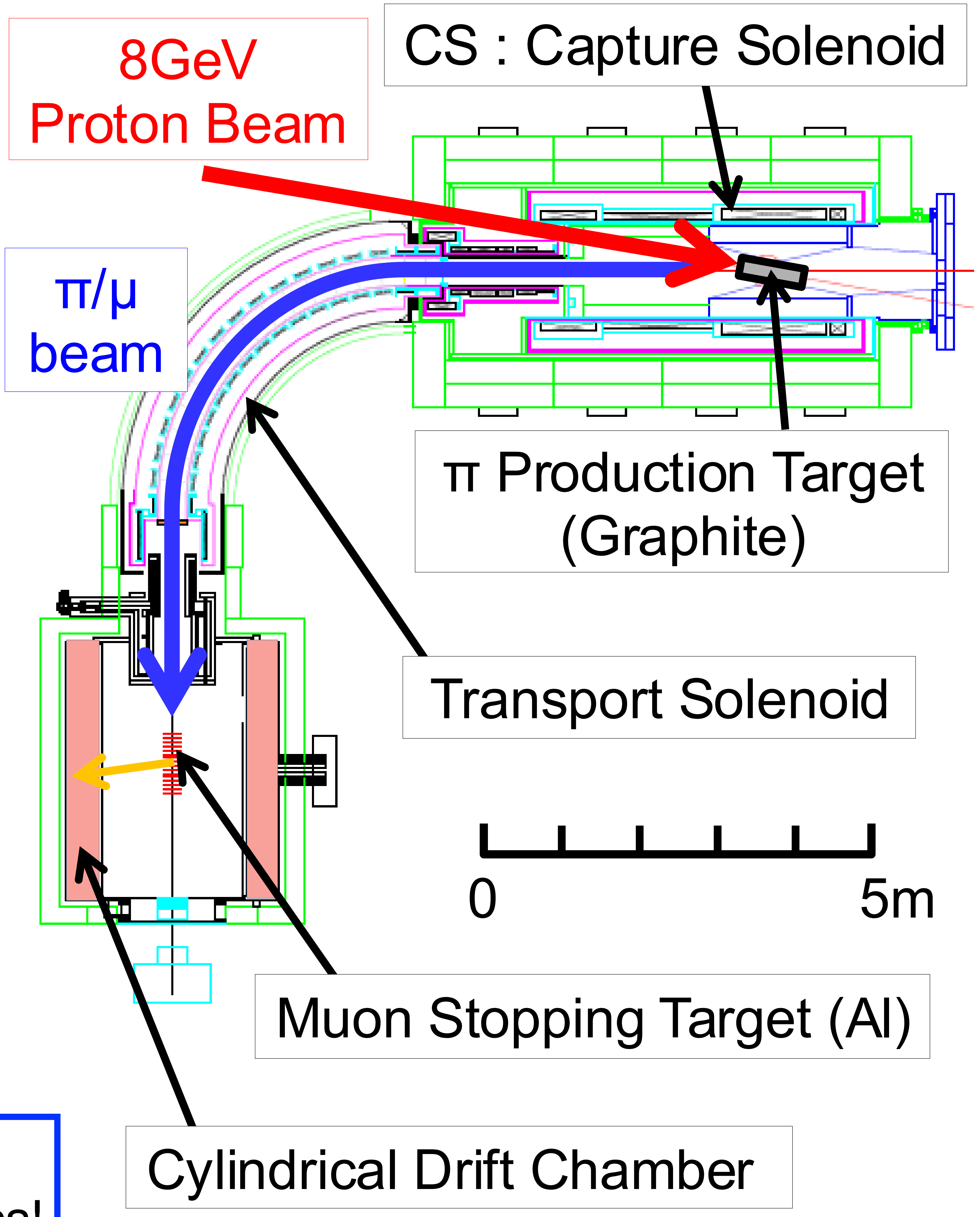


What do we do in COMET: Muon to Electron Transition



Search for neutrino-less muon to electron conversion.
$\mu^- + (A, Z) \rightarrow e^- + (A, Z)$

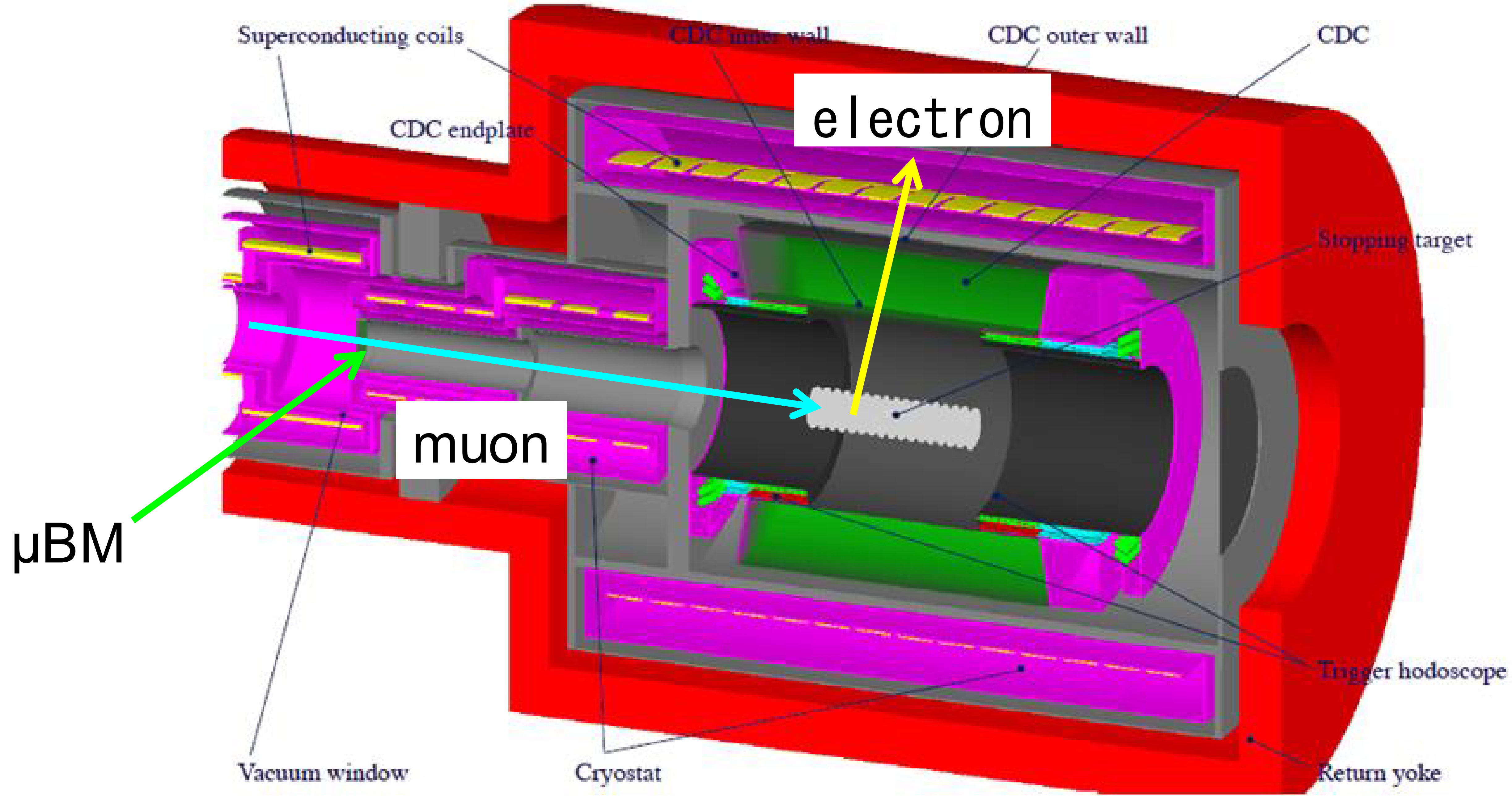
Contribution from Standard Model by neutrino oscillation is ~$O(10^{-54})$.
Good probe for new physics search.



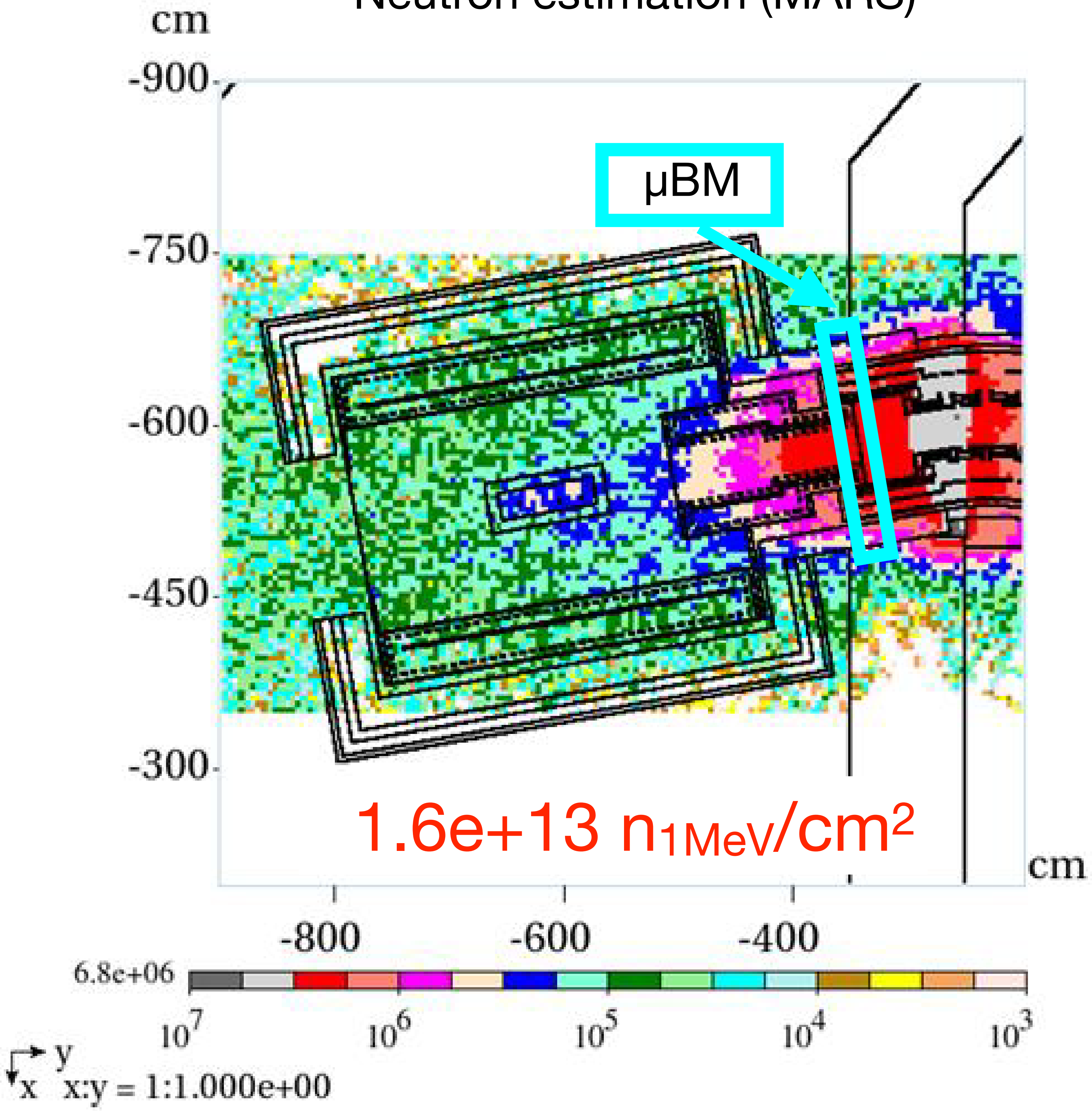
- COMET aims to achieve x100 higher sensitivity from the past.
- It's good opportunity to install "own" detectors to contribute to new physics!

COMET Phase-1 and muon beam monitor (μBM)

- Pions decay to muons during transportation in Solenoid magnet.
- Muons are decayed into electrons in the stopping target.
- Beam profile monitor, bunch stability, ToF background estimation etc.

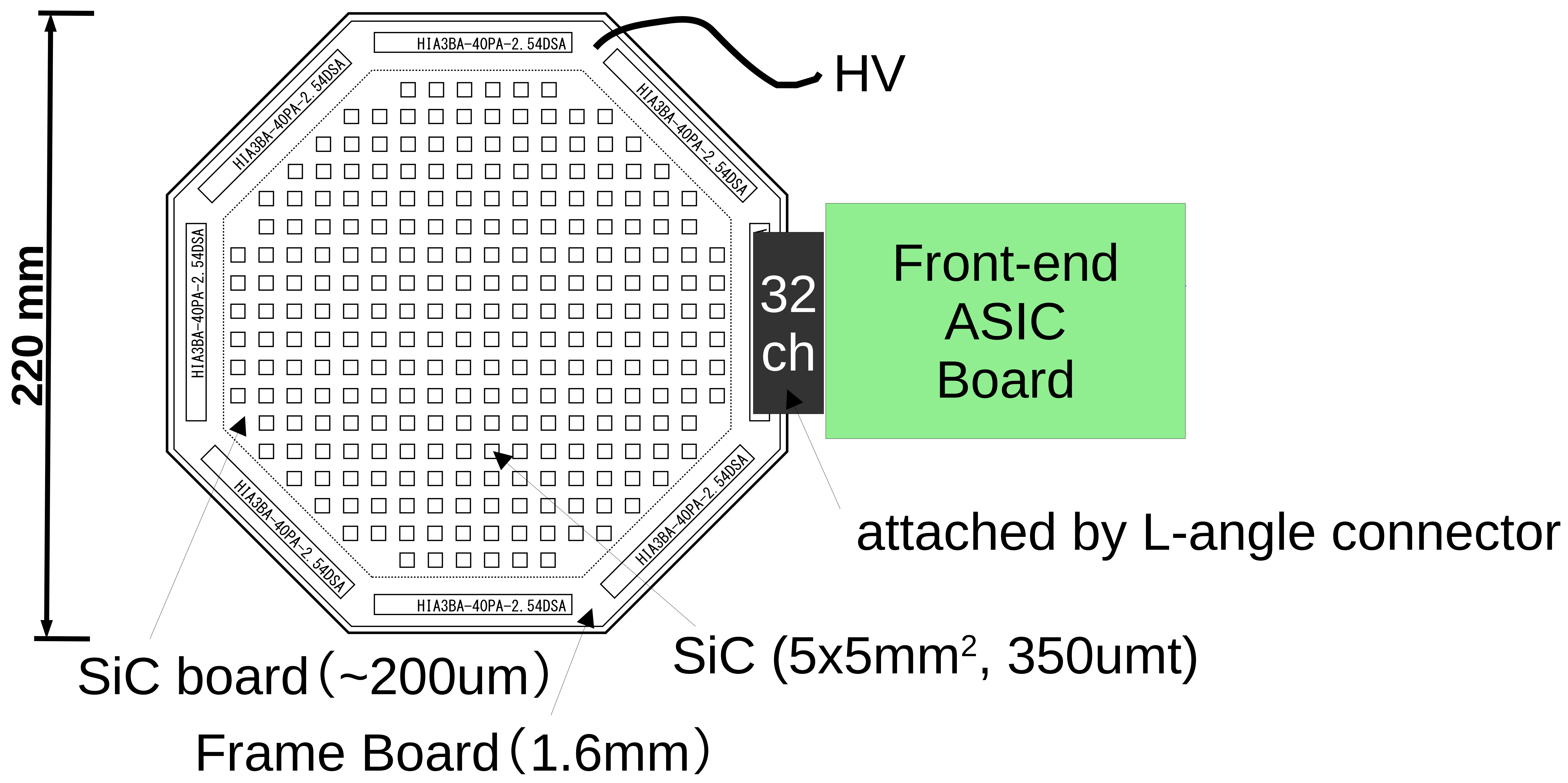


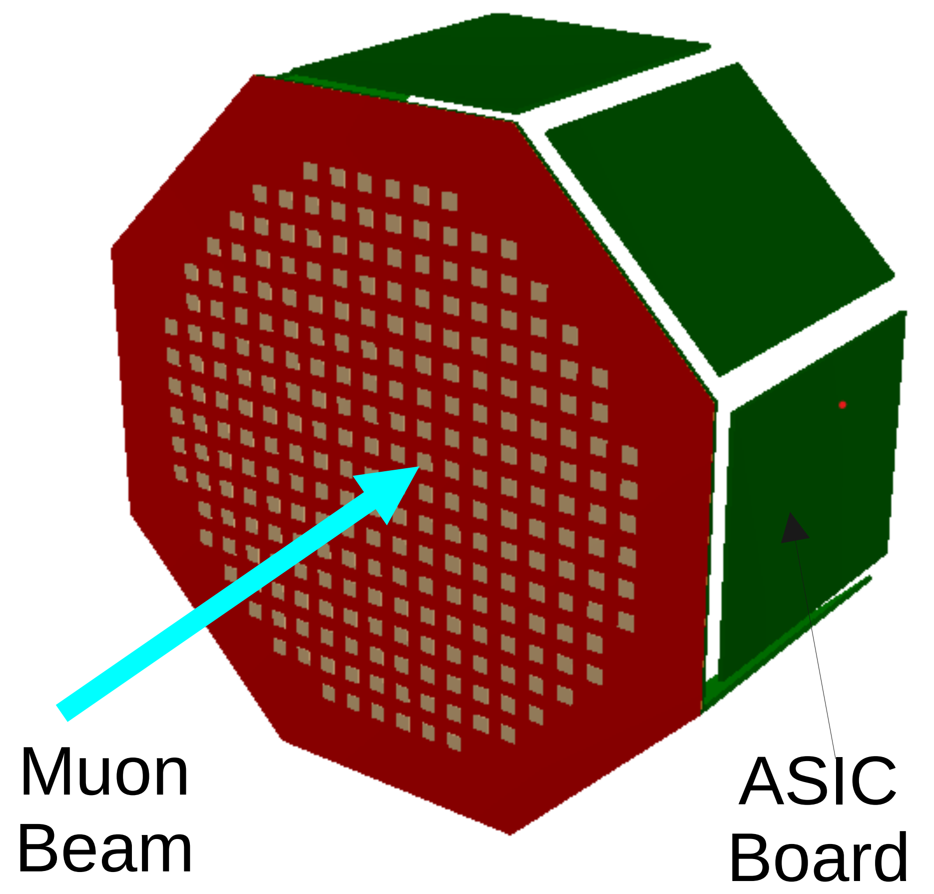
Neutron estimation (MARS)

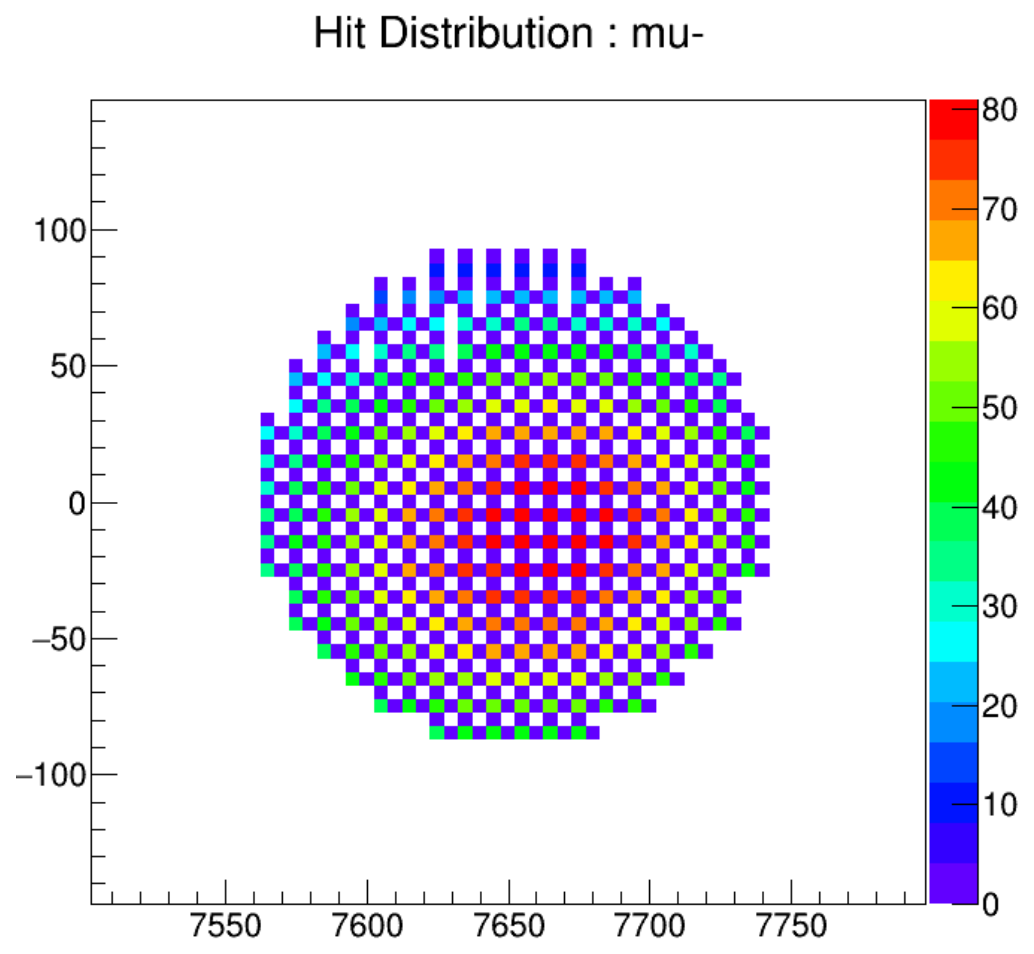


- Radiation-tolerance is the key to the muon beam monitor.

Concept of SiC-based μBM







- 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.

Beam test results

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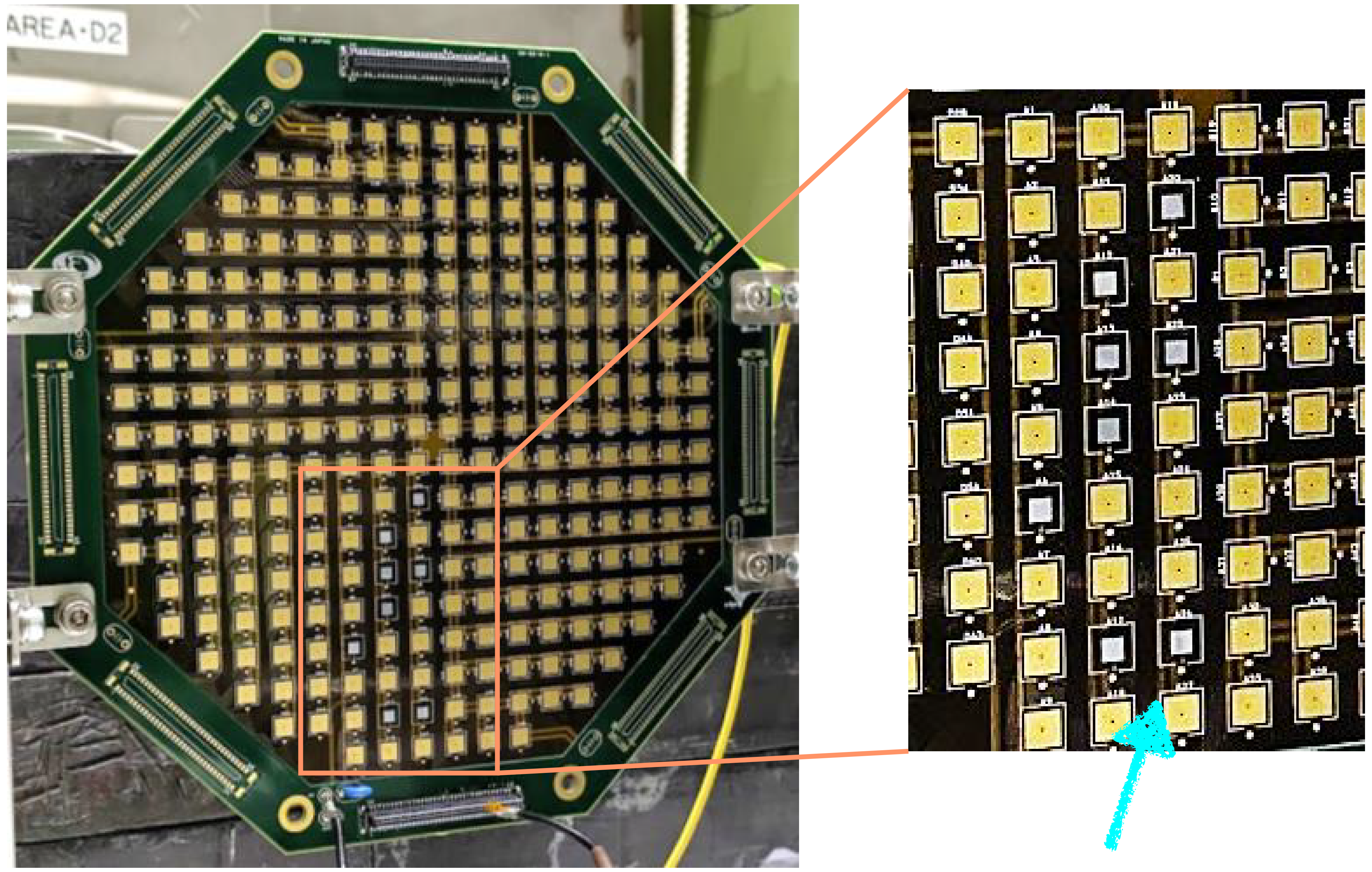
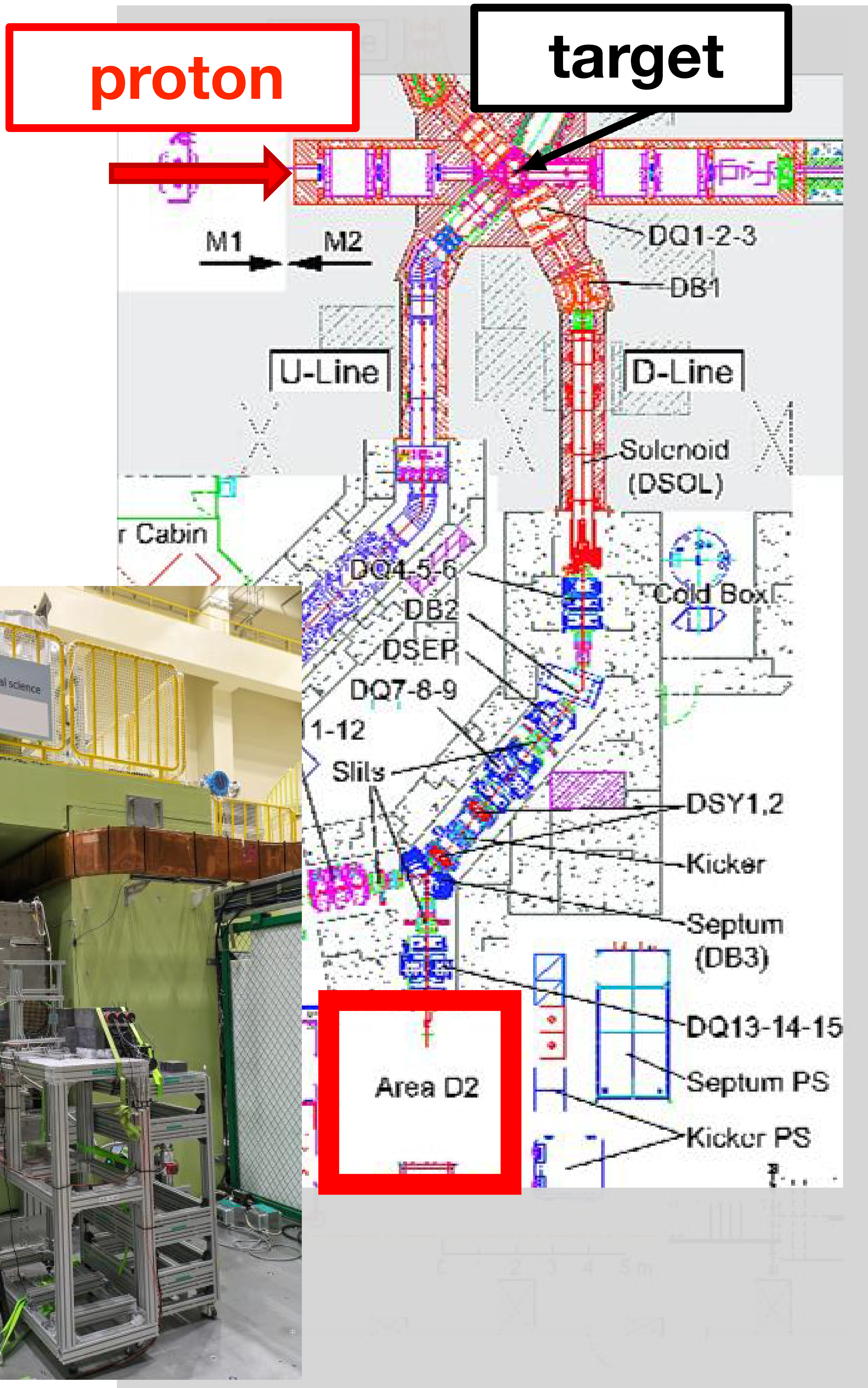
- MLF (Materials and Life science experimental Facility), D2 beam line
- Pulsed muon beams (25 Hz, ~20 muons/bunch), 20~100 MeV/c.
- Very close to the actual experiment
- Readout electronics not ready in time for this beam test…(commercial CSA+shaper)



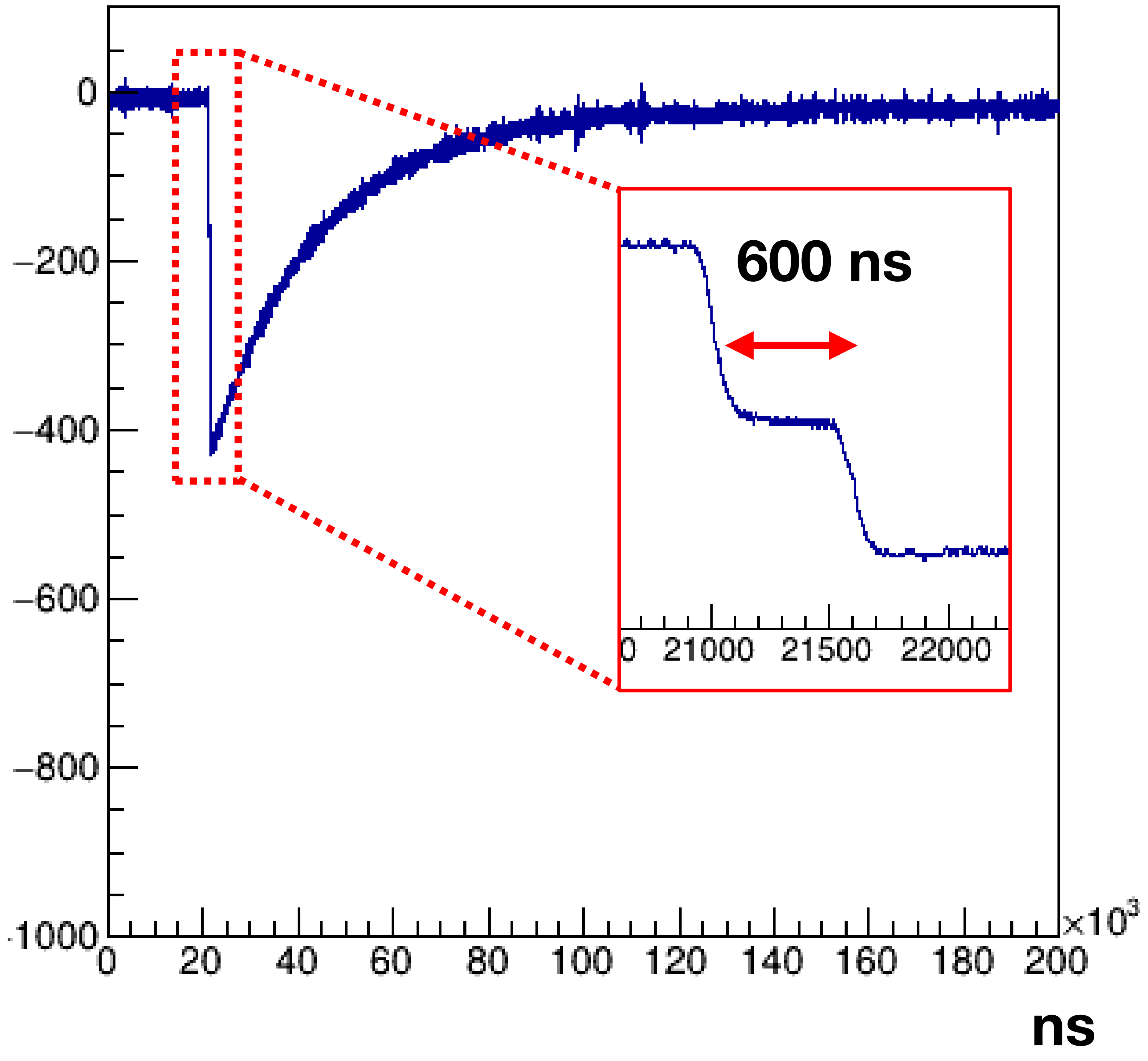
solder paste + Au wire



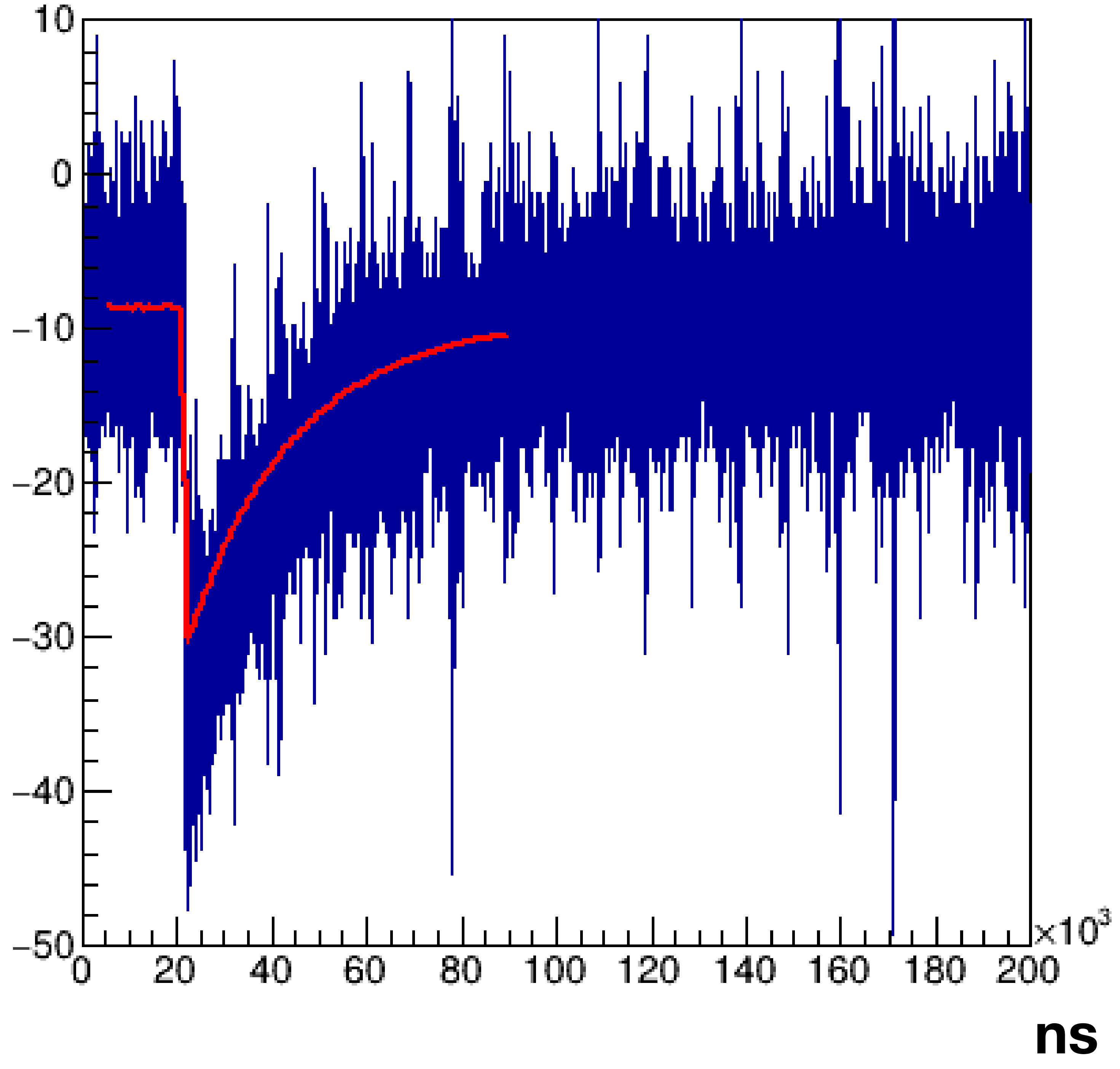
Signals from SiC sensors

- Triggered by beam-injection timing

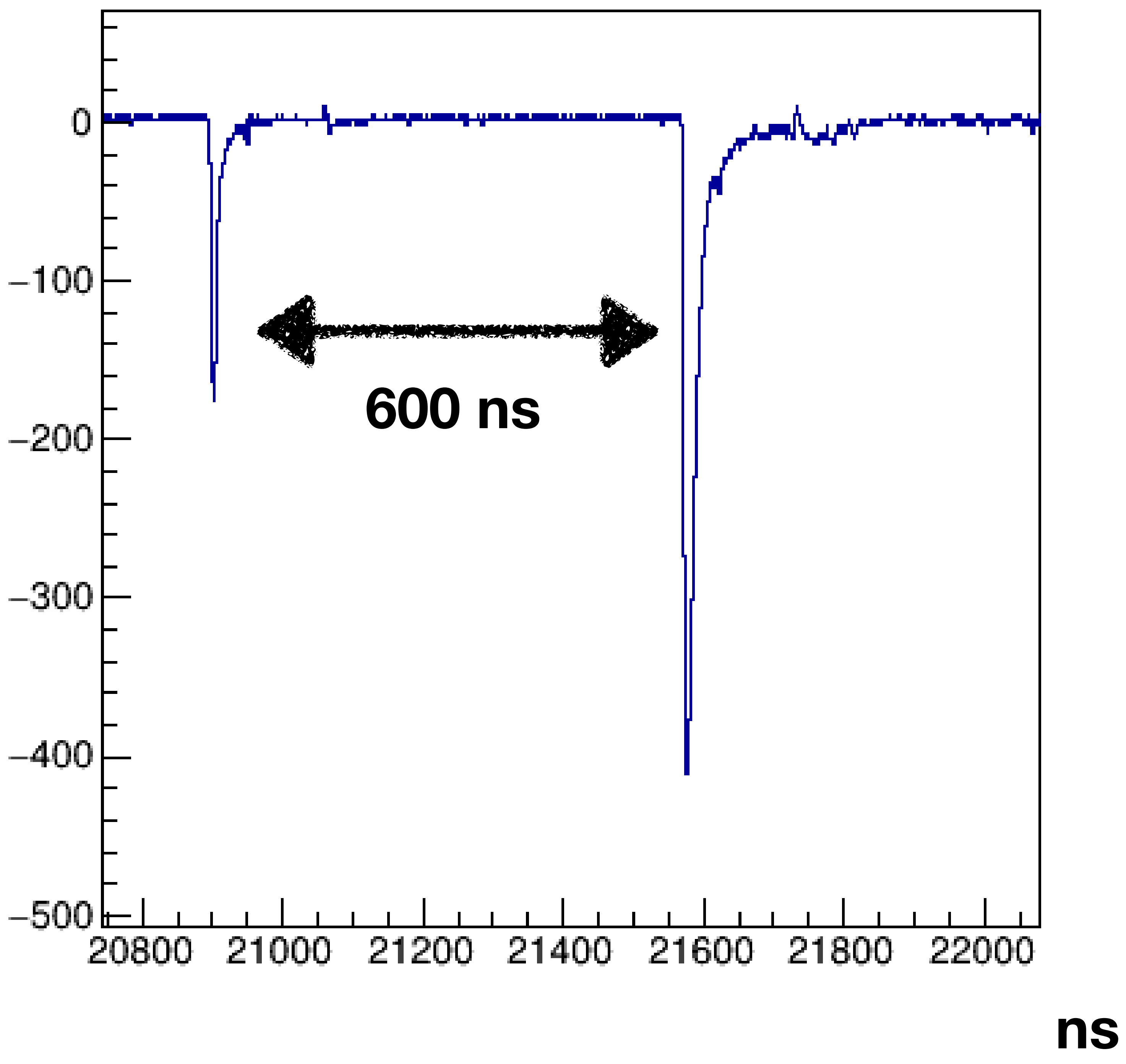
Signals from SiC (>10 muons)



Signals from SiC (2-3 muons)



Time structure of muons (double pulses/bunch)



Pulse height distribution@ low intensity μ-beams

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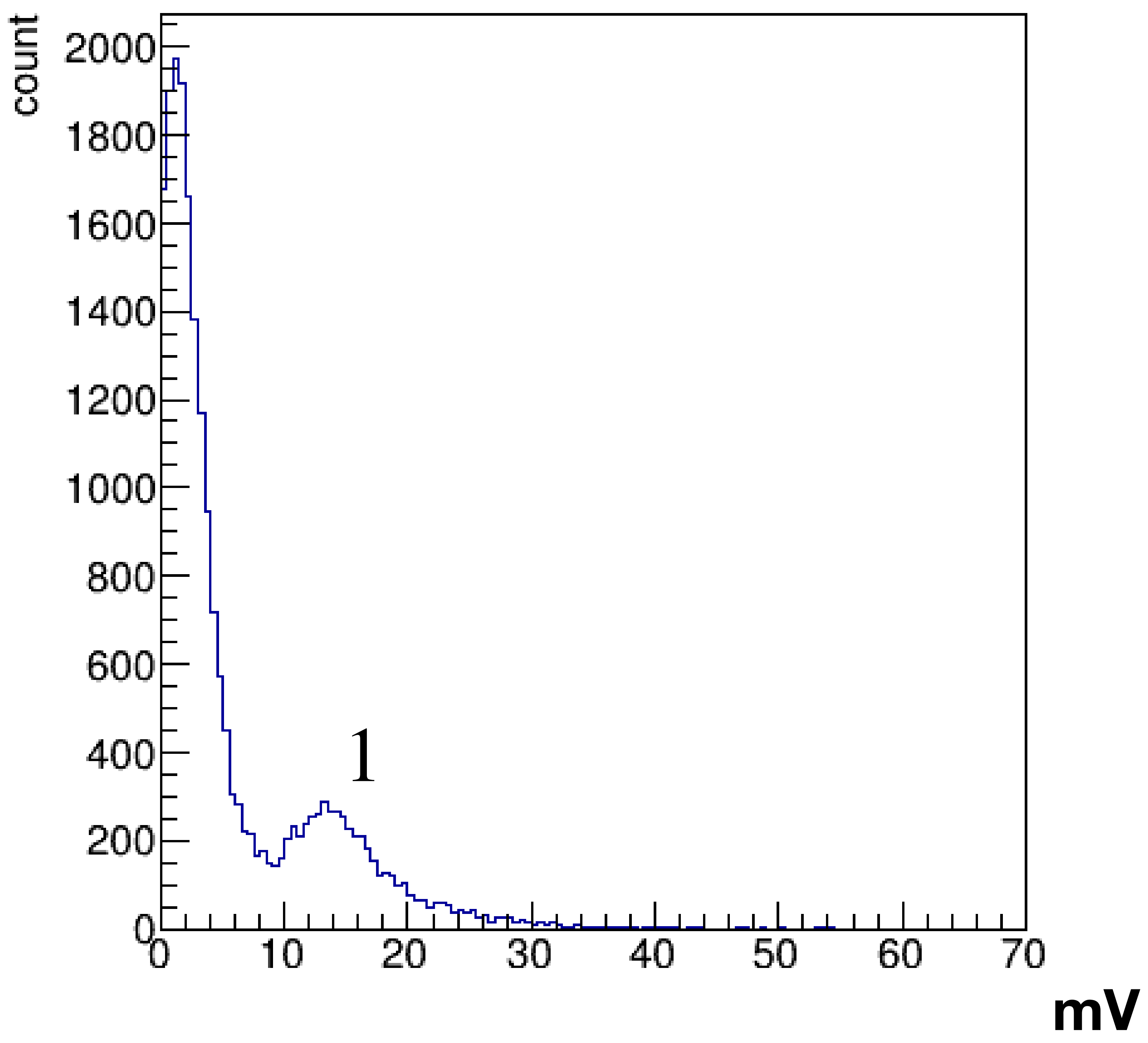
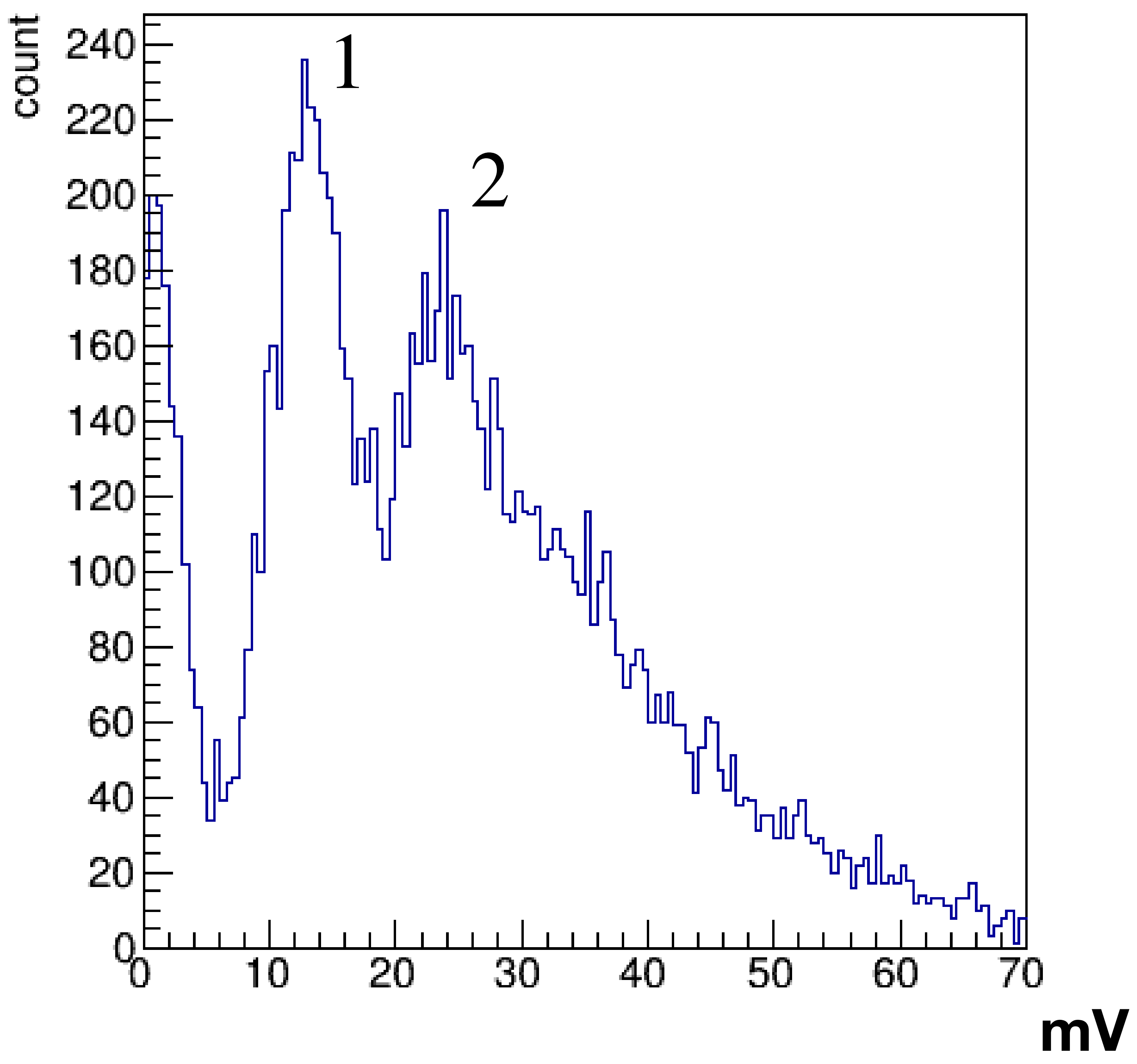
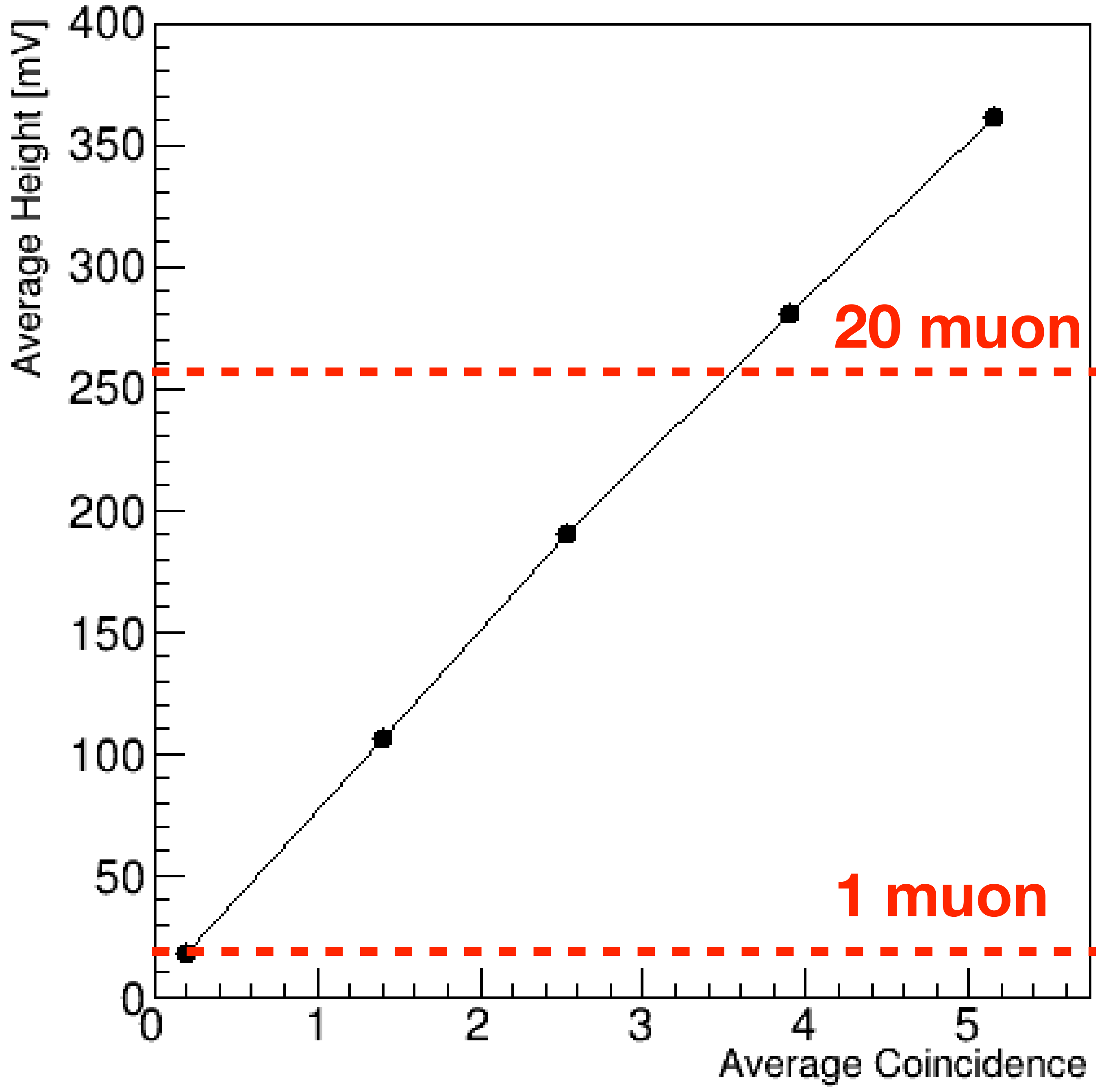
@lowest intensity beams

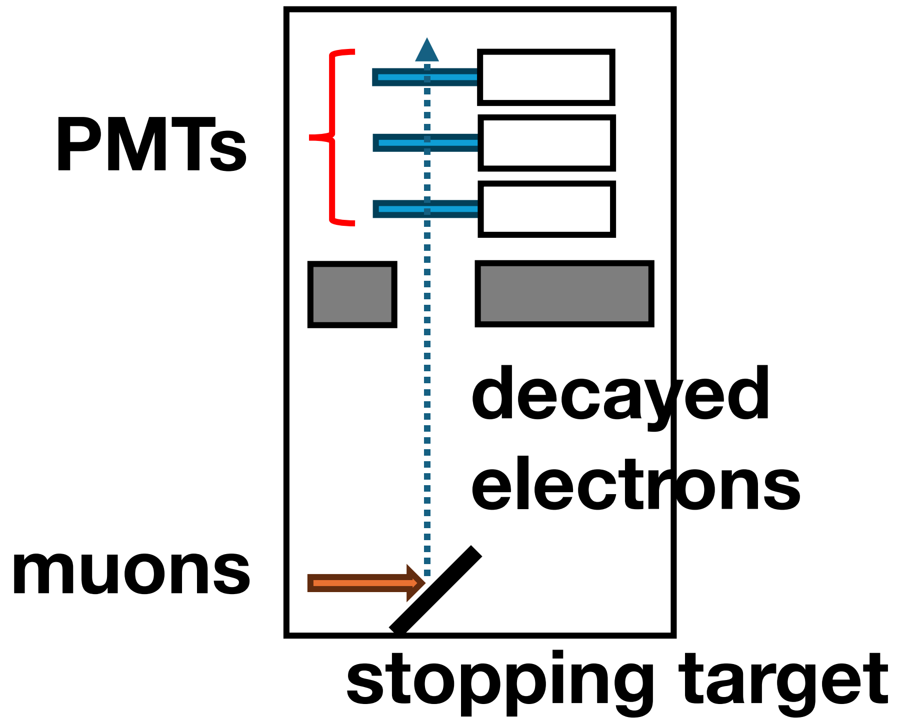






- Discretized peaks (like photons)
- Pulse heigh determined by fitting, ~13 mV/muon
- Linear correlation with electrons, up to 30 muons

SiC sensors are ready for the muon beam monitor.

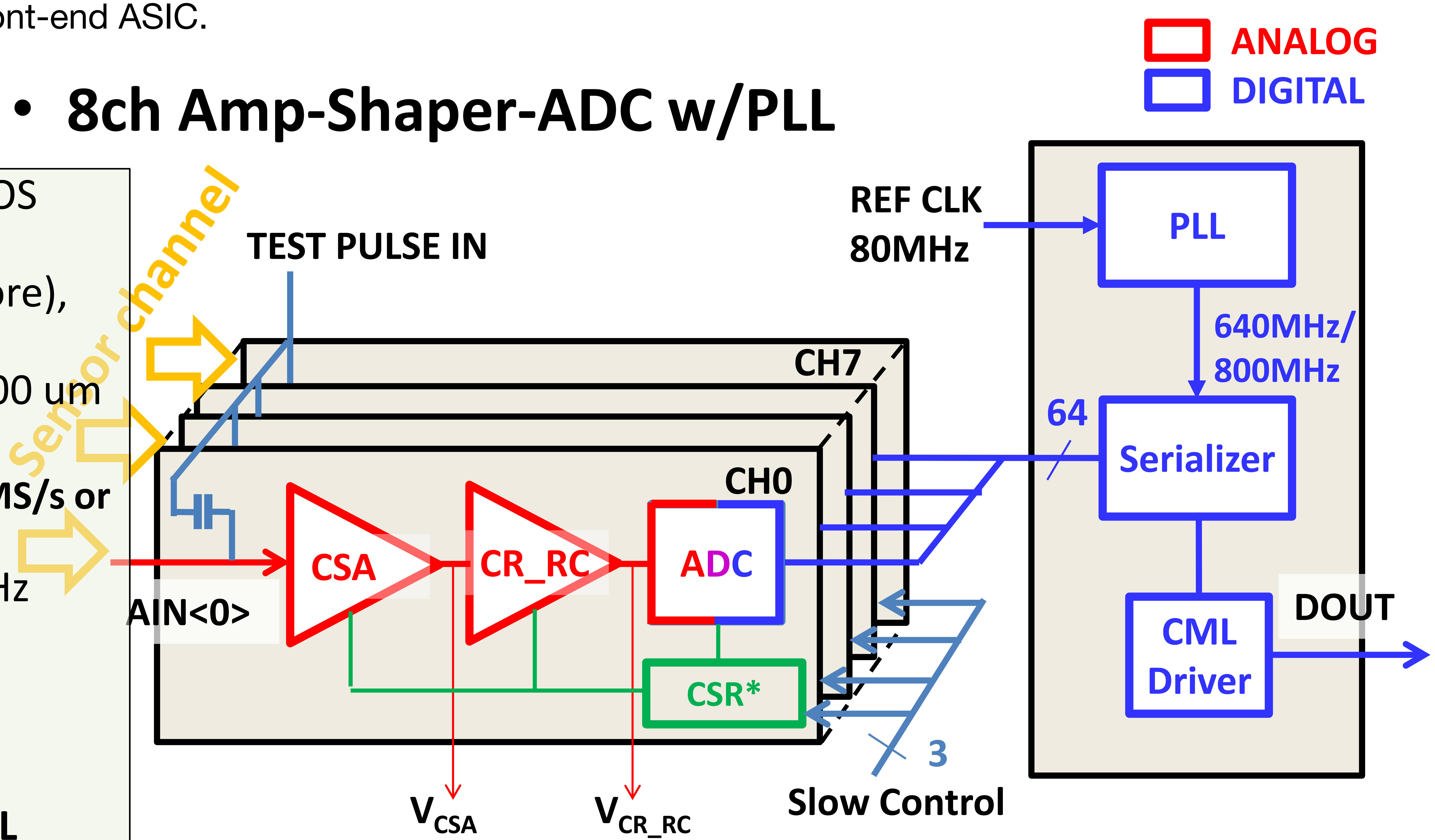


Readout electronics (SCIBER, Silicon Carbide IC for beam monitor)

Radiation-tolerance also required to front-end ASIC.

- **8ch Amp-Shaper-ADC w/PLL**

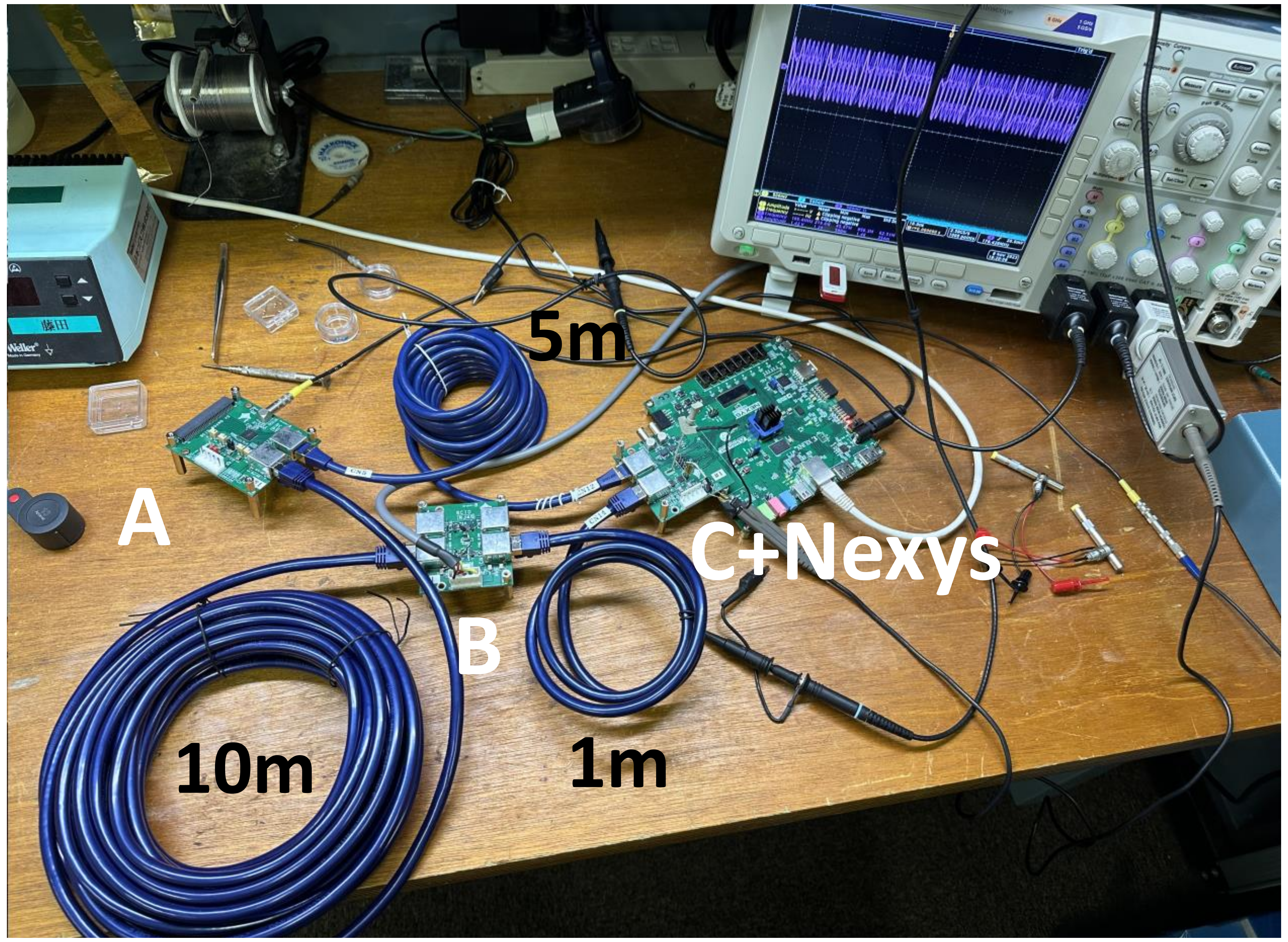
- Technology: TSMC CMOS 65nm LP
- Supply Power: 1.2V (Core), 1.8V (I/O)
- Chip size: 960um x 2,000 um
- 8-bit SAR ADC
  - Sampling Rate: **12.5MS/s or 10MS/s**
- PLL: 800MHz or 640MHz (w/80MHz REF CLK)
- Inputs: 8 channels to connect sensors
- Outputs: Digitized differential signals, **CML**



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

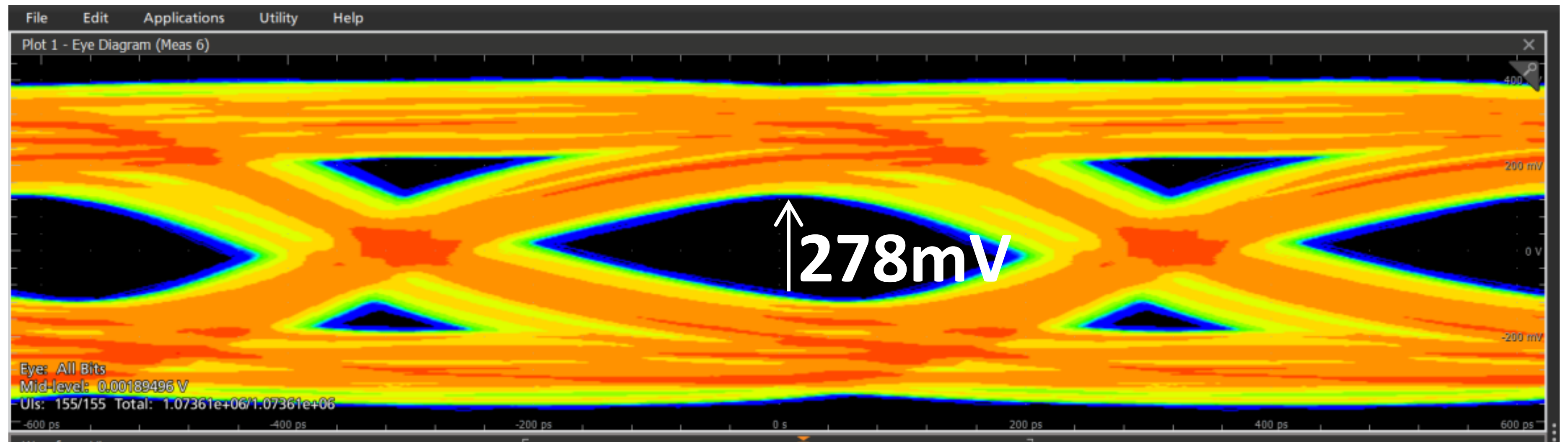
Signal integrity test (ADC+CML)

Cable length estimated as 10-15 m from μBM to backend electronics.



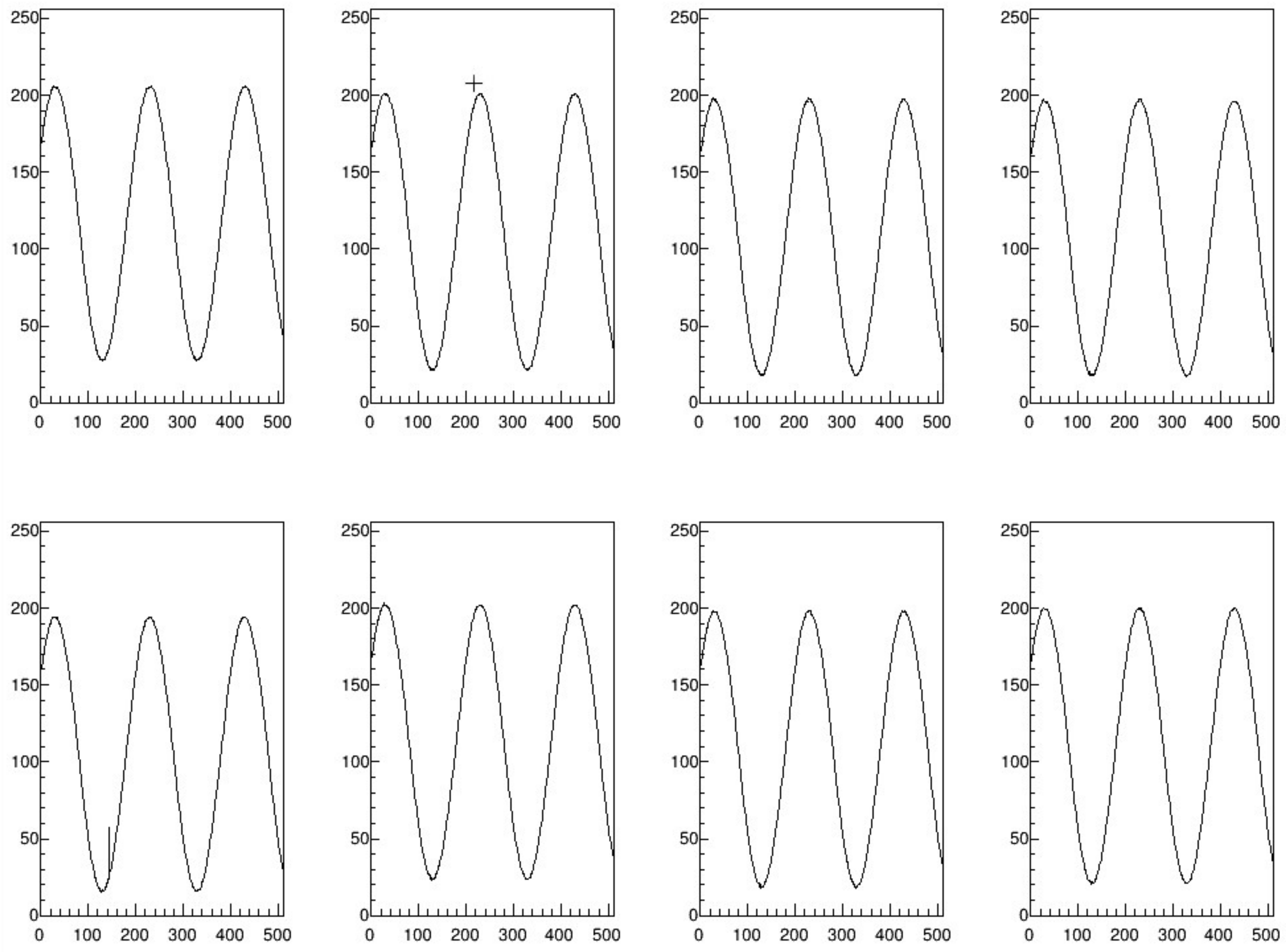
640 Mbps

@10 m



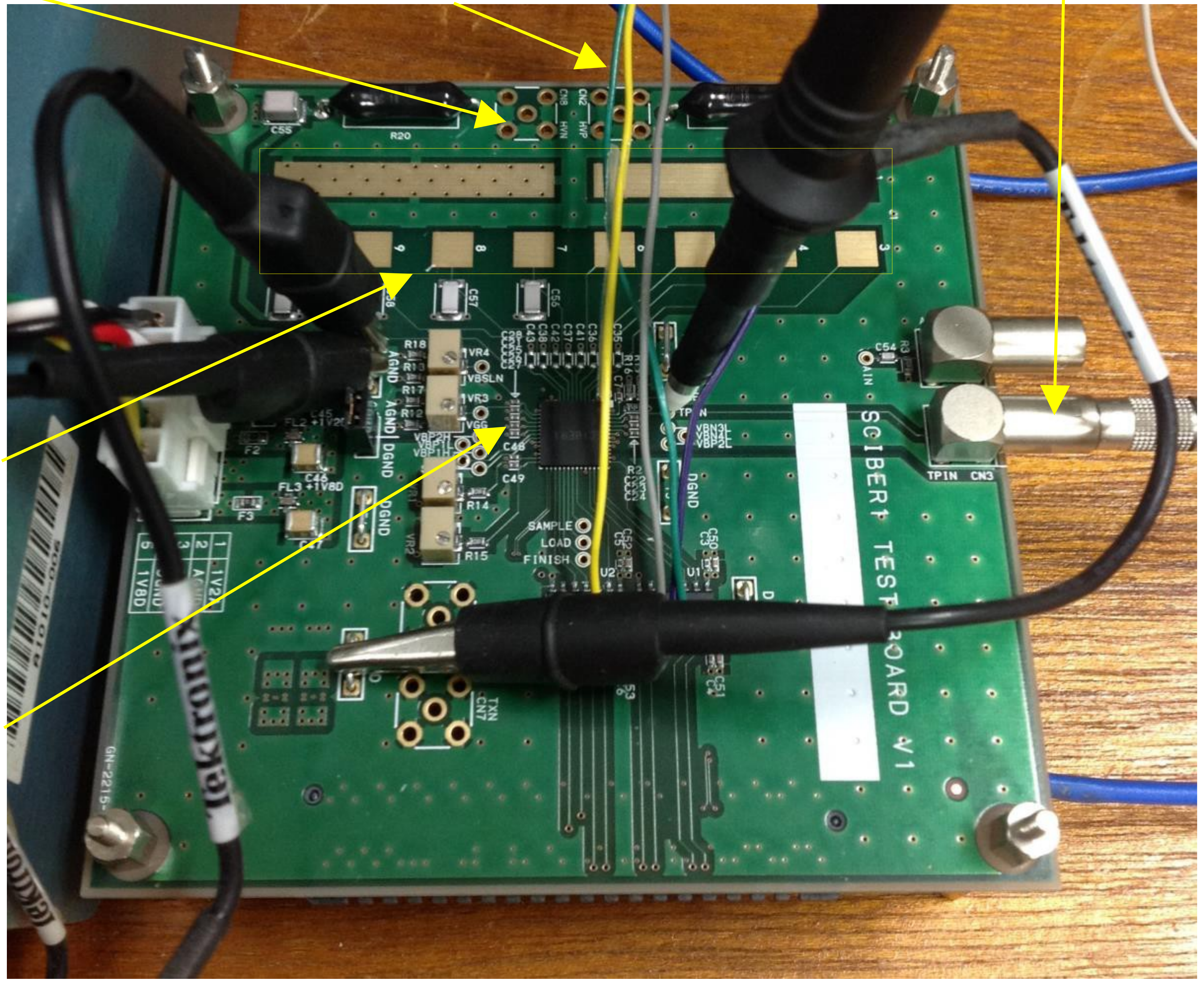
Eye height: 275.7 mV, Eye width: 449.8 ps

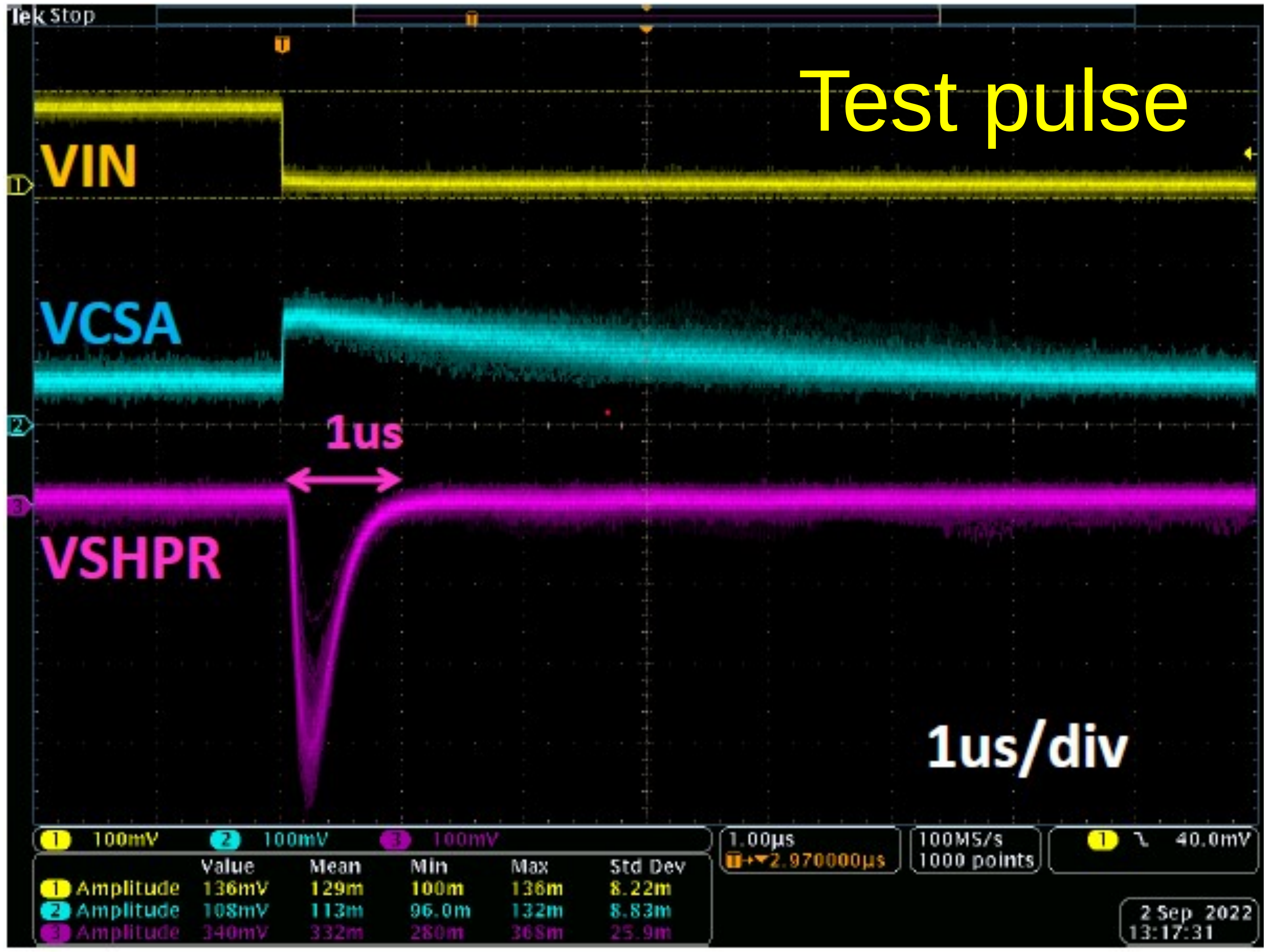
- @ Cable 10m



CML-TX is sufficient for driving 10 m cables.

Analog blocks (CSA+CRRC)



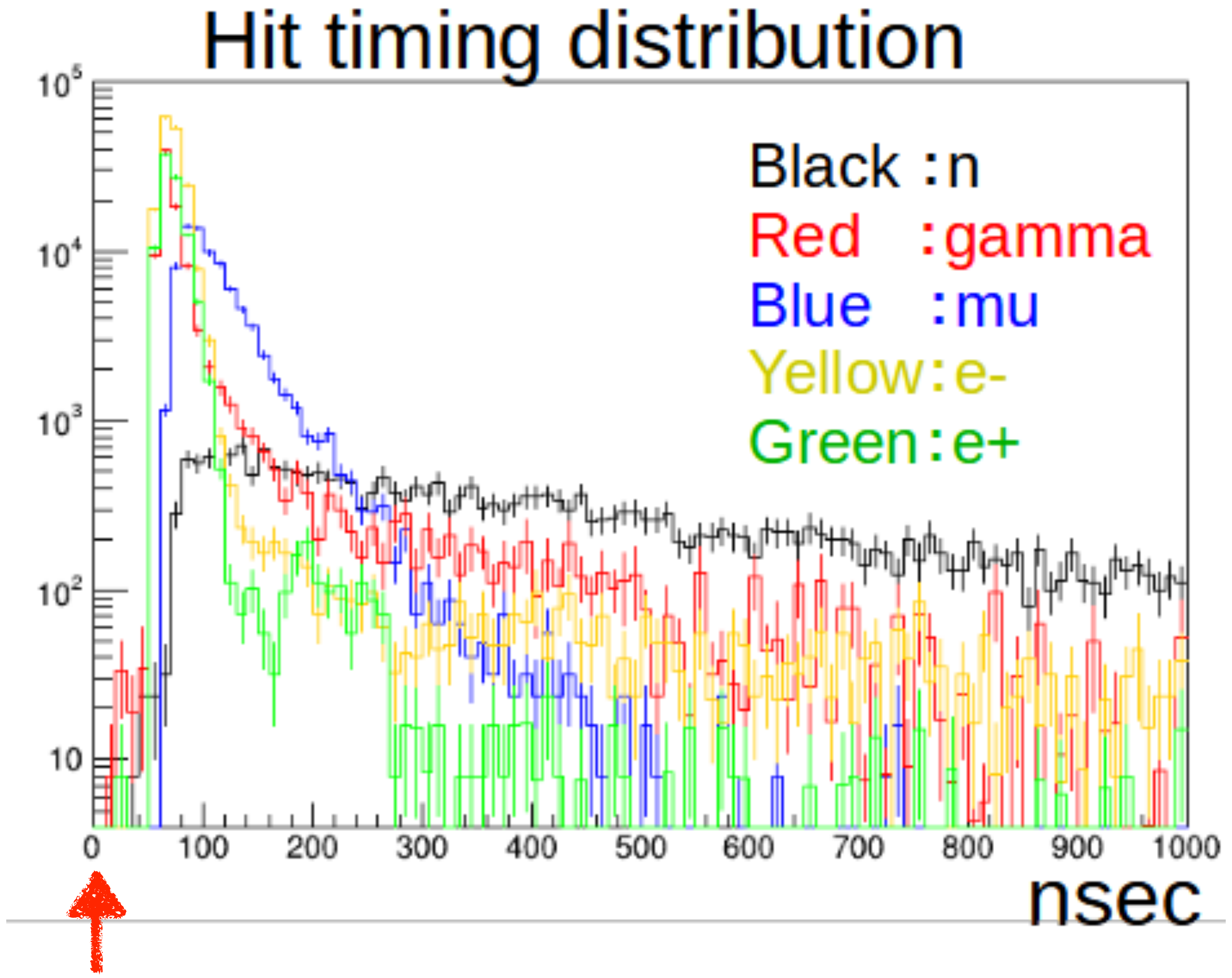


- Analog blocks working, but we need faster shaping times.
- We changed the architecture from CSA to TIA in the 2nd prototype chip.

TIA+CRRC architecture

- 2nd prototype ASIC is under testing.

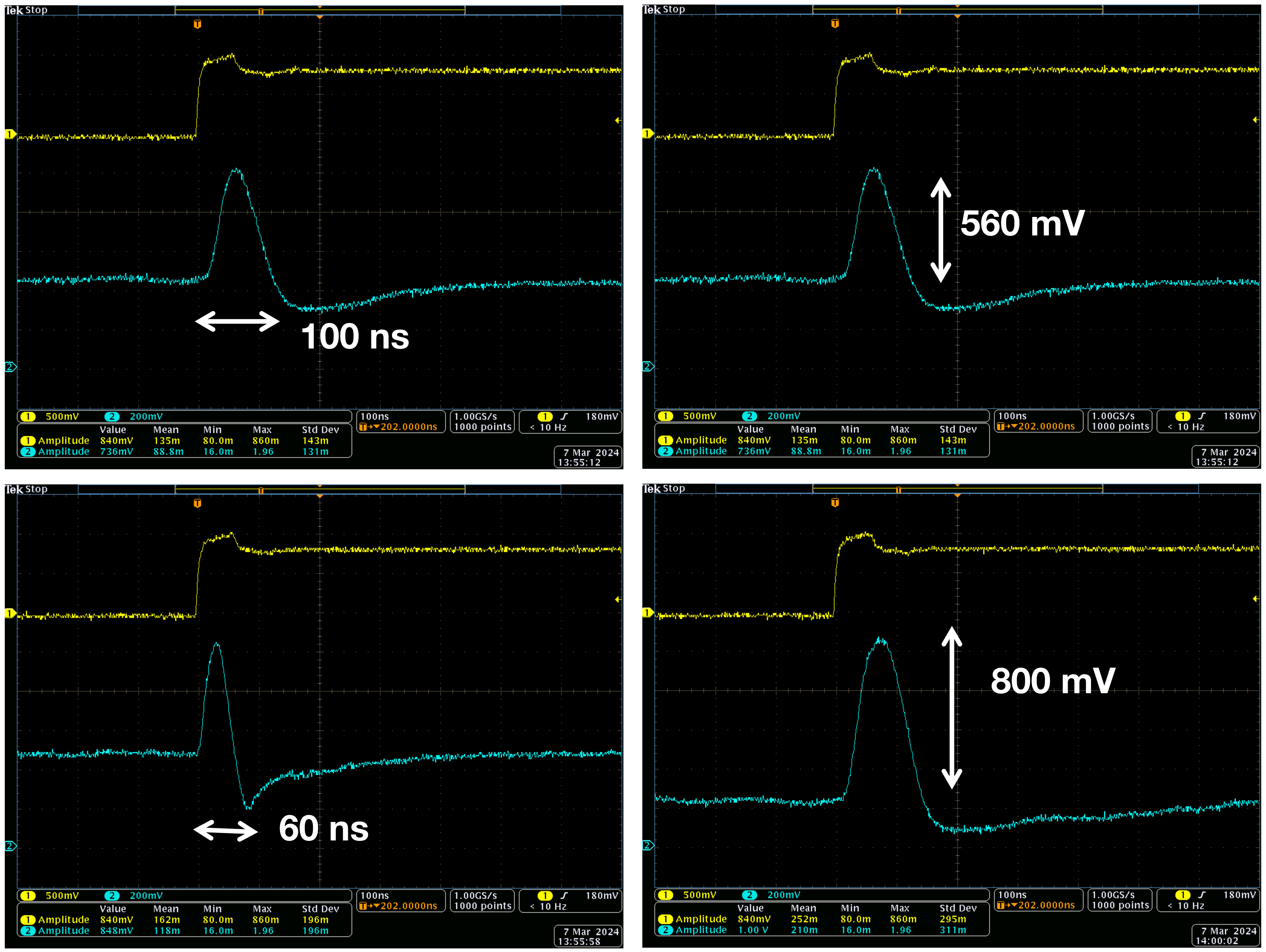
- **Fast shaping time of <100 ns** required since muons arrive at 100~300 ns in the hit timing distribution.



Bunch timing with every 1.17/1.75 us

Variable peaking times

Variable voltage gains



We submit the final ASIC in this December.

Further Demand for SiC sensors (more challenging)

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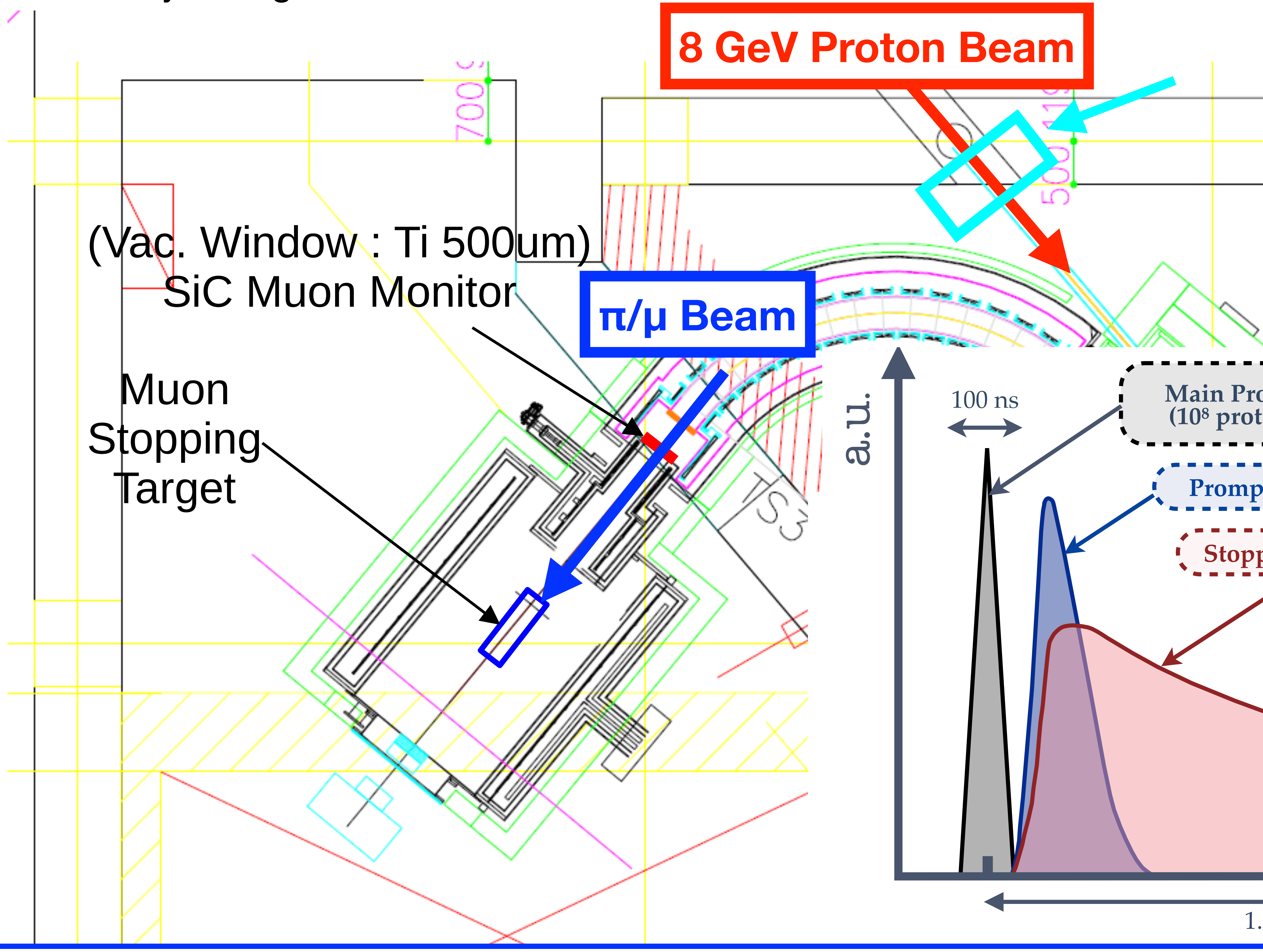
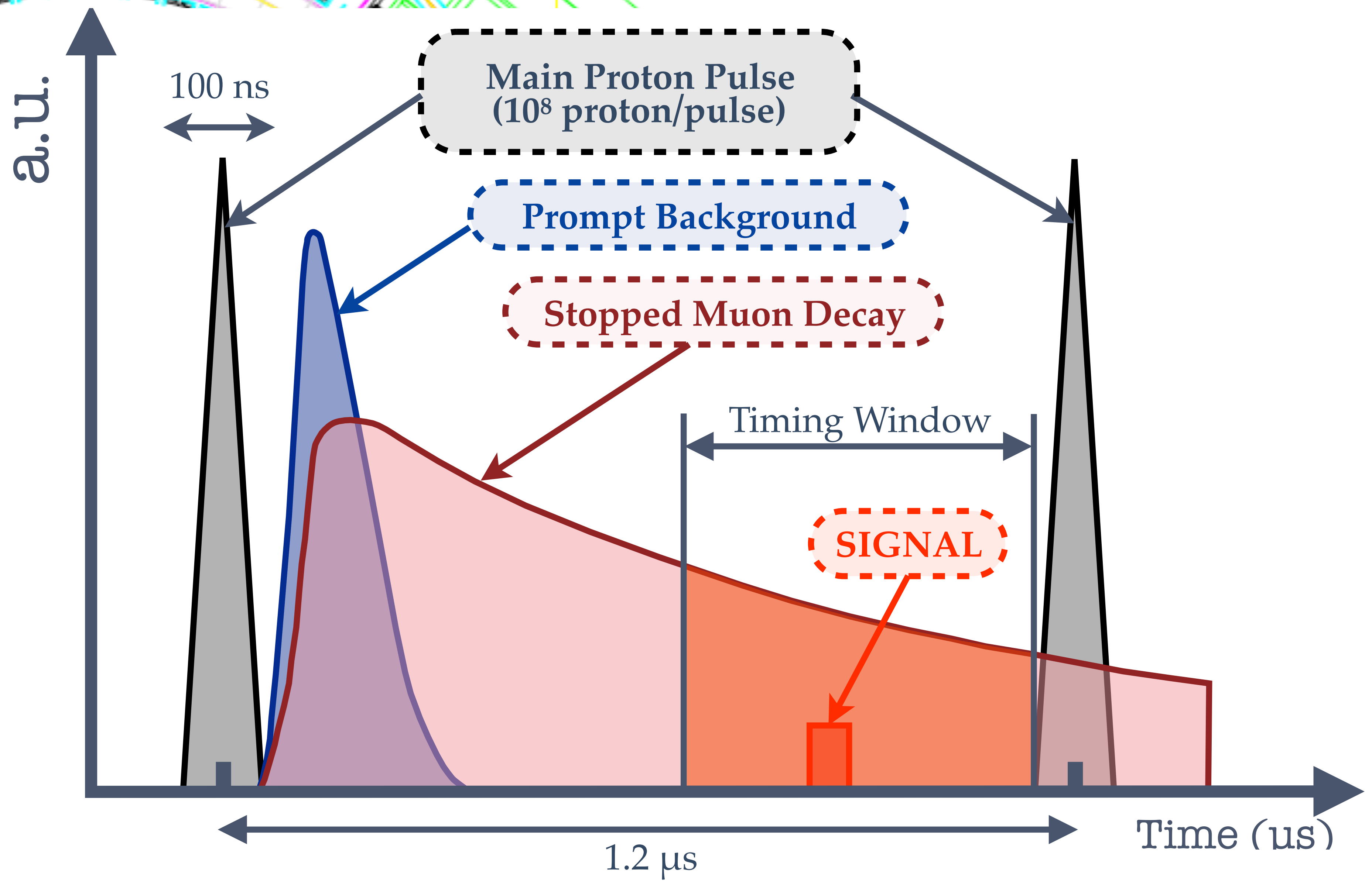
- 8 GeV proton beam is bunched in every 1.2us.
- Pion is BGD. Select muon events by timing difference.

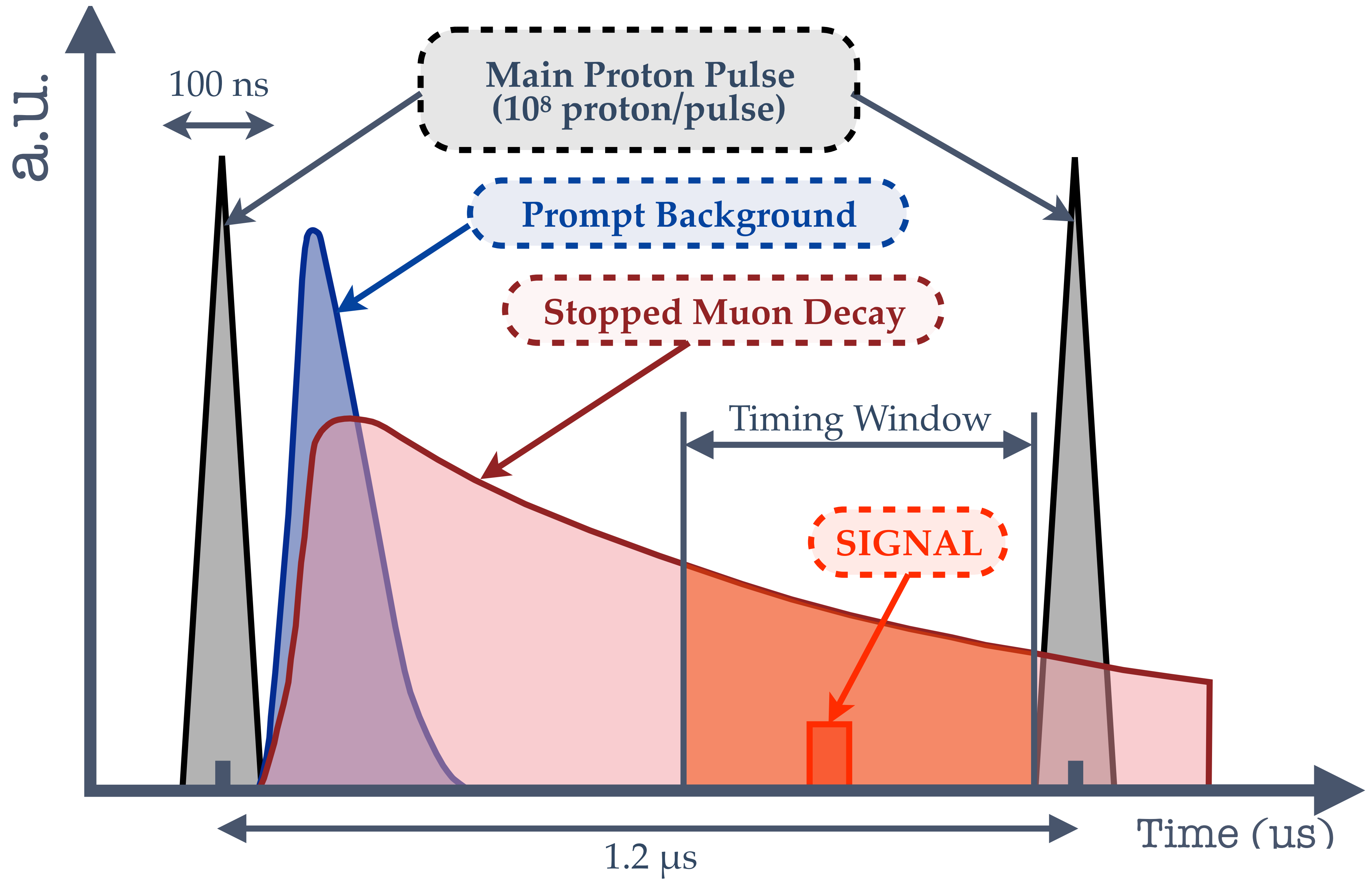




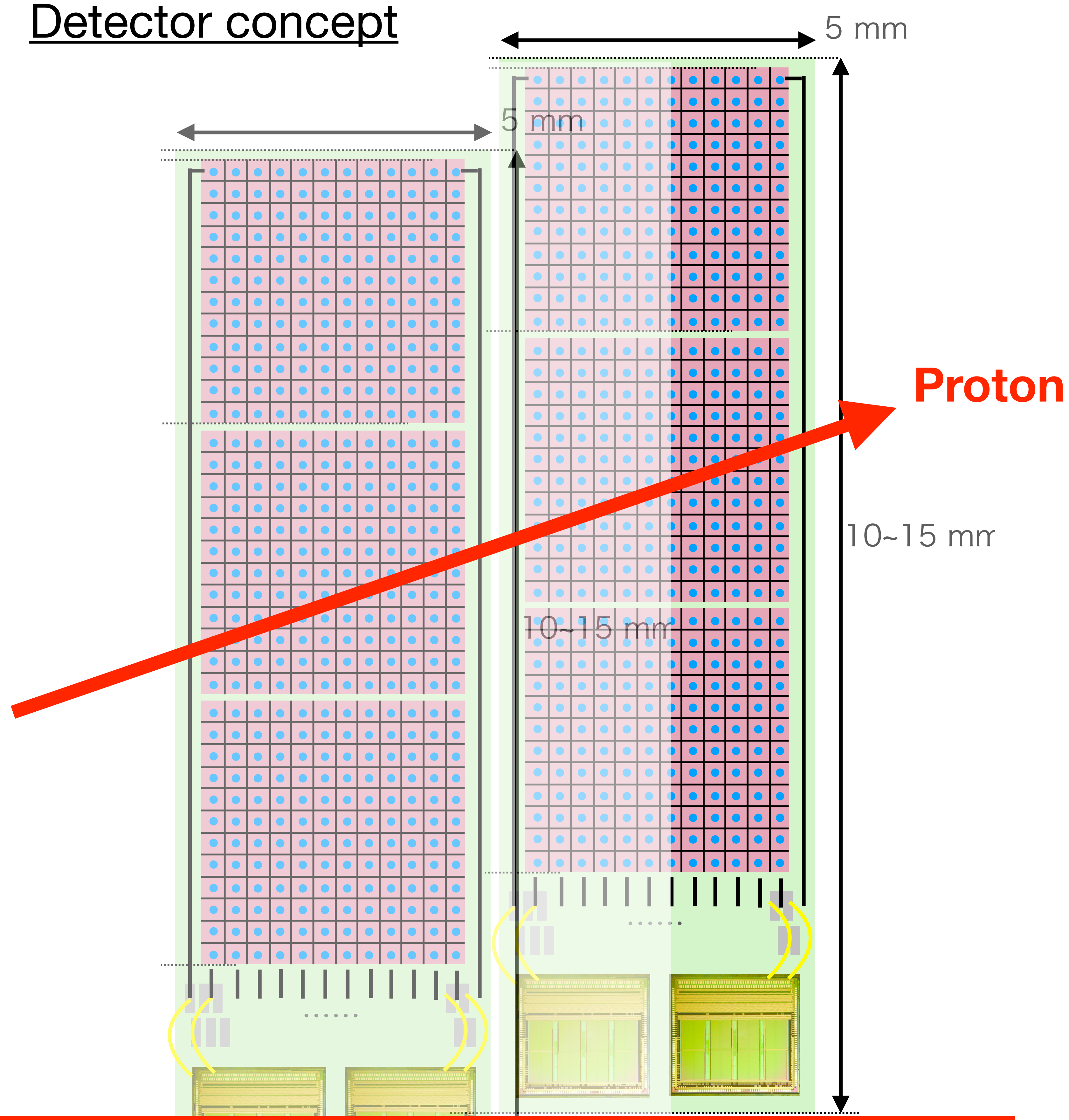
Want to confirm no leaky protons (extinction) between bunches. → **On-axis** beam monitor with SiC!

Requirements for Extinction Monitor

- 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



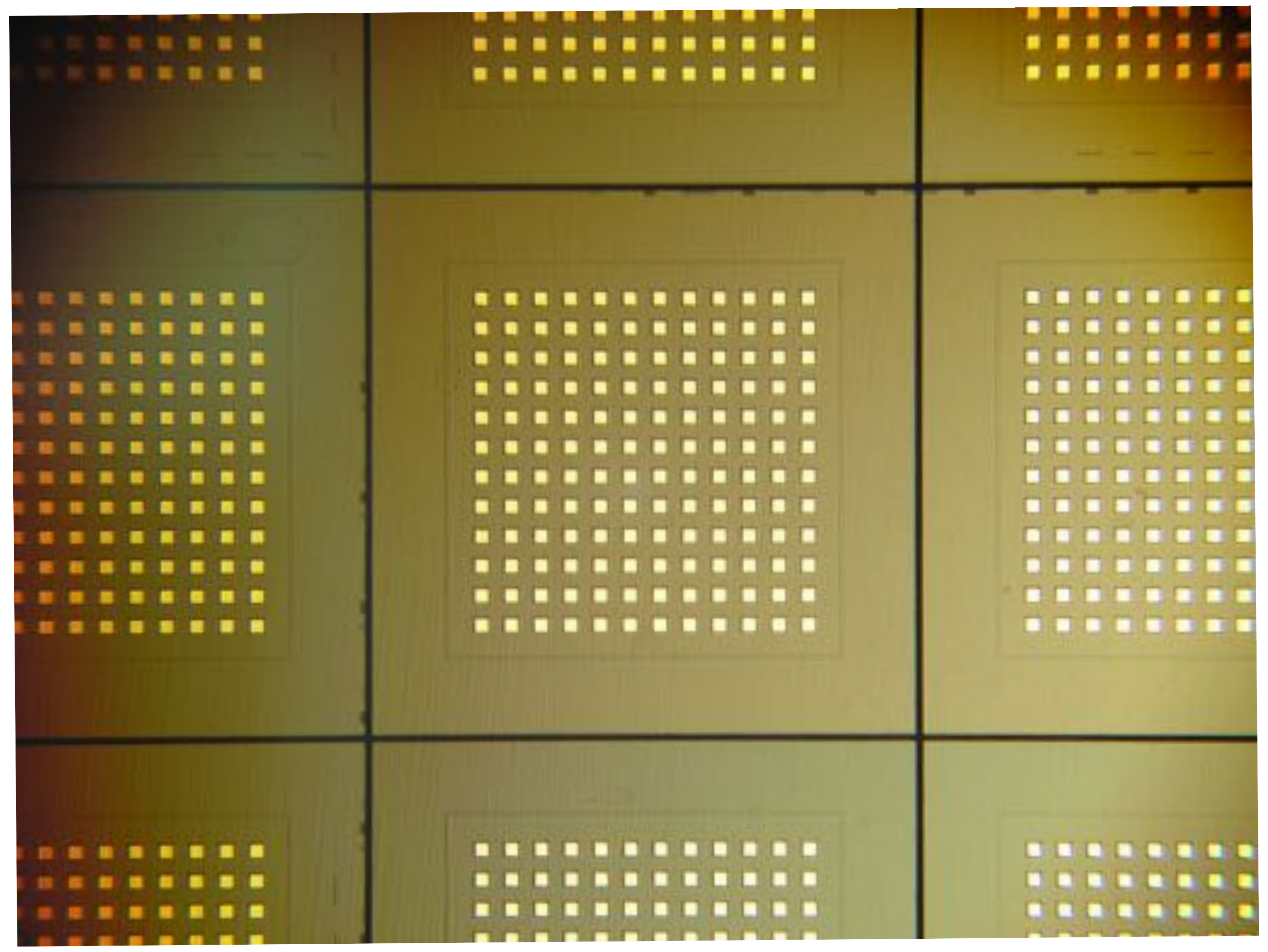
- Need larger active area (~1 cm x 1 cm)
- Segmented electrodes (**pixels or strips**) to reduce event rates
- Dedicated electronics with timing-gate structure → see the Poster, “The GAROP-2, a Radiation-Hard ASIC for Particle Beam Monitor Readout of the COMET Experiment”, by X. Xu

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

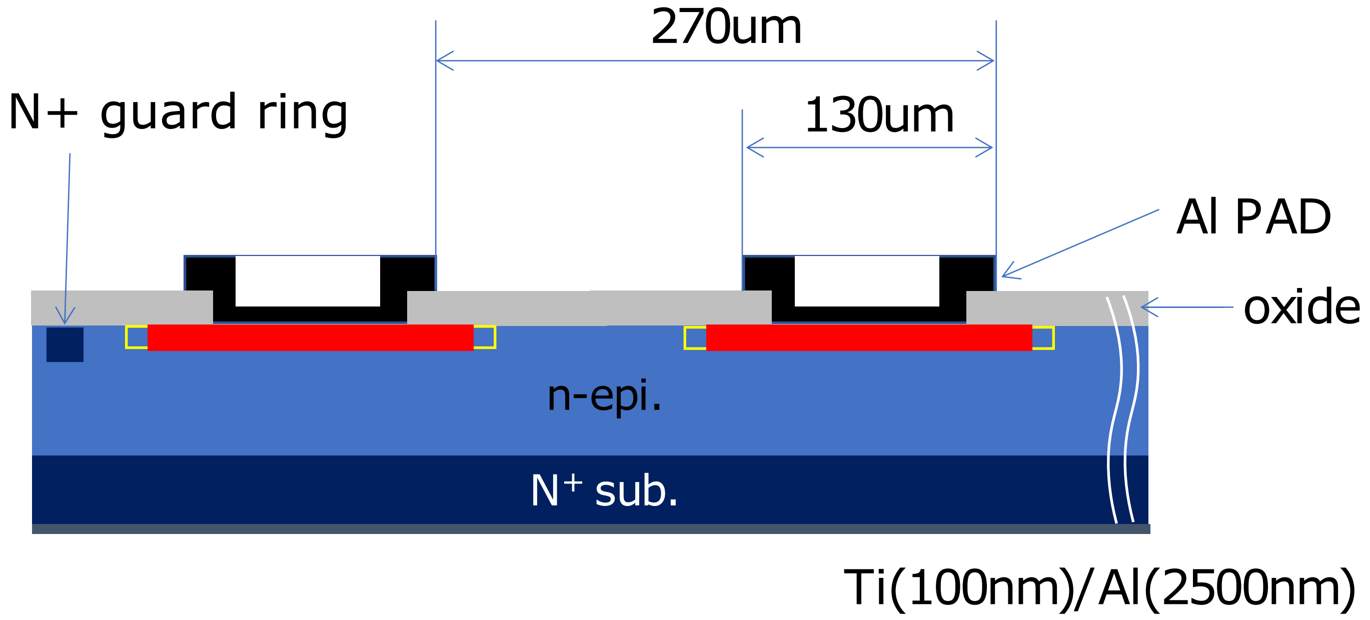
Sensor segmentation (hybrid pixel detector)

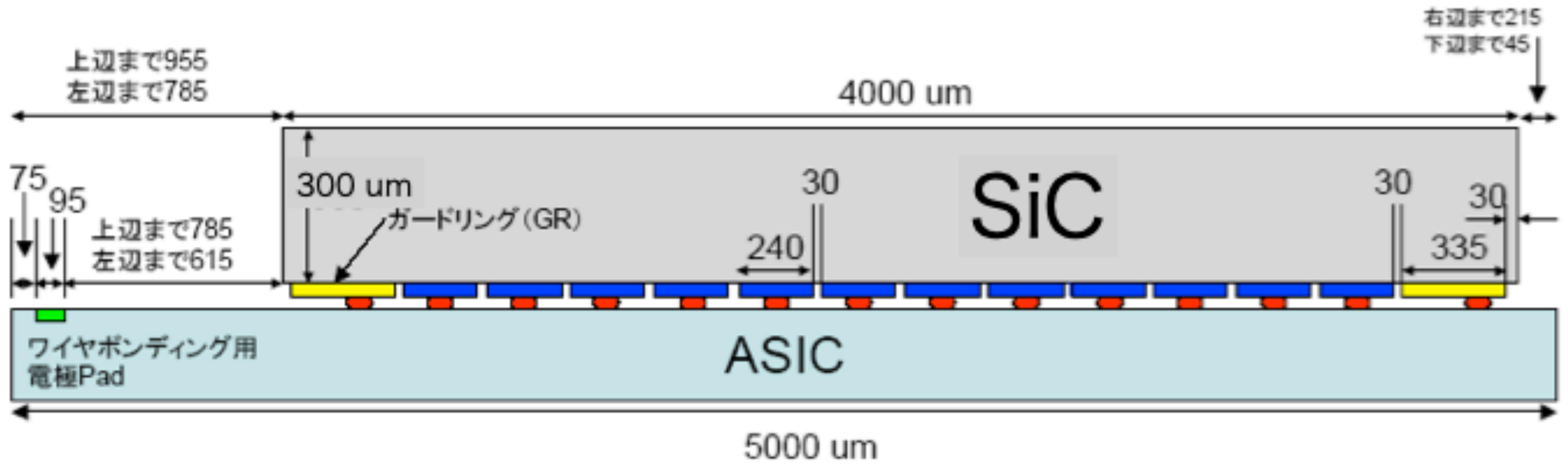
- 5 mm x 5 mm with 12 x 12 electrodes, 270 um pitch
- readout with low-noise ASIC
- Au/In stud bump technology

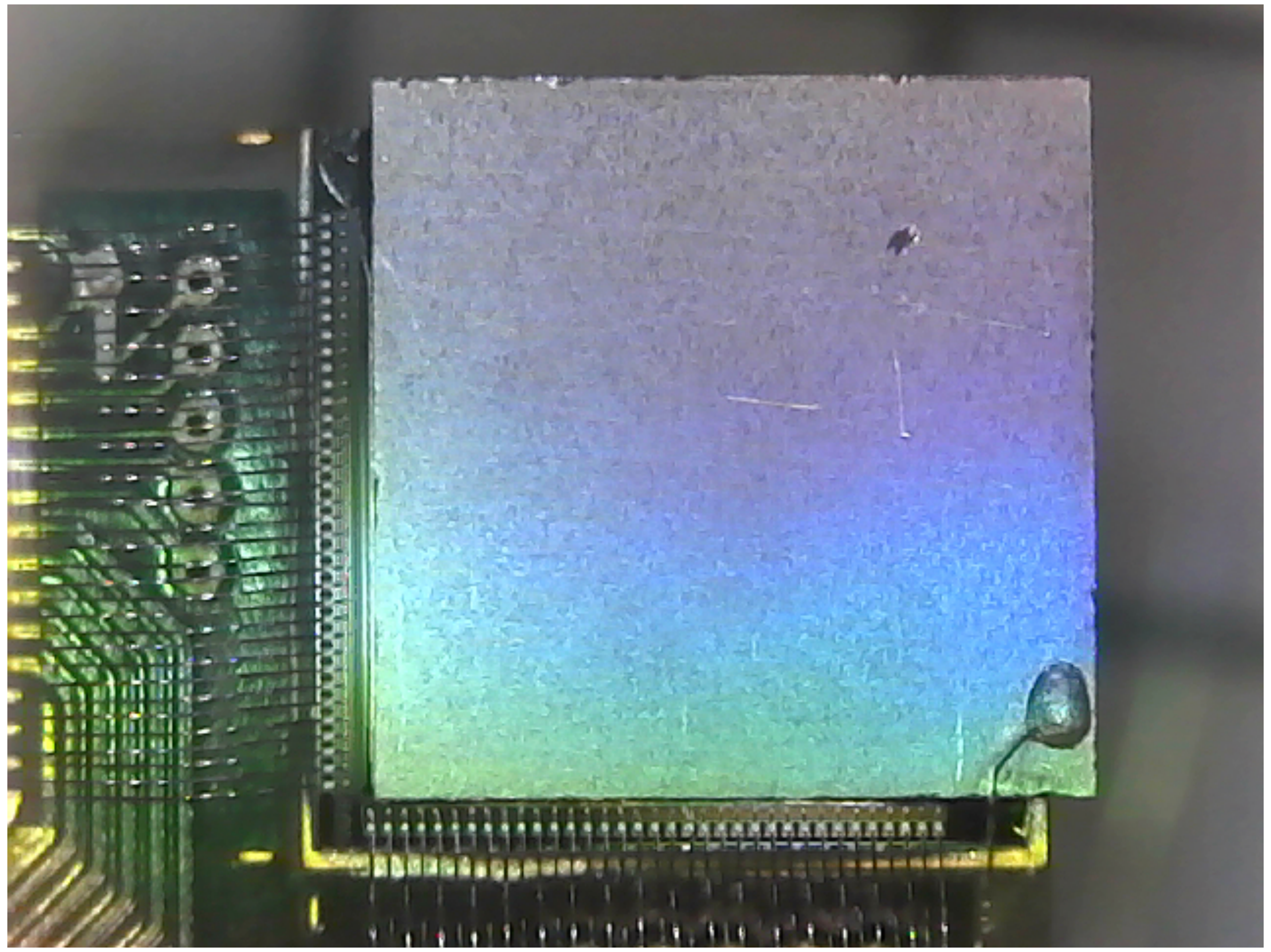
(a)



(b)





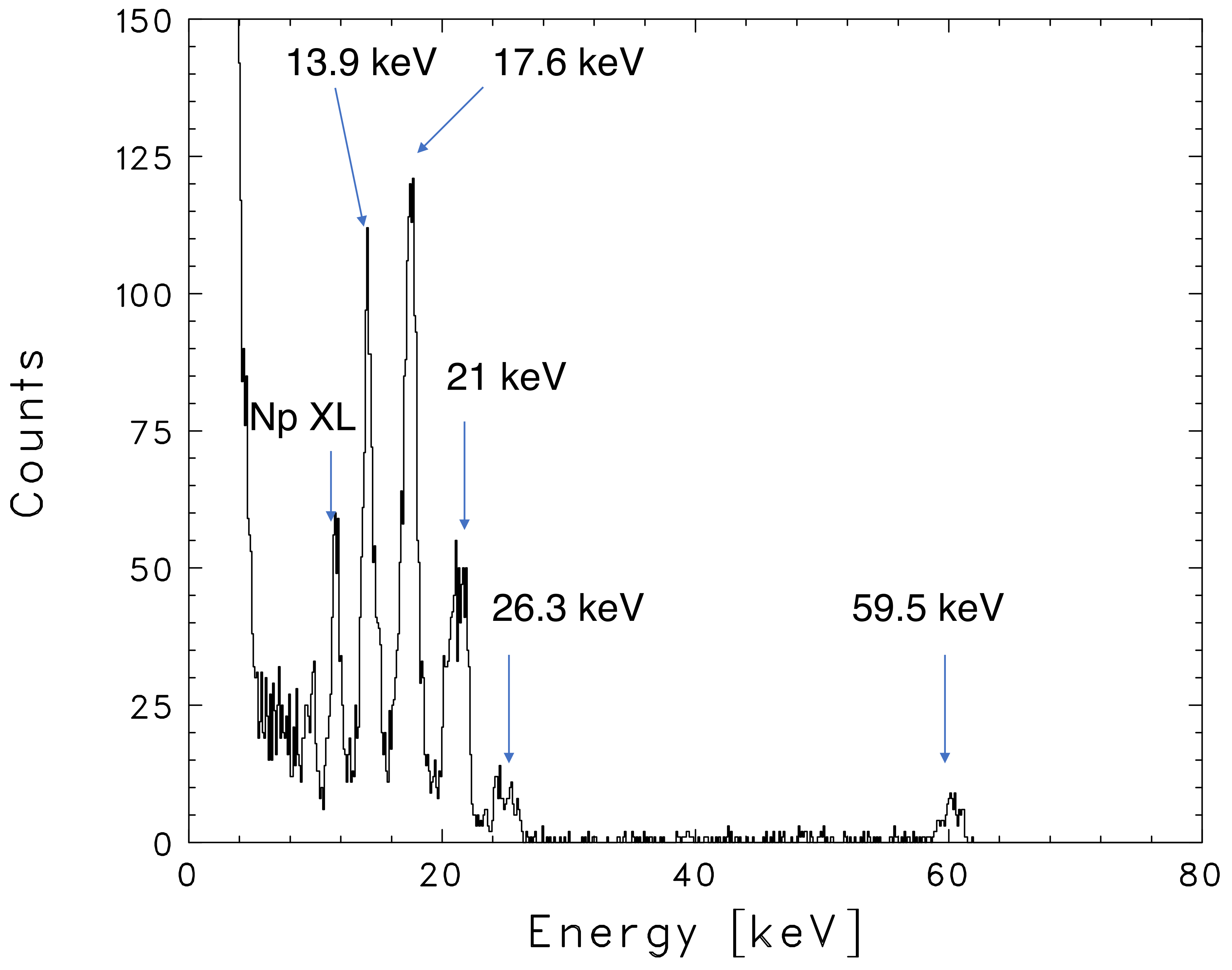


Passivation (Parylen or Silicone rubber) is necessary to prevent electric discharges @1 kV.

Spectral performance

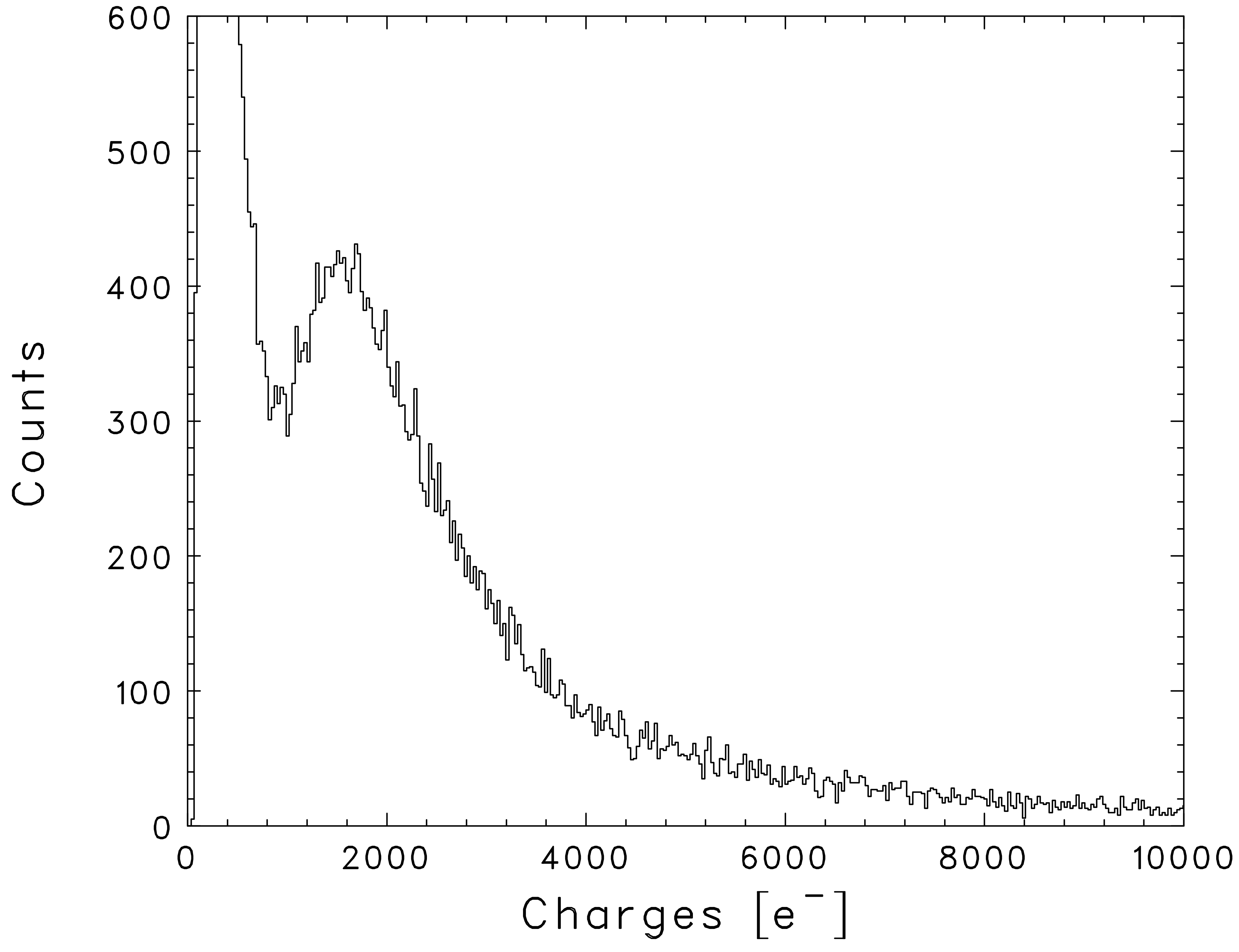
IEEE TNS, vol.70, p.1210, 2023.

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



FWHM: 1.72 keV @17.6 keV

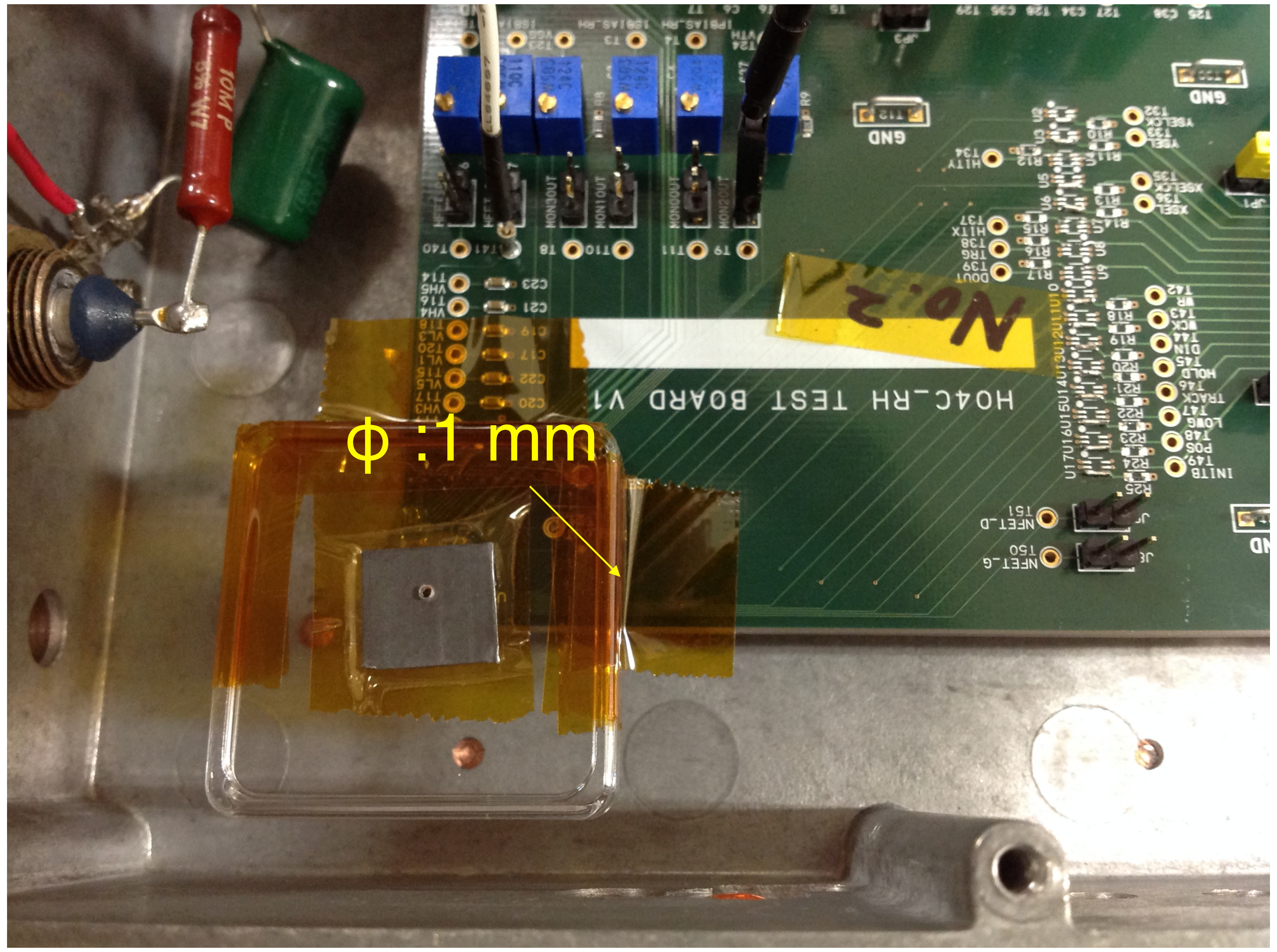
- HV: +600 V
- Exposure: 0.5 days
- Mode: HG

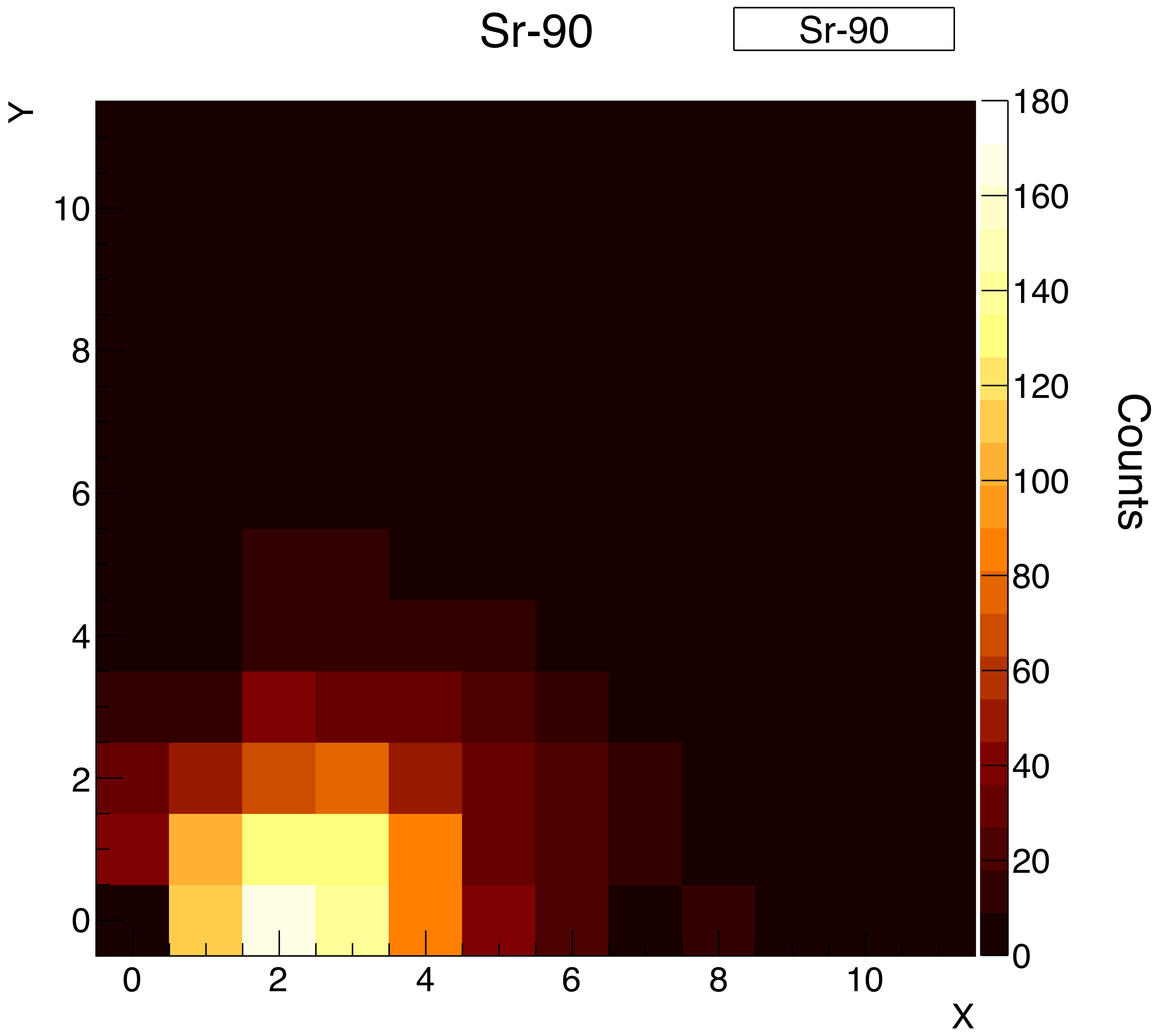


Confirmed β-ray events from all pixels.

Imaging performance

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

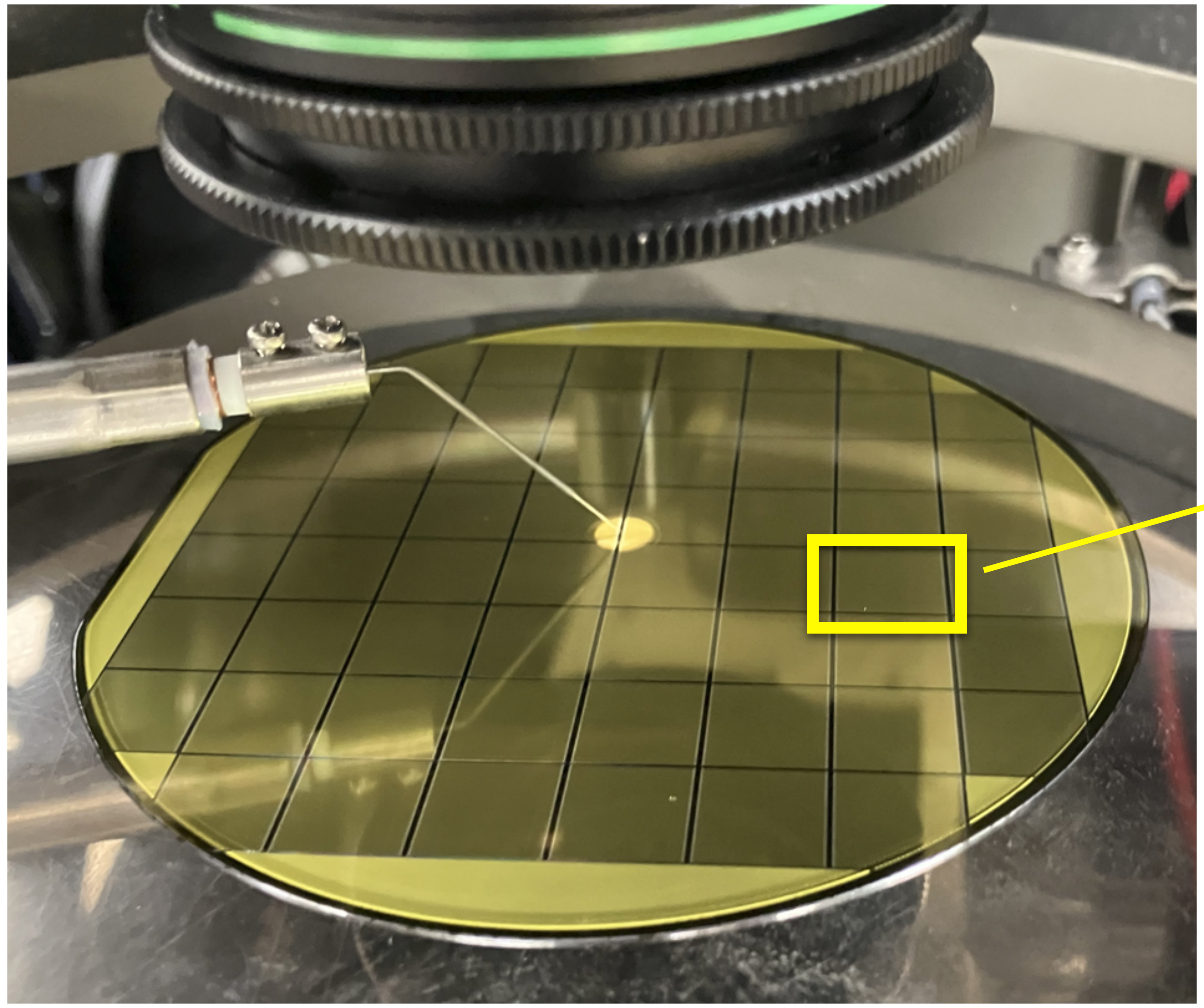


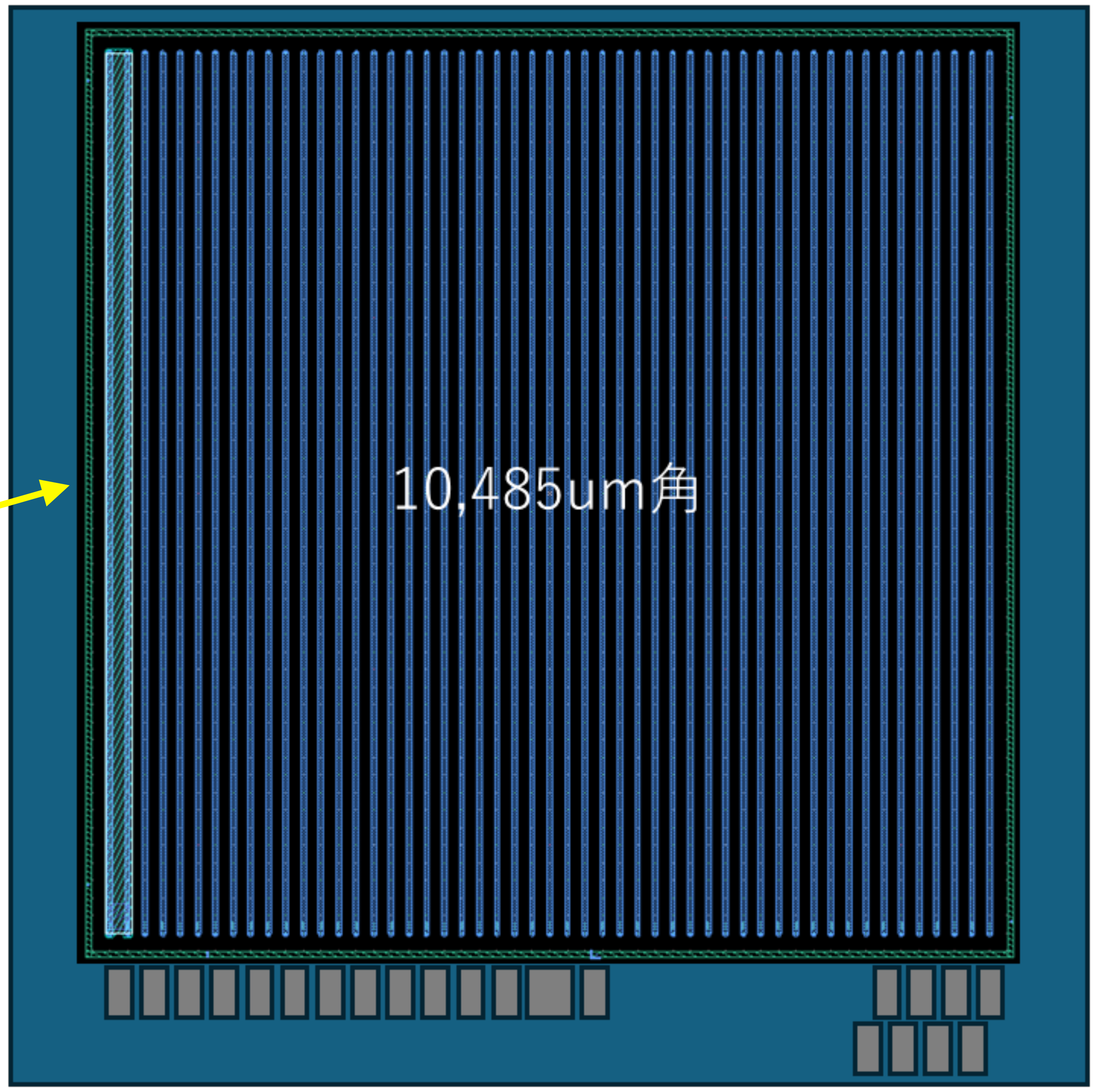


- Finer segmentation is realistic and nice uniformity expectable in larger devices
- SiC performance is closing to silicon.
- Still long way to realize the proton extinction monitor, but SiC is an important candidate.

Future prospect

For the extinction monitor, **SiC-strip sensor** (1 cm x 1 cm, 52 strips with 200 um pitch) will be available soon!





Thank you very much for your attention.