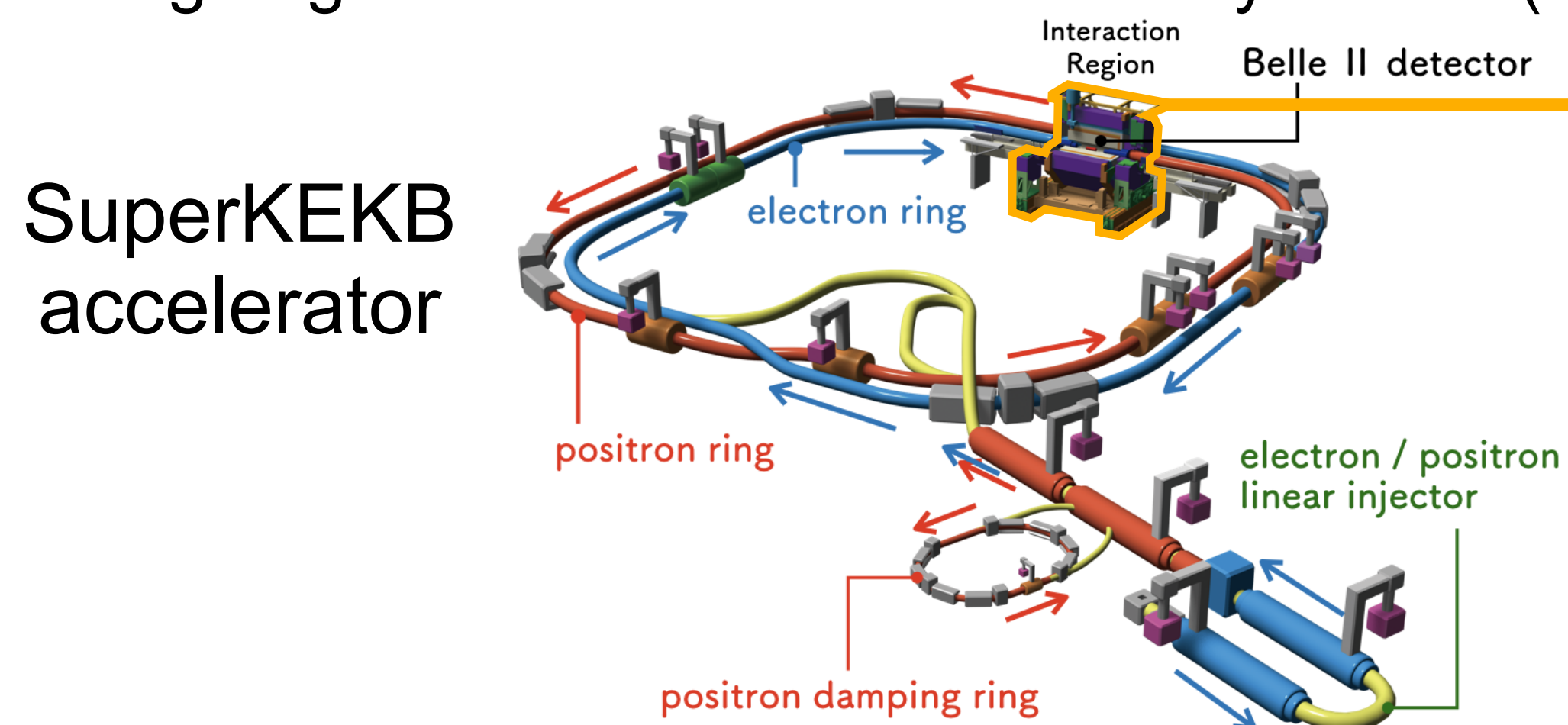
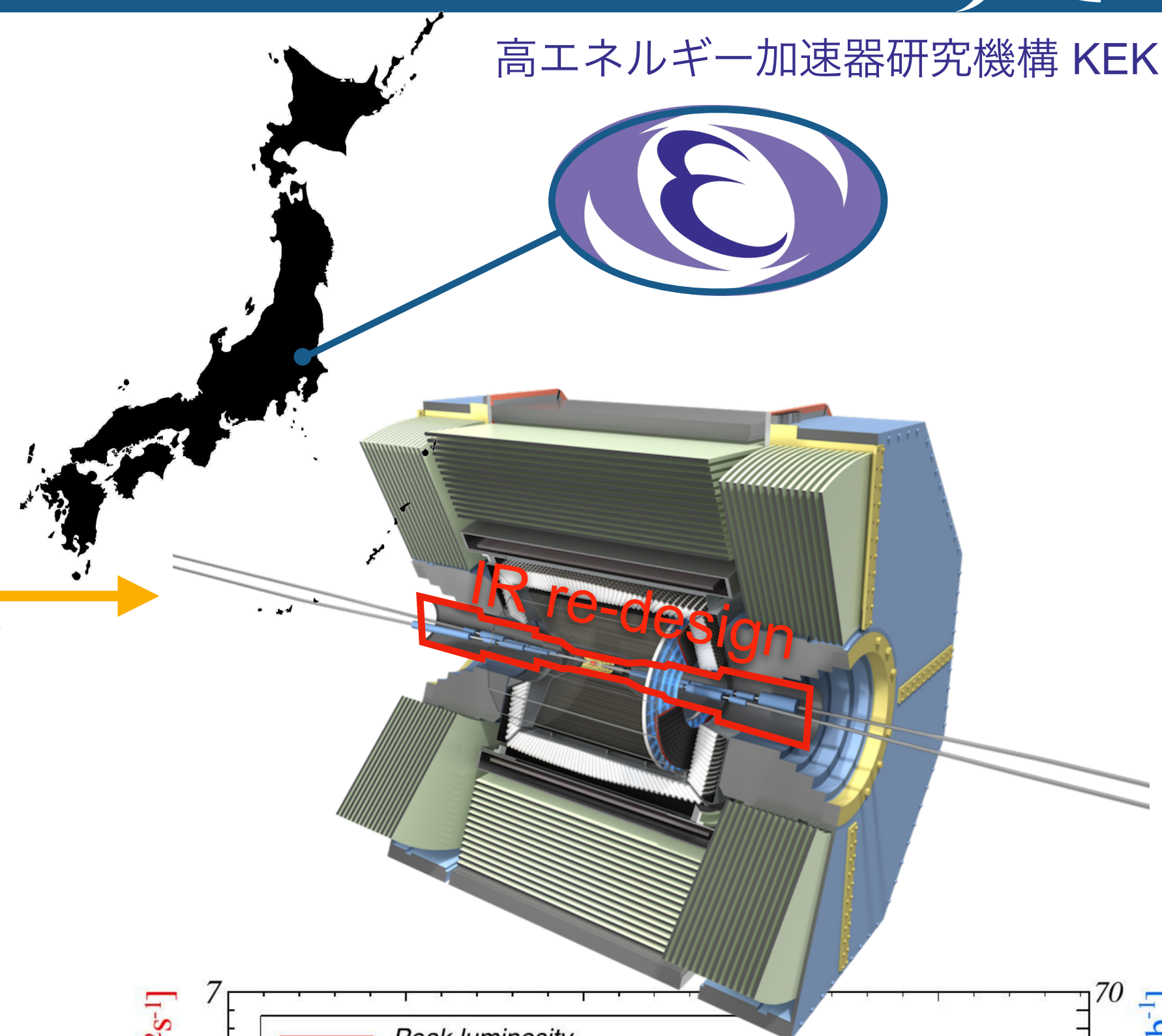


Impact of radiation damage to the performance of depleted monolithic active pixel sensors for Belle II vertex detector upgrade

Shijie WANG, The University of Tokyo & KEK, Japan
On behalf of the Belle II VTX Collaboration

The Belle II experiment located at KEK, Tsukuba (筑波), Japan.

- ▶ Running at the SuperKEKB accelerator.
 - ▶ Collecting 10.58 GeV e^-e^+ collision events.
- ▶ Exploring physics beyond the Standard Model.
 - ▶ Using large statistics of B meson decay events (aiming for 50 ab^{-1}).

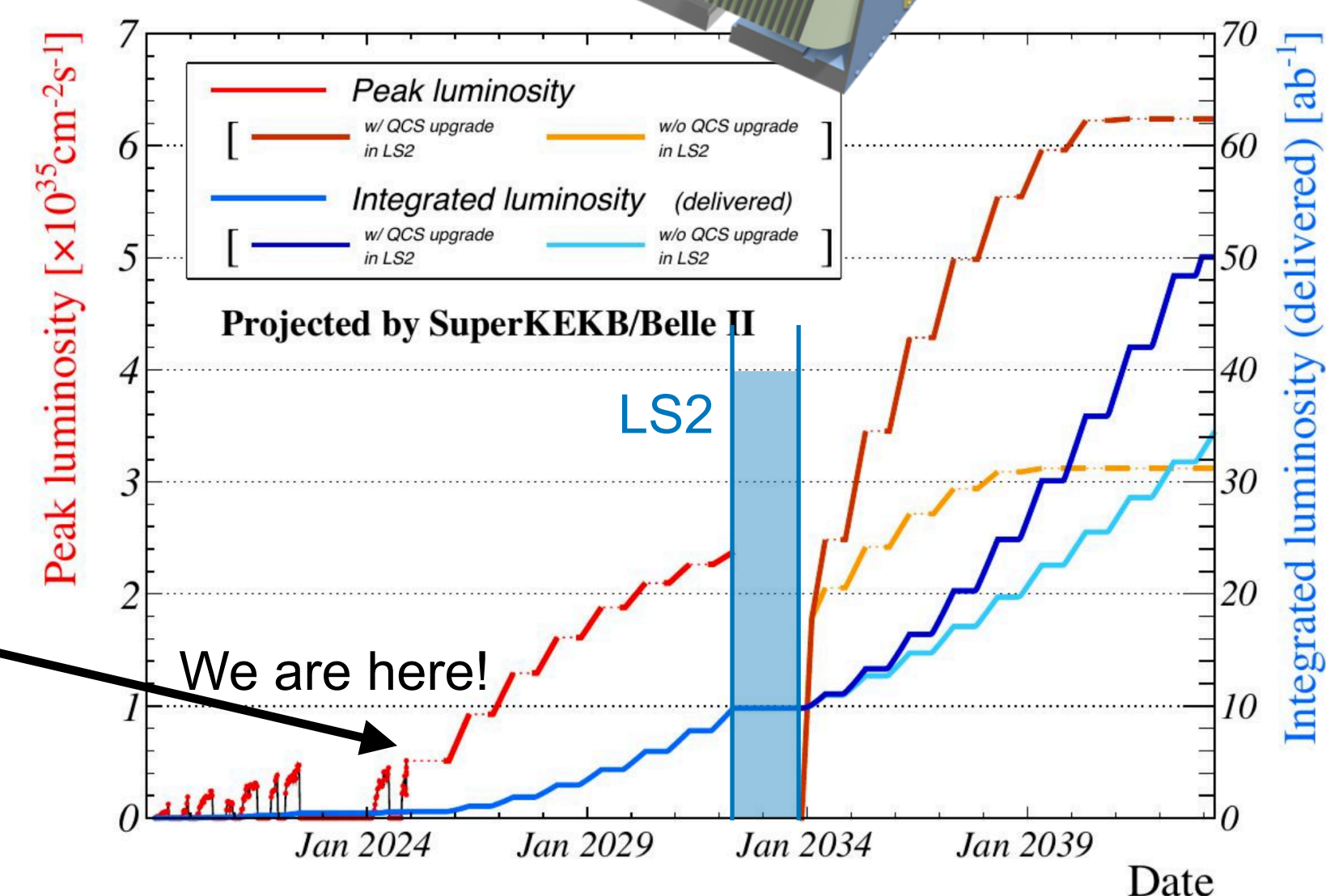


Belle II detector

▶ Luminosity upgrade

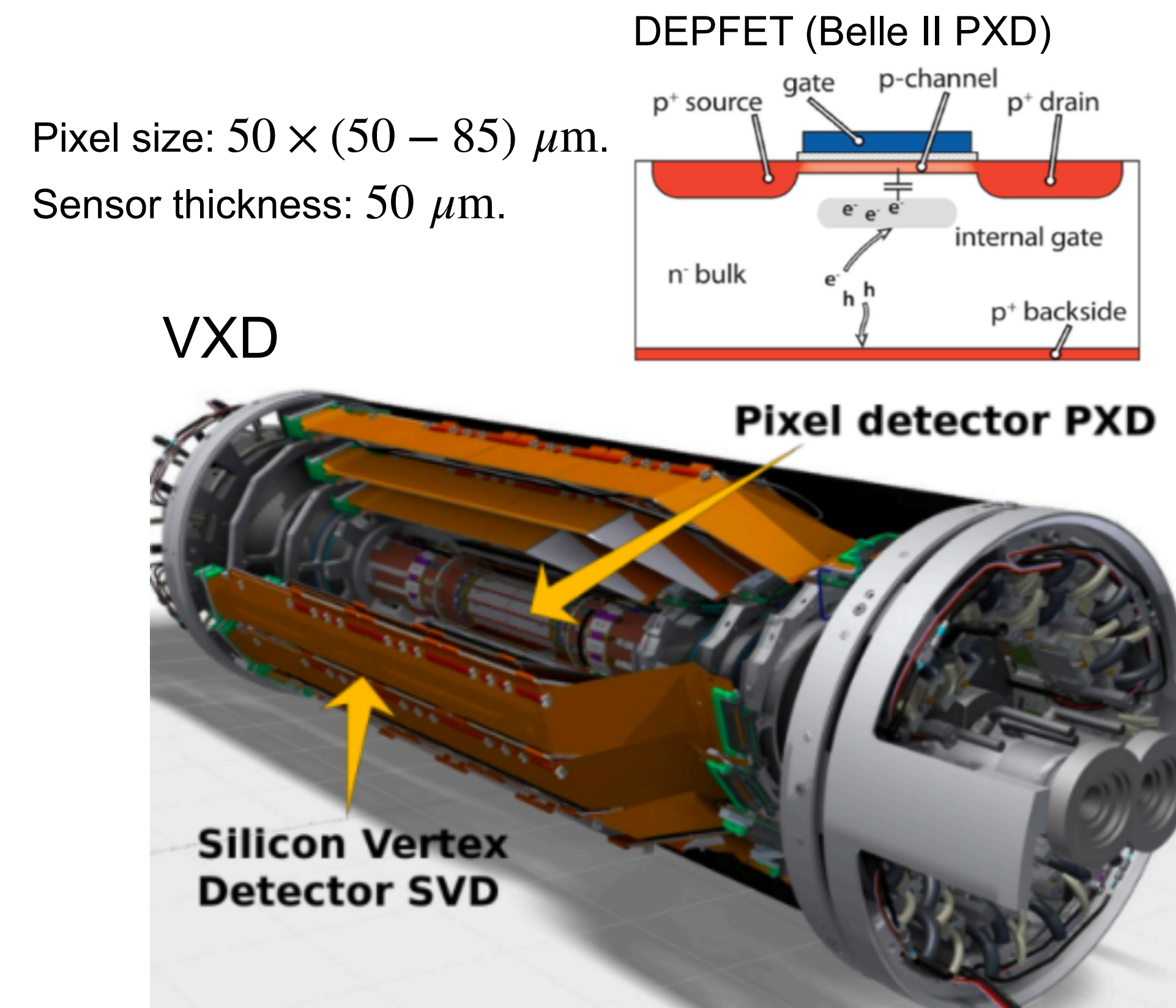
- ▶ Luminosity record: $5.1 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$.
- ▶ Target luminosity: $6 \times 10^{35} \text{ cm}^{-2}\text{s}^{-1}$.
- ▶ Redesign of the interaction region (IR) is planned during long shutdown 2 (LS2) to reach the target.

▶ IR redesign requires the upgrade of vertex detector.



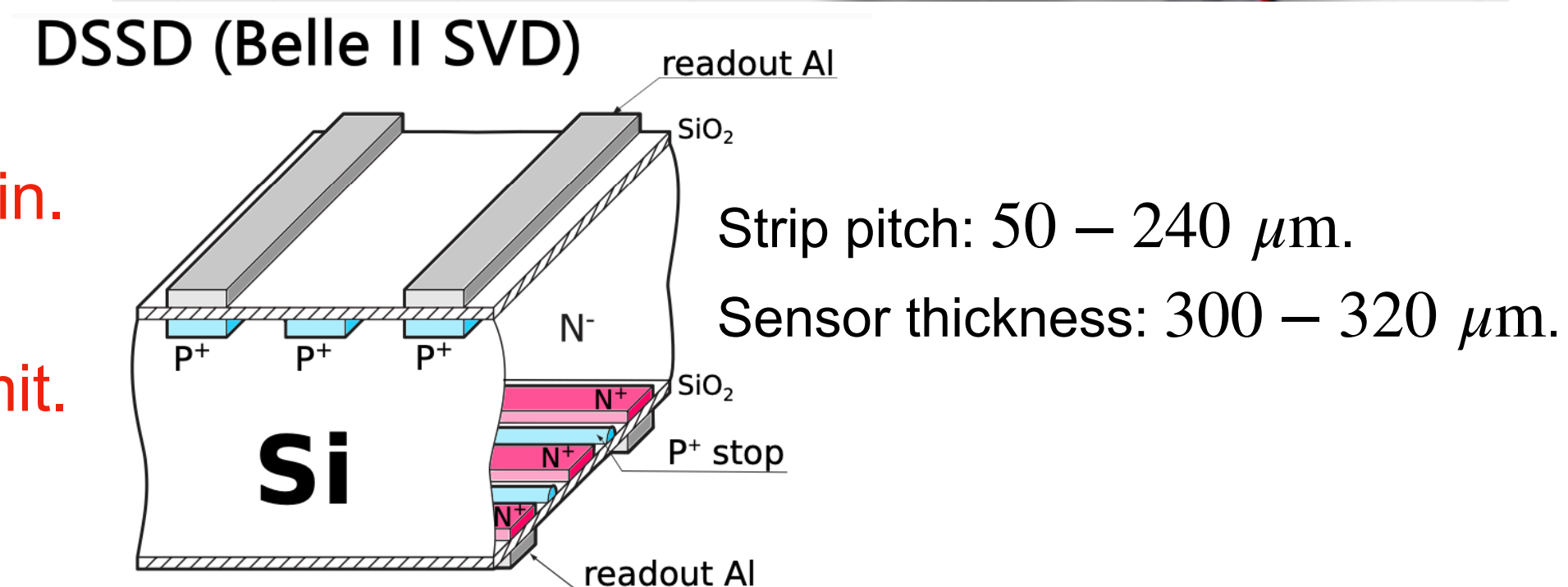
Current vertex detector: VXD see talk by Kieran yesterday

- ▶ **2 inner layers: Pixel Detector (PXD).**
 - ▶ DEPLETED Field Effect Transistor (DEPFET) sensor.
 - ▶ Occupancy limit: 3%.
- ▶ **4 outer layers: Silicon Vertex Detector (SVD)**
 - ▶ Double-sided silicon strip detector (DSSD).
 - ▶ Occupancy limit: 6%.
- ▶ **Total material budget: $3.5 \% X_0$.**
- Current occupancy on all VXD layers: $<1\%$.**



Background expectation at target luminosity

- ▶ **Expected occupancy at the target luminosity:**
 - ▶ PXD innermost layer: up to $2 \% (\sim 32 \text{ MHz/cm}^2)$. **Small safety margin. Very delicate.**
 - ▶ SVD innermost layer: up to $9 \% (\sim 9 \text{ MHz/cm}^2)$. **Exceeds safety limit.**
- ▶ **Large uncertainty due to potential IR upgrade.**
- ▶ **A new vertex detector is needed for better background tolerance.**



Vertex detector upgrade: VTX

► Upgrade baseline:

- Total ionizing dose (TID): 100 Mrad.
- Non-ionizing energy loss (NIEL) flux: $5 \times 10^{14} \text{ n}_{\text{eq}} \text{cm}^{-2}$
- Hit rate: $120 \text{ MHz} \cdot \text{cm}^{-2}$
- Spatial resolution: $< 15 \mu\text{m}$

► Fully pixilated detector.

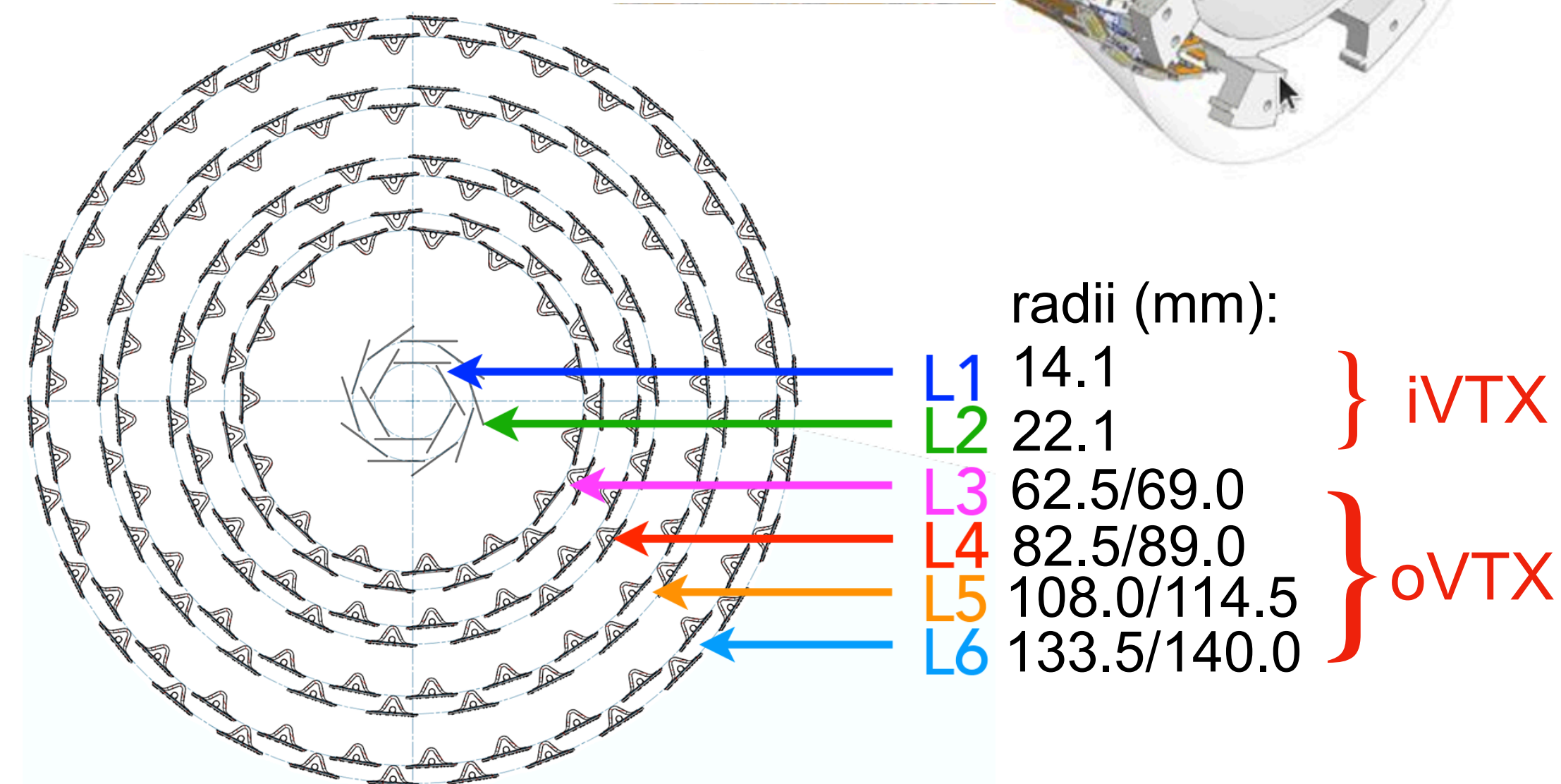
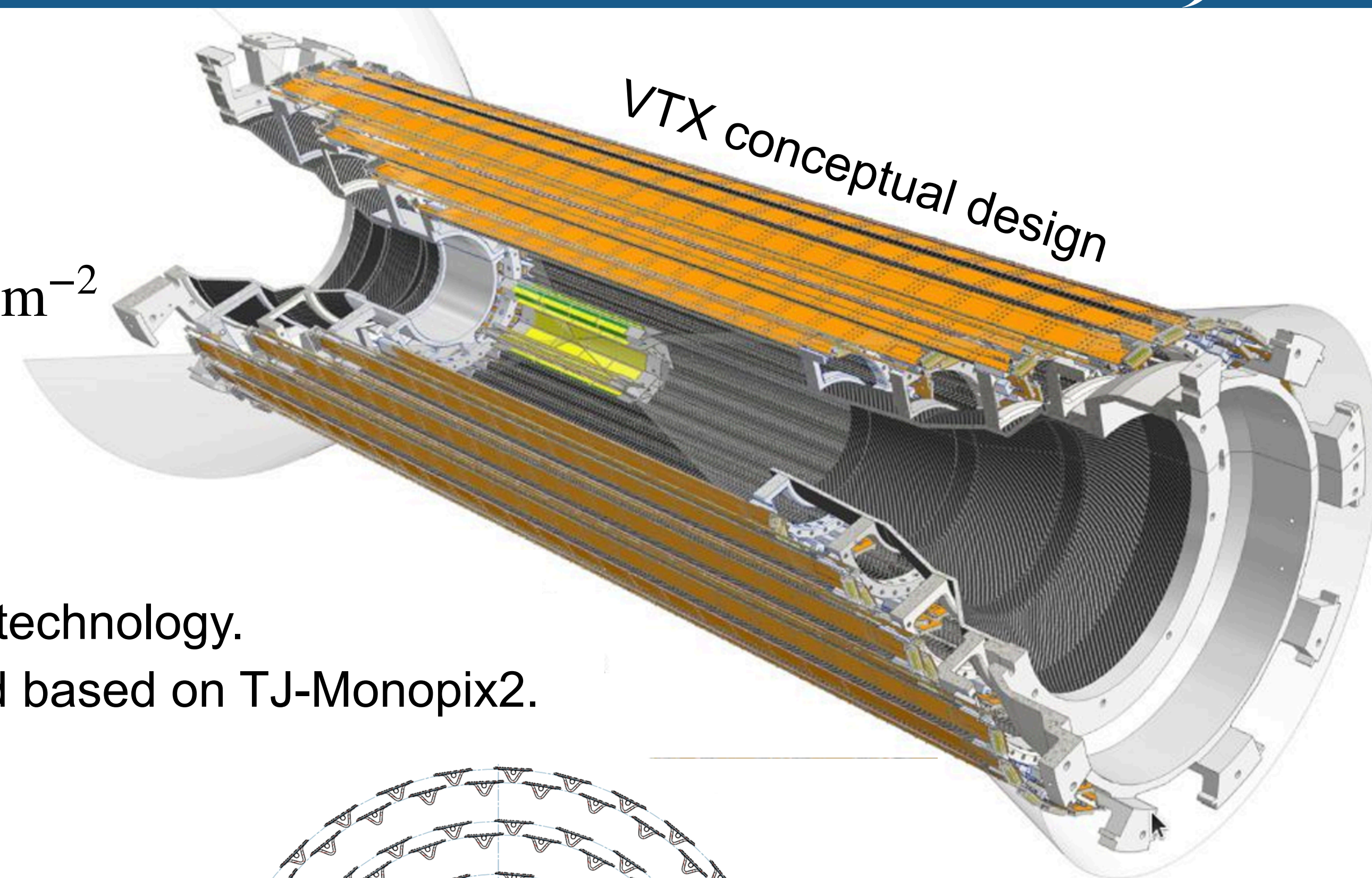
- CMOS Depleted Monolithic Pixel Sensor (DMAPS) technology.
- Optimized BELle II pIXel (OBELIX) sensor designed based on TJ-Monopix2.
- Pixel size: $33 \times 33 \mu\text{m}^2$.

► 6 layers equipped with identical sensor.

- iVTX (2 inner layers) and oVTX (4 outer layers).
- Thinner layers with total material budget targeting $\sim 3 \% X_0$.

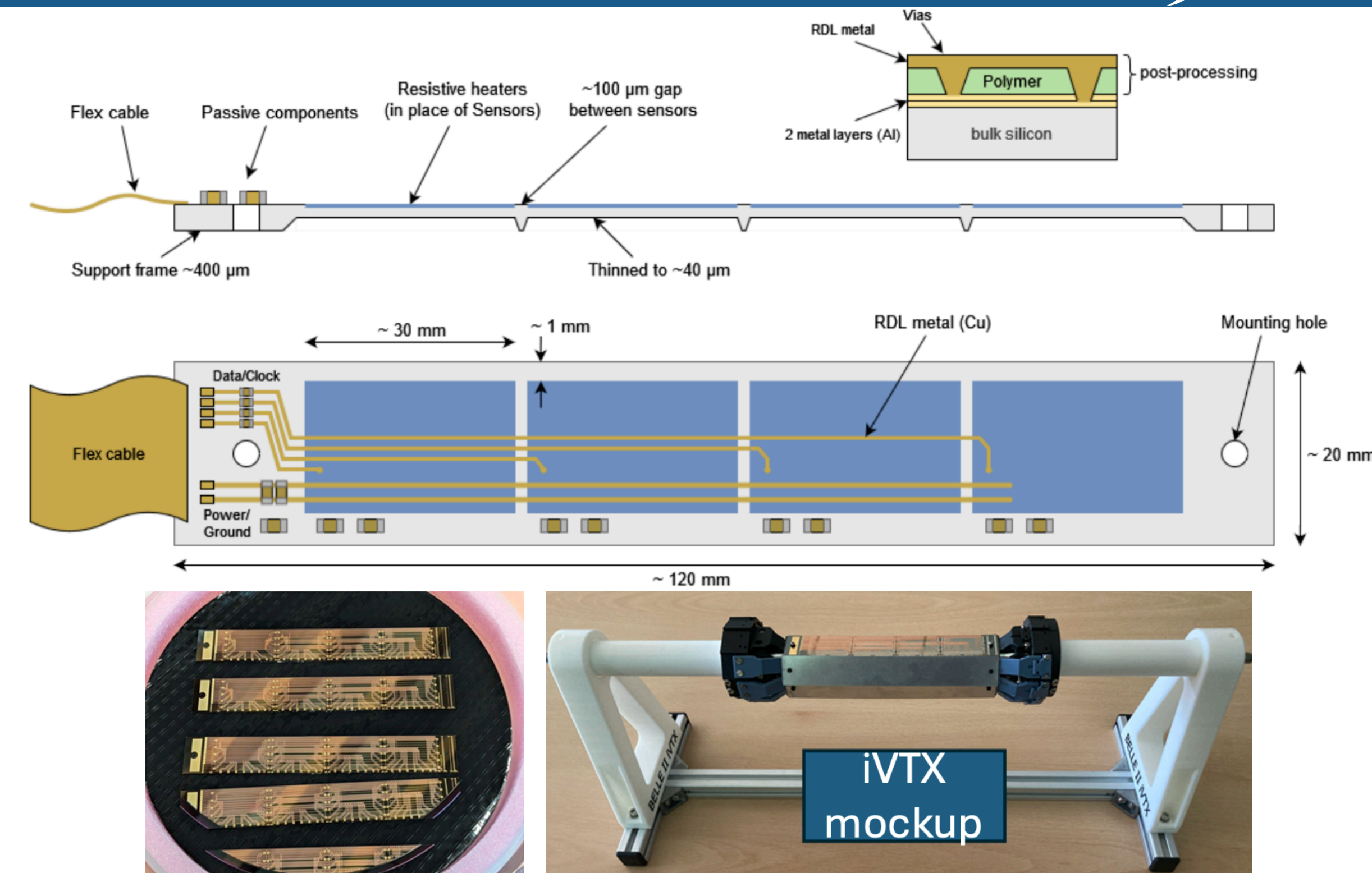
► Better tracking performance.

- Higher tracking efficiency.
- Better vertex reconstruction precision.
- Fast readout contributing to first-level trigger.



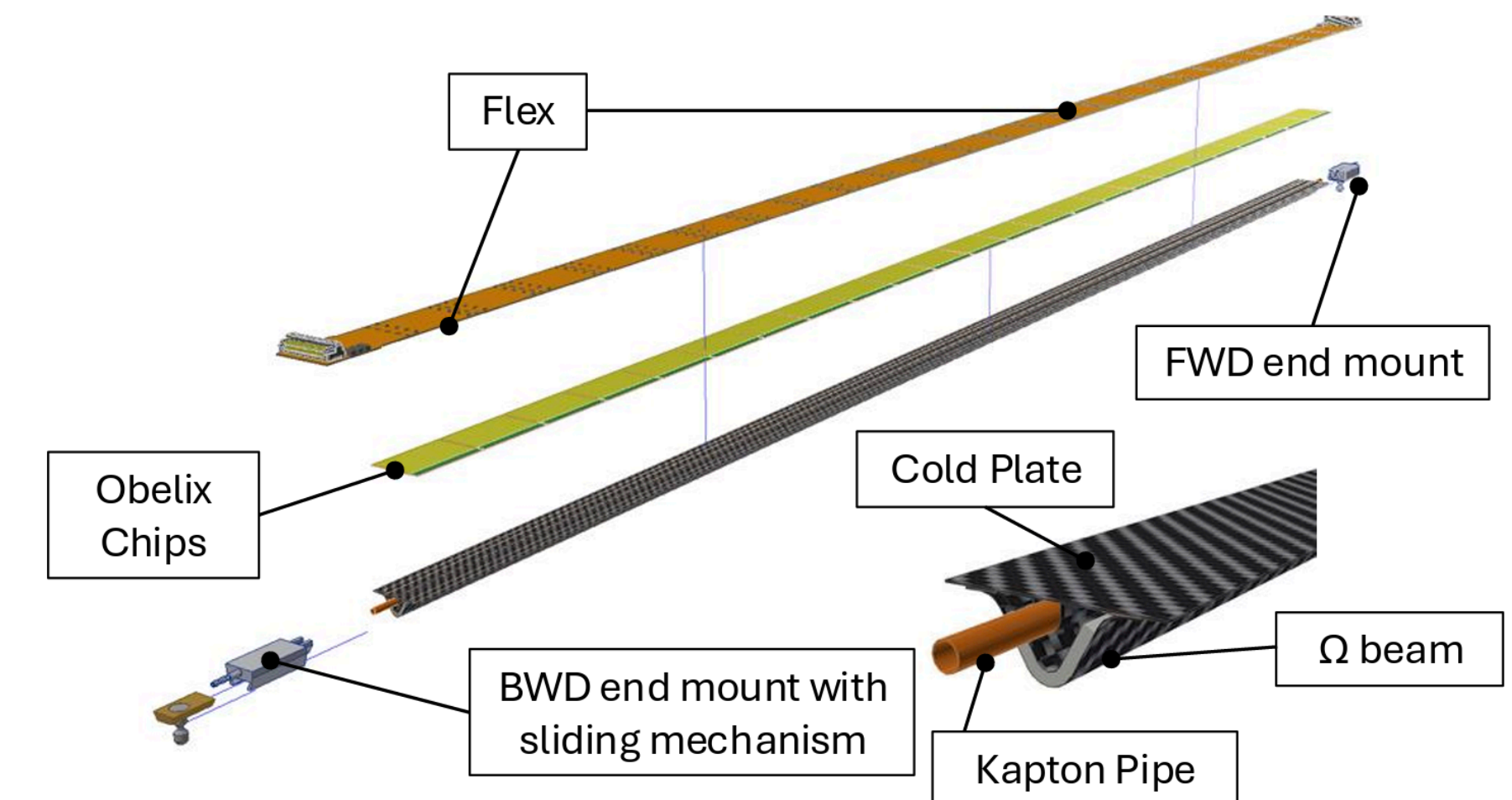
iVTX, 2 innermost layers

- ▶ **All silicon design, 0.3% X_0 per ladder**
 - ▶ Sensors are supported directly on diced wafer.
 - ▶ Sensor part thinned to 40 μm .
 - ▶ Post-processed redistribution layer (RDL) interconnects the sensors.
- ▶ **Cooling strategy under investigation**
 - ▶ Developed based on temperature dependency test of the performance of TJ-Monopix2.
 - ▶ Expected to operate sensors at $\sim$ room temperature to minimize cooling system.
 - ▶ Heat sink made of thermal pyrolytic graphite (TPG).
 - ▶ Liquid cooling with cooling pipes.



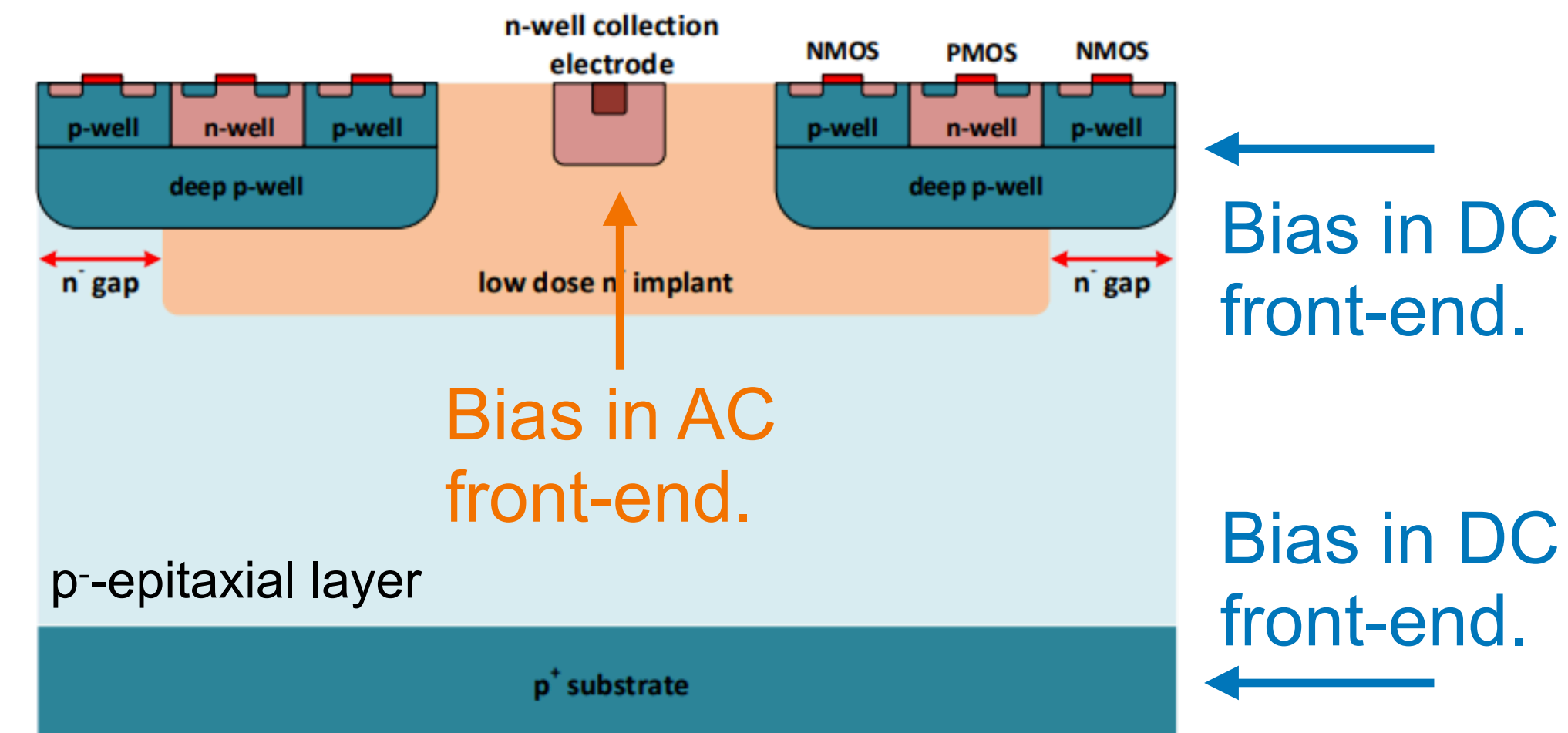
oVTX, 4 outer layers

- ▶ **Carbon fiber layers, 0.6% X_0 per ladder**
 - ▶ Sensors are aligned on carbon fiber support.
 - ▶ Flex circuits interconnects sensors.
 - ▶ Liquid cooling with cooling pipes.



DMAPS OBELIX sensor

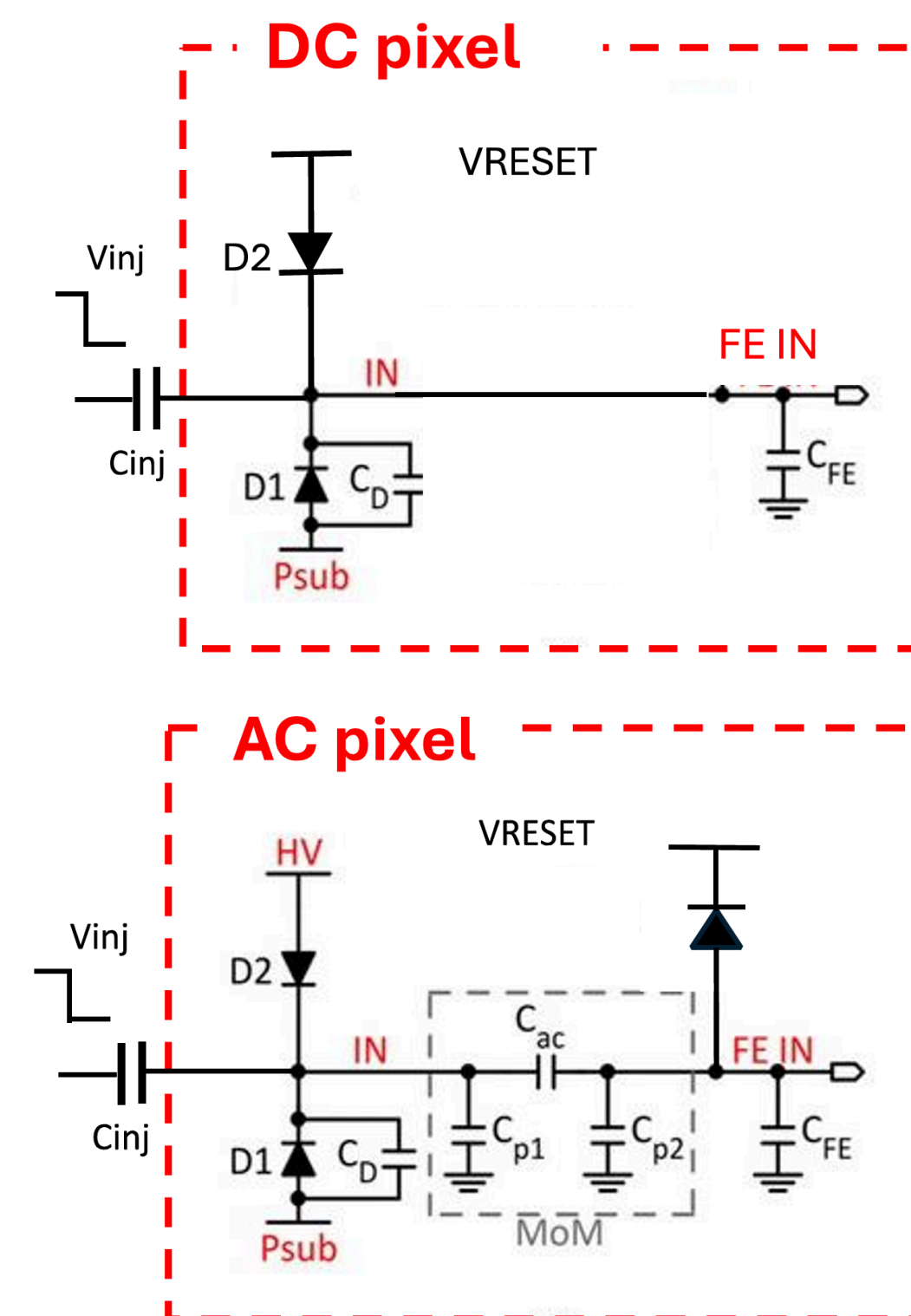
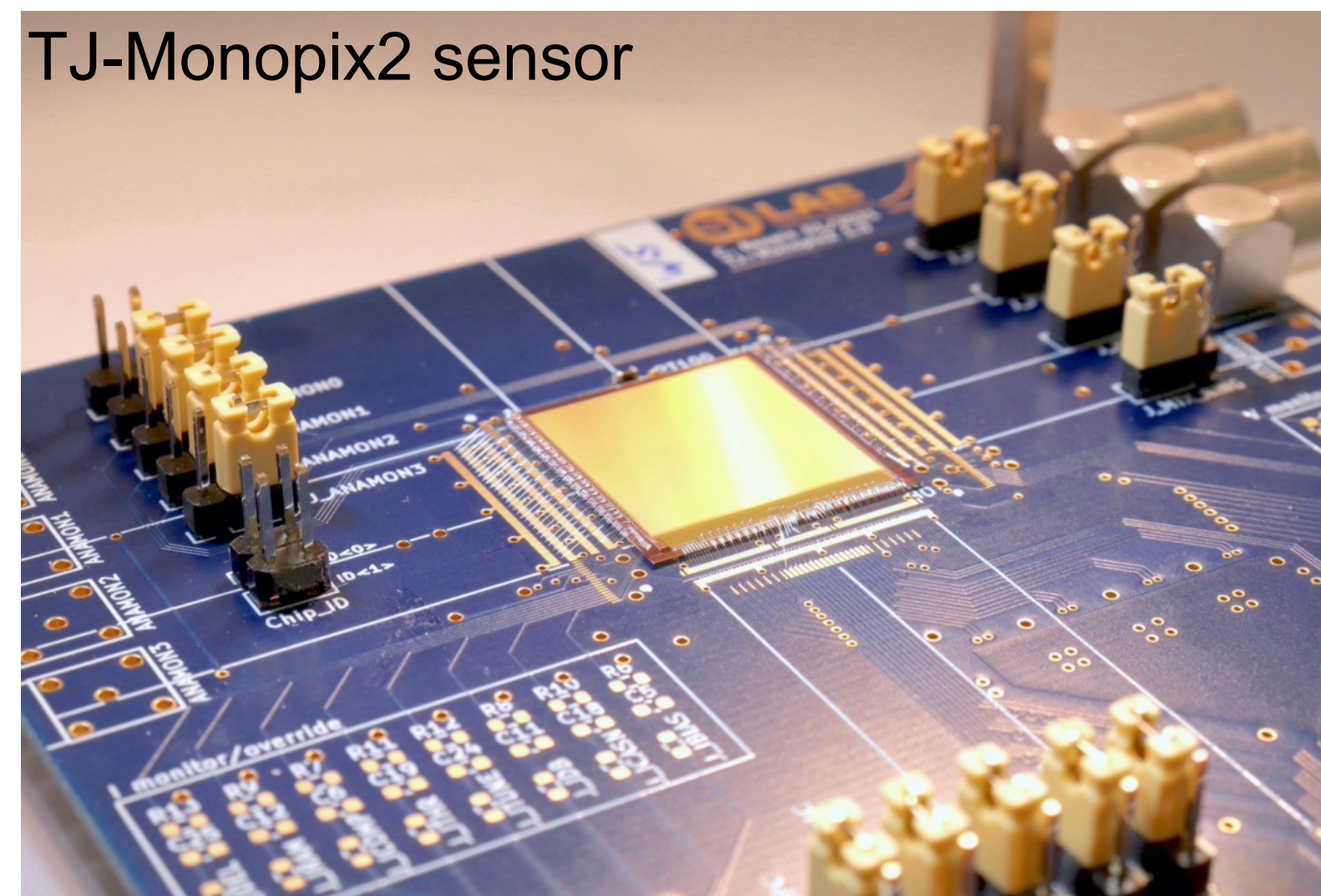
- ▶ Designed based on TJ-Monopix2 prototype
 - ▶ Inherited analog matrix from TJ-Monopix2.
 - ▶ Modified digital periphery receiving level-1 trigger and adapted to Belle II DAQ system.



TJ-Monopix2 as a predecessor of OBELIX

- ▶ A DMAPS prototype designed for HL-LHC ATLAS
 - ▶ 512 × 512 pixels in 2 × 2 cm² area.
 - ▶ Pixel size of 33 × 33 μm².
 - ▶ 25 ns timestamping precision.
 - ▶ 30 μm epitaxial layer depth.
 - ▶ Trigger less.
 - ▶ Column drain readout architecture.
- ▶ Front-ends: DC/AC coupling
 - ▶ Biased in different ways.

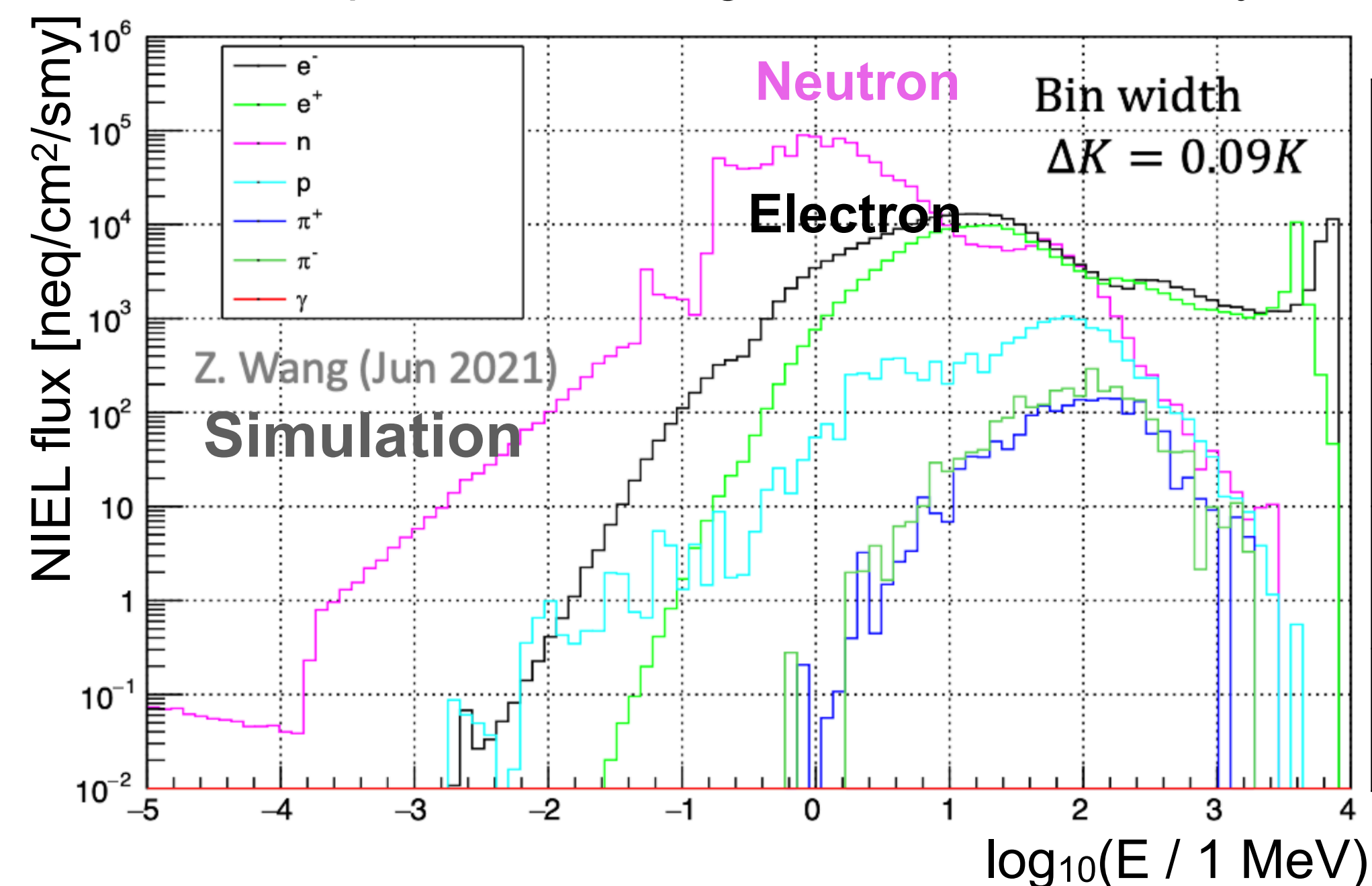
TJ-Monopix2 sensor



Characterization activities of TJ-Monopix2

- ▶ **Performance measurement of TJ-Monopix2 as a reference for future OBELIX sensor.**
 - ▶ A series of laboratory measurement, test beam and irradiation activities have been conducted to investigate the detection performance.
 - ▶ Several irradiated samples have been created to compare the impact of radiation damage, in order to make sure the good performance of VTX after long-term irradiation and define the operation temperature.

Particle components creating NIEL flux to VXD Layer 3



Different irradiated samples studied

TJ-Monopix2 samples	Irradiation type	NIEL flux n_{eq}/cm^2
Chip-1	24 MeV proton	1×10^{14}
Chip-2	24 MeV proton	2×10^{14}
Chip-3	24 MeV proton	5×10^{14}
Chip-4	90 MeV electron	5×10^{14}

Items to be checked

1. Temperature dependency of performance after irradiation.
2. DC/AC front-end performance comparison.

Main contributions of NIEL flux in Belle II environment come from 1~10-MeV level Neutrons and electrons.

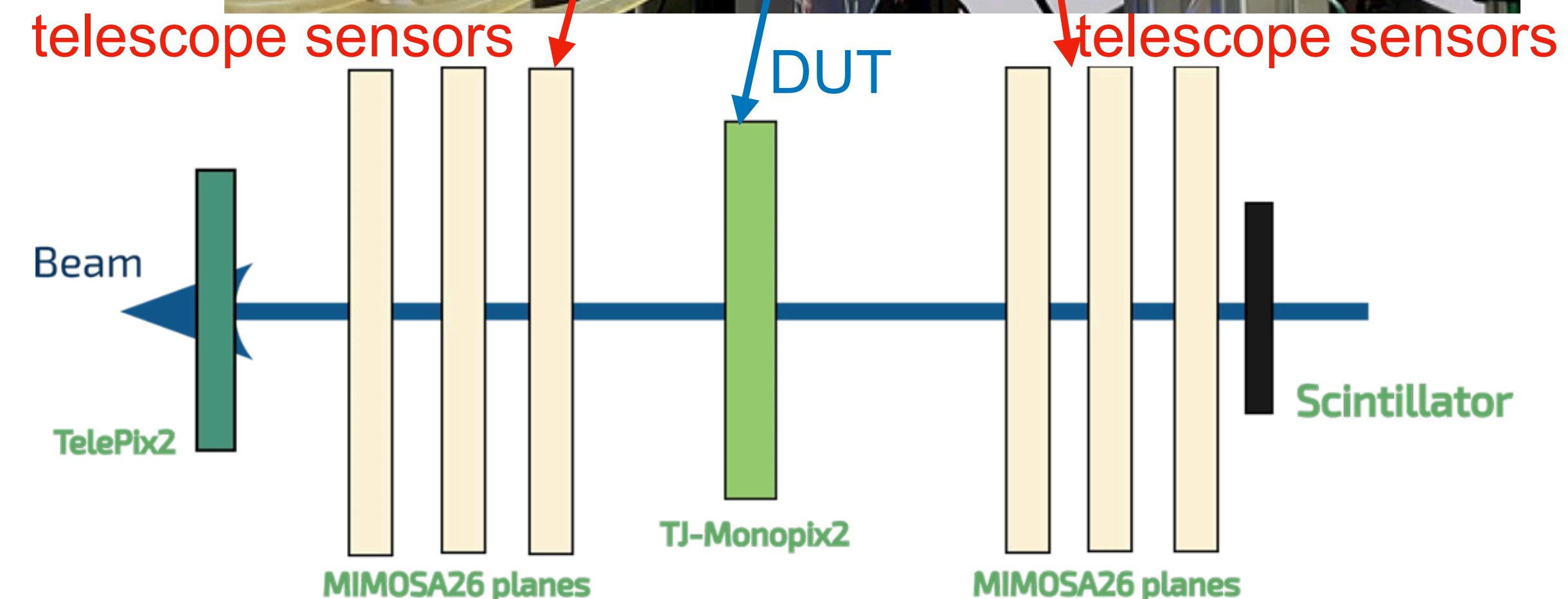
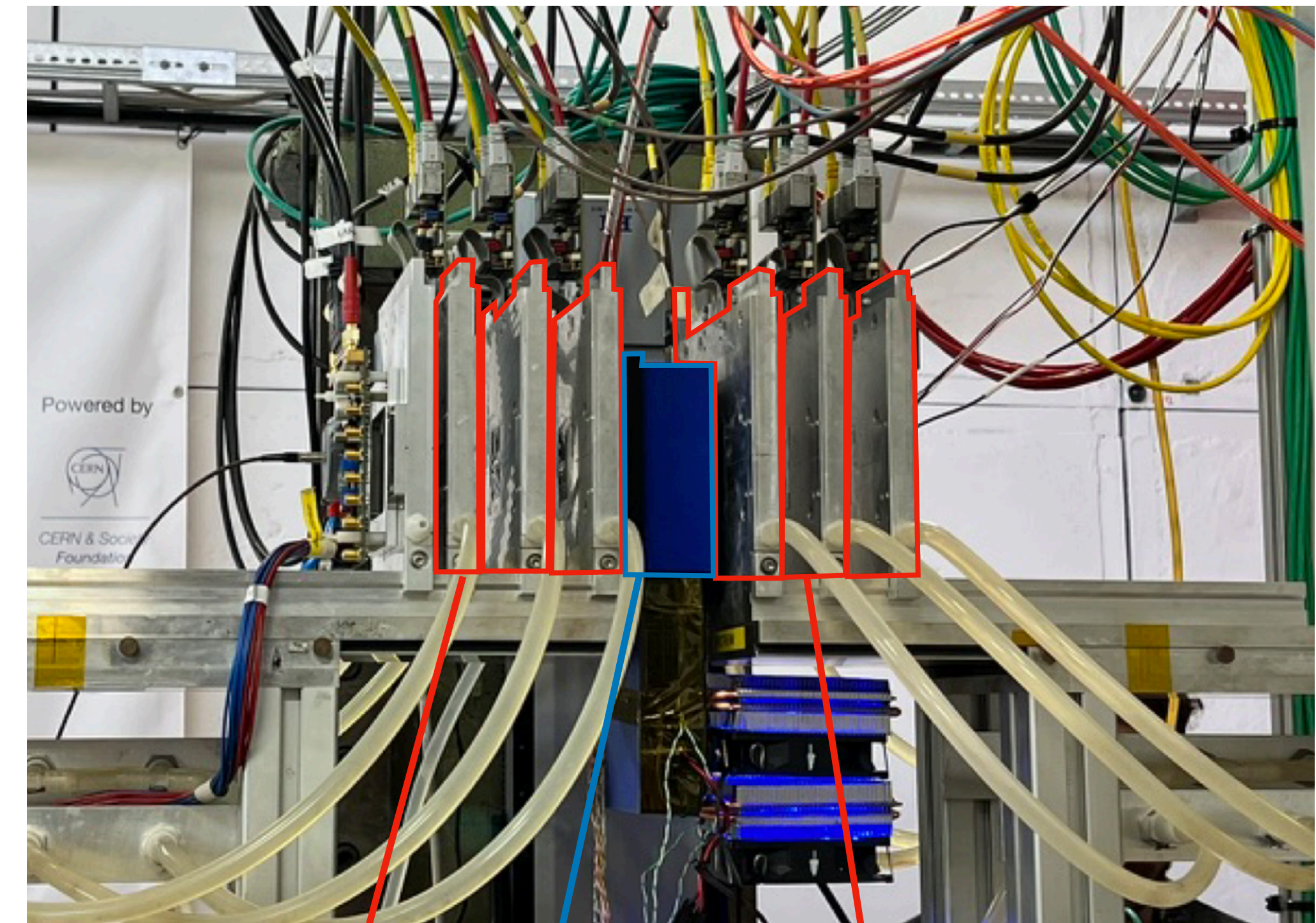
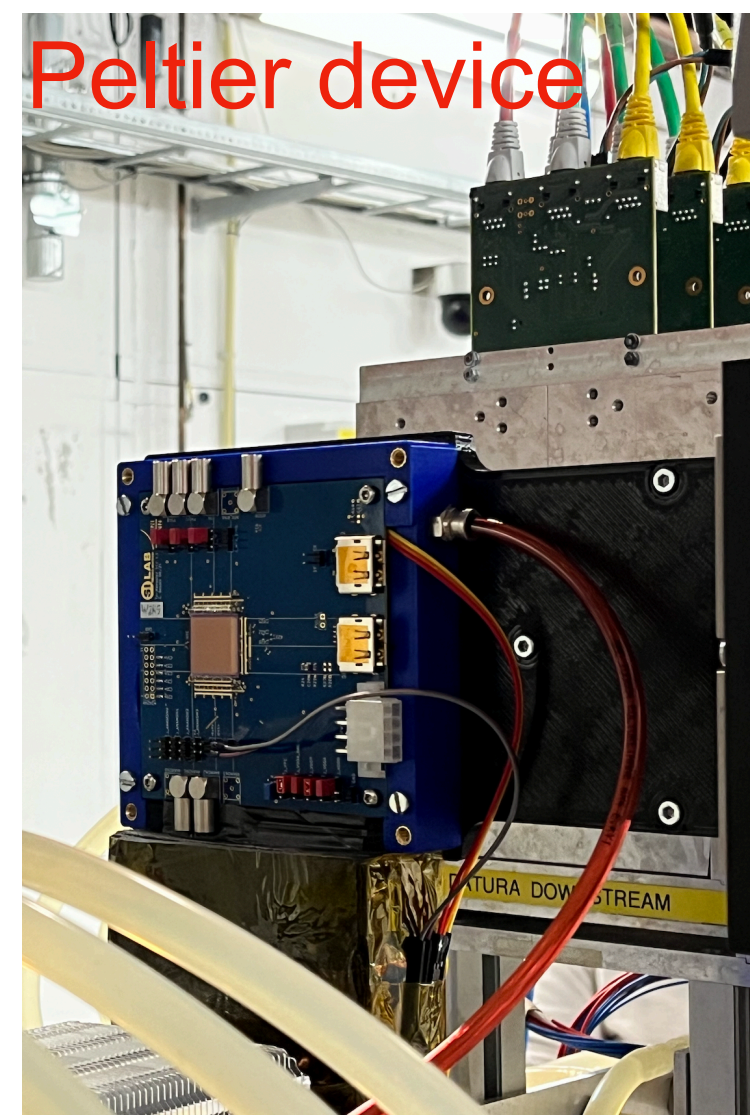
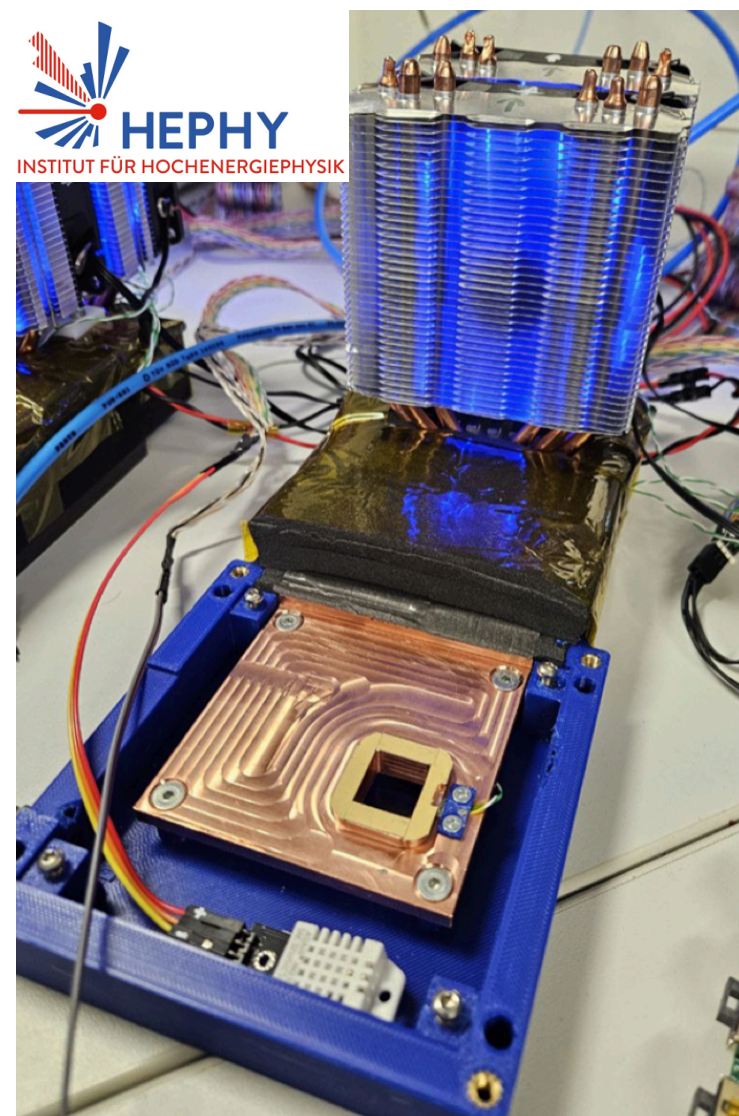
DESY Test beam March 2025

► DESY II Test Beam Facility

- 4.2 GeV electron beam.
- EUDET telescope.
- 1 e-irrad. & 3 p-irrad. samples to compare the impact of different irradiation and study the temperature performance.

► Peltier device

- Monitor an NTC temperature sensor near sensor chip.
- Control the temperature of DUT within $10^{\circ}\text{C} \sim 50^{\circ}\text{C}$.



Detection efficiency measurement:

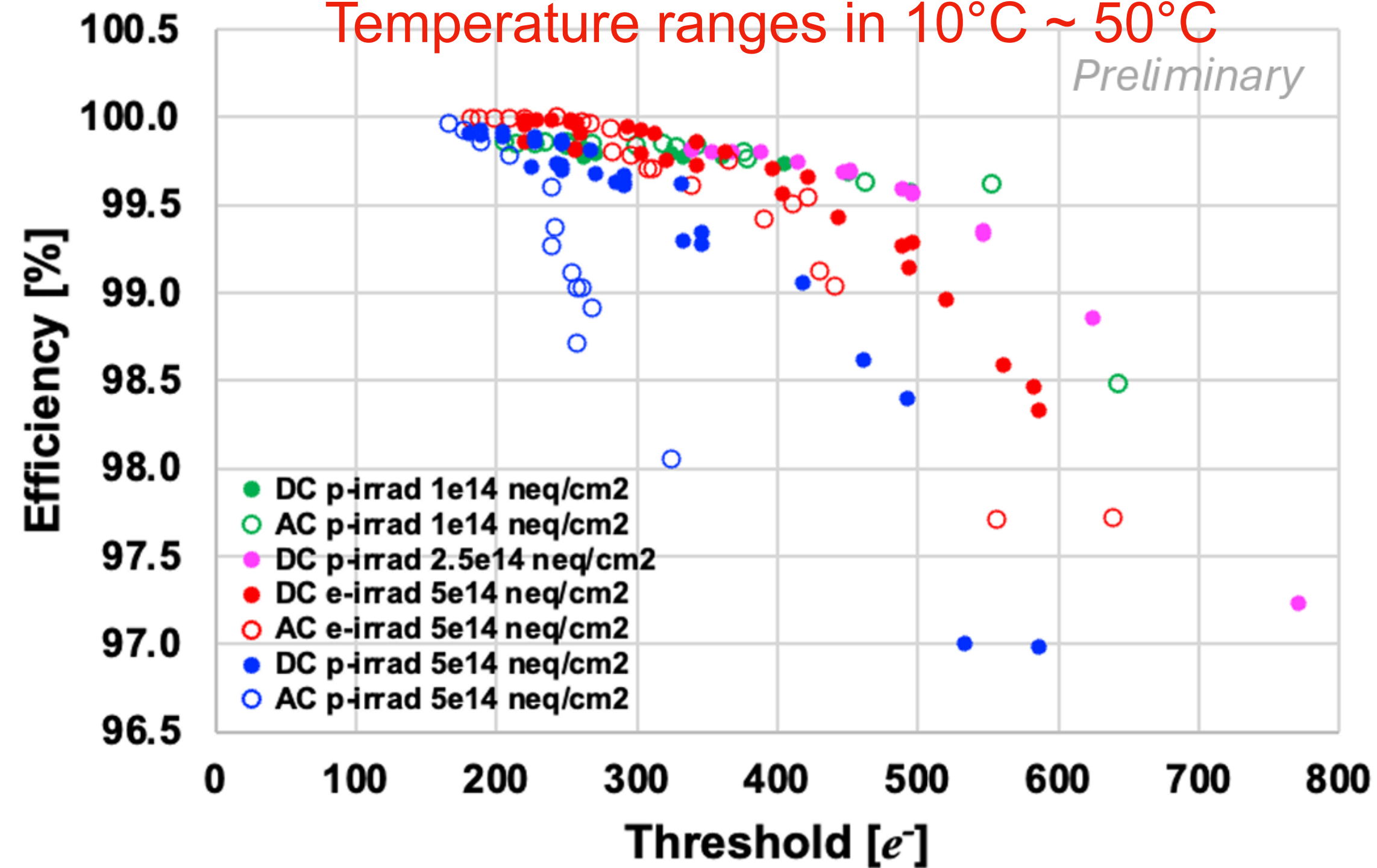
Reconstruct a particle using telescope → check if this particle is detected on DUT.

DESY Test beam 2025

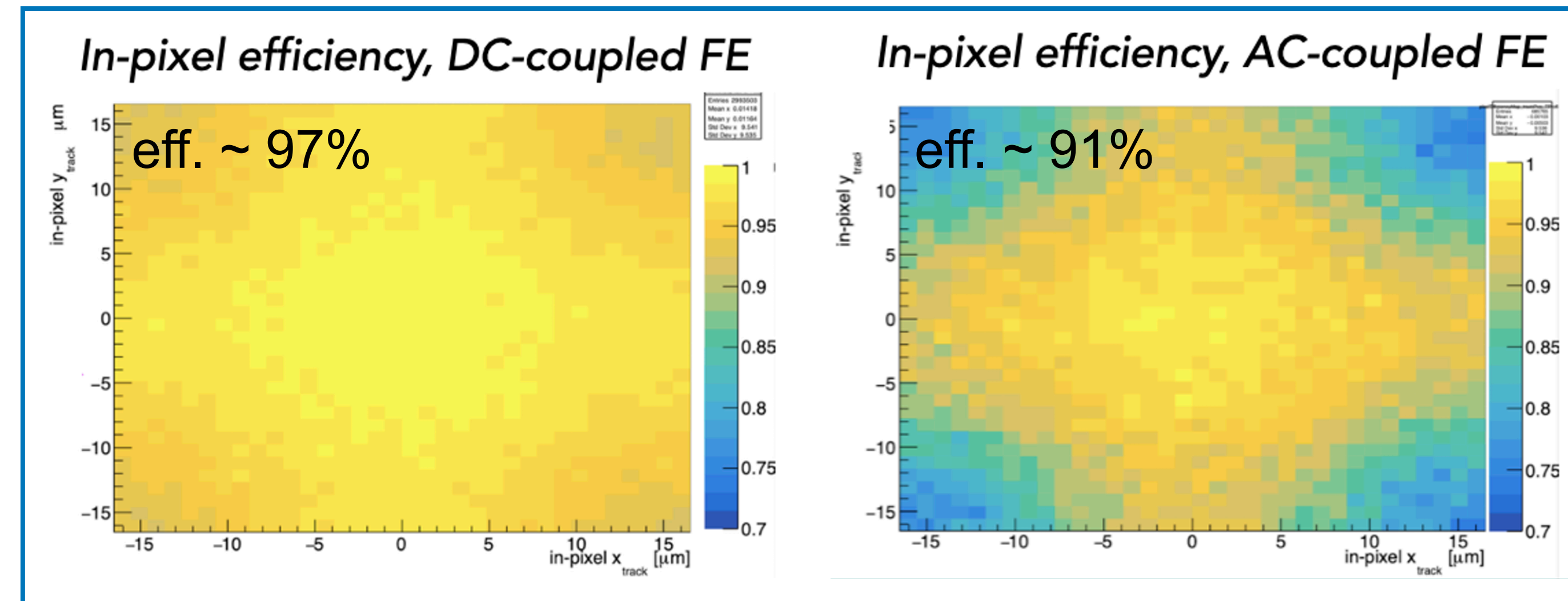
Efficiency vs Threshold - Max bias

Temperature ranges in 10°C ~ 50°C

Preliminary



Comparison of p-irrad DC and AC FE at ~THR 550 e^-



Temperature 40°C

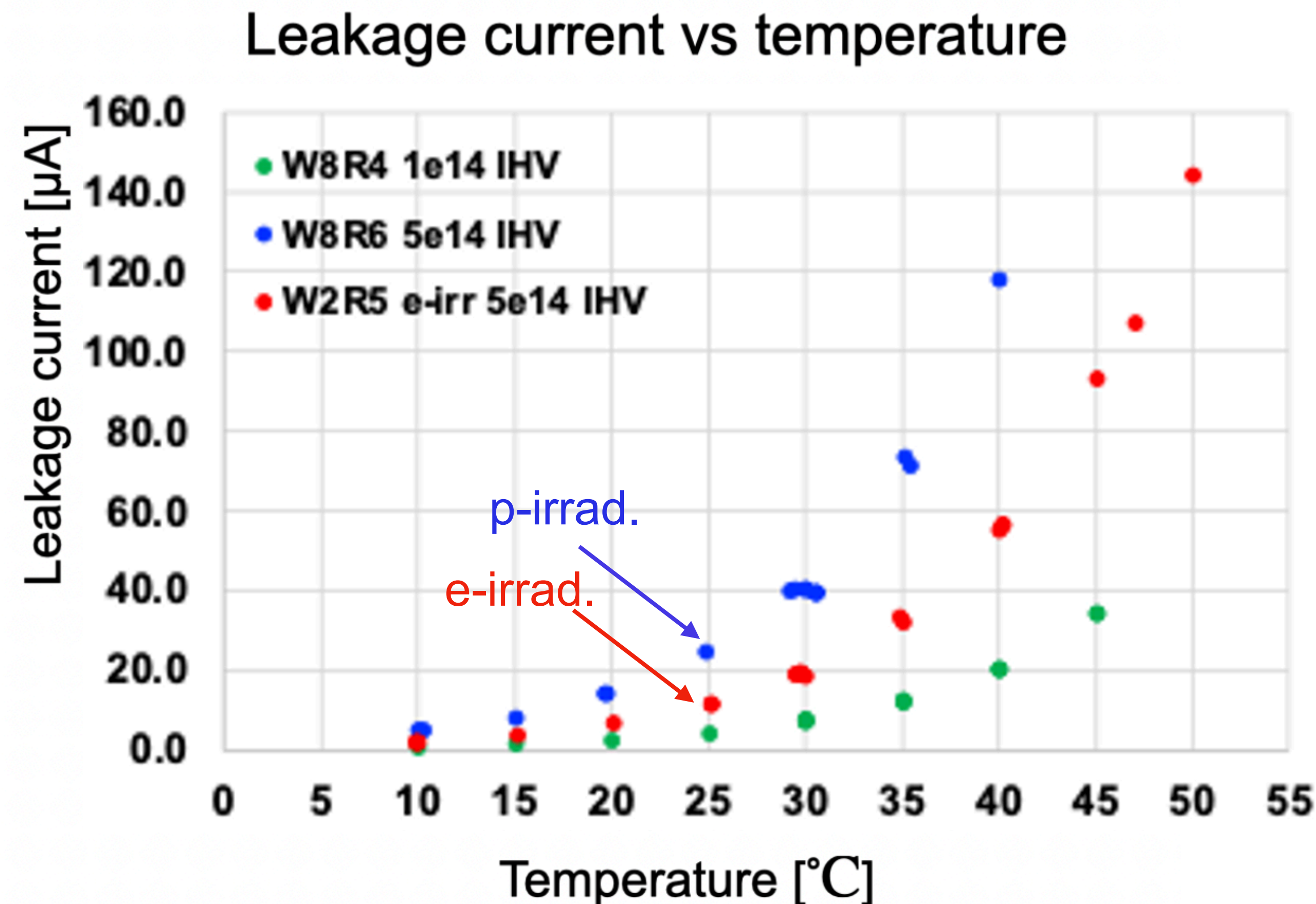
► Preliminary result (I):

- Efficiency is degraded due to the charge collection loss resulted from larger radiation damage .
- P-irrad. samples shows smaller efficiency than e-irrad. sample with the same NIEL flux, **suggesting more bulk damage in proton-irradiation.**
- Comparing DC and AC front-end, **DC front-end shows better performance.**

Leakage current measurement

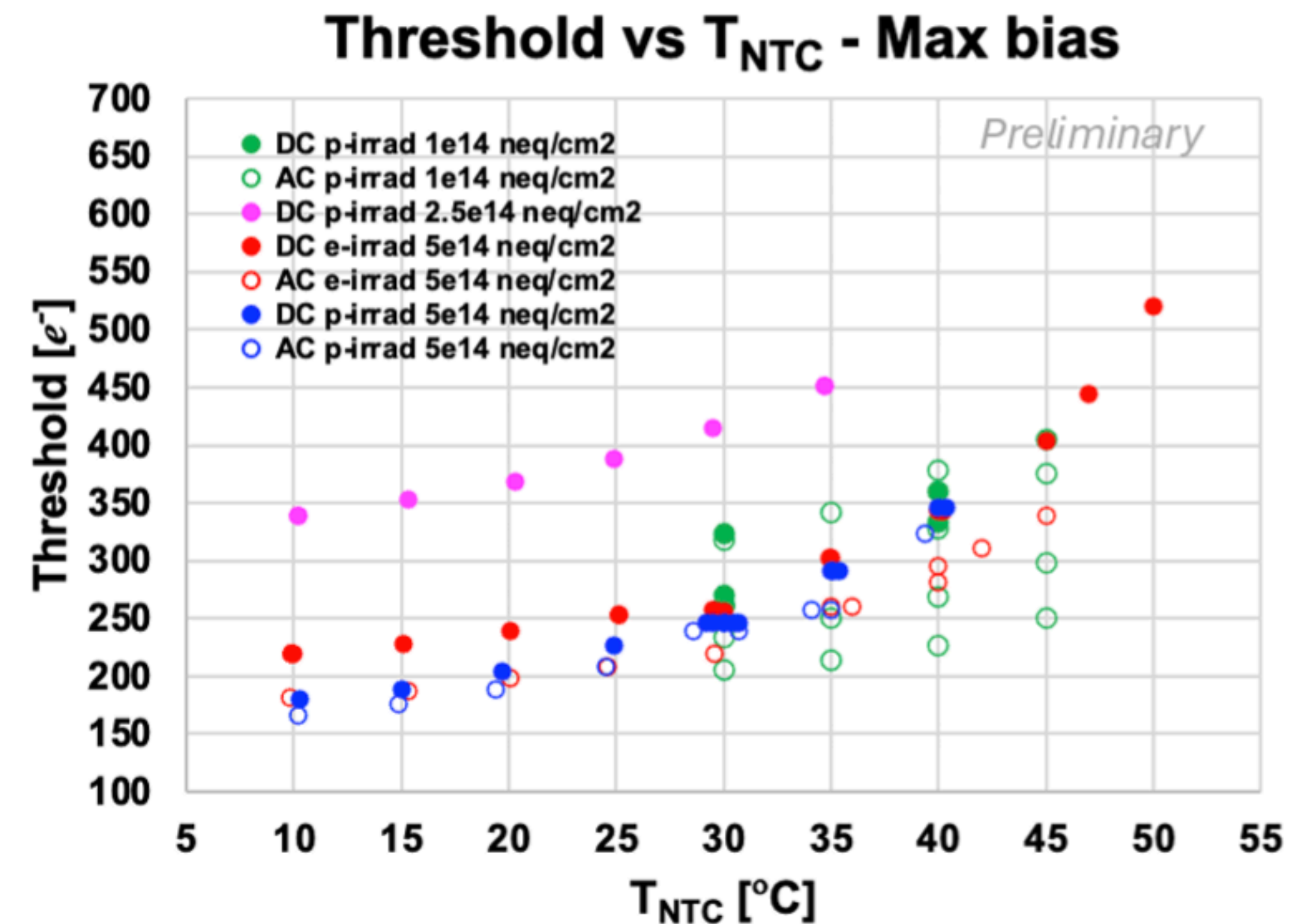
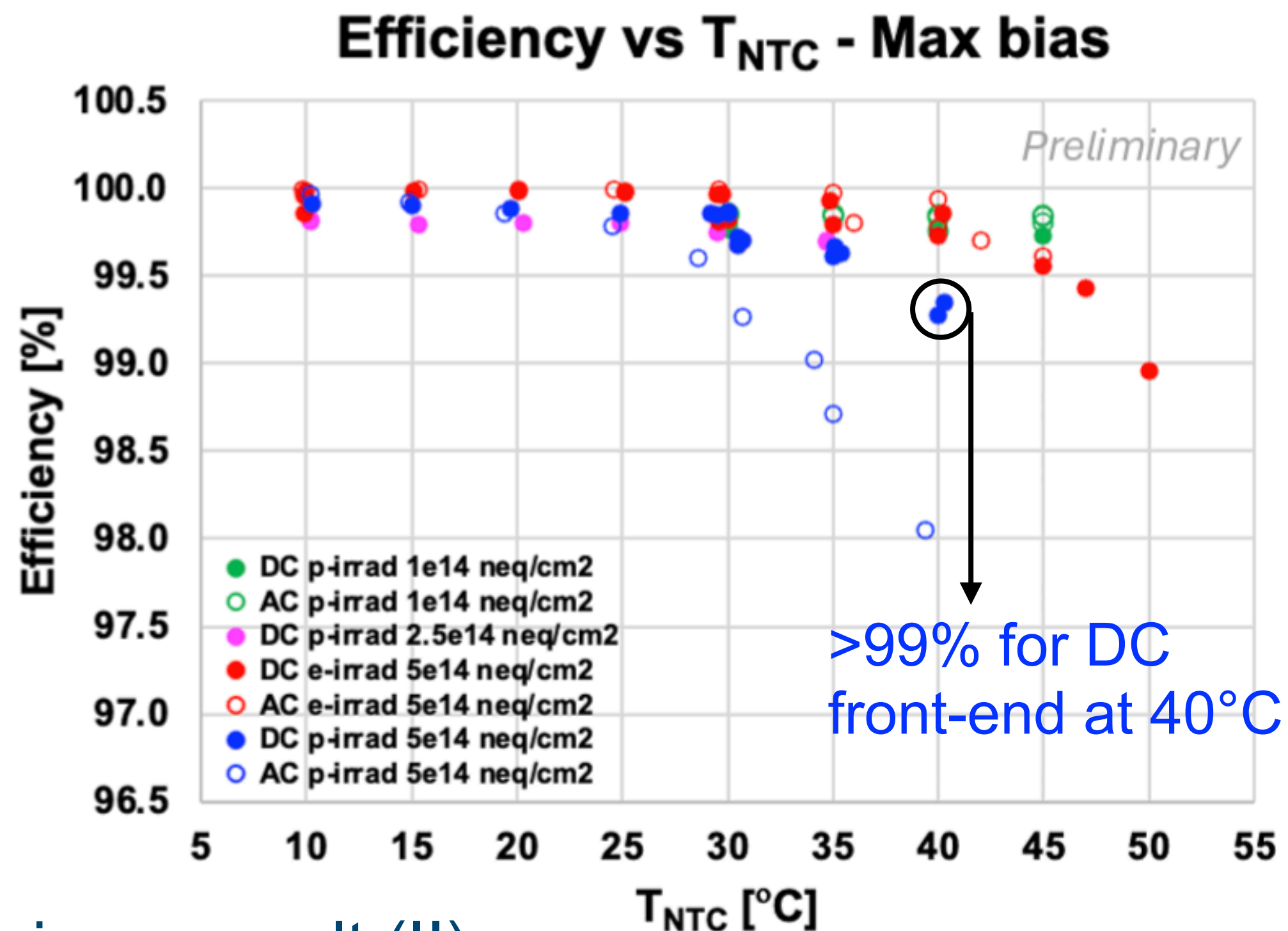
► Comparison among different irradiated samples

- Proton-irradiated sample shows larger leakage current compared with electron-irradiated sample despite the same NIEL flux, **consistent with the indication from efficiency comparison.**



DESY Test beam 2025

$$T_{\text{chip}} \sim T_{\text{NTC}} + 7^{\circ}\text{C}$$



► Preliminary result (II):

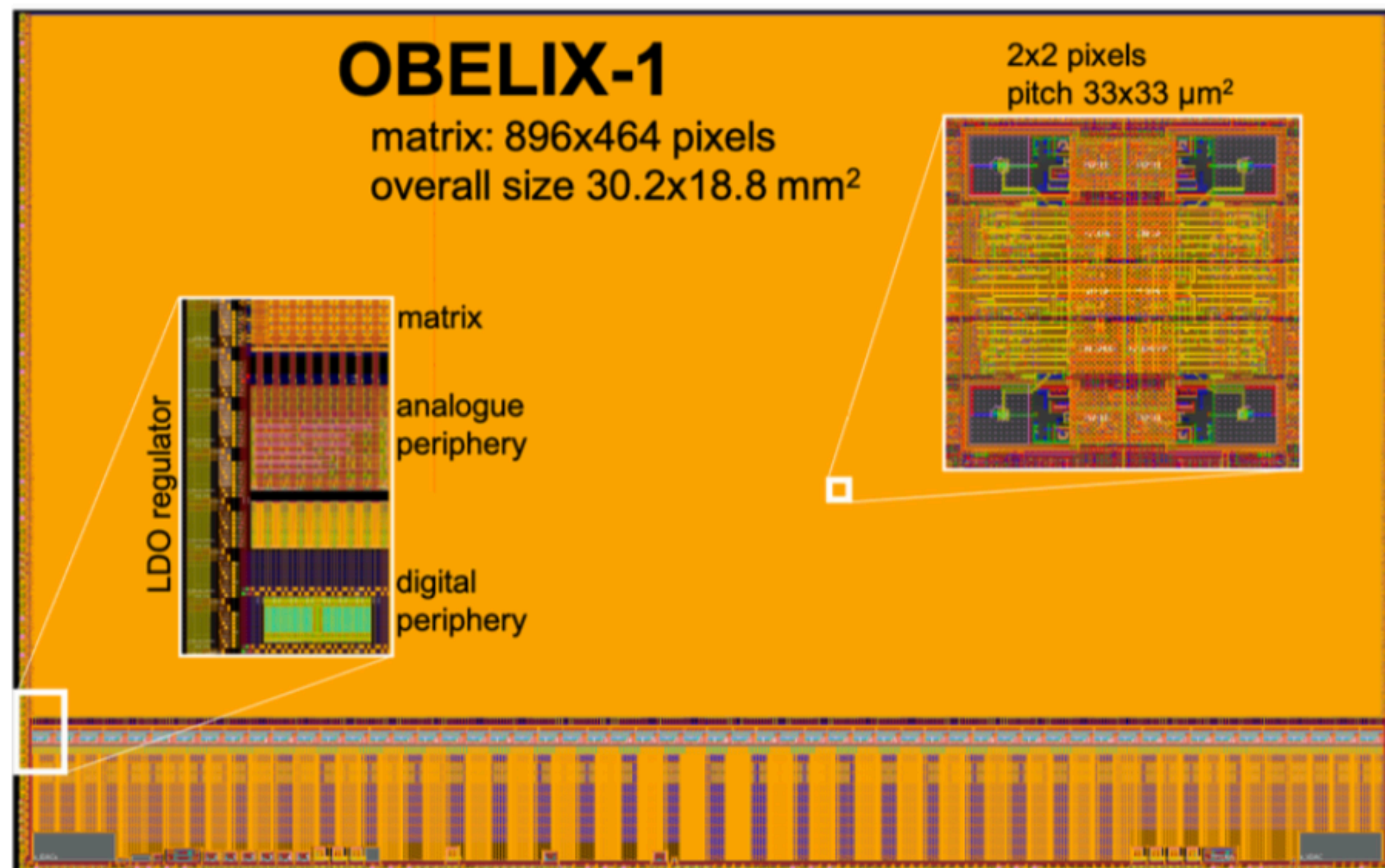
- Efficiency is degraded at high temperature due to the increased threshold by the fast discharge with leakage current.
- AC front-end shows larger impact for p-irrad. sample.
- **Difficulties in operating above NTC 40°C** due to large noise by increased leakage current and the increased lower limit of achievable detection threshold.

DC front-end is chosen due to the high detection efficiency.

OBELIX-1

- ▶ Analog matrix inherited from TJ-Monopix2.
 - DC coupling front-end chosen.
 - Column drain readout architecture.
- ▶ Modified digital part adapting to Belle II DAQ system.
 - Receive trigger decision and send out triggered data to Belle II DAQ system.
 - Contribute to level 1 trigger by providing simplified hit data.

**Submission targeting December 2025.
First test starts in summer 2026.**



Specification	OBELIX-1
Pixel pitch	33 μm
Sensitive layer thickness	$\sim 30 \mu\text{m}$
Sensor thickness	$< 100 \mu\text{m}$
Hit rate capability	$> 120 \text{ MHz/cm}^2$
Trigger delay	$\sim 10 \mu\text{s}$
Trigger rate	30 kHz
Overall integration time	$< 100 \text{ ns}$
Time precision	50 ns
Total ionizing dose tolerance	100 Mrad
NIEL flux tolerance	$5 \times 10^{14} \text{ n}_{\text{eq}}/\text{cm}^2$
Sensitive matrix dimensions	around $30 \times 16 \text{ mm}^2$
Overall sensor dimensions	around $30 \times 19 \text{ mm}^2$
Powering	through voltage regulators

Summary

- ▶ Proposing VTX as an upgrade plan, utilizing DMAPS technology.
 - ▶ Improved physics performance.
 - ▶ Better background tolerance.
 - ▶ Compatible to interaction region redesign.
- ▶ As predecessor of OBELIX sensor, the performance of TJ-Monopix2 has been studied.
 - ▶ Detection efficiency degradation is observed with larger irradiation. However, the efficiency can still reach >99% in DC front-end up to NTC temperature of 40 °C.
 - ▶ Comparison between e-irrad. and p-irrad. sample shows more bulk damage in proton-irradiation, crosschecked by leakage current measurement.
- ▶ OBELIX-1 is coming soon. More detailed test will be performed from summer 2026.
- ▶ VTX milestone:
 - ▶ OBELIX-1 submission in Dec. 2025. → Preparing TDR in 2027. → Installation during Long Shutdown 2 in ~2032.



Thanks for Listening

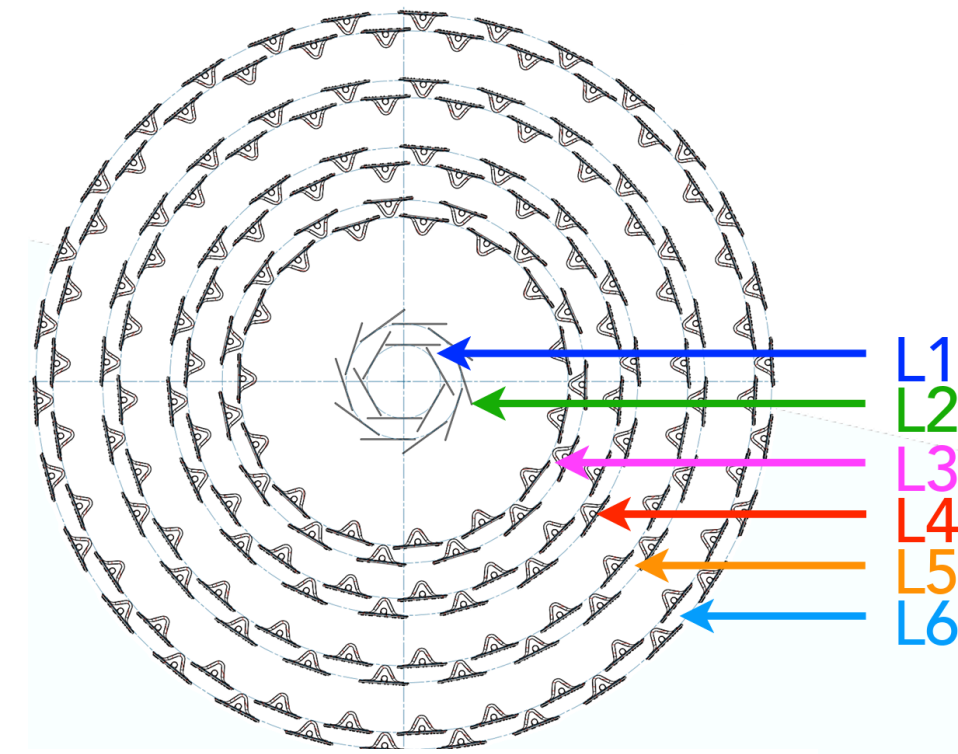
The measurements leading to these results have been performed at the Test Beam Facility at DESY Hamburg (Germany), a member of the Helmholtz Association (HGF).





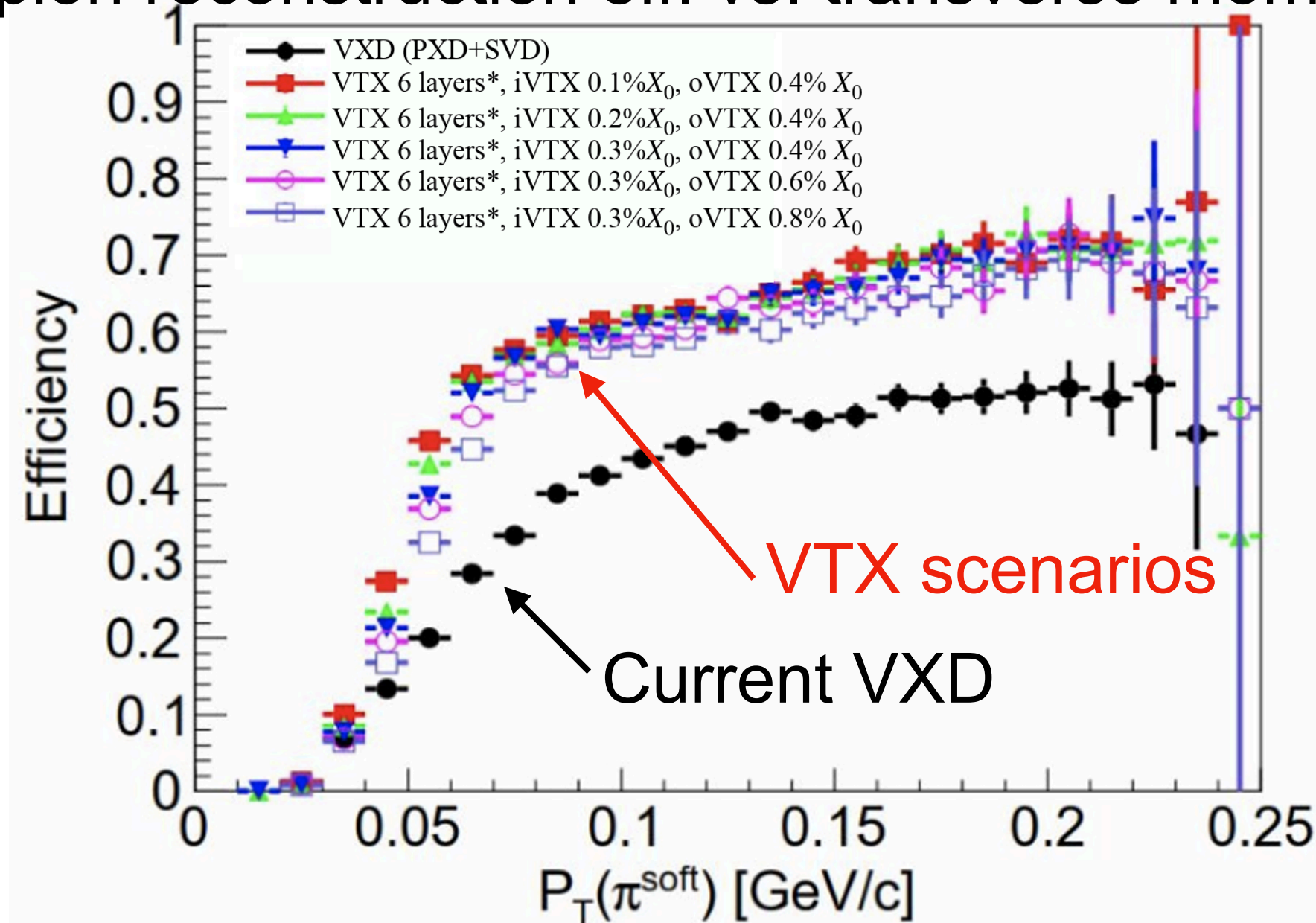
VTX tracking performance study based on simulation

- ▶ Significant improvement in soft pion reconstruction (reconstructed only with VXD).
 - ▶ Studied with $B^0 \rightarrow D^{*-}(\rightarrow D^0 \pi^{\text{soft}-}) \mu^+ \nu_\mu$
- ▶ Vertex resolution is improved with 5-layer VTX.
 - ▶ Studied with $B^0 \rightarrow J/\psi K_S$
- ▶ Different material budget scenario studied
 - ▶ iVTX: 0.1%, 0.2%, 0.3% X_0 per ladder.
 - ▶ oVTX: 0.4%, 0.6%, 0.8% X_0 per ladder.

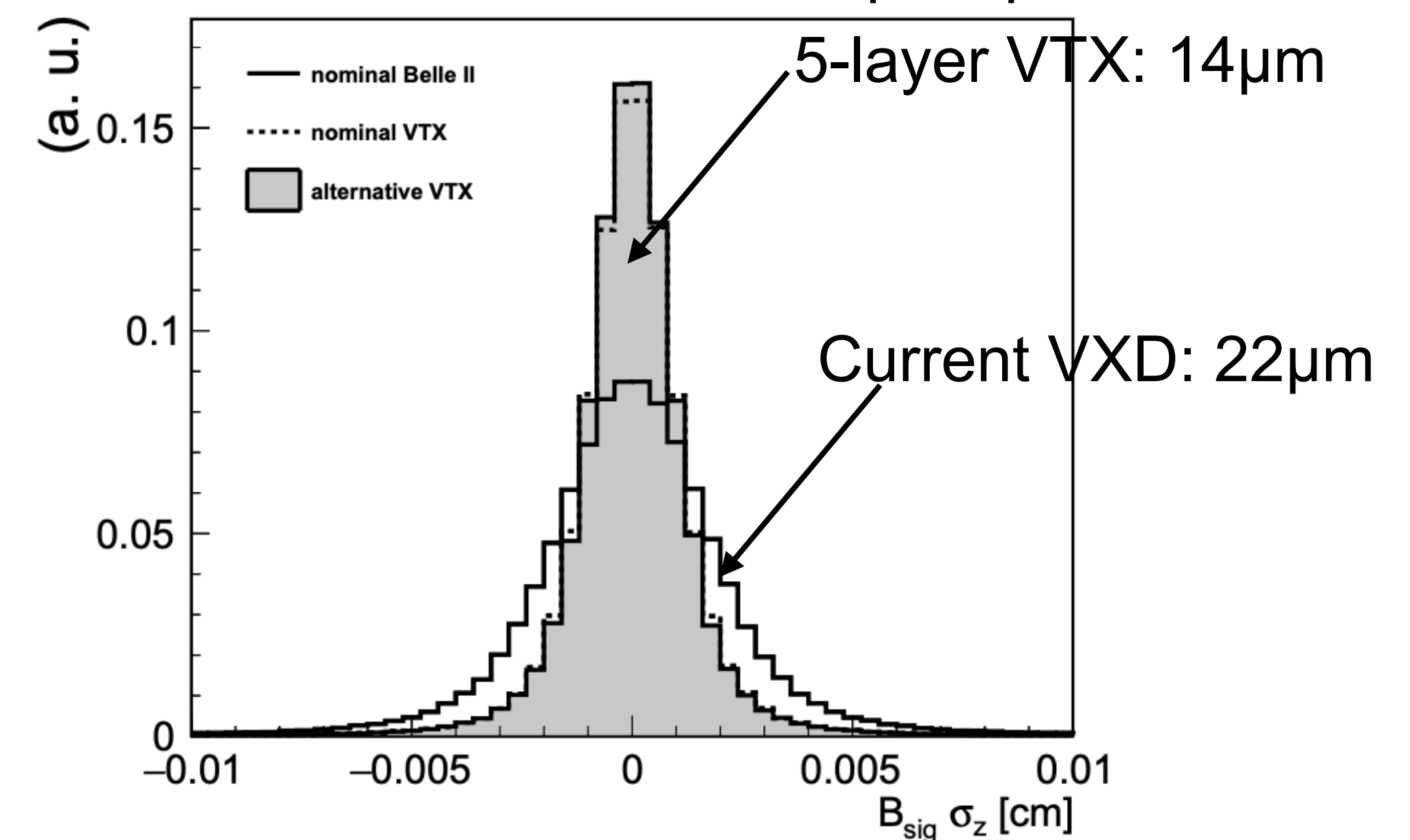


	L1	L2	L3	L4	L5	L6
Radius (mm)	14.1	22.1	62.5/69.0	82.5/89.0	108/114.5	133.5/140
# Ladders	6	10	30	36	48	60
# Sensors per ladder	4	4	12	16	20	24
Material budget (% X_0)	0.3	0.3	0.6	0.6	0.6	0.6

Soft pion reconstruction eff. vs. transverse momenta

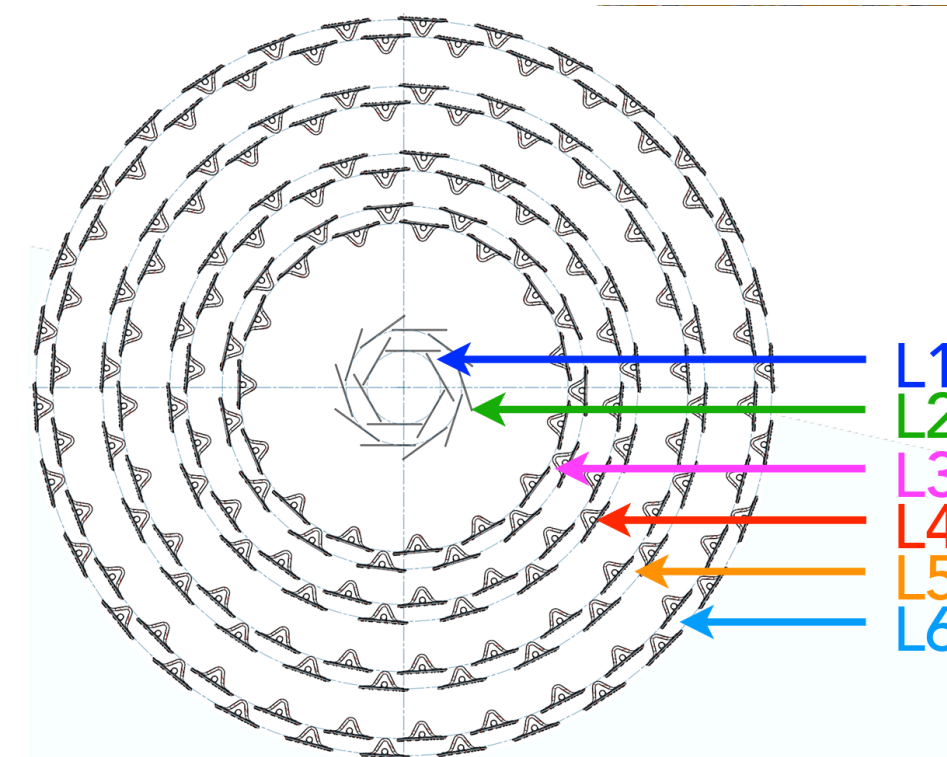


Reconstructed B meson impact parameter

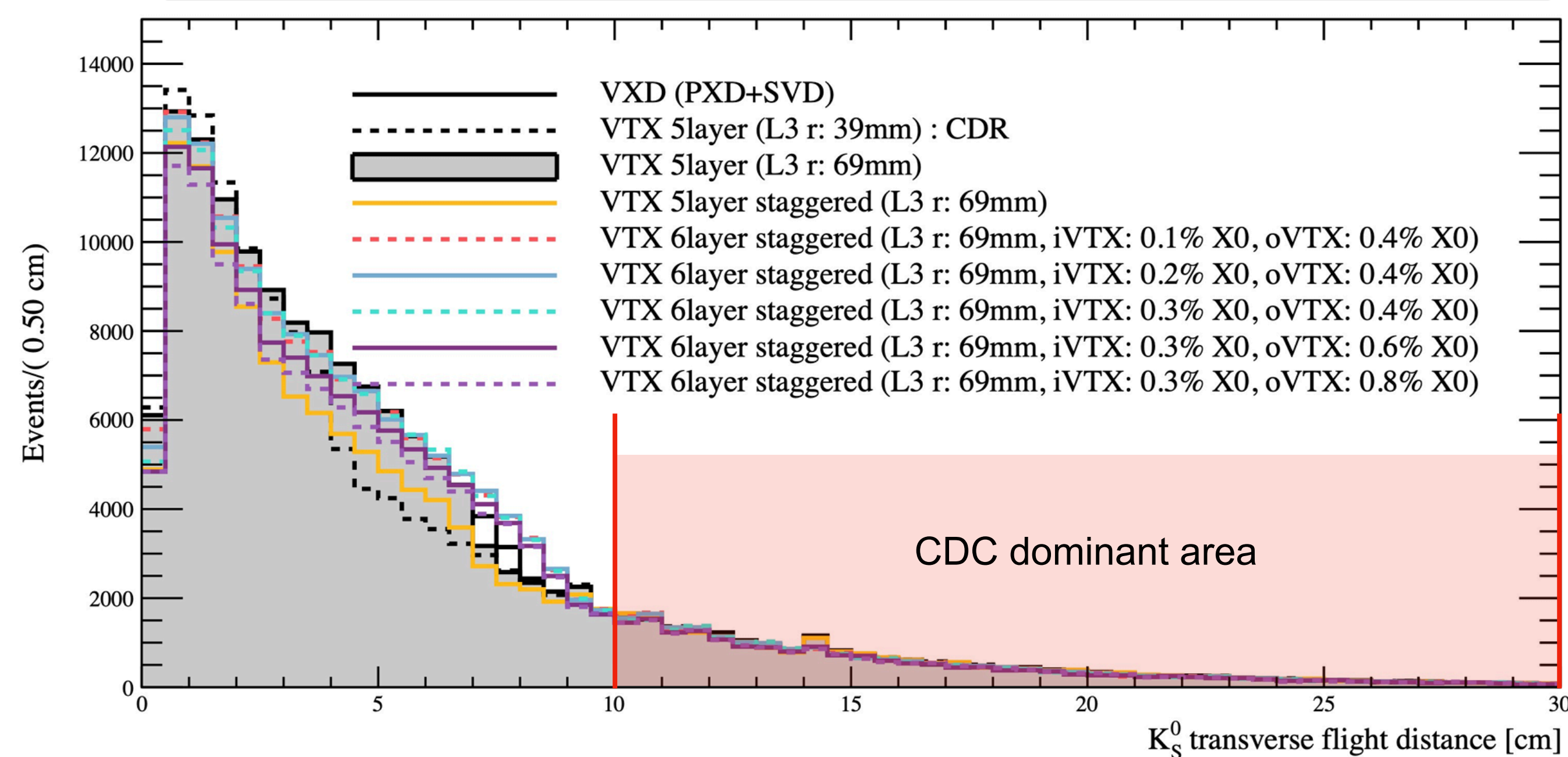
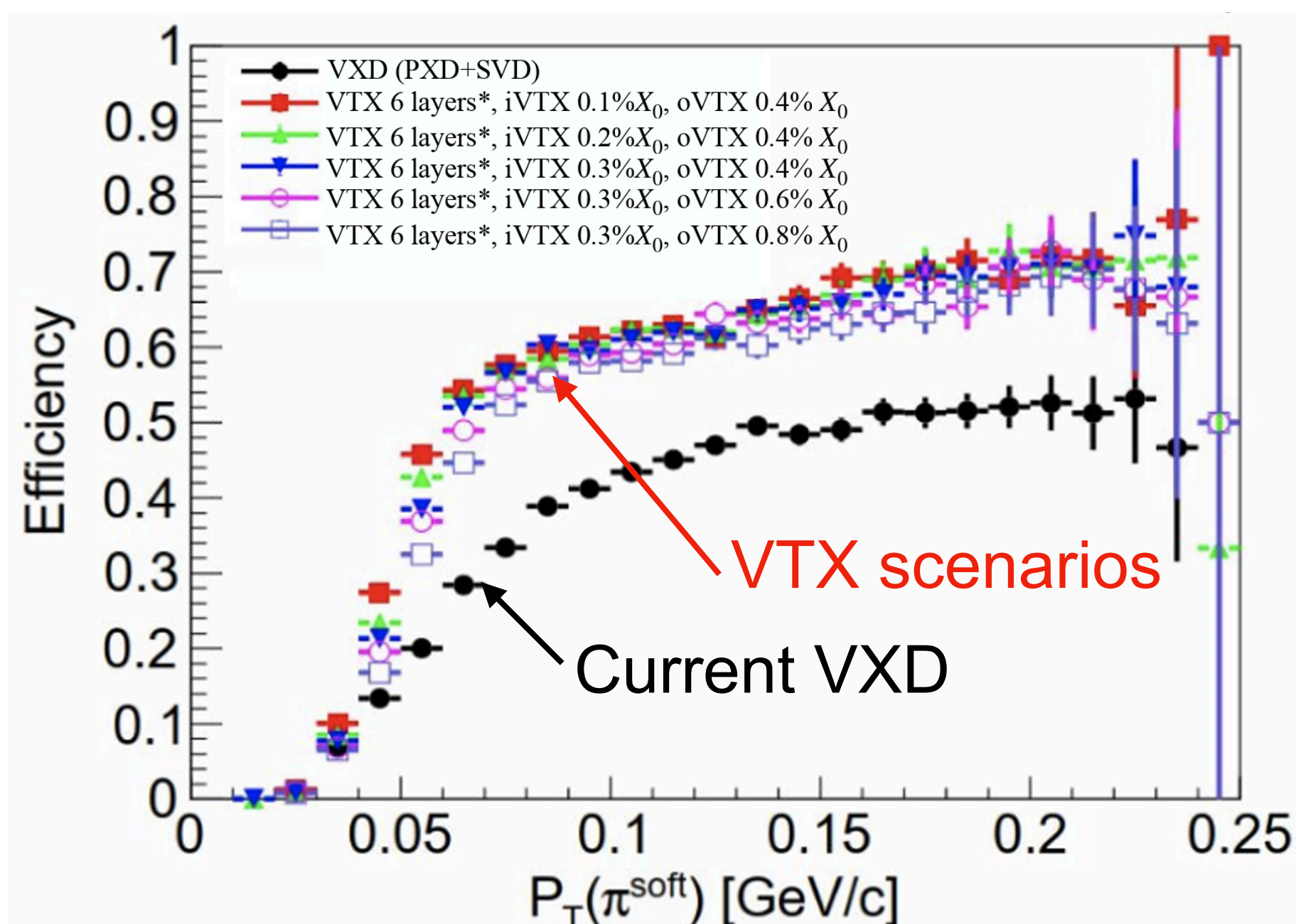


VTX tracking performance study based on simulation

- ▶ Different material budget scenario studied
 - ▶ iVTX: 0.1%, 0.2%, 0.3% X_0 per ladder.
 - ▶ oVTX: 0.4%, 0.6%, 0.8% X_0 per ladder.
- ▶ Significant improvement in soft pion reconstruction (reconstructed only with VXD).
 - ▶ Studied with $B^0 \rightarrow D^{*-}(\rightarrow D^0 \pi^{\text{soft}-}) \mu^+ \nu_\mu$
- ▶ Slight impact to K_S reconstruction.
 - ▶ Studied with $B^0 \rightarrow J/\psi K_S$

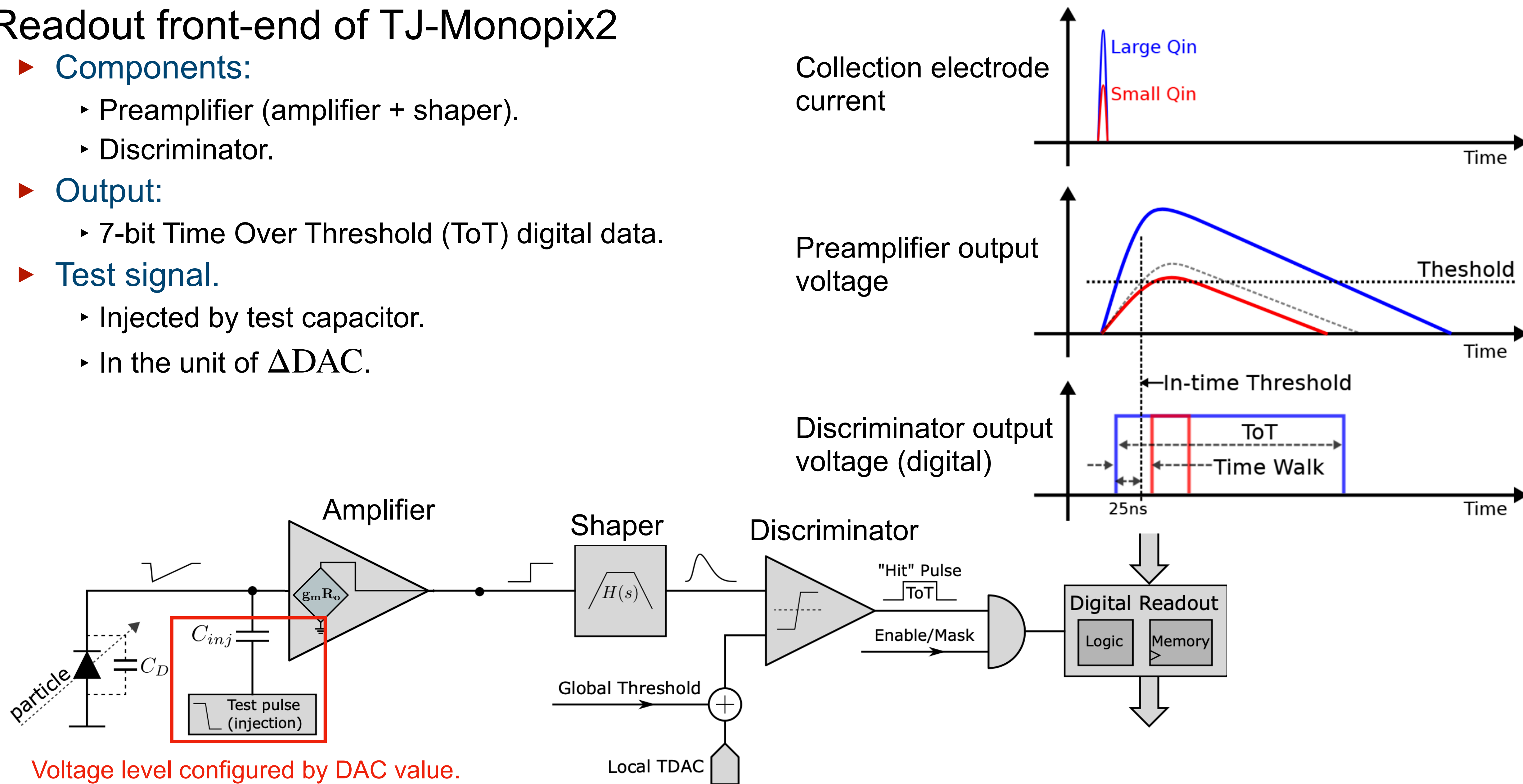


	L1	L2	L3	L4	L5	L6
Radius (mm)	14.1	22.1	62.5/69.0	82.5/89.0	108/114.5	133.5/140
# Ladders	6	10	30	36	48	60
# Sensors per ladder	4	4	12	16	20	24
Material budget (% X_0)	0.3	0.3	0.6	0.6	0.6	0.6



Readout front-end of TJ-Monopix2

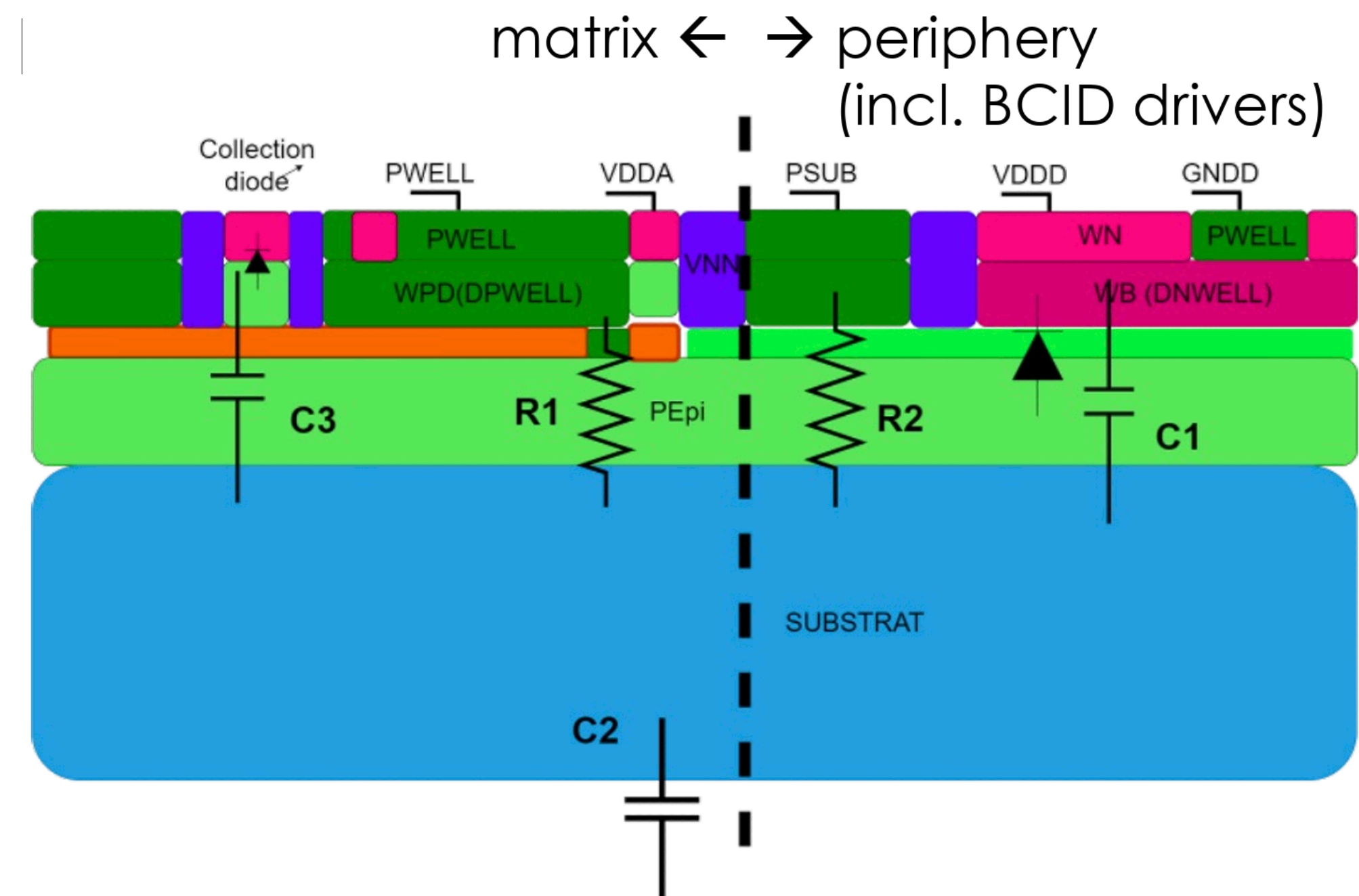
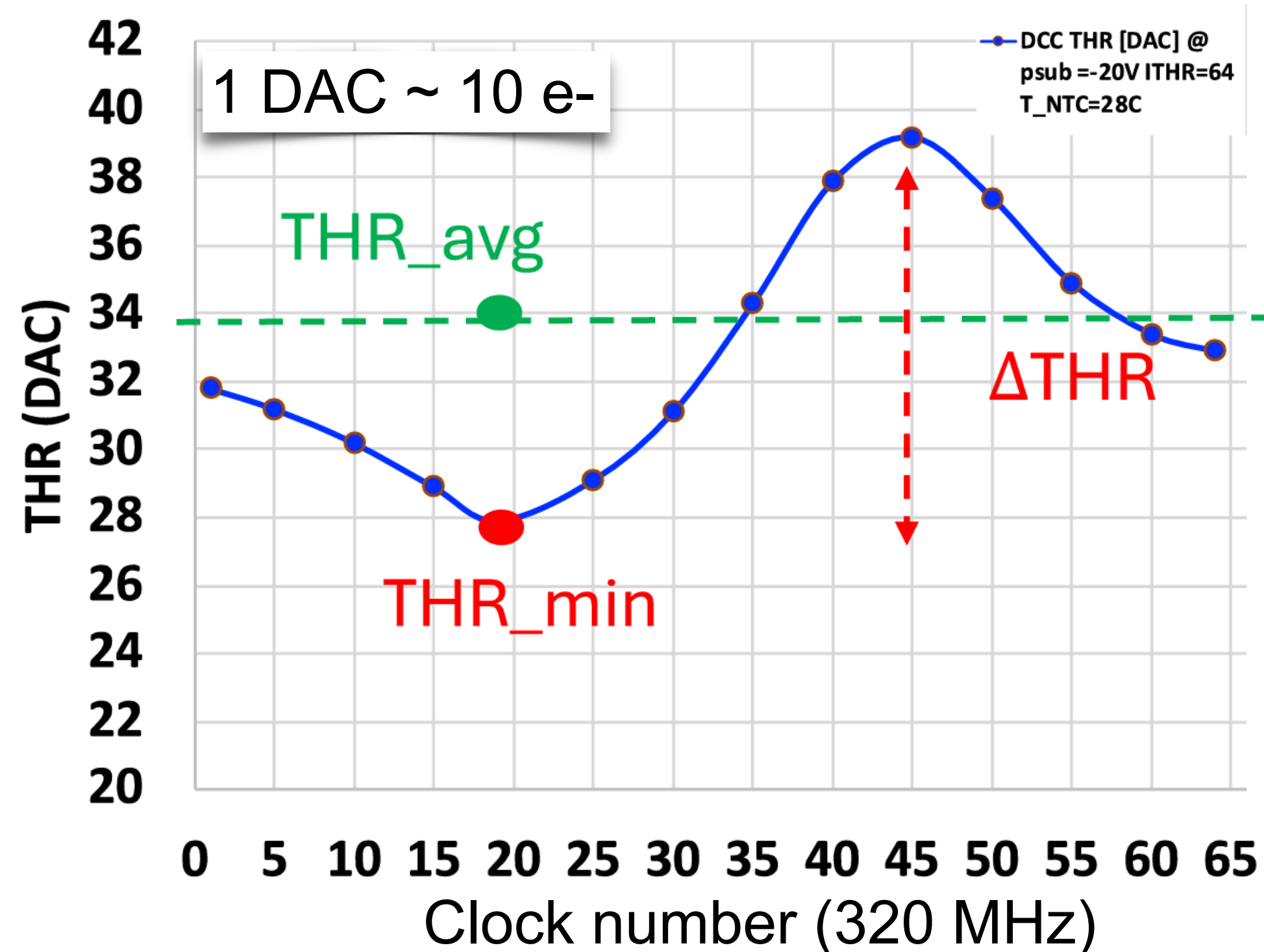
- ▶ **Components:**
 - ▶ Preamplifier (amplifier + shaper).
 - ▶ Discriminator.
- ▶ **Output:**
 - ▶ 7-bit Time Over Threshold (ToT) digital data.
- ▶ **Test signal.**
 - ▶ Injected by test capacitor.
 - ▶ In the unit of ΔDAC .



Voltage level configured by DAC value.

Threshold oscillation due to clock signal crosstalk

- ▶ Detection threshold oscillates with clock phase
 - ▶ Deviation of threshold is in the order of 100 electrons.
 - ▶ Deviation depends on the number of pixels, hence could be larger in OBELIX sensor.
 - ▶ **Resulting in clock phase-dependent detecting performance.**
- ▶ Originates from digital periphery
 - ▶ Digital fluctuation flows into substrate, coupling with front-end circuits through detector capacitor.
 - ▶ **Expected to be improved in OBELIX sensor.**



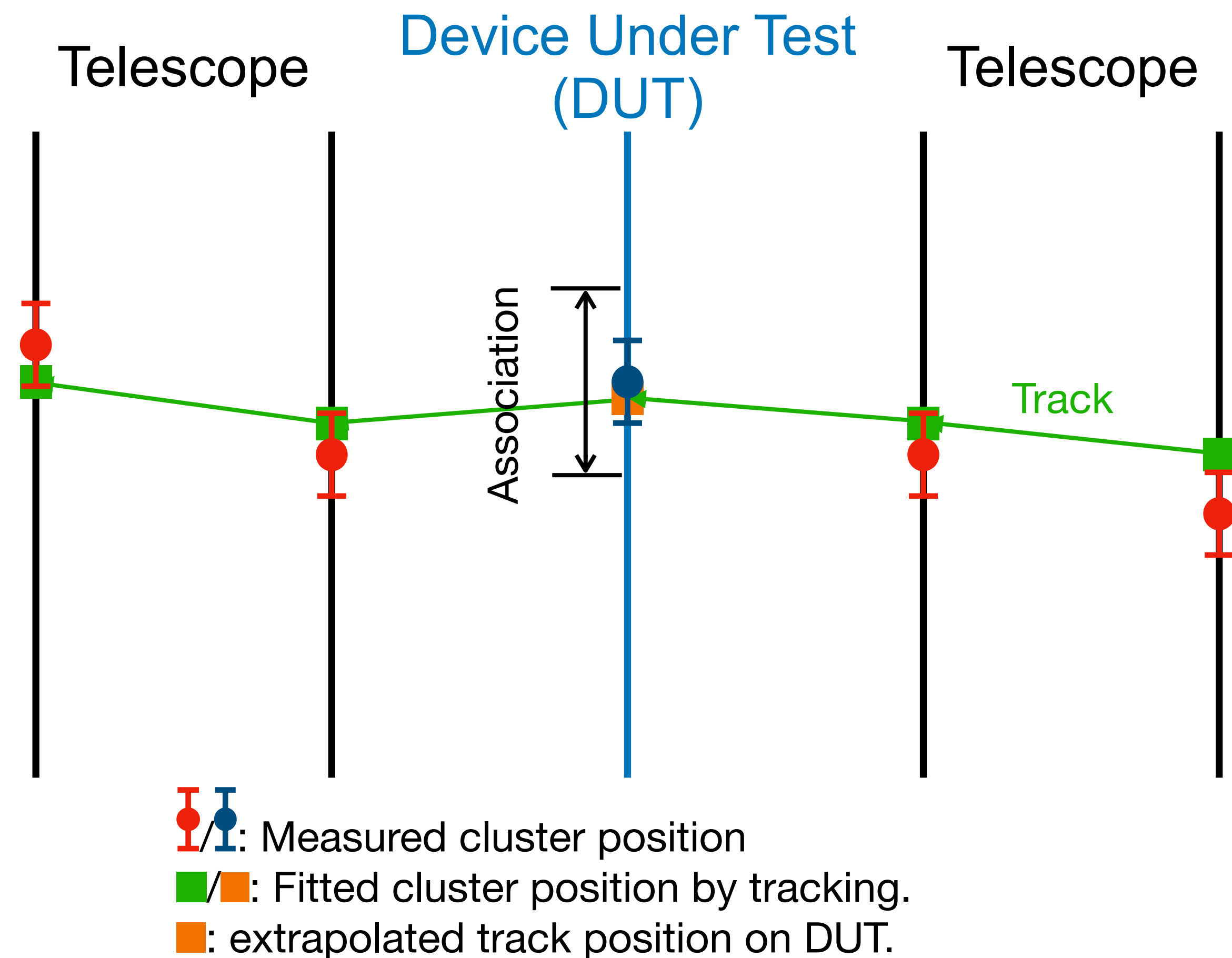
Test beam measurement

► Device components

- Telescope sensors reconstructing particle trajectories.
- Device under test (DUT).
- Trigger system to event-ize data.

► Track reconstruction using telescope hit data

- Global-broken-line model.
- Multiple scattering considered.
- A successful track means the confirmation of a particle passing through.



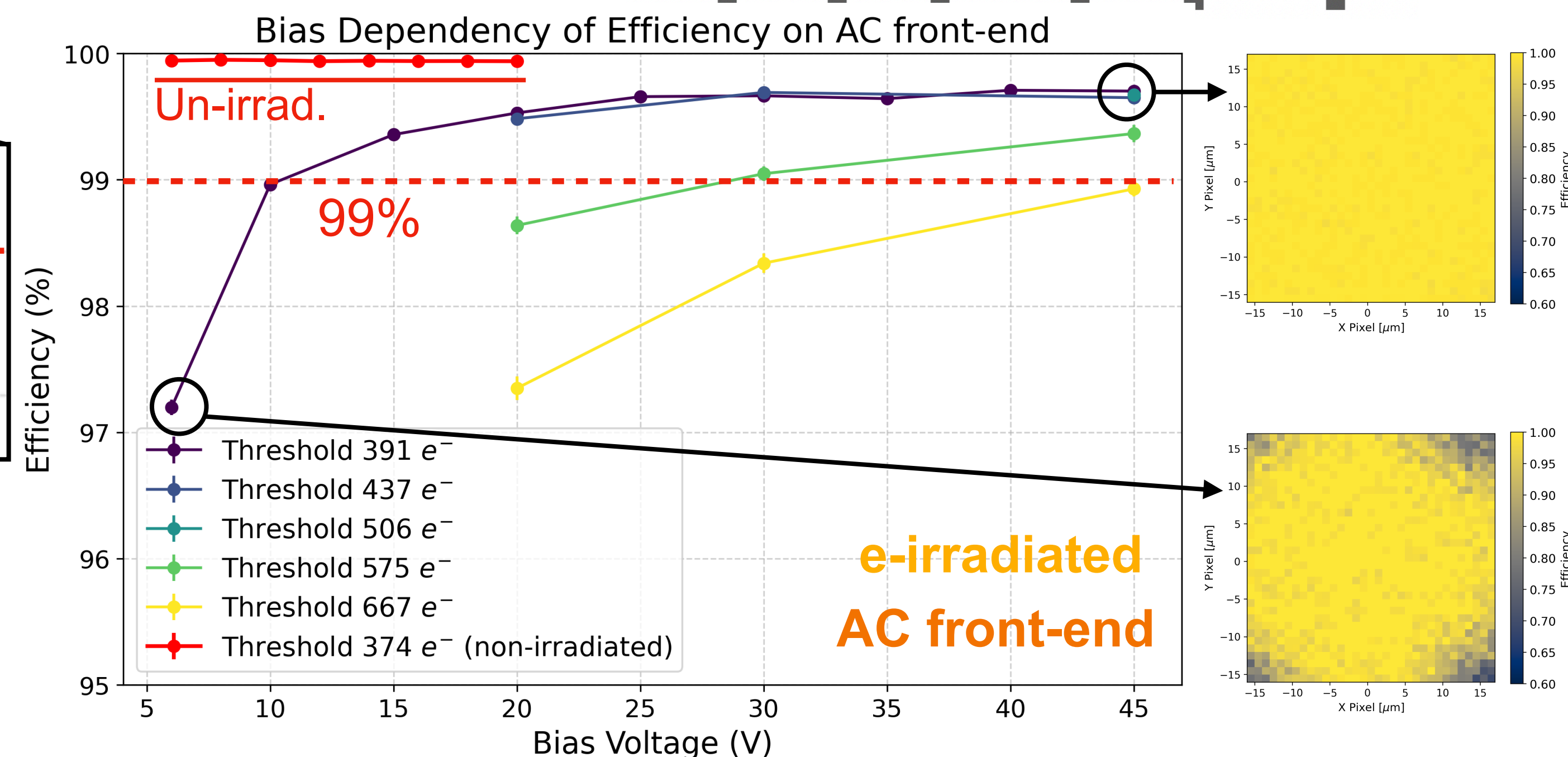
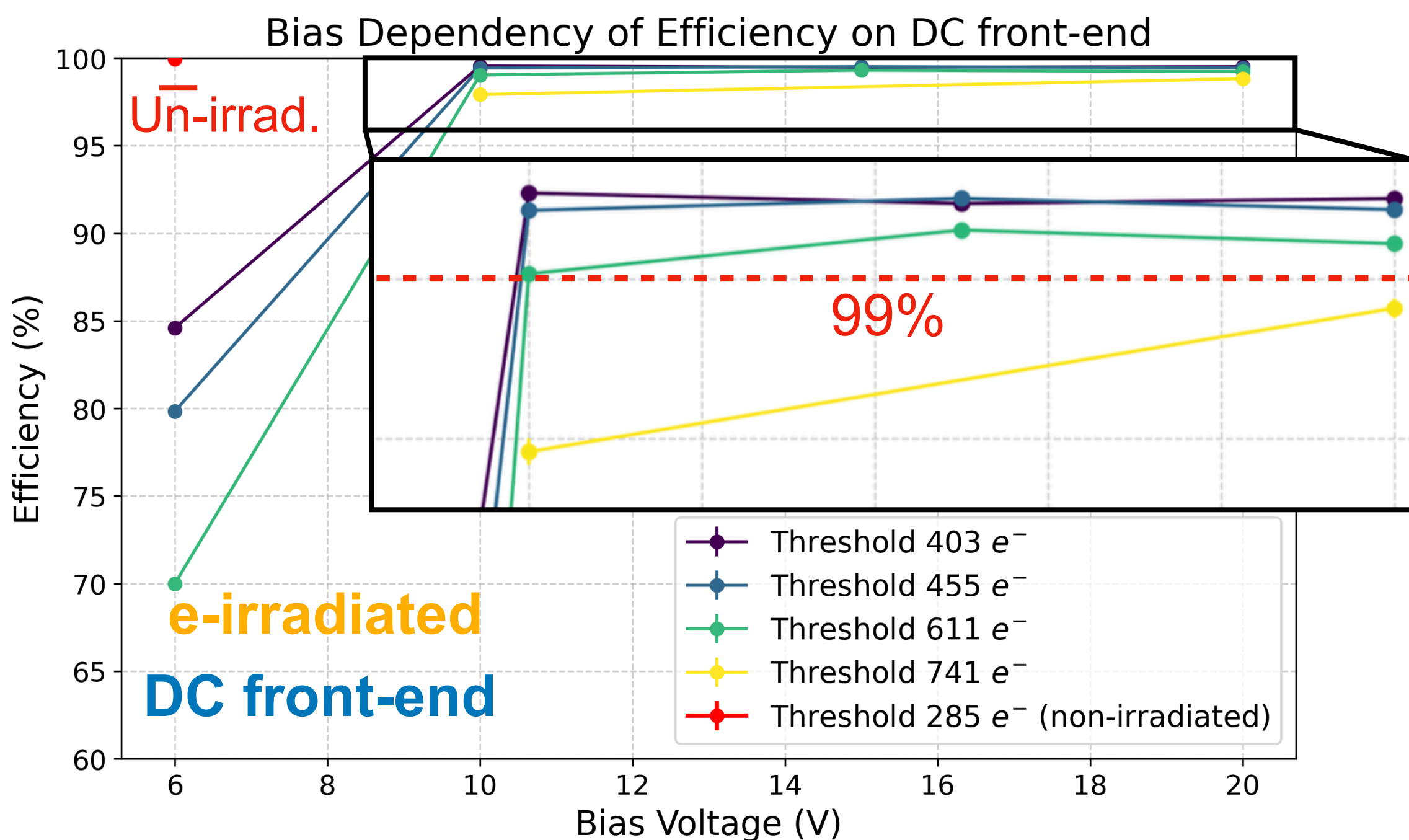
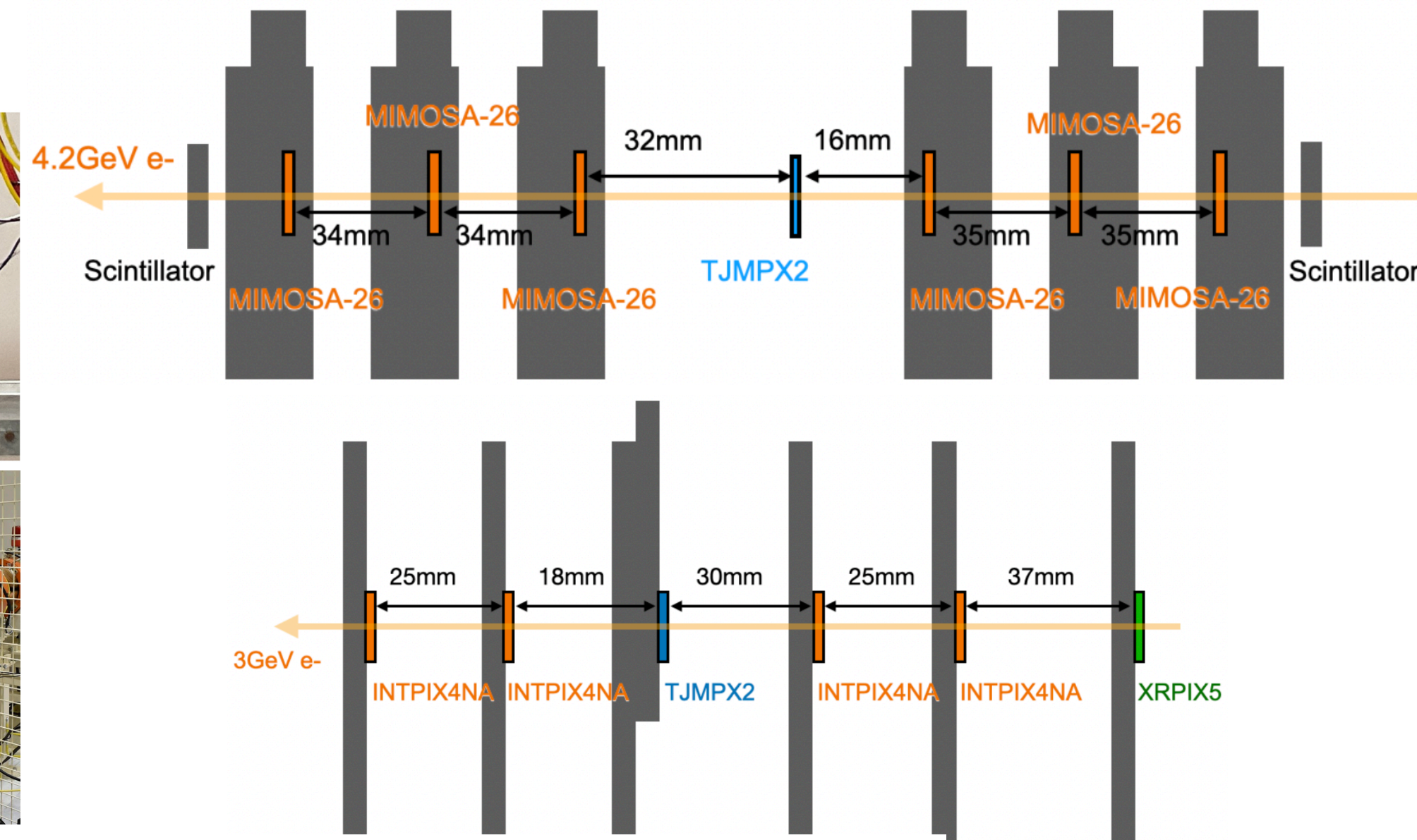
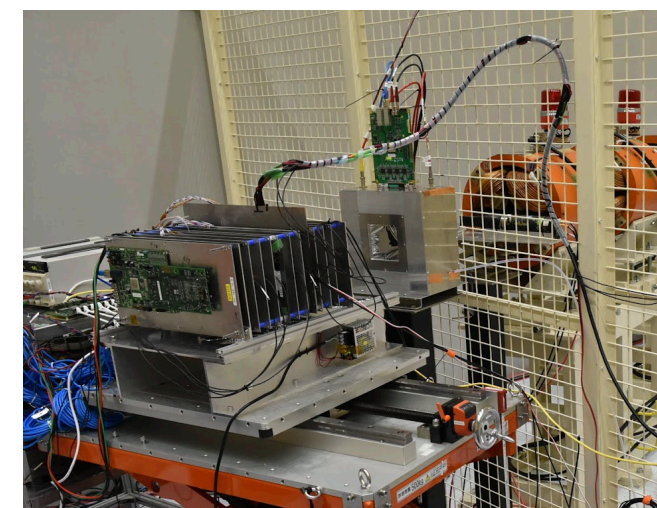
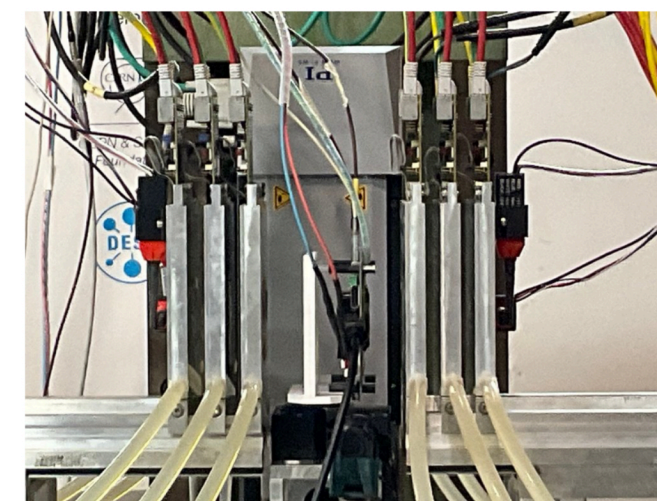
► Measurement result: detection efficiency

- **Association:** If  and  on DUT are close with each other, associate the track and  on DUT.
- **Detection efficiency:** $\epsilon = N_{\text{associated tracks}} / N_{\text{total tracks}}$

Confirm a particle using telescope → check if this particle is detected on DUT.

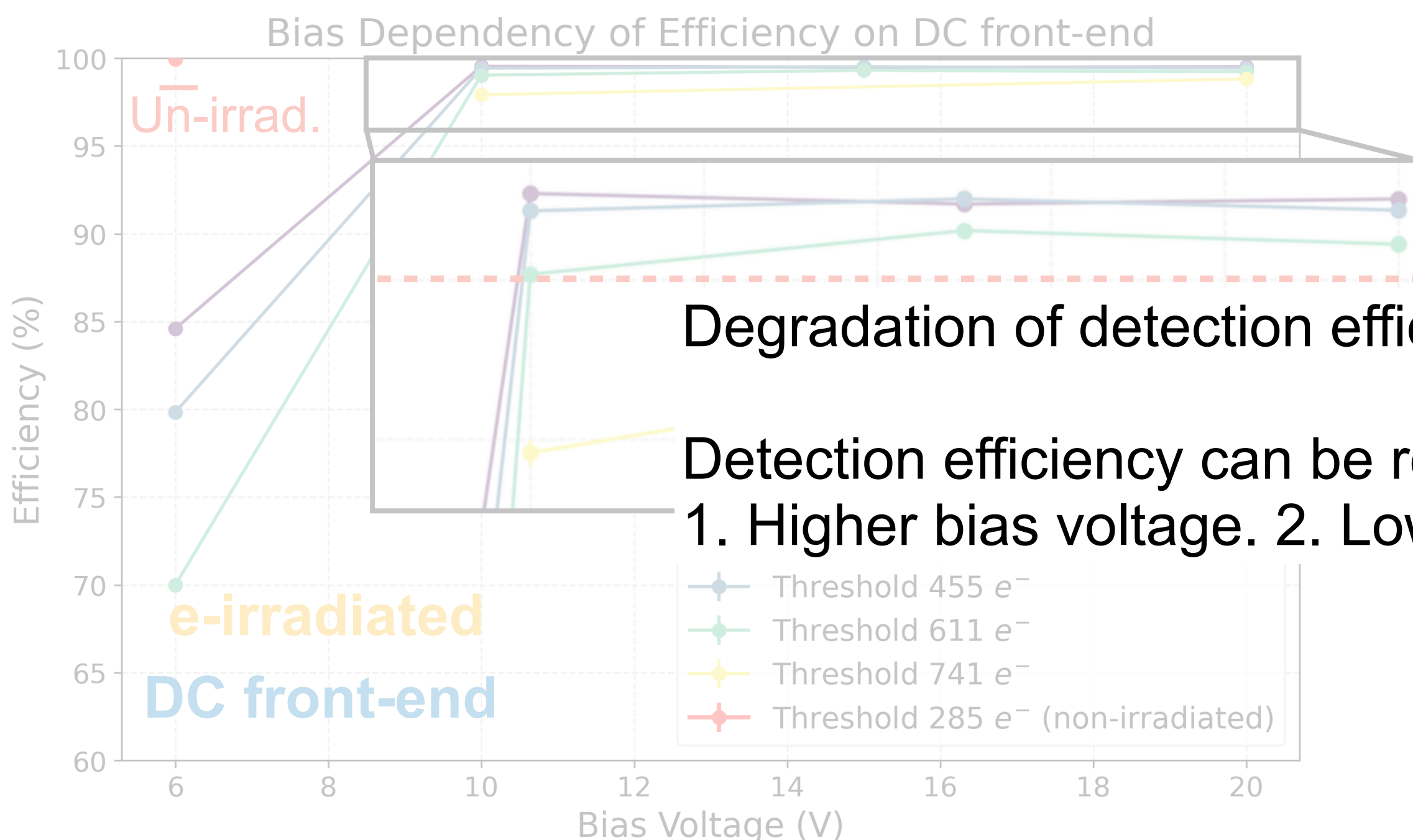
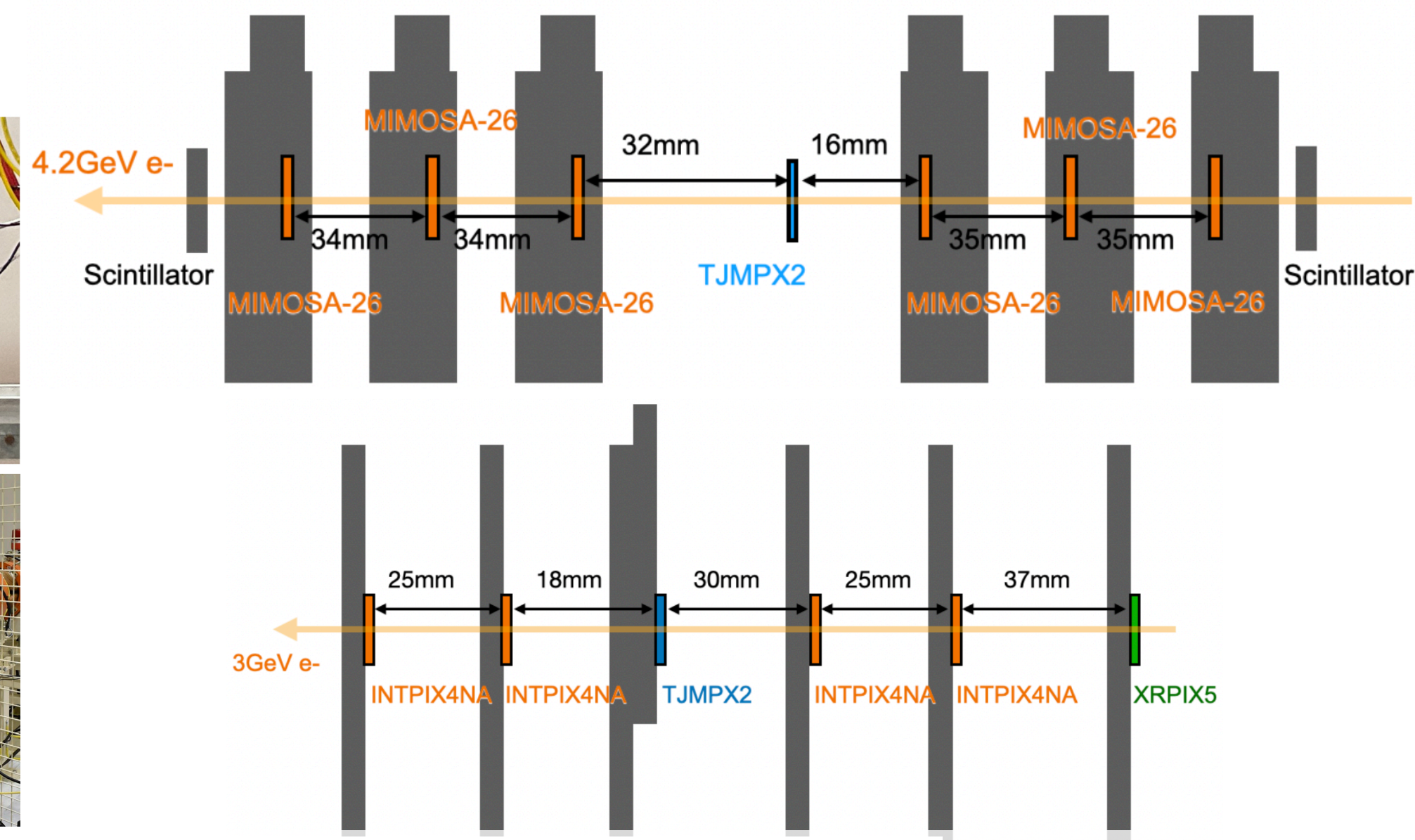
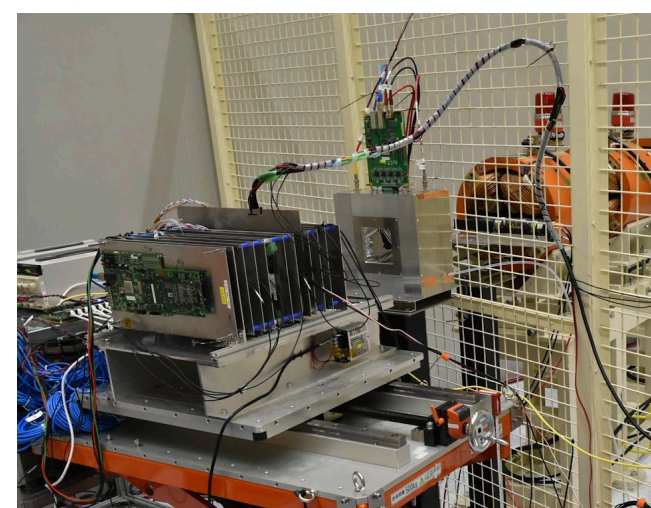
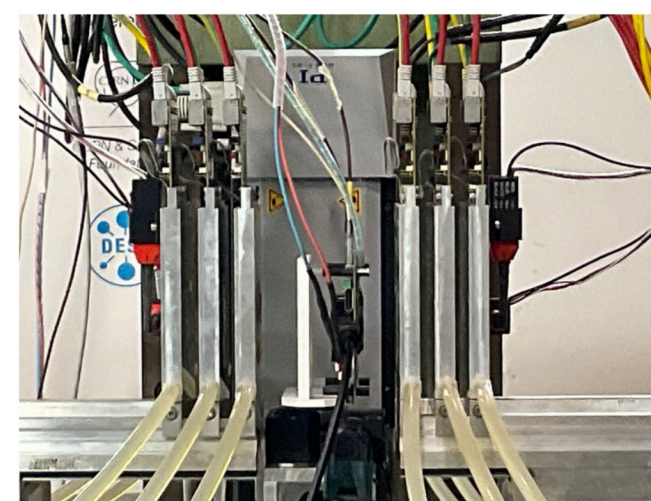
Test beam activities before and after irradiation

- Before irradiation: DESY II Test Beam Facility
 - 4.2 GeV electron beam.
 - EUDET telescope.
- After irradiation: KEK PF-AR Test Beam Line
 - 3 GeV electron beam.
 - SOI telescope.



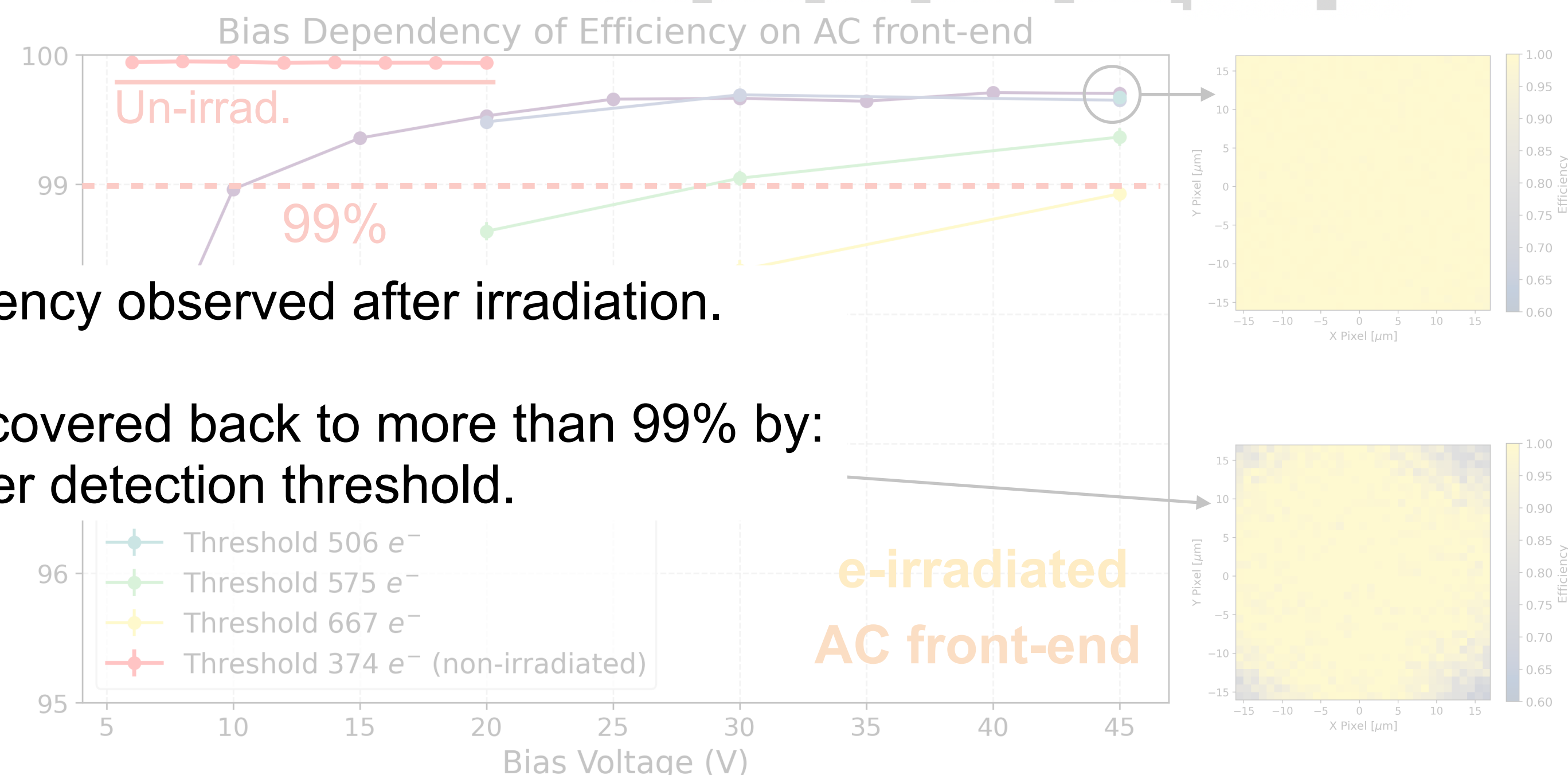
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- ▶ **After irradiation: KEK PF-AR Test Beam Line**
 - ▶ 3 GeV electron beam.
 - ▶ SOI telescope.



Degradation of detection efficiency observed after irradiation.

Detection efficiency can be recovered back to more than 99% by:
1. Higher bias voltage. 2. Lower detection threshold.



Fast discharge

- ▶ Threshold increase due to leakage current
 - ▶ Fast discharge causing early reset of signal.
 - ▶ Smaller signal duration for a certain amount of signal charge.
 - ▶ Effectively larger detection threshold.

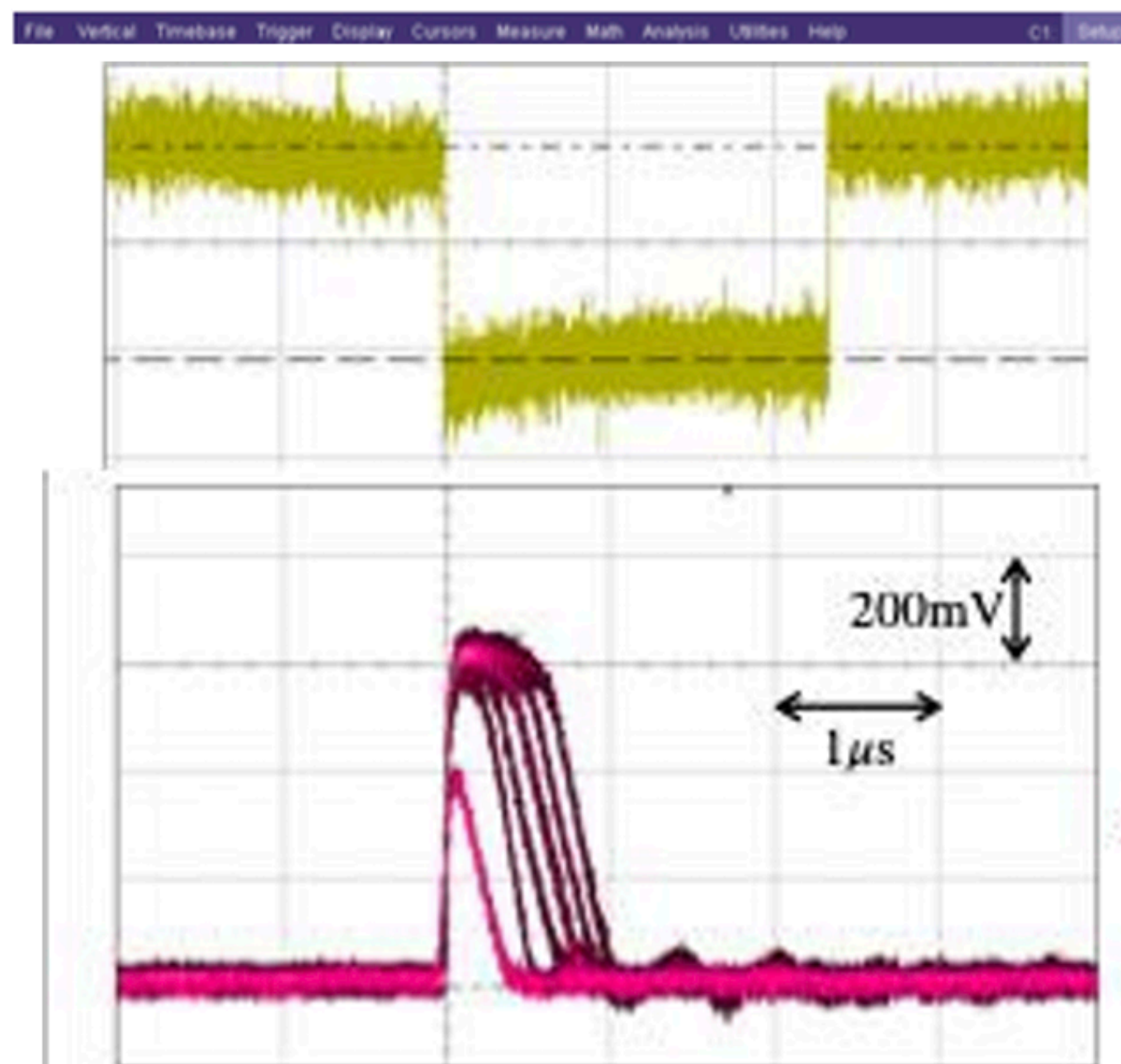
injection pulse



Not irradiated chip

V_{FE_IN} = sensor = ANAMON0

V_{OUT} = amp output = ANAMON1



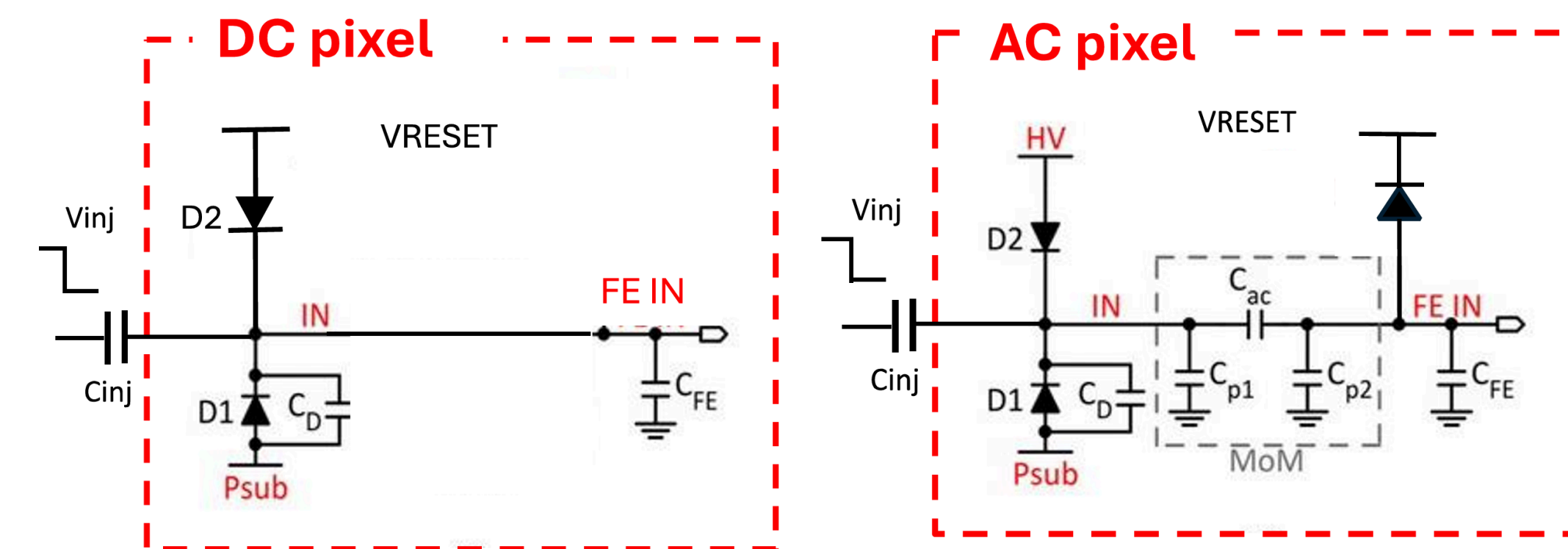
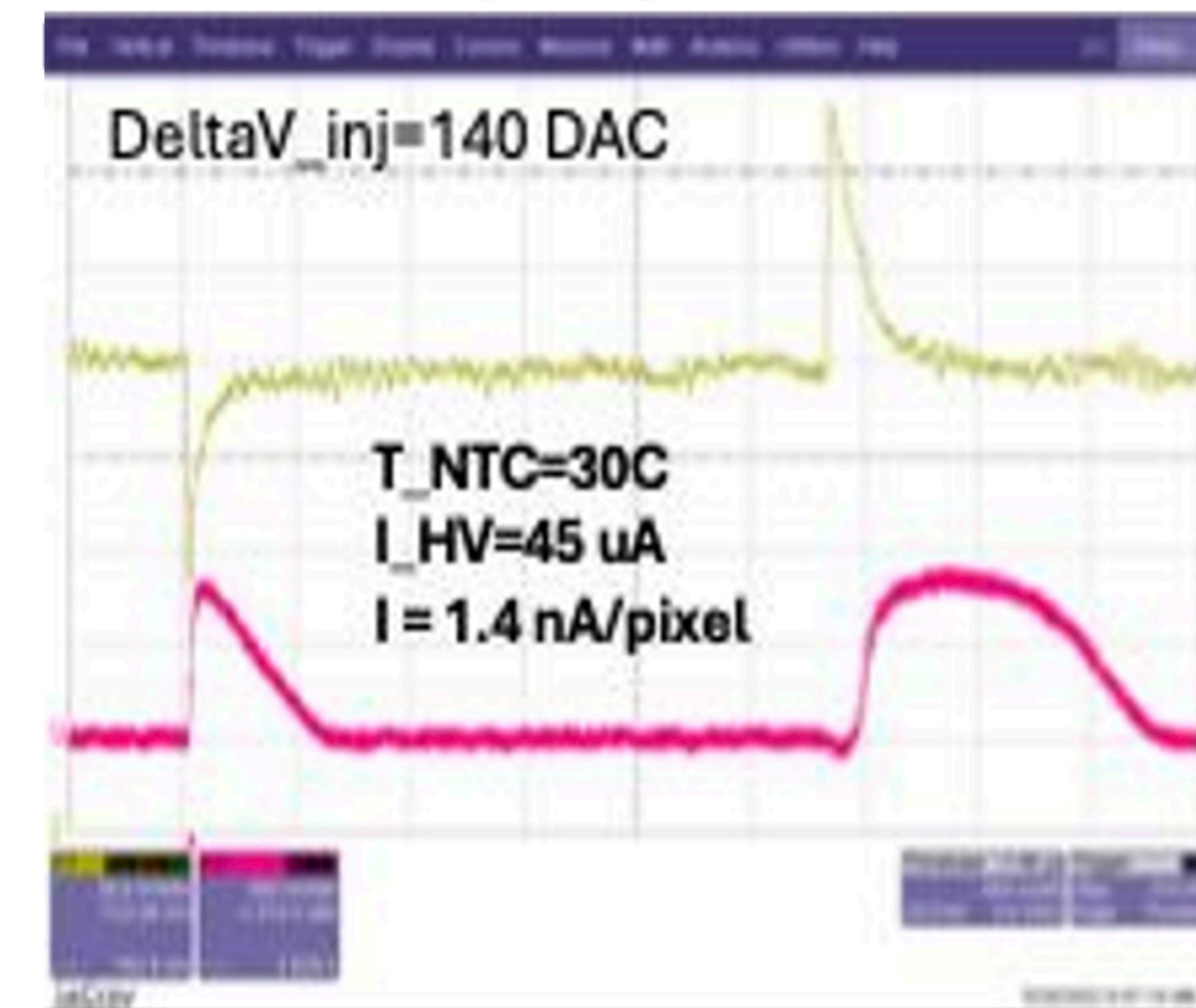
injection pulse



Irradiated chip

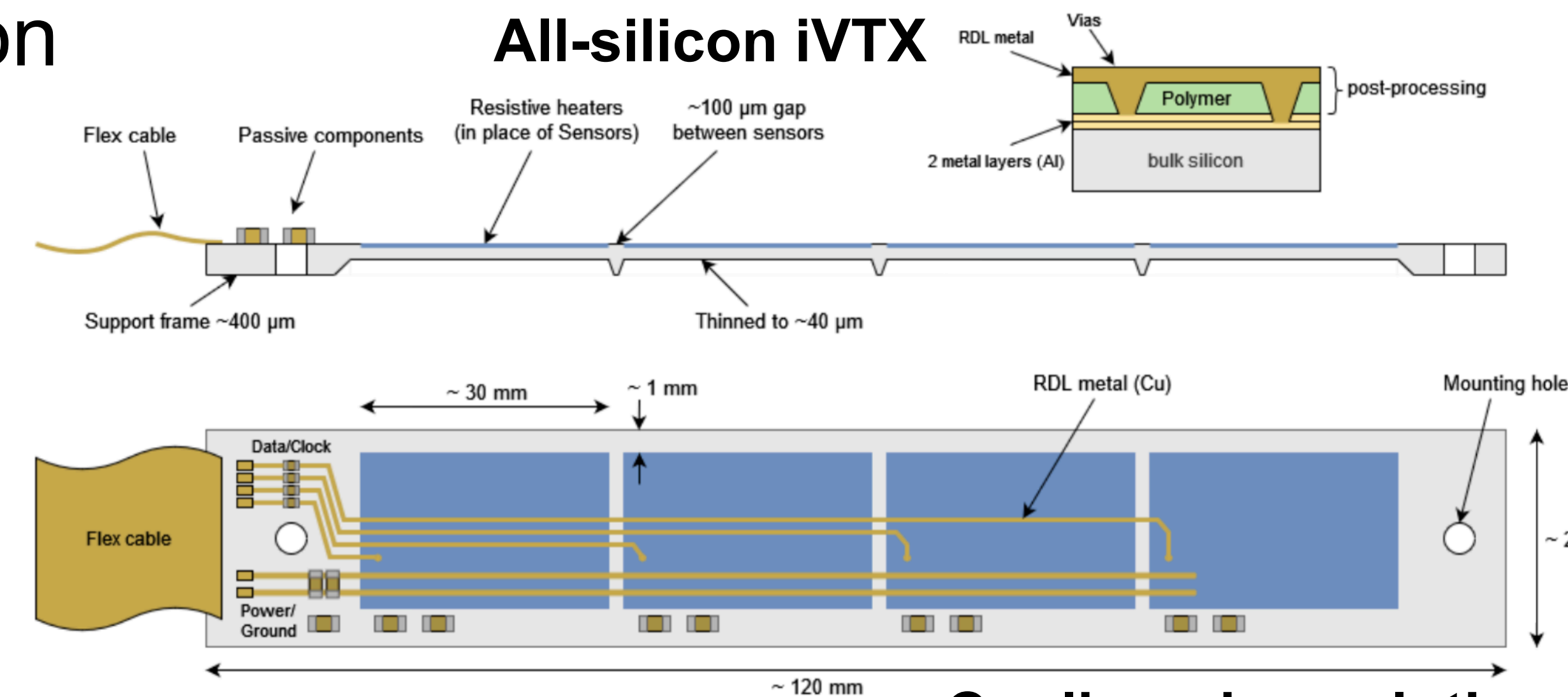
V_{FE_IN} = sensor = ANAMON0

V_{OUT} = amp output = ANAMON1



Cooling strategy of iVTX is under investigation

- ▶ **Initially preferred: air cooling**
 - ▶ Not enough or have small safety margin.
- ▶ **Thermal pyrolytic graphite (TPG) solution.**
 - ▶ TPG plate holding silicon layers.
 - ▶ Mediated by thermal interface.
 - ▶ 0.3% X_0 / ladder.
- ▶ **Cooling pipe solution.**
 - ▶ Liquid cooling.
 - ▶ 0.4% X_0 / ladder.



Cooling pipe solution

