CMOS MAPS development for Belle II vertex detector upgrade

-- OBELIX sensor for VTX project --

Katsuro Nakamura (KEK)

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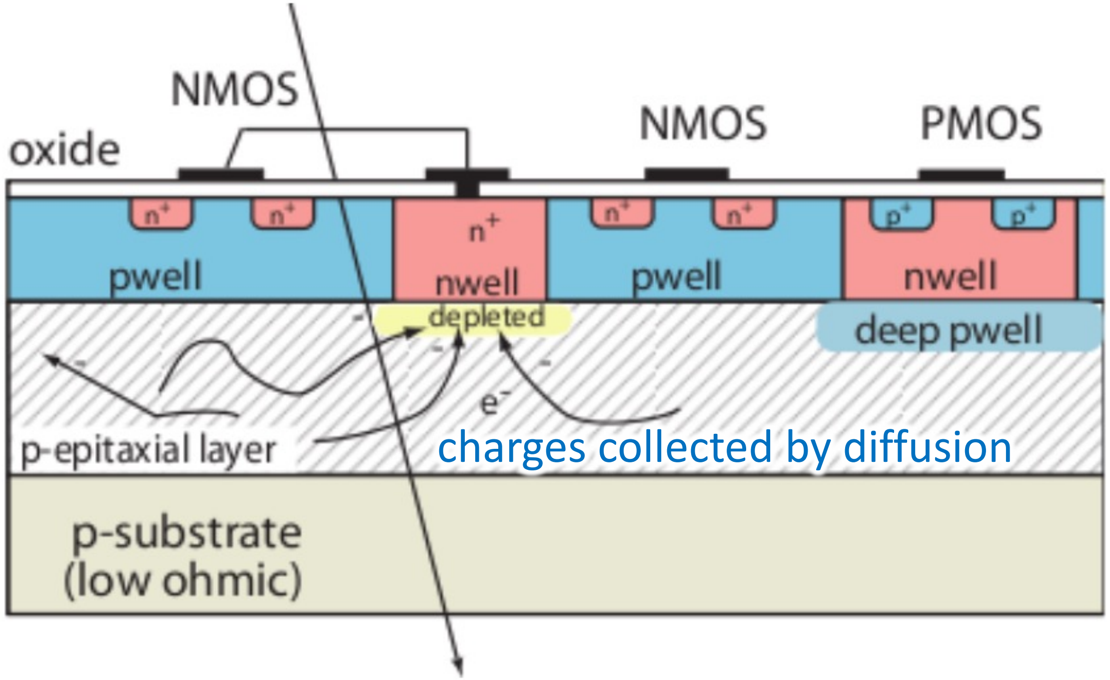
研究会「EICで展開する新たな原子核・素粒子物理」

CMOS Monolithic active pixel sensors (MAPS)

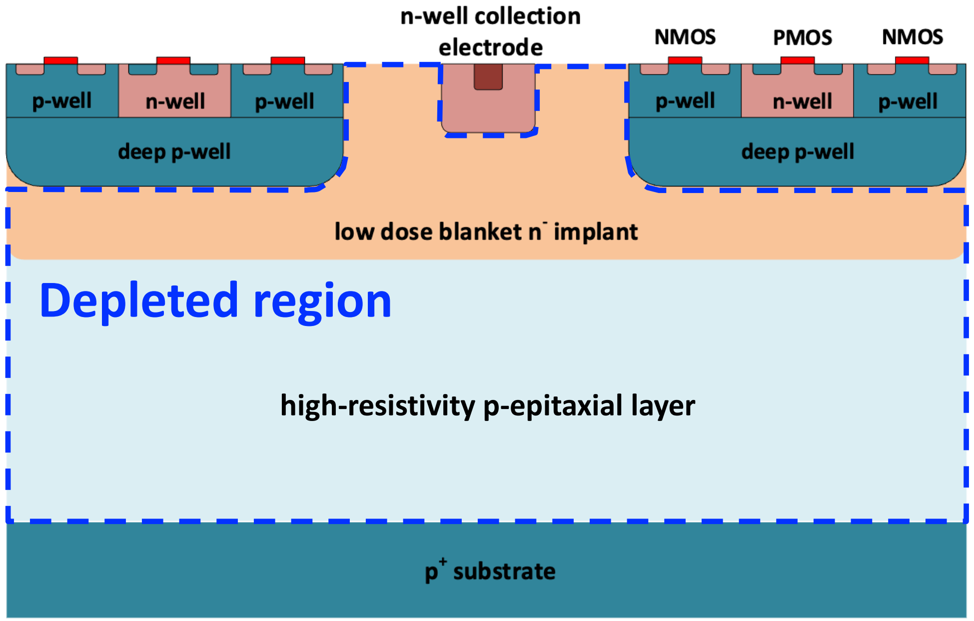
- **Monolithic Active Pixel Sensor (MAPS) based on CMOS imaging processes**
  - – Sensor: the epitaxial silicon layer grown on low-cost and low-ohmic substrate wafers
  - – Monolithic: full CMOS circuitry integrated into active area and periphery
  - – Because in standard CMOS technologies the allowed biasing voltages and epi-material resistivity are low, the depleted region is localized around the electrode.
  - – → Charge collection mainly by **diffusion** : slow and incomplete collection was bottleneck.
  - – Successfully used in lower hit rate and radiation level than LHC(p-p), like STAR and ALICE.
    - NIEL < 10^{13} n_{eq}/cm^2



Depleted Monolithic Active Pixel Sensor (DMAPS)

Depleted CMOS MAPS

- Improved CMOS technologies utilize high resistivity depleted silicon layers to achieve a depletion region underneath the collection electrode (typically about 20um)
- Charge collection by **drift** : Fast (~10ns) and efficient charge collection
- Small collection electrode: Small noise and low power consumption due to small C_{det}
- Low-dose n layer: full depletion with uniform electric field
- → High hit rate and radiation environment tolerance
  - NIEL ~ 10^{15} n_{eq}/cm^2 is achievable.

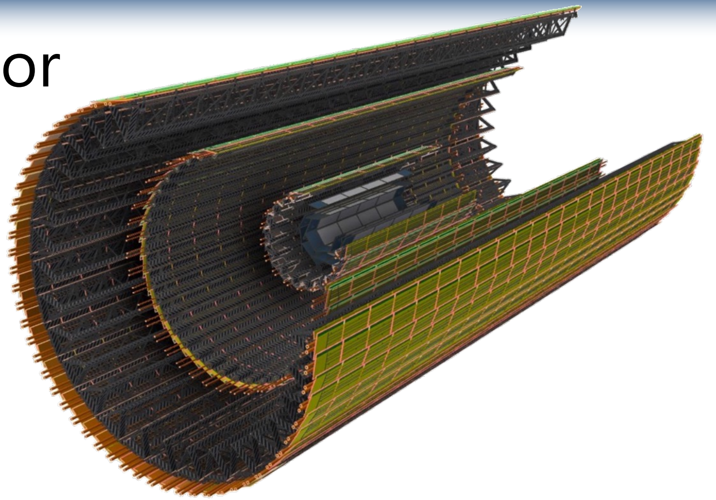


Belle II Vertex Detector Upgrade

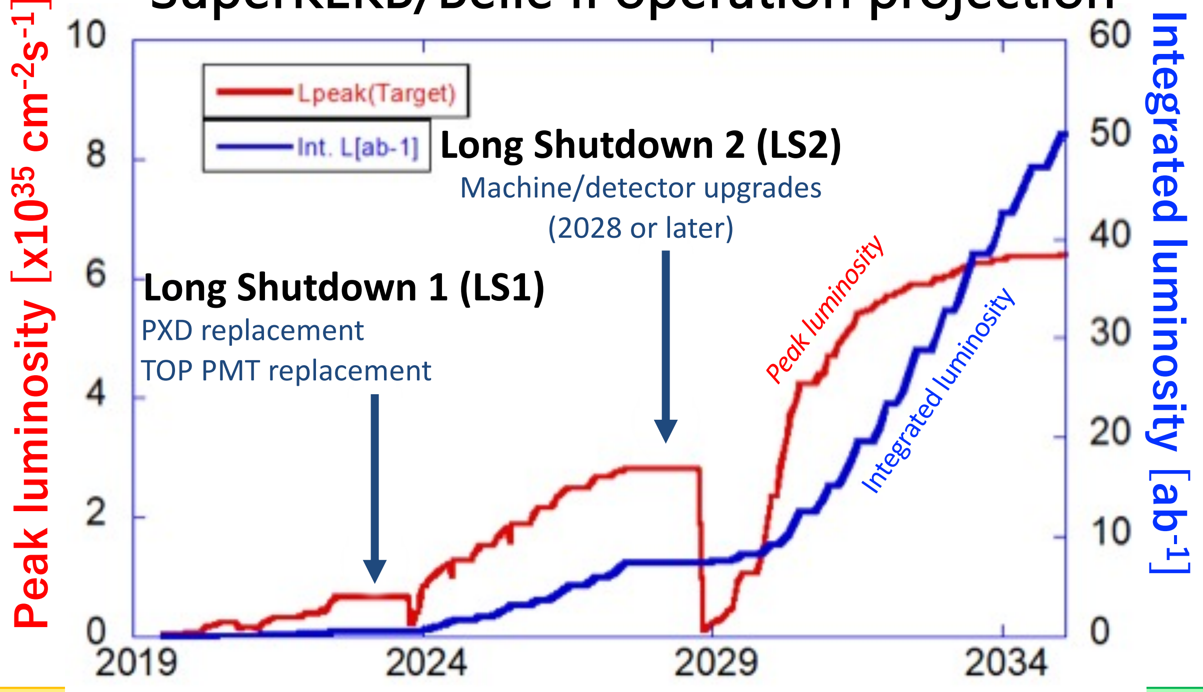
- **New vertex detector VTX: Fully pixelated 5-layer detector, using CMOS MAPS**
  - Higher space-time granularity
  - Small material budget: about 2.4%X_0
- **Target installation timescale is LS2 for SuperKEKB machine upgrade.**
  - Still, detailed plans for LS2 are under discussion

- **Thin DMAPS sensor: Optimized BELle II pIXel (OBELIX) chip**
  - New sensor for Belle II vertex upgrade
  - TowerJazz 180nm
- **OBELIX matrix design is based on TJ-Monopix2 for HL-LHC ATLAS**
  - Implementing new digital periphery and trigger logic for Belle II
  - Detailed performance characterization of TJ-Monopix2 is crucial for OBELIX design

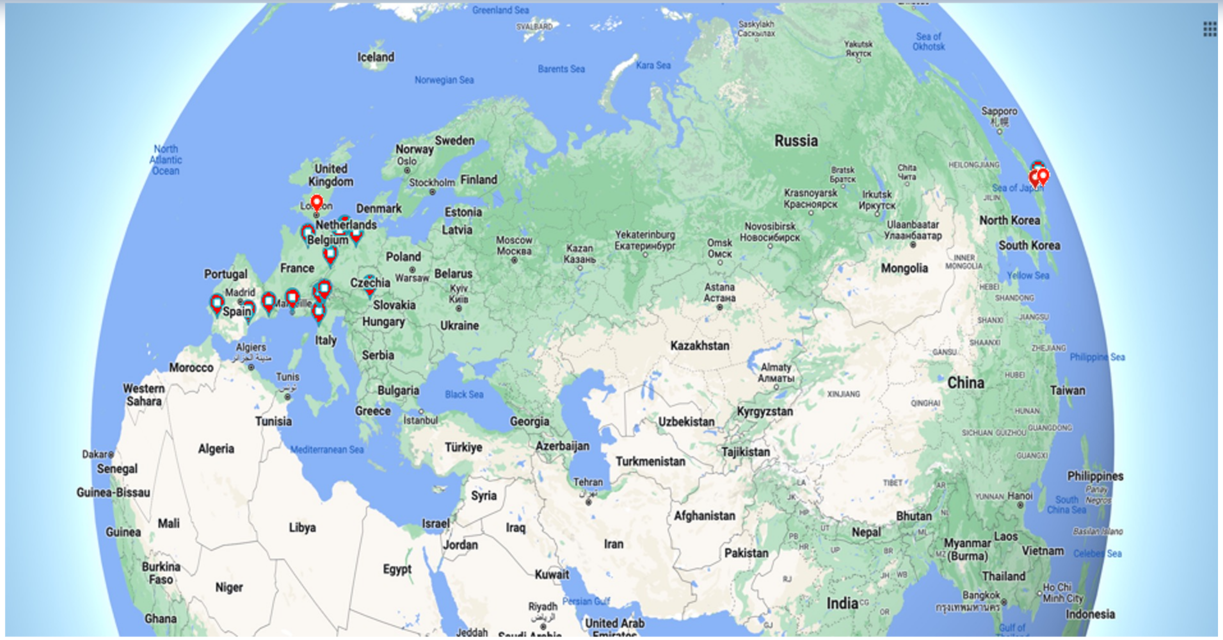
VTX detector



SuperKEKB/Belle II operation projection



VTX project: DMAPS development for Belle II upgrade

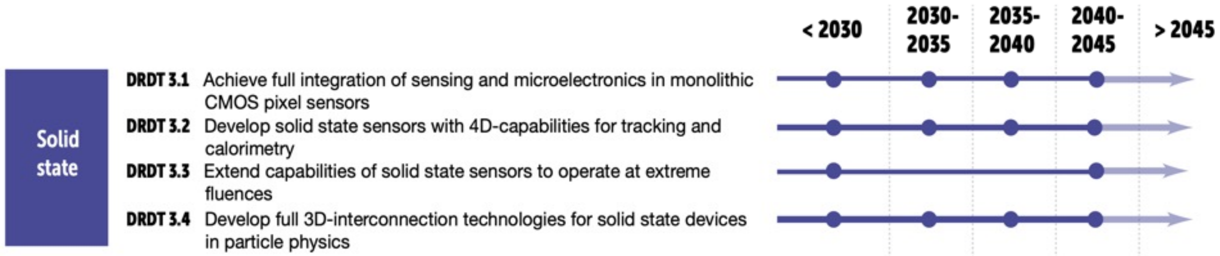


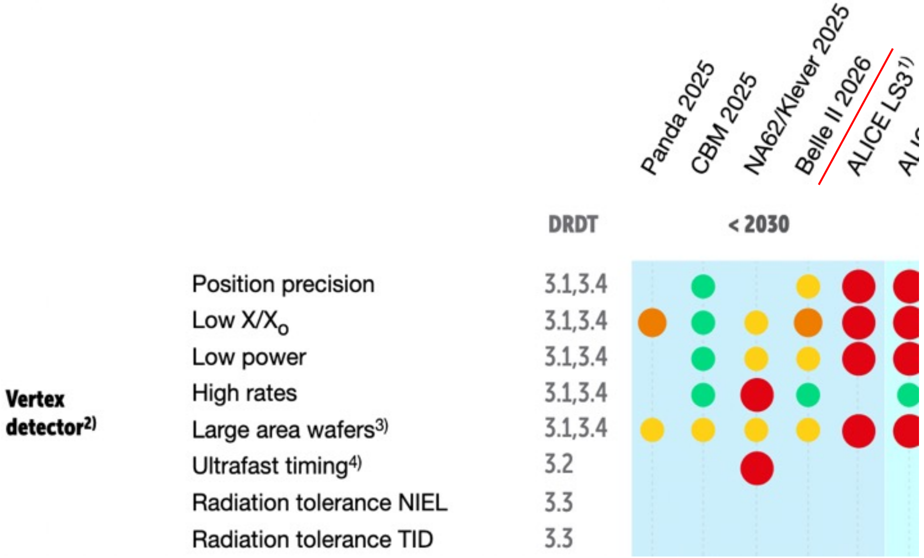
VTX collaboration

HEPHY (Vienna)
CPPM (Marseille)
IJCLab (Orsay)
IPHC (Strasbourg)
University of Bonn
University of Dortmund
University of Goettingen
KIT (Karlsruhe)
KEK (Tsukuba)
University of Tokyo
IPMU (Kashiwa)

University of Bergamo
INFN & University of Pisa
INFN Pavia
IFAE (Barcelona)
IMB-CNM-CSIC (Barcelona)
IFCA (CSIC-UC) Santander
IMSE-CNM-CSIC (Seville)
IFIC (CSIC-UV) Valencia
ITAINNOVA (Zaragoza)
QMU (London)

- **MAPS in the ECFA Roadmap (DRDT3.1)**
  - Identified as critical to achieve the science program outlined in European Strategy for Particle Physics





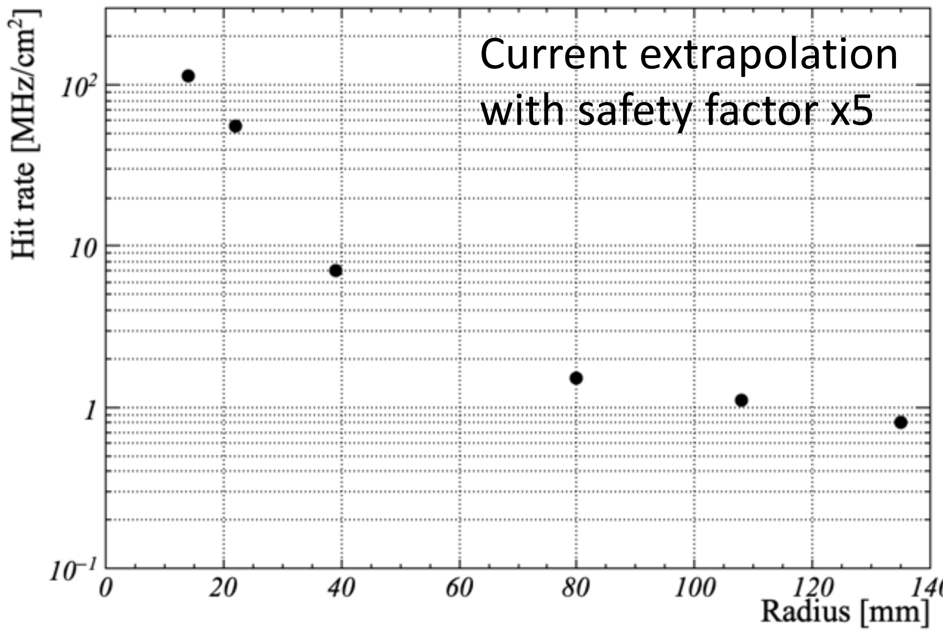
Requirements for the VXD upgrade

Targets

Radius range	14 – 135 mm
Tracking & Vertexing performance at least as good as current VXD	
Single point resolution	< 15 um
Material budget per layer	~0.2% X_0 (inner), ~0.8% X_0 (outer)
Hit time resolution	< 100 ns
Robustness against radiation environment current extrapolation with safety factor x5	
Hit rate(*)	~ 120 MHz/cm^2
Total Ionizing Dose(*)	~ 0.1 MGy/year
NIEL fluence(*)	~ 5.0 × 10^{13} n_{eq}/cm^2/year

(*) requirement for the innermost layer (R=14mm)

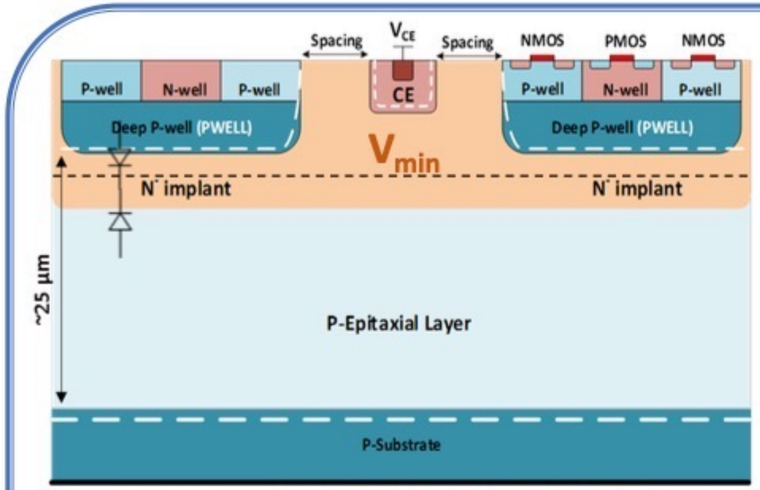
Required hit rate tolerance vs. Radius



Possible other improvements by upgrade

- Impact parameter resolution
- Tracking performance for low-p_T tracks
- Longer trigger latency
- Capability of Level-1 trigger creation

TowerJuzz Monopix-2 (TJ-Monopix2)



W. Snoeys et al. https://doi.org/10.1016/j.nima.2017.07.046

$$C_d \leq 3fF$$

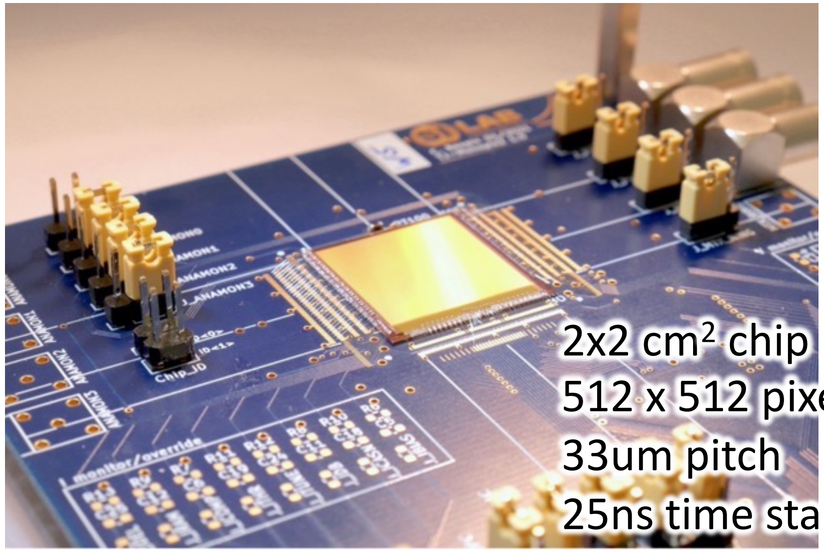
$$P \approx \frac{S}{N} \approx \frac{Q}{C_d}$$

DMAPS in TJ 180 nm: Concept

- Small sensor capacitance (Cd)
  - Key for low power/low noise
- Radiation tolerance challenges
  - Modified process
  - Small pixel size
- Design challenges
  - Compact, low power FE
  - Compact, efficient R/O

W. Snoeys et al.: NIM A 871 (2017) 90

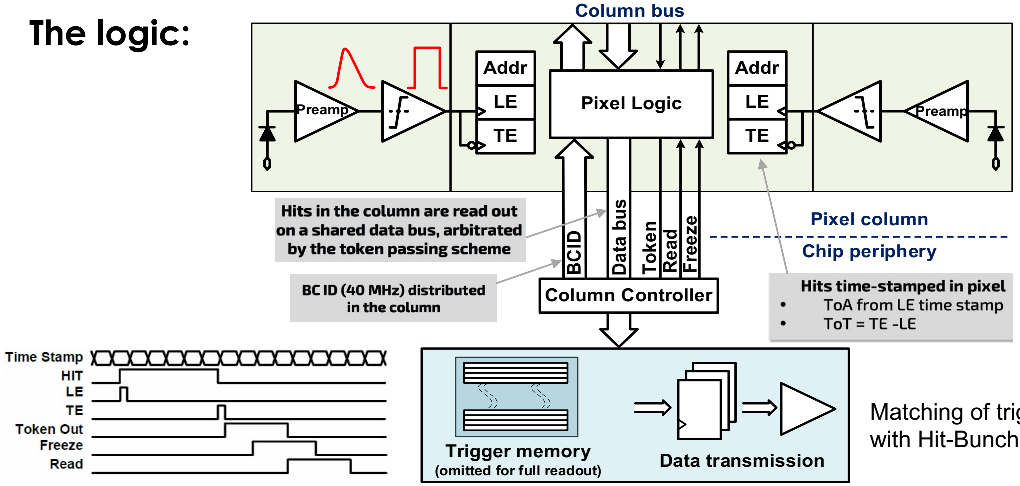
TJ-Monopix2 sensor



2x2 cm^2 chip
512 x 512 pixels
33um pitch
25ns time stamping

- **TJ-Monopix2 sensor: developed for HL-ATLAS**
  - DOI: 10.1016/j.nima.2020.164403
  - 7-bit ToT, 3-bit in-pixel threshold tuning
  - Column-drain read-out inherited from ATLAS FE-I3
  - Detection efficiency assessed up to 10^{15} neq/cm^2

The logic:

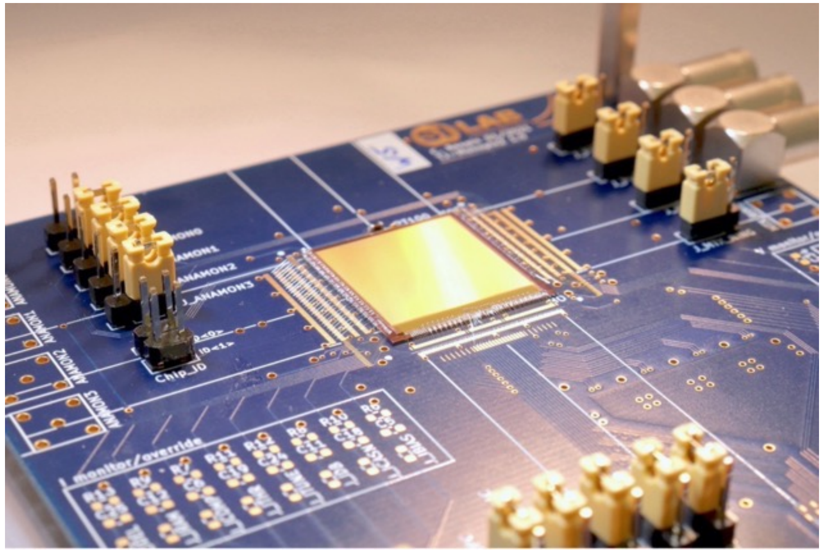


Matching of trigger-ID with Hit-BunchCrossingID

K. Moustakas: CERN-THESIS-2021-146

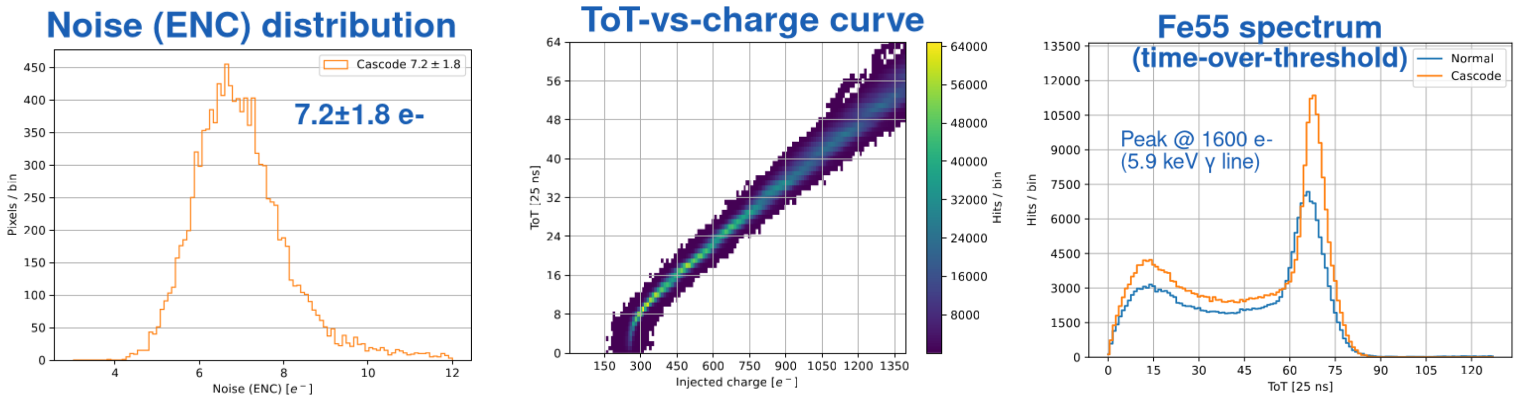
TJ-Monopix2 Performance Characterization

TJ-Monopix2 sensor

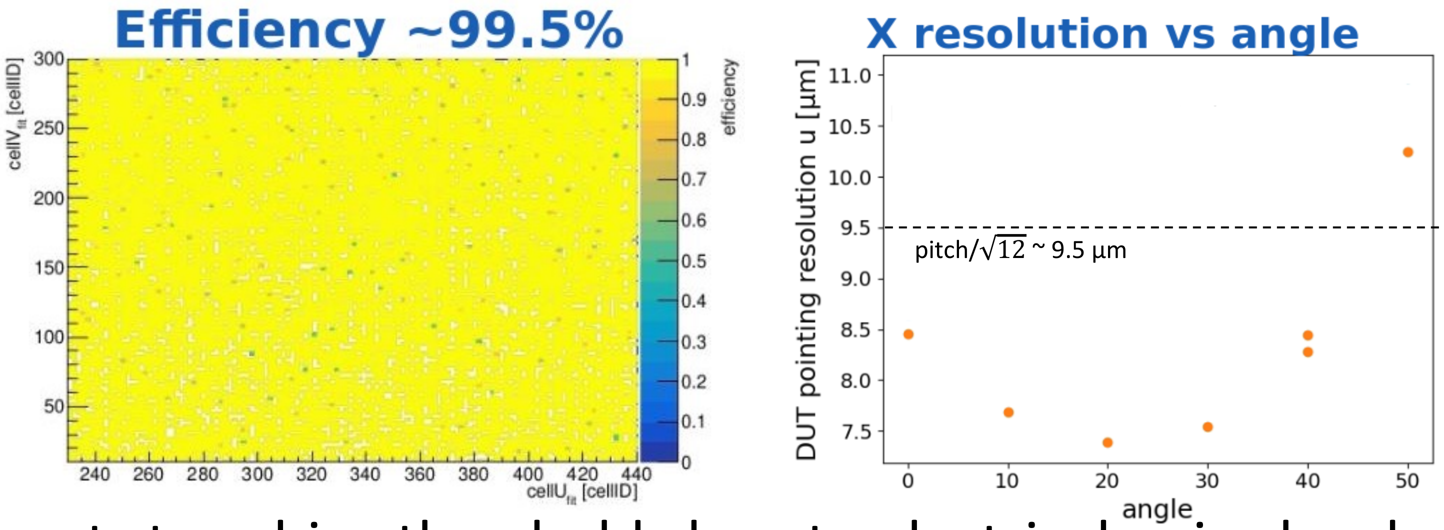


- **Detailed performance characterization of TJ-Monopix2**
  - Laboratory testbench test
  - Several beam tests
- **Including irradiated samples**
  - High efficiency even w/ 5×10^{14} n_{eq}/cm^2

Lab-testbench measurement



DESY electron beam measurements



- Cross-talk from FREEZE singal prevents to achive threshold close to electrical noise level
- Bonding issues while preparing new test modules: → Currently, ~30% success rate

TJ-Monopix2 test setup in KEK

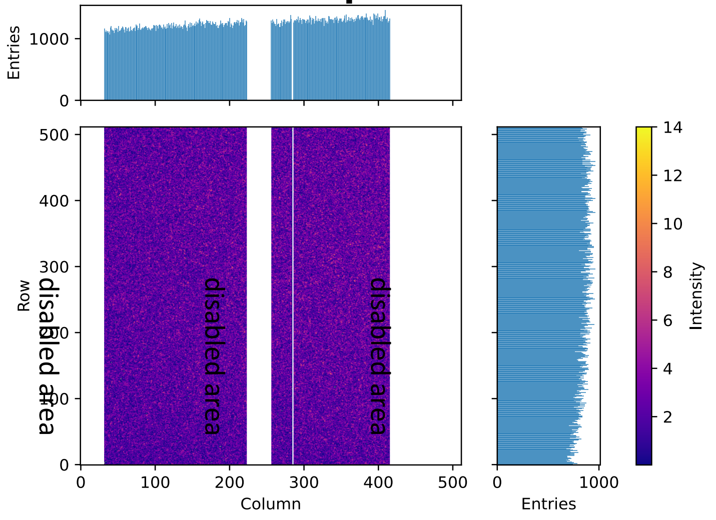
- **Test bench in KEK Fuji Hall B1 floor.**
  – Supported by KEK ITDC
- **In Japan, KEK, UTokyo, ICEPP, IPMU contribute to characterisation of the TJ-Monopix2 chip.**

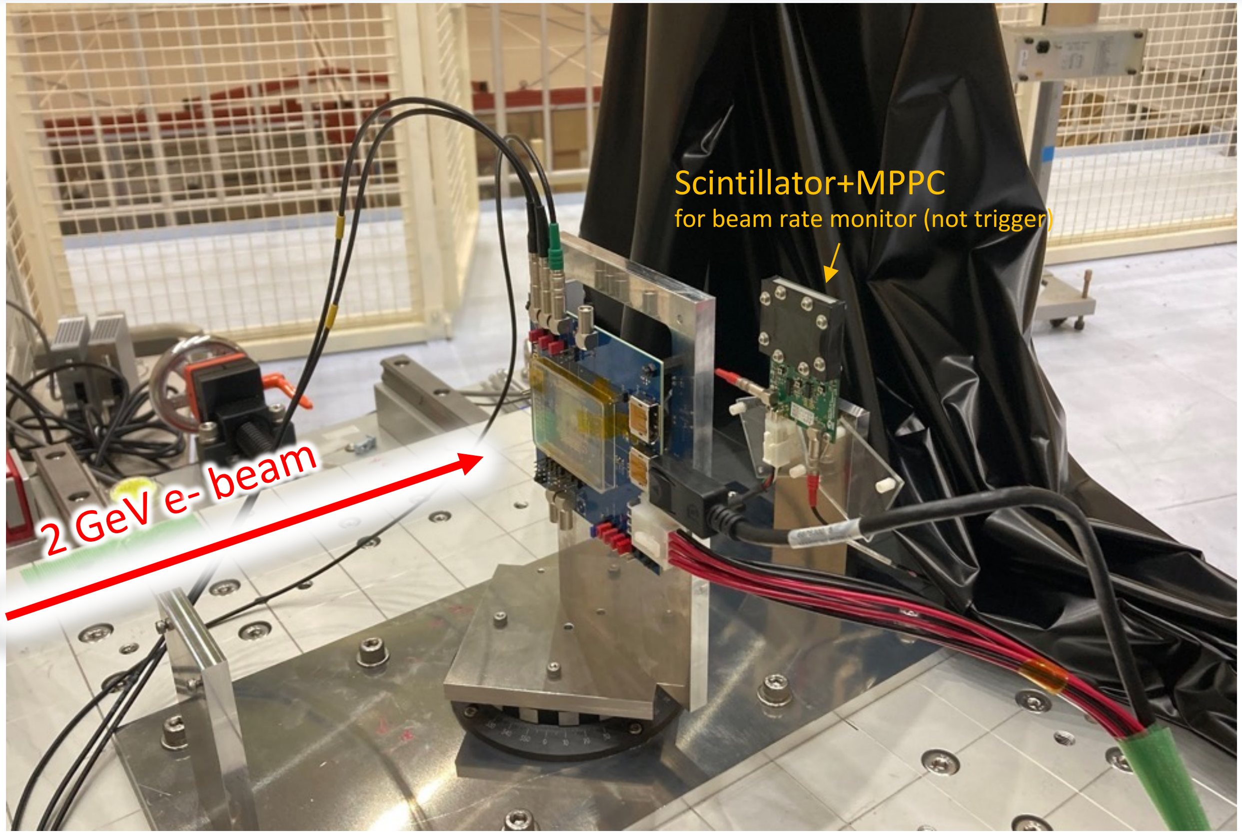
Test in KEK PF-AR electron testbeam line

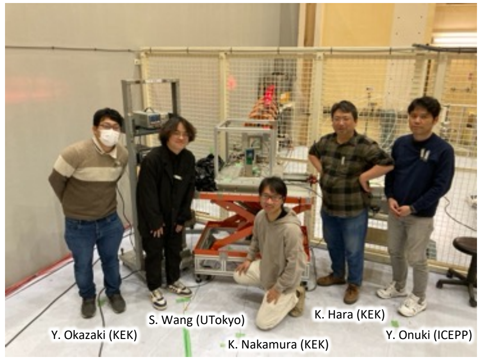
- **KEK PF-AR e- beam (2-5 GeV)**
  - New MAPS performance test hub in Japan

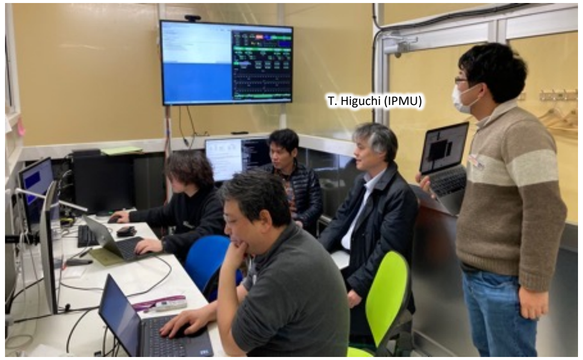
- **Tested a TJ-Monopix2 chip in the beamline on Mar 2024 as a start-up**
  - cluster size measurement with different incident angles
    - → evaluate depletion layer depth

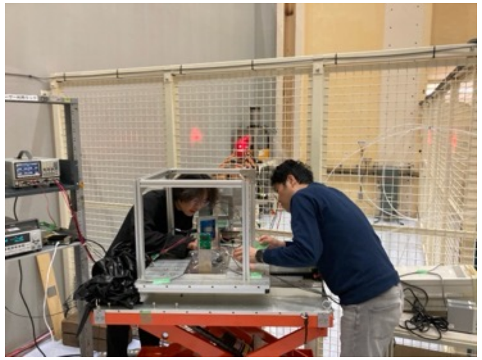
Hit Map Distribution





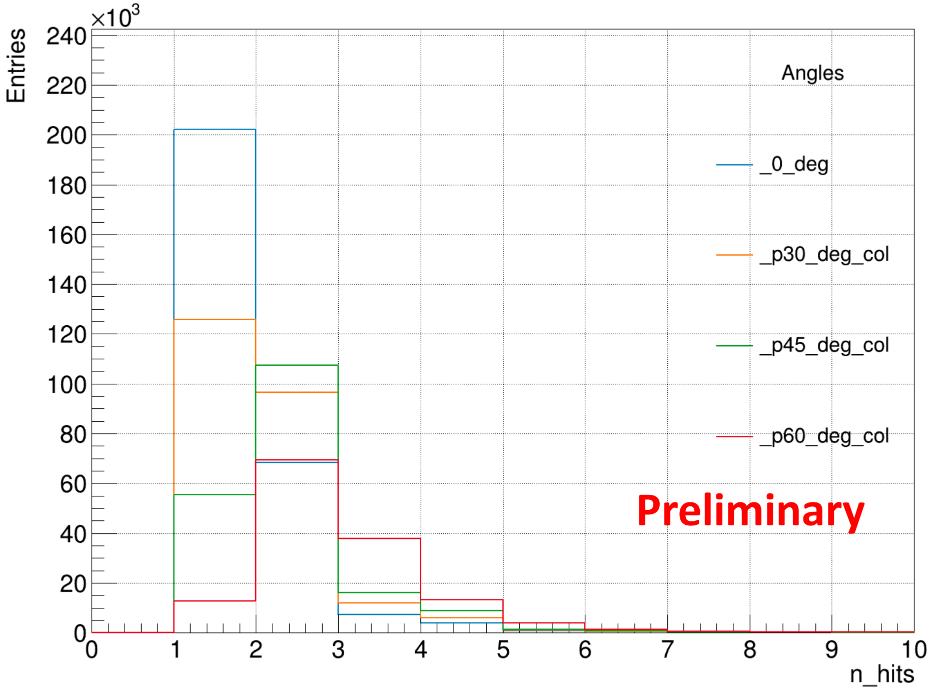




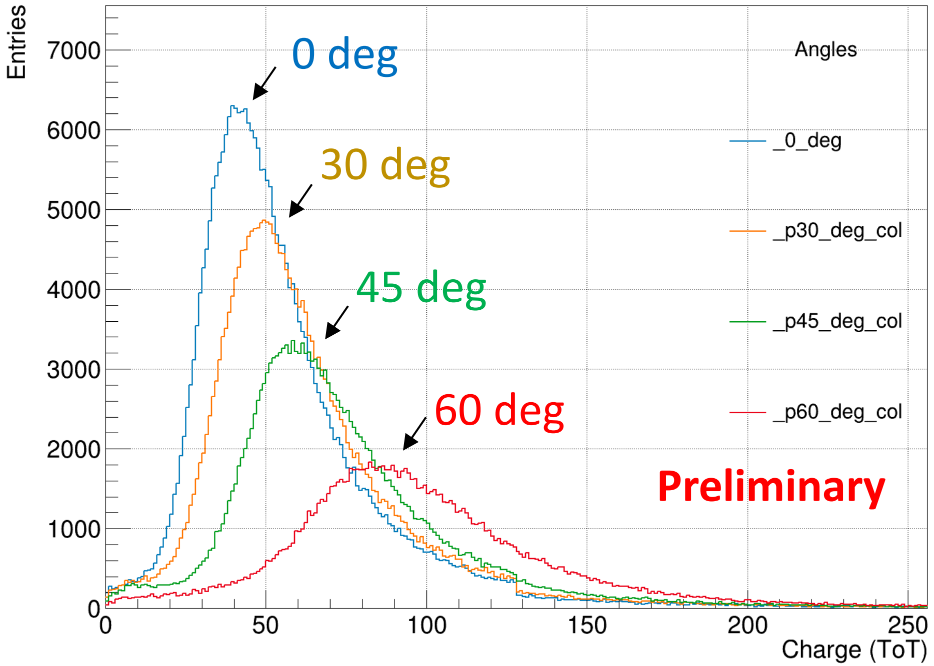


Preliminary test results

Cluster size (# of pixels)



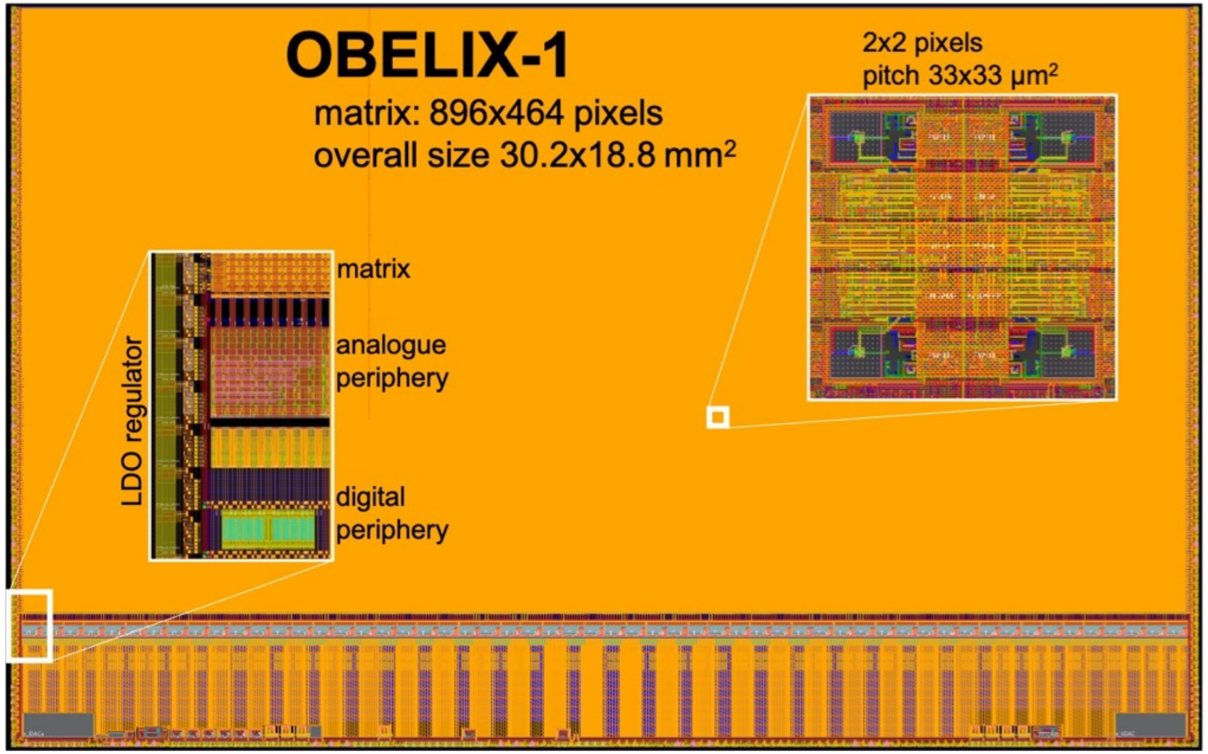
Cluster charge (sum of ToT)



- **Reasonable cluster size and charge distributions under various incident angles**
- **Analysis of depletion zone depth is ongoing**

OBELIX prototype production

OBELIX prototype sensor (OBELIX1)

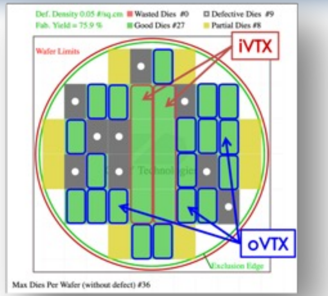


- **1st OBELIX prototype sensor: OBELIX1**
  - All necessary functions for operation will be integrated.
  - Finalizing the design now.
- **OBELIX1 design ongoing: submission in late 2024**

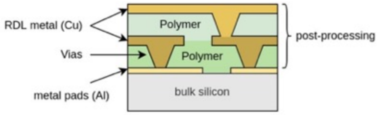
	TJ-Monopix2	OBELIX (target)
Year	2020	2024 (1st prototype)
Pixel pitch	33 µm	33 µm
Sens. area	17x17 mm^2	~30x16 mm^2
Sens. thickness	25-100 µm	~30 µm
ToT	7-bit	7-bit
Integration	25 ns	25 to 100 ns
Bandwidth	320 MHz	320 MHz
Power	200 mW/cm^2	< 200 mW/cm^2
TID fluence	0.1 MGy 10^{15} n_{eq}/cm^2	< 1 MGy < 5×10^{14} n_{eq}/cm^2

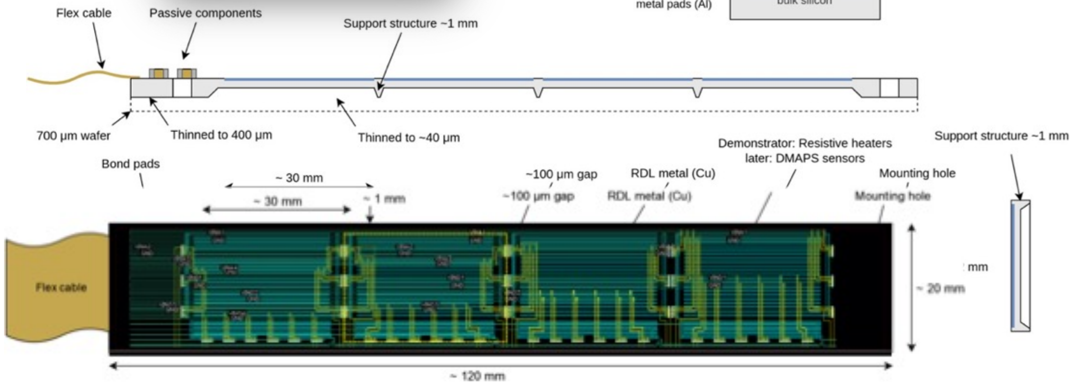
iVTX Inner Layer Concept

- All-silicon module < 0.15 % X_0
  - 4 contiguous sensors diced as a block from the wafer
  - Redistribution layer for interconnection
  - Heterogeneous thinning for thinness & stiffness



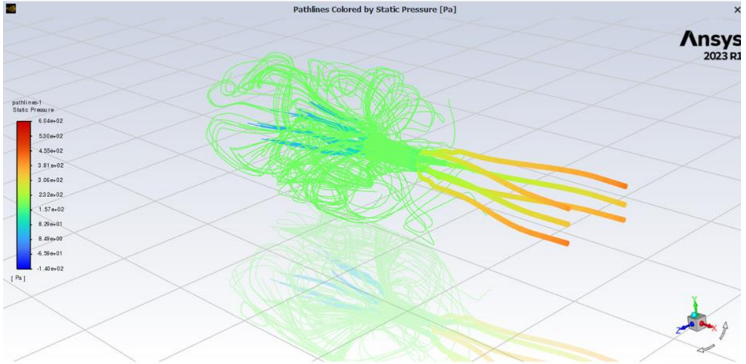
Cu Redistribution layer (RDL)

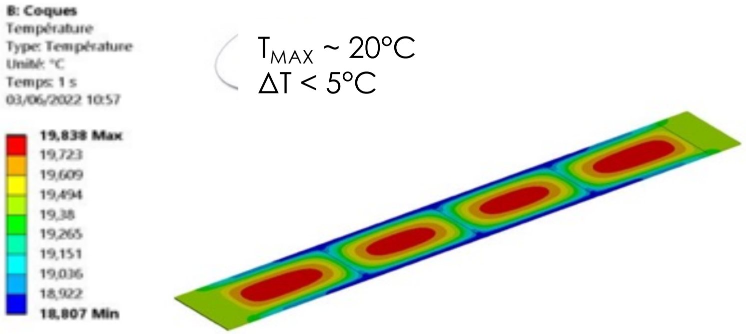




- Prototyping
  - First real-size ladders at IZM-Berlin with dummy Si
    - True iVTX geometry available

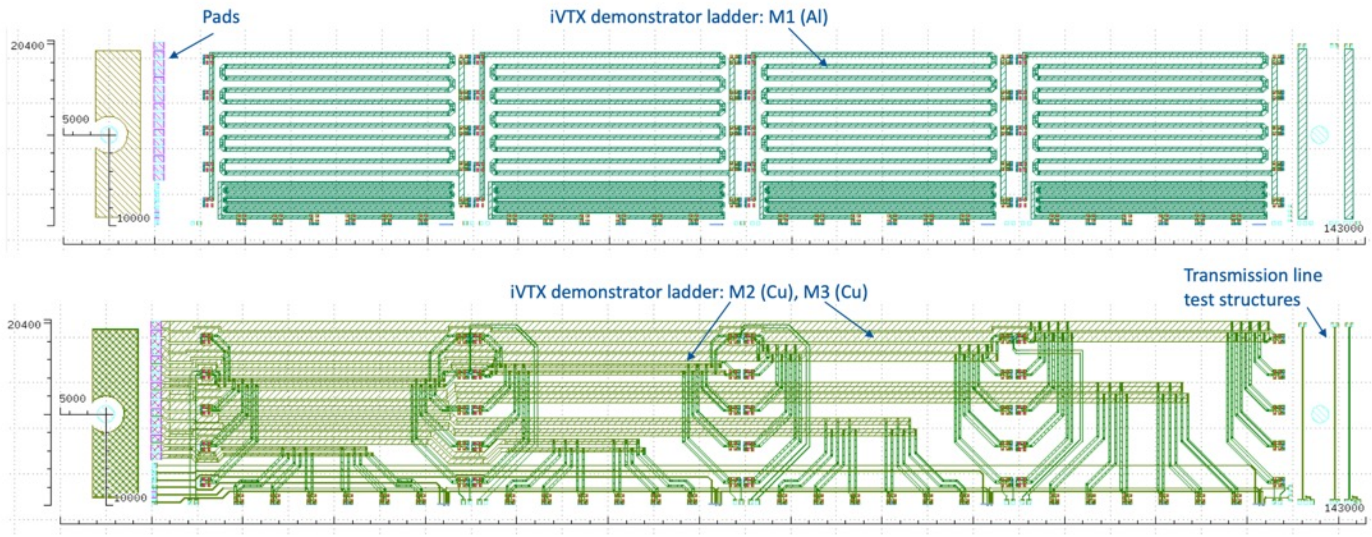
- Simulation on cooling
  - Dry air cooling 15°C
  - Assume 200 mW/cm^2





T_{MAX} ~ 20°C
ΔT < 5°C

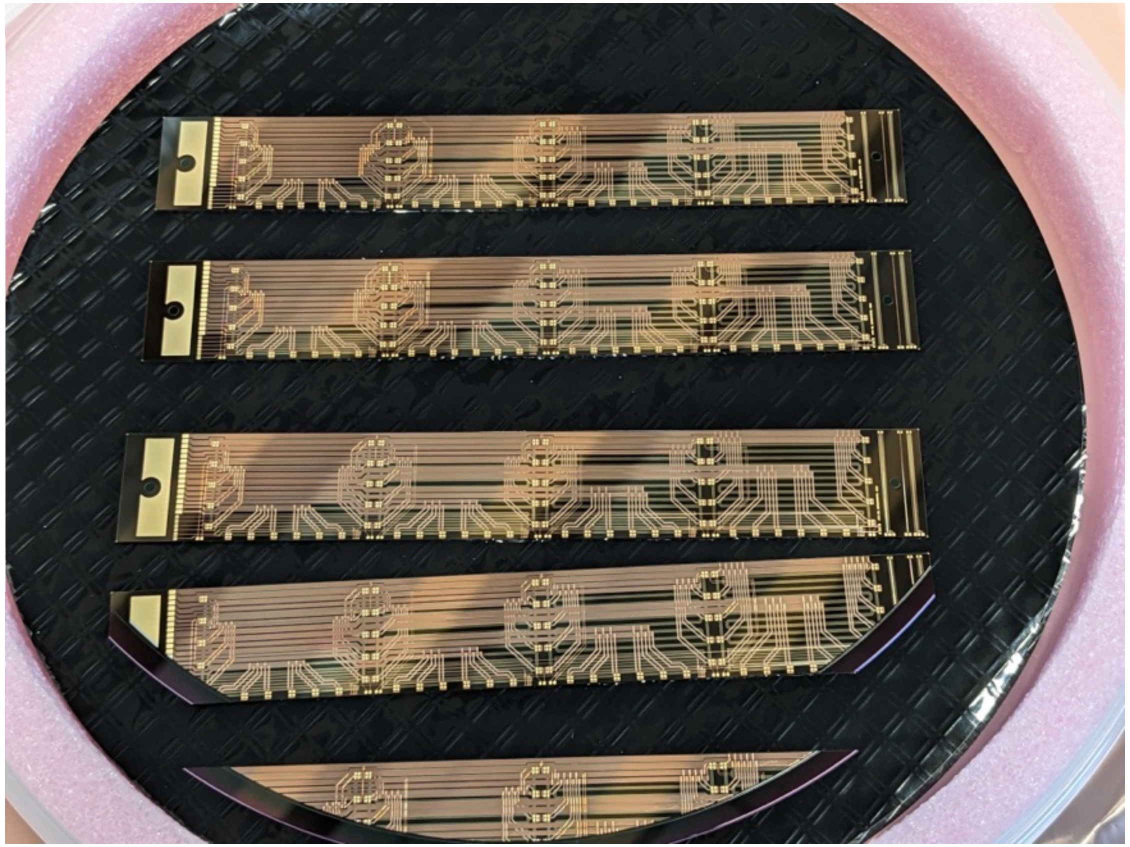
Demonstrator mockup with dummy Si



Metal system:

- Resistive heaters: 1.5 um Al (M1)
- 2 RDL metal layers: 3 um Cu (M2, M3)
- Top metal finish: NiAu (M4)
  Wirebonding, SMD soldering

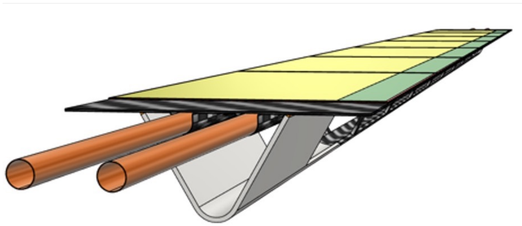
Final ladder dimension: 143 x 20.4 mm^2



Production finished smoothly
Characterization starting

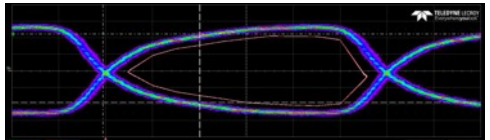
oVTX Outer Layer Concept

- Long ladders
  - Evolving from ALICE-ITS2
    - Carbon-fiber truss support frame
    - Cold-plate with water coolant
    - Long-flex for power & data



- L3-4, radius 4-9 cm, length < 50 cm
  - Single sensor row, ~0.5 % X_0
- L5, radius 14 cm, length 70 cm
  - Double sensor rows , ~0.8 % X_0

- Prototypes for L5 under test
  - Deformation & vibration
    - Max sagitta ~500 µm
    - First resonance f=250 Hz
  - Signal propagation
  - Cooling at T_{room} ~24^{o}C
    - Leakless water flow at T_{in} = 10^{o}C
    - Heaters dissipating 200 mW/cm^2
    - 22^{o}C < $T_{sensors}$ < 26^{o}C


eye diagram @250 MHz s)

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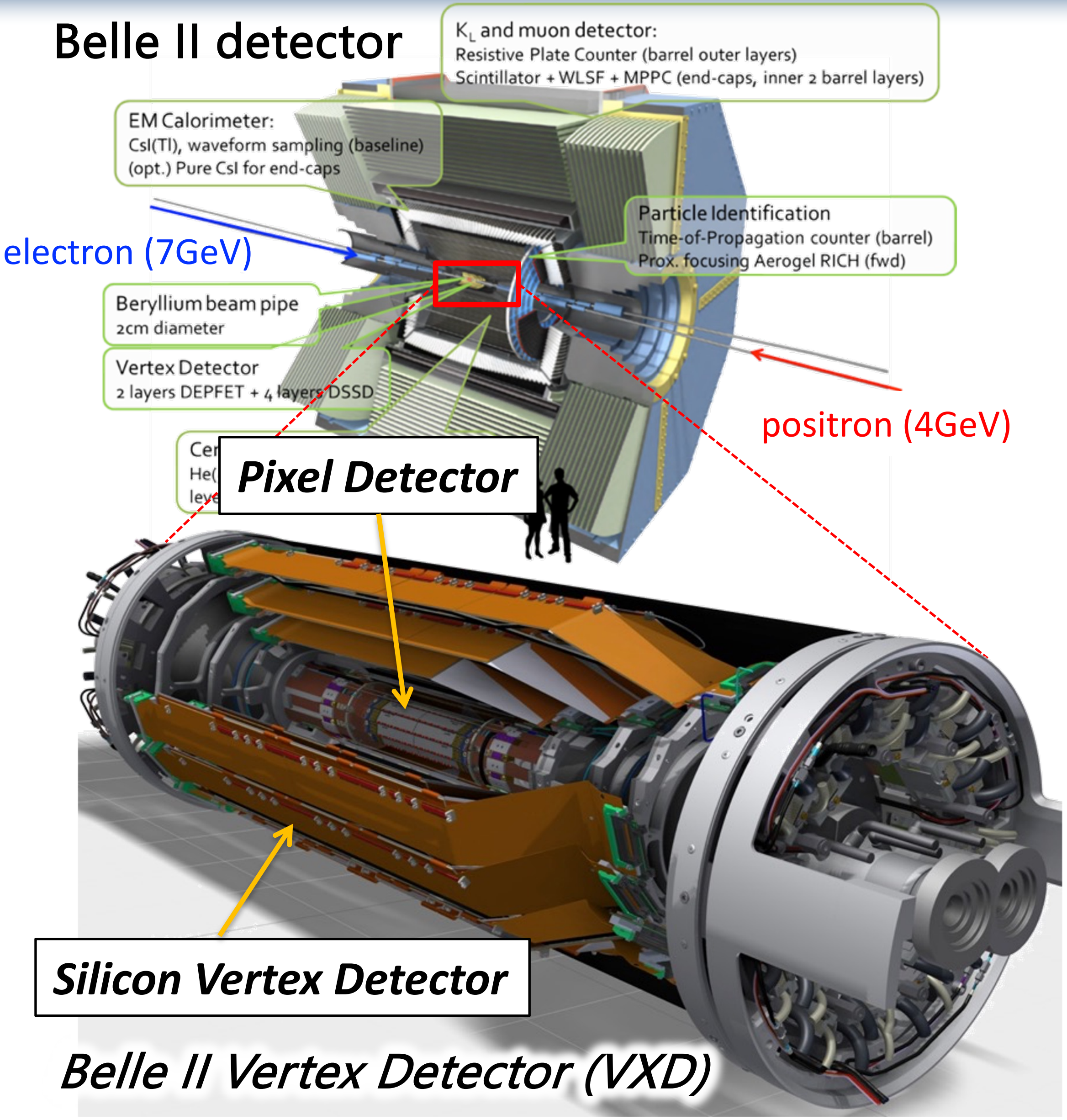
Summary

- **CMOS DMAPS for Belle II vertex detector upgrade**
  - OBELIX sensor: based on TJ-Monopix2 matrix design
- **Detailed performance characterization of TJ-Monopix2 is being performed for tuning OBELIX design.**
  - Excellent performance is confirmed.
  - KEK and other Japanese institutes are participating in the performance test, using the KEK PF-AR electron beam facility.
- **The first prototype OBELIX1 plan to be submitted in late 2024.**
- **Mechanics design work for the VTX detector is ongoing.**

backup

Current Vertex Detector at Belle II Experiment



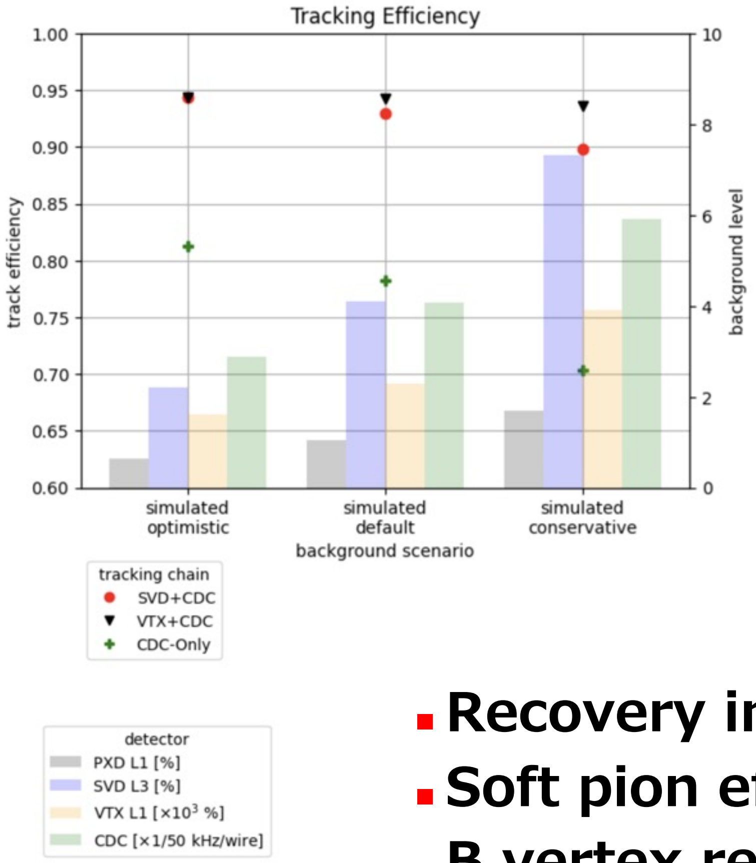
Belle II Vertex Detector (VXD)

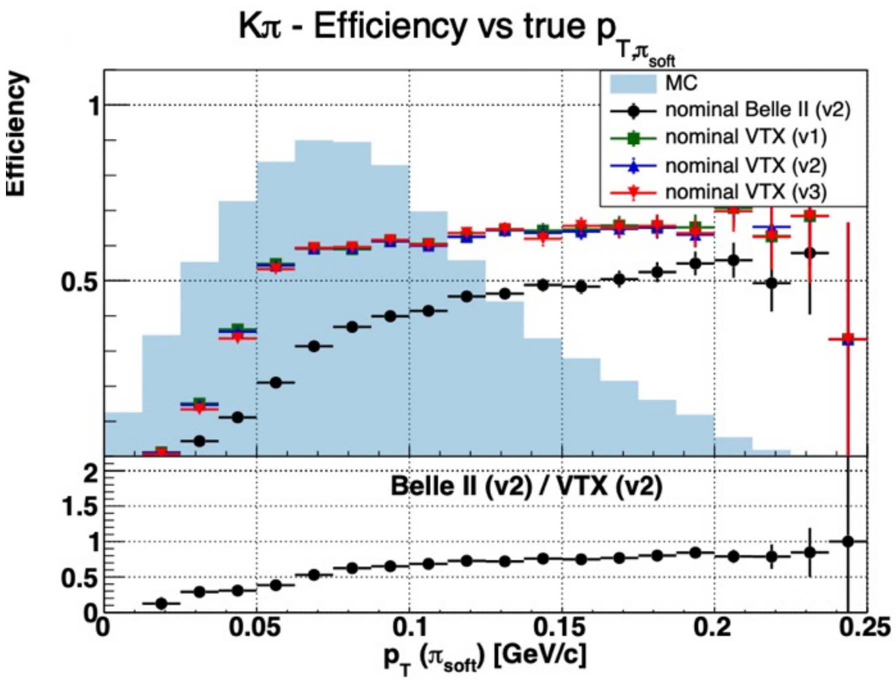
- **VXD: Current Vertex detector in Belle II**
  - 2 layers of PiXel Detector (PXD): DEPFET sensor
  - 4 layers of Silicon Vertex Detector (SVD): Double-sided silicon strip (DSSD) sensor

SVD technical paper: arXiv:2201.09824

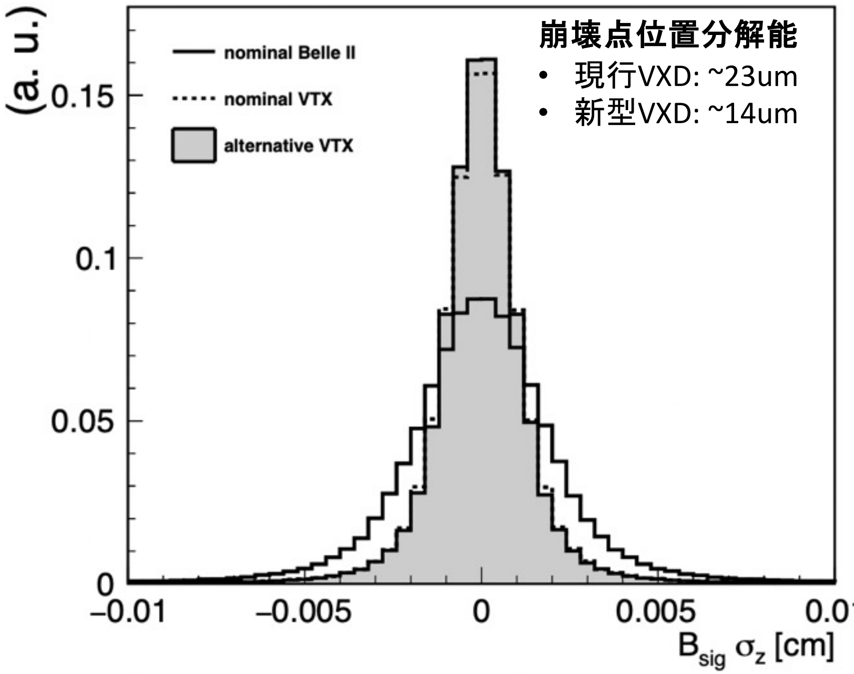
- **Roles of VXD**
  - Determine the vertex position
  - Standalone tracking
  - PID using SVD dE/dx for low p_T tracks

Performance improvement by VTX





崩壊点residual分布

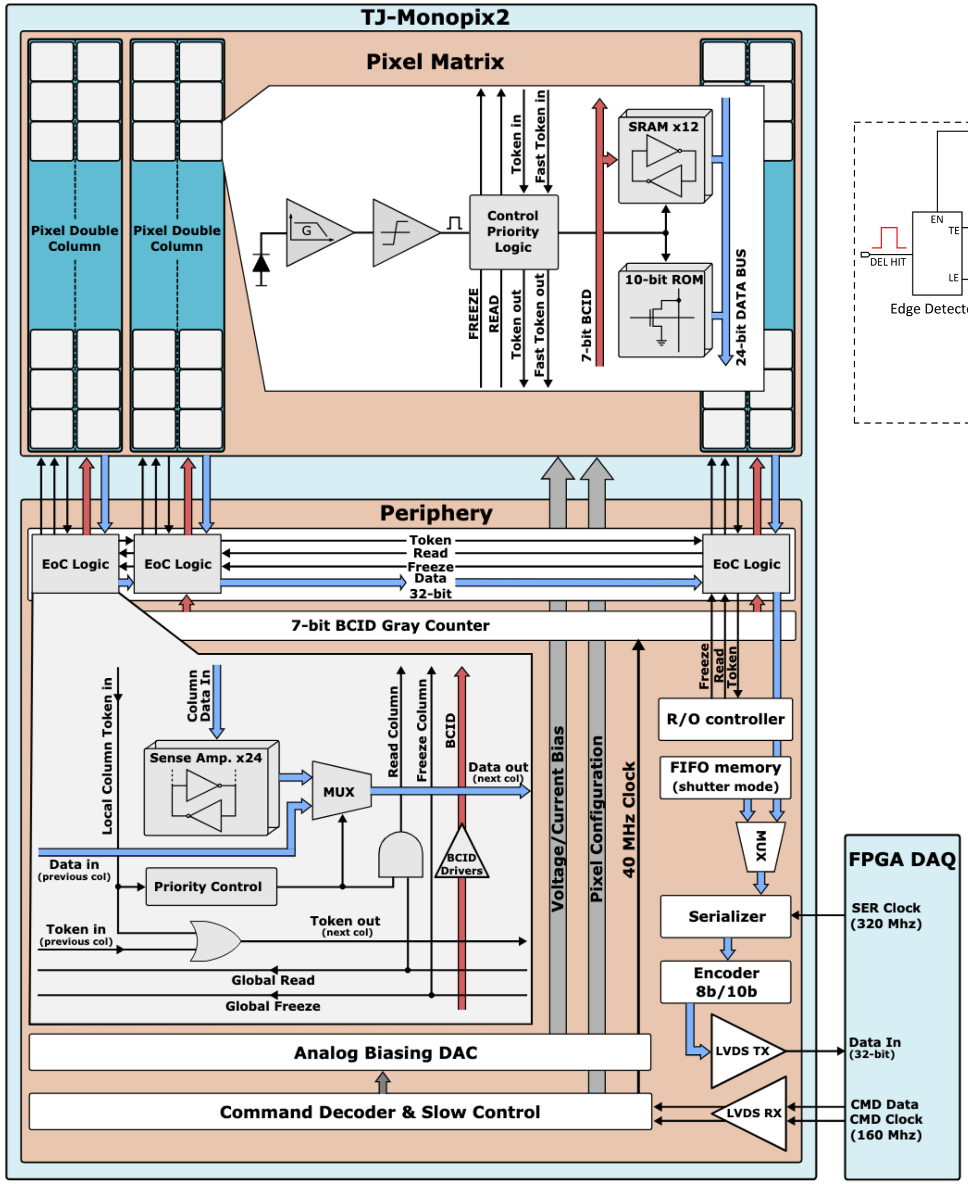


- **Recovery in the tracking efficiency at future background level**
- **Soft pion efficiency: Factor 1.5-4.0 improvement below 75MeV/c**
- **B vertex resolution: ~40% better resolution**

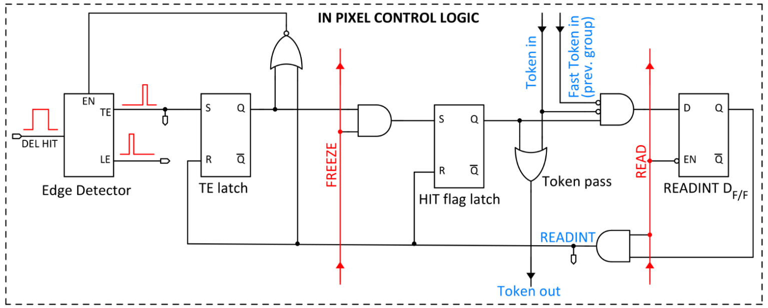
Column-Drain Readout Scheme

Toke-pass logic to read out 24-bit ToT+ToA data only from hit pixels

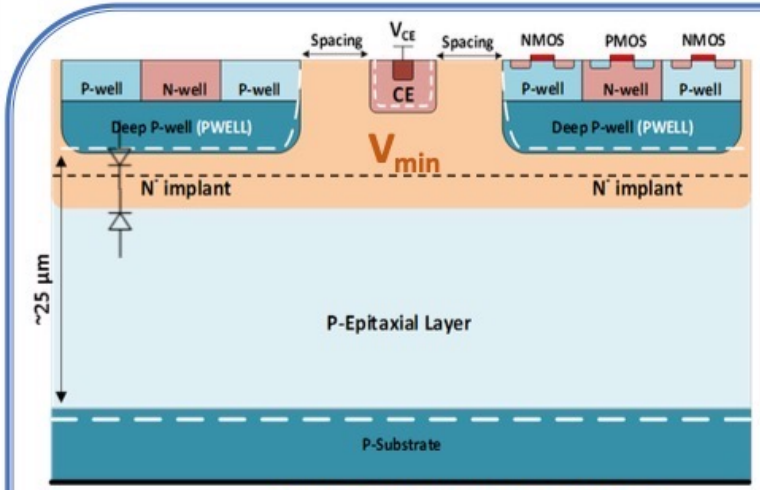
- Hit pixels generate tokens.
- When R/O controller finds the token, it starts reading out 24-bit data, selecting each hit pixel one-by-one using FREAZE/READ signals.



Control Priority Logic



OBELIX (Optimized BELle II monolithic pIXel sensor)



W. Snoeys et al. https://doi.org/10.1016/j.nima.2017.07.046

$$C_d \leq 3fF$$

$$P \approx \frac{S}{N} \approx \frac{Q}{C_d}$$

DMAPS in TJ 180 nm: Concept

- Small sensor capacitance (Cd)
  - Key for low power/low noise
- Radiation tolerance challenges
  - Modified process
  - Small pixel size
- Design challenges
  - Compact, low power FE
  - Compact, efficient R/O

W. Snoeys et al.: NIM A 871 (2017) 90

- **OBELIX sensor for Belle II VXD upgrade (VTX)**
  - Extension from TJ-Monopix2, adapting digital part for Belle II requirement
  - TowerJuzz 180nm
- **1st prototype design ongoing**

	TJ-Monopix2	OBELIX (target)
Year	2020	2024 (1st prototype)
Pixel pitch	33 µm	33 µm
Sens. area	17x17 mm^2	~30x16 mm^2
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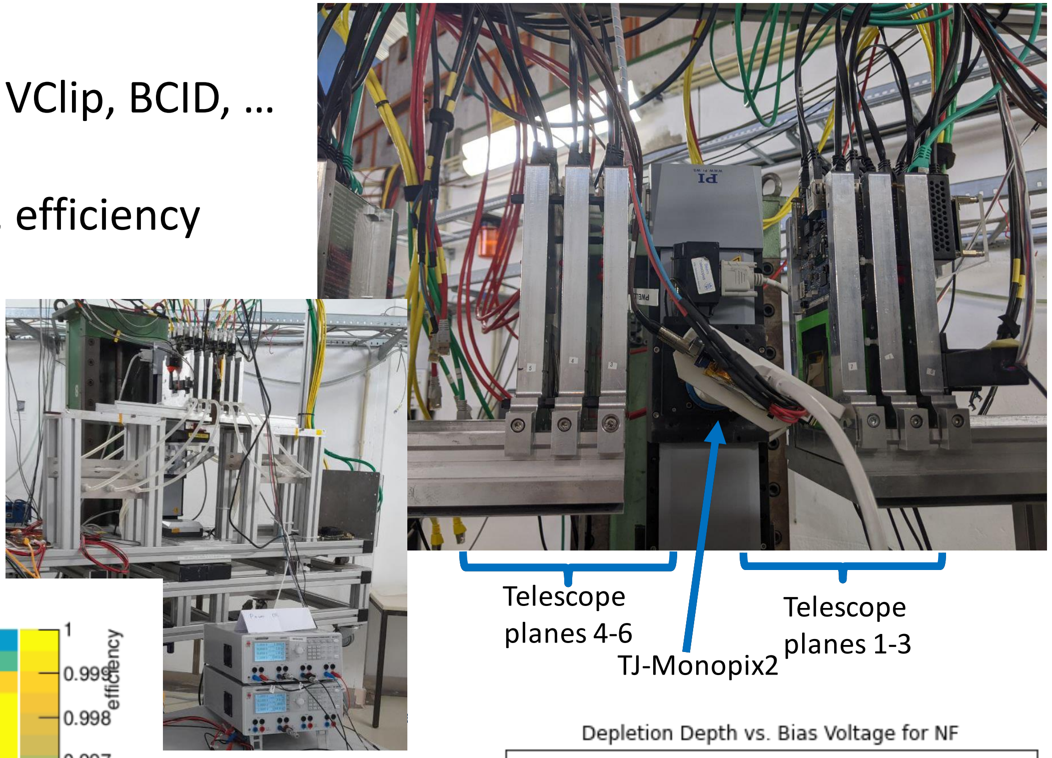
Bandwidth	320 MHz	320 MHz
Power	200 mW/cm^2	< 200 mW/cm^2
TID fluence	0.1 MGy 10^{15} n_{eq}/cm^2	< 1 MGy < $5x10^{14}$ n_{eq}/cm^2

Irradiated TJ-Monopix2 Beam Test

Serial	Irradiation	Substrate
W02R05	None	30 μm EPI
W02R09	Neutrons 1×10^{14}	30 μm EPI
W05R16	Protons 5×10^{14}	30 μm EPI
W08R19	None	30 μm EPI
W14R12	None	Cz

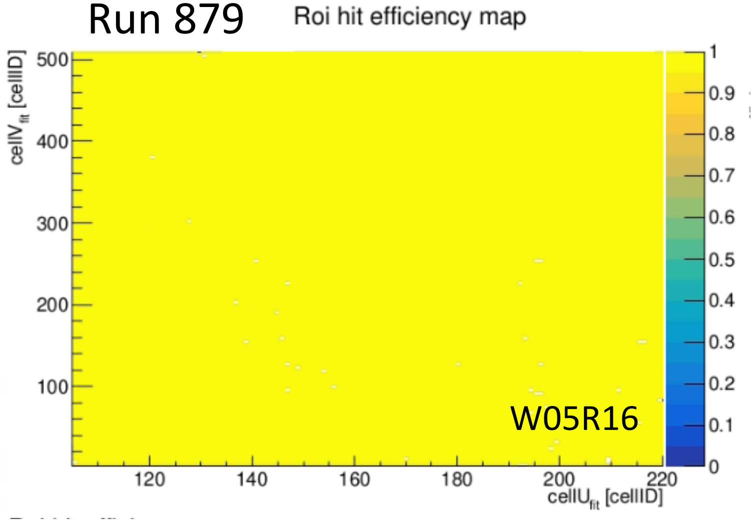
Parameter scans:
HV, IBias, PSub, VClip, BCID, …

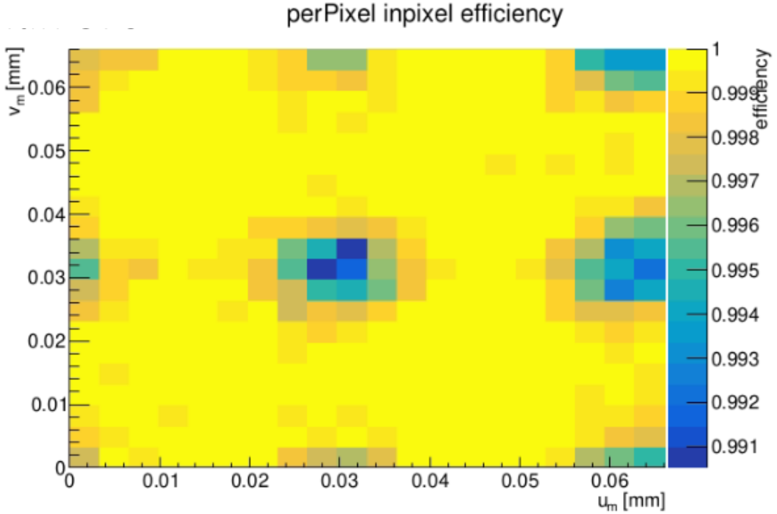
Angular scans, resolution, efficiency

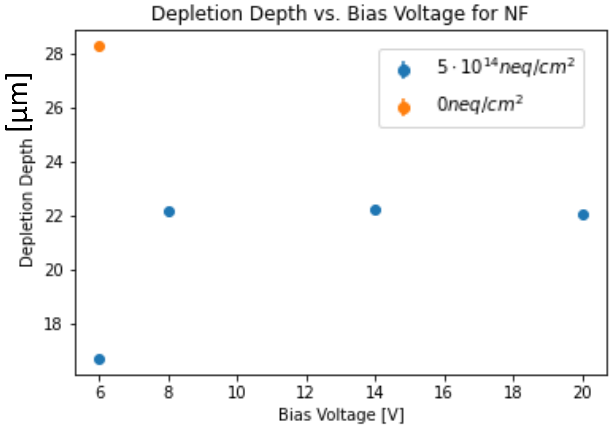


Efficiency >99% for $5\text{x}10^{14}\ n_{eq}/cm^2$ (310 e^- threshold)
Cluster position residuals ~9.5 μm

Run 879







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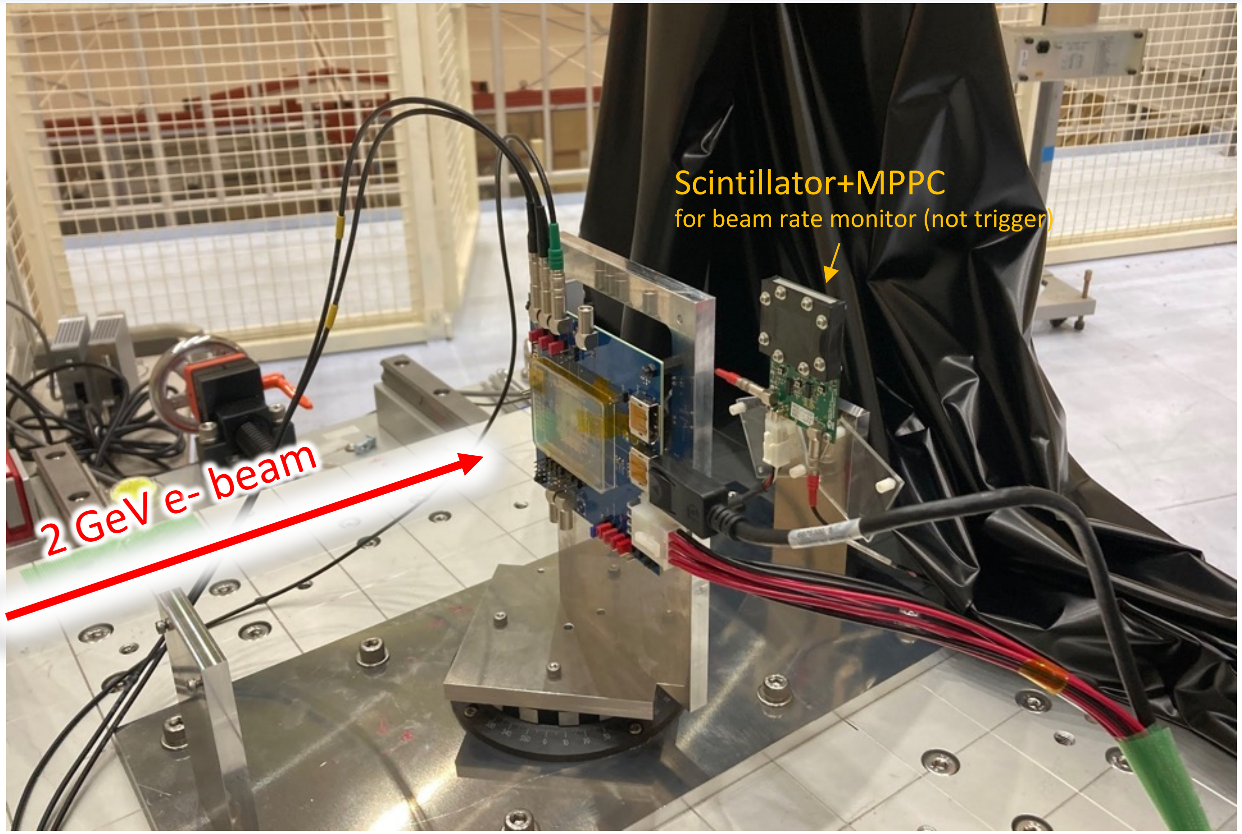
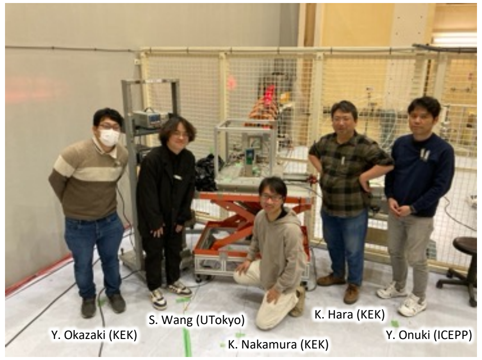
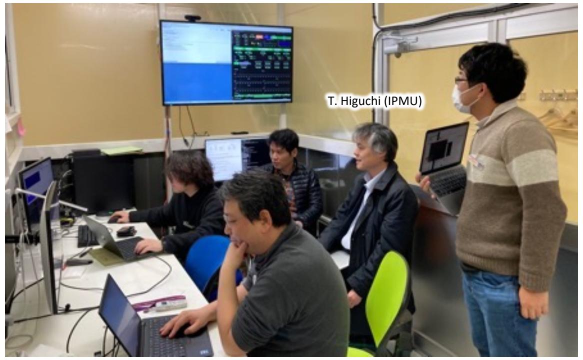
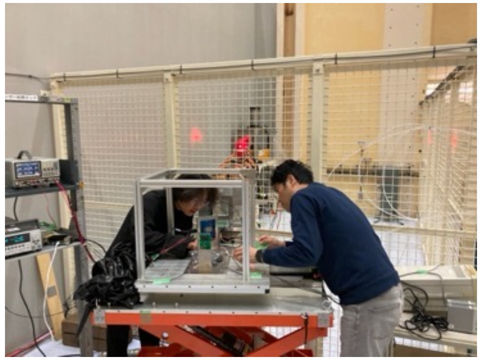
KEK PF beam test (Mar 1-4, 2024)

- **2 GeV e- beam**
  - Beam rate:
    - Counter in beamline: ~800Hz
    - Downstream scintillator (32x28mm^2): ~50Hz
- **Tested single TJ-Monopix2 chip**
  - No telescope
  - cluster size measurement with different incident angles
    - → evaluate depletion layer depth



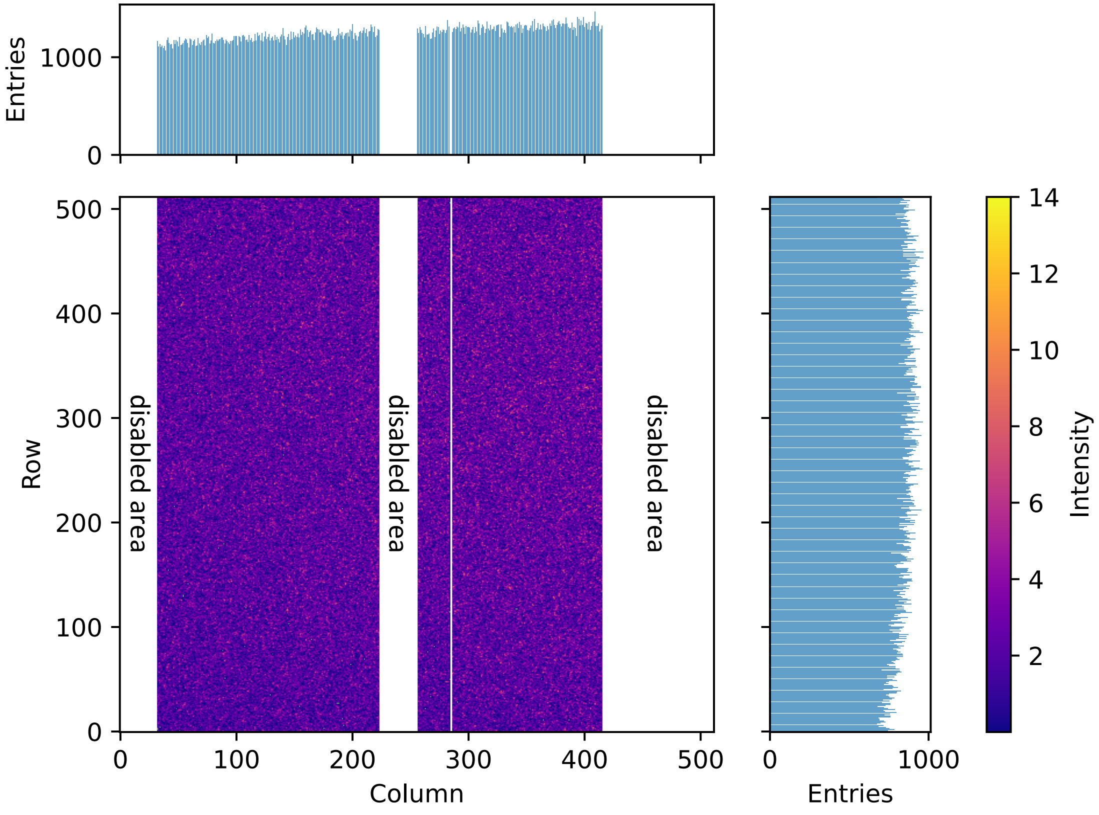




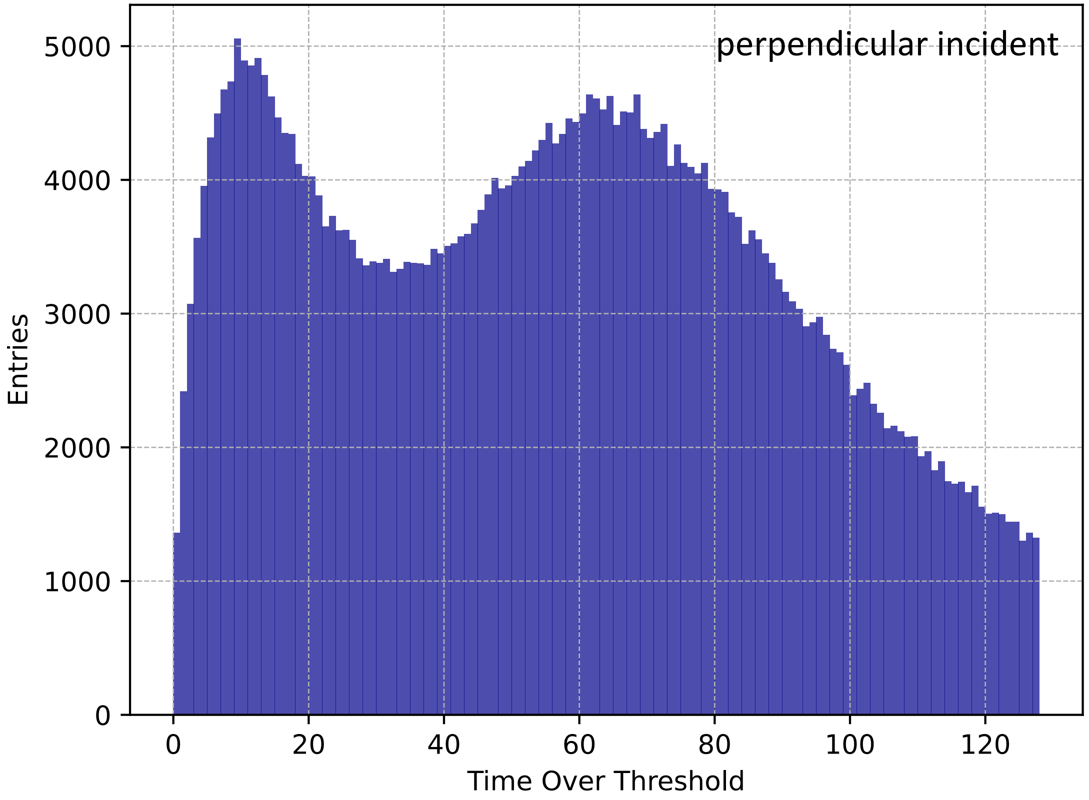


Quick results from beam test

Hit Map Distribution



ToT Distribution



DMAPS chip for Belle II vertex detector upgrade

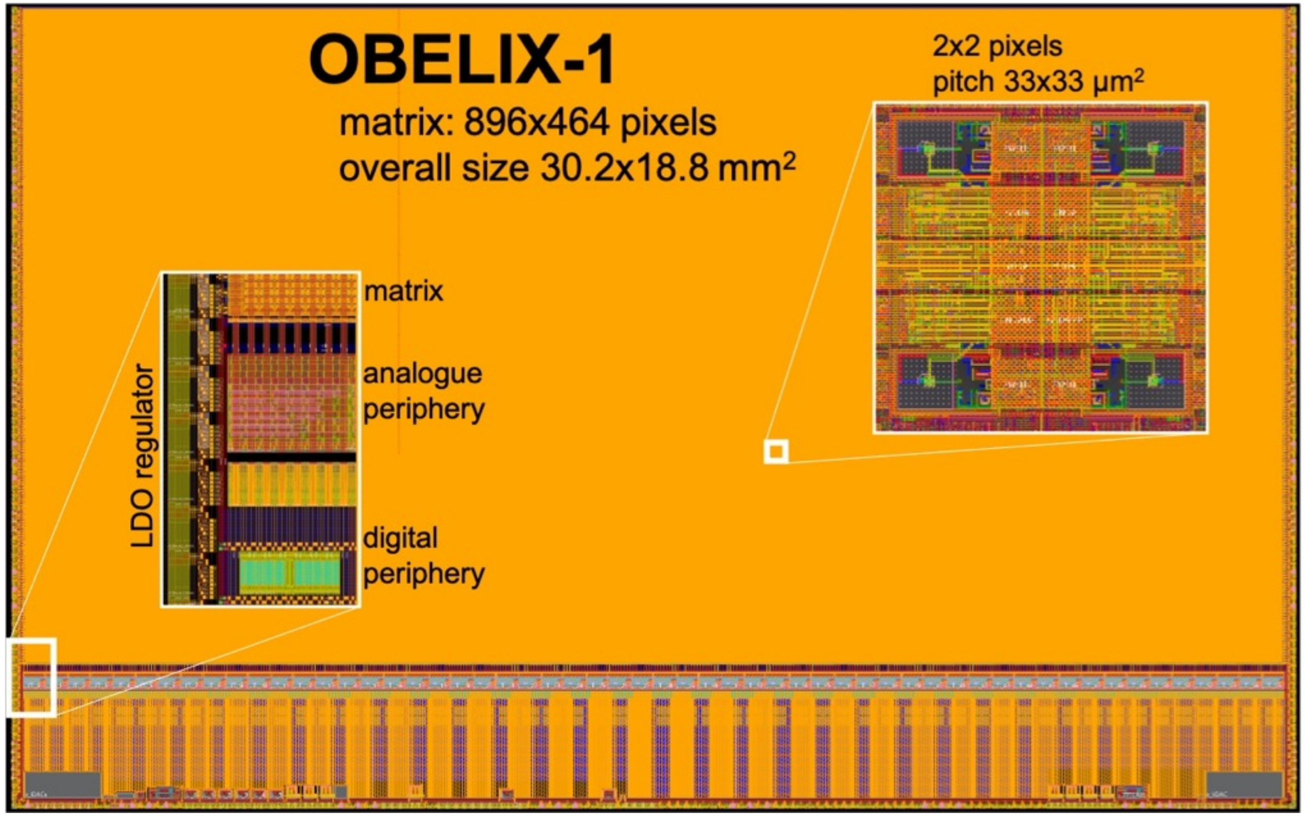
OBELIX chip

- Optimized BELle II monolithic pIXel sensor

- **Pixel matrix**
  - Extension from TJ-Monopix2
  - Clock frequency ~10-20 MHz
- **Power pads**
  - Power regulators added
- **Periphery**
  - Trigger-base readout

1st prototype: OBELIX-1

- **Design & production plan**
  - Designing main functionalities done (but regulator)
  - Final integration on-going
  - Simulation/verification is main activity
- **Submission: expected in late 2024**
  - after last in-person meeting



KEK ITDC E-sys (T. Kishishita) is contributing to designing matrix.

Column-drain readout