

# **BASHI: Bootstrapping mAps development in a Shared Investigation**

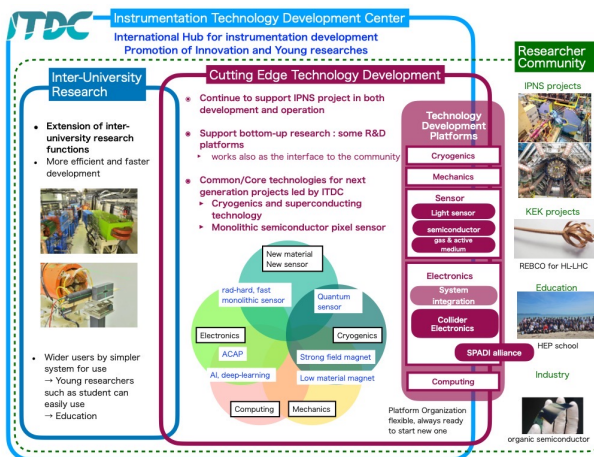
Katsuro Nakamura (KEK)

May 23, 2024

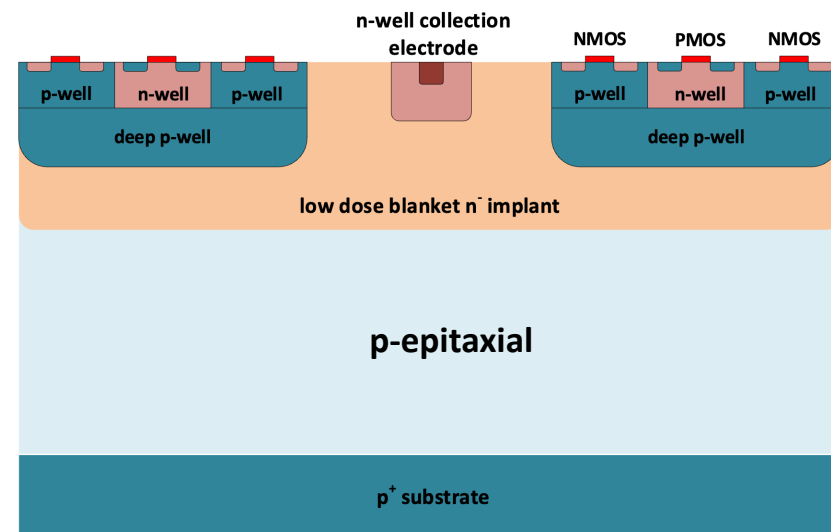
2024 Joint Workshop of FKPPN and TYL/FJPPN

# BASHI project

- **BASHI: Bootstrapping MAPS development in a shared investigation**
  - A project building a bridge between two main detector development centers, ITDC (KEK) and C4Pi (IPHC), and participating development institutes for CMOS monolithic active pixel sensor (MAPS) development
- **Two main goals:**
  - Development of OBELIX sensor (TowerJazz 180nm) for Belle II vertex upgrade VTX
  - R&D on the new generation MAPS (TPSCo 65nm) for ALICE ITS3 and future applications



## CMOS Monolithic Active Pixel Sensor (MAPS)



# Project institutes and members



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ENARI Yuji

OKAZAKI Yuta

NAKAMURA Koji

TOGAWA Manabu

NAKAMURA Katsuro

CHUJO Tatsuya

INABA Motoy

GUNJI Taku

YAMAGUCHI Yorito

KEK – ITDC

KEK – ATLAS

KEK – Belle II

U. Tsukuba – ALICE

U. Tokyo – ALICE

U. Hiroshima – ALICE

IPHC – C4Pi

IPHC – Belle II

IPHC – PICSEL

IPHC – ALICE

LPSC – ALICE

BAUDOT Jerome

HU-GUO Christine

KUMAR Ajit

BESSON Auguste

EL BITAR Ziad

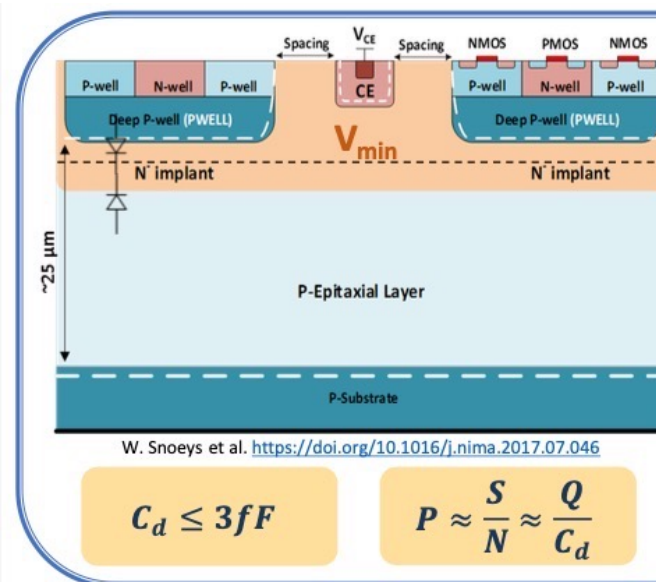
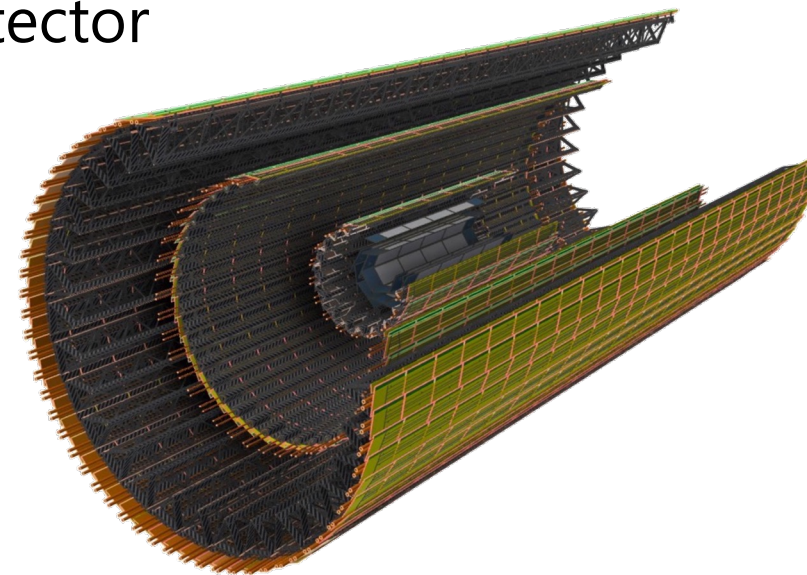
MAIRE Antonin

GUERNANE Rachid

# 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  $2.4\%X_0$
  
- **Thin MAPS sensor:**  
**Optimized BELLe II pIXel (OBELIX) chip**
  - new CMOS MAPS for Belle II vertex upgrade
  - TowerJazz 180nm
- **OBELIX matrix 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



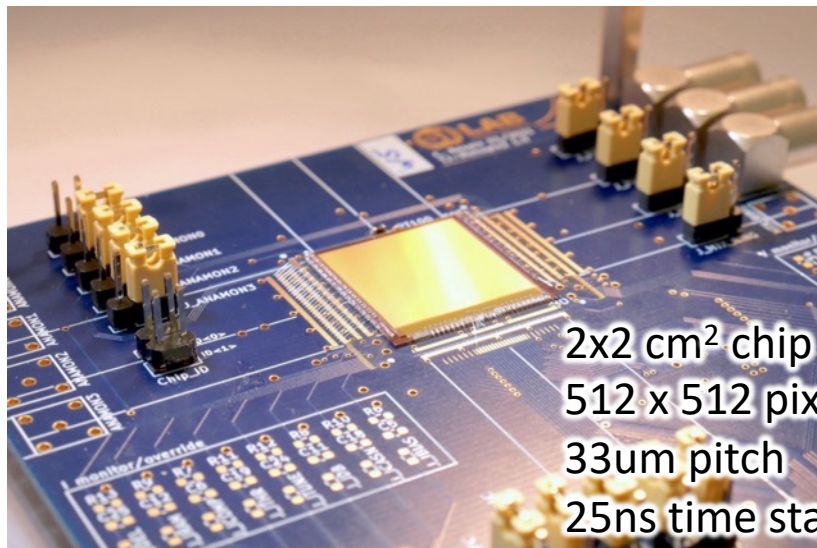
## DMAPS in TJ 180 nm: Concept

- **Small sensor capacitance ( $C_d$ )**
  - 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](https://doi.org/10.1016/j.nima.2017.07.046)  
 DOI: [10.1016/j.nima.2020.164403](https://doi.org/10.1016/j.nima.2020.164403)

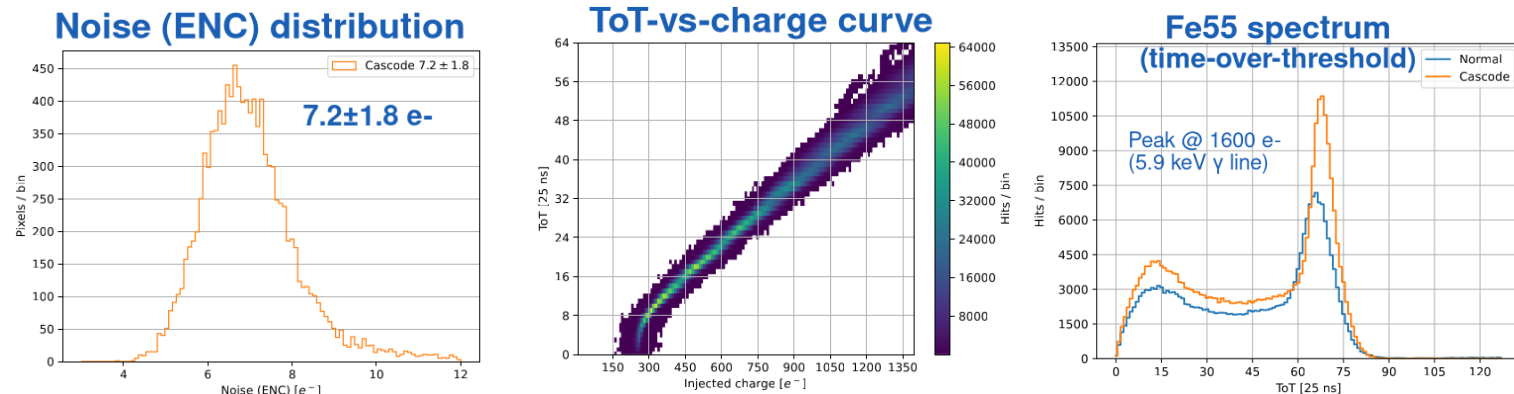
# TJ-Monopix2 Performance Characterization

## TJ-Monopix2 sensor



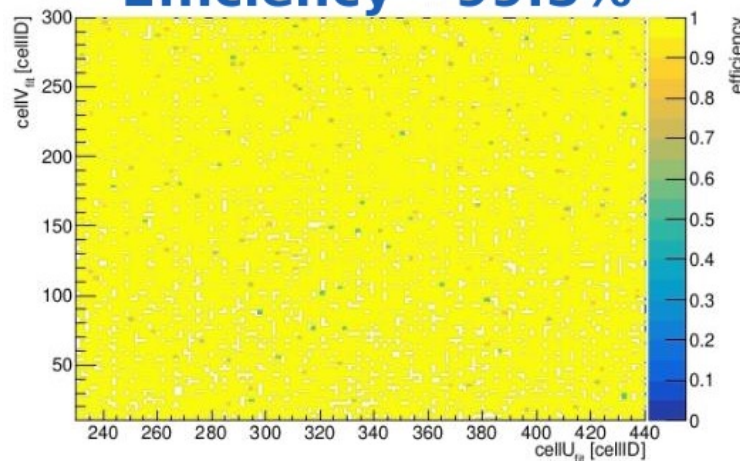
2x2 cm<sup>2</sup> chip  
512 x 512 pixels  
33um pitch  
25ns time stamping

## Lab-testbench measurement

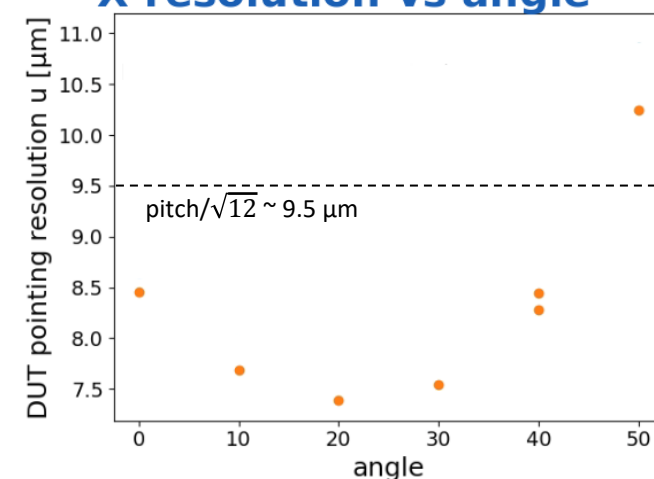


## DESY electron beam measurements

**Efficiency ~99.5%**



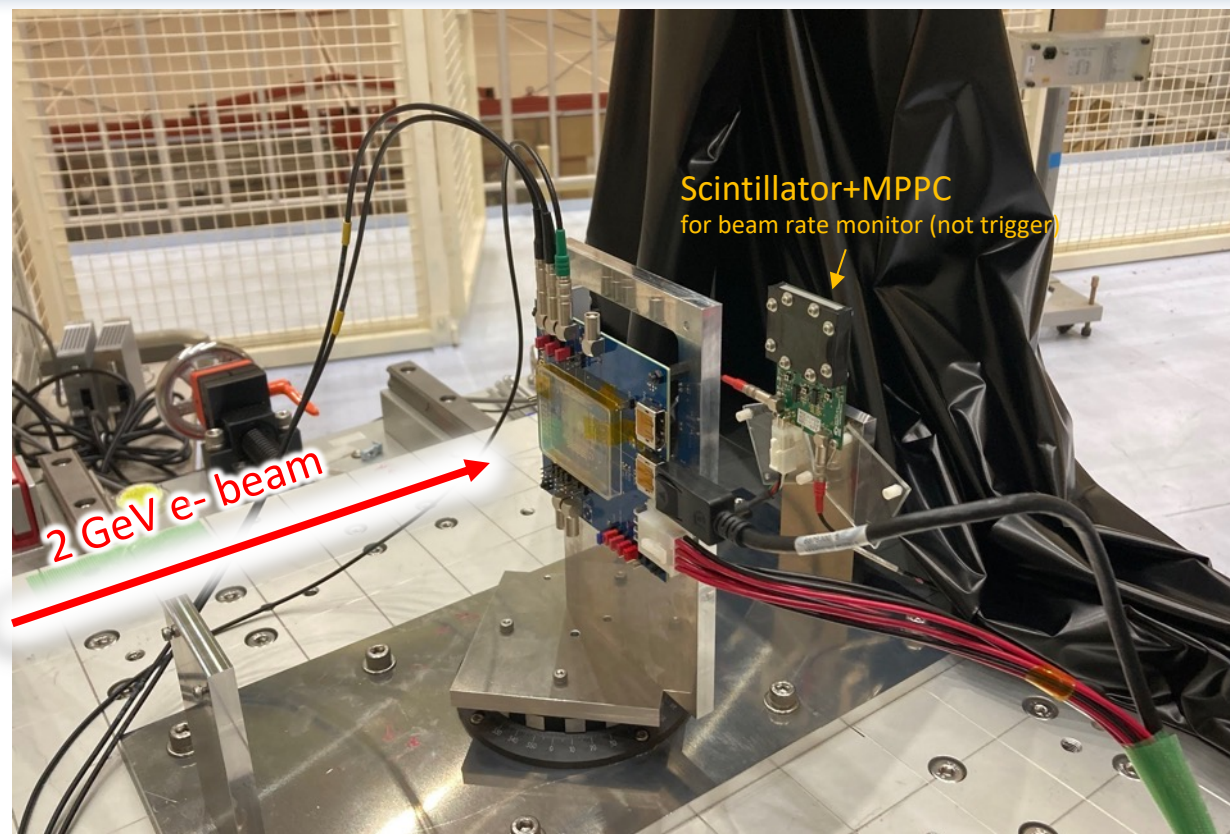
**X resolution vs angle**



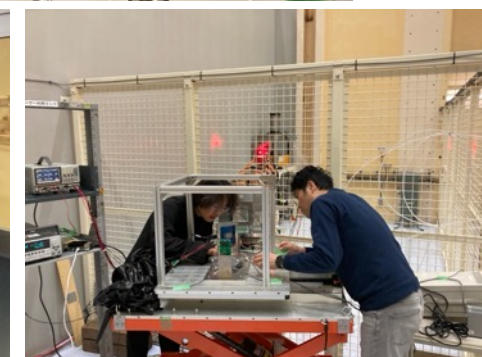
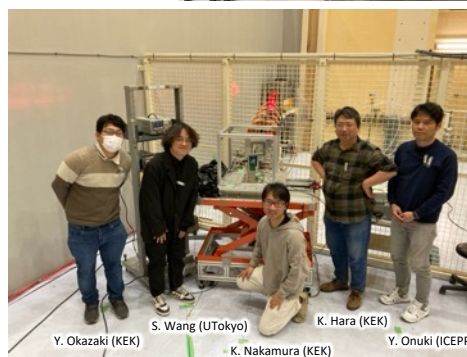
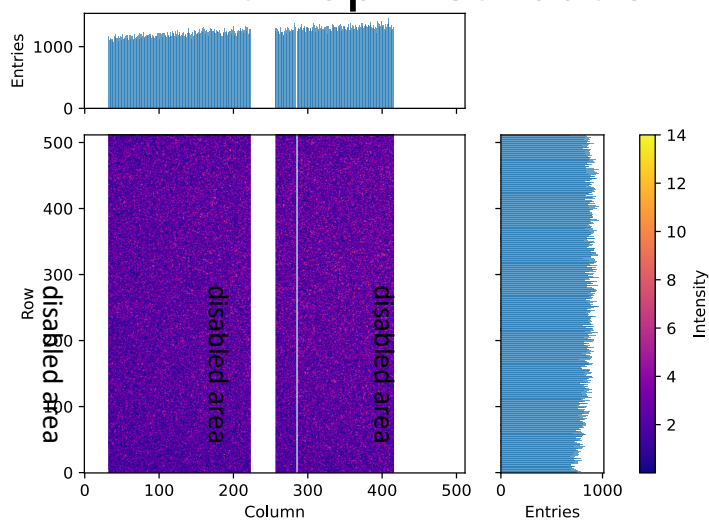
- Detailed performance characterization of TJ-Monopix2
  - Laboratory testbench test
  - Several beam tests
- Including irradiated samples
  - High efficiency even w/  $5 \times 10^{14} \text{ n}_{\text{eq}}/\text{cm}^2$

# 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

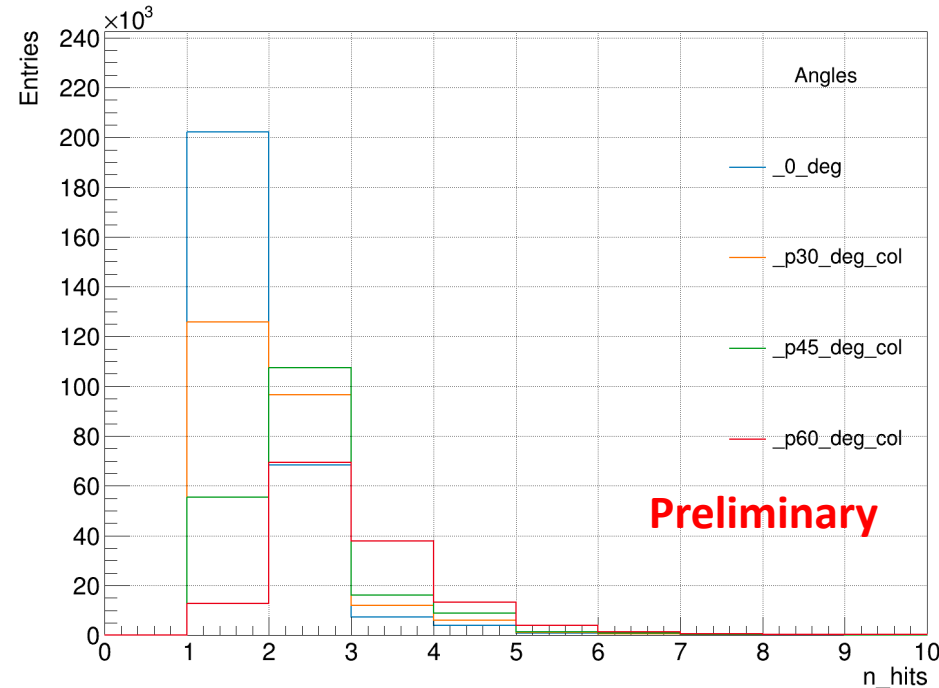


## Hit Map Distribution

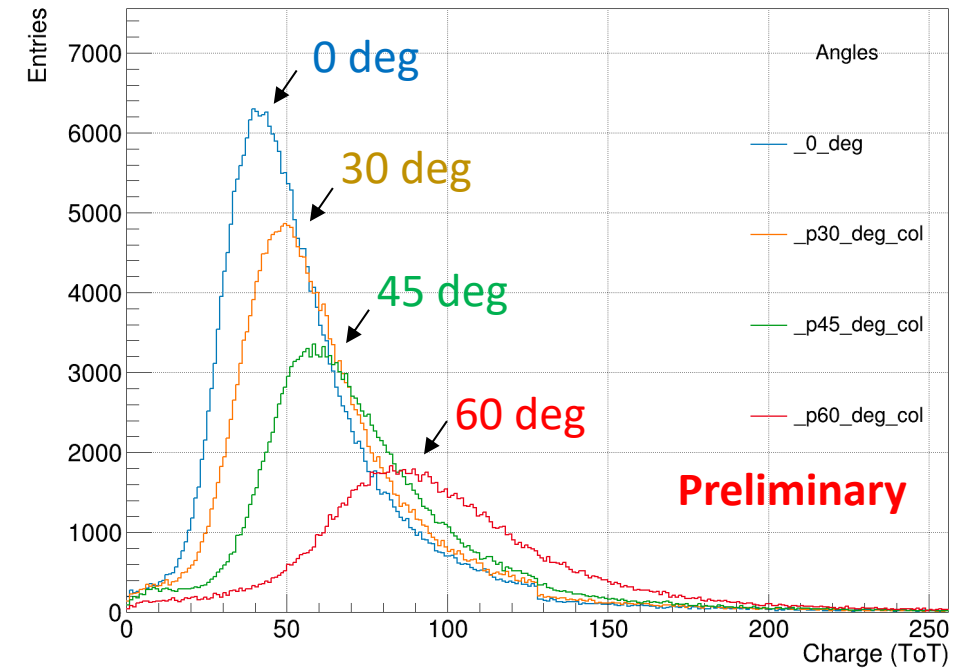


# Preliminary test results

## Cluster size (# of pixels)



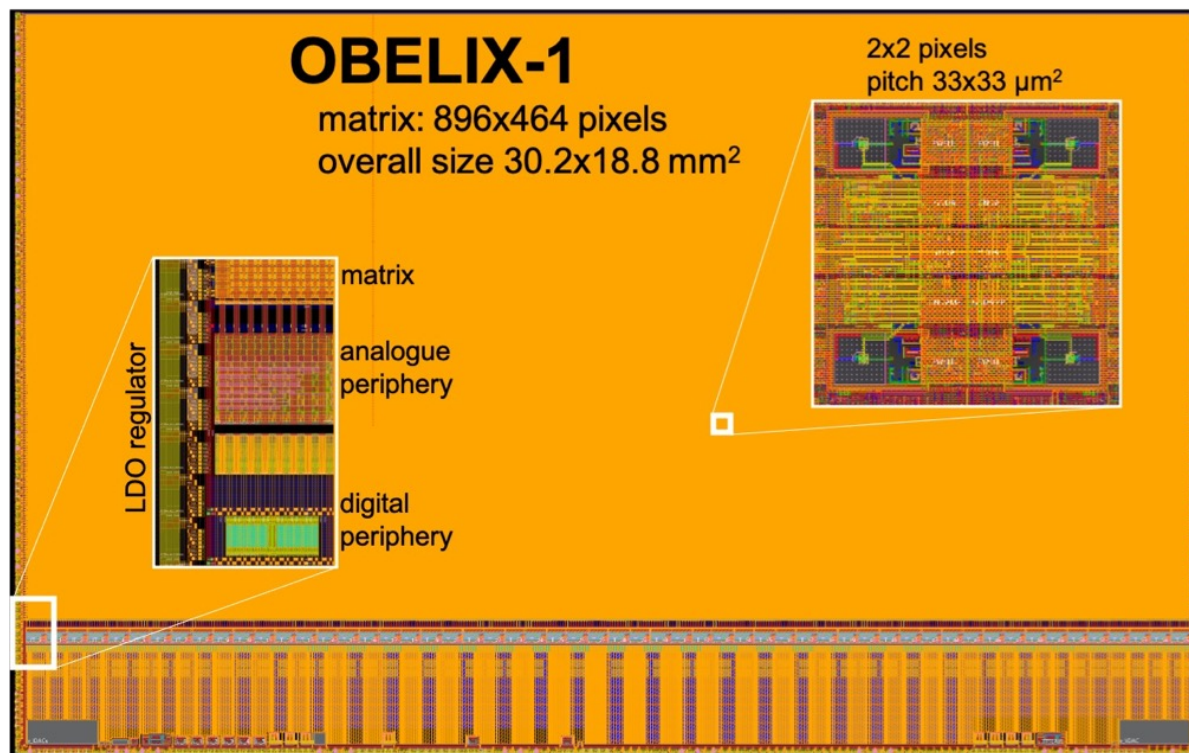
## Cluster charge (sum of ToT)



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

# OBELIX prototype production

## OBELIX prototype sensor (OBELIX1)

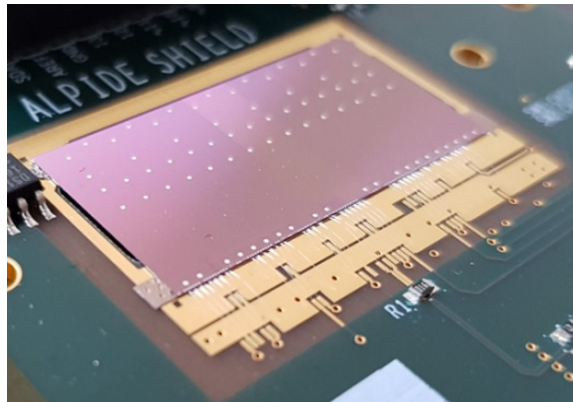


- **OBELIX prototype sensor: OBELIX1**
  - All necessary functionalities will be integrated
- **OBELIX1 design ongoing: submission in late 2024**

	TJ-Monopix2	OBELIX (target)
Year	2020	2024 (1st prototype)
Pixel pitch	33 μm	33 μm
Sens. area	17x17 mm <sup>2</sup>	~30x16 mm <sup>2</sup>
Sens. thickness	25-100 μm	~30 μm
Integration	25 ns	25 to 100 ns
Bandwidth	320 MHz	320 MHz
Power	200 mW/cm <sup>2</sup>	< 200 mW/cm <sup>2</sup>
TID fluence	0.1 MGy 10 <sup>15</sup> n <sub>eq</sub> /cm <sup>2</sup>	< 1 MGy < 5x10 <sup>14</sup> n <sub>eq</sub> /cm <sup>2</sup>

# Next-generation MAPS for ALICE

## ALPIDE ALICE Pixel Detector



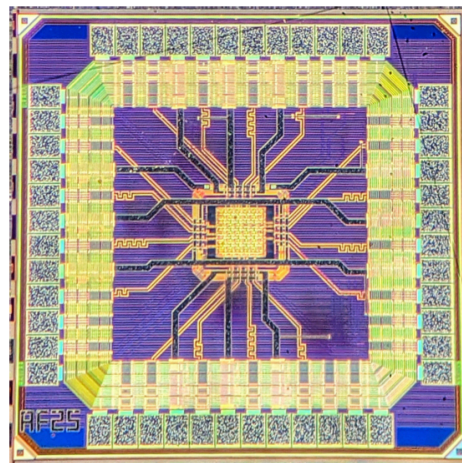
**Matrix** : 1024×512  
**Readout** : digital  
**Pitch** : 28 μm  
**Process** : standard

**Characterisation test** aims at validating

- 65nm technology
- process variants
- pixel architecture

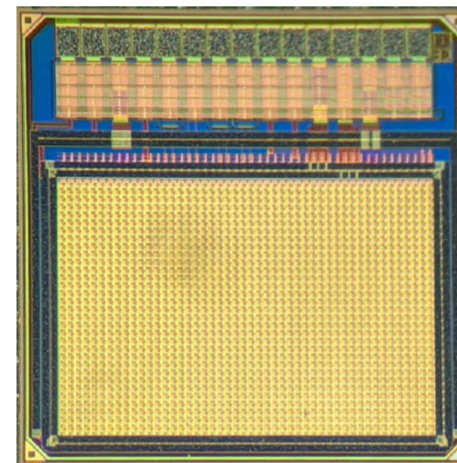
**Test beam experiments can provide sensor validation**

## APTS Analog Pixel Test Structure

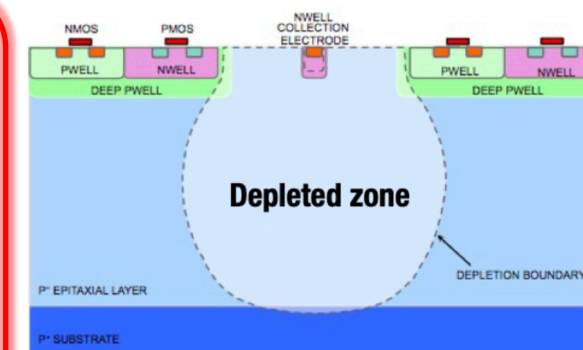


**Matrix** : 6×6  
**Readout** : analog  
**Pitch** : 10, 15, 20, 25 μm  
**Process** : all 3 variants

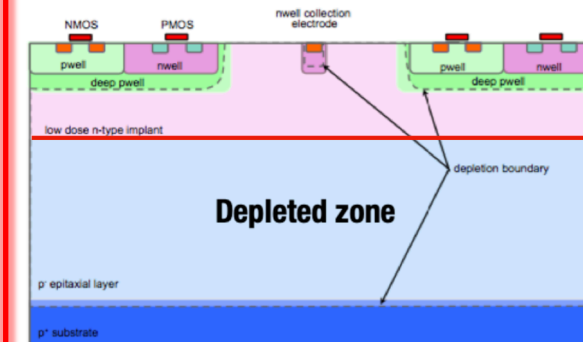
## CE65 Circuit Exploratoire 65 nm



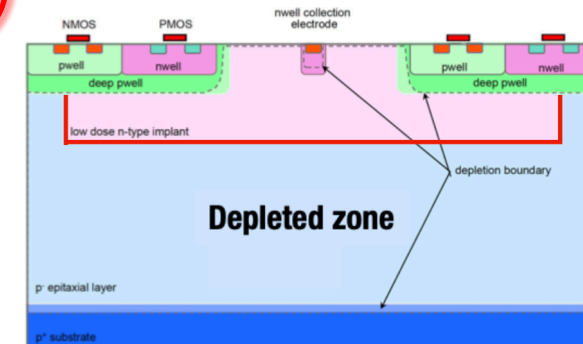
**Matrix** : 48×32  
**Readout** : analog  
**Pitch** : 18, 22.5 μm  
**Process** : all 3 variants



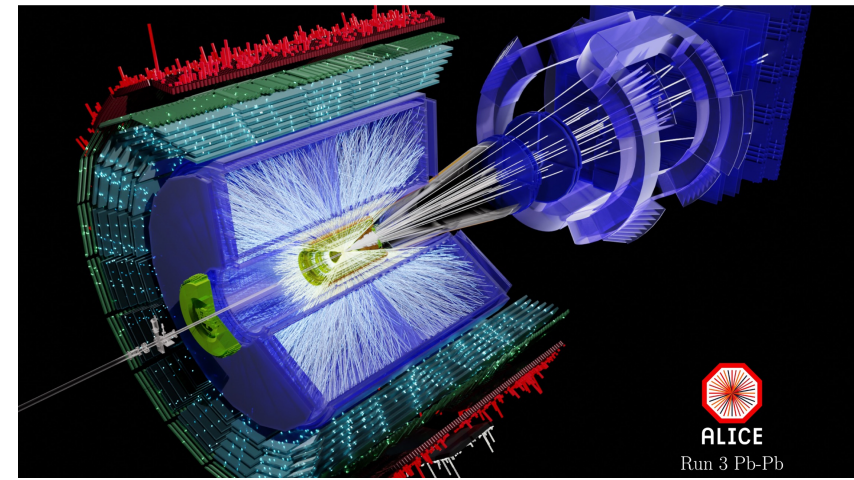
### Modified process



### Modified process with gap



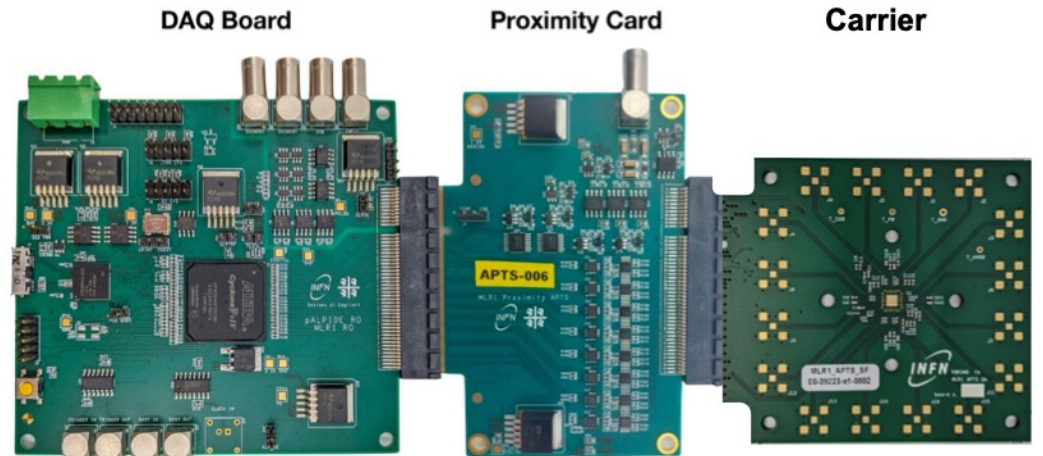
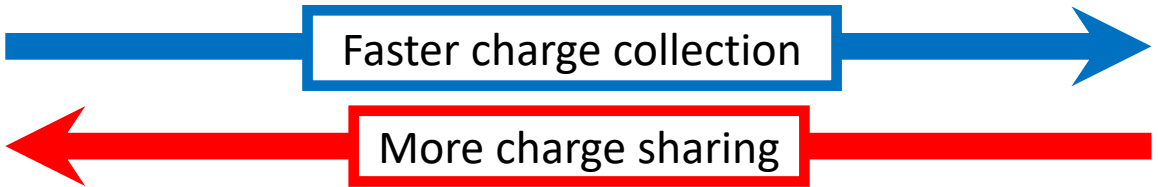
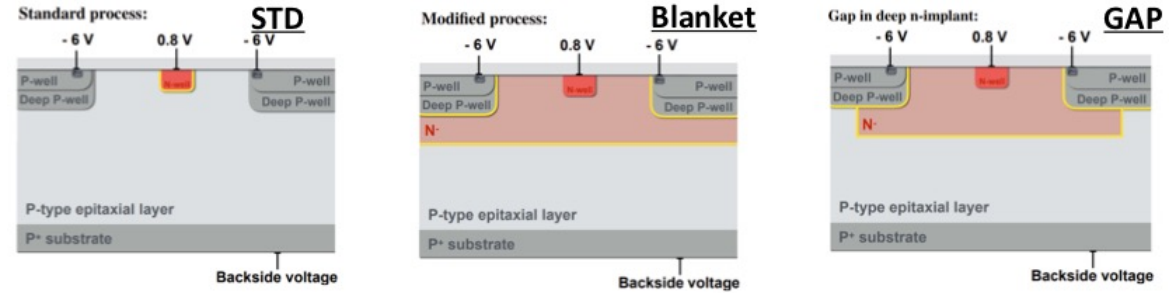
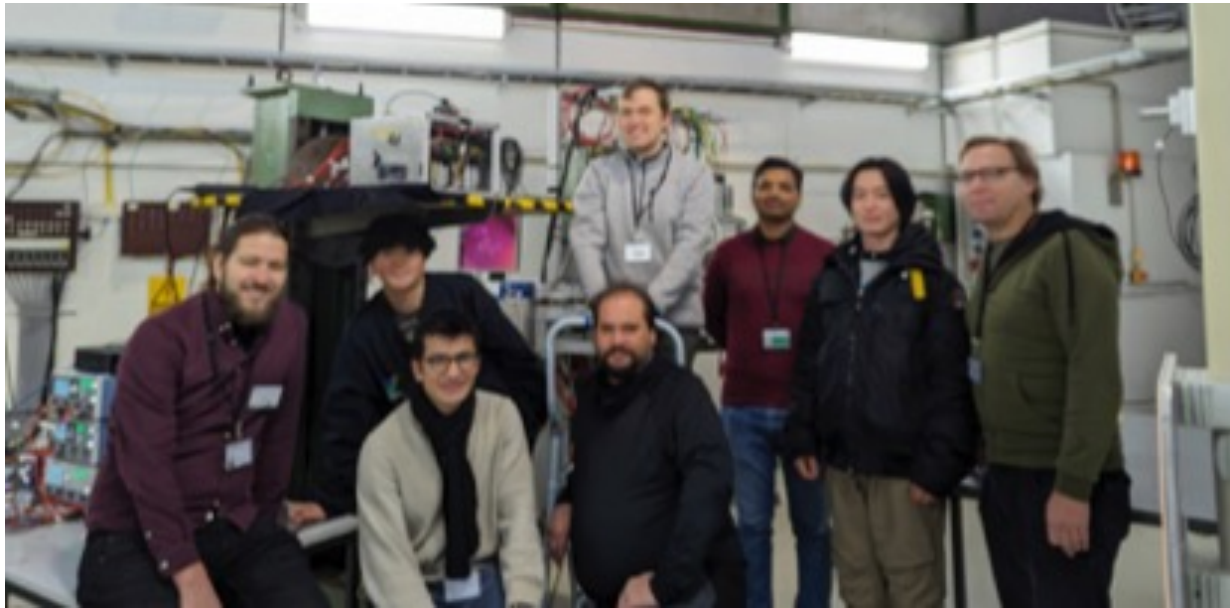
# ALICE-J activities in 2023



- Visit to Strasbourg in fall 2023
  - ✓ Learned how to operate a CE65 chip
  - ✓ Participated in DESY beam test led by IPHC
- Characterization of CE65v2 chips w/ different sensor designs
  - ✓ Lab tests using  $\gamma/\beta$  sources
  - ✓ Beam test at PF-AR test facility in the last March
    - In collaboration with ALICE Korea team
- Simulation study (allpix<sup>2</sup>)
  - ✓ Sensor response w/ different geometries
  - ✓ Initial discussion about readout and digitization

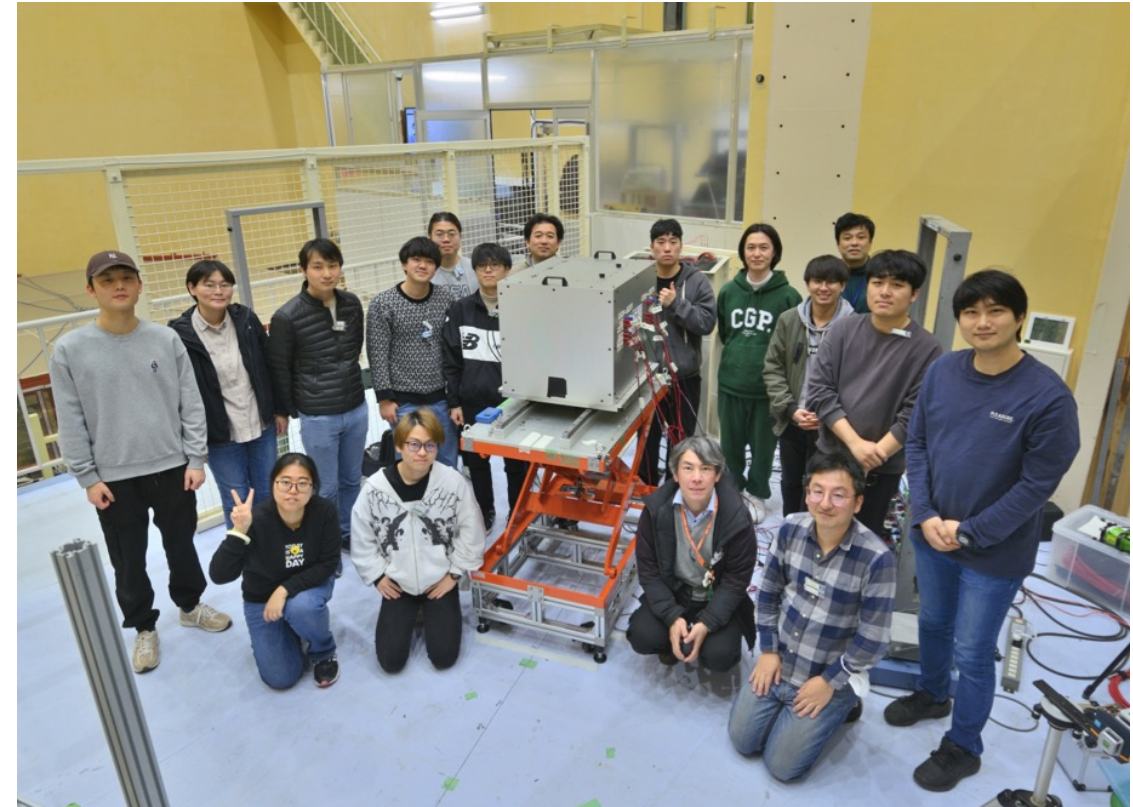
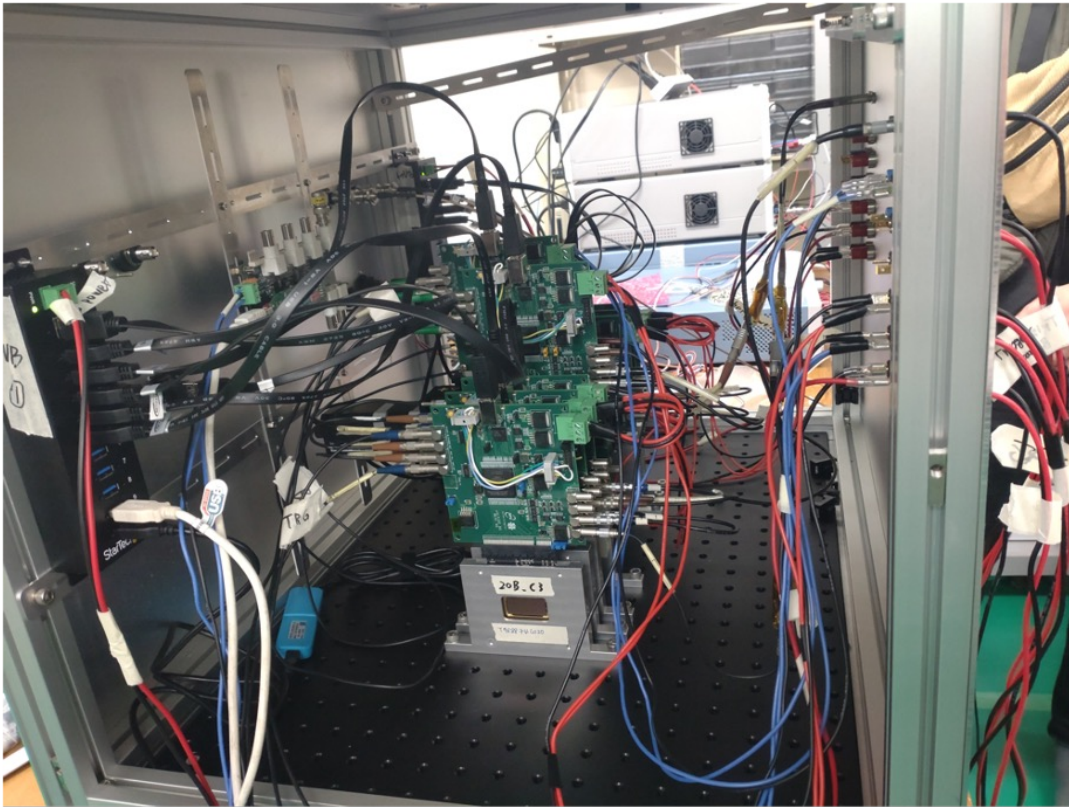
# DESY beam test & lab test setup

Participants of DESY beam test



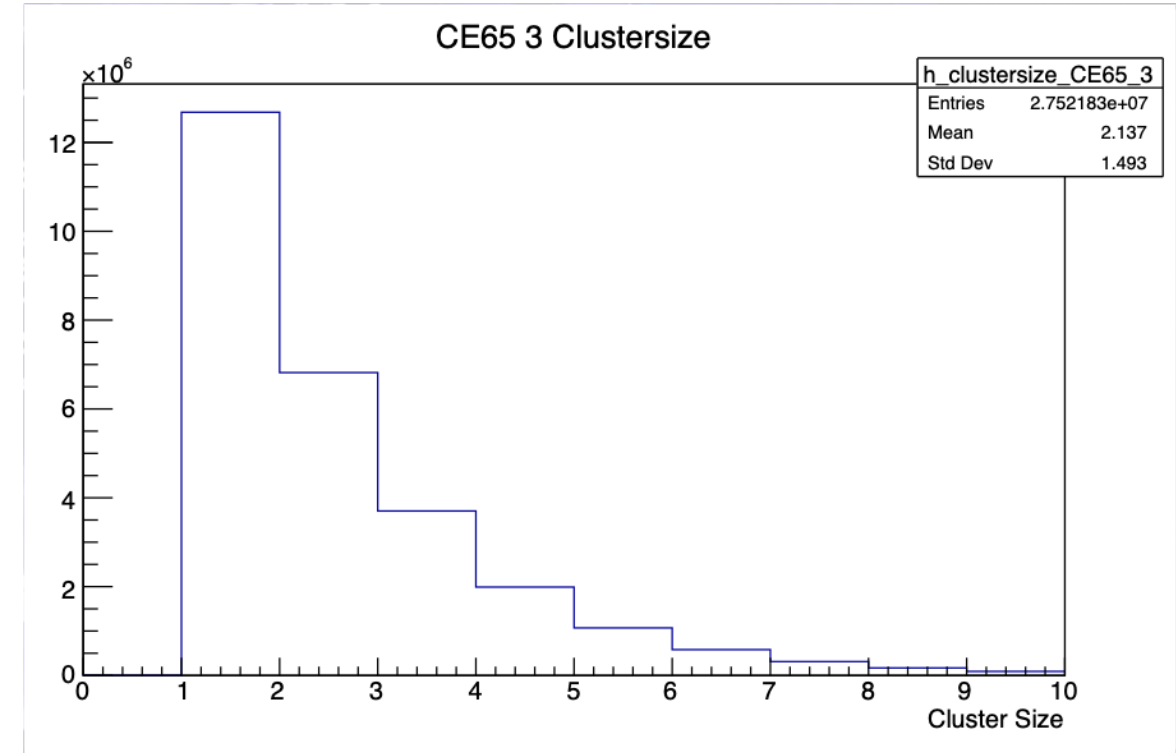
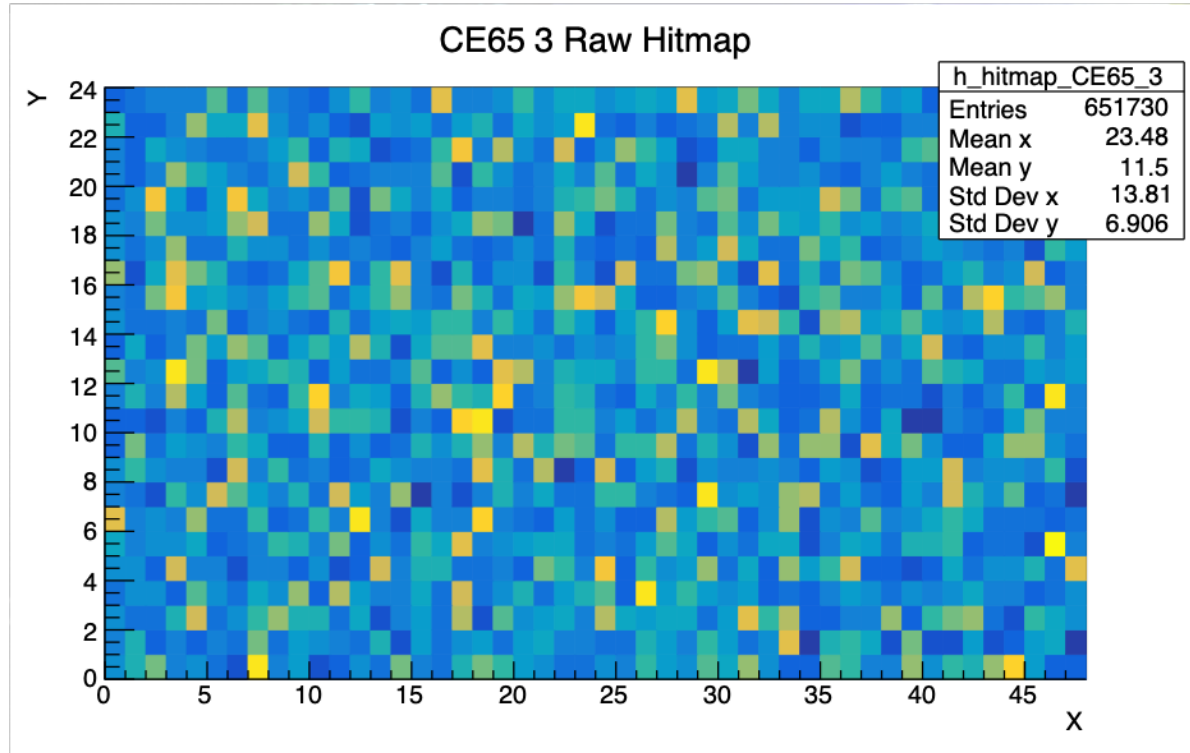
Single module test setup

# Beam test at KEK



- Telescope test with 3-5 GeV/c electron beams
  - ✓ Telescope box with 3+3 ALPIDEs from Korean colleagues
  - ✓ Low beam rate due to a large beam spot
  - ✓ Trigger provided by 10x10 mm<sup>2</sup> scintillators behind the last ALPIDE

# Quick look at KEK beam test data



- Look fine so far and further analysis is ongoing
  - ✓ Uniform hit distributions in X & Y axes of CE65 active area
  - ✓ Single cluster for most of hits

# Summary

- **Two main goals of BASHI project:**

- Development of OBELIX sensor (TowerJazz 180nm) for Belle II vertex upgrade VTX
- R&D on the new generation MAPS (TPSCo 65nm) for ALICE ITS3 and future applications

- **OBELIX sensor development for Belle II**

- TJ-Monopix2 characterization confirmed excellent performance of noise, efficiency and single-position resolution.
- OBELIX prototype design is ongoing, and submission will be late-2024.

- **TPSCo 65nm MAPS R&D for ALICE and future applications**

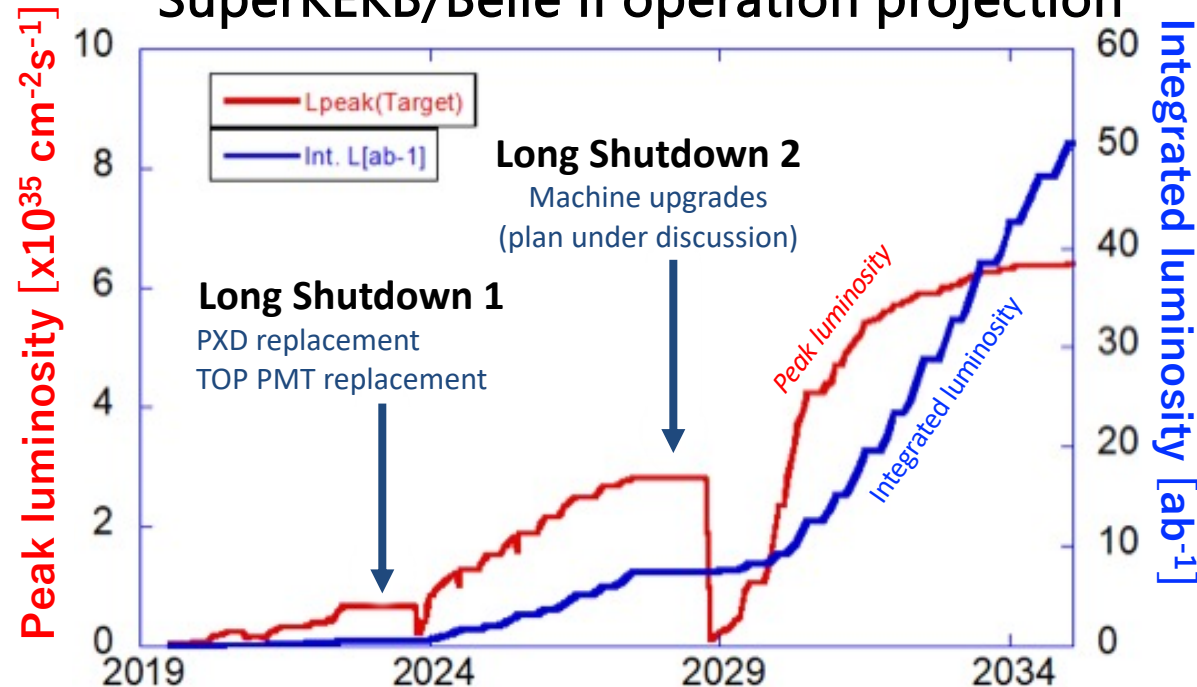
- Characterization of CE65v2 chips with different sensor designs. A beam test at KEK PF-AR test beamline was done; a quick look of the data shows excellent performance and detailed analysis is ongoing.
- Simulation study with allpix<sup>2</sup>

backup

# VXD upgrade project

- Upgrade of Vertex Detector (VXD) is one of the major activities in the Belle II detector upgrade.
  - Improve the beam BG tolerance
  - Improve the tracking/vertexing performance
  - Relax the limit of trigger latency
  - Necessity due to the possible IR/QCS modification
- Fully-pixelated detector will replace the current VXD (DEPFET+DSSD)
  - DMAPS or SOI
- The possible opportunity of the VXD upgrade is LS2.

SuperKEKB/Belle II operation projection



## DMAPS pixel technology

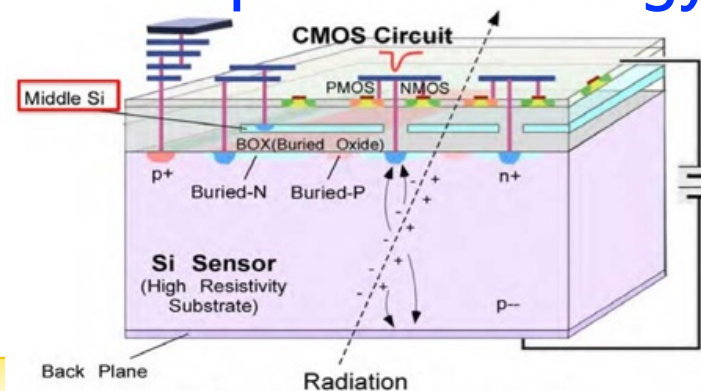
**DMAPS in TJ 180 nm: Concept**

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  - Compact, low power FE
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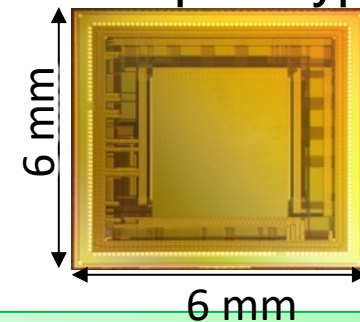
$C_d \leq 3fF$        $P \approx \frac{S}{N} \approx \frac{Q}{C_d}$

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

## SOI pixel technology



DuTiP 1<sup>st</sup> prototype sensor



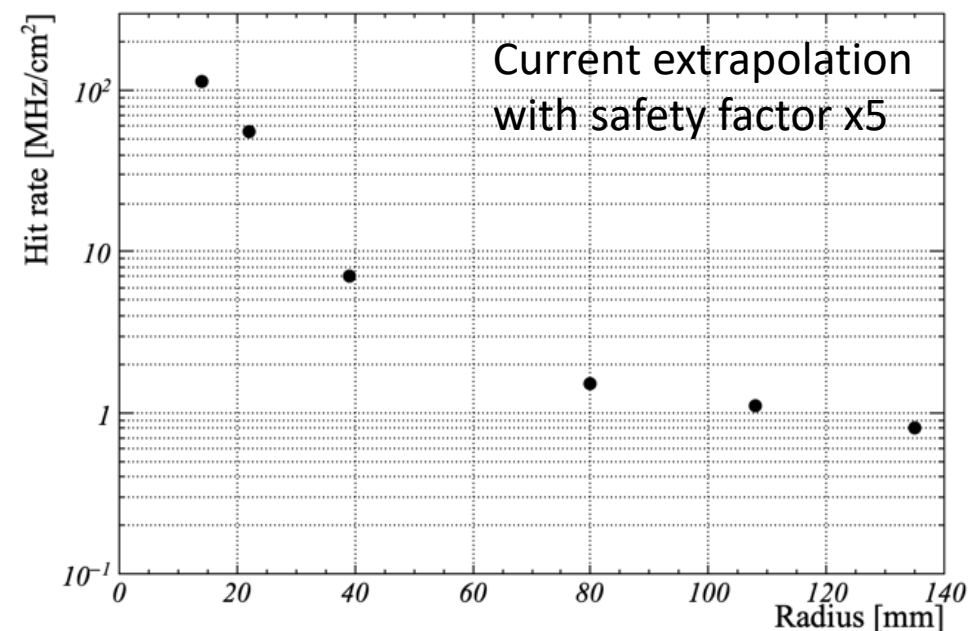
# Requirements for the VXD upgrade

## Targets

Radius range	14 – 135 mm
<b>Tracking &amp; Vertexing performance</b> at least as good as current VXD	
Single point resolution	< 15 $\mu\text{m}$
Material budget per layer	$\sim 0.2\% X_0$ (inner), $\sim 0.8\% X_0$ (outer)
Hit time resolution	< 100 ns
<b>Robustness against radiation environment</b> current extrapolation with safety factor x5	
Hit rate <sup>(*)</sup>	$\sim 120 \text{ MHz/cm}^2$
Total Ionizing Dose <sup>(*)</sup>	$\sim 0.1 \text{ MGy/year}$
NIEL fluence <sup>(*)</sup>	$\sim 5.0 \times 10^{13} \text{ n}_{\text{eq}}/\text{cm}^2/\text{year}$

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

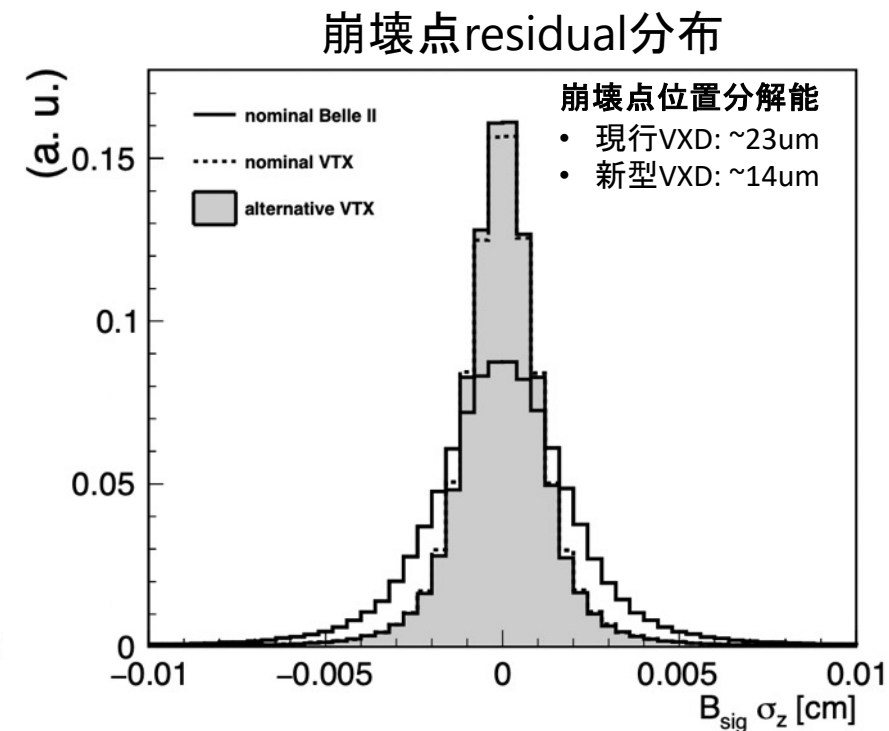
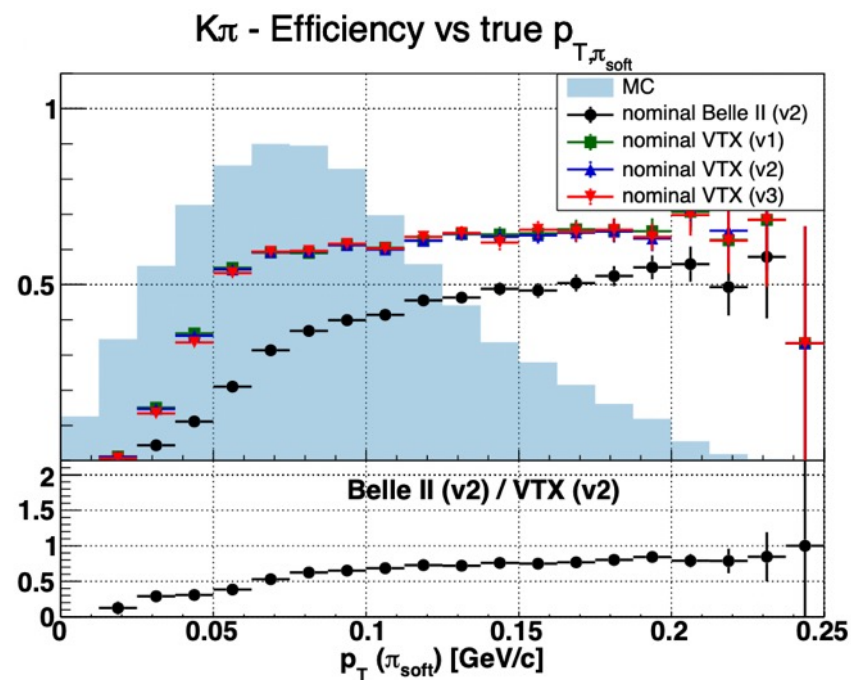
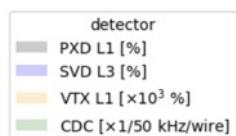
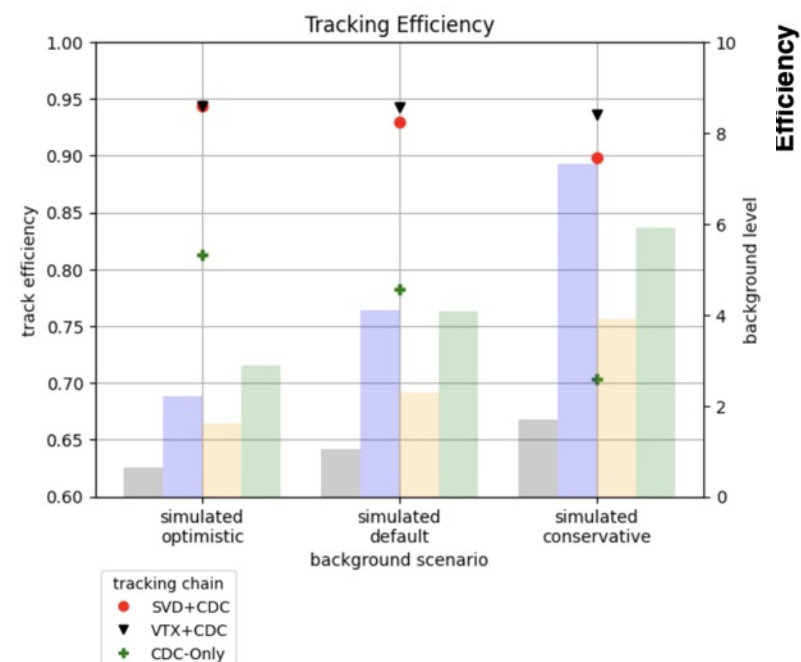
## Required hit rate tolerance vs. Radius



## Possible other improvements by upgrade

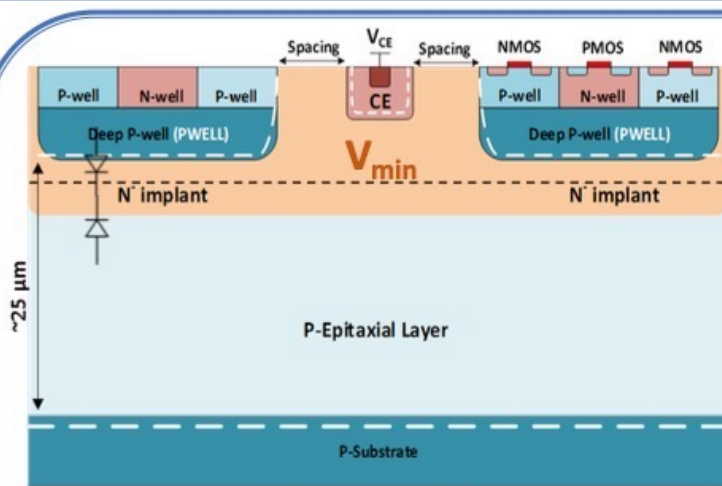
- Impact parameter resolution
- Tracking performance for low- $p_T$  tracks
- Longer trigger latency
- Capability of Level-1 trigger creation

# Performance improvement by VTX



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

# TowerJuzz Monopix-2



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

$$C_d \leq 3fF$$

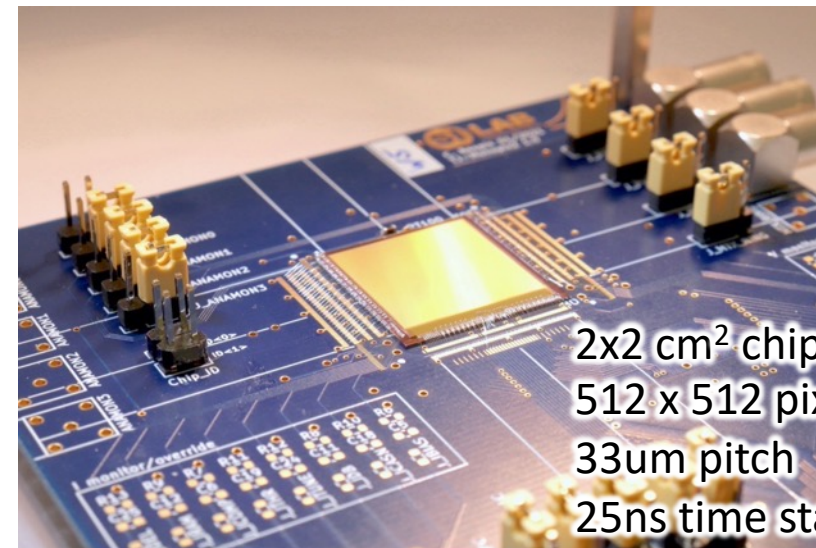
$$P \approx \frac{S}{N} \approx \frac{Q}{C_d}$$

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W. Snoeys et al.: [NIM A 871 \(2017\) 90](#)

## TJ-Monopix2 sensor

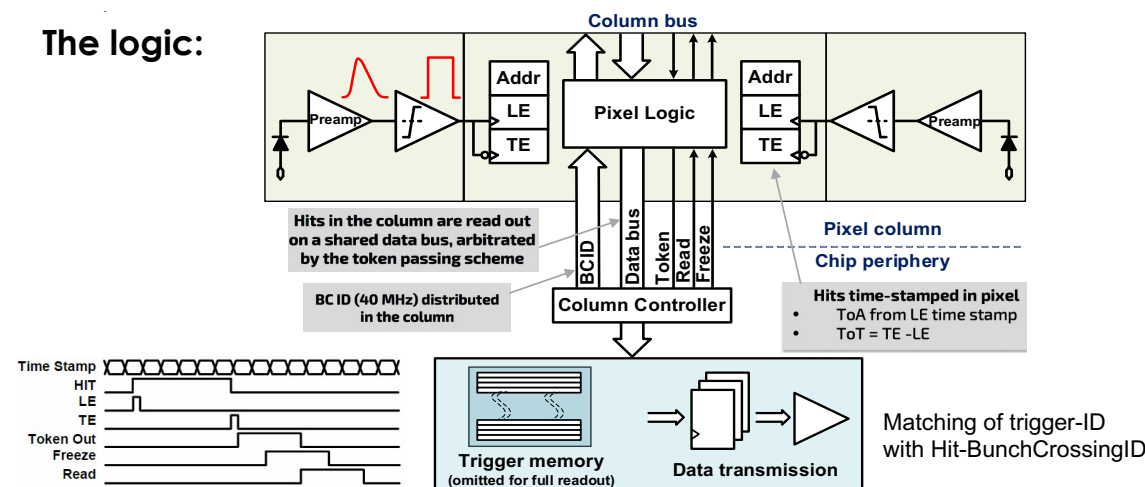


2x2 cm<sup>2</sup> chip  
512 x 512 pixels  
33μm pitch  
25ns time stamping

## TJ-Monopix2 sensor: developed for HL-ATLAS

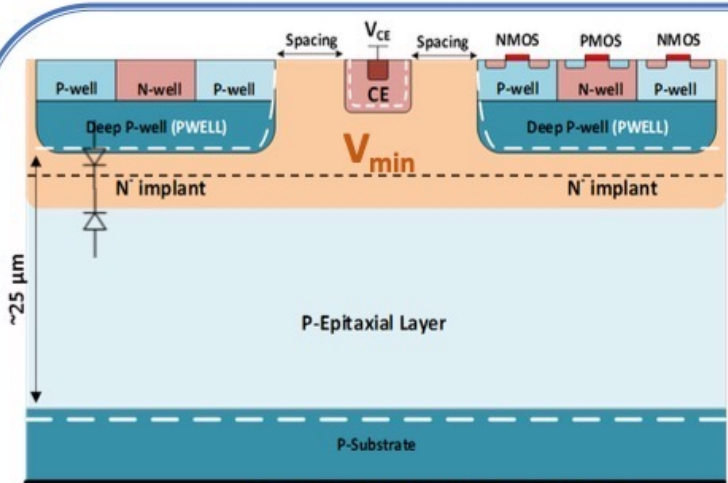
- DOI: [10.1016/j.nima.2020.164403](https://doi.org/10.1016/j.nima.2020.164403)
- 7-bit ToT, 3-bit in-pixel threshold tuning
- Column-drain read-out inherited from ATLAS FE-I3
- Detection efficiency assessed up to 10<sup>15</sup> neq/cm<sup>2</sup>

The logic:



K. Moustakas: CERN-THESIS-2021-146

# OBELIX (Optimized BELle II monolithic pIXel sensor)



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

$$C_d \leq 3fF$$

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

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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
- TowerJazz 180nm

## 1st prototype design ongoing

	TJ-Monopix2	OBELIX (target)
Year	2020	2024 (1st prototype)
Pixel pitch	33 μm	33 μm
Sens. area	17x17 mm <sup>2</sup>	~30x16 mm <sup>2</sup>
Sens. thickness	25-100 μm	~30 μm
Integration	25 ns	25 to 100 ns
Bandwidth	320 MHz	320 MHz
Power	200 mW/cm <sup>2</sup>	< 200 mW/cm <sup>2</sup>
TID fluence	0.1 MGy 10 <sup>15</sup> n <sub>eq</sub> /cm <sup>2</sup>	< 1 MGy < 5x10 <sup>14</sup> n <sub>eq</sub> /cm <sup>2</sup>

# Irradiated TJ-Monopix2 Beam Test

Serial	Irradiation	Substrate
W02R05	None	30 $\mu\text{m}$ EPI
W02R09	Neutrons $1 \times 10^{14}$	30 $\mu\text{m}$ EPI
W05R16	Protons $5 \times 10^{14}$	30 $\mu\text{m}$ EPI
W08R19	None	30 $\mu\text{m}$ EPI
W14R12	None	Cz

Parameter scans:

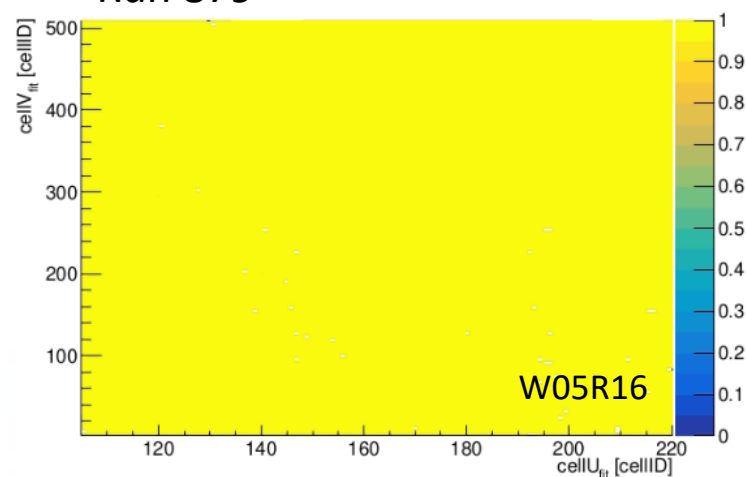
HV, IBias, PSub, VClip, BCID, ...

Angular scans, resolution, efficiency

Efficiency  $>99\%$  for  $5 \times 10^{14} \text{ n}_{\text{eq}}/\text{cm}^2$  (310  $e^-$  threshold)

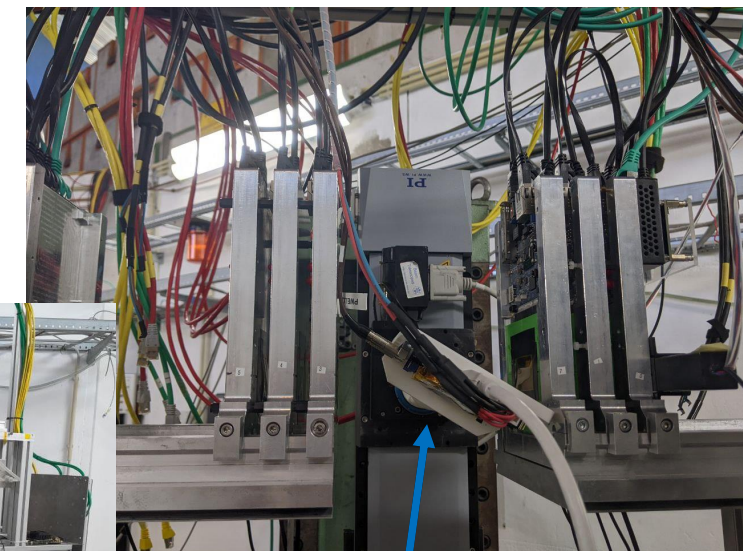
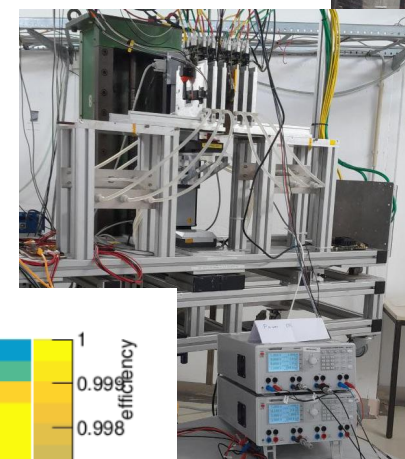
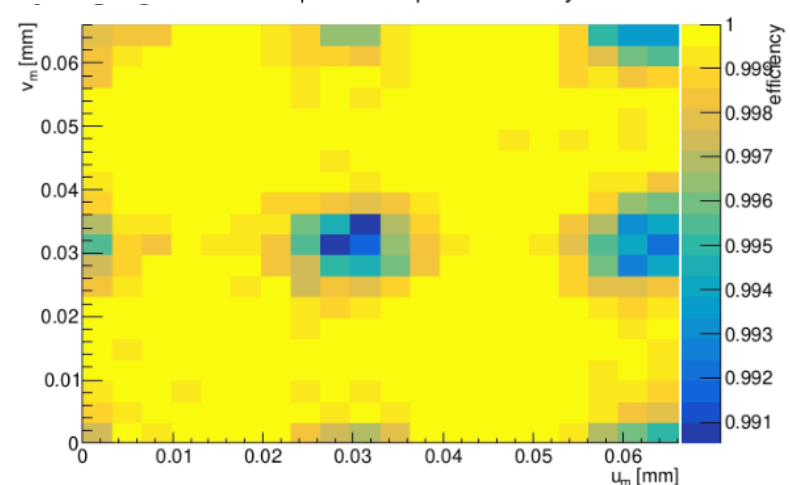
Cluster position residuals  $\sim 9.5 \mu\text{m}$

Run 879 Roi hit efficiency map



cmarinas@ific.uv.es

perPixel inpixel efficiency

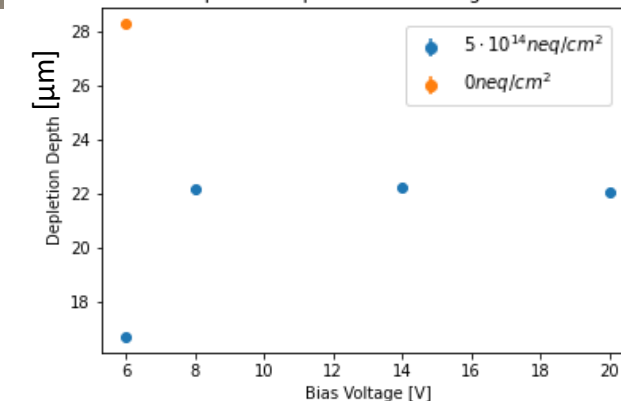


Telescope  
planes 4-6

TJ-Monopix2

Telescope  
planes 1-3

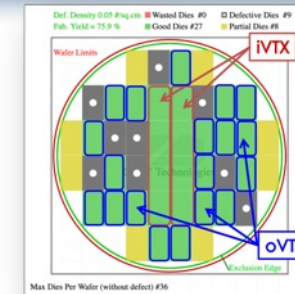
Depletion Depth vs. Bias Voltage for NF



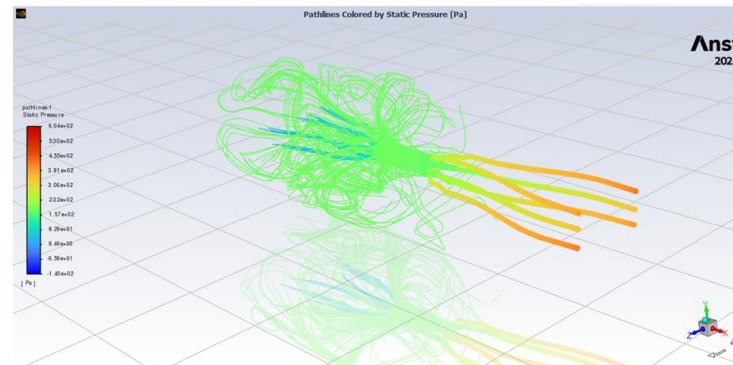
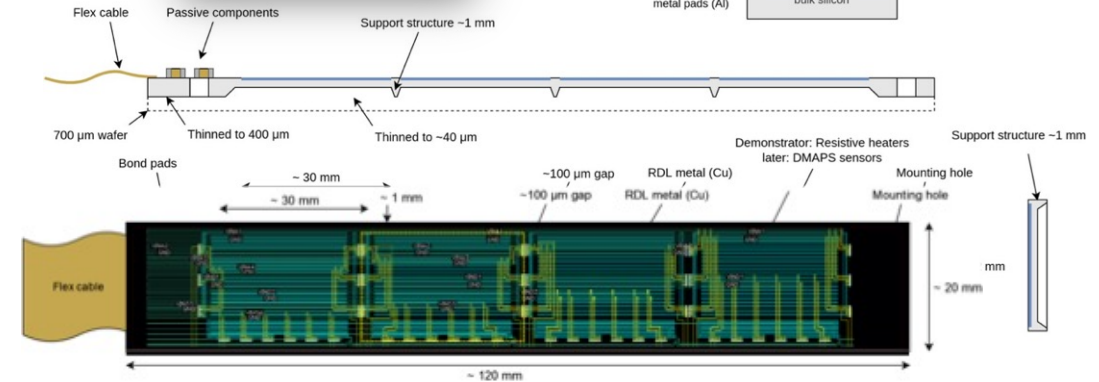
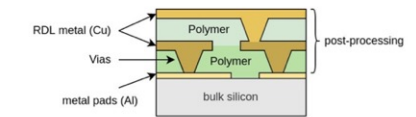
# iVTX Inner Layer Concept

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

- Simulation on cooling
  - Dry air cooling  $15^\circ\text{C}$
  - Assume  $200 \text{ mW/cm}^2$



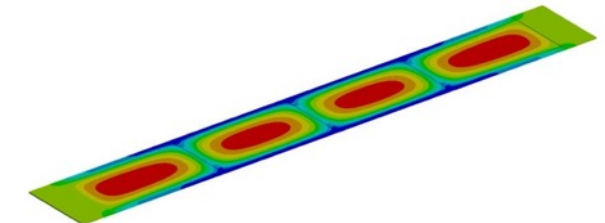
## Cu Redistribution layer (RDL)



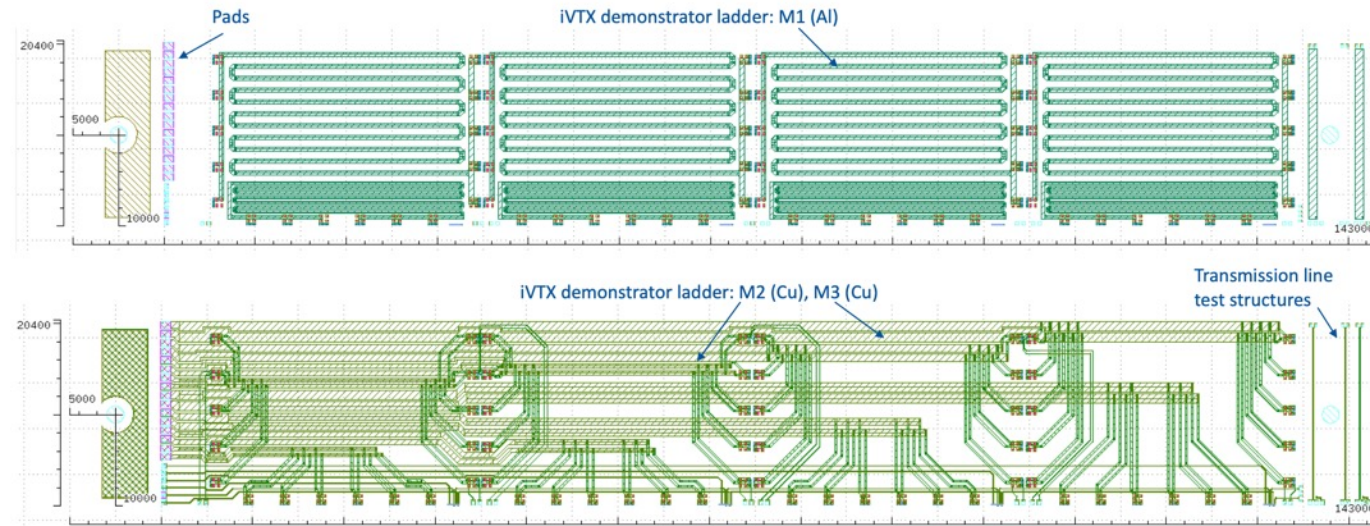
B: Coques  
 Temperature  
 Type: Temperature  
 Unit: °C  
 Temps: 1 s  
 03/06/2022 10:57

19,838 Max  
 19,723  
 19,609  
 19,494  
 19,38  
 19,265  
 19,151  
 19,036  
 18,922  
 18,807 Min

$T_{\text{MAX}} \sim 20^\circ\text{C}$   
 $\Delta T < 5^\circ\text{C}$



# Demonstrator mockup with dummy Si

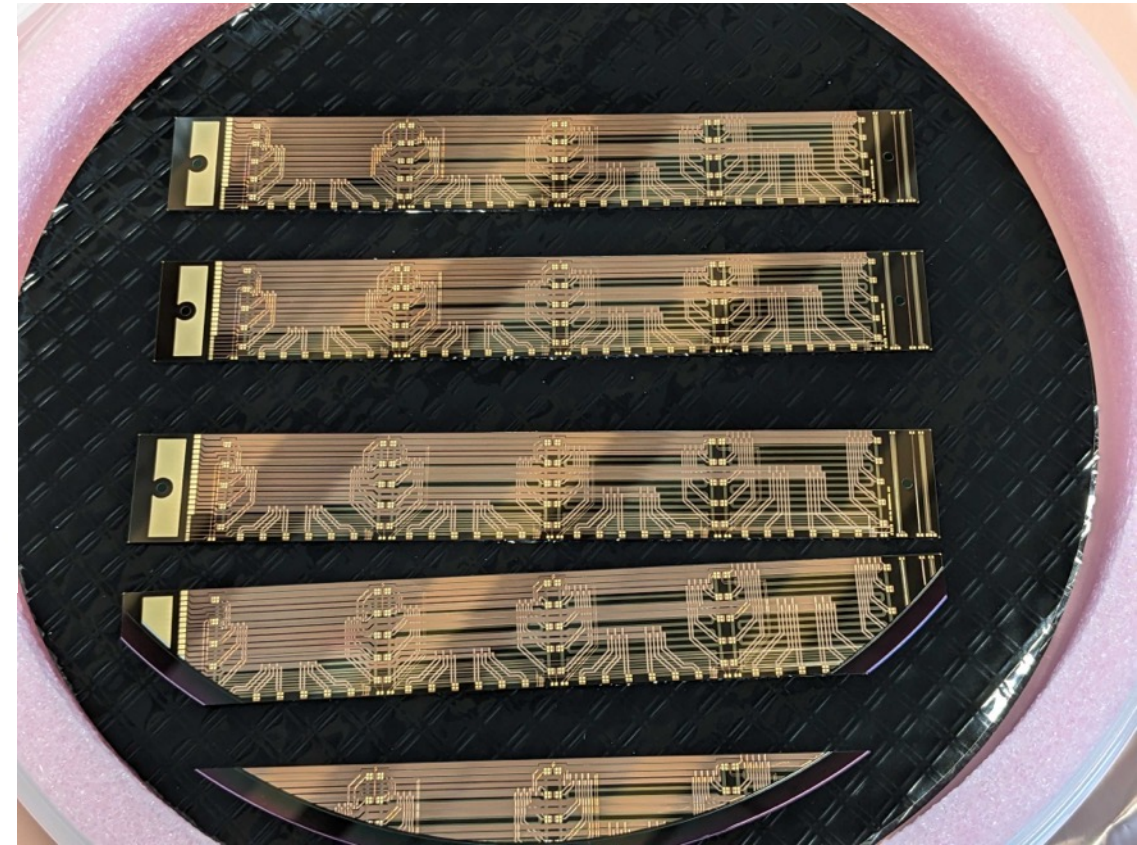


## Metal system:

- Resistive heaters: 1.5  $\mu\text{m}$  Al (M1)
- 2 RDL metal layers: 3  $\mu\text{m}$  Cu (M2, M3)
- Top metal finish: NiAu (M4)

Wirebonding, SMD soldering

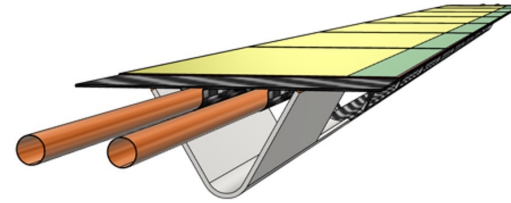
Final ladder dimension: 143 x 20.4  $\text{mm}^2$



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



- L3-4, radius 4-9 cm, length  $< 50 \text{ cm}$ 
  - Single sensor row,  $\sim 0.5 \% X_0$
- L5, radius 14 cm, length 70 cm
  - Double sensor rows,  $\sim 0.8 \% X_0$

