OCTOPUS Project

Optimized CMOS Technology fOr Precision in Ultra-thin Silicon

Towards Lepton Collider Vertex Detector Demonstrator

Gianpiero Vignola on behalf of the OCTOPUS project

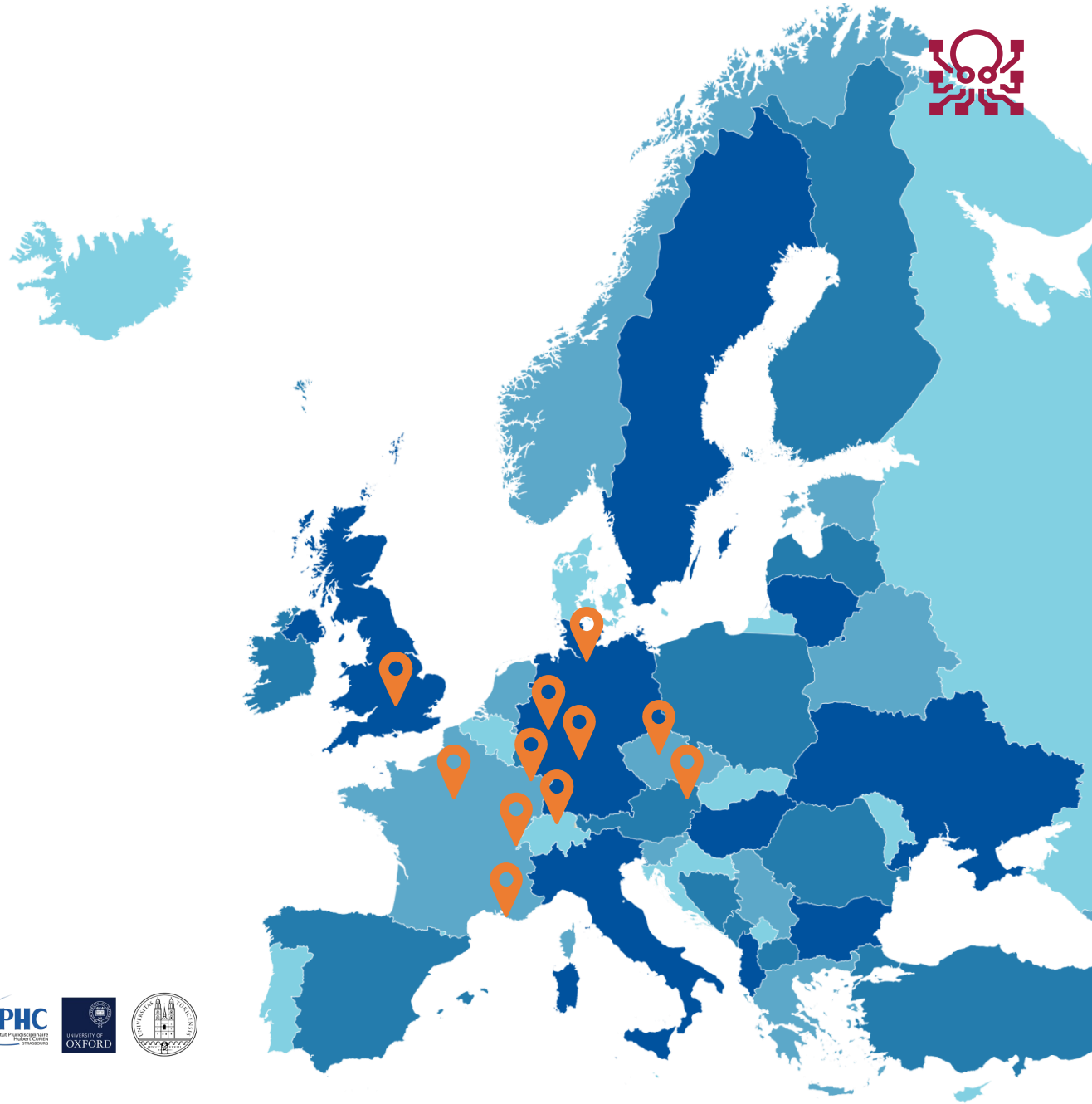
13th Beam Telescopes and Test Beams Workshop
Valencia, 22 May 2025

HELMHOLTZ

OCTOPUS Institutes

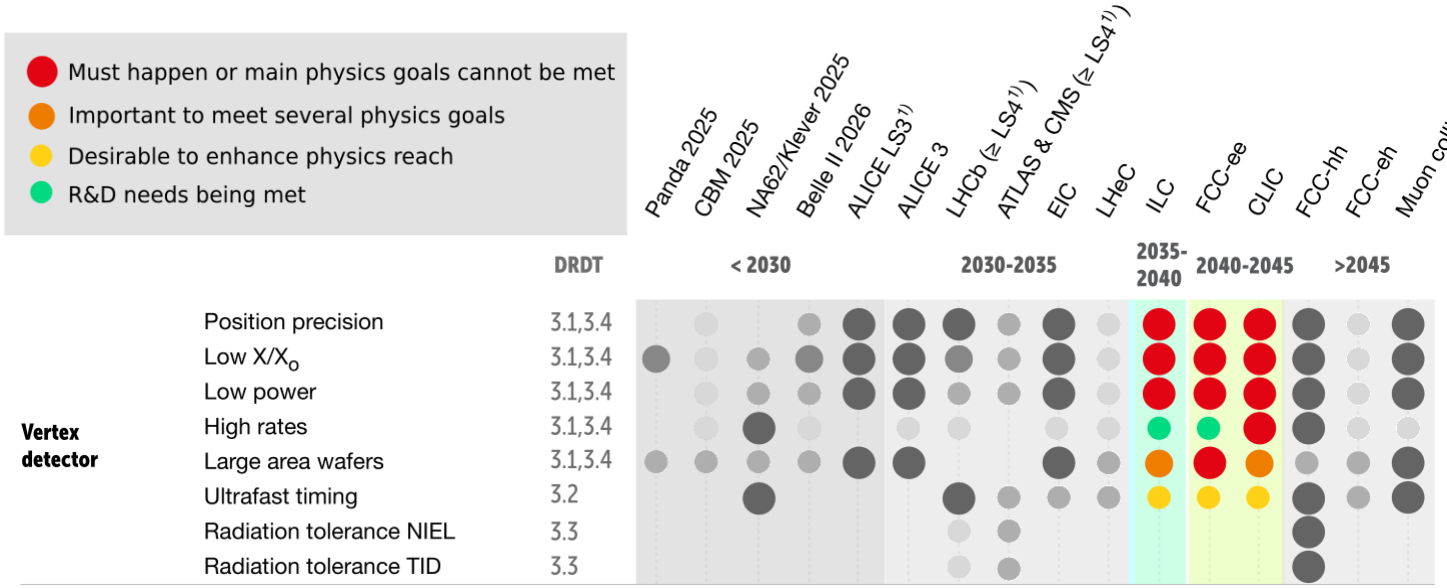
International Project within DRD3 Collaboration

Member institute	Representative
Laboratoire Astroparticule & Cosmologie	M. Bomben
Universität Bonn	J. Dingfelder
Centre de Physique des Particules de Marseille	M. Barbero
CERN	D. Dannheim
Deutsches Elektronen-Synchrotron	S. Spannagel
Eidgenössische Technische Hochschule Zürich	M. Backhaus
Faculty of Nuclear Sciences and Physical Engineering, Czech Technical University	P. Svihra
GSI Helmholtzzentrum für Schwerionenforschung	M. Deveaux
Institut für Hochenergiephysik der Österreichischen Akademie der Wissenschaften	T. Bergauer
Institut Pluridisciplinaire Hubert Curien	A. Besson
University of Oxford	D. Bortoletto
Universität Zürich	A. Macchiolo

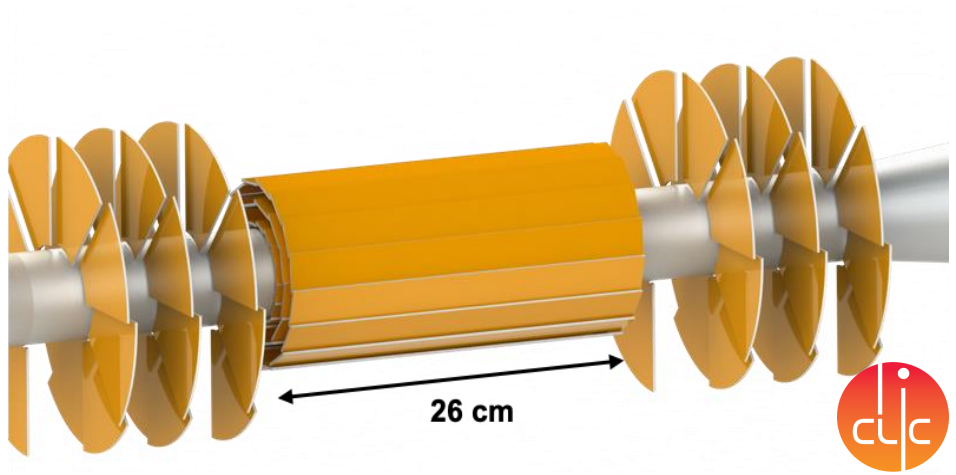


Goal: Vertex Detectors for Future Lepton Colliders

Precise Detectors for Precision Physics



Key R&D activities for solid-state vertex detector, from ECFA detector R&D roadmap (2021)



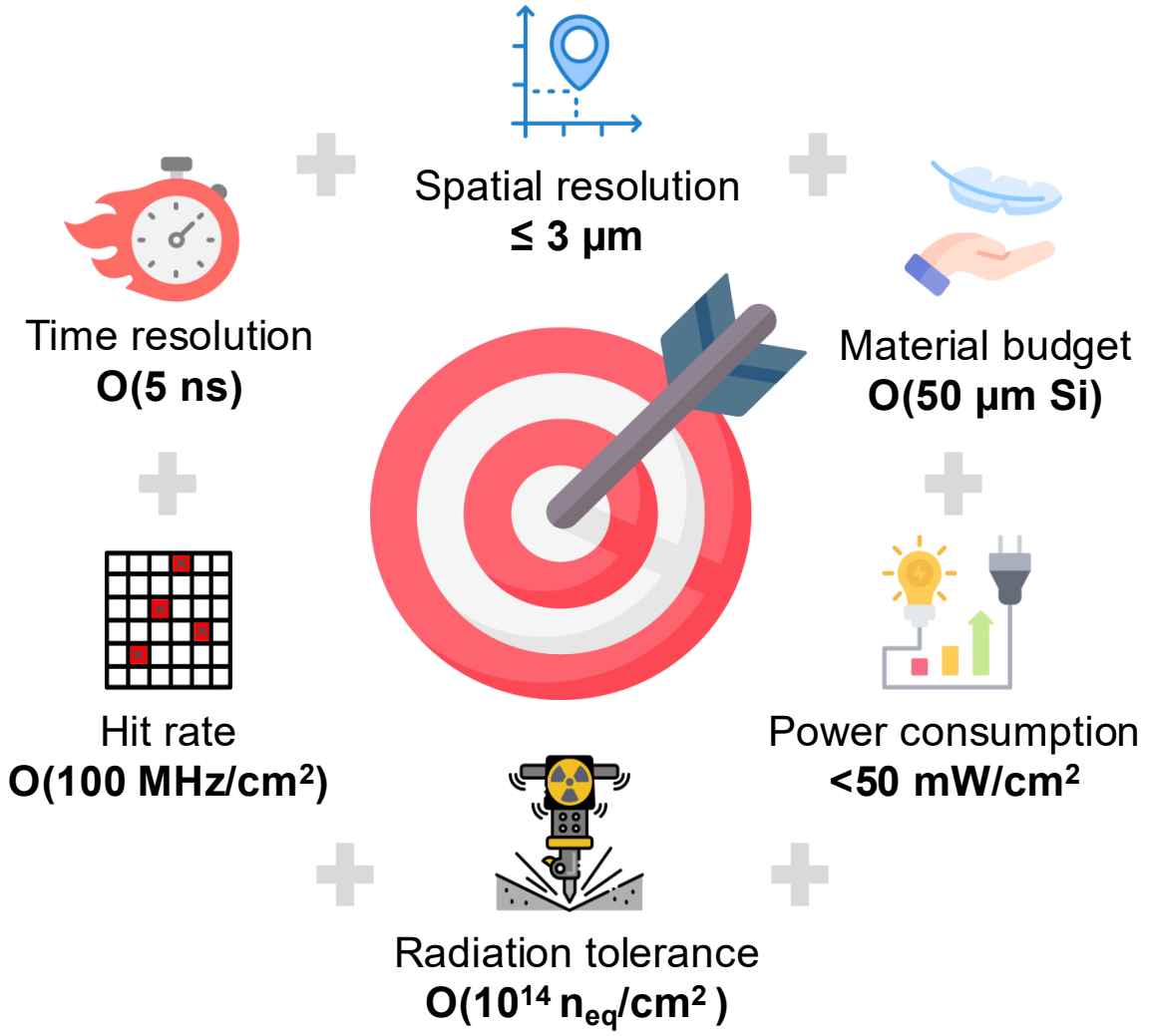
CLIC vertex detector concept

- Similar silicon-based vertex detector concept for all the major lepton colliders experiments proposals
- More stringent requirements compared to the existing vertex detectors

OCTOPUS Project: Final Target

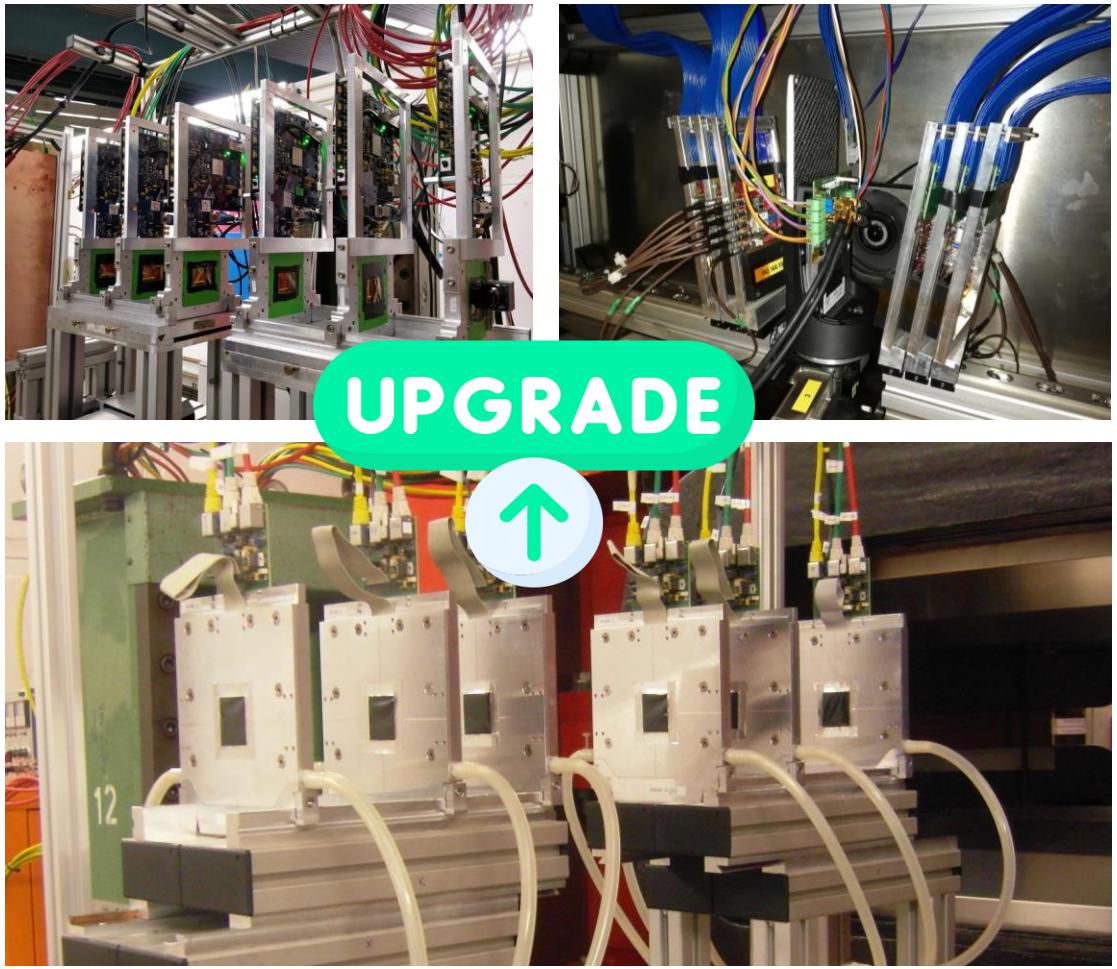
Vertex Sensor Demostrator

- Development of a full-size sensor demonstrator for future lepton collider vertex detectors
- Targhet vertex-detector requirements outlined in the ECFA detector roadmap
- Simulate, develop and test fine-pitch pixel sensors prototypes
- Exploiting synergies with related R&D activities and other DRD groups
- Staged approach: adapting to upcoming strategy update raccomandations



OCTOPUS Project: Intermediate Target

Development of High Resolution Sensor for Beam Telescopes



Spatial resolution
≤ 3 µm

Time resolution
~~**O(5 ns)**~~
O(100 ns)

Material budget
O(50 µm Si)

Hit rate
O(100 MHz/cm²)

Power consumption
~~**<50 mW/cm²**~~
<500 mW/cm²

Radiation tolerance
O(10^{14} n_{eq}/cm²)

OCTOPUS Project Structure

Four Workpackages

WP1: Simulations
A. Ilg, A. Velyka

WP2: ASIC
F. Guezzi, L. Huth, S. Senyukov

WP3: Data Acquisition
Y. Otarid

WP4: Testing & Characterization
F. King, M. Franks

Current Timeline and Deliverables

OCTOPUS Project

2025 | 2026 | 2027 | 2028 | 2029 | 2030

Simulations & Measurements Validation

ASIC Design & Verifications

DAQ Preparation and Assembly

DAQ Preparation and Assembly

Summary of Related Studies

1st Prototype Testing

2th Prototype Testing

Report
on Previous
Related Studies

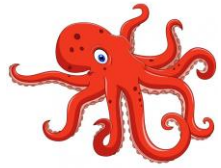
(WOLFI)

1st prototype
Matrix demonstrator

Report
on 1st prototype

2th prototype
Beam telescope

Report
On 2th prototype

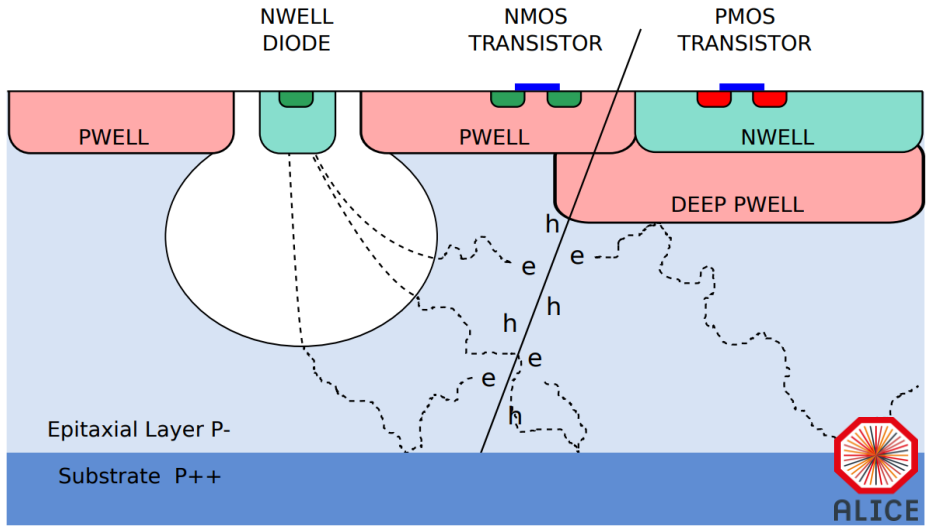


3rd prototype
Vertex sensor
demonstrator

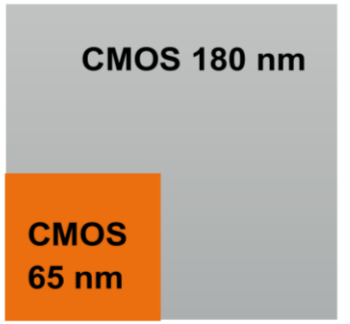
Technology: Monolithic Active Pixel Sensors

Towards New Generation of MAPS

- Small collection electrode MAPS developed in commercial CMOS processes
- Already in use as detectors in HEP experiments
- Several R&D ongoing for the next-gen. MAPS produced using a 65 nm process
- MLR1 (2021) and ER1 (2023) multi-project submission to TPSCo65 CIS



ALPIDE MAPS pixel sketch

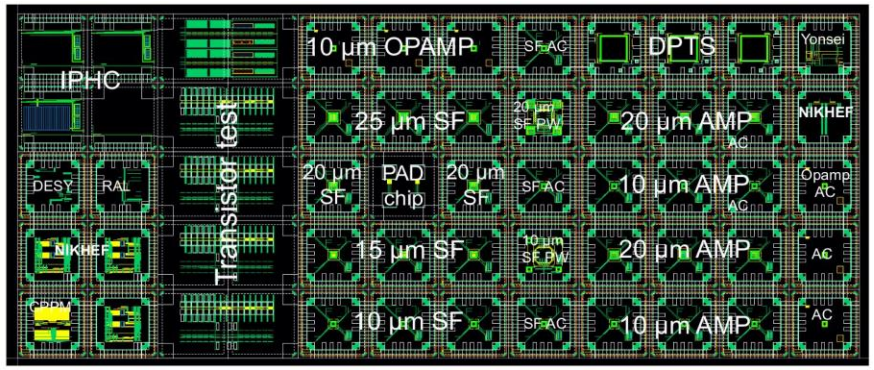


Higher logic density

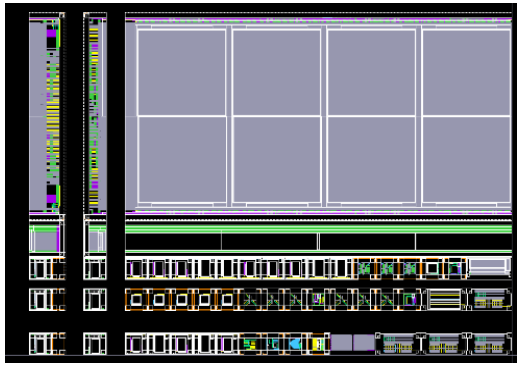
✓ Smaller pixel

✓ Decrease in power

✓ More in-pixel functionality



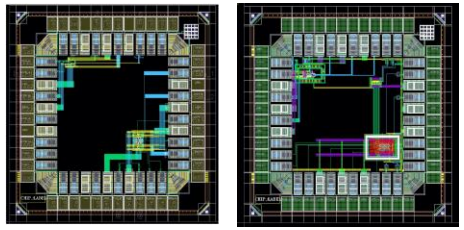
MLR1 reticle

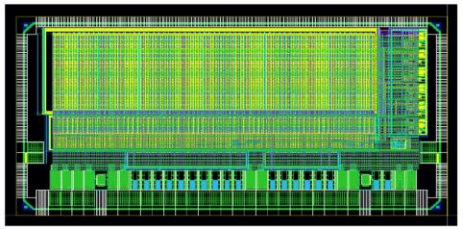


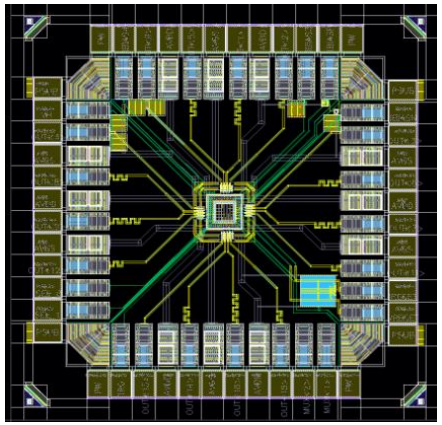
ER1 reticle

Previous Experience: Tangerine Project

Converging in the OCTOPUS Project







Studies on DESY Chip V1 and V2

- Implementation and testing of a fast CSA with Krummenacher feedback
- Verified the possibility of achieving ns timing

Studies on Hybrid To Monolithic (H2M)

- Ported an hybrid pixel detector architecture into a monolithic chip with digital on top design
- Extensive prototype calibration and characterizations

Studies on Analog Pixel Test Structures

- Conducted in collaboration with ALICE group
- Studied and compared different sensor layouts and pixel pitches
- Validation of TCAD+Allpix^2 simulations results

See:
BTTB13 Larissa Mendes
BTTB13 Finn King, Sara Ruiz Daza

Publications:
[1], [2], [3], [4], [5], [6], [7], [8]

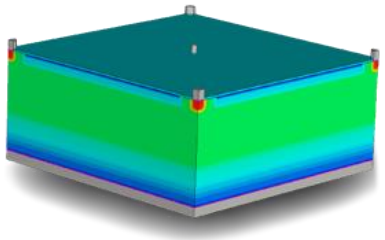
WP1: Simulations

Workflow in OCTOPUS

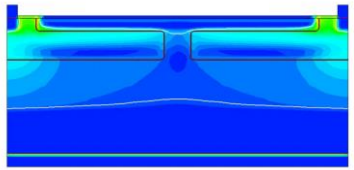
Sentaurus TCAD SYNOPSYS® Silicon to Software™

ap² allpix squared

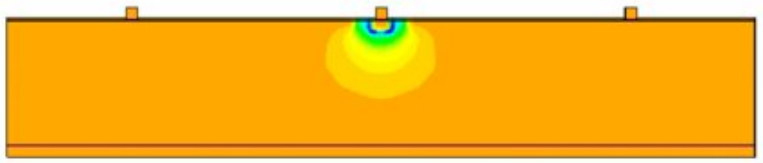
LTspice®



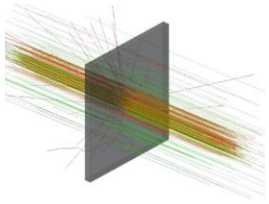
Generic doping profile



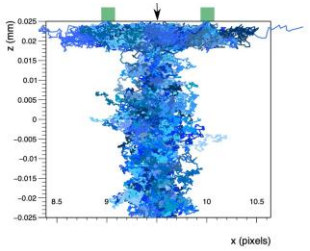
Electric field



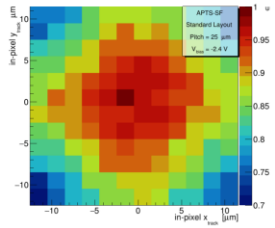
Weighting potential



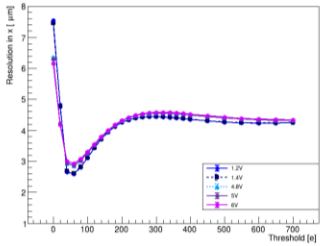
Particle interaction



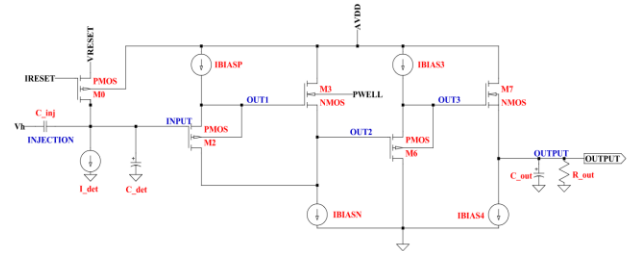
Sensor response

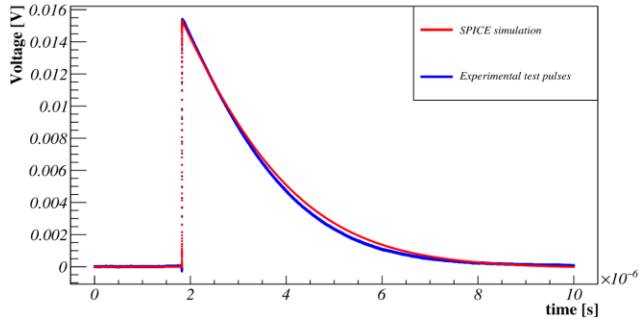


Efficiency



Spatial resolution

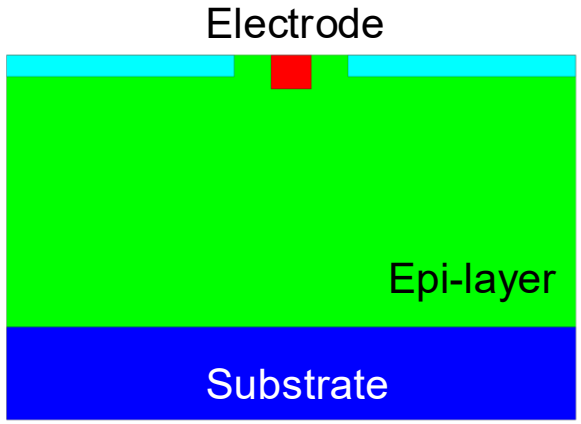




Realistic front-end response simulation

WP1: Simulations

Sensor Layout

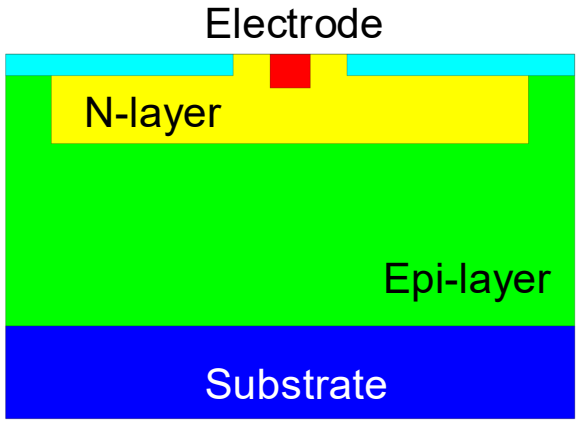


Standard Layout

- Good spatial resolution (charge sharing)
- More space for electronics (larger pitch)
- Slow charge collection (diffusion)
- Low efficacy at high thresholds

Standard Simulations WORK IN PROGRESS

Pitch	20 - 25 µm
Voltage	1.2 - 6.0 V
Read-out	0 – 8 bins



N-Gap Layout

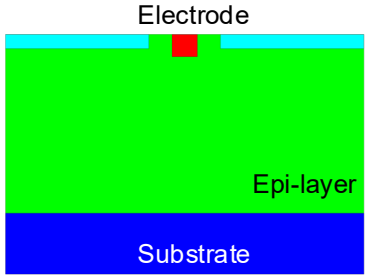
- Fast charge collection (drift)
- High efficacy at high thresholds
- Limited spatial resolution (binary)
- Less space for electronics (smaller pitch)

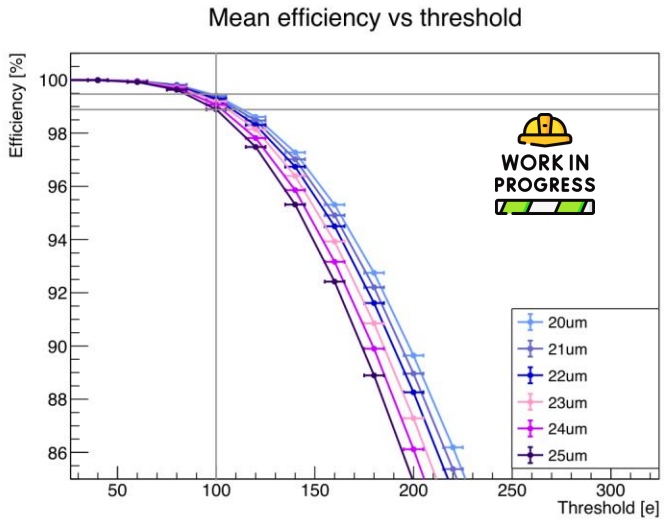
N-Gap Simulations WORK IN PROGRESS

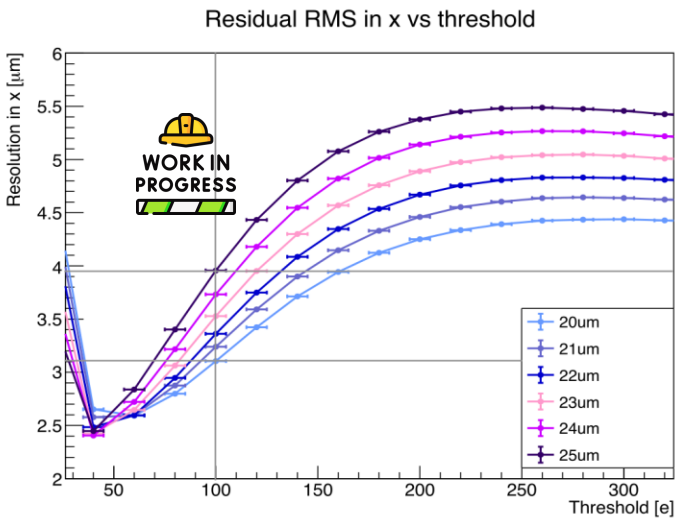
Pitch	10 - 14 µm
Gap-size	1 – 2 µm
Voltage	1.2 - 6.0 V
Read-out	0 – 1 bins

WP1: Simulations

First results

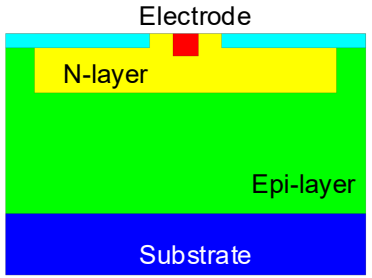


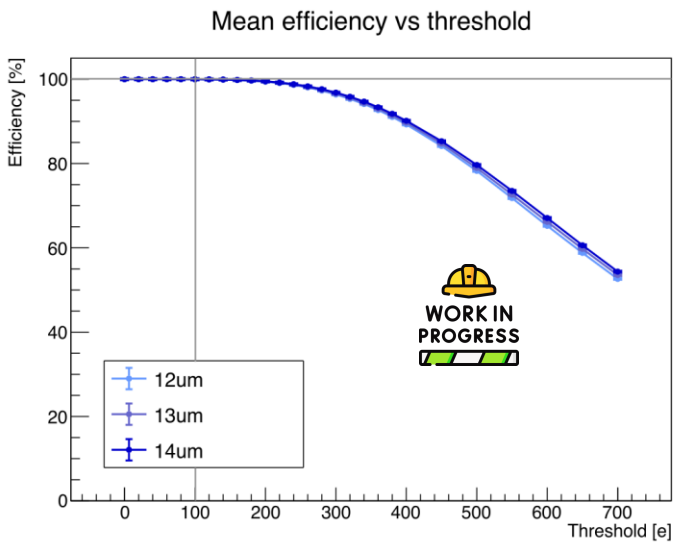


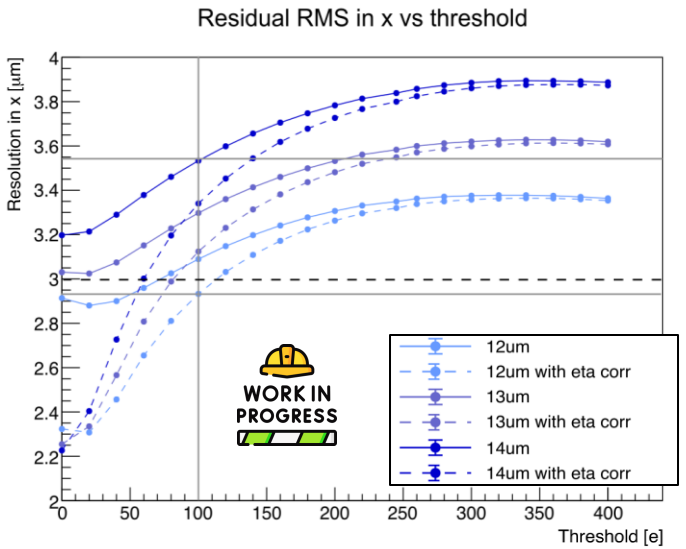


Standard Layout

- O(20 µm) pitch required
- Lose efficiency at low thr.
- Require charge measurement (few bits)





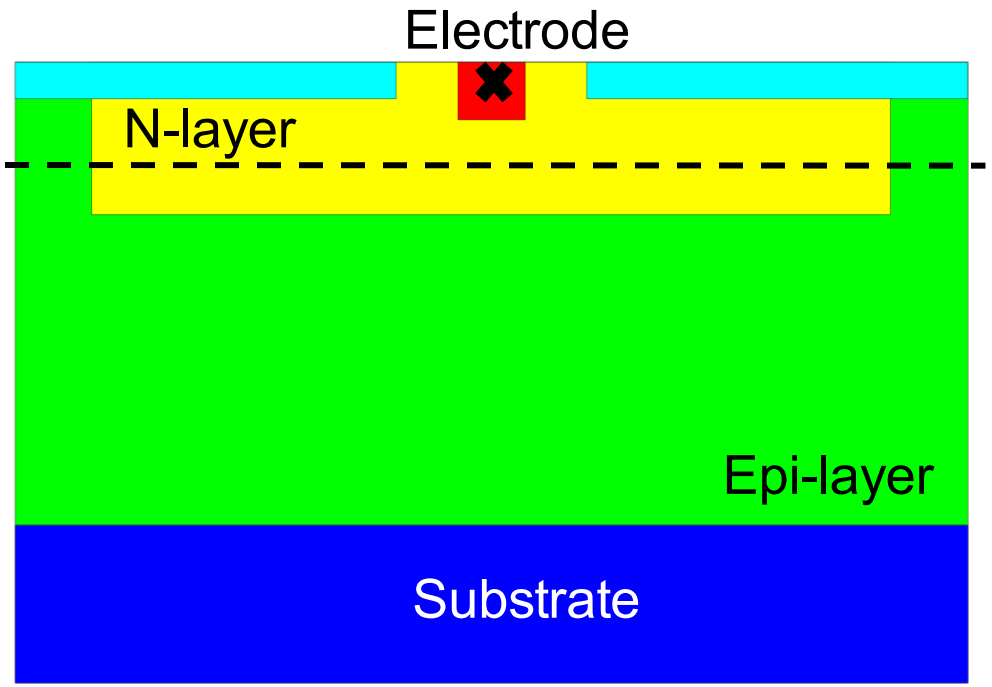


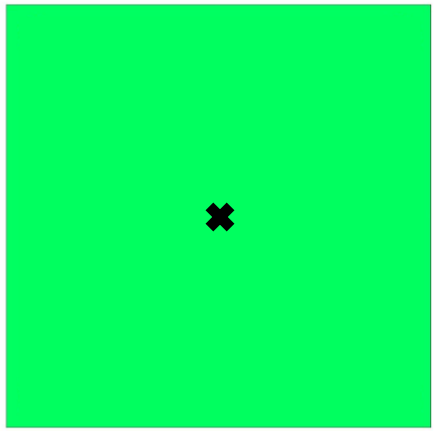
N-Gap Layout

- O(12 µm) pitch required
- Good efficiency up to high thr.
- Require η-correction for optimal spatial performances

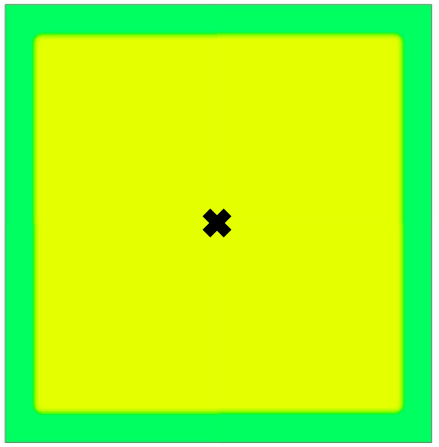
WP1: Simulations

Investigation on Possible New Sensor Layouts

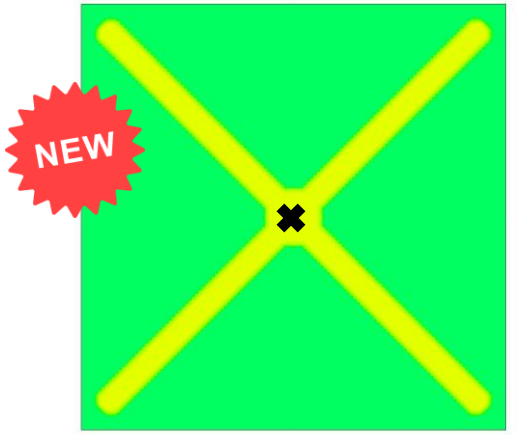




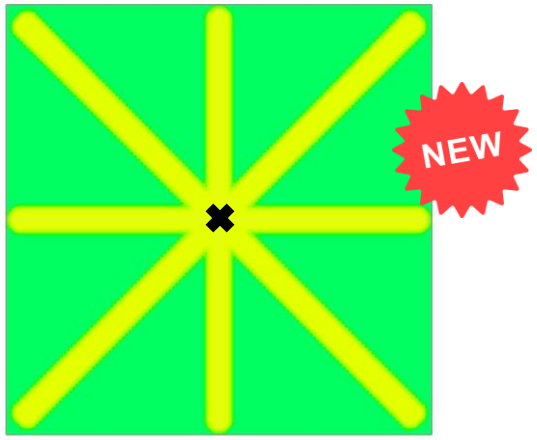
Standard



NGap



N-Opt-Cross



N-Opt-Octo

- New layouts try to balance performance of Standard and N-gap variants
- N-structures optimized to improve efficiency/timing while preserving spatial resolution (diffusion regions)

WP1: Simulations

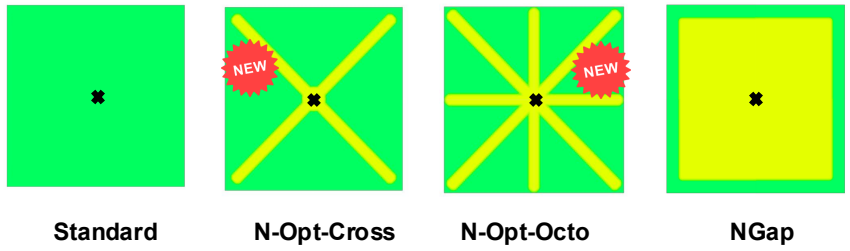
Investigation on Possible New Sensor Layouts

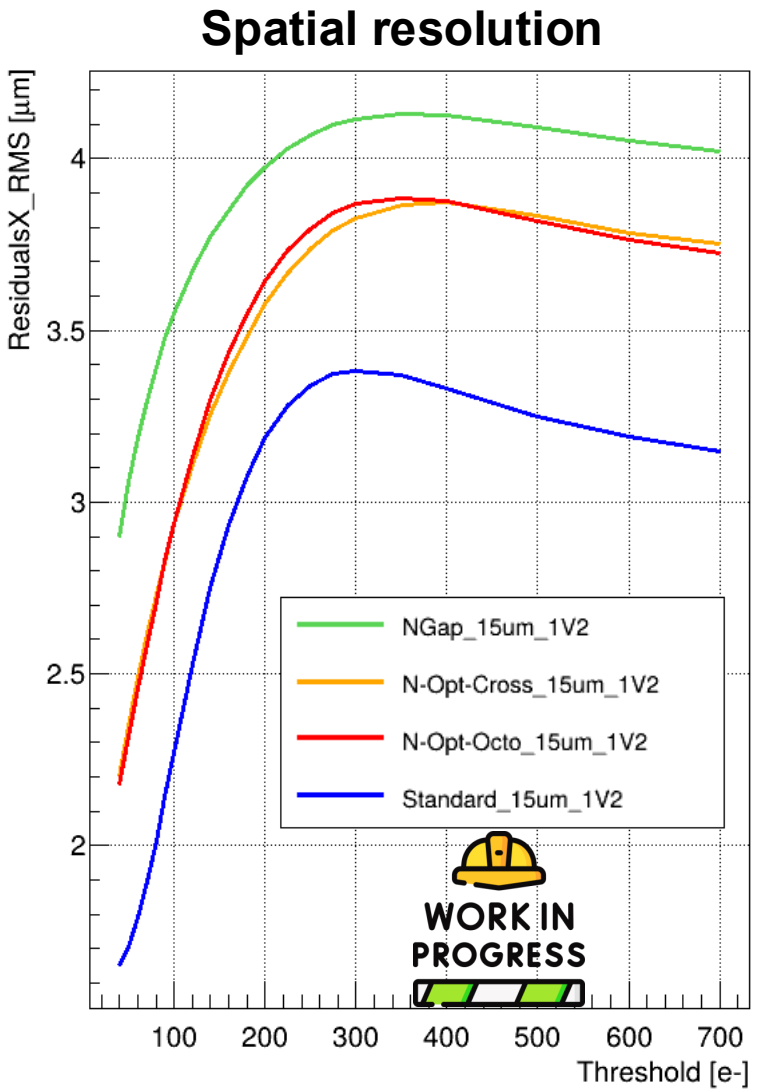
Results for New Layouts

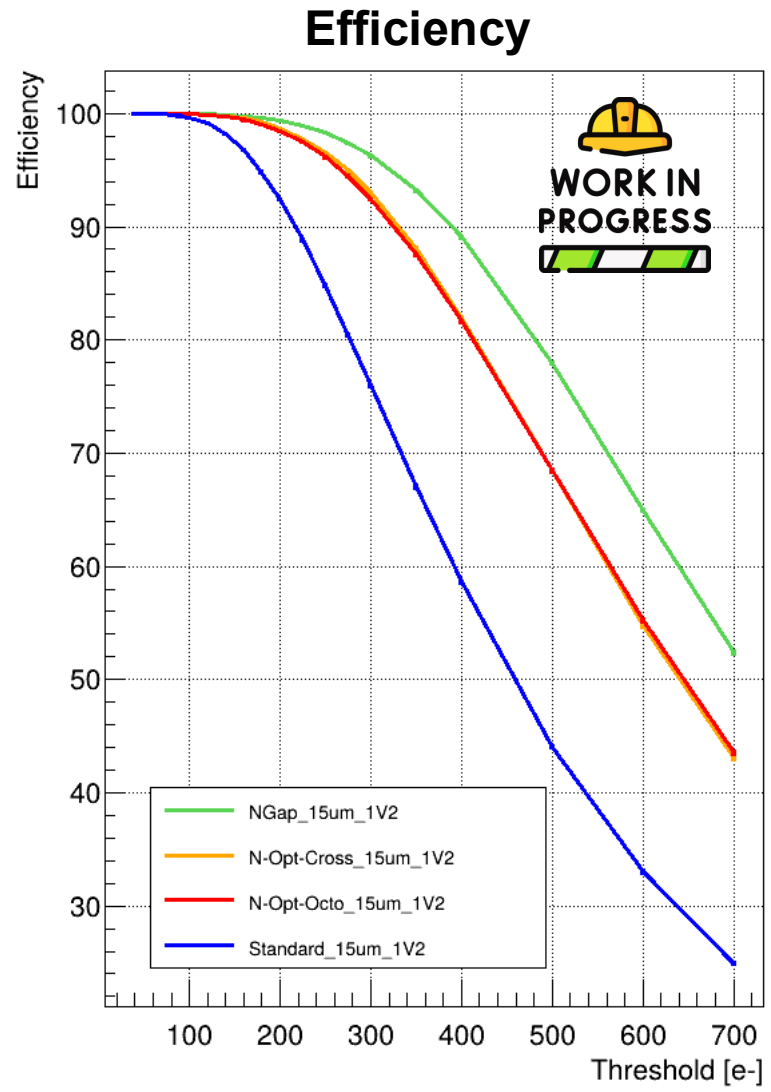
- Using 15 µm pixel-pitch
  - Efficiency > 99% up to O(200 e-) thr.
  - Spatial resolution of 3 µm at O(110 e-) thr.

Next Steps

- Optimization of sensor layout design
- Transient simulation & timing studies
- Verify the feasibility of these layouts



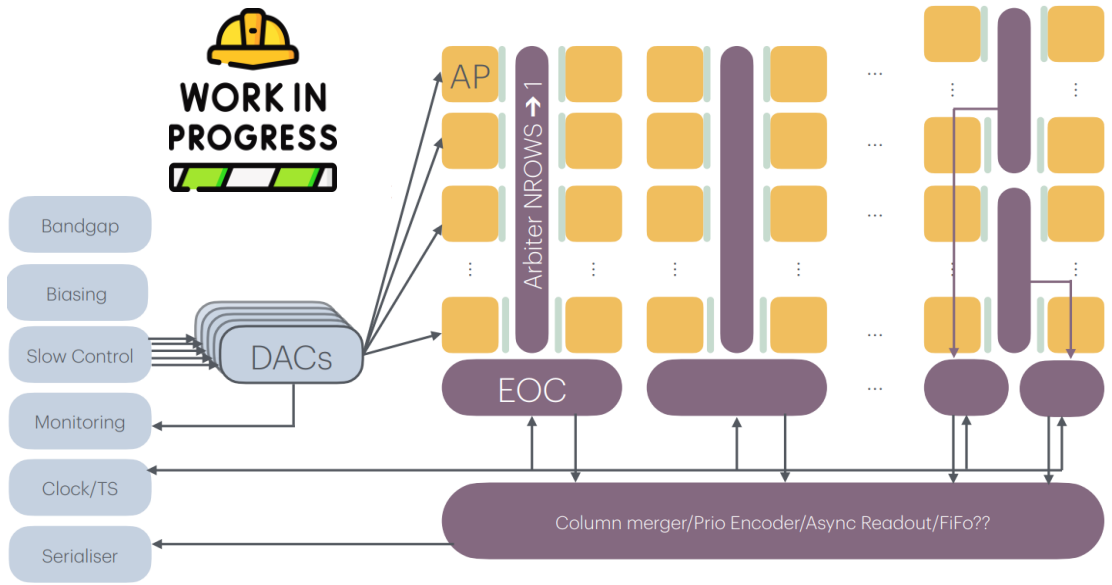




WP2-WP3: ASIC & Data Acquisition

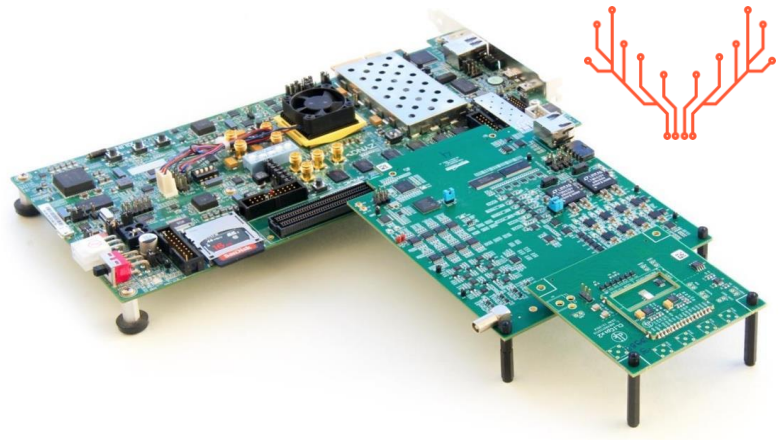
Ongoing Activities

WP2: ASIC



- All blocks identified & design effort started
- Aim for a prototype with full functionality and column height

WP3: Data Acquisition



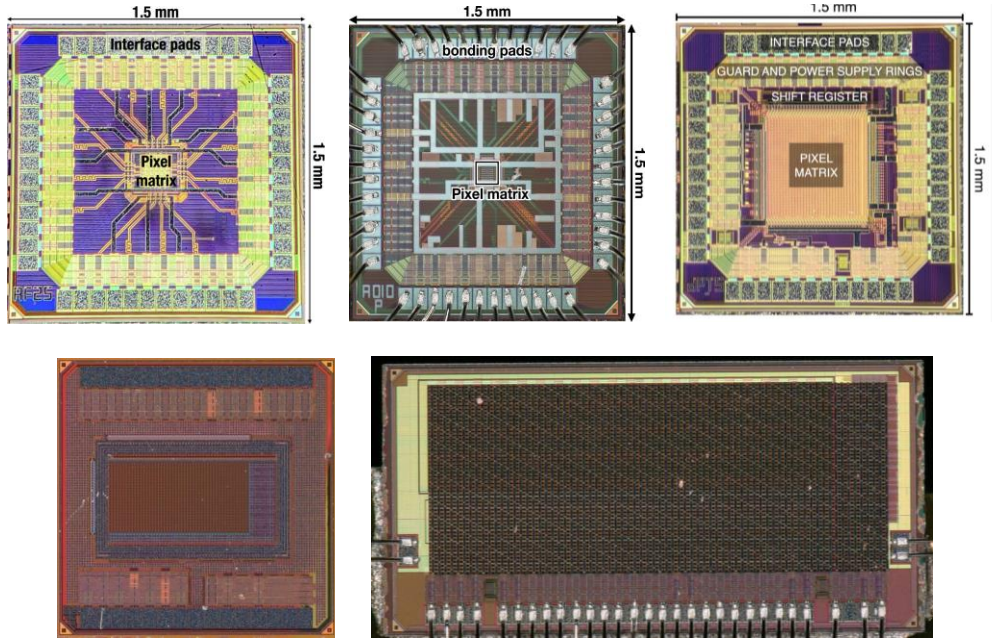
BTTB13 Younes Otarid

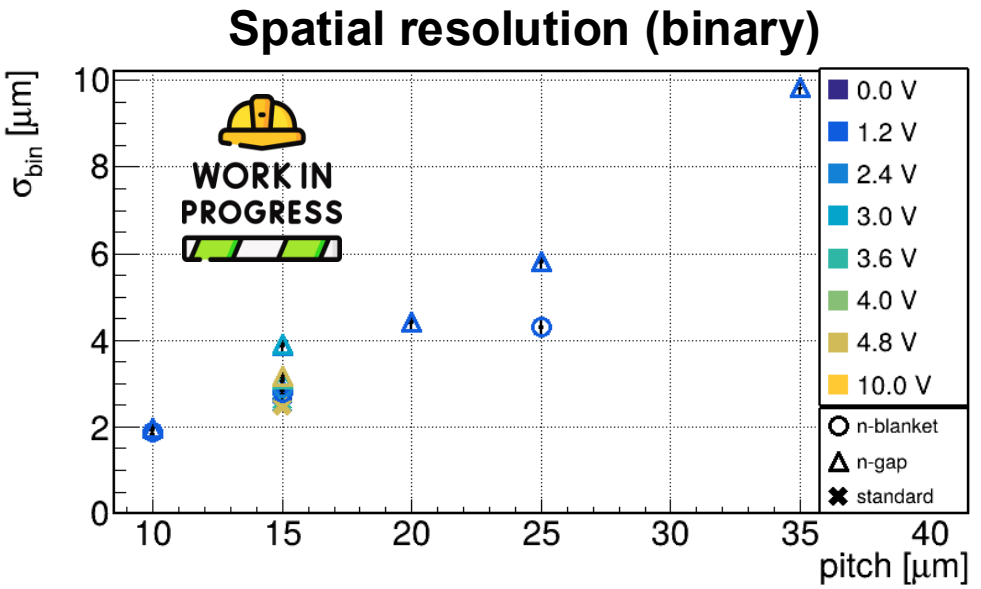
- Using Caribou versatile DAQ
- Open source common platform
- Caribou v2.0 in preparation

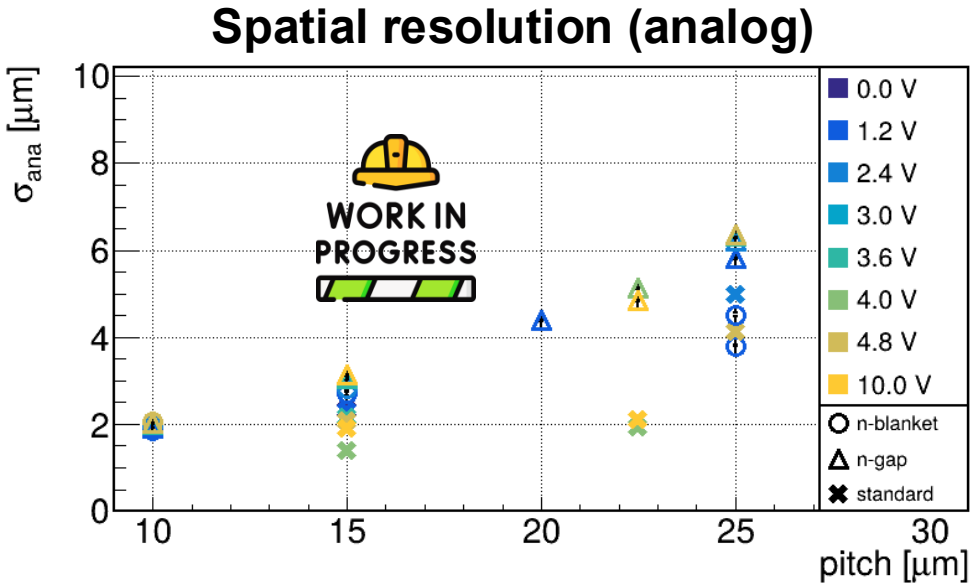
WP4: Testing & Characterization

Ongoing Activities

- Summarising results from recent studies on MAPS in TPSCo65 process in the context of project goals
- Will be the starting reference for OCTOPUS activities
- Investigated prototypes: APTS (SF-OA) [1], [2], [2], [4], DPTS [5], CE-65(V2) [6], H2M [7]



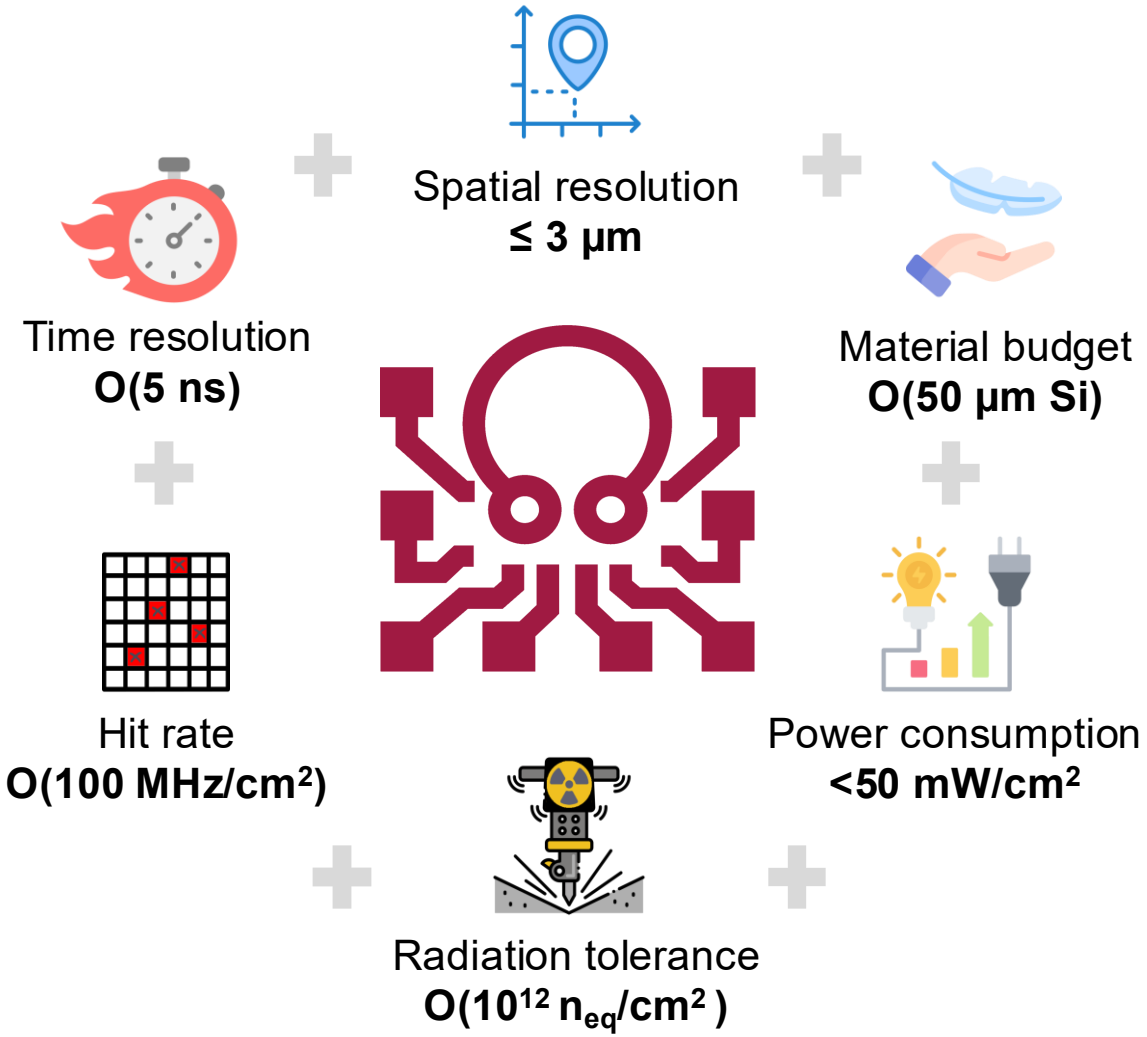




Summary

Towards Lepton Collider Vertex Detector Demonstrator

- OCTOPUS aims to develop a MAPS vertex sensor demonstrator for future lepton colliders by 2030
- As an intermediate target envisions the development of a sensor for the next-generation of beam telescopes
- Builds on experience of 12 institutes involved in MAPS development and related activities
- Is already well-structured into four workpakages and several activities are already in progress:
  - Simulation ongoing in order to define optimal sensor layout and pixel pitch
  - ASIC design effort for first prototype started
  - Review of previous main 65 nm MAPS measurements in preparation



Thank you.

Gianpiero Vignola
gianpiero.vignola@desy.de

Deutsches Elektronen-Synchrotron DESY
Notkestraße 85, 22607 Hamburg
1C, O1.331, ATLAS

Detector R&D for Future HEP Experiments

Driven by ECFA Roadmap

- In 2020, the European Particle Physics Strategy Update (EPPSU) recommended the creation of a roadmap for detector R&D
- In 2021, key R&D activities and technologies defined by European Commission for Future Accelerators (ECFA)
- In 2022 CERN approved a roadmap implementation plan establishing eight Detector Reaserch and Development DRD collaborations
- The OCTOPUS project develops in this context, within DRD3 collaboration (Semiconductor Detectors)

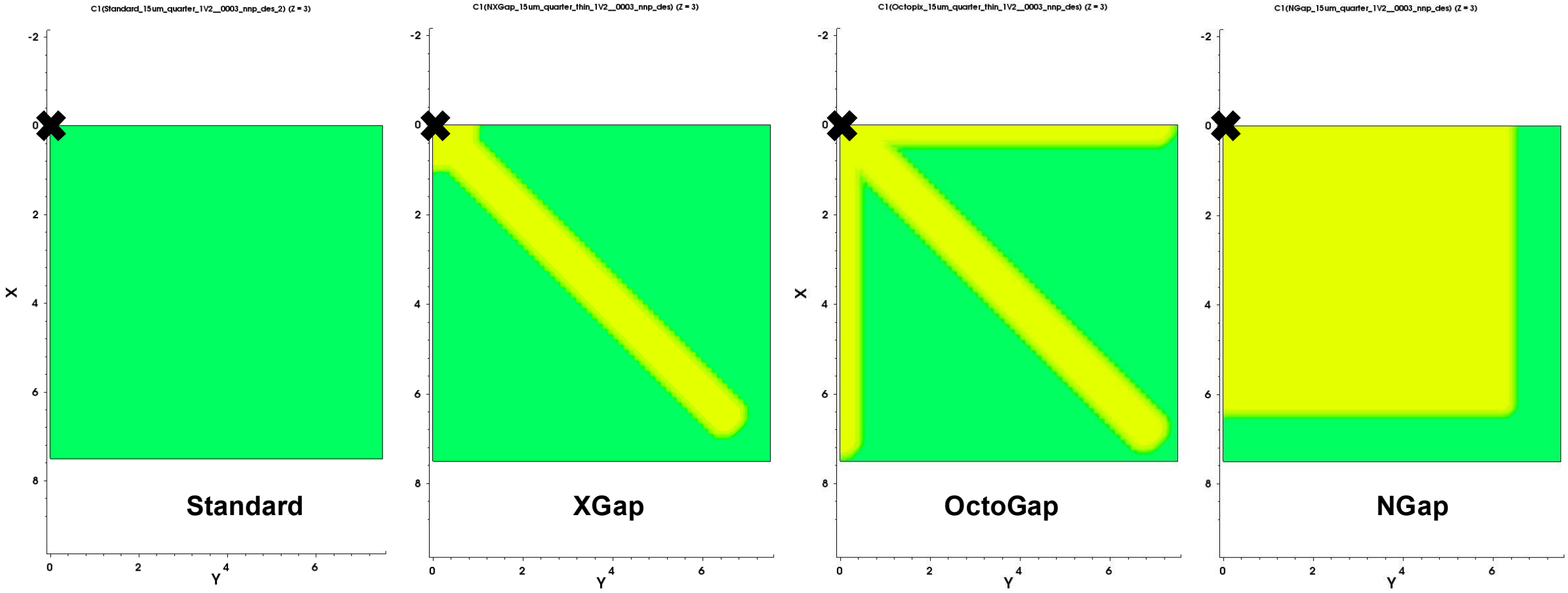
DRD1 Gaseous Detectors	**DRD2** Liquid Detectors	**DRD3** Semiconductor Detectors	**DRD4** Photodetectors & Particle ID
DRD5 Quantum Sensors	**DRD6** Calorimetry	**DRD7** Electronics	**DRD8** Integration

ECFA detector R&D roadmap (2021)

N-Doping Layout

At 2µm Depth

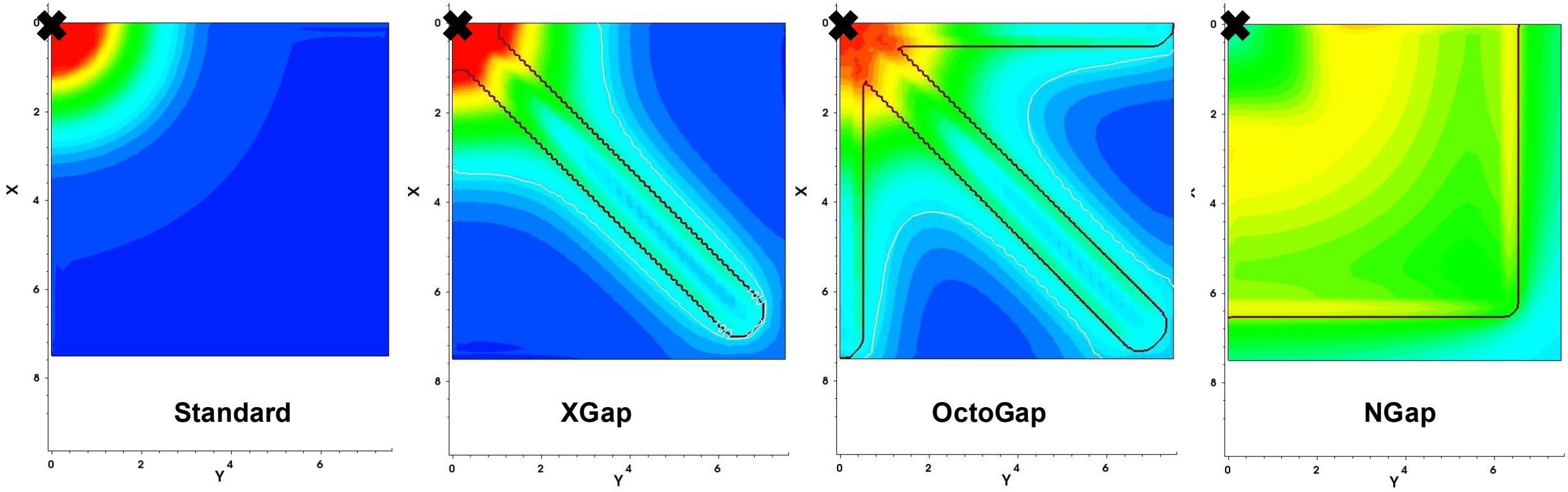
✖ **Electrode**



Electric Field XY

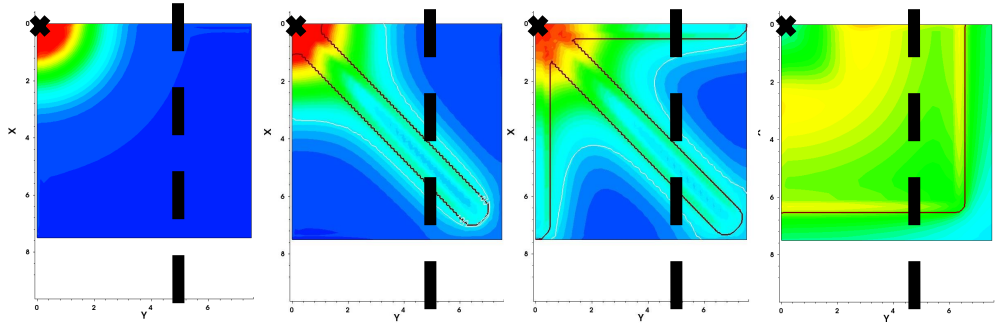
At 2µm Depth

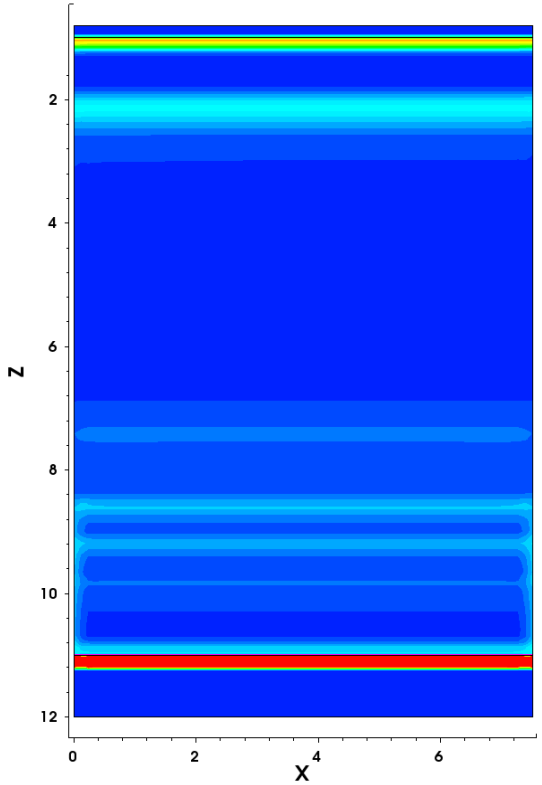
✖ Electrode



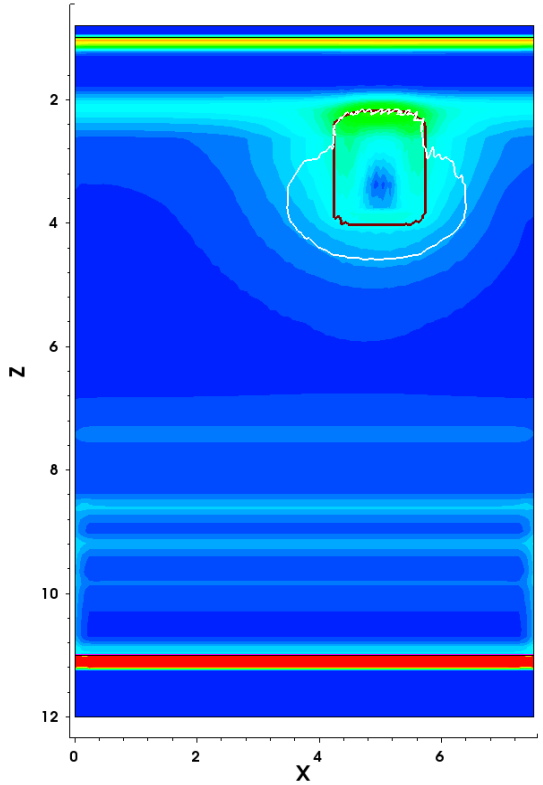
Electric Field XZ

At y=5µm

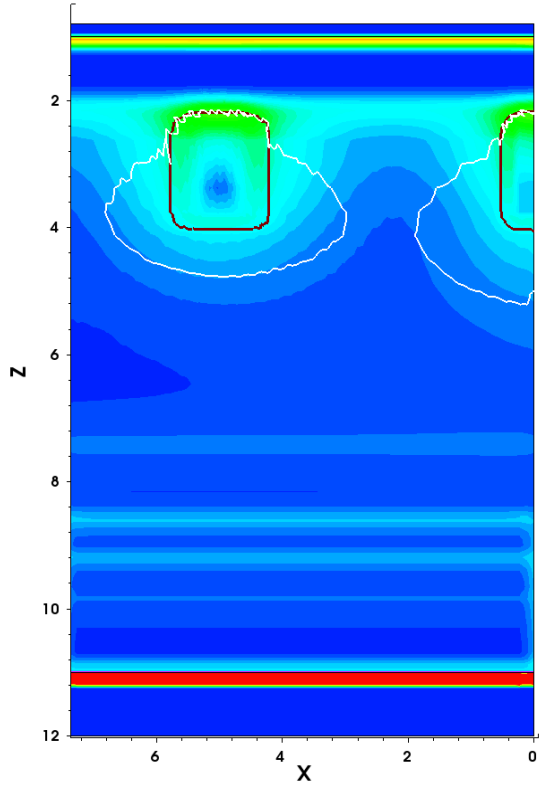




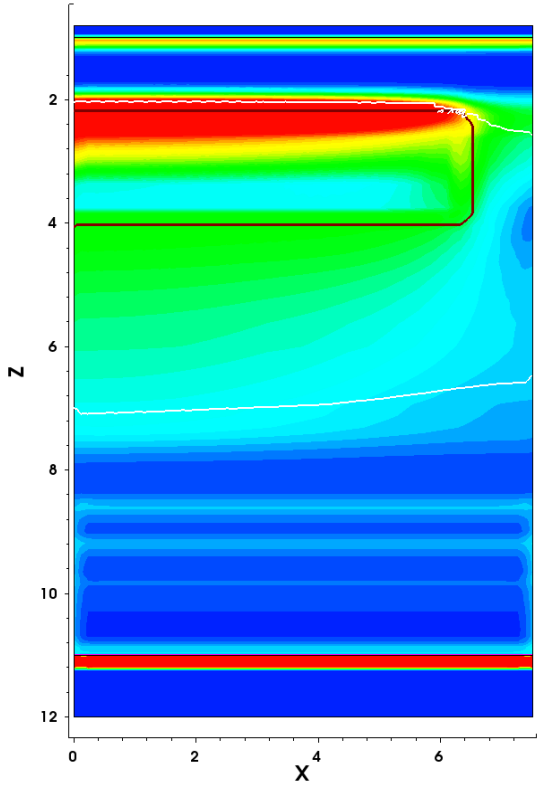
Standard



XGap



OctoGap



NGap

OCTOPUS Project Structure

Four Workpackages

WP1: Simulations
A. Ilg, A. Velyka

- TCAD simulations: sensor optimization
- Allpix^2 simulations: detector performance
- Contribution to Allpix^2 development
- Physics performance and geometry optimization

WP2: ASIC
F. Guezzi, L. Huth, S. Senyukov

- Pixel front-end and matrix architecture design
- Periphery, DACs & slow control design
- Transceivers and readout design
- Chip integration and verifications
- Submission coordination & interface with DRD7

WP3: Data Acquisition
Y. Otarid

- Chipboard design for prototypes & DAQ integration
- Chip/board assembly, bonding & logistics
- Contribution to Caribou development

WP4: Testing & Characterization
F. King, M. Franks

- Summary of current TPSCo65 demonstrator results

- Lab characterization, FE optimization, calibration
- Testbeam characterization, performance

First Prototype Concept

Design Effort Started