Advancement and Innovation for Detectors at Accelerators

Depleted Monolithic Active Pixel Sensors (WP5) - Summary

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The 2023 International Workshop on the High Energy Circular Electron Positron Collider

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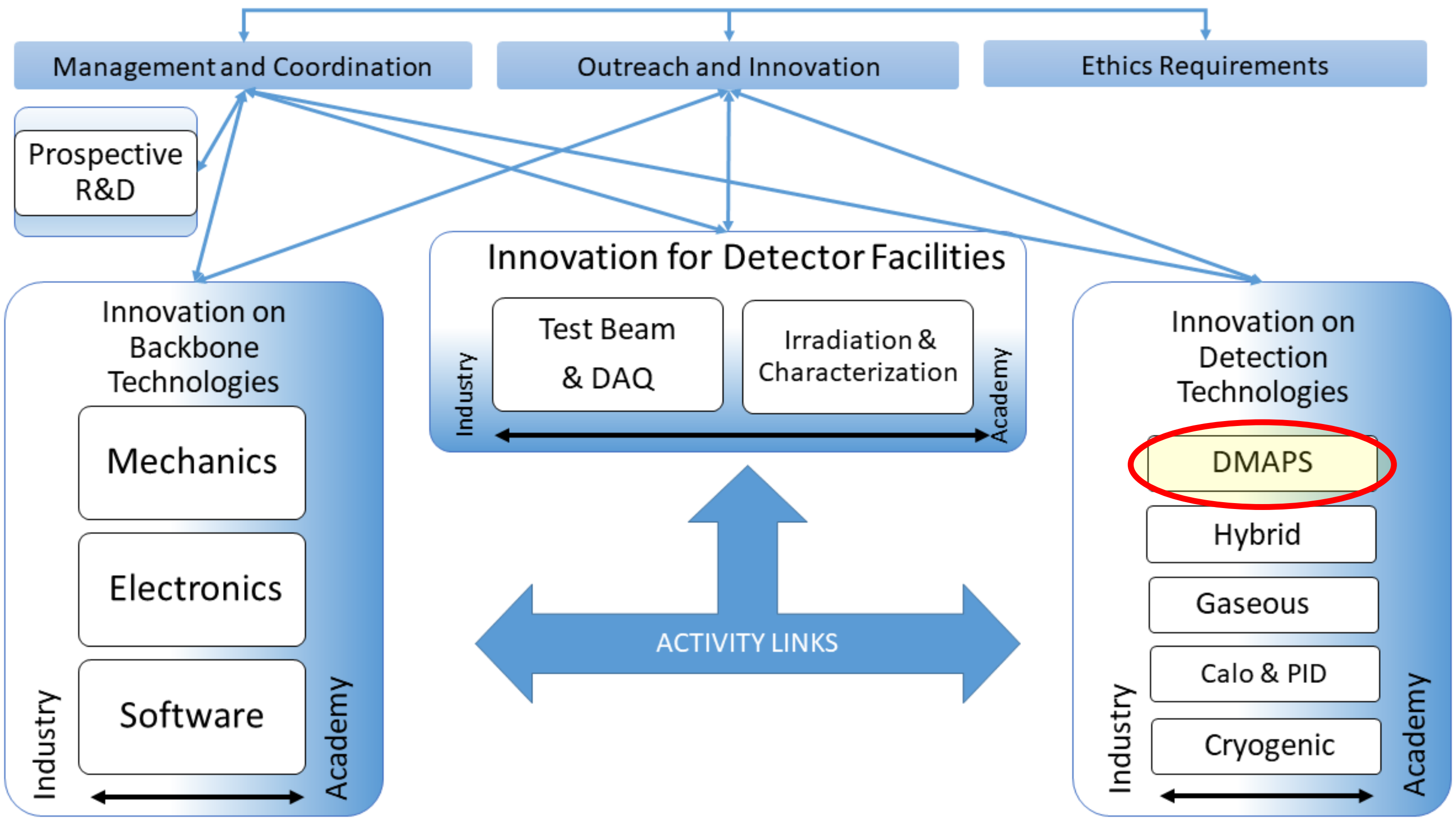
Overview – Key aims of AIDAinnova

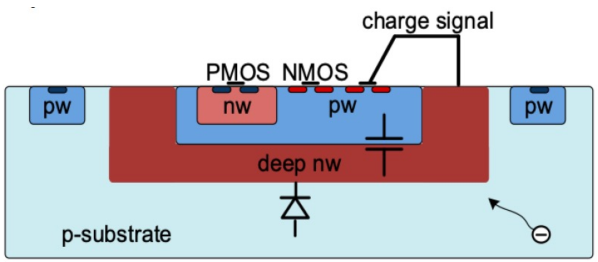
- **To explore applications of novel technologies** such as integrated CMOS sensors, additive manufacturing or machine learning, and to assess their performance for the **challenging needs of future or upgraded HEP experiments**.
- …

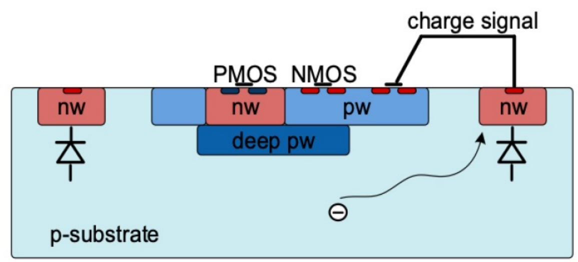


WP5: Depleted Monolithic Active Pixel Sensors

- **7 projects** are (partially, not exclusively) supported by the AIDAinnova framework using 4 different processes provided by 2 foundries: **LFoundry** (Wuxi Xichanweixin Semiconductor) and **TowerJazz** → Tower Semiconductor (Intel as of 2022)
- All developments have samples, characterisation in full swing

large electrode (radhard)



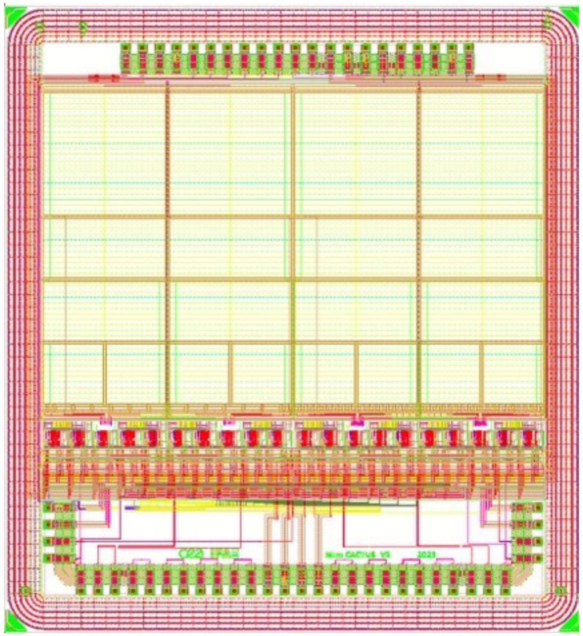


small electrode (high granularity)

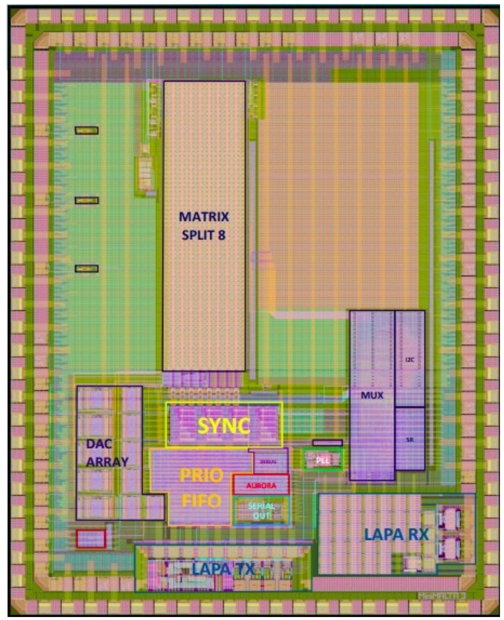
Submission	Process	Availability	Target	Comments	Contact Institute	Task Contact
TJ-MALTA 2 /3	TowerJazz 180 nm	Beginning 2021 MPW Q1 2022	High-gran./ Rad. hard Task 5.2/5.3	LHC	CERN	Carlos Solans Sanchez
TJ-Monopix 2 /3 (OBELIX)	TowerJazz 180 nm	Spring 2021 Initiating design	High-granularity Task 5.2	Belle II	Bonn	Jochen Dingfelder
TJ 65	TowerJazz 65 nm	September 2021	High-granularity Task 5.2	Generic R&D / ALICE	IPHC	Jerome Baudot
ARCADIA	LFoundry 110 nm	Summer 2021	High-granularity Task 5.2	Demonstrator chip	INFN	Manuel Rolo
LF-Monopix 2	LFoundry 150 nm	Beginning 2021	Radiation hard Task 5.3	High granularity foreseen	Bonn/CPPM	Marlon Barbero
RD50-MPW 3 /4	LFoundry 150 nm	Spring 2022	High-granularity/ Radiation hard Task 5.3	R&D	Liverpool	Eva Vilella
MiniCactus	LFoundry 150 nm	Beginning 2021	Radiation hard Task 5.3	Timing R&D	IRFU	Philippe Schwemling

DMAPS – Summary of activities

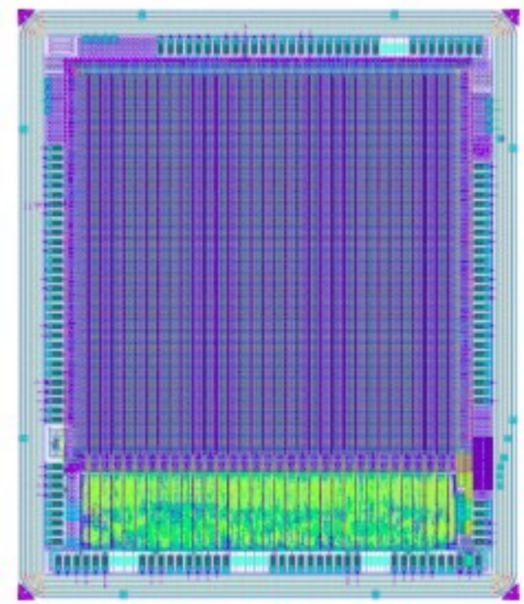
- In the next slides I present a brief overview and latest results for each development line



Mini Cactus 2



Mini-Malta 3



RD50-MPW4

- Disclaimer: In AIDAinnova the focus is the analog FE and sensor development. Readout aspects are usually too experiment specific and thus are less of a focus in our work

Tower 180 nm

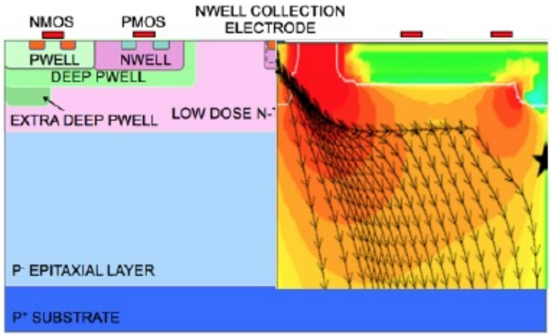
TJ-MALTA-2&3

TJ-Monopix-2

TJ-MALTA
High granularity, small electrode

Goal: large (1x2 cm^2 (Malta2) → 3x2 cm^2 (Malta3)) radhard sensor/chip w/ small electrode and high granularity, HL-LHC-layer-5 compatible with low power asynchonous readout architecture. Sensor&FE same as TJ-Monopix.

CERN and others (Bonn, CPPM, Oxford ...)
- 180 nm technology -



- main objective of **TJ-MALTA2**:
  - make design radhard (> 1e15 neq/cm2):
    i. shape charge collection geometry
    ii. optimize FE against RTS noise
    iii. use high resistive Cz-Si substrate (100 µm) rather than epi-Si (25 µm).
  - improve asynchronous readout

- objective **TJ-MALTA3**:
  - exploit full reticle size: 3x2 cm^2
  - improve on remaining MALTA2 issues
  - add 1.28 GHz local clock
  - target: mini-MALTA MPW in Q2 2023

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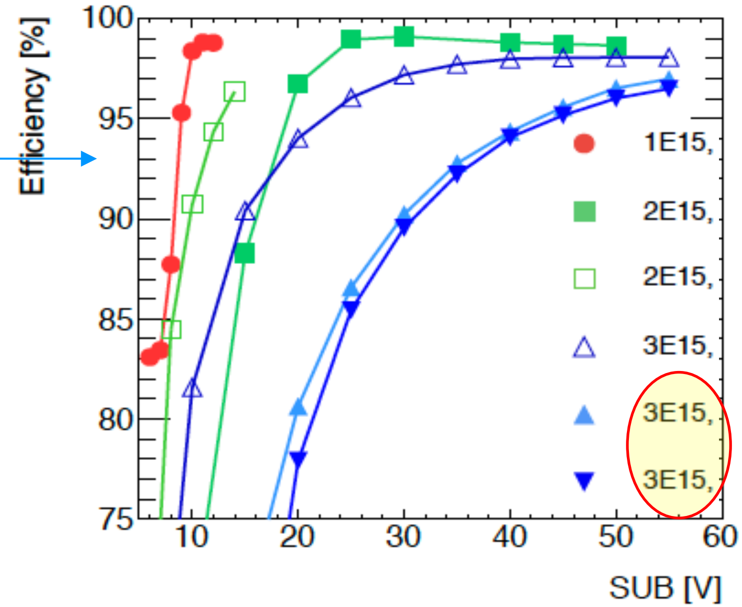
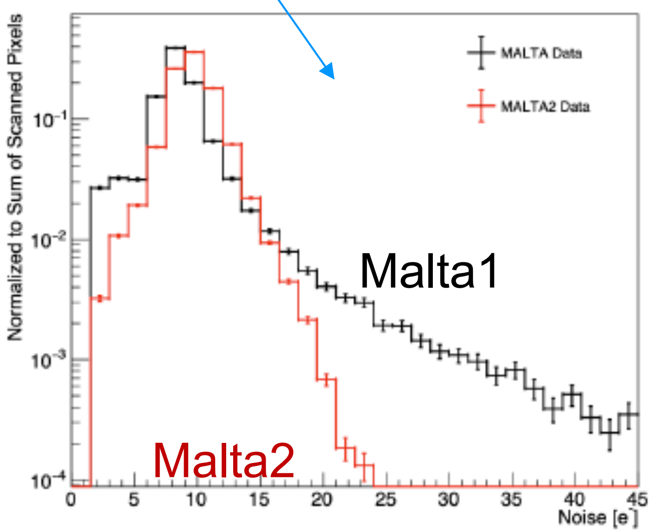
TJ-MALTA
High granularity, small electrode

Goals of MALTA2 achieved:

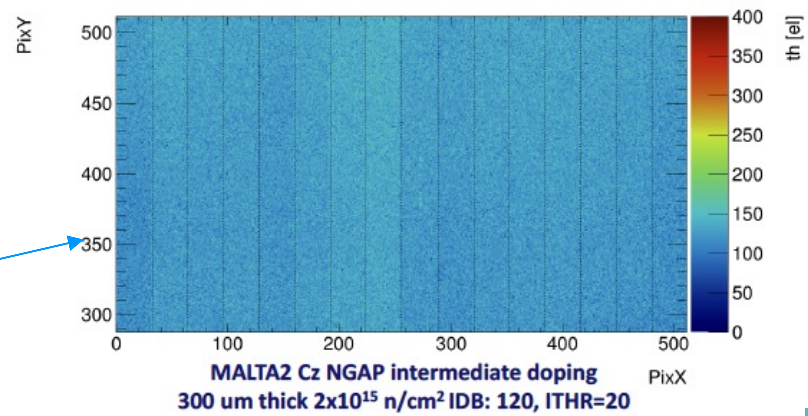
- radhard to >1E15 neq/cm2
- @ 3E15 neq/cm^2 > 95% in 25ns



- RTS noise mitigated



- excellent matrix homogeneity 2x1 cm^2



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TJ-MALTA

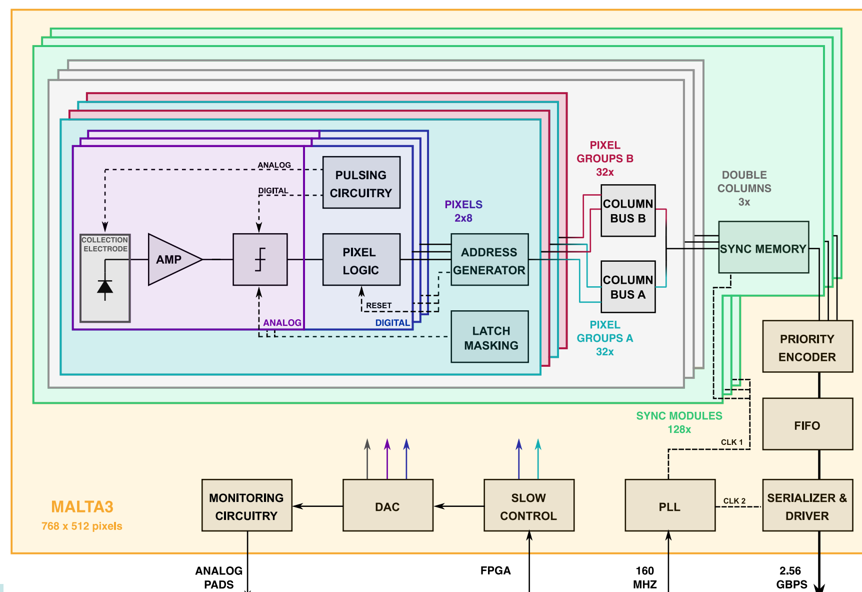
High granularity, small electrode

Mini-MALTA3 submitted in June 2023:

- 5x4 mm^2 demonstrator
- 48x64 matrix size of 36.4 um^2
- No clock over the matrix
- Synchronization memory with 0.78 ns time resolution
- Fast clock generation with STFC PLL from 80 MHz clock
- Output data scrambled using Aurora

Full MALTA3 expected to submit Q3 2024:

- Next step in asynchronous read-out architecture
- Full reticle size 3x2 cm^2
- Asynchronous hit propagation
- Time tagging at end of column
- Add a 1.28 GHz local clock generated from a PLL for time tagging
- Fast read-out with standard protocol



Flow diagram of MALTA3

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TJ-Monopix 2
High granularity, small electrode

Goal: mature large (2x2 cm^2) high granularity (small electrode) fully functional, HL-LHC compatible (5th layer) DMAPS sensor with column drain readout, w/ low noise and low power consumption

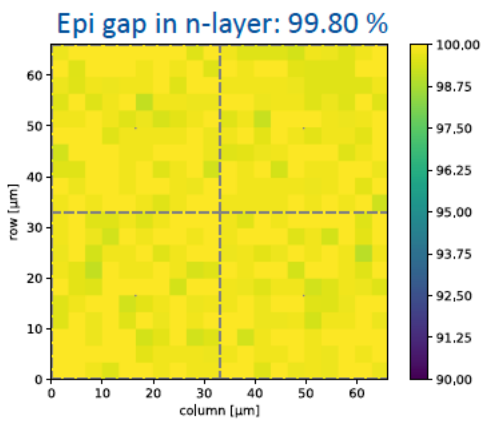
	TJ-Monopix1	TJ-Monopix2
Chip Size	1x2 cm^2 (224x448 pix)	2x2 cm^2 (512x512 pix)
Pixel size	$36 \times 40\ \mu m^2$	$33.04 \times 33.04\ \mu m^2$
Total matrix power	130 mW/cm^2	170 mW/cm^2
Noise	≅11 e^-	< 8 e^- (improved FE)
LE/TE time stamp	6-bit	7-bit
Threshold Dispersion	≅ 30 e^- rms	< 10 e^- rms (improved FE + tuning)
Minimum threshold	≅ 300 - 400 e^-	< 200 e^-
In-time threshold	≅ 350 - 450 e^-	< 250 - 300 e^-
Efficiency at 10^{15} n_{eq}/cm^2, 30 µm epi	≅ 87 %	> 97 %
Efficiency at 10^{15} n_{eq}/cm^2, Cz	≅ 98.6 %	> 99 %

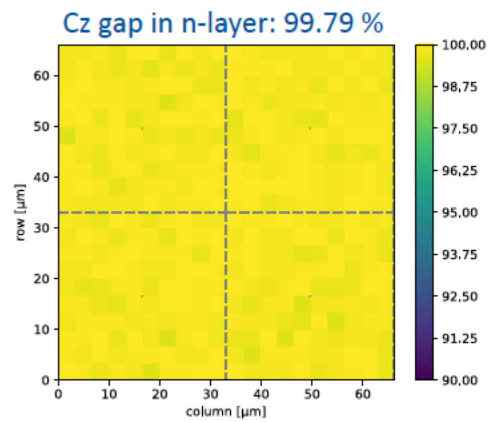
- Clear improvements wrt TJ-M1 before and after irradiation

Bonn, CERN, CPPM, IRFU
- 180 nm technology -

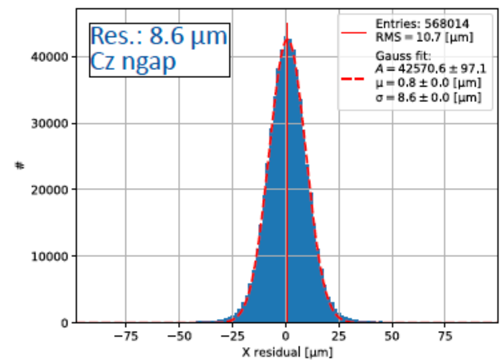
- sensor and chip working
- assembly problems (wire bonding sensibility) reduce yield, is now manageable, but still problematic
- a temporary major problem at 5 MHz BC-ID clock interfering now understood and circumvented
- characterisation finally in full swing
- baseline for Belle II VTX upgrade → Obelix chip:
  - Uses analog part from TJ Monopix 2
  - New digital periphery with several additional features

TJ-Monopix 2
High granularity, **small** electrode



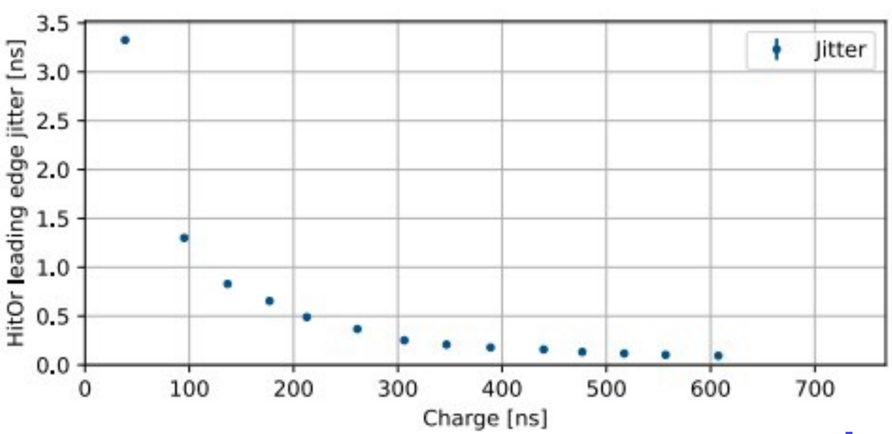


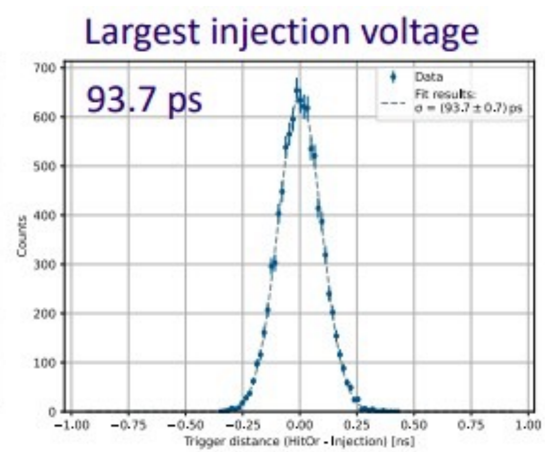
resolution 8.6 µm



- very high efficiency (before irradiation)
- irradiation planned Q1/Q2

- Recent timing characterization
- Contribution from jitter (device electronic noise





Lab measurement

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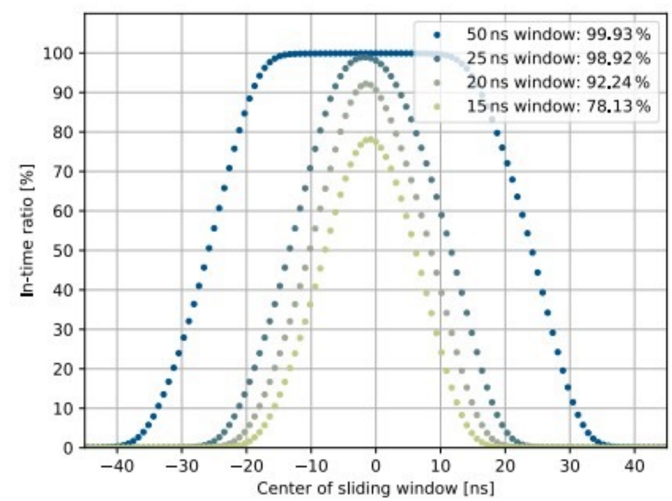
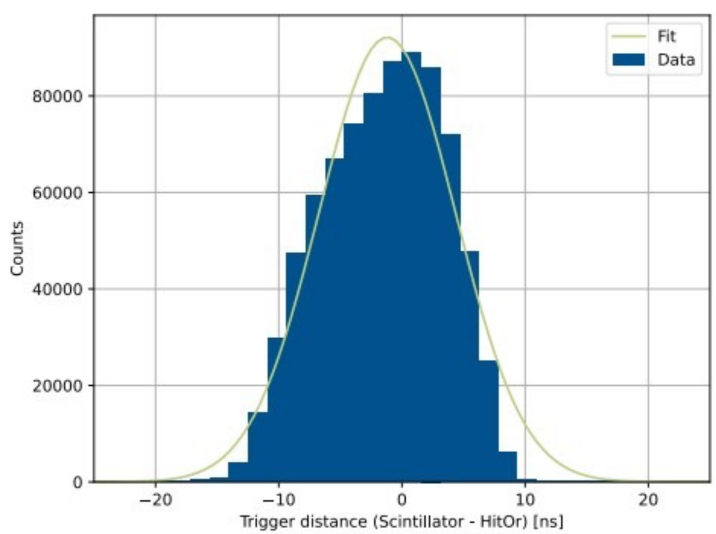
TJ-Monopix 2
High granularity, small electrode

- In-time ratio: percentage of hits within 25 ns
- Move sliding window over (projected) trigger distance distribution
- 15 ns, 20 ns, 25 ns, 50 ns window width
- **98.92 % for 25 ns window**

Test beam measurement

	15 ns	20 ns	25 ns	50 ns
Cz normal	78.4 %	92.2 %	98.6 %	99.7 %
Cz cascode	79.2 %	92.3 %	98.2 %	99.7 %
Epi normal	78.1 %	92.2 %	98.9 %	99.9 %
Epi cascode	78.4 %	93.1 %	99.1 %	99.9 %





- Time walk corrected
- Distribution is skewed, matches with time walk curve
- (Bad) fit yields 5.5 ns time resolution
- Trigger scintillator resolution of approx. 1 ns
- **Detector time resolution: 5.4 ns**
  - Detector contribution dominates
  - To investigate other flavors (Cz...)

TPSCo 65 nm process of Tower
(new window of opportunity)

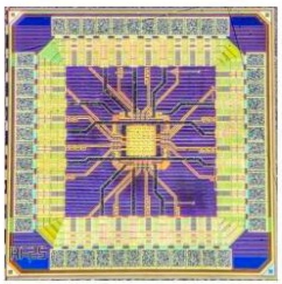
Tower 65nm

TPSCo 65 nm
High granularity (Tower)

Goal: exploring the new technology (large collaboration effort, CERN + 24 institutions) including stitching, ... small electrode designs

1+2 submissions so far: MLR1 (2020), ER1 (2022) each containing several structures and designs

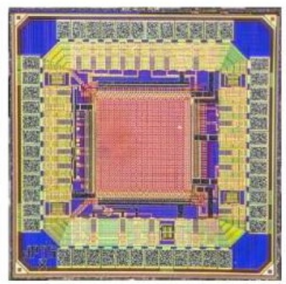
APTS Analogue Pixel Test Structure



1.5 mm

Matrix: 6x6
Readout: analogue readout of 4x4
Pitch: 10,15,20,25 μm
Process: all 3 variants

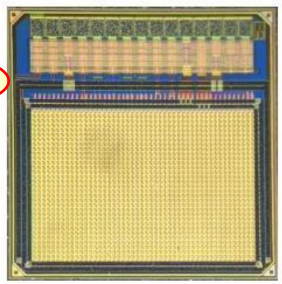
DPTS Digital Pixel Test Structure



1.5 mm

Matrix: 32x32
Readout: async. digital with ToT
Pitch: 15 μm
Process: 1 variant (modified with gap process)

CE-65 Circuit Exploratoire 65

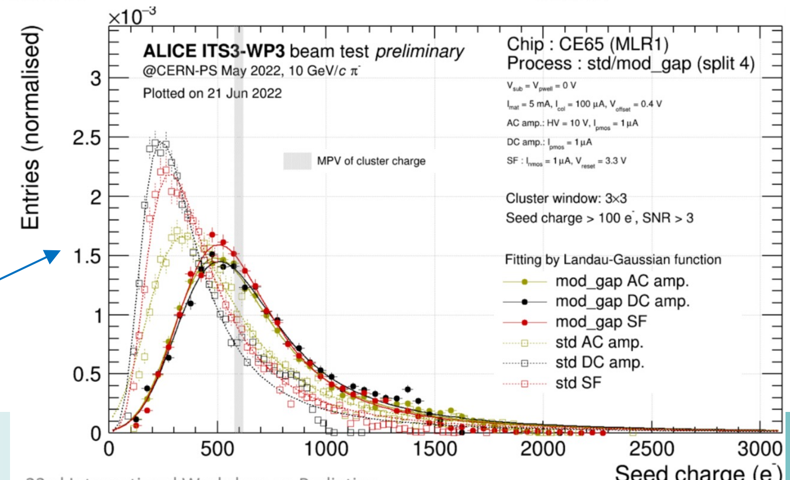


1.5 mm

Matrix: 48x32
Readout: rolling shutter analog
Pitch: 15, 25 μm
Process: 1 variant (modified with gap process)

from MLR1

promising results from MLR1
leakage cur. ✓
Testbeam with DPTS (digital 15 μm) proved that process modification works

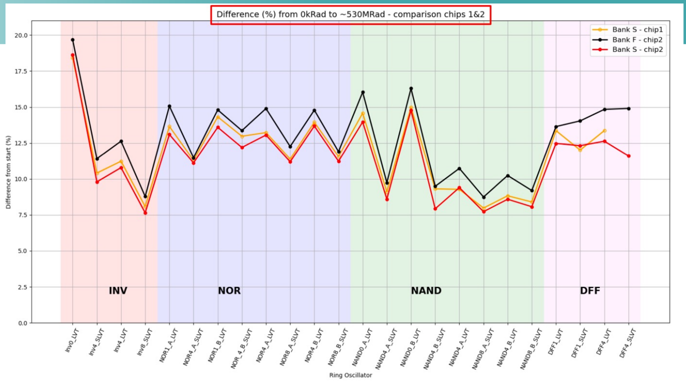


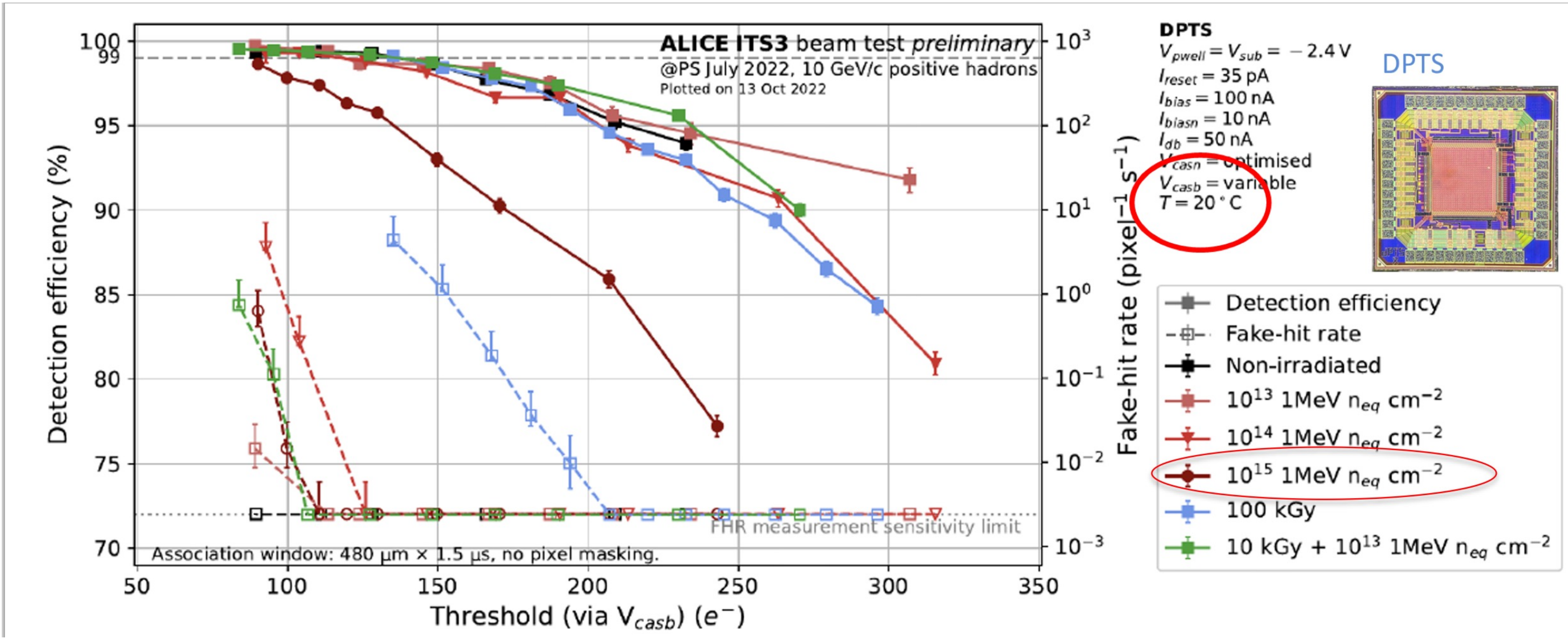
TPSCo 65 nm
High granularity (Tower)

Promising radiation tolerance:

- DPTS (digital) with 15 µm pitch
- Beam test results
- also for digital cells as shown

with TID measurements on ring oscillators





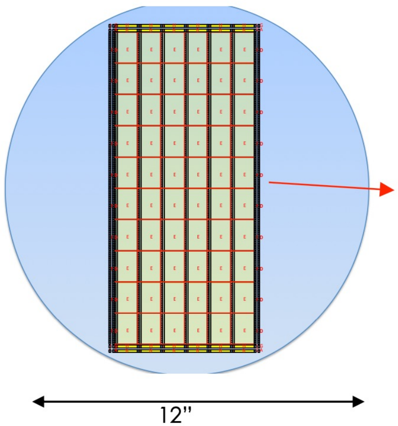
2^{nd} submission: Engineer Run 1 (ER1)

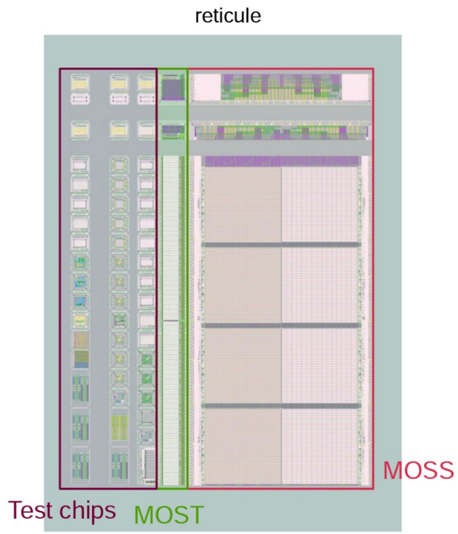
- Main goal = exercise stitching (in 1D) to assess yield
- Submission November 2022
- Back from fab April 2023

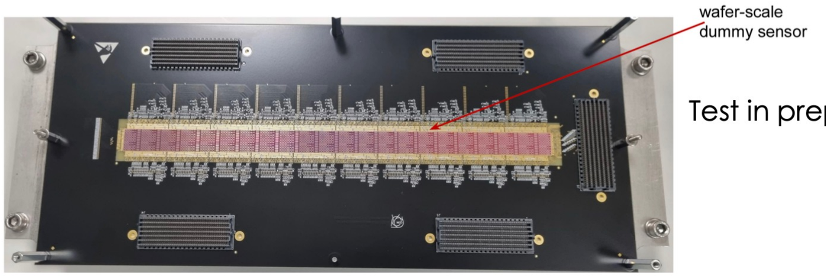
- 2 long (~26 cm) sensors
  - **MOSS:** priority-encoder readout (ALPIDE-like)
    - 1.4 cm wide
    - 18 & 22.5 µm pitch
  - **MOST:** low power asynchronous readout
    - 0.25 cm wide

- Many (51) **chiplets**
  - Pixel prototypes
  - SEU test chips
  - Functional blocks (PLL, serial links)

- New metal staks
- New methodology for submission
  - Digital-on-top







Test in preparation

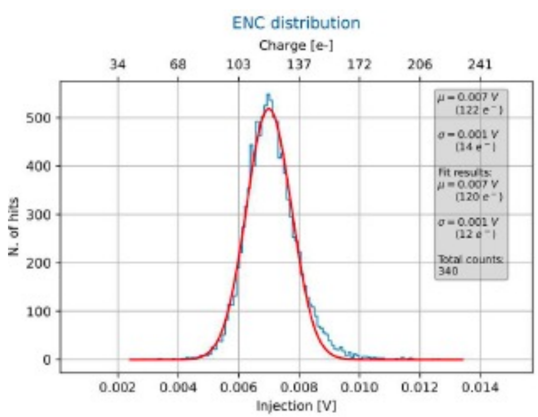
LFoundry 150 nm

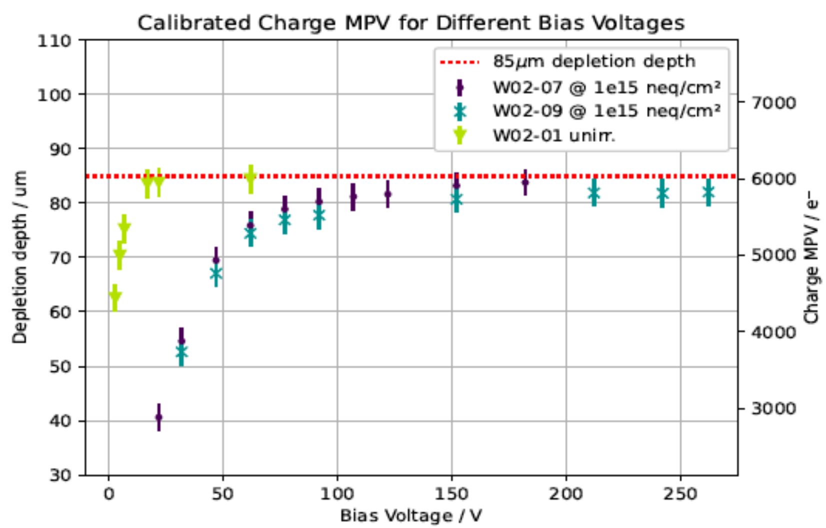
- LF-Monopix-2
- RD50 – MPW2/3
- CACTUS

Goal: mature large (1x2 cm^2) (very) radhard, large electrode fully functional, HL-LHC compatible (5th layer) DMAPS sensor with column drain readout

irradiated devices (1e15 n_{eq}/cm^2 @ Bonn Cyclotron)

- no significant degradation at this level except for leakage current increase





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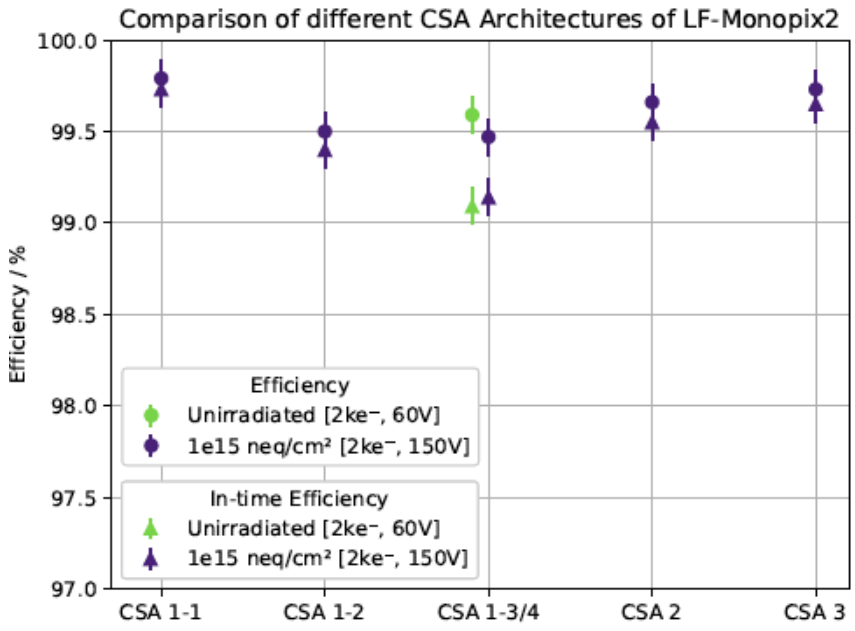
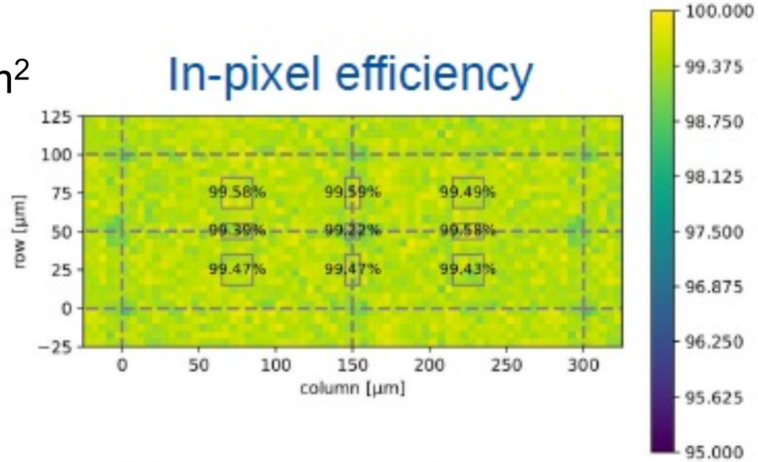
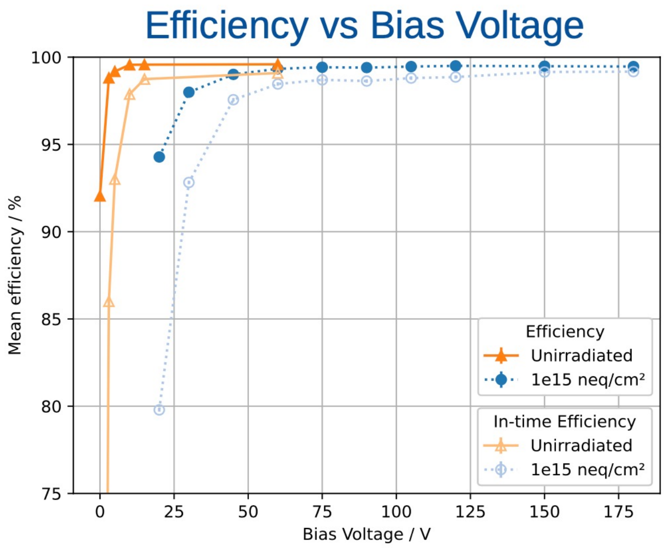
- fully depleted @ 100 V bias (15 V unirr.)

LF-Monopix 2
Large electrode, radiation hardness

- intensive test beam characterisation
- very high (>99%) efficiency (in-time) after 1e15 n_{eq}/cm^2
- ~no efficiency degradation w.r.t. unirradiated devices







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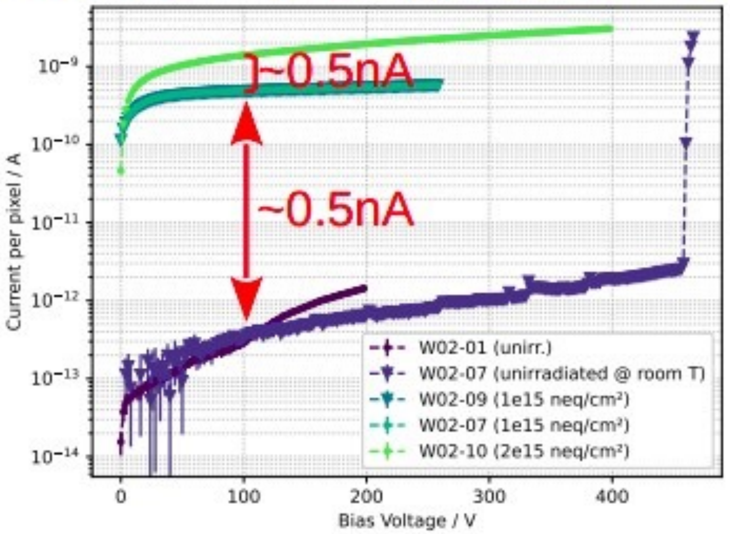
LF-Monopix 2
Large electrode, radiation hardness

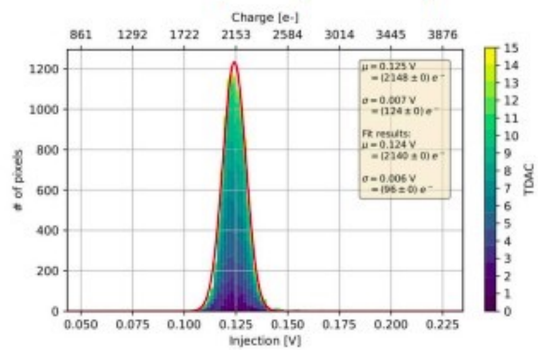
Recently exploring **the radiation hardness limit** by going from 1e15 n_{eq}/cm^2 → 2e15 n_{eq}/cm^2

I-V curve comparison @ different fluences

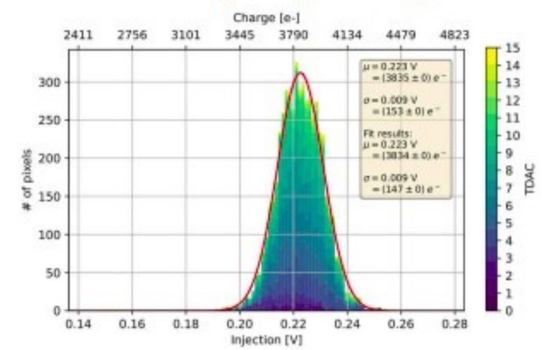


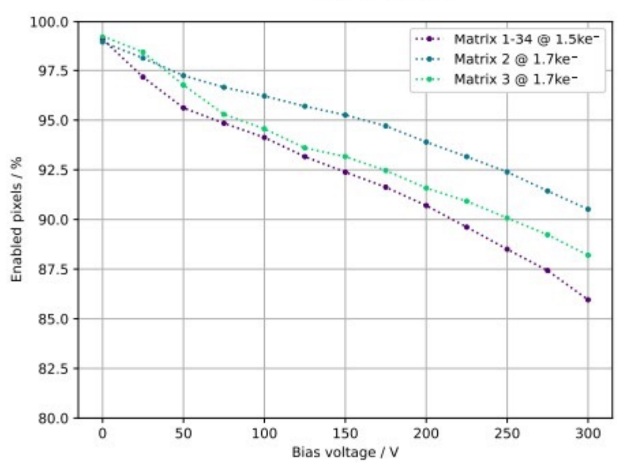
- High noise increase observed:
  - Unirr @ -40V bias (~90e)
  - 1e15 @ -150V bias (120e)
  - 2e15 @ -250V bias (~170e)
- Difficult to reach low threshold for stable operation

1e15 neq/cm² (W02-07)



2e15 neq/cm² (W02-10)





- Challenging to operate chip at such high radiation level
  - missing leakage current compensation
  - beyond original target of outer tracking layer
- Studies on-going …

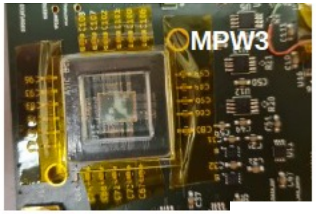
RD50-MPW2/3
Large electrode, radiation hardness, high granularity

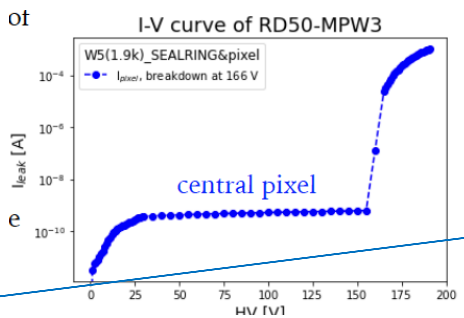
Goal: series of MPWs (1 ... 4) to achieve very small pixels (60 x 60 µm^2) radhard @ HL-LHC level 5th layer by large electrode design (all electronics inside deep well)

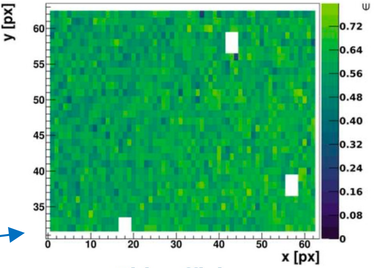
MPW2: small prototype
- pixels: 60 x 60 µm2
- in-pix CSA + discriminator, analog R/O
- testbeams performed
- charge collection ok

MPW3: added digital R/O (column drain)
- $V_{breakdown}$ ~ 150V
- very high noise (> 2000 e) due to noise coupling from digital periphery
- Poor test beam efficiency due to high thresholds

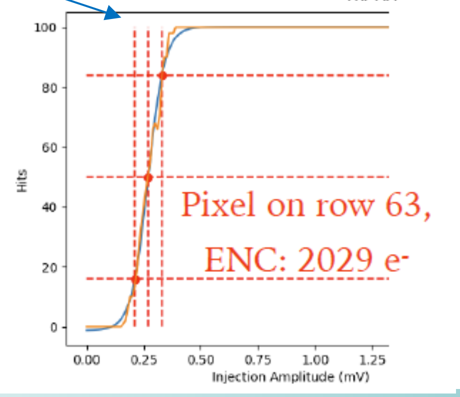
MPW4 (sub. May 2023):
- backside processing to improve radiation hardness
- Address noise limitation of MPW3 by separate power domains of pixel matrix and periphery

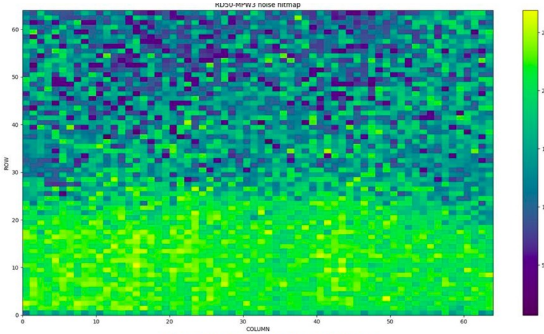






Chip efficiency




Pixel matrix noise hitmap

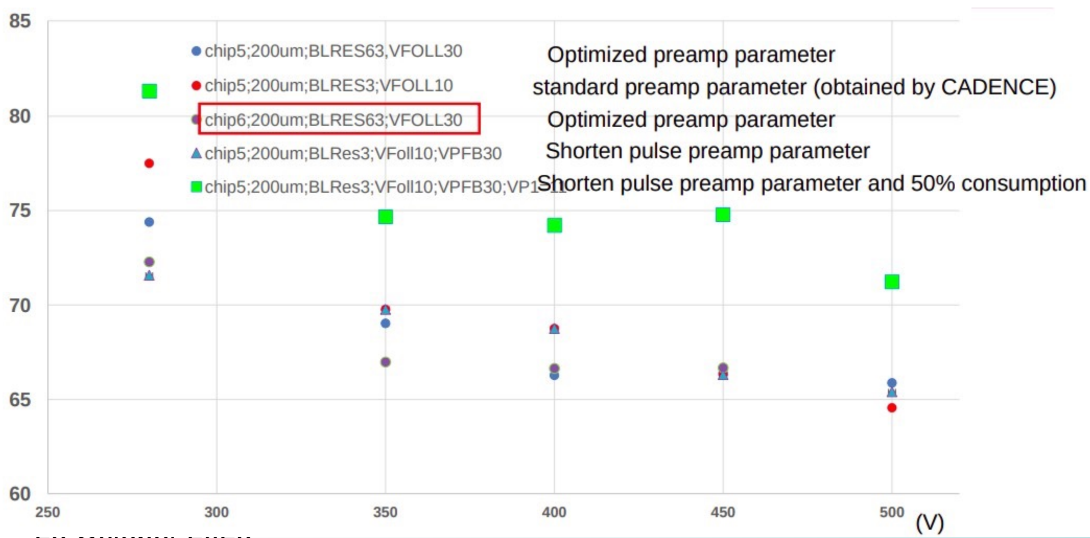
E. Vilella, R. Hernandez et al

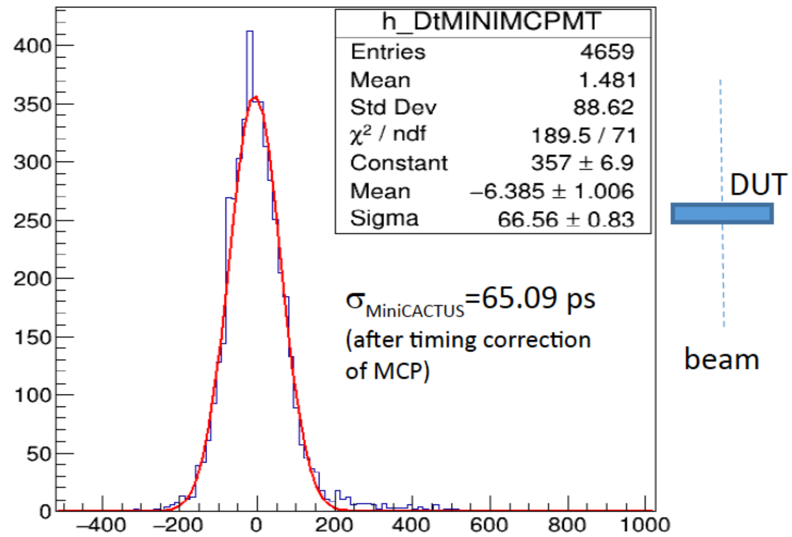
CACTUS
large electrode

Goal: Develop CMOS pixels for timing applications (~50 ps)

Mini CACTUS = small prototype to address limitations of CACTUS (low S/N) in **LFondry 150nm**

- **65 ps mip time resolution achieved** in test beams for unirradiated devices
- compared calibrations and resolutions using photons of different energies (^{241}Am and @SOLEIL)
  - calibrations ✓
  - σ_t for photons (understandably) worse (320 ps)





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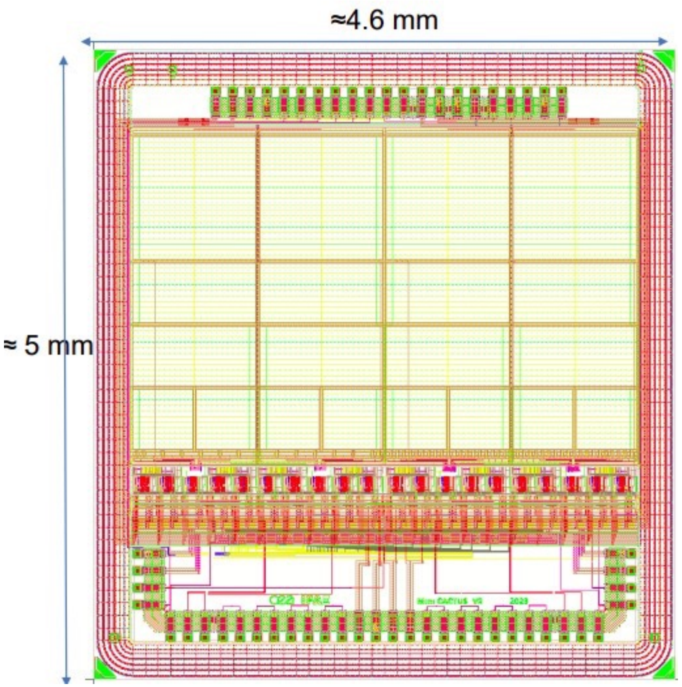


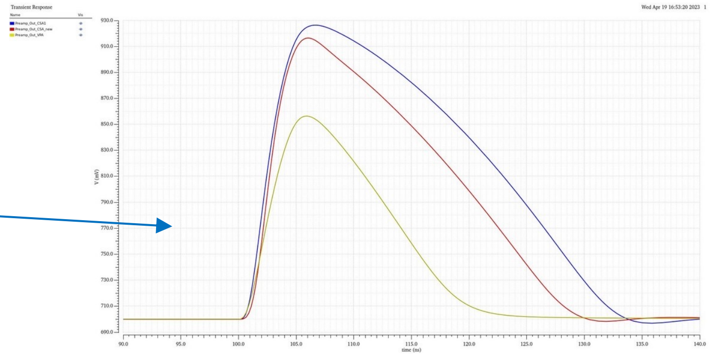
Next:

- characterisation after 1e14, 1e15, and 1e16 neq/cm^2
- new Mini-CACTUS submission May 2023, back December 2023

Mini-CACTUS2:

- ~ 2 times larger than Mini-CACTUS
- 0.5 mm x 1 mm (baseline), 1 mm x 1 mm and 0.5 mm x 0.5 mm diodes
- 50 μm x 150 μm and 2 50 μm x 50 μm small test diodes
- 3 different preamps
- New multistage discriminator with **programmable hysteresis**
- Improved layout for better mixed-signal coupling rejection
- **CEA-IRFU** & **IFAE-Barcelona** coll.

- Expect better timing performance from simulation …



P. Schwemling, Y. Degerli et al

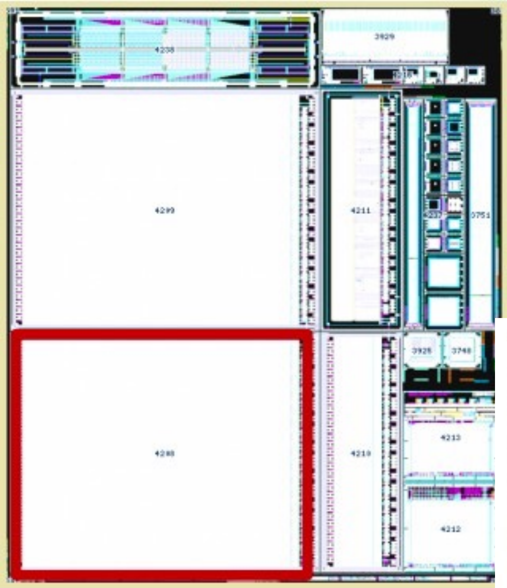
LFoundry 110 nm

ARCADIA

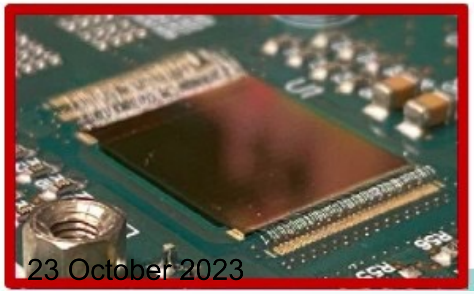
ARCADIA
High granularity

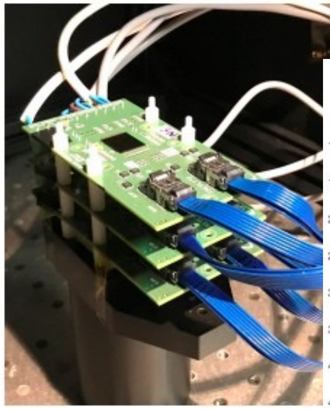
Goal: Develop DMAPS technology platform in 110 nm technology. Largely funded by INFN. Targeting small pixels, very low power, various thicknesses

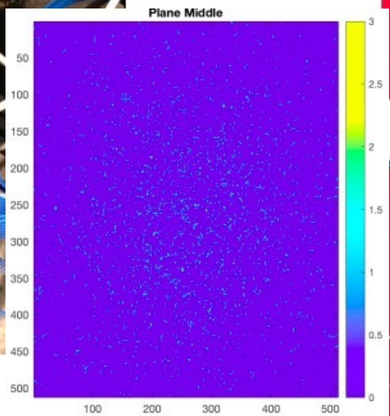
- 110nm CMOS node (quad-well, both PMOS and NMOS), high-resistivity bulk
- Custom patterned backside, patented process developed with LFoundry



- ARCADIA-MD3 Demonstrator
- Included several structures/chips
  - Pixel down to 10 μm
  - ASIC for strip r/o
  - X-ray counter
  - Timing detector
  - …

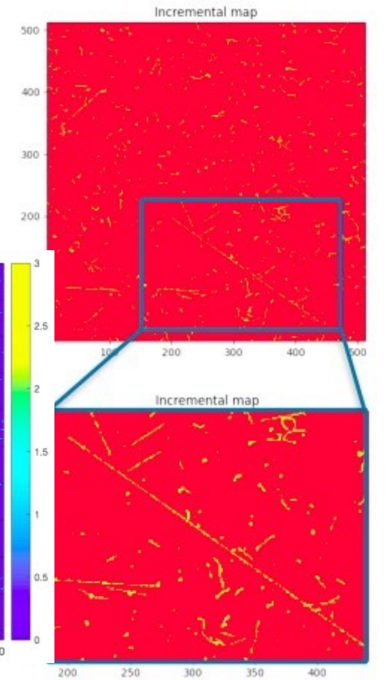




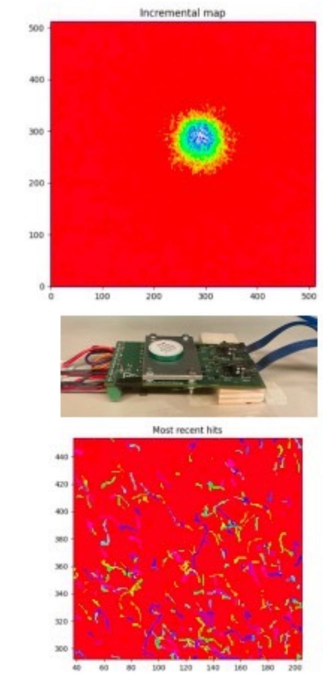


CR tests: telescope

Cosmic rays (tilted sensor)

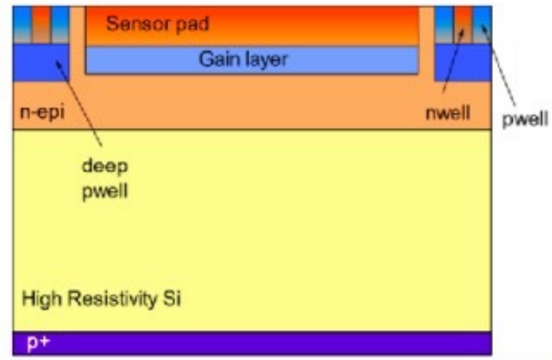


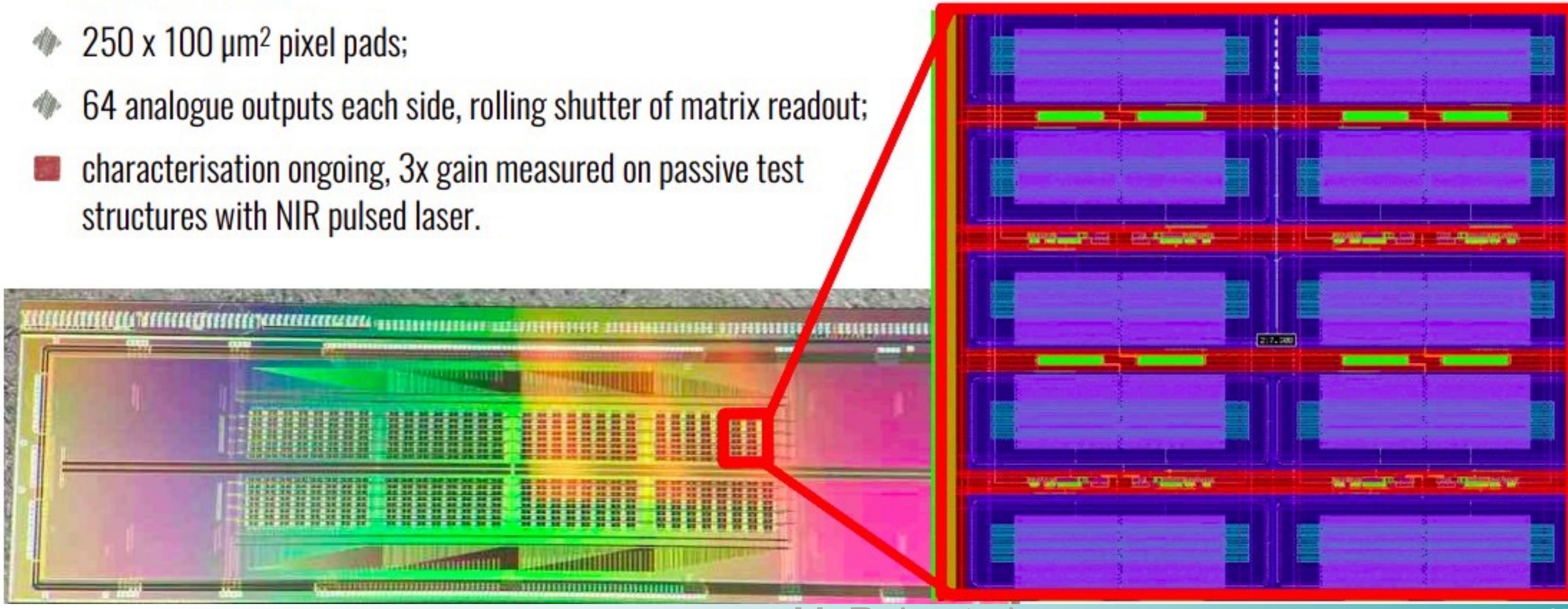
^{90}Sr (collimated 1mm)



Timing detector

- partial lot of HR and p+ wafer splits implement an extra gain layer added to the sensor;
- first small-scale demonstrator 4 x 16 mm^2;
- 8 matrices (64 pixel pads each) implementing different sensor and front-end flavours;
- 250 x 100 µm^2 pixel pads;
- 64 analogue outputs each side, rolling shutter of matrix readout;
- characterisation ongoing, 3x gain measured on passive test structures with NIR pulsed laser.





Summary

- AIDAinnova contributes significantly to DMAPS developments for future HEP experiments
- Many different projects targeting different requirements such as high resolution, high radiation tolerance, fast timing and fast readout
- Very good results on all fronts and we expect more in the next two years of AIDAinnova

Further readings

TJ-MALTA

- JINST 2021 https://doi.org/10.5281/zenodo.6951327
- TWEPP 2021 https://doi.org/10.1088/1748-0221/17/04/C04034
- IEEE TNS 2022 https://doi.org/10.1109/TNS.2022.3170729
- NIM A 2022 https://doi.org/10.1016/j.nima.2022.167390
- NIM A 2022 https://doi.org/10.1016/j.nima.2022.167226
- NIM A 2023 https://doi.org/10.1016/j.nima.2022.167809
- EPJ-C 2023 https://doi.org/10.1140/epjc/s10052-023-11760-z
- JINST 2023: https://doi.org/10.1088/1748-0221/18/03/C03011
- JINST 2023: https://doi.org/10.1088/1748-0221/18/03/C03013

TJ-Monopix

- NIM A 2022 https://doi.org/10.1016/j.nima.2022.167189
- arXiv 2023 https://doi.org/10.48550/arXiv.2301.13638

LF-Monopix

- NIM A 2022 https://doi.org/10.1016/j.nima.2022.167224
- NIM A 2022 https://doi.org/10.1016/j.nima.2022.166747

CACTUS

- NIM A 2022 https://doi.org/10.1016/j.nima.2022.167022

TJ 65nm

- NIM A 2022 https://doi.org/10.1016/j.nima.2022.167213

RD50-MPW

- NIM A 2022 https://doi.org/10.1016/j.nima.2022.166826
- NIM A 2022 https://doi.org/10.1016/j.nima.2022.167020
- JINST 2023 https://doi.org/10.1088/1748-0221/17/12/C12017

- 18 publications so far
- More to come

WP5 meetings at:
https://indico.cern.ch/category/13503/