Status of DMAPS (WP5) Activities

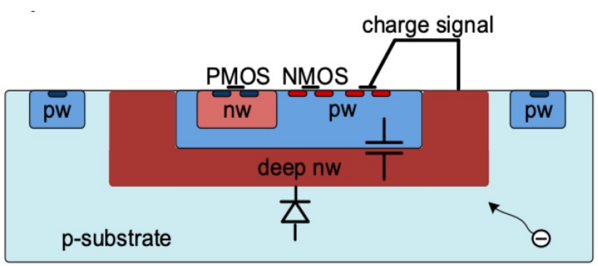
S. Grinstein (IFAE-Barcelona) and F. Hügging, N. Wermes (Bonn)

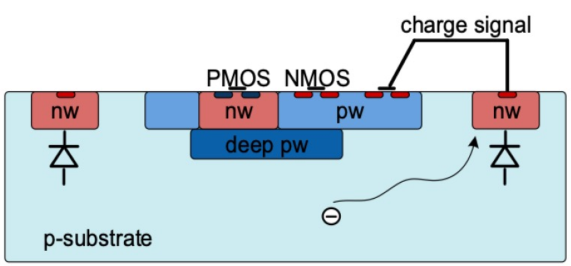
2nd Annual Meeting Valencia – 26 Apr 2023
https://indico.cern.ch/event/1191719/

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101004761.

- **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)

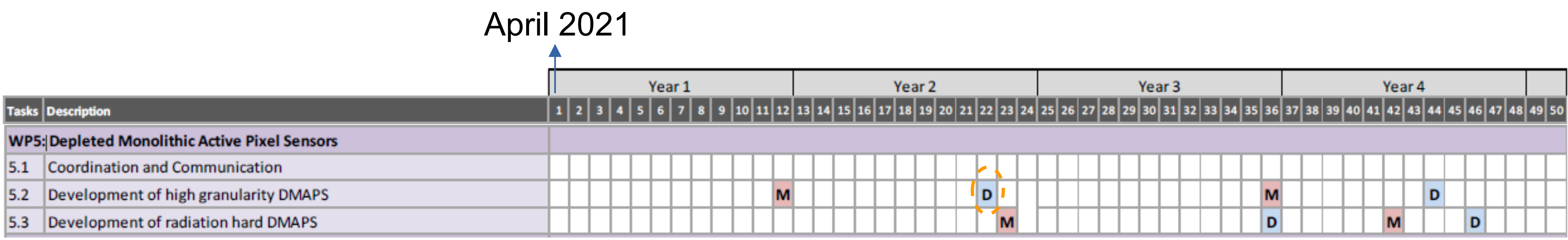




small electrode (high granularity)

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

WP5 Deliverables



WP5 Deliverables consist of reports, which are the responsibility of the institutes in the last column.

Due Jan 2023, results available, report written

March 2023 ✓

Deliverables related to WP5		
D5.1: Report on performance of high granularity DMAPS Version 1 *Report on performance of high granularity monolithic pixel sensor 1 (task 5.2)*	22	CNRS-IPHC
D5.2: Report on performance of high granularity DMAPS Version 2 *Report on performance of high granularity monolithic pixel sensor 2 (task 5.2)*	44	INFN
D5.3: Report on performance of radiation-hard DMAPS *Report on performance of structures and the radiation hard monolithic pixel 1 (task 5.3)*	36	Bonn
D5.4: Report of beam tests of irradiated radiation-hard DMAPS *Report of beam tests of radiation-hard devices after high irradiation (task 5.3)*	46	CERN

See also: https://aidainnova.web.cern.ch/wp5

WP5 Milestones

April 2021

		Year 1												Year 2												Year 3												Year 4													
Tasks	Description	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50
WP5:	**Depleted Monolithic Active Pixel Sensors**																																																		
5.1	Coordination and Communication																																																		
5.2	Development of high granularity DMAPS												M										D														M								D						
5.3	Development of radiation hard DMAPS																							M													D						M				D				

Milestones have short associated reports and are within the responsibility of the institutes in the last column.

April 2022 ✓

MS5.1	High granularity prototype fabrication 1	5.2	M12	Devices available
MS5.2	High granularity prototype fabrication 2	5.2	M36	Devices available
MS5.3	Radiation hard prototype fabrication	5.3	M23	Devices available
MS5.4	Test beam of the radiation hard monolithic pixel 1	5.3	M42	Test beam with prototypes measured

CNRS-IPHC

INFN

Bonn

CERN

Rad hard prototypes exist, characterization is far advanced,
due: end of Feb 2023 => report written

See also: https://aidainnova.web.cern.ch/wp5

Publications & Meetings

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

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

15 publications
so far

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

Summary of Activities

- Next slides are a brief summary of recent achievements as presented during the Annual meeting
- See details in WP5 session on Apr. 25:
  - https://indico.cern.ch/event/1191719/sessions/454935/#20230425

15:00	**Recent Results on irradiated LF Monopix 2**	*Lars Philip Schall*	*https://cern.zoom.us/j/61522320218?pwd=ZGpWT3F6YXk0ZmRYT1dFTSswRkpmQT09, Aula 2.7*	15:00 - 15:20
	Results on TJ Malta	*Marcos Vazquez Nunez*	*https://cern.zoom.us/j/61522320218?pwd=ZGpWT3F6YXk0ZmRYT1dFTSswRkpmQT09, Aula 2.7*	15:20 - 15:40
	Performance of unirradiated TJ-Monopix 2	*Christian Bespin*	*https://cern.zoom.us/j/61522320218?pwd=ZGpWT3F6YXk0ZmRYT1dFTSswRkpmQT09, Aula 2.7*	15:40 - 16:00
16:00				
	Coffee break		*https://cern.zoom.us/j/61522320218?pwd=ZGpWT3F6YXk0ZmRYT1dFTSswRkpmQT09, Aula 2.7*	16:15 - 16:30
	Obelix for Belle II	*Maximilian Babeluk*	*https://cern.zoom.us/j/61522320218?pwd=ZGpWT3F6YXk0ZmRYT1dFTSswRkpmQT09, Aula 2.7*	16:30 - 16:50
	Sub 100 ps time measurements with non-amplified DMAPS	*Jean-Pierre Meyer et al.*	*https://cern.zoom.us/j/61522320218?pwd=ZGpWT3F6YXk0ZmRYT1dFTSswRkpmQT09, Aula 2.7*	16:50 - 17:10
17:00	**Development and evaluation of the RD50-MPW chips in the LFoundry 150 nm HV-CMOS process**	*Ricardo Marco Hernandez et al.*		
	DMAPS activities at PSI	*Stephan Tobias Burkhalter*	*https://cern.zoom.us/j/61522320218?pwd=ZGpWT3F6YXk0ZmRYT1dFTSswRkpmQT09, Aula 2.7*	17:30 - 17:50
	DMAPS developments in TPSCo 65nm	*Jerome Baudot*	*https://cern.zoom.us/j/61522320218?pwd=ZGpWT3F6YXk0ZmRYT1dFTSswRkpmQT09, Aula 2.7*	17:50 - 18:10
18:00	**Ring oscillator tests in TJ/TPSCo 65**	*Marlon B. Barbero*	*https://cern.zoom.us/j/61522320218?pwd=ZGpWT3F6YXk0ZmRYT1dFTSswRkpmQT09, Aula 2.7*	18:10 - 18:30

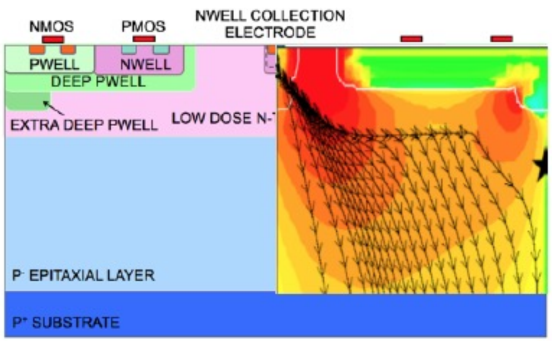
Tower 180 nm

TJ-MALTA-2&3

TJ-Monopix-2

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):
    1. shape charge collection geometry
    2. optimize FE against RTS noise
    3. 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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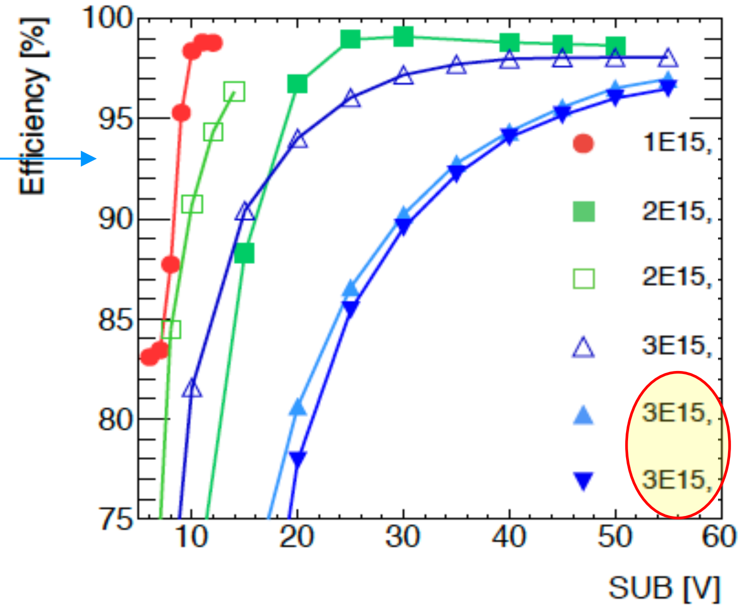
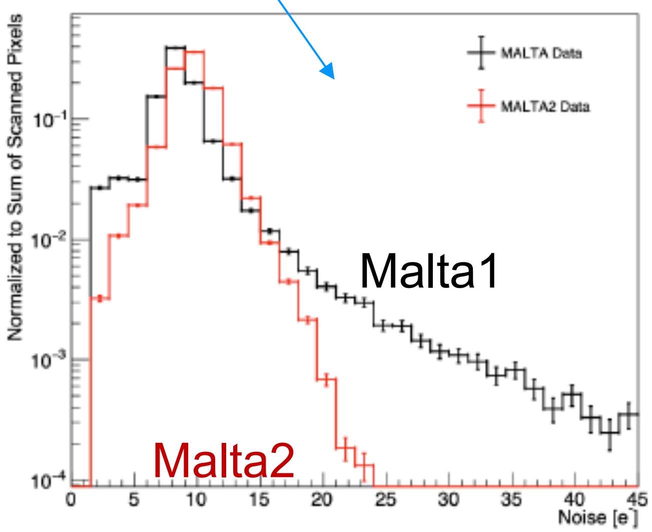
TJ-MALTA
High granularity, small electrode

Goals of MALTA2 achieved:

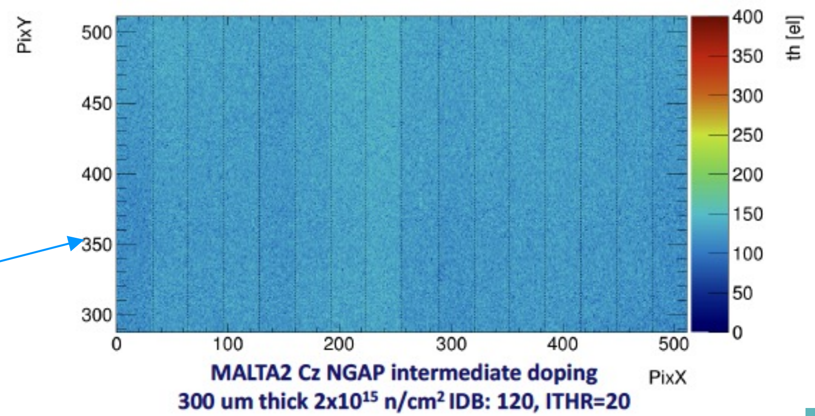
- radhard to >1E15 neq/cm2
- @ 3E15 neq/cm^2 > 95% in 25ns



- RTS noise mitigated



- excellent matrix homogeneity



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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

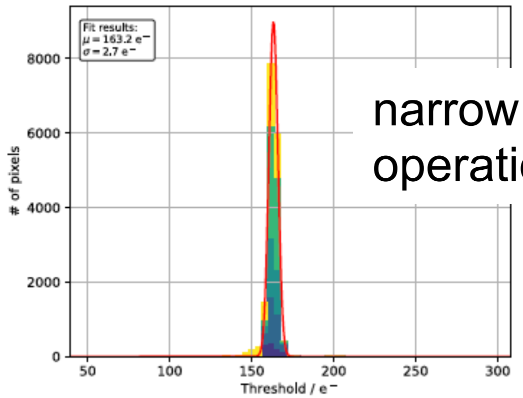
	TJ-Monopix1	TJ-Monopix2
Chip Size	1x2 cm^2 (224x448 pix)	2x2 cm^2 (512x512 pix)
Pixel size	36 × 40 μm^2	33.04 × 33.04 μm^2
Total matrix power	130 mW/cm^2	170 mW/cm^2
Noise	≅11 e$^-$	< 8 e$^-$ (improved FE)
LE/TE time stamp	6-bit	7-bit
Threshold Dispersion	≅ 30 e$^-$ rms	< 10 e$^-$ rms (improved FE + 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

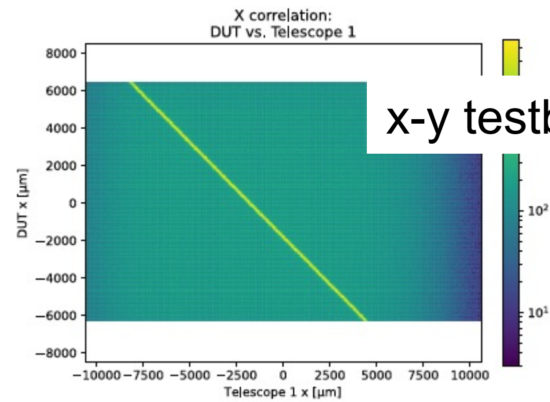
Bonn, CERN, CPPM, IRFU
- 180 nm technology -

- 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

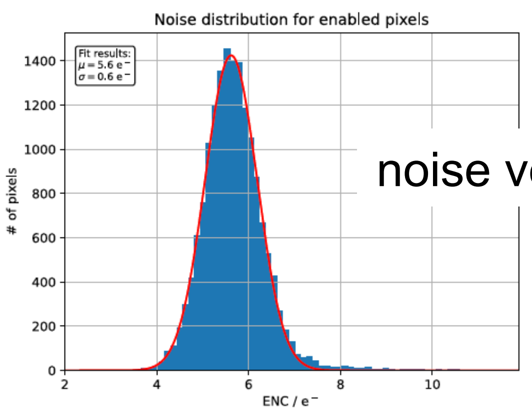
TJ-Monopix 2
High granularity, small electrode



narrow (tuned) operation threshold

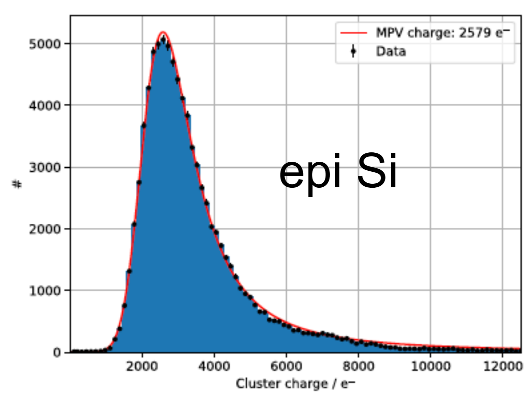


x-y testbeam correlation



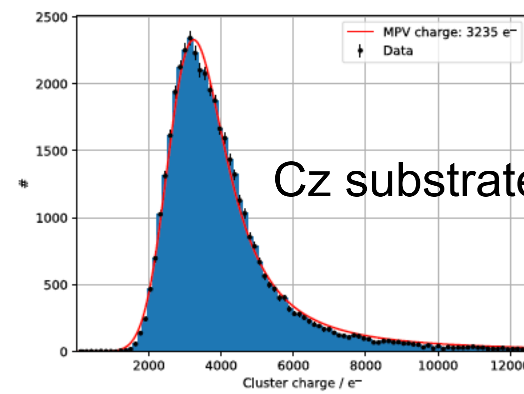
noise very low

Epi gap in n-layer: 2.5 ke- MPV



epi Si

Cz gap in n-layer: 3.2 ke- MPV



Cz substrate

mip signals

(→ depletion profile still to be understood)

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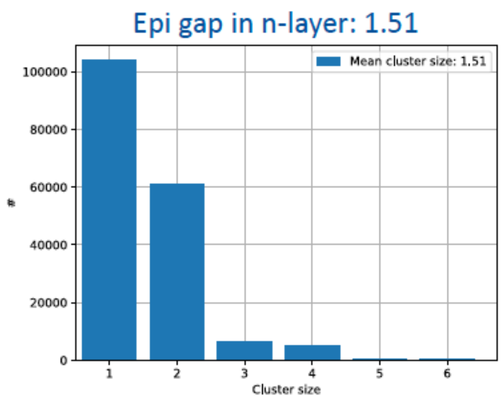
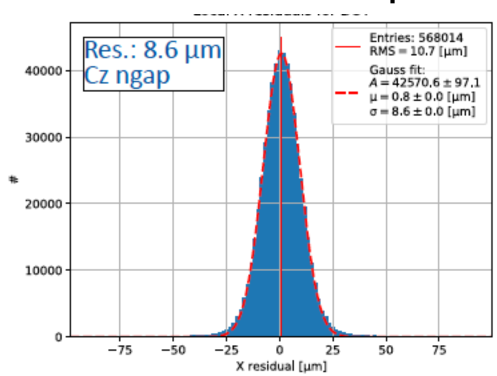
TJ-Monopix 2
High granularity, small electrode

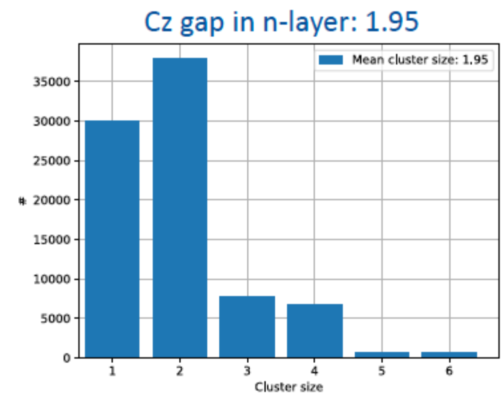
epi Si

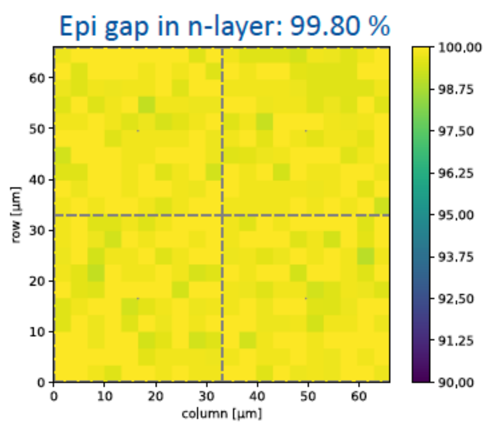


resolution 8.6 µm



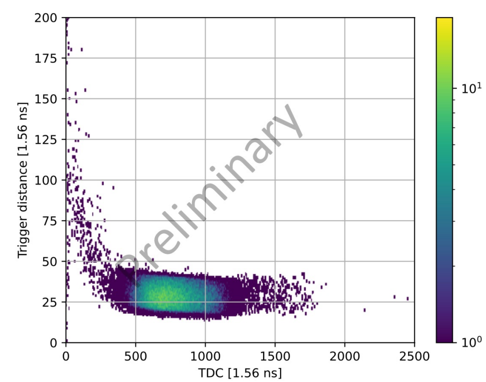
Cz substrate

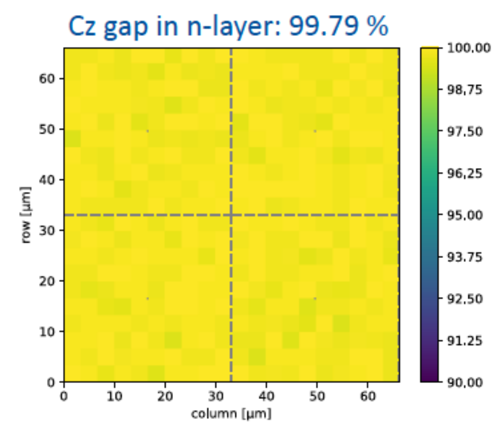




very high efficiencies (before irradiation)

irradiation planned Q1/Q2





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

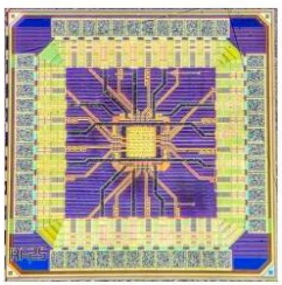
Tower 65nm

TPSCo 65 nm (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

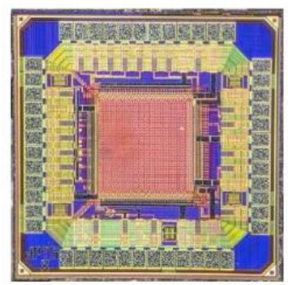
APTS Analogue Pixel Test Structure



1.5 mm

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

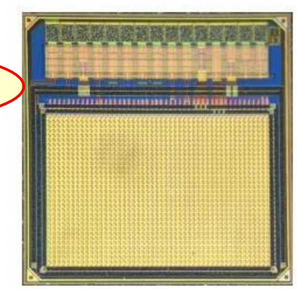
DPTS Digital Pixel Test Structure



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

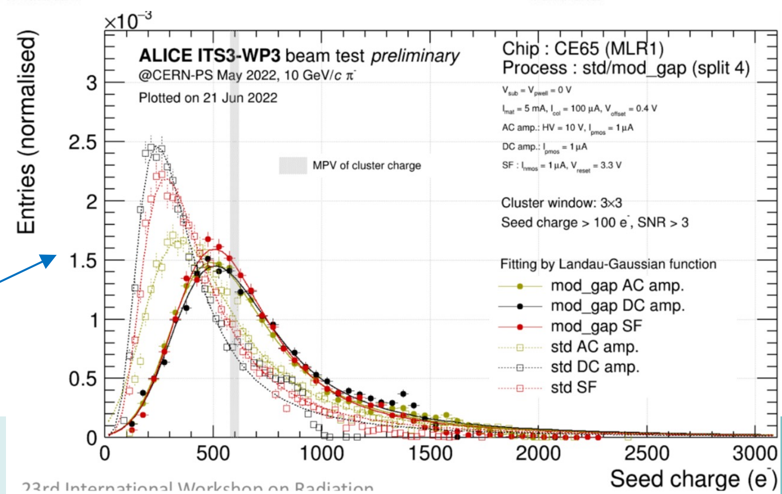


1.5 mm

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



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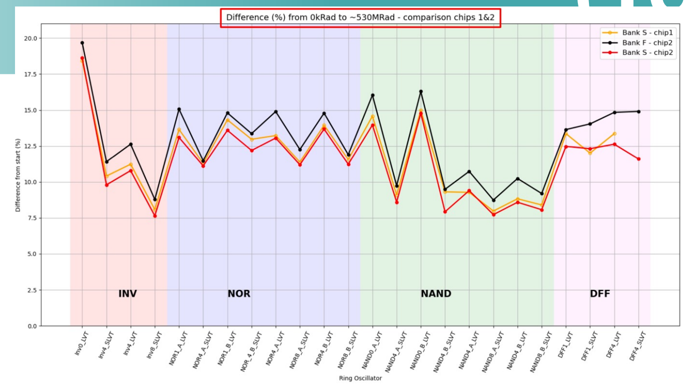
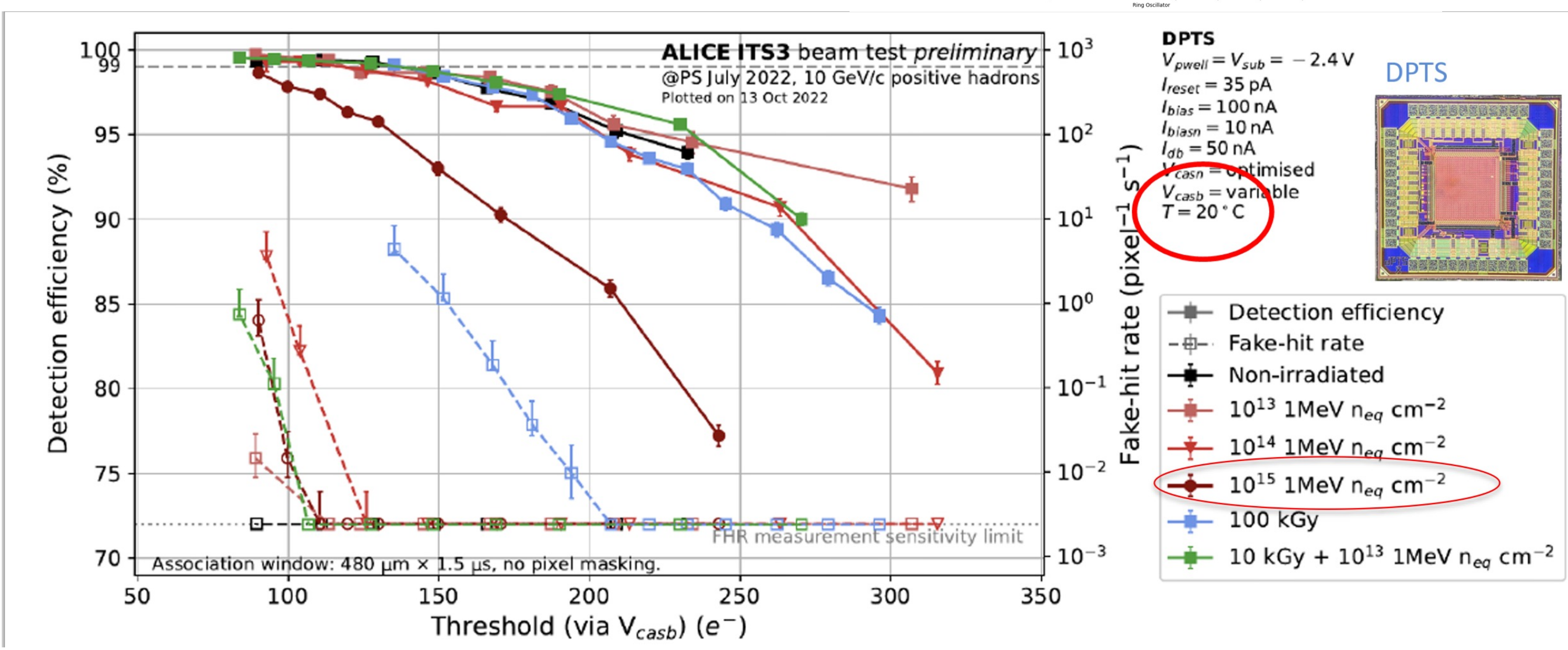
TPSCo 65 nm (Tower)



Promising radiation tolerance:

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

with TID measurements on ring oscillators



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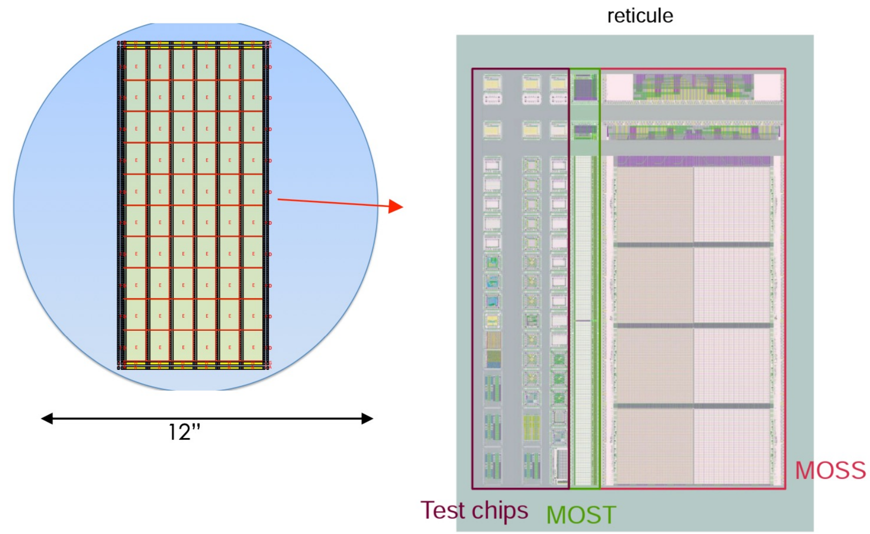
2nd submission: Engineer Run 1 (ER1)

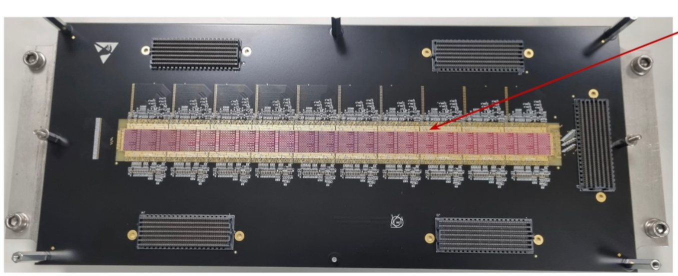
- Main goal = exercise stitching (in 1D) to assess yield
- Submission November 2022
- Back from fab April 2023

- 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

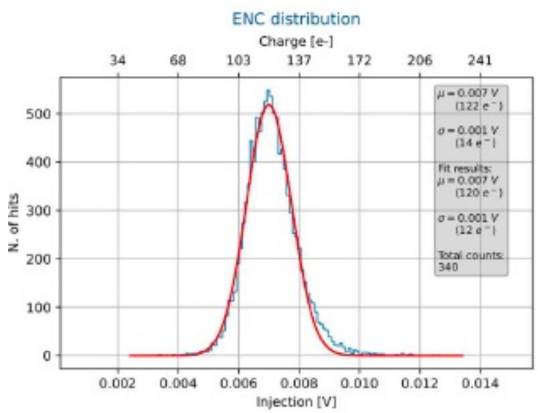
- LF-Monopix-2
- RD50 – MPW2/3
- CACTUS

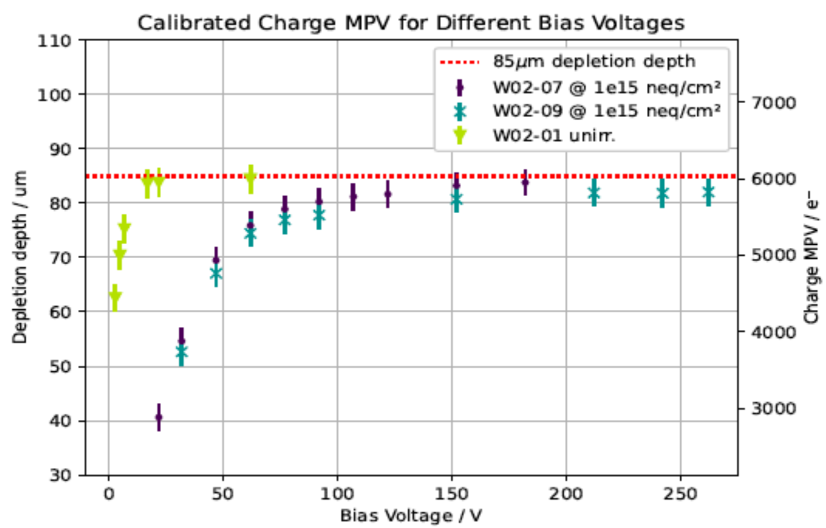
LF-Monopix 2
Large electrode, radiation hardness

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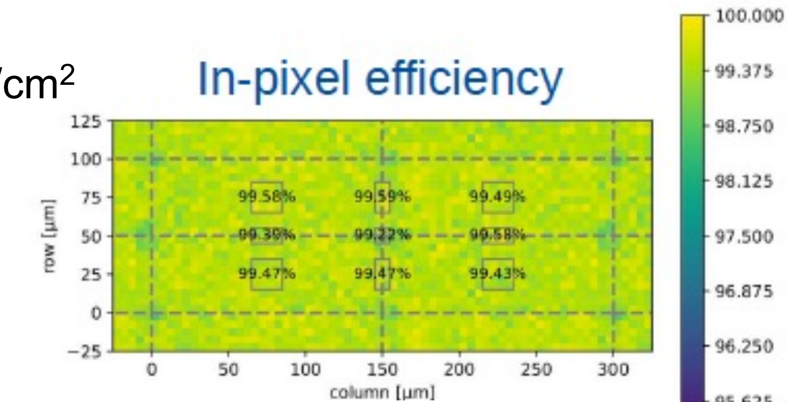
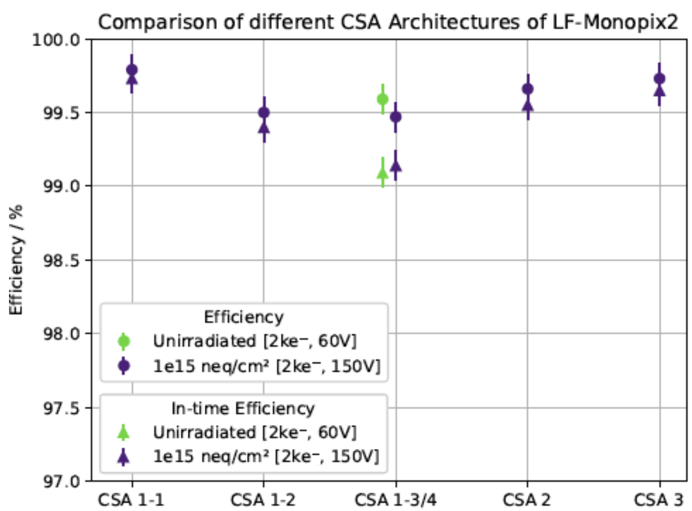
- fully depleted @ 100 V bias (15 V unirr.)

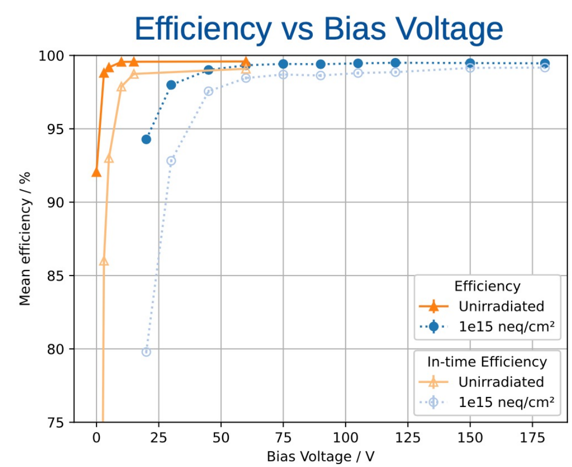
LF-Monopix 2
Large electrode, radiation hardness

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

- intensive testbeam characterisation
- very high (>99%) efficiency (in-time) after 1e15 neq/cm^2
- ~no efficiency degradation wrt unirradiated devices







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next: 1e15 n_{eq}/cm^2 → 2e15 n_{eq}/

RD50-MPW2/3

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)

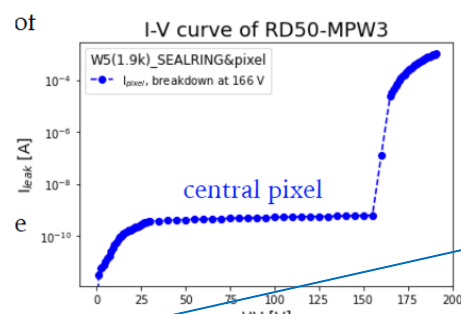
MPW2: small prototype

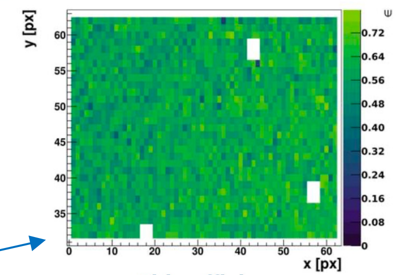
- pixels: 60 x 60 µm2
- in-pix CSA + discriminator, analog R/O
- testbeams performed
- charge collection ok

MPW3: added digital R/O (column drain)

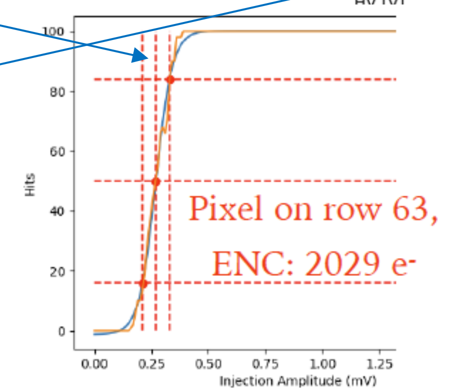
- $V_{breakdown}$ ~ 150V
- very high noise (> 2000 e) due to noise coupling from digital periphery
- Poor test beam efficiency due to high thresholds

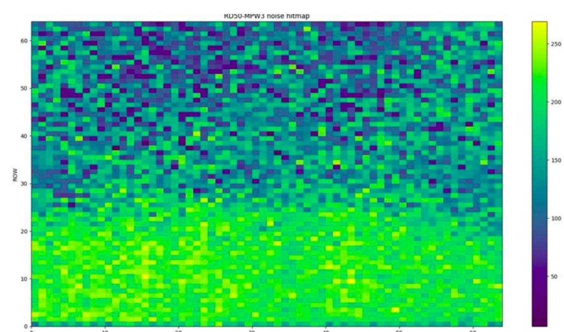
MPW4 (2024): backside processing to improve radiation hardness





Chip efficiency





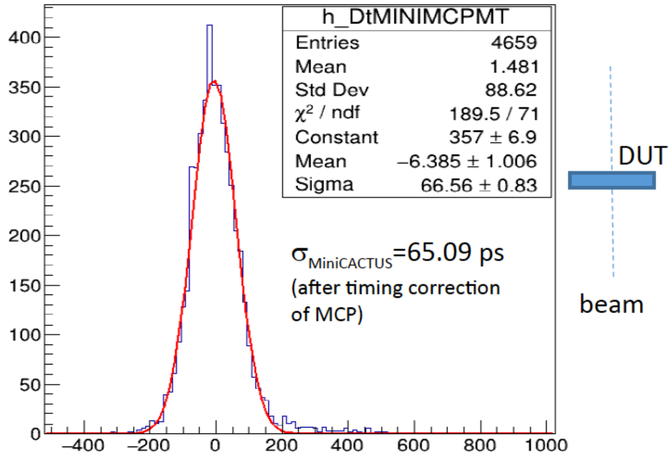
Pixel matrix noise hitmap

 E. Vilella, R. Hernandez et al

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

Mini CACTUS = small prototype to address limitations of CACTUS (low S/N)

- 65 ps mip time resolution achieved in testbeams
- compared calibrations and resolutions using photons of different energies (^{241}Am and @SOLEIL)
  - calibrations ✓
  - σ_t for photons (understandably) worse (320 ps)
- next:
  - characterisation after 1e14, 1e15, and 1e16 n_{eq}/cm^2
  - new Mini-CACTUS submission May 2023



P. Schwemling, Y. Degerli et al

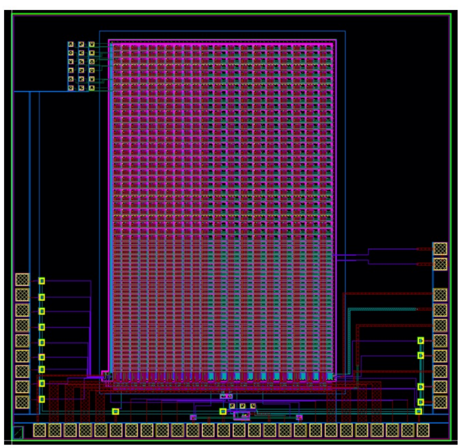
LFoundrxy 110 nm, TSI

PSI developments

PSI developments

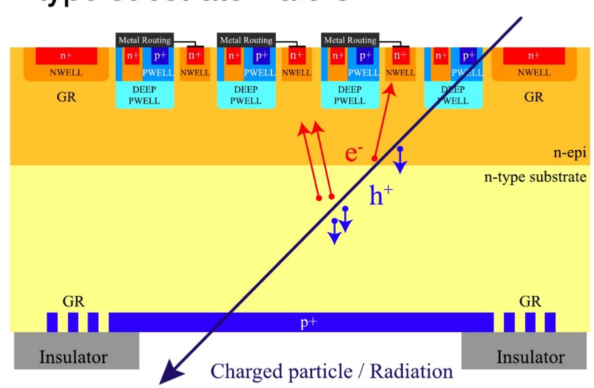
Goal: Generic R&D on DMAPS with TSI and technology platform in LF 110 nm provided by ARCADIA

- 2 PSI TSI MAPS chips designed and manufactured with promising results, more test underway
- First LF 110 prototype designed and manufactured using the ARCADIA platform
- First results in test beam looks good → high efficiency (99,7%) and good spatial resolution (10 μm)
- Second version just arrived

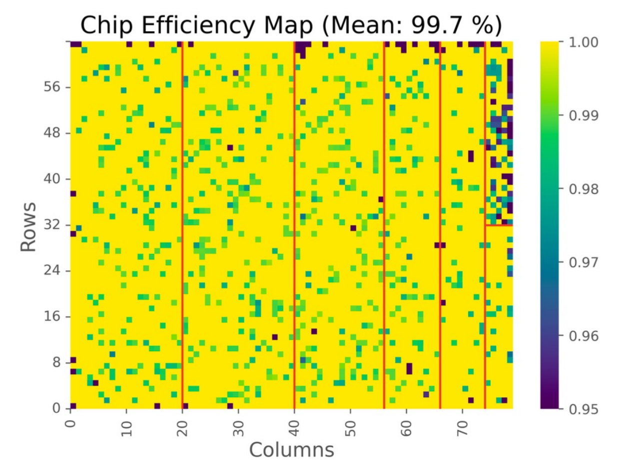


2nd PSI TSI MAPS chip

N-type substrate wafers



Modified LF 110 nm process



TB results of 1st LF 110 chip

S. Burkhalter et al.

Summary

- Lots of activity at all fronts: *high granularity, radiation hardness and timing*
- Fabrication of devices completed in all lines
- First Milestones achieved (reports done or in process for review)
- All research lines are currently intensively characterizing their devices
- Many publications

BACK UP SLIDES

LFoundry 110 nm

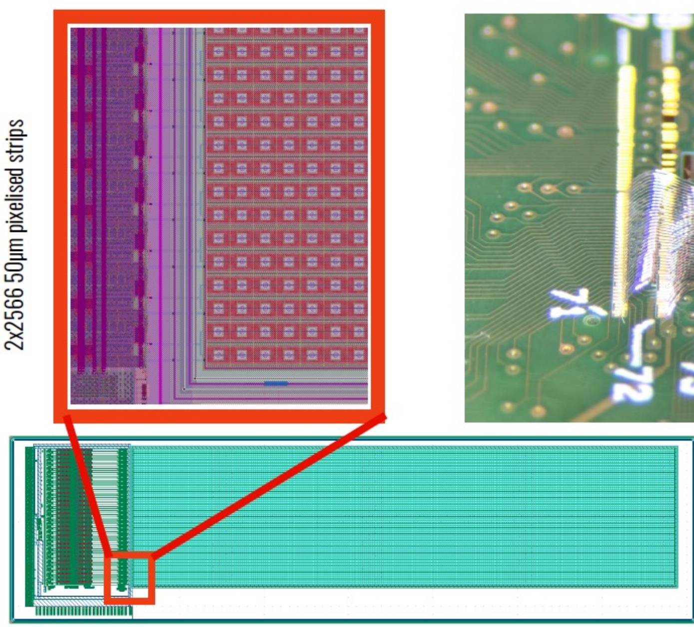
ARCADIA

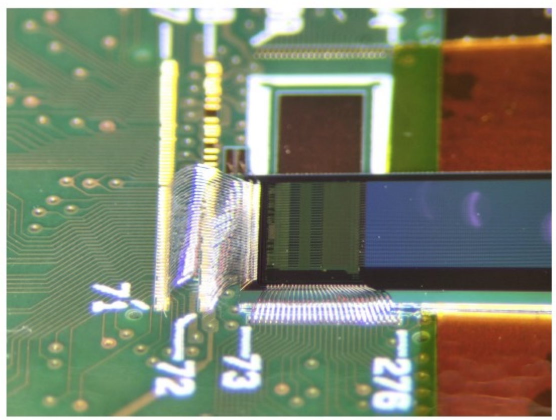
ARCADIA Tests

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

- MD1 main-demonstrator
- under test: Fully Depleted Monolithic Active Microstrip demonstrator -> looks good
- 27 wafers out from fab recently
- adding gain layer considered for LC3

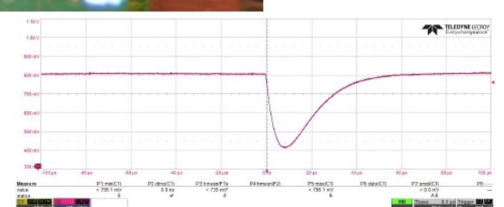
Figure: CAD Layout of 32-block of 2x2566 50µm pixelised strips





Fully Depleted Monolithic Active Microstrip Sensors: TCAD Simulation Study of an Innovative Design Concept. Sensors 2021, 21, 1990. https://doi.org/10.3390/s21061990

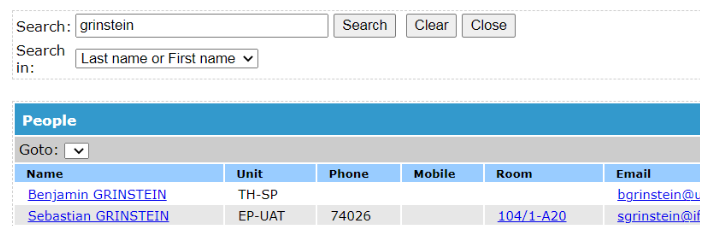
ARCADIA



M. Rolo et al.

Reminders

- To subscribe to the AIDAInnova-WP5 mail list:
  - Go to https://e-groups.cern.ch/e-groups/EgroupsSearchForm.do
  - Search for our mailing list (aidainnova-wp5), and sign up
  - Also gives access to indico (use same CERN mail)



- **Acknowledge AIDAinnova support of activities (where relevant)**
  - Articles, pre-prints, notes, slides at conferences… *proceedings of VCI2022!*
  - Official acknowledge text at AIDAinnova web site:

    https://aidainnova.web.cern.ch/publications

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- Let us know of changes above.
- The AIDAinnova-WP5@cern.ch mailing list is used for general announcements and information.