Simulations and characterization of the first monolithic CMOS LGAD implemented in 110nm

2nd DRD3 week on Solid State Detectors R&D
CERN, 05/12/2024

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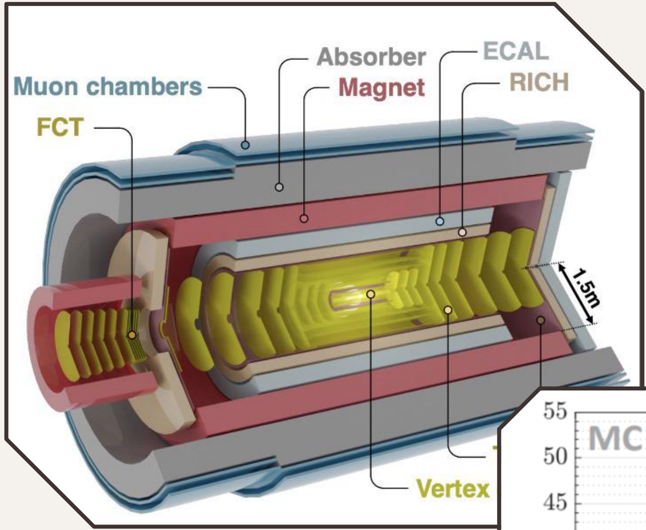
Motivation

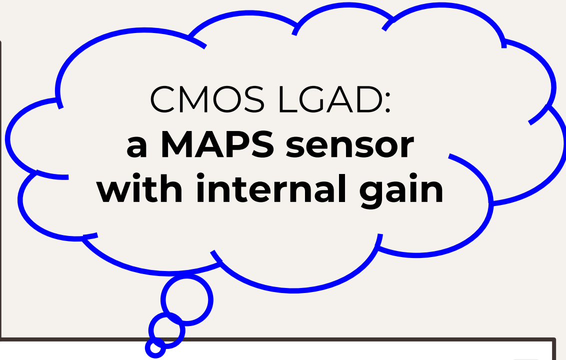
Main driver: **ALICE 3 ToF layers**

Constraints:

- Time resolution ≈ 20 ps
- Power consumption
- Material budget
- Cost

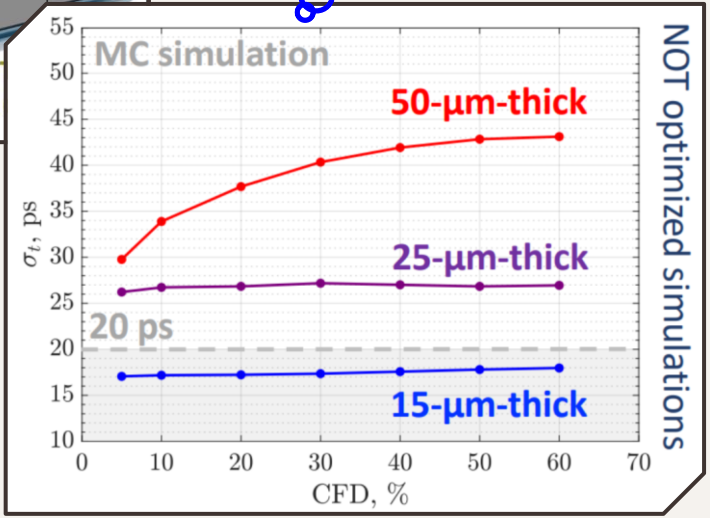
Monolithic timing detectors are considered as an option





Other fields: 4D tracking, very low power pixel sensors (space), medical applications

Low Gain Avalanche Diodes (LGADs): workhorse for high resolution silicon timing detector.



From simulations: **<20ps** for thicknesses **<15um**

Starting point: ARCADIA monolithic sensors

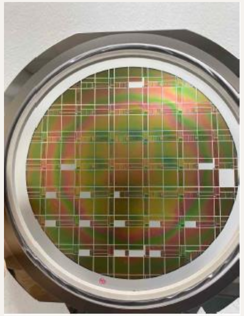
Fully depleted MAPS in 110nm CMOS

Available **thicknesses**:
- **48um, 100um, 200um** (full depletion demonstrate up to 400um)

Target **applications**:
- Medical Imaging (PCT)
- Space applications
- HEP experiments
- X-ray imaging

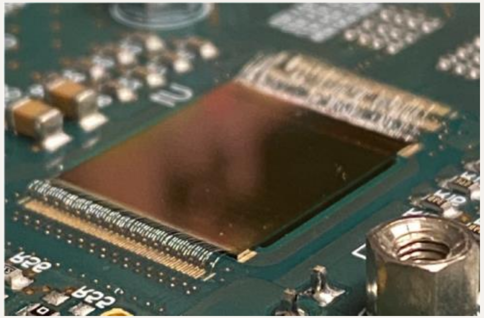
3 engineering runs:
- 1st – mid 2021
- 2nd – beginning 2022
- 3rd – beginning 2023

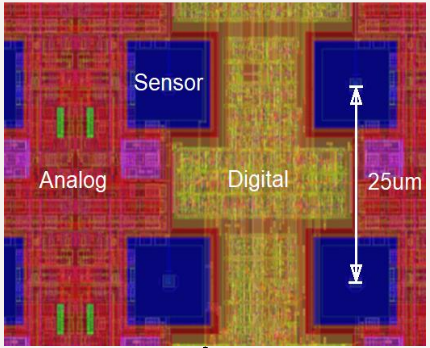
Main demonstrator (MD):
- Sensor array of **512x512 pixels**
- Pixel pitch: **25um**
- **Binary pixel** with **event-driven readout**



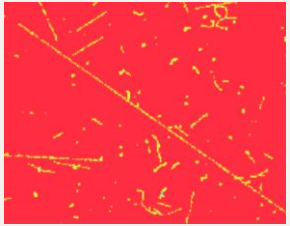
ARCADIA

Andrea Patternò, Vertex 2021
ARCADIA Main Demonstrator

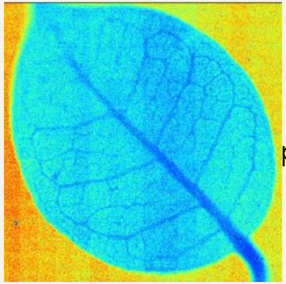




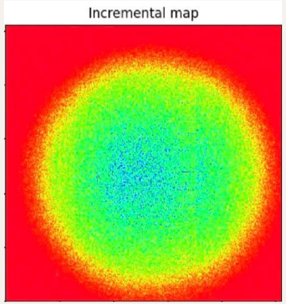
M. Rolo, **Pixel layout**



Cosmic Rays

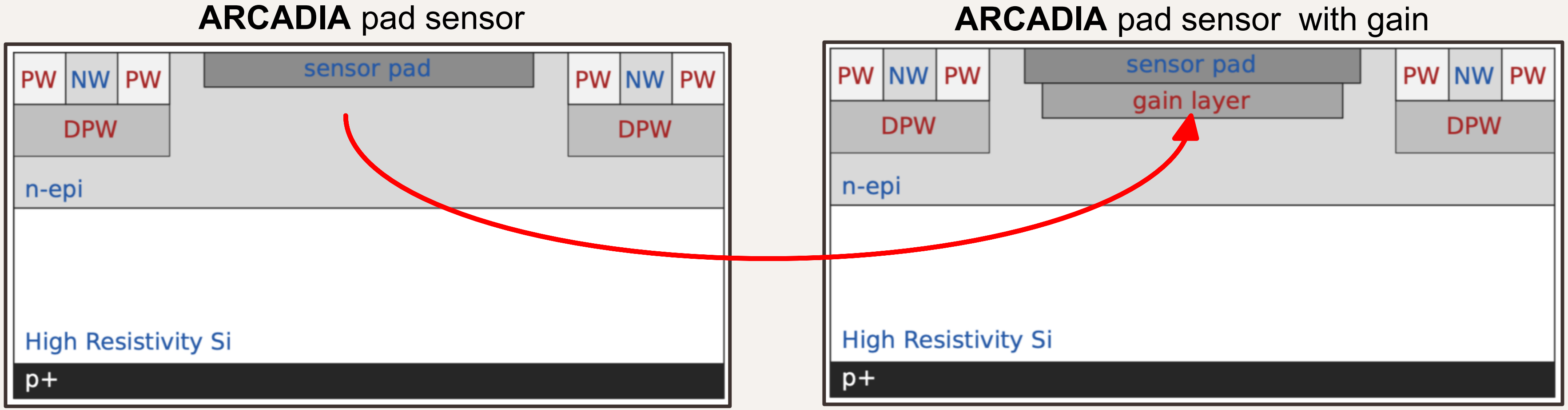


X-ray image - photon counting



^{90}Sr source

ARCADIA MAPS: gain add-on option



- Add-on **p-gain** below the collecting electrode starting from 3rd run
- Lfoundry CMOS 110nm with 48um active thickness
- ARCADIA production:
  - **passive structures** and **monolithic structures**
- Requires **negative bias** of the backside, **positive bias** at the sensor pad and **AC coupling** of readout electronics

MadPix

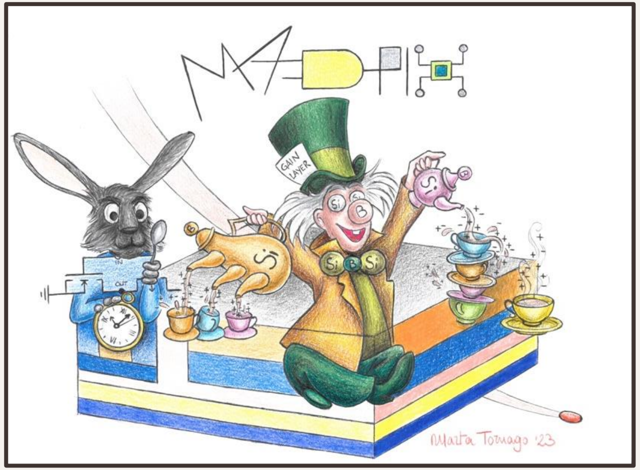
***M**onolithic CMOS **A**valanche **D**etector **PIX**elated Prototype*

First prototype with **integrated electronics** and **gain layer**

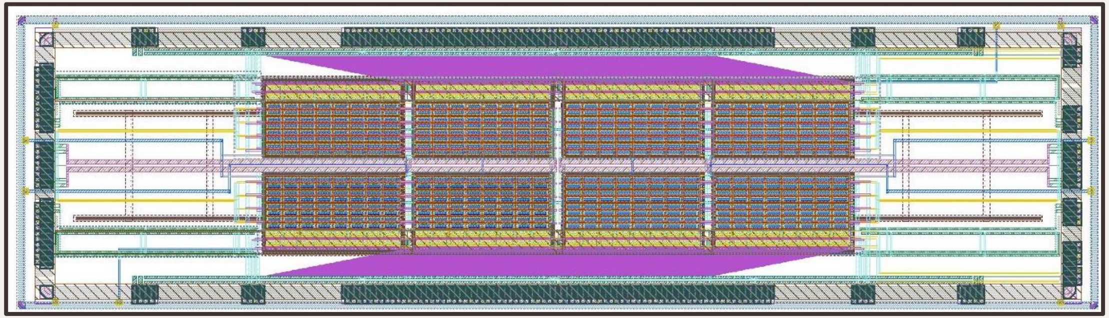
Active thickness: 48 µm

- **Backside HV**: allow full depletion → -20 V to -40 V
- **Topside HV**: manage the gain → 35 V to 65 V

- 8 matrices of 64 pixels each
- 64 x 2 analogue outputs
- 4 flavours
- Pixels of 250 µm x 100 µm



Thanks to M. Tornago

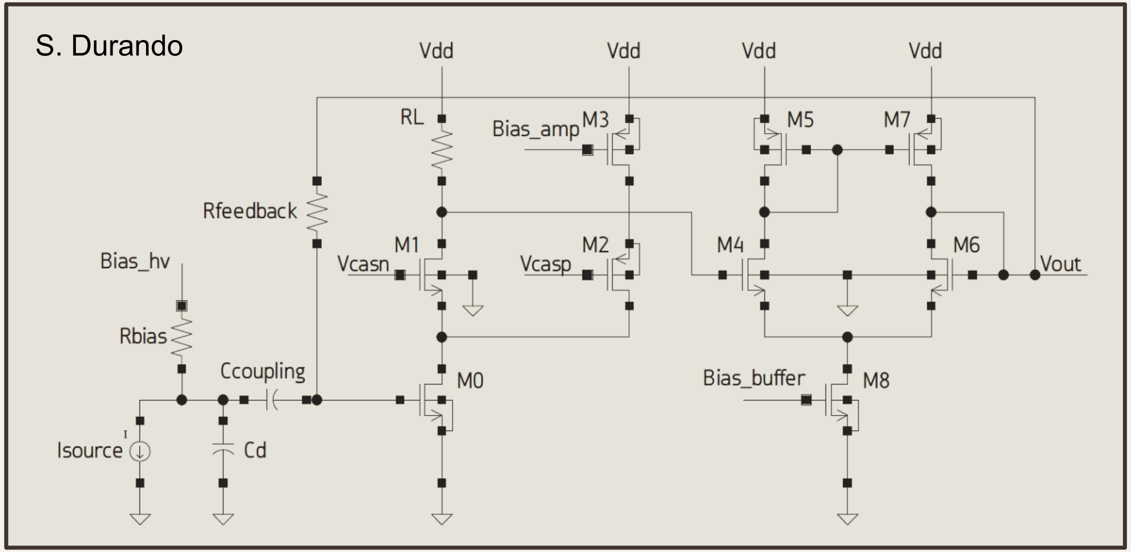


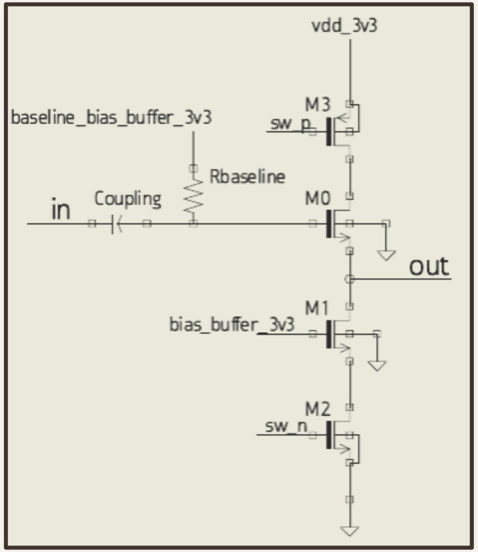
Symmetrical

MadPix Electronics

- Cascoded common source + differential buffer (1.2V)
- FE **AC coupled** with sensor
- Power: **0.18mW/ch**

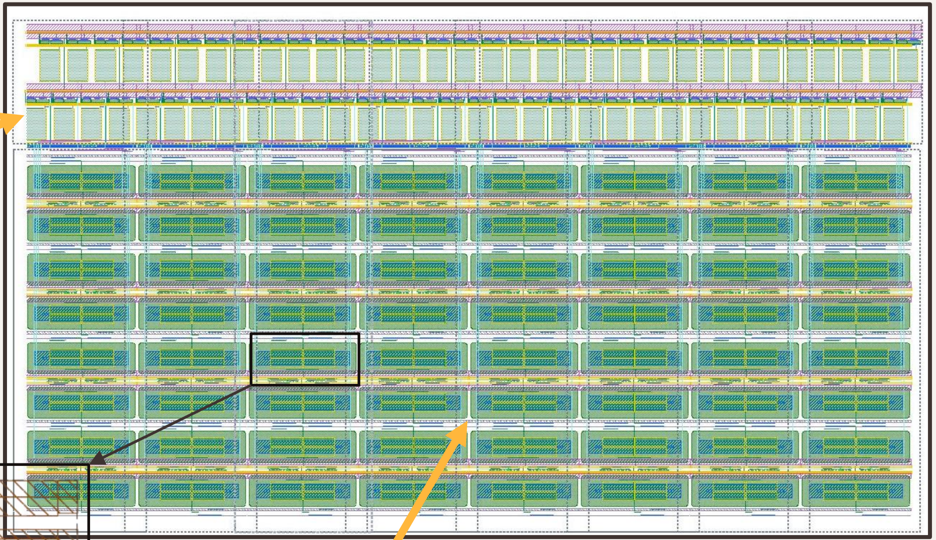
- Source follower (3.3V)
- AC coupled with FE
- Power: 1.65mW/ch

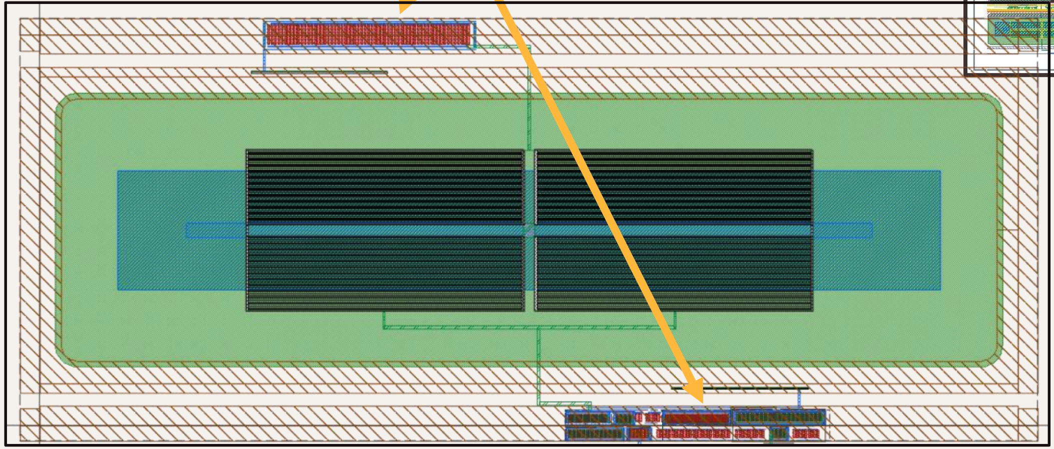




MadPix Layout

- 3.3V buffer out-pixel
- 1.2V **FE electronics in-pixel**



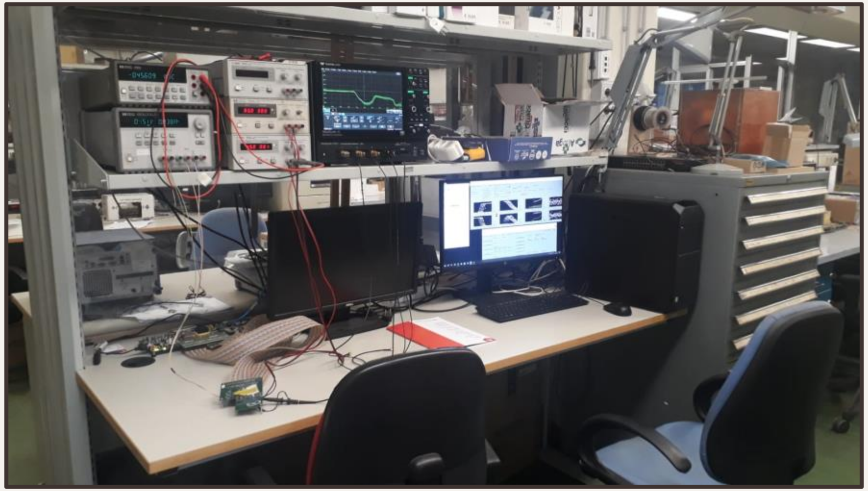


- 8x8 pixels in one matrix
- Pixel dimension: non optimal for timing (Distortion term) but crucial in this R&D phase
  - ↳ **Bigger pixels** can be implemented **in dedicated run**

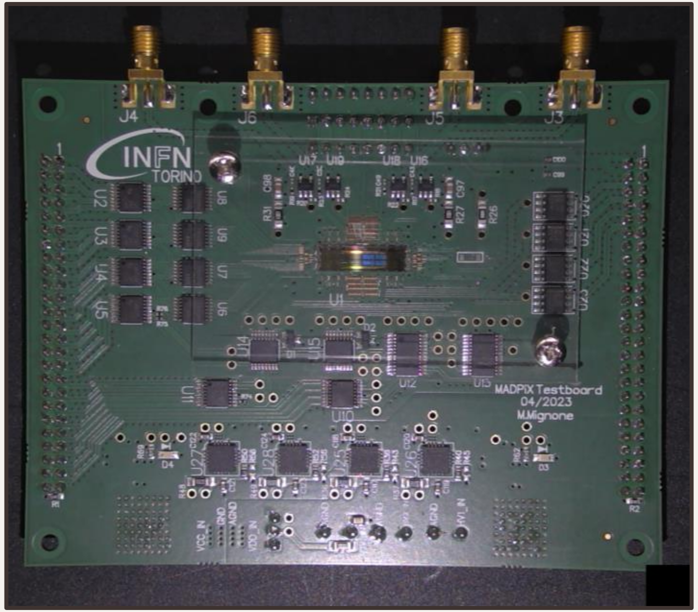
MadPix Test Board

Controlled through FPGA (DACs, Digital potentiometers, Test pulse)

- **4 SMA** driving 50Ω line (top 4 matrices)
  → **Analogue** read-out (Oscilloscope/Digitizer)
- **4 Discriminator** (bottom 4 matrices)
  → **Digital** read-out (FPGA)

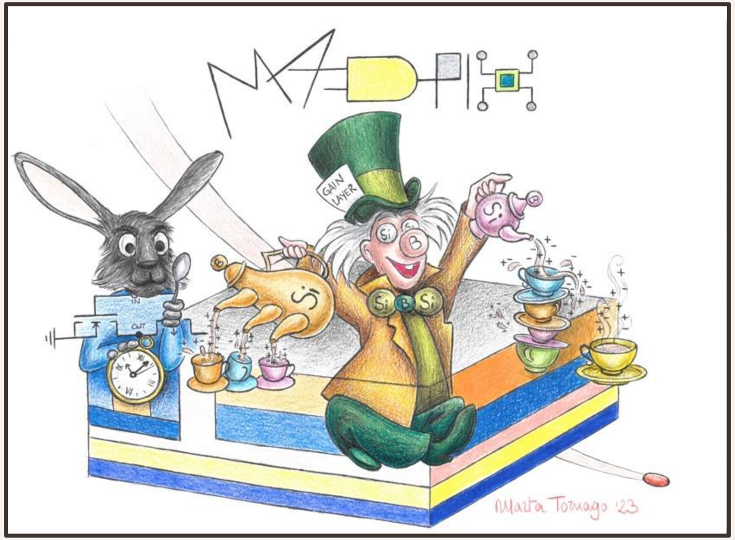


Only **four adjacent pixels** can be read simultaneously

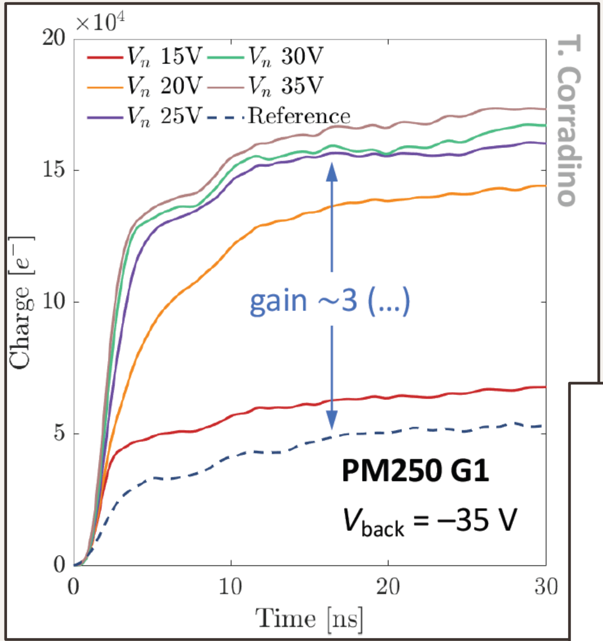


- Board designed by Marco Mignone (INFN Torino)
- Firmware written by Richard Weadon (INFN Torino)

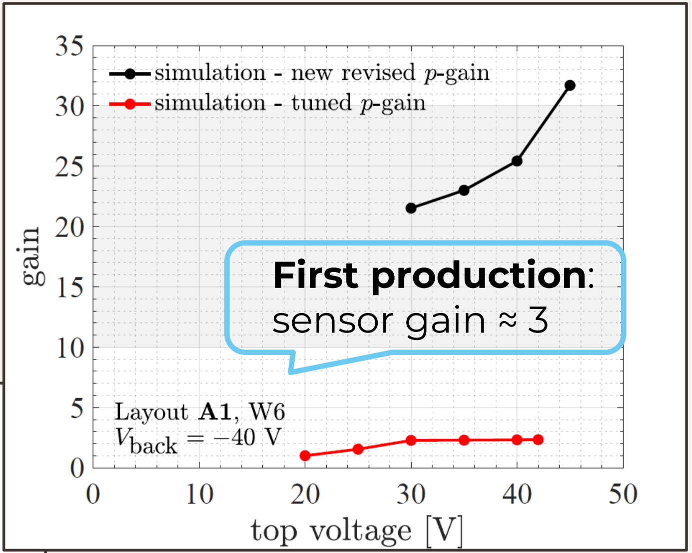
Chip Characterization



First results



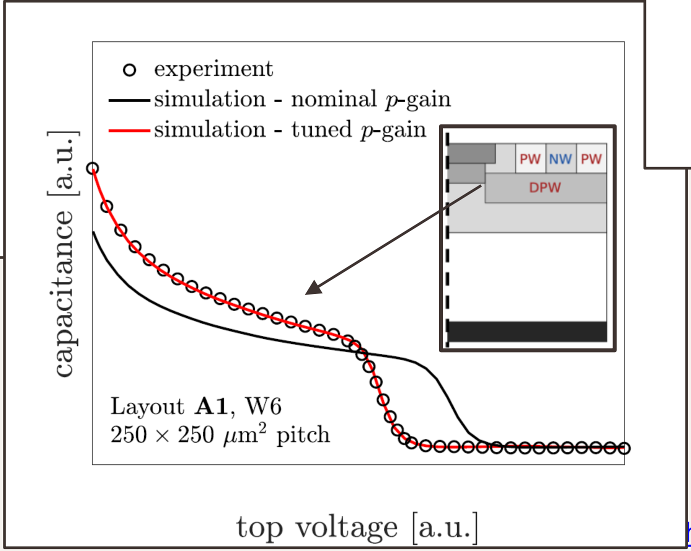
- Lateral **CV**
- P-gain **implantation energy is -2.5x** to recover mismatch (TCAD simulations)
- **Gain target** with nominal profile: **20-30**



- **Passive structures** under focused **IR laser**
- Backside Illumination
- Integrated charge in time

We have **gain**...

... but lower than expected



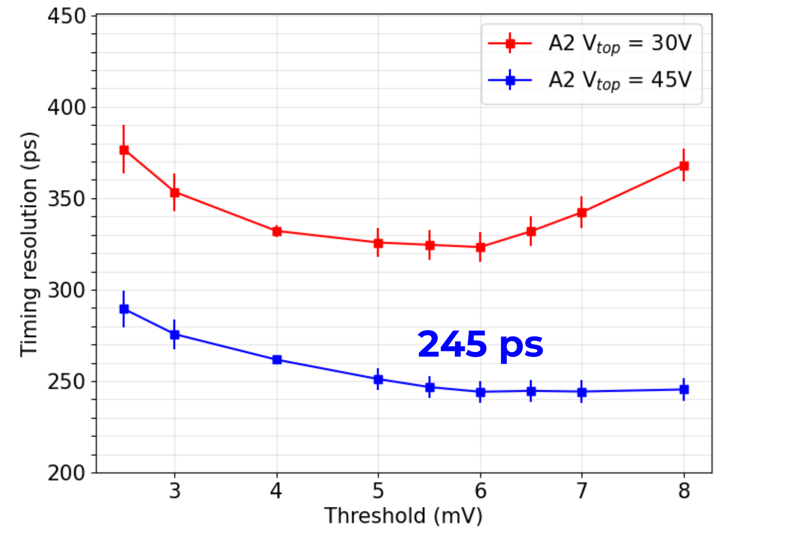
- Gain extraction using TCAD simulations with tuned p-gain profiles (TCAD simulations)
- **Gain simulated ≈ 3**
- **Good agreement** between data and simulation

https://dx.doi.org/10.1088/1748-0221/19/07/P07033

First test beam : Time resolution

October 2023

Time resolution measured in a test beam



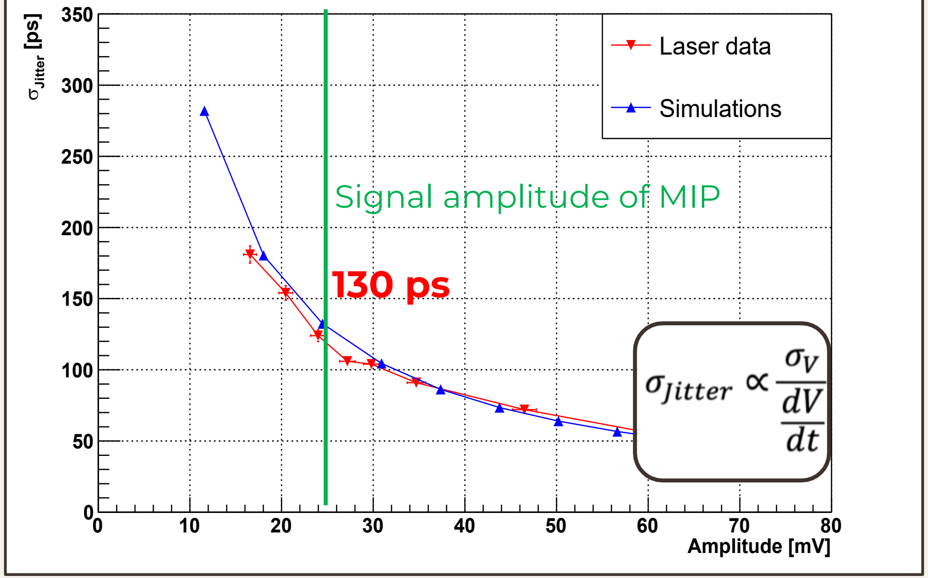
$$\sigma_t^2 = \sigma^2_{\text{Time Walk}} + \sigma^2_{\text{Landau Noise}} + \sigma^2_{\text{Distortion}} + \sigma^2_{\text{Jitter}} + \sigma^2_{\text{TDC}}$$

Time resolution of **245 ps** can **not** be explained with **jitter**

Main contributor: Sensor

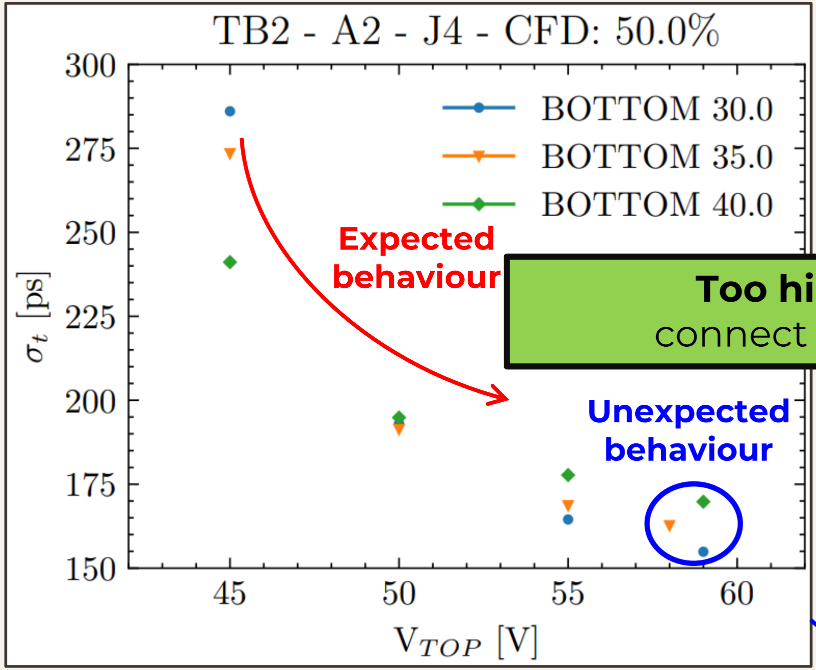
Jitter:

- RMS of the time difference between laser trigger out (TTL) and analogue output of MadPix (@ 50% signal amplitude)



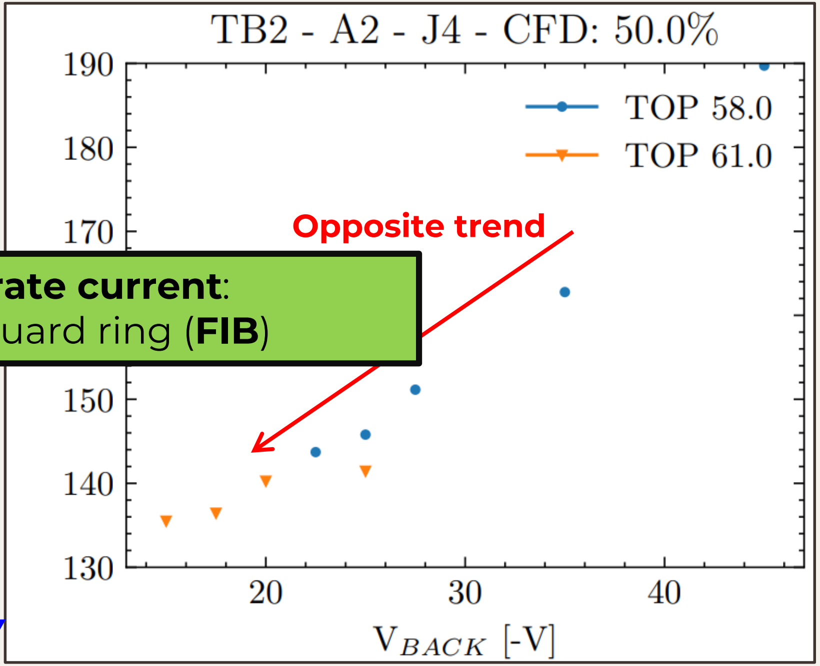
Second test beam: a lot to process

July 2024



Too high substrate current:
connect floating guard ring (**FIB**)

Investigated

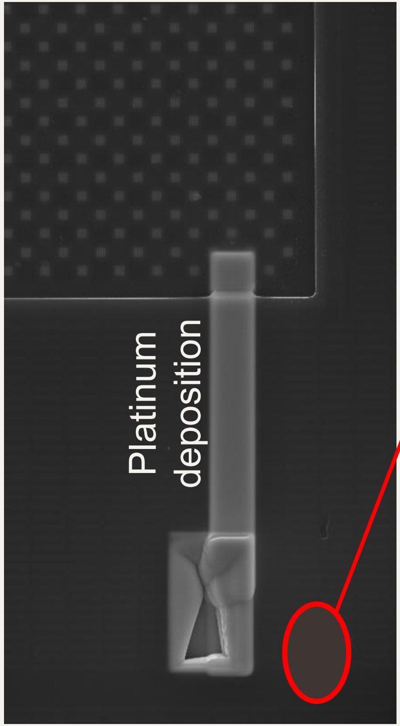


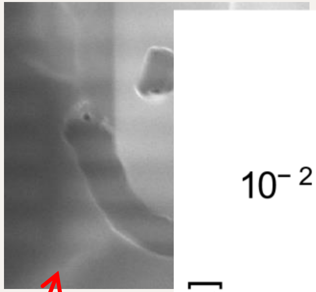
Increasing the collection electrode voltage, the time resolution improves

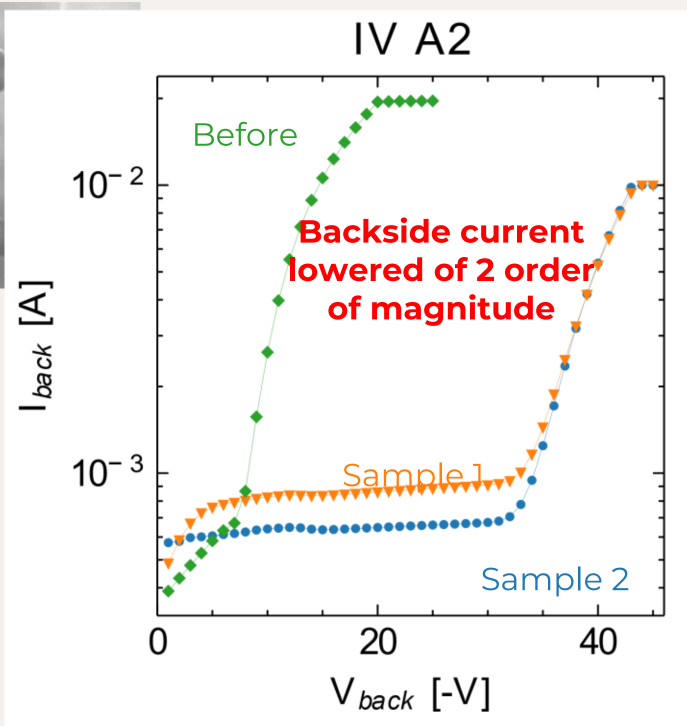
Decreasing the substrate voltage, the time resolution improves

Solving the problem: Focused Ion Beam

Floating guard ring to be shorted



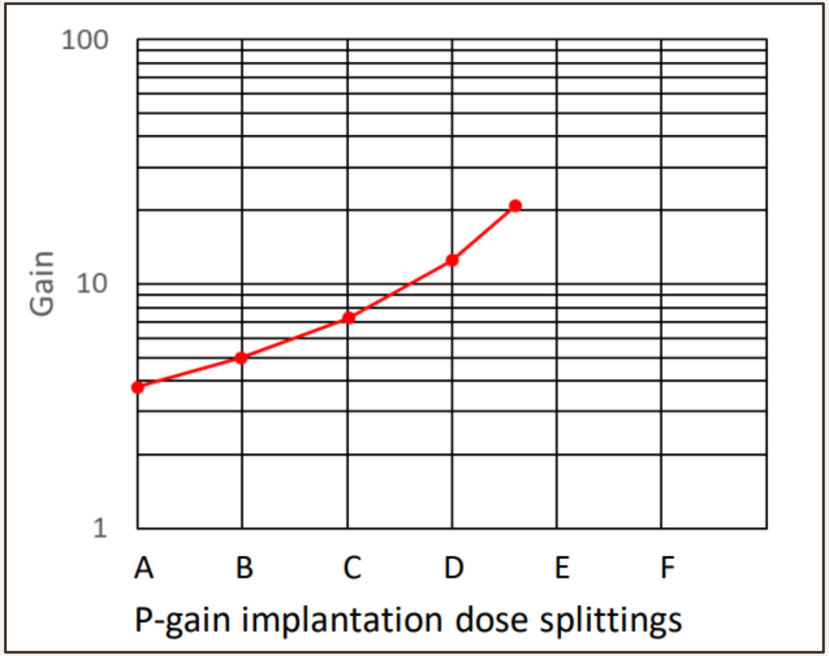


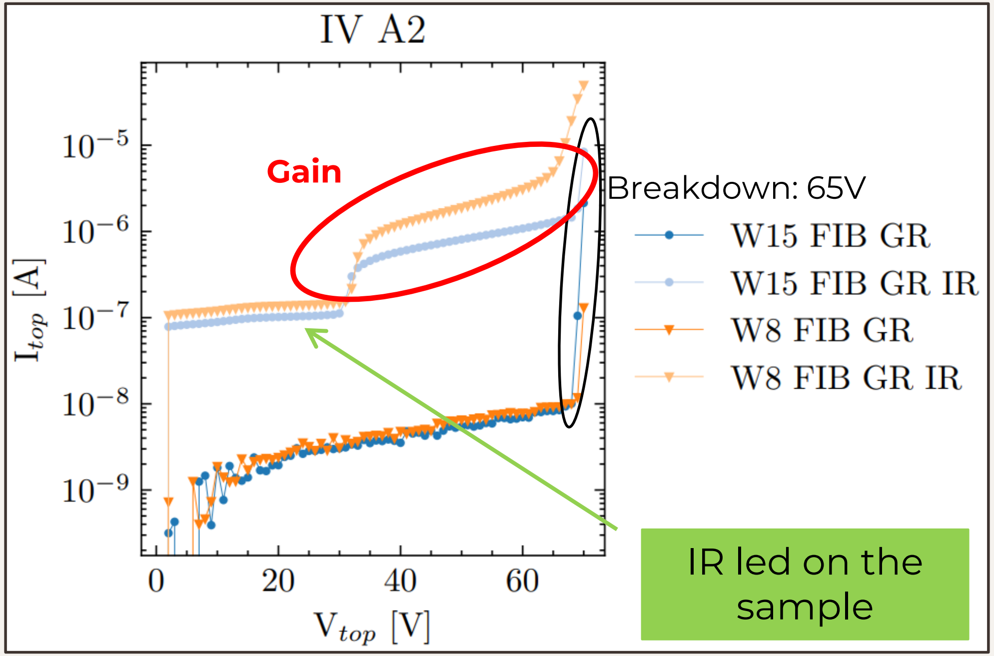


New production: Increased gain

MadPix – Short loop

Short loop: same mask set with different implant dose -> optimization of sensor at low price
New **sensor** production with **higher gain** arrived in September 2024
Expected **gain range: 5-20**

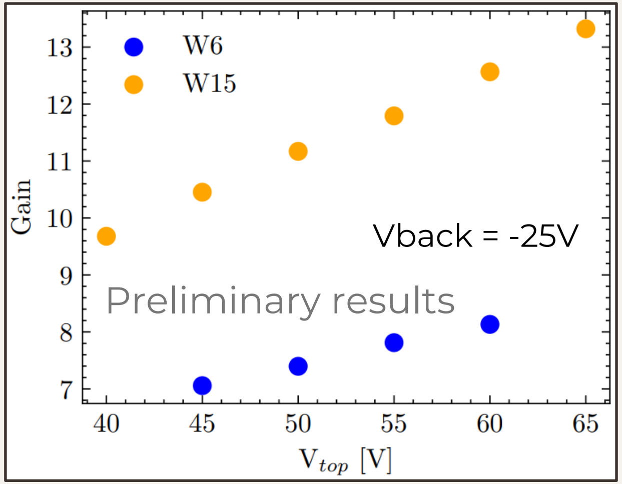




MadPix – Short loop

October 2024

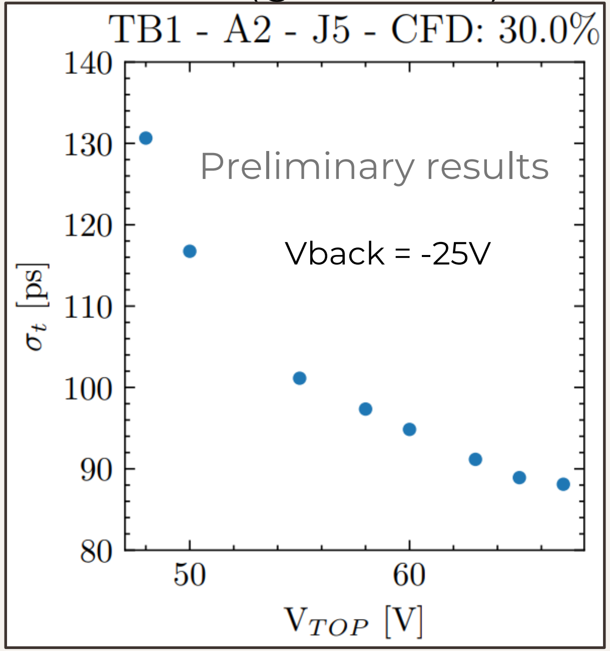
First estimation of **gain** using a non collimated radiation source of ^{55}Fe

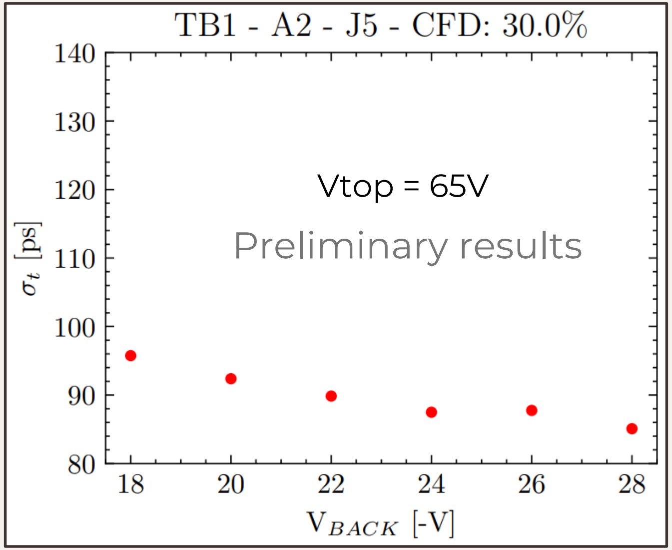


$$Gain = \frac{Peak\ [V/e]}{Electronics_{gain}[V/e]}$$

From electronics simulations matched with data

Time resolution sensor + front end (@0.18mW/ch)



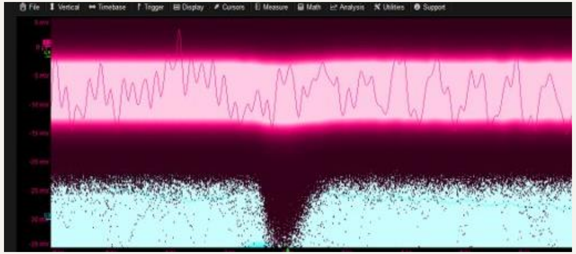


Time resolution sensor + front end (@0.18mW/ch): 88 ps

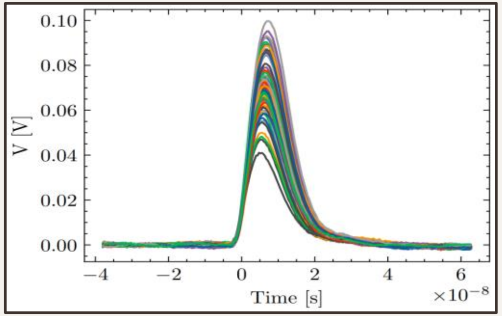
Time resolution sensor: ≈ 75 ps

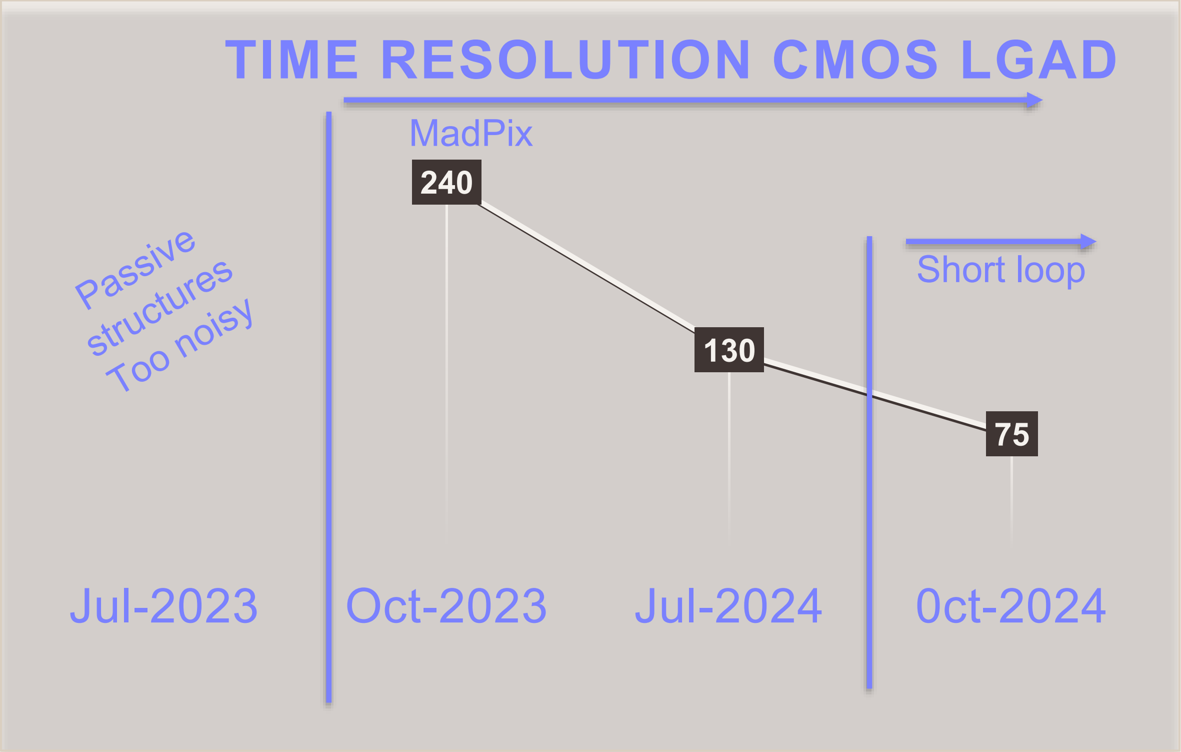
Back where we started from

First signals observed in a test beam, passive structure with gain - 50um thick - July 2023



Signals observed in last test beam, MadPix with gain - 50um thick - Oct 2024





Conclusions and Outlook

- → Prototype for timing application in 110nm technology design in the ARCADIA project
  - ↳ **MadPix**
- → Test beam characterization of devices with **low gain ≈ 3**
  - ↳ Time resolution ≈ **130ps** (Electronics + Sensor) but **high substrate current**
- → Performed Focused Ion Beam (**FIB**) on multiple samples
  - ↳ Substrate **current**: **2 orders of magnitude lower**
- → Laboratory characterization of structure with **improved gain**
  - ↳ **Gain** of the sensor between **5 and 13**
- → **Total time resolution** below **90ps** (@ 0.18mW/ch)
  - ↳ **Sensor** time resolution **≈ 75ps**

What's next?

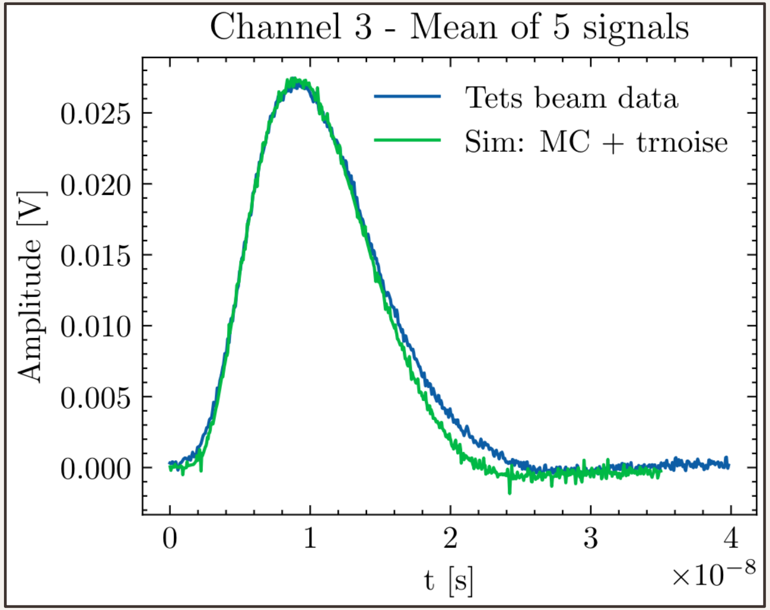
- → Position – time correlation of MadPix test beam of March 2025 @ DESY
- → Characterization of MadPix without gain
- → Simulation activities to match test beam results
- → Short loop with lower active thicknesses

Thank you for the attention!

Spare

Simulation matching

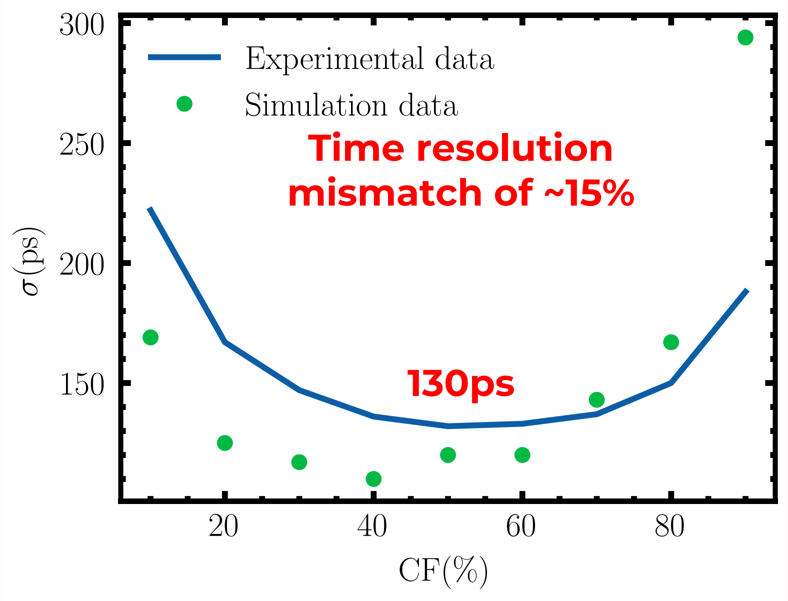
MonteCarlo simulation of the sensor → **Transient noise** simulation of the electronics → **Comparison** of simulation results and experimental data



Test beam data:
TOP -> 61V
BACK -> -15V

Simulation:
TOP -> 45V
BACK -> -40V

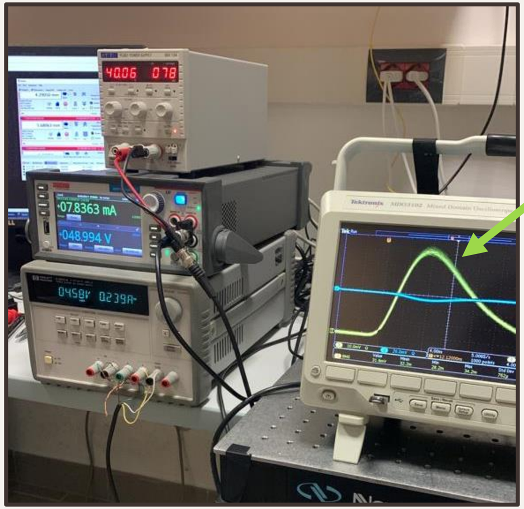
Different biasing condition!
More tuning is needed

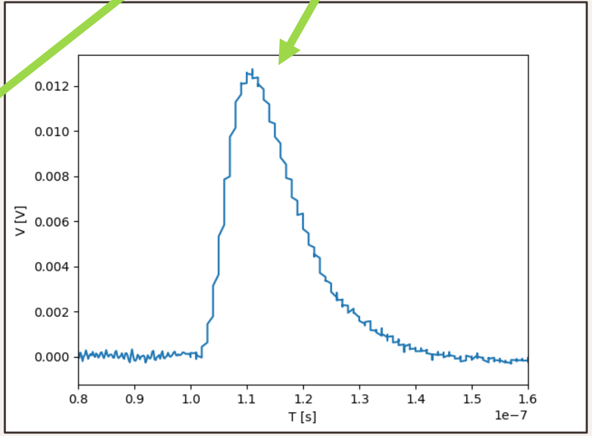


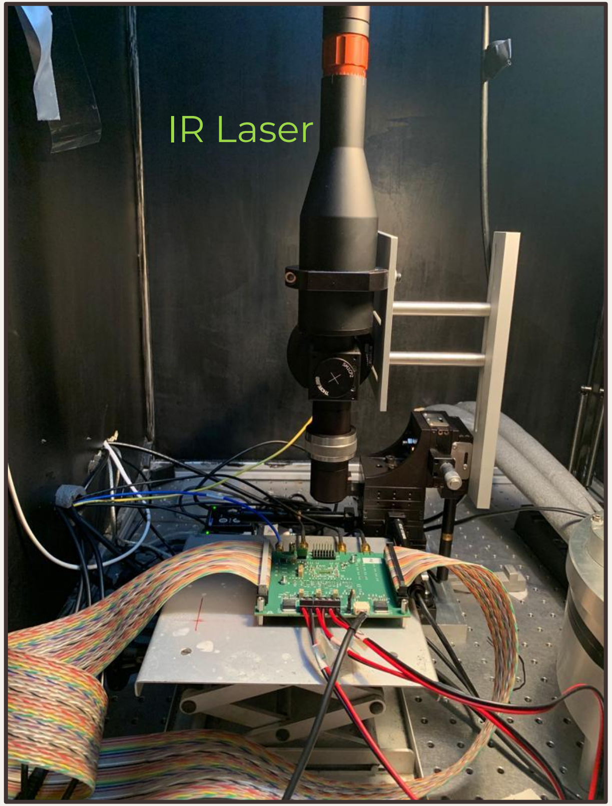
Laser setup

- Optical characterization at UNITN (Trento)
  - → IR laser from the back of the sensor
  - → laser pulse ~ 100 ps
  - → laser spot ~ 20 μm

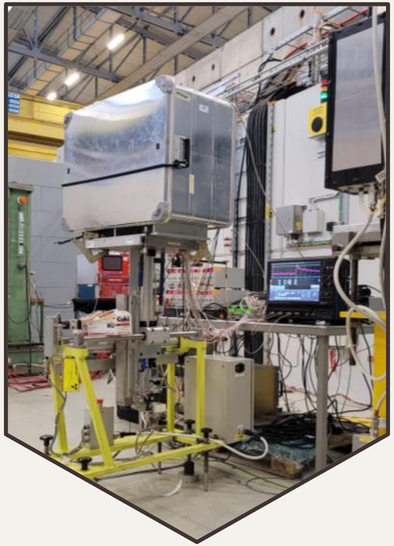
MadPix
Output signals
(ΔV_{out})







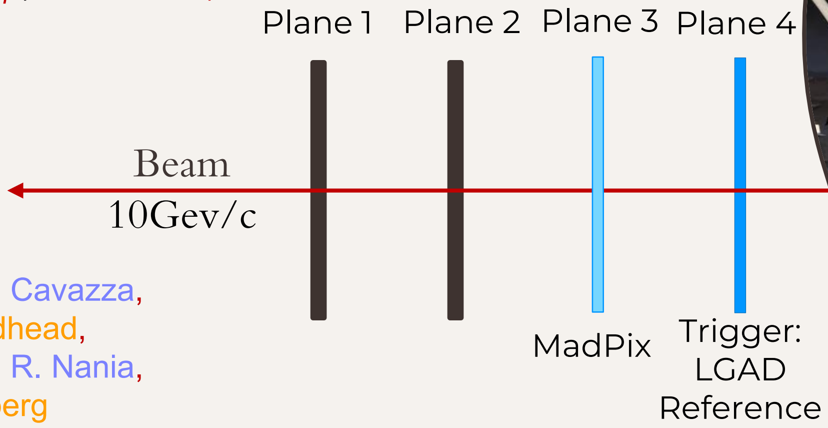
T. Corradino

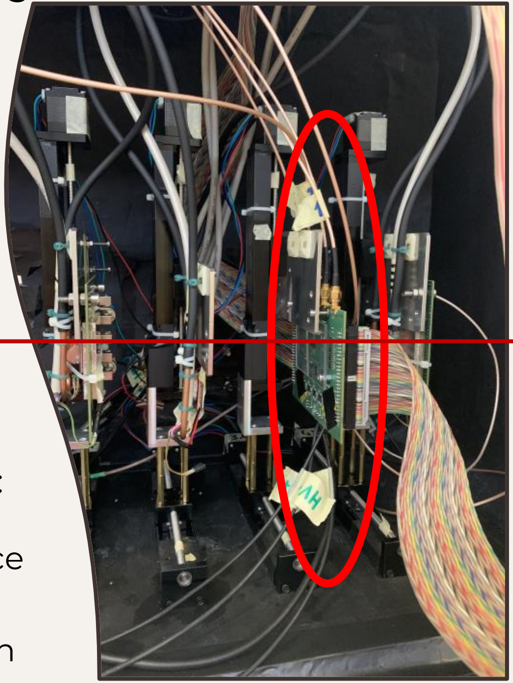


Madpix at the Test Beam

Test beam setup in collaboration with INFN Bologna

In July 2024 ***second test beam*** with ***MadPix***
→ at CERN Proton Synchrotron (PS)
→ with p/π of 10 GeV/c





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S. Förtsch, G. Gioachin, M. Mandurrino, R. Nania,
B. Sabiu, G. Souza, S. Strazzi, S. Wimberg

INFN Torino,
INFN Bologna,
iThemba LABS,
Universidade de São Paulo

- 4 planes telescope
- MadPix linked to a Xilinx FPGA controlled in control room
- Readout → Oscilloscope for signal acquisition

Passive structures characterization

I(V) scan to study the sensor behavior

New production: Increased gain

$\mathbf{I_{back}}$ → current between **p⁺** on the backside and the **p-wells**
→ Punch through for V_{back} > 45V

DC Gain → ratio between leakage current of gain and no gain structures measured in n⁺ **collection electrode** illuminating with IR LED