MAPS devices for timing applications

with internal gain

State of the art and future developments

Last 43rd **RD50 Workshop** on Radiation Hard
Semiconductor Devices for High Luminosity Colliders

28 Nov – 1 Dec 2023

CERN

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on behalf of the **ARCADIA Collaboration**

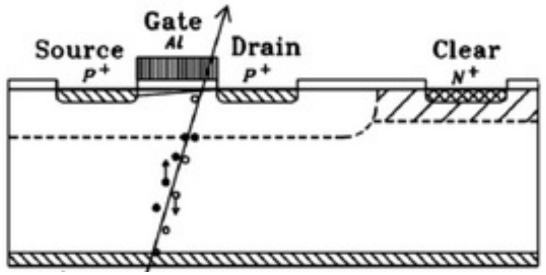
[1] *INFN* Torino

Monolithic particle detectors

Three main types of **monolithic** sensors

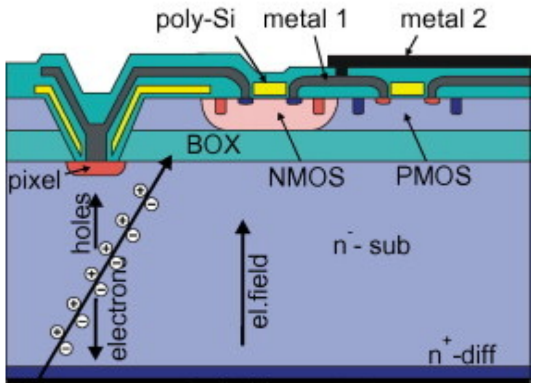
▻ Depleted Field Effect Transistor (DEPFET):

low input C ⇒ low noise
gate reset due to leakage saturation



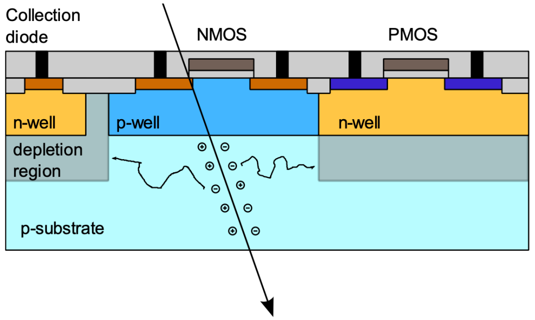
▻ Silicon-on-Insulator (SOI):

low input C ⇒ low noise
back-gate effect
hole accumulation layer after irradiation ⇒ low rad-hard



▻ Complementary Metal-Oxide Semiconductor (CMOS):

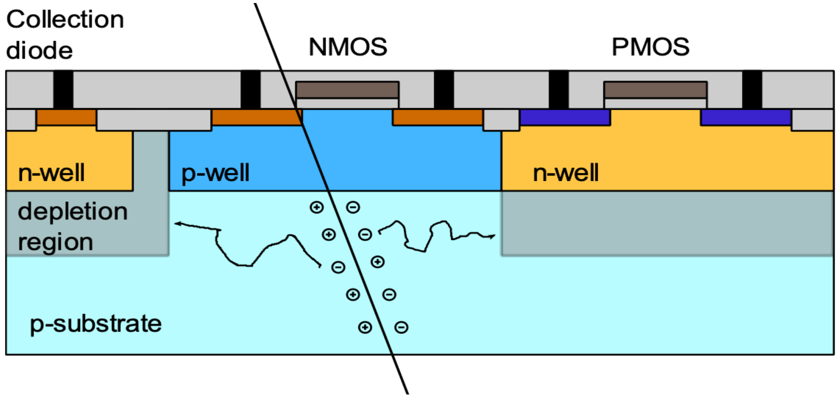
low power, high-rate capability, low material budget
commercial technology ⇒ low cost per unit area
slow diffusion in undepleted substrate
competitive collection by *n*-wells



Monolithic particle detectors

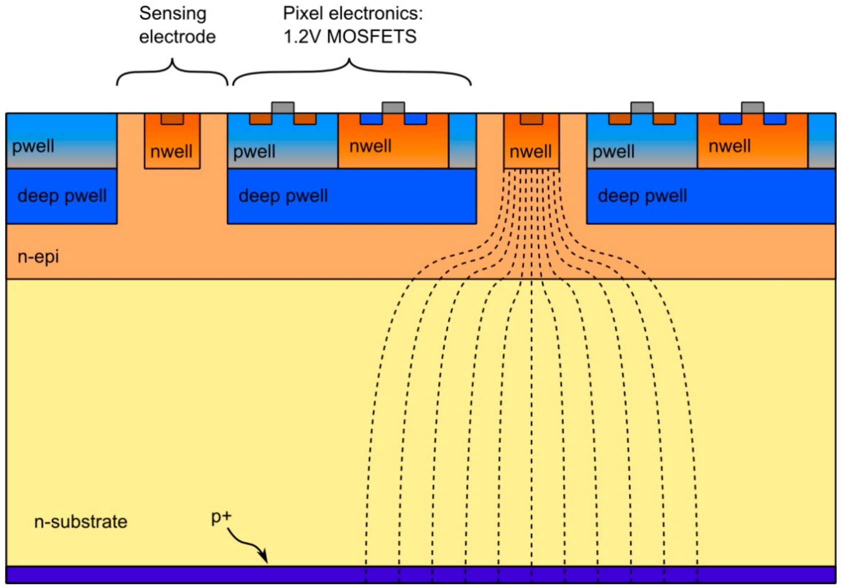
Possible solutions in standard CMOS:

- ▻ lowering substrate doping (high resistivity)
- ▻ use high bias voltage
- ▻ isolate the *n*-wells with deep-*p*-wells
- ▻ put the electronics inside the collection diode
- ▻ isolate the electonics with a buried oxide (SOI)



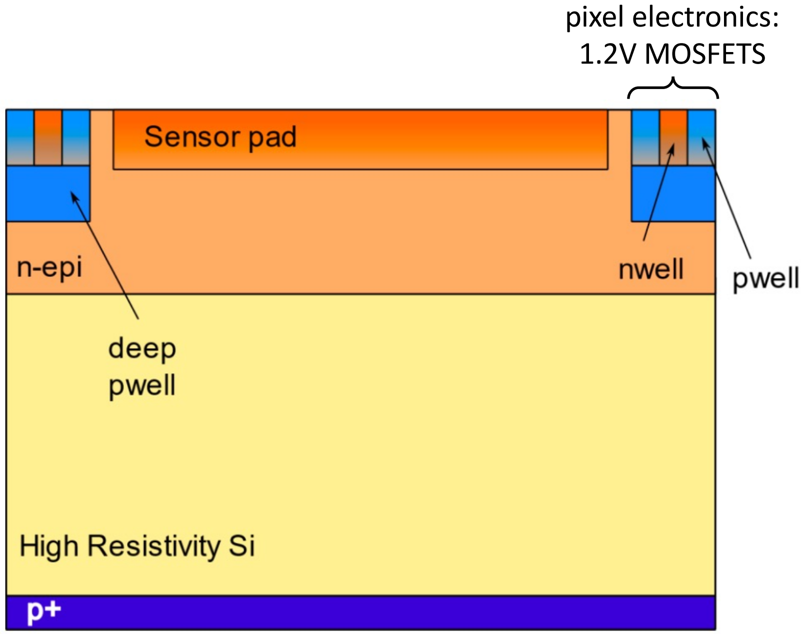
The ARCADIA approach (from SEED project):

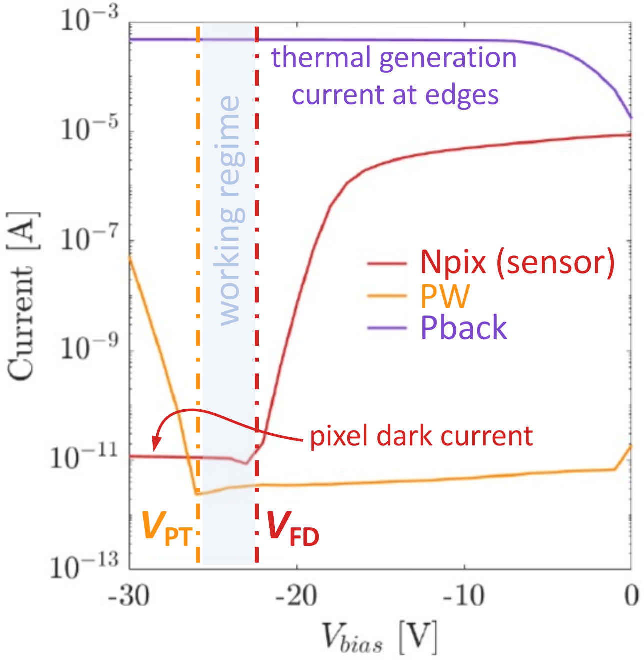
- ▻ **MAPS**, Monolithic Active (integrated amplifier) Pixel Sensor
- ▻ **fully depleted** pixel sensor with integrated electronics
- ▻ use of **deep-*p*-wells**
- ▻ ***n*-type epitaxial layer** to better control the potential barrier
- ▻ **110 nm** CMOS process (LFoundry)

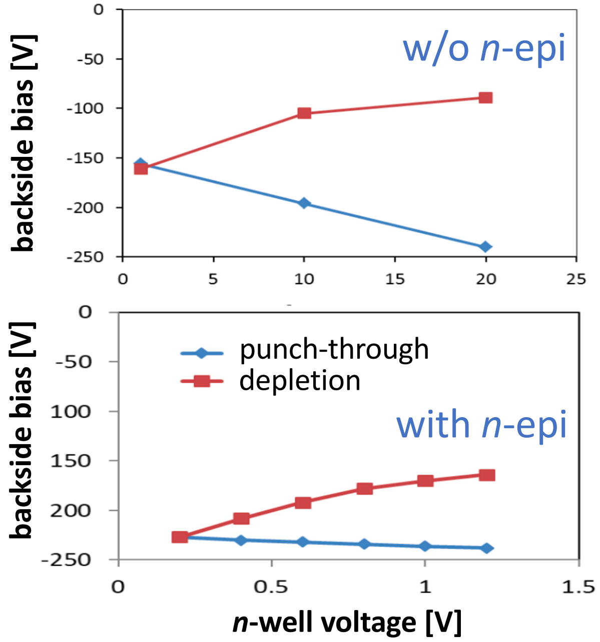


Monolithic particle detectors

The ARCADIA sensor concept







Main limitations:

- **edge breakdown** due to the **topside voltage**
- **punch-through** due to the **backside bias**

- ***n*-type high resistivity** active region
- **deep-*p*-wells** shielding *n*-wells with electronics
- **reverse-biased** junction: depletion grows from back to top
- **sensing** electrodes can be biased at **low voltage** (< 1 V)
- ***n*-epi** layer delays the onset of **punch-through** hole current

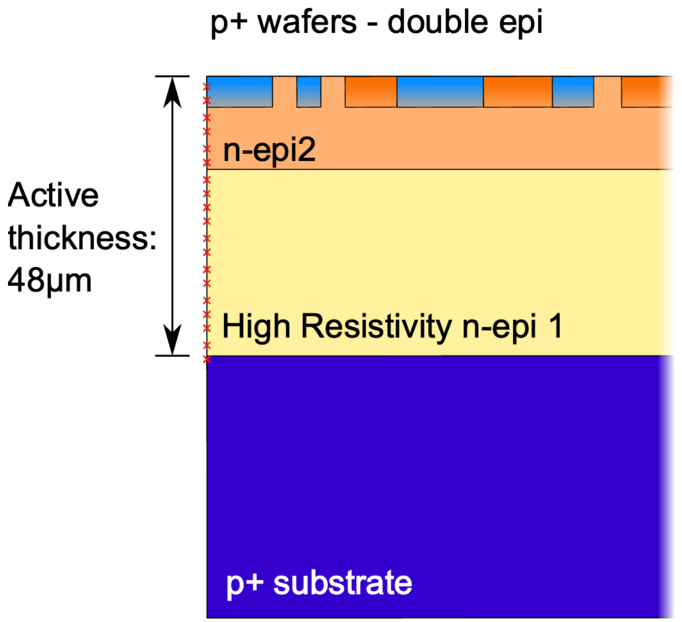
Monolithic particle detectors

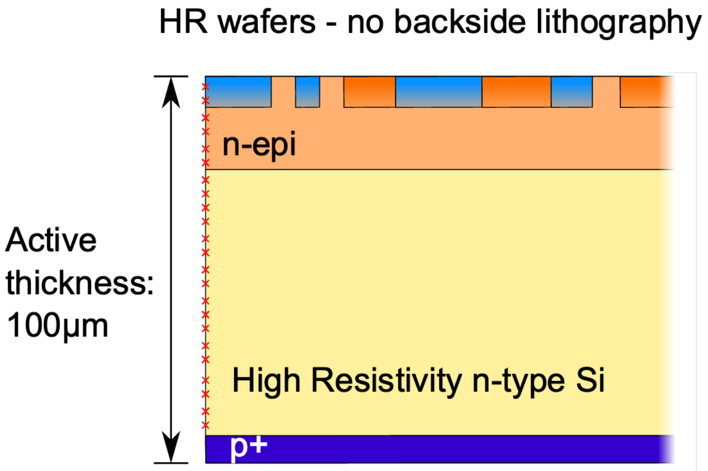
The ARCADIA substrates and post-processing

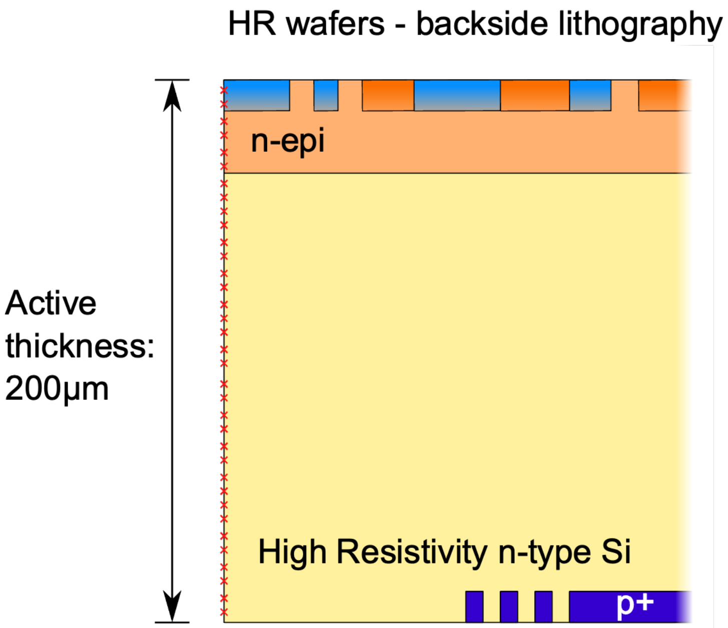
Type 1:
thinning to 100 or 300 µm total thickness

Type 2:
thinning, backside ***p*⁺ implantation** and laser annealing

Type 3:
thinning, **lithography**, backside ***p*⁺ implantation** and laser annealing, **insulators/metal** deposition and patterning



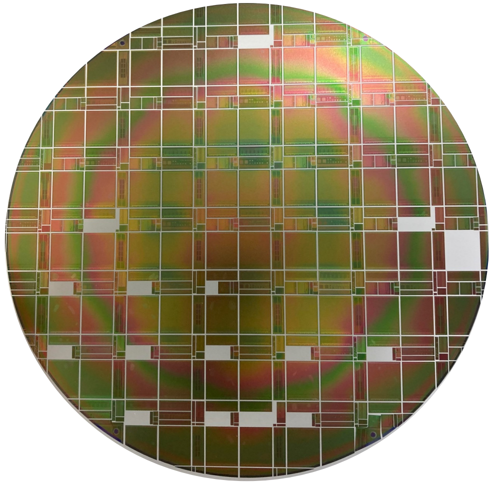




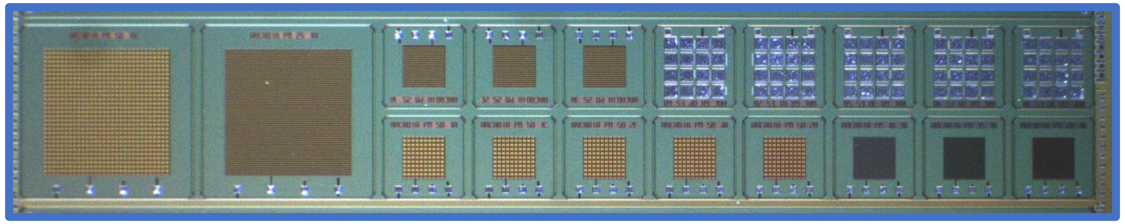
First ARCADIA engineering runs

8” wafers

front side



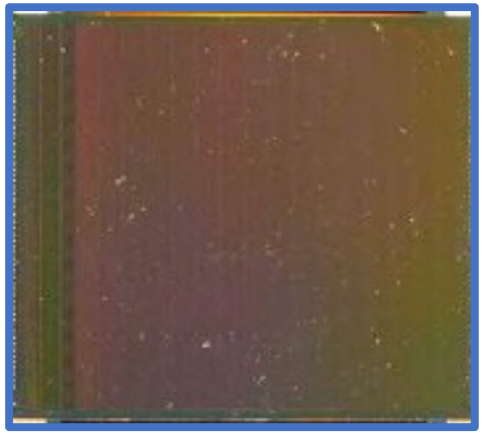
back side (type 3)



passive test structures block

Structures:

- small **pixel arrays** with **different pitch** (10 µm - 25 µm - 50 µm) with and w/o active readout
- **strip detectors** with and w/o active readout
- **passive test structures** for sensors characterization and process qualification
- **Main Demonstrator**: **25-µm-pitch** pixel sensor, **512 × 512** array

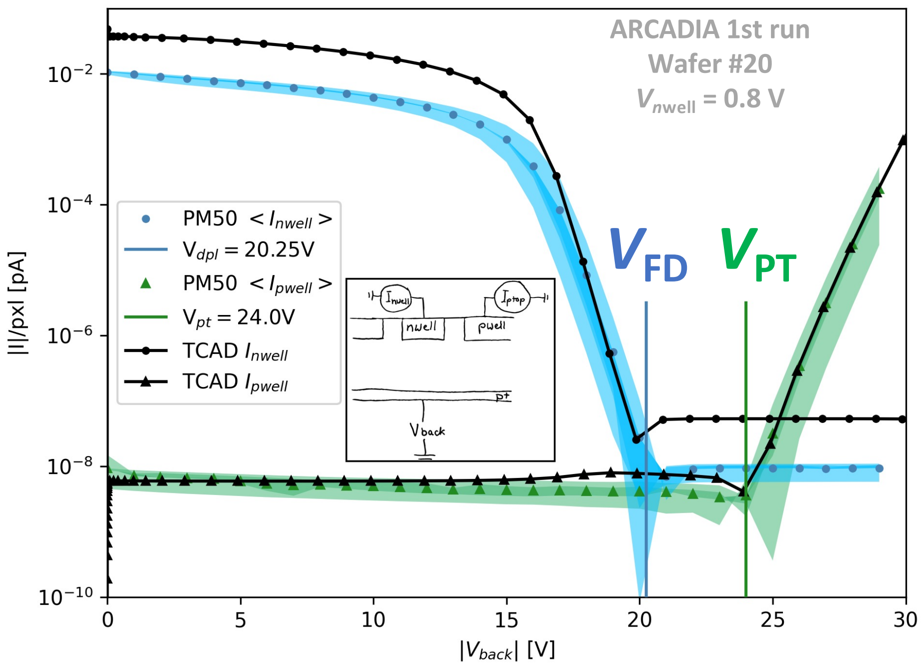


ARCADIA Main Demonstrator

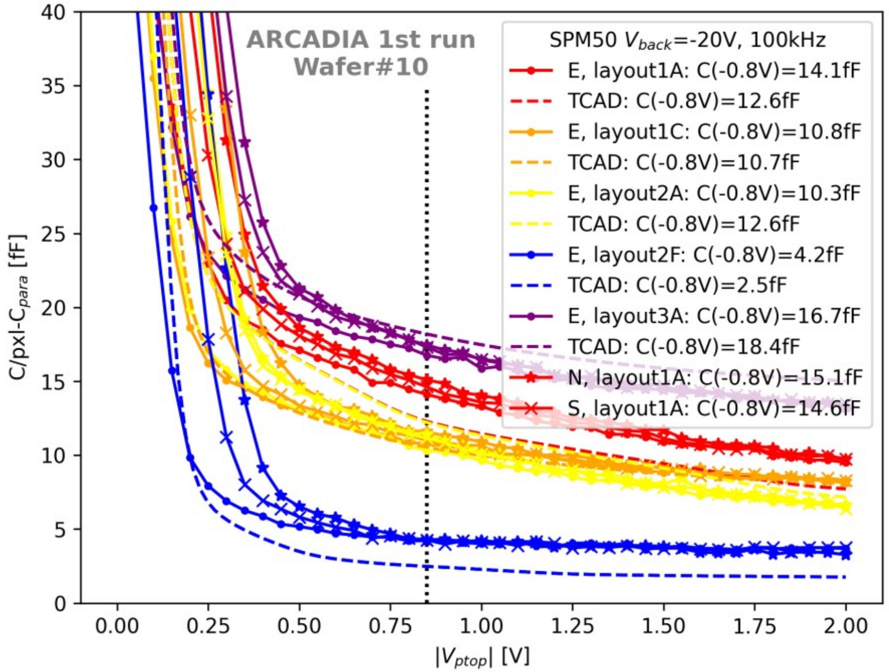
First ARCADIA engineering runs

Electrical characterizations

C. Neubüser



C. Neubüser



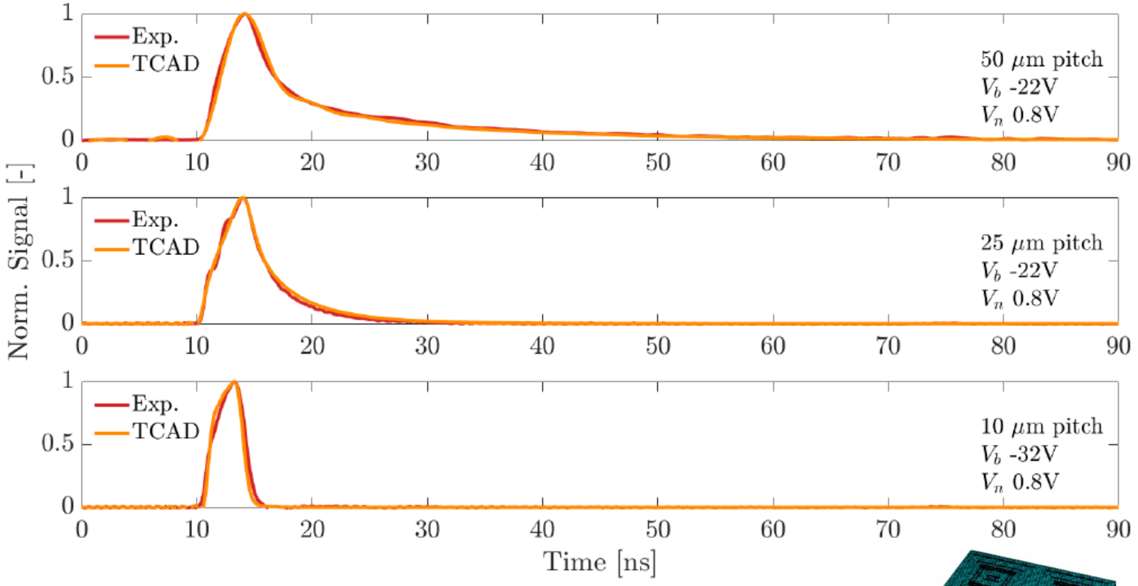
- different **pixel layouts** have been tested
- **intra-** and **inter-wafer uniformity** evaluated
- **TCAD parameters** adjusted on experimental results

- **capacitance** dominated by the **sensor perimeter**

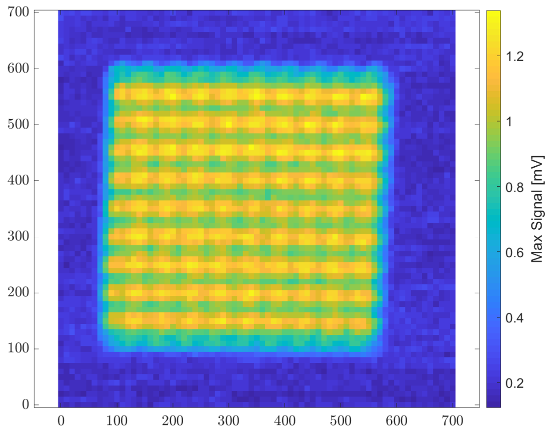
First ARCADIA engineering runs

Dynamic response with laser

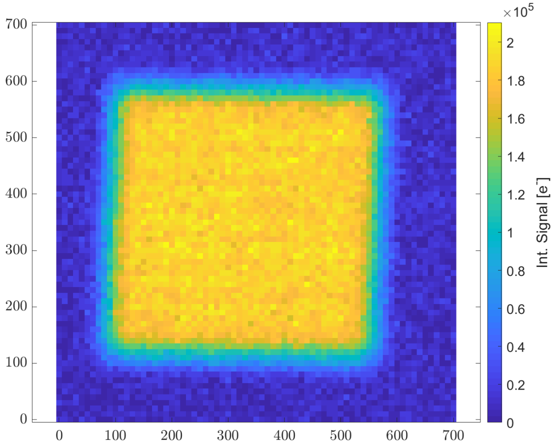
T. Corradino



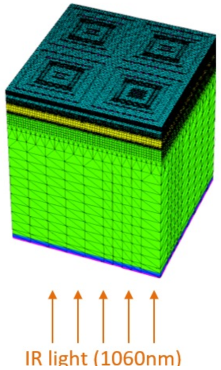
signal peak amplitude



integrated charge



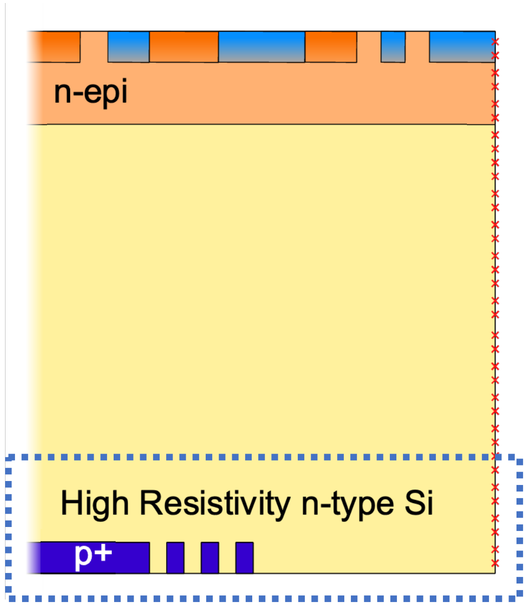
- < **100 ps** FWHM IR laser pulse
- passive **pixel array** test structures
- **100 µm** active thickness
- different **pixel pitch**: **50 µm** - **25 µm** - **10 µm**



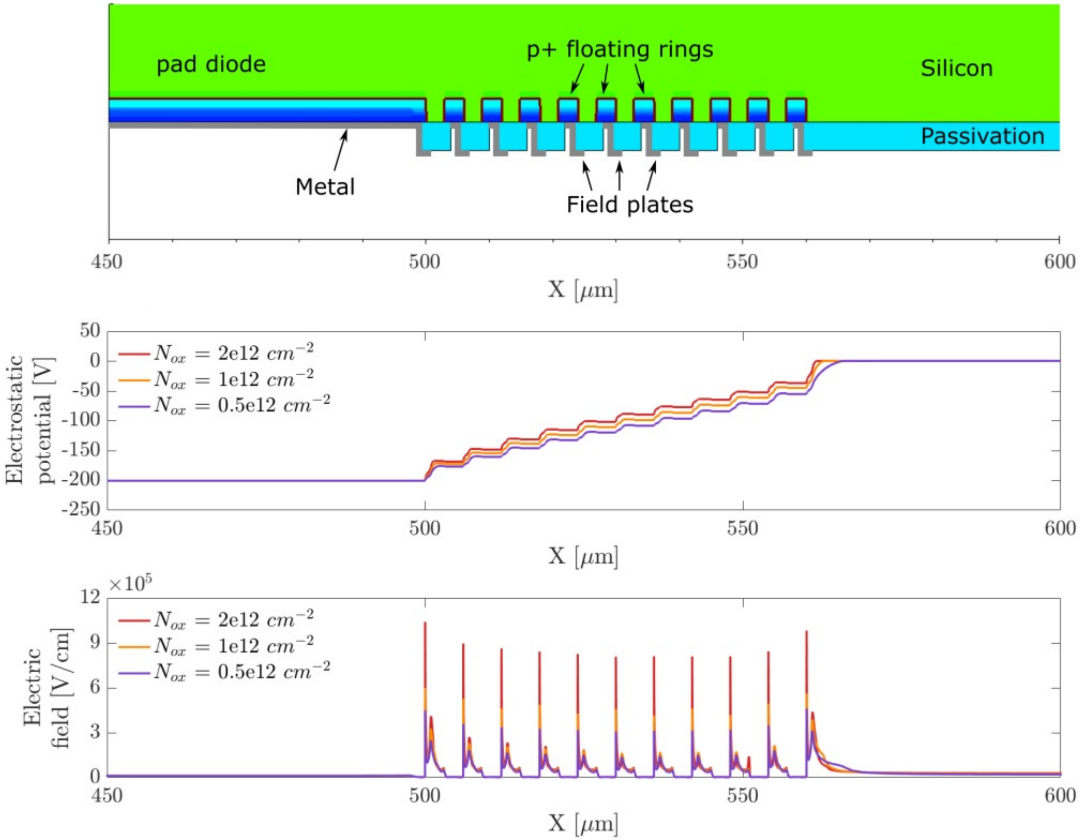
- **10 µm** FWHM focused red laser
- **50-µm-pitch** test structure
- V_{top} **= 0.8 V** and V_{back} **= –22 V**
- **10 µm** steps in *X* and *Y* directions

First ARCADIA engineering runs

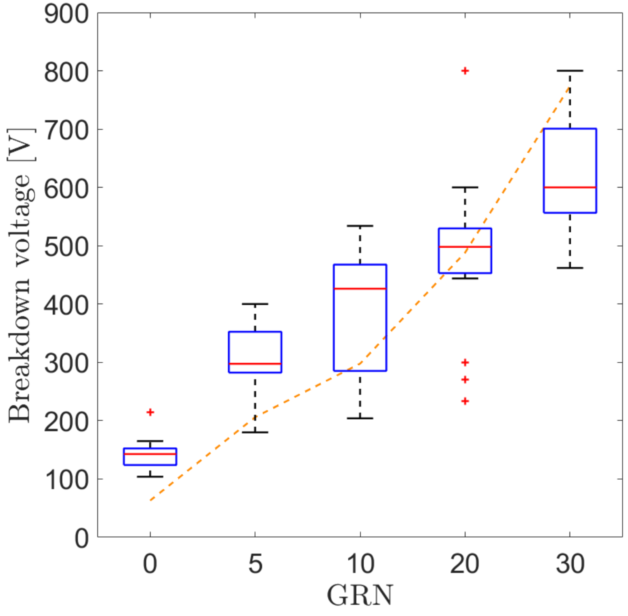
Backside layout optimization (Type 3)



T. Corradino



breakdown voltage for different numbers of **GRs**



First ARCADIA engineering runs

Pixel characterization

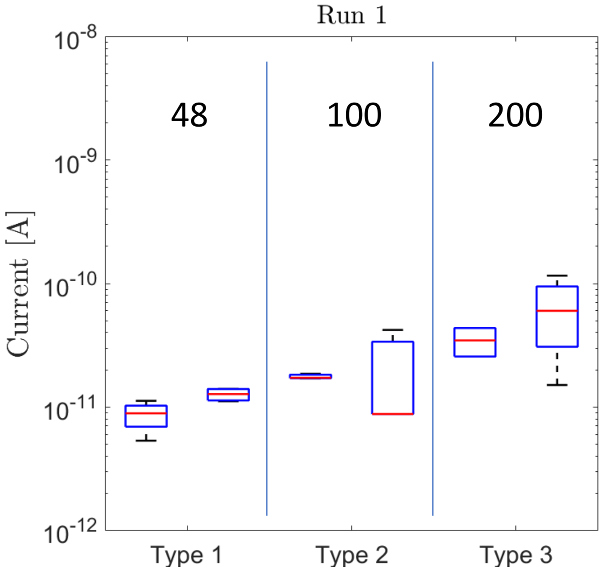
static characteristics

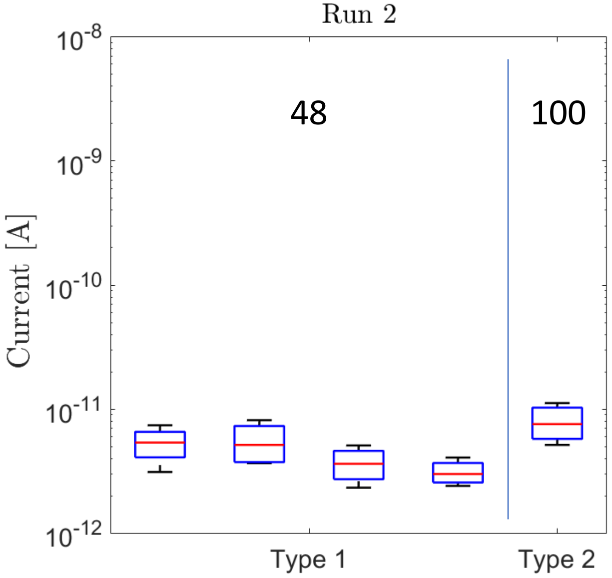
Active thickness (µm)	48	100	200
bias voltage (V)	25	20-35	60-100
dark current density (pA/cm²)	100-350	230 - 500	650 - 2000

dynamic characteristics

Pixel pitch (µm) @ 100-µm-thick	10	25	50
capacitance (fF)	1.9	3	12.7
time for 90% charge collection with picosecond IR laser (ns)	4	10	31

dark currents in **1.5 mm × 1.5 mm pixel** arrays with different active **thicknesses**



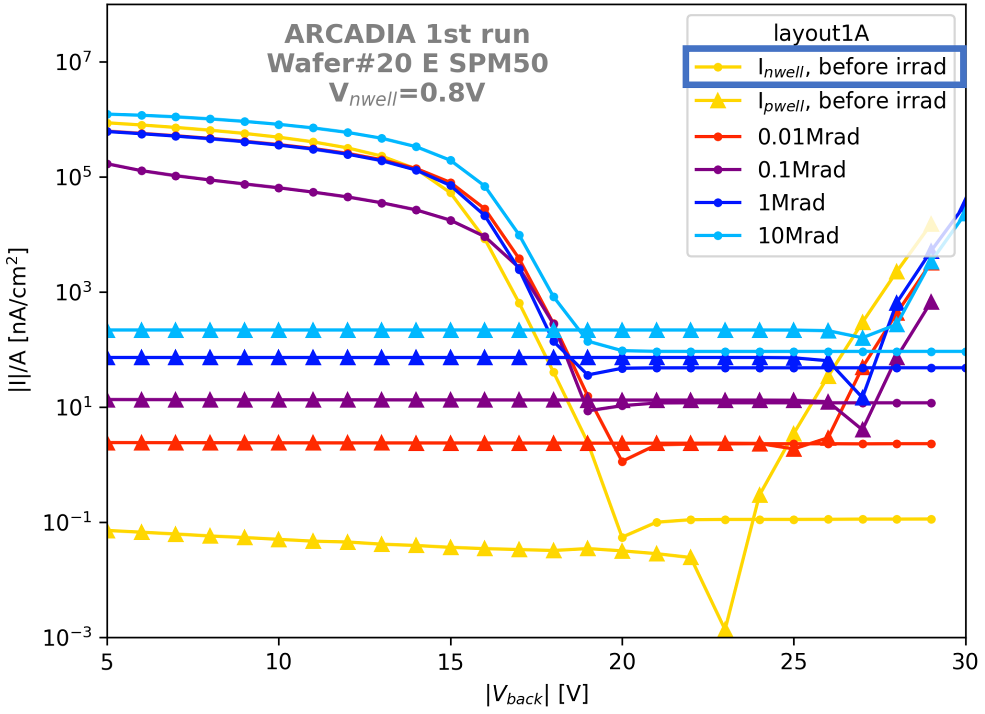


T. Corradino

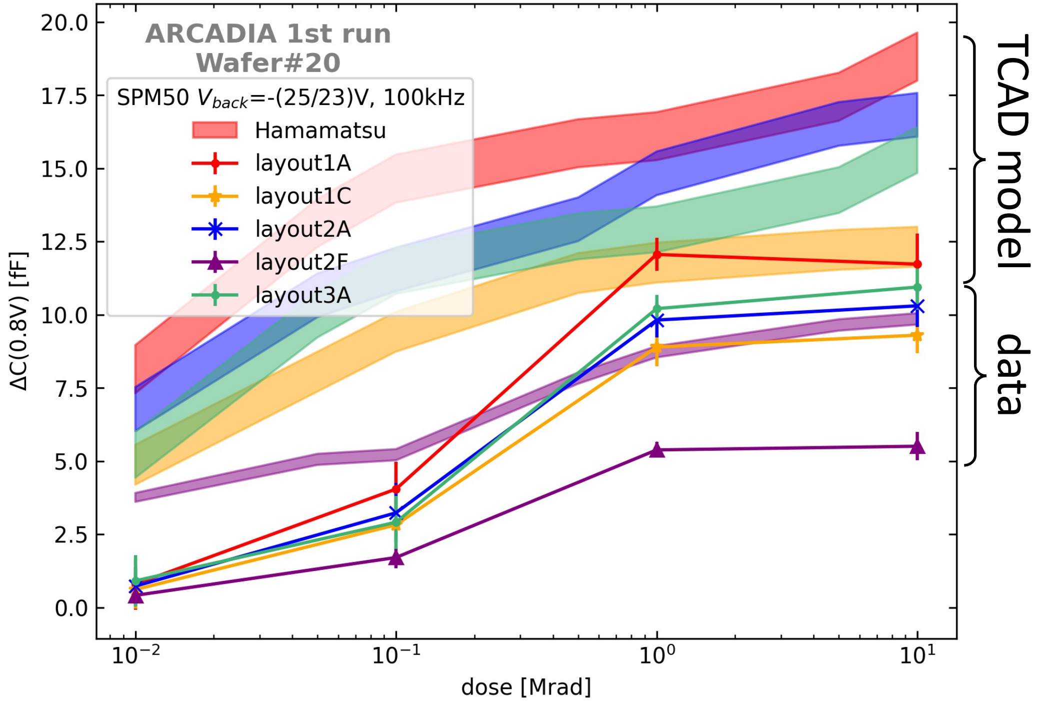
First ARCADIA engineering runs

Pixel radiation hardness: X-rays @ University of Padova, Italy

C. Neubüser



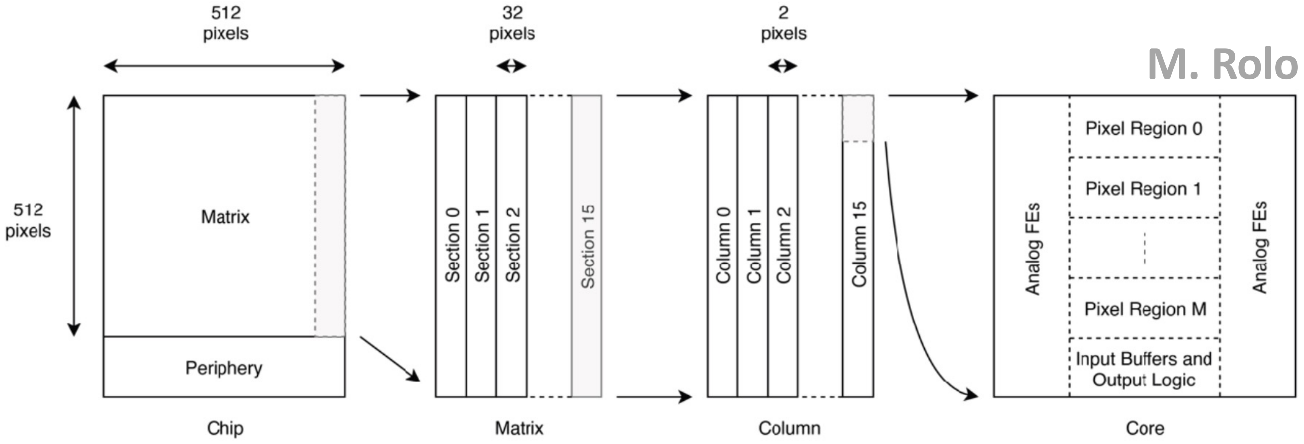
C. Neubüser

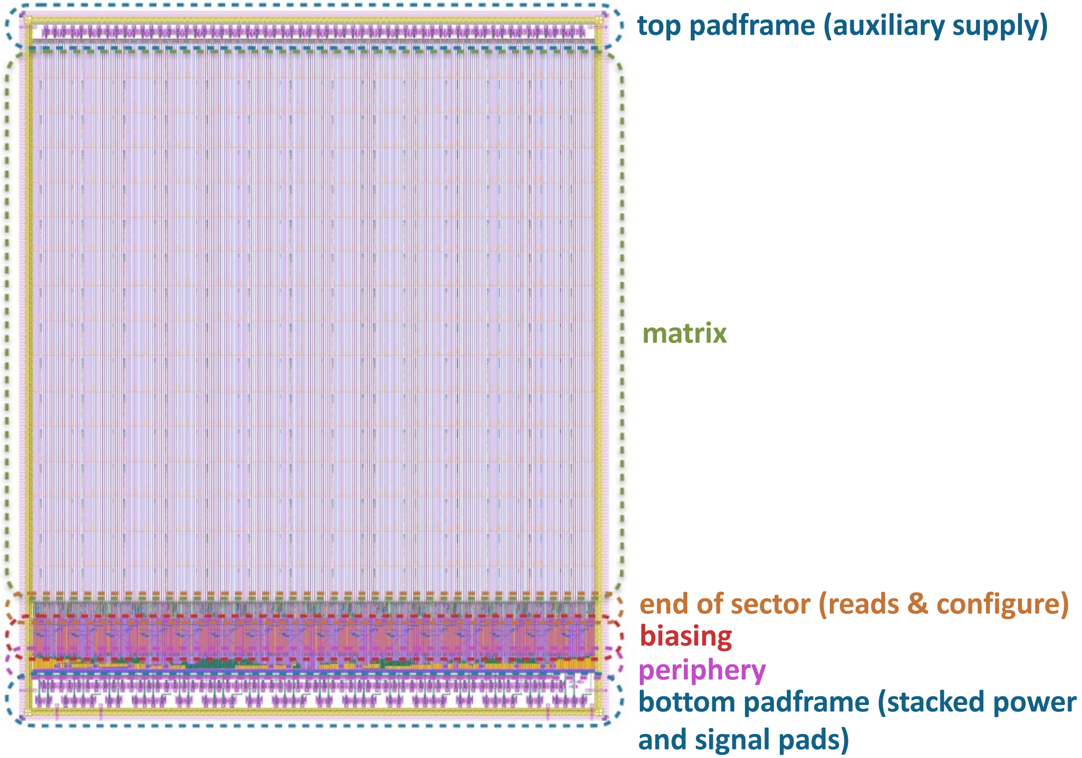


- increase of **pixel leakage** current with **Total Ionizing Dose** (TID) due to **surface generation**
- capacitance post-irradiation overestimated by the Perugia model with Hamamatsu parametrization

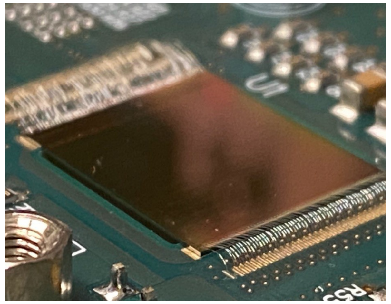
First ARCADIA engineering runs

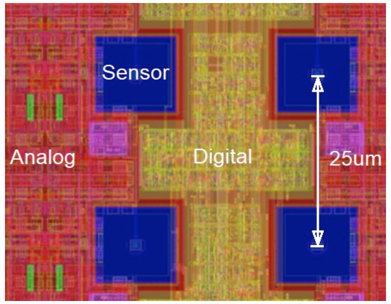
Main Demonstrator - architecture





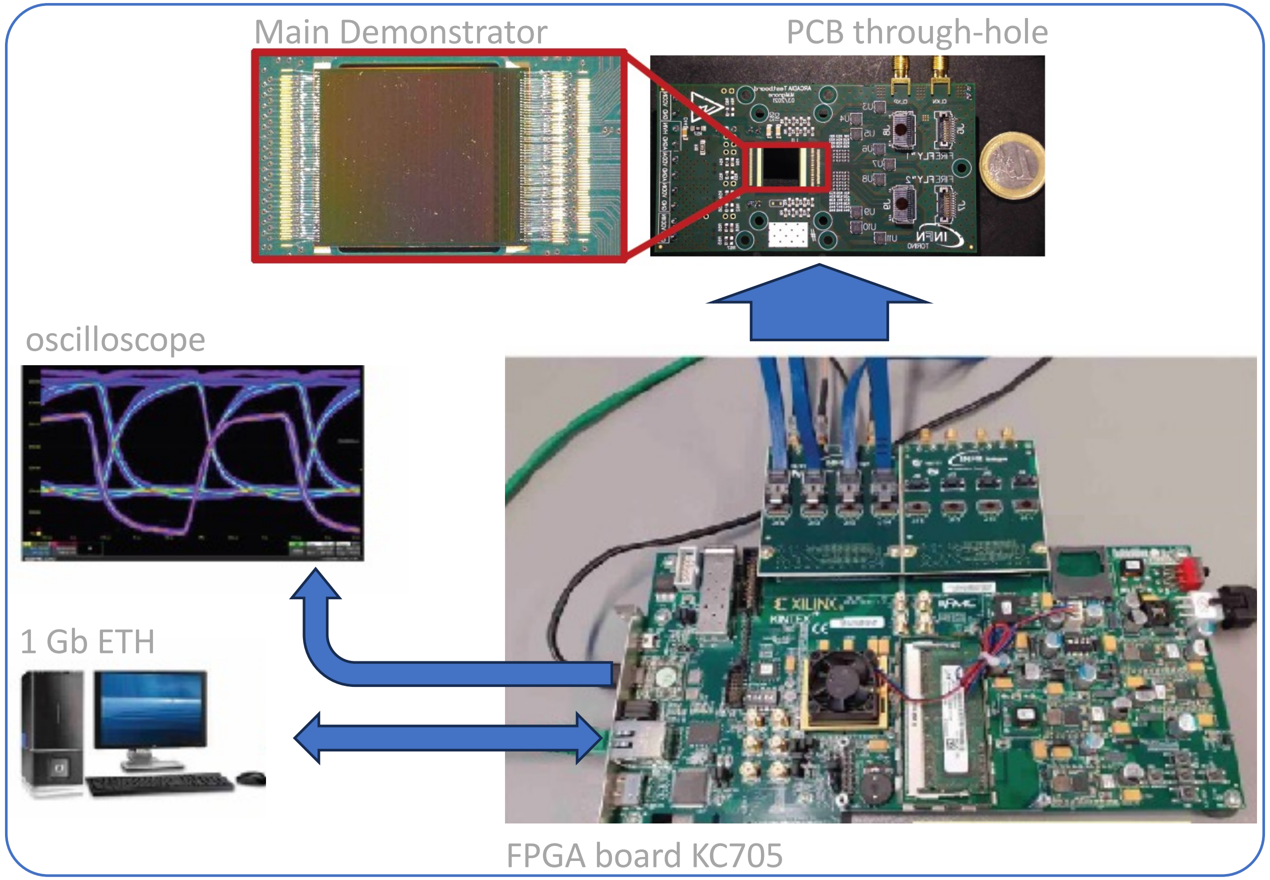
- Pixel **pitch**: **25 µm**
- Array core **area**: **1.28 cm × 1.28 cm** (262144 pixels)
- Electronics: **analog** and **digital**, with in-pixel **threshold** and **data storage**
- Architecture: **event-driven**, with active pixels sending their address to the chip peripheral circuits
- (Low) **power**: **20 mW/cm^2**
- (High) **event rate**: **100 MHz/cm^2**

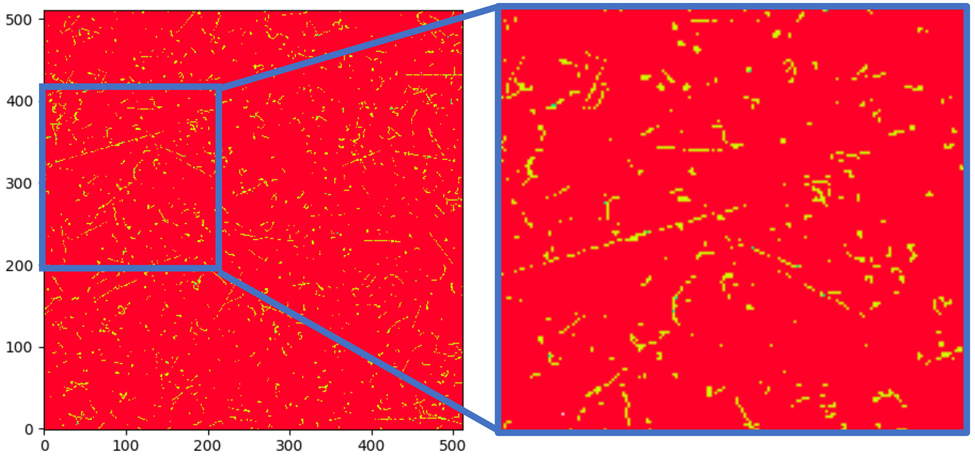




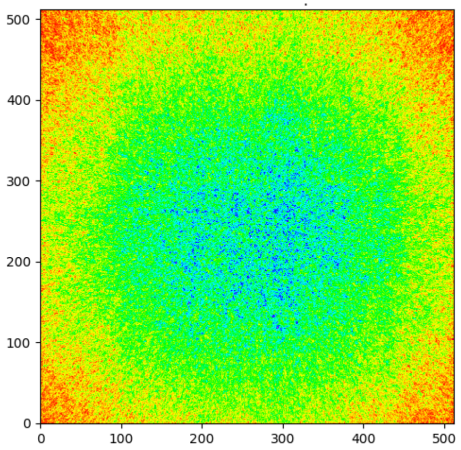
First ARCADIA engineering runs

Main Demonstrator - acquisition setup

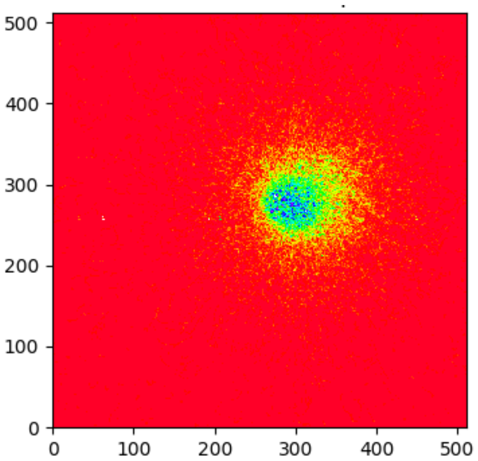




Cosmic rays acquisition (4h)



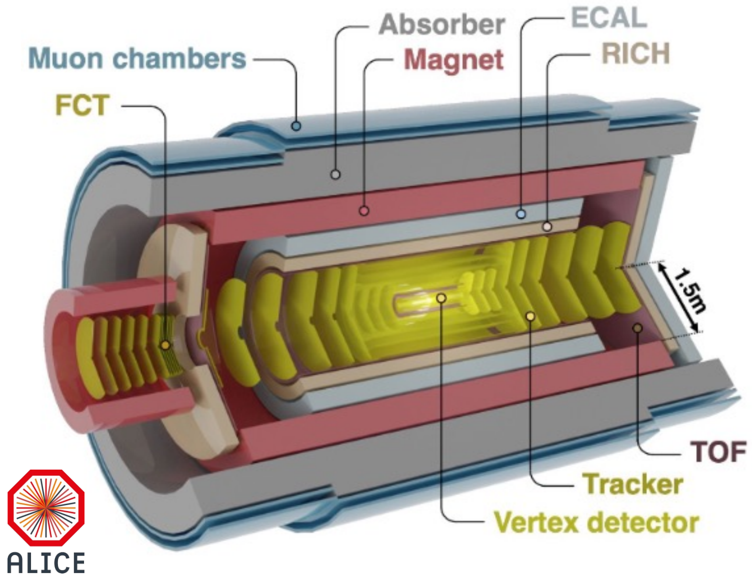
^{90}Sr beta source (1cm^2) 8 mm from the sensor surface



Collimated ^{90}Sr beta source
Collimator diameter: 1mm

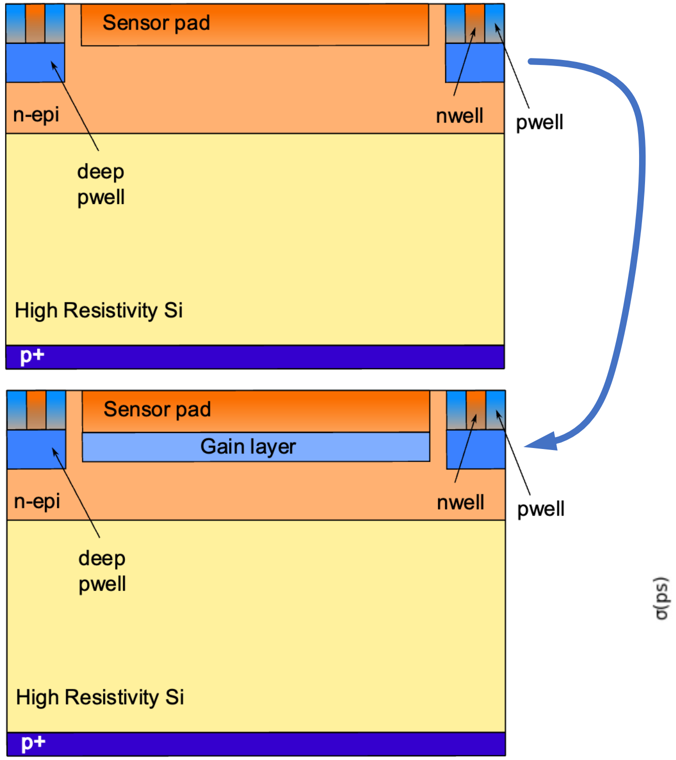
- Total **power consumption: 10 mW/cm^2** at low event rates
- **Design specification: 20 mW/cm^2** at rates up to 100 Mevents/cm^2

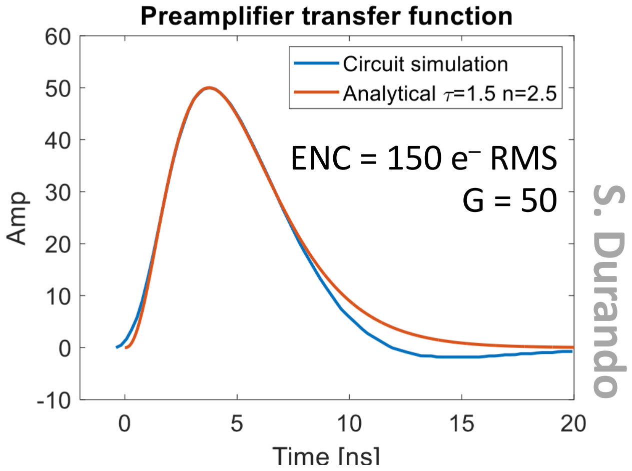
The ARCADIA run-3

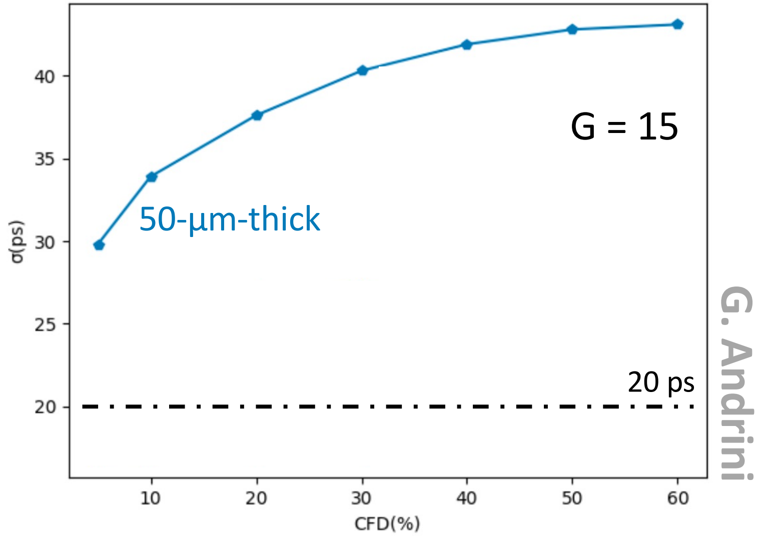


ALICE 3 **TOF** detector:

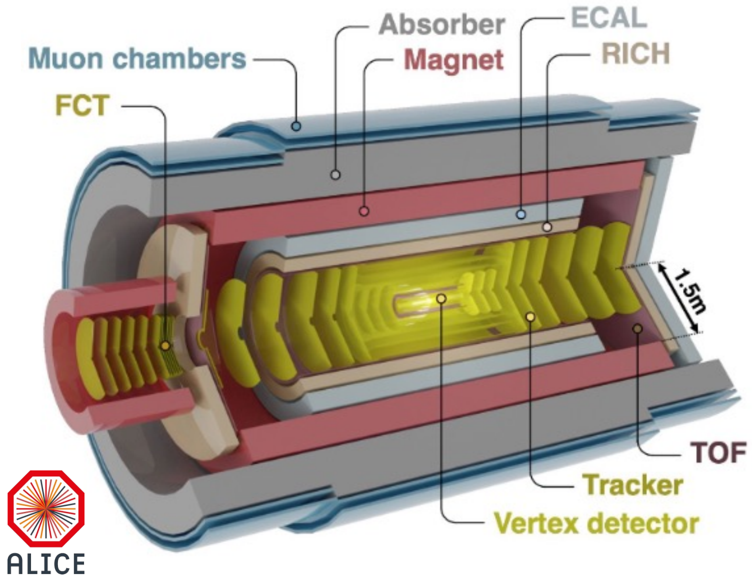
- high-resolution tracking and vertexing
- particle ID with low $p_T \Rightarrow \sigma_t \sim 20$ ps







The ARCADIA run-3



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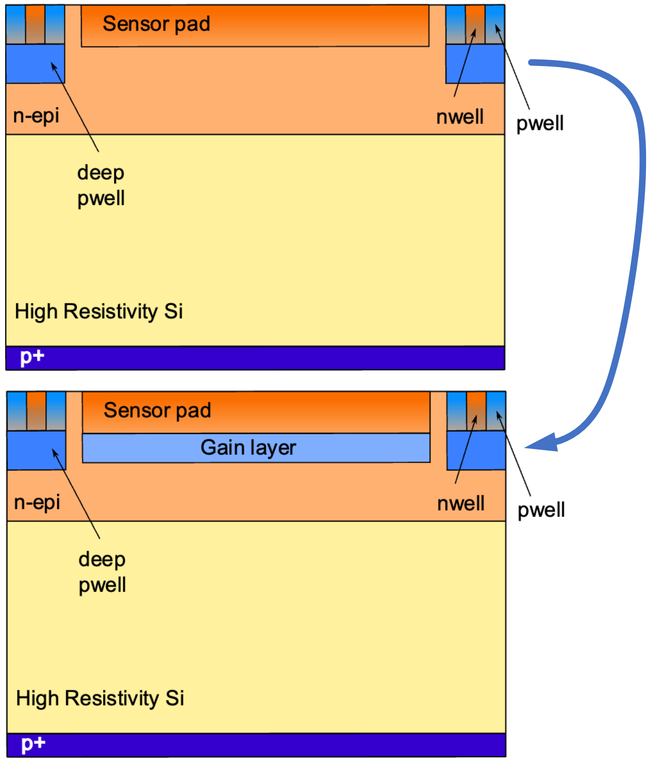
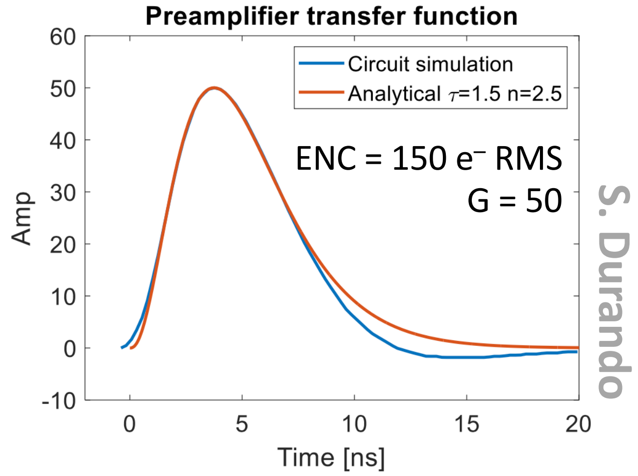
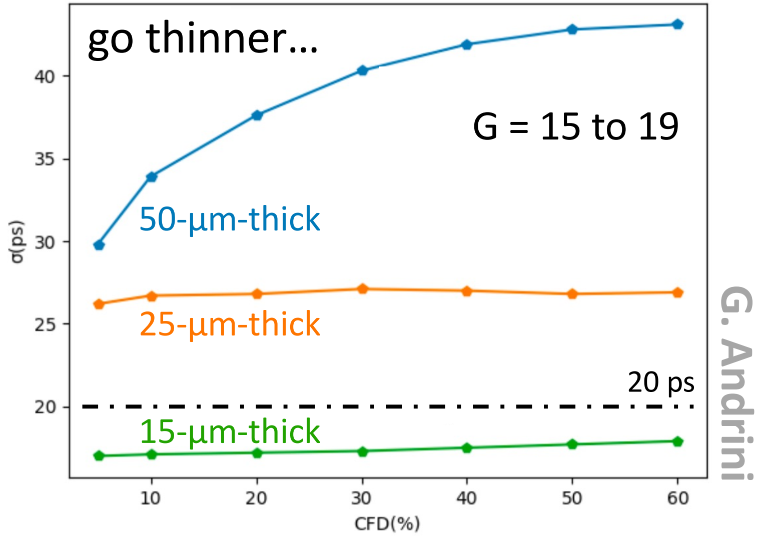
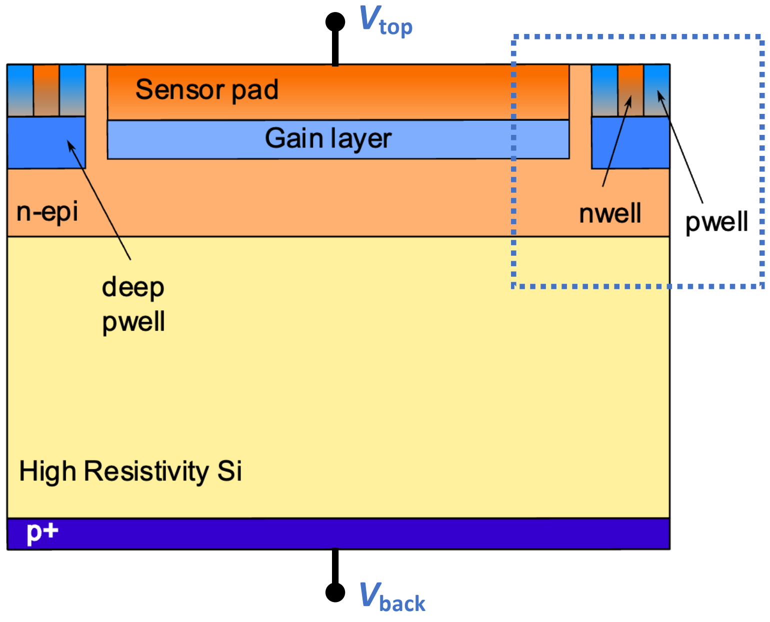






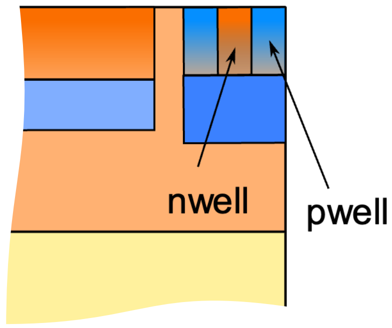
The ARCADIA run-3

Sensor structure and layout



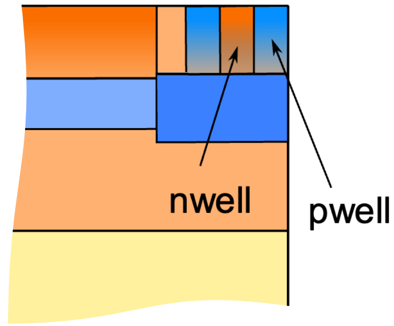
Layout A2:

standard solution ⇒ **direct path** to the n^+ collecting electrode for **charges at border**



Layout A1:

deep-*p*-wells are in connection with the ***p*-gain** implant ⇒ more **uniform charge multiplication**



V_{top} (30-40 V) determines the **gain**, while
V_{back} (–30 V) defines the **drift field** in the substrate

top voltage limited by **edge breakdown**
backplane bias limited by **punch-through**

- four **gain dose splittings** to cope with implantation uncertainties
- target: **gain** in the range **10 – 30**
- **50**, **100** and **200 µm** active **thicknesses**

The ARCADIA run-3

MadPix: first small-scale (**4 × 16 mm²**) demonstrator with **gain** and **integrated electronics**

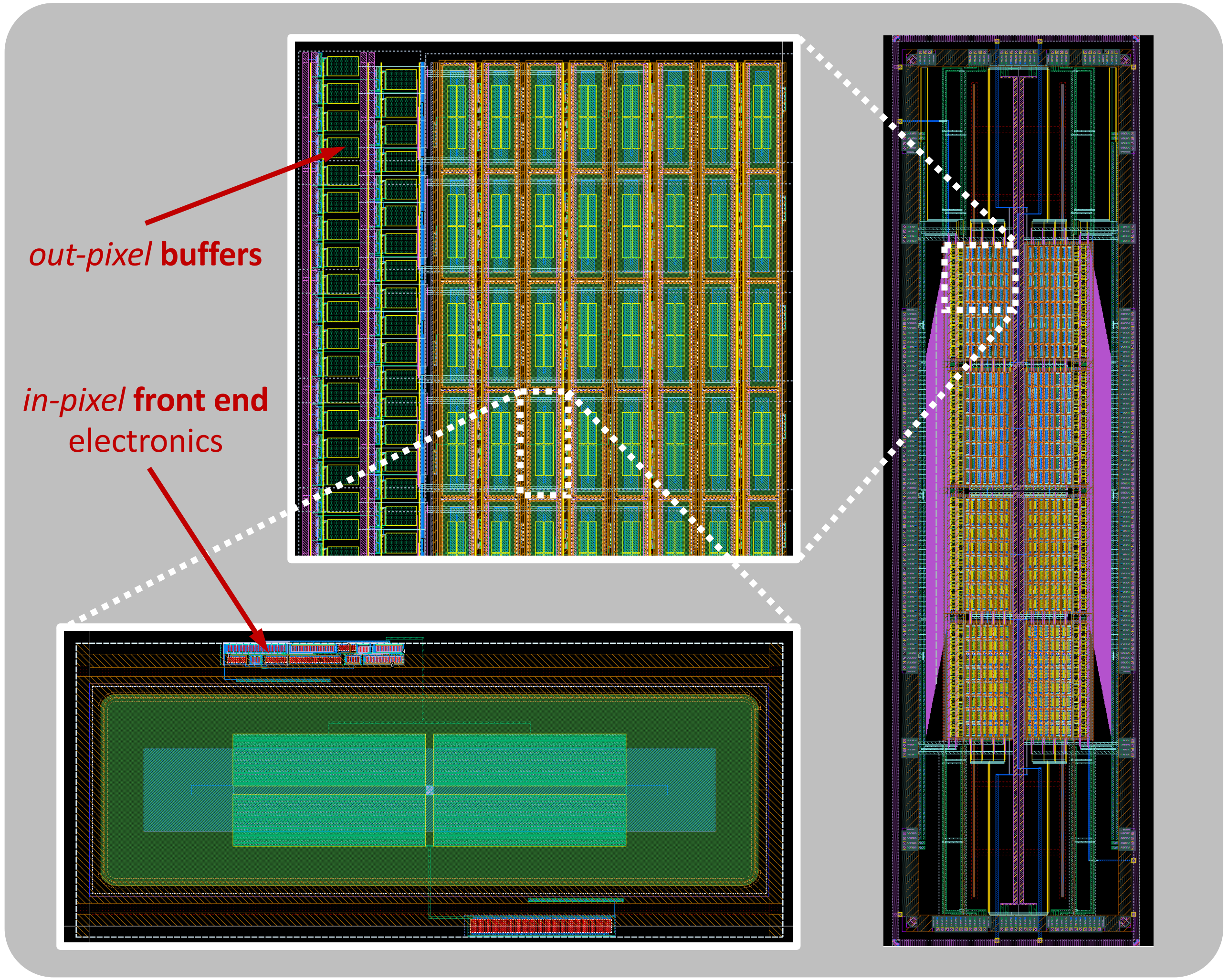
- **8 matrices** (**64 pixel pads** each) implementing different sensor and front-end flavours
- pads of **250 × 100 μm²**
- readout: **64 × 2 analog outputs** on each side
- **rolling shutter** of single matrix readout

Front-end (*in-pixel*)

- **Cascoded common source** amplifier, followed by a **differential buffer** (1.2V)
- **AC-coupled** with **sensor** (in order to decouple it from the sensor top voltage)
- **Power** consumption: **0.18 mW/ch**

Source follower *out-pixel* buffers (3.3V)

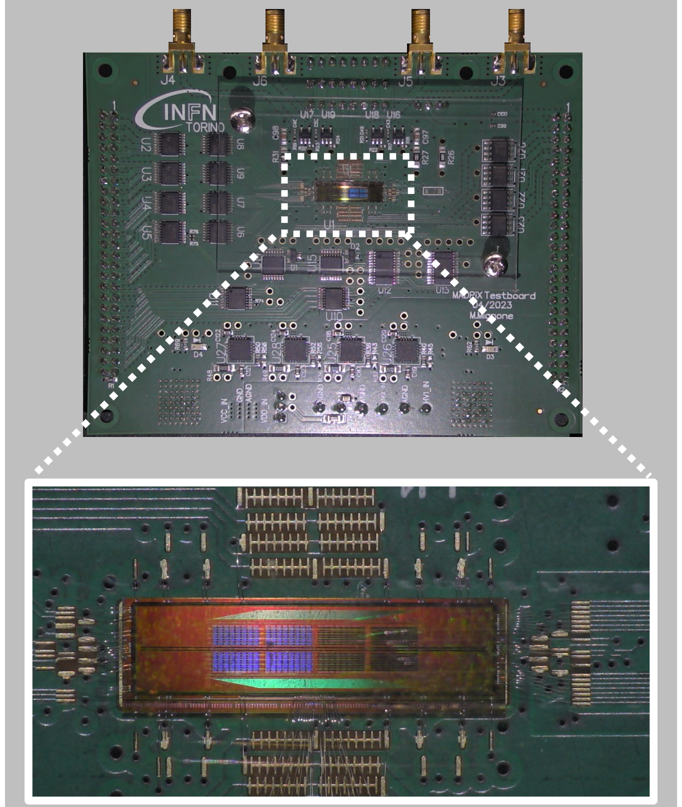
- **AC-coupled** with **FE**
- **Power** consumption: **1.65 mW/ch**



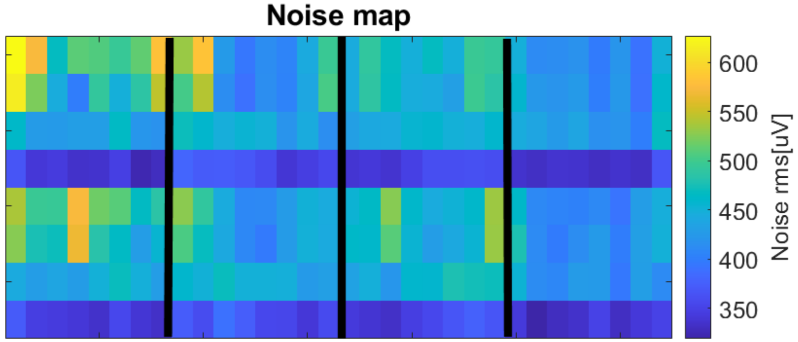
The ARCADIA run-3

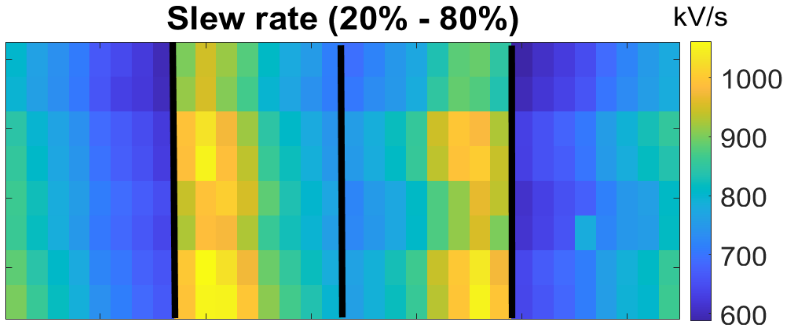
MadPix: first small-scale (**4 × 16 mm²**) demonstrator with **gain** and **integrated electronics**

MadPix testboard



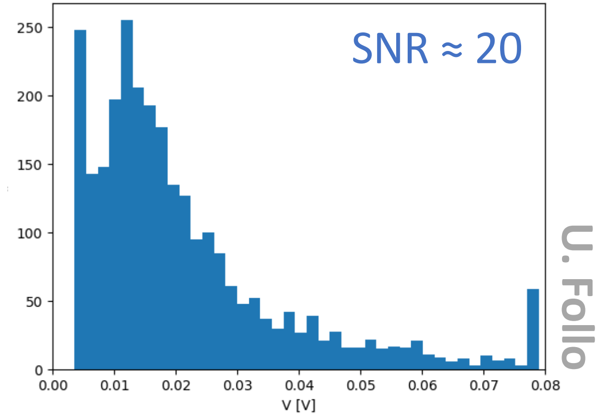
Noise and **slew-rate** characterization with external **test-pulse** injection

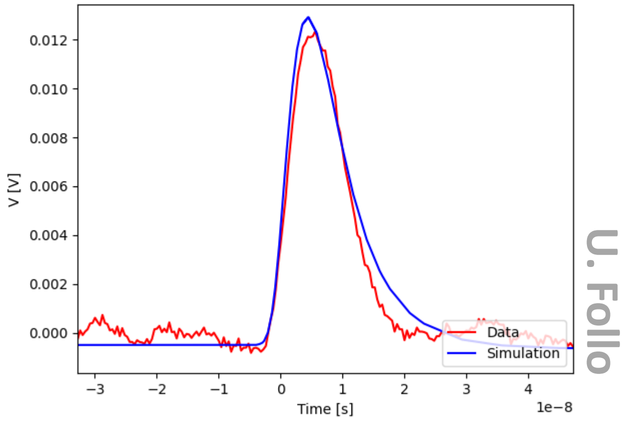




U. Follo

First data with **beta source** (^{90}**Sr**)

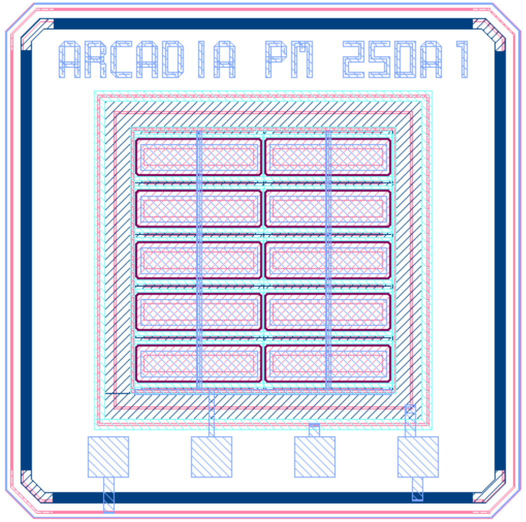




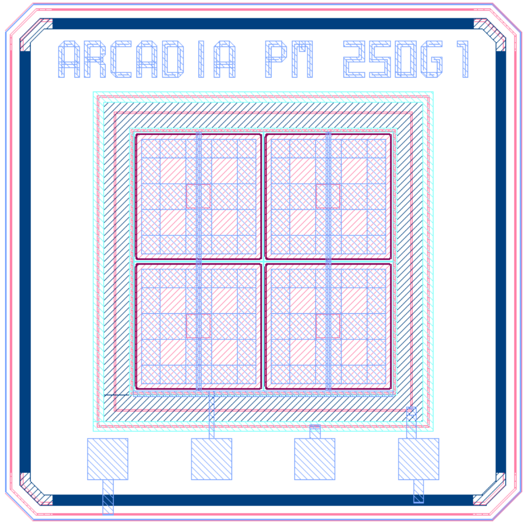
The ARCADIA run-3

Electrical characterization – standalone **passive test-structures**

Designed for test at the probe station and with external amplifiers



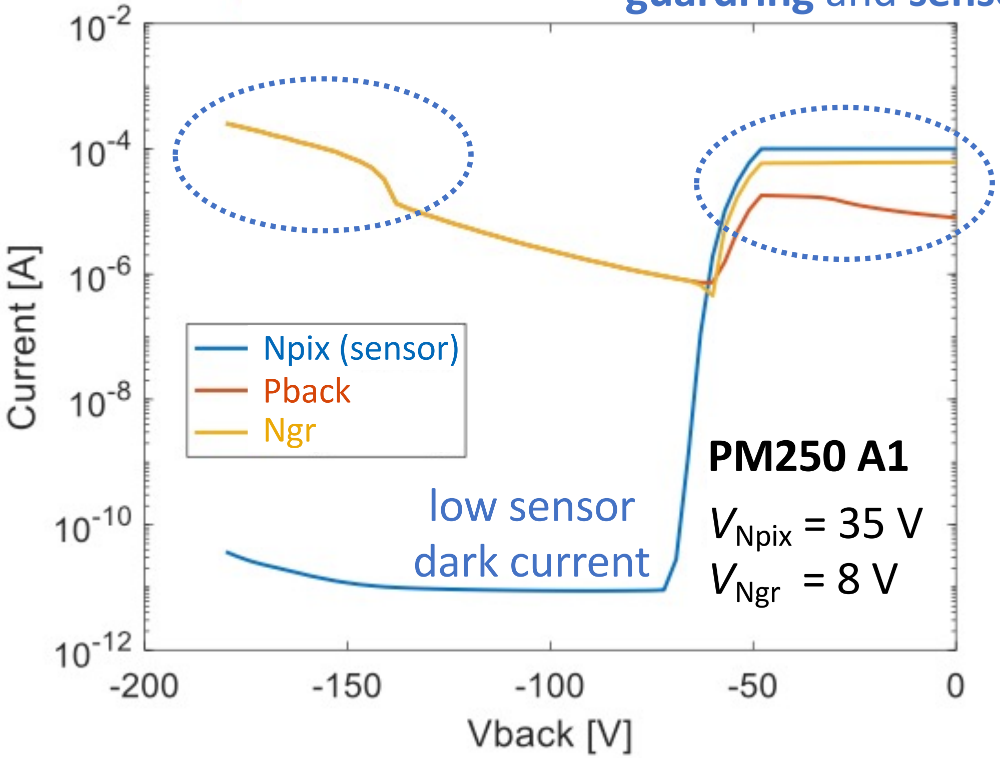
Rectangular passive pads:
70 µm × 250 µm



Square passive pads with large fill-factor: 250 µm × 250 µm

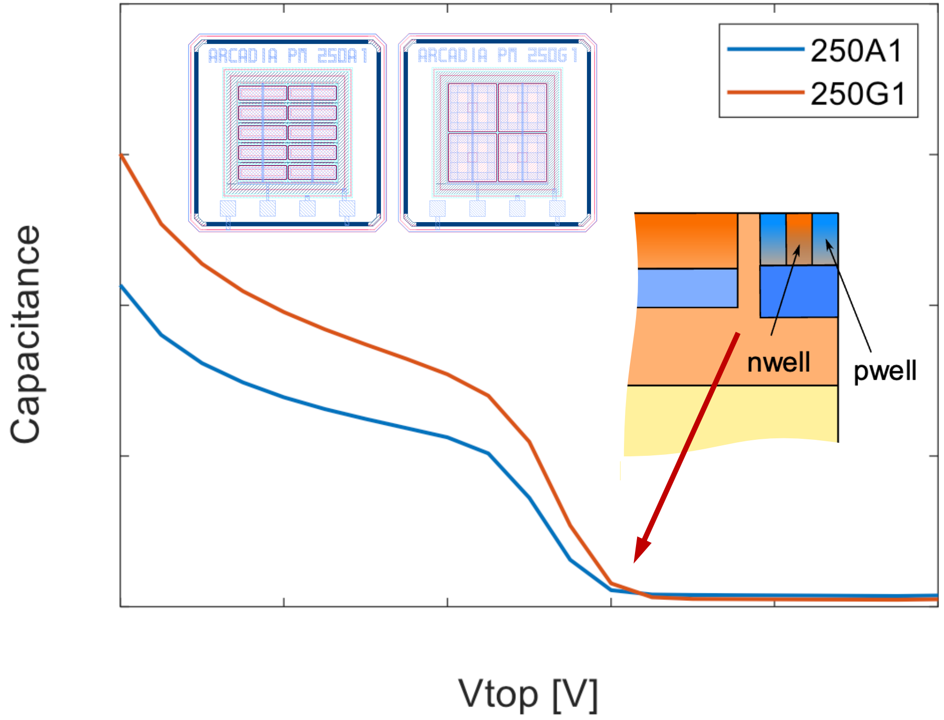
dark current between **guardring** and **backside**

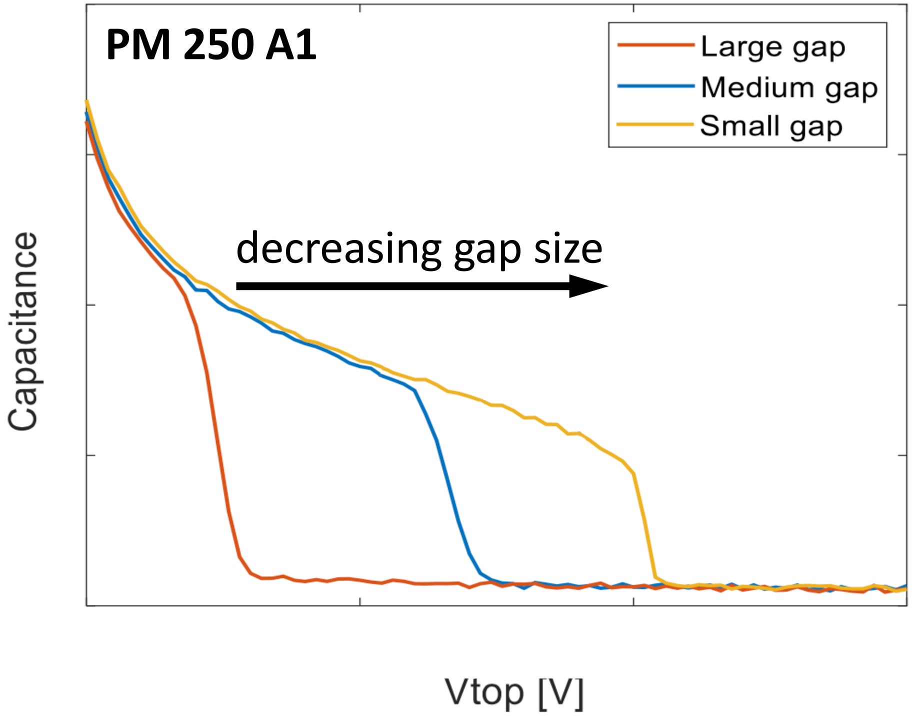
current mostly flowing between **guardring** and **sensor**



The ARCADIA run-3

Electrical characterization – standalone **passive test-structures**





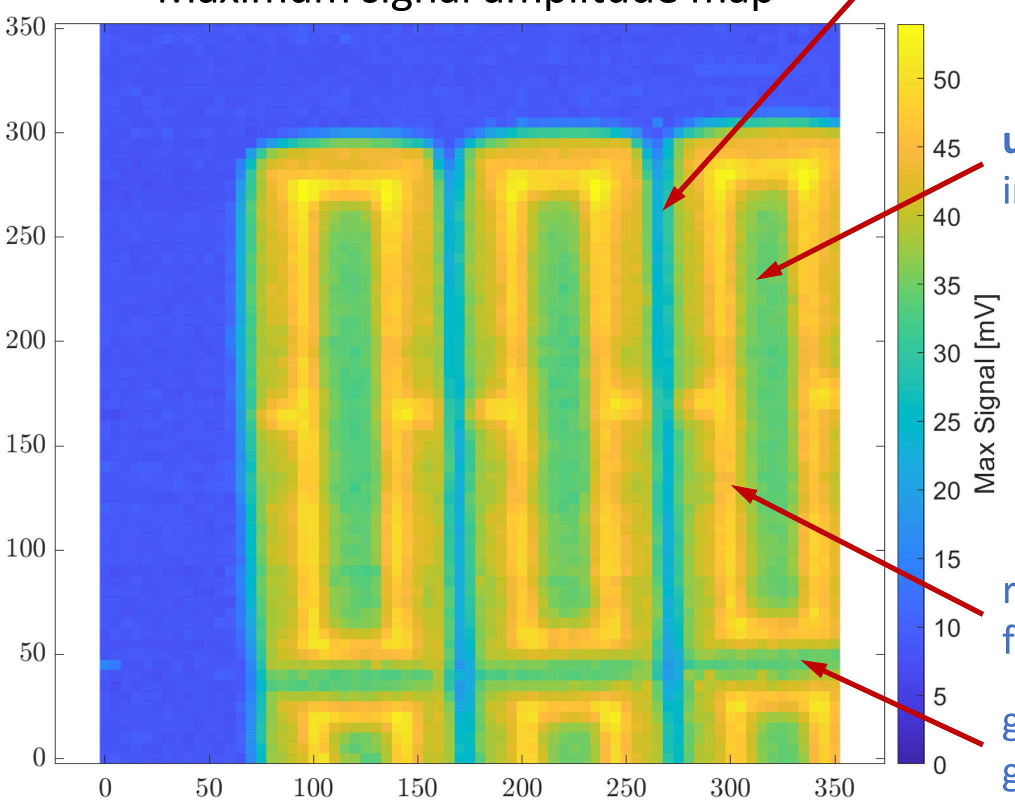
Differently from standard LGADs, the *C*(*V*) does not allow to reconstruct the whole gain implant profile, since the **gaps** between **deep-*p*-well** and ***p*-gain** are depleted earlier

The **knee** observed in the *C*(*V*) curves depends on the **size** of the gap. A **larger gaps** are fully **depleted** at **lower voltage**

The ARCADIA run-3

Dynamic characterization – standalone **passive test-structures**

Maximum signal amplitude map



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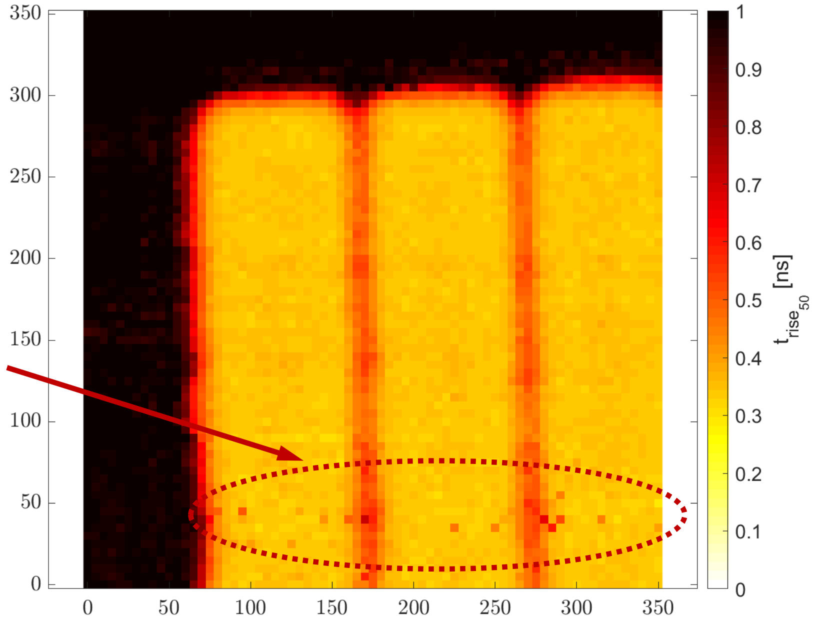
Signal risetime map

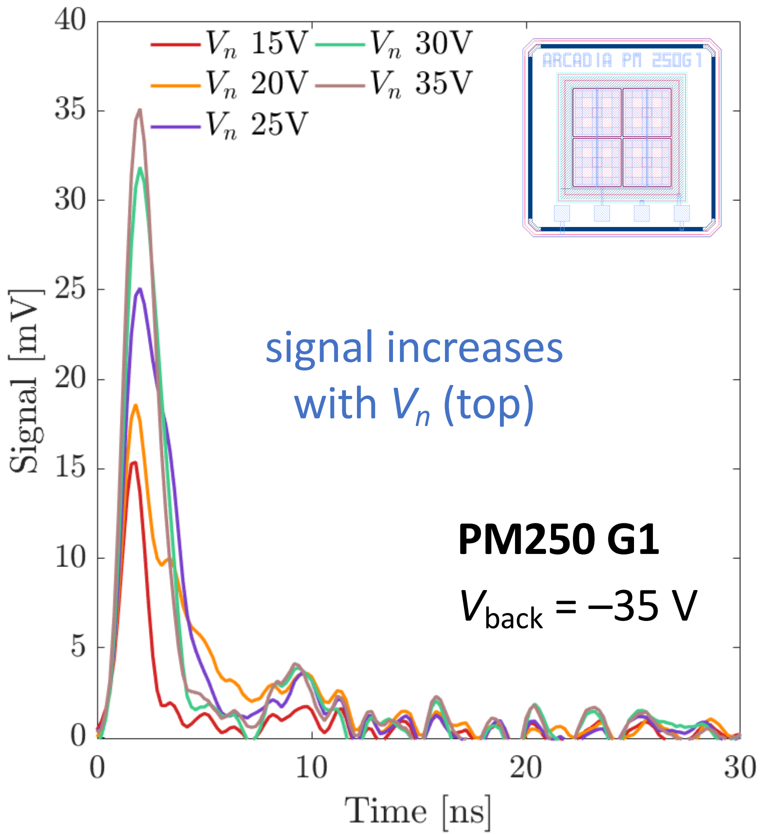


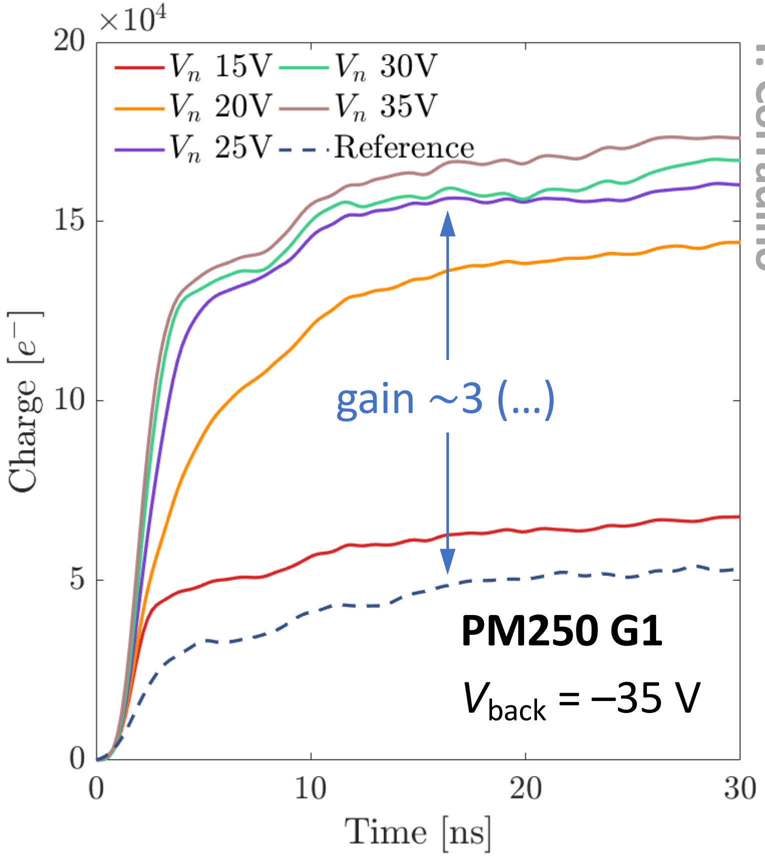
- 70 µm × 250 µm **PM250 A1** array
- V_{pix} = 40 V, V_{back} = –35 V
- Focused laser spot (~10 µm)
- 5 µm motor step

The ARCADIA run-3

Dynamic characterization – standalone **passive test-structures**

Backside illumination with a **focused IR laser** spot (~10 µm)





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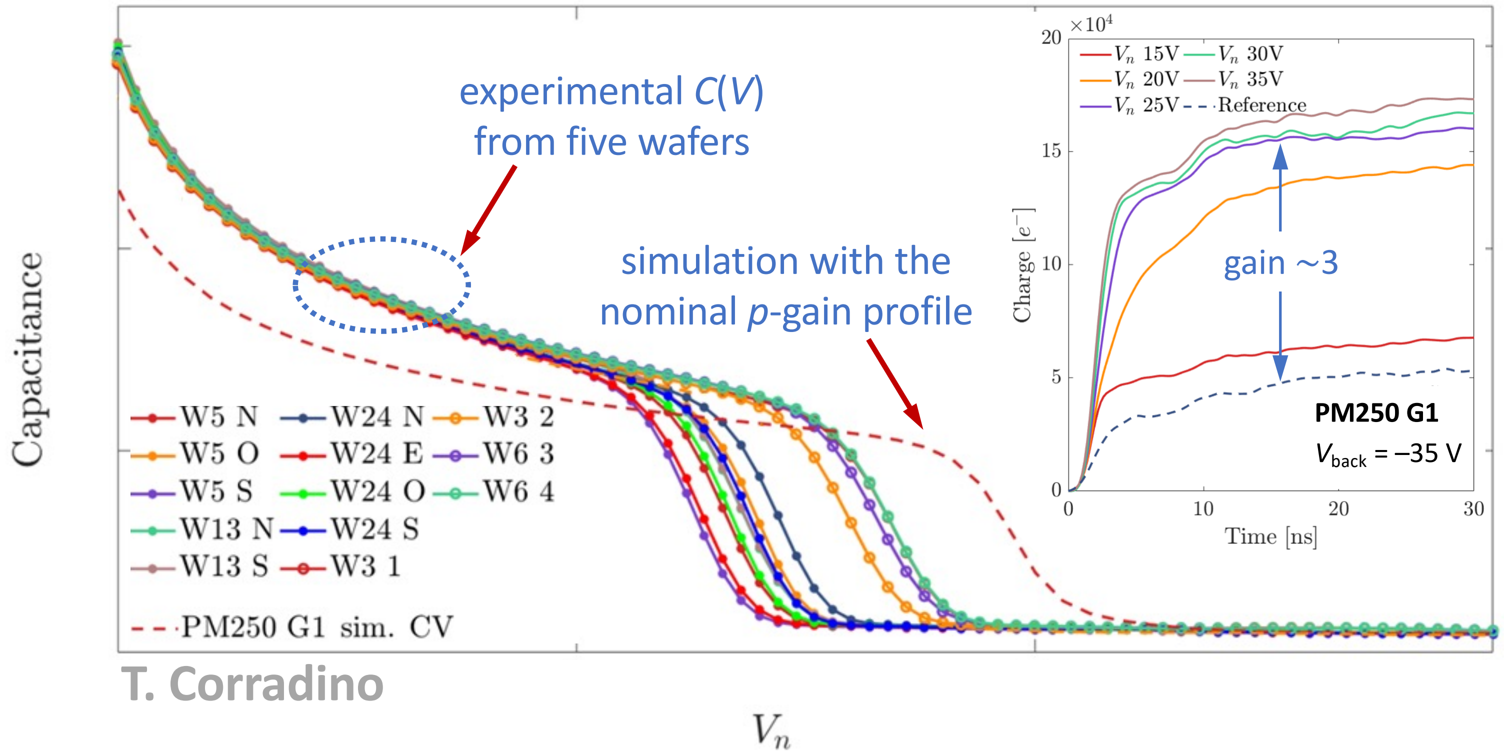
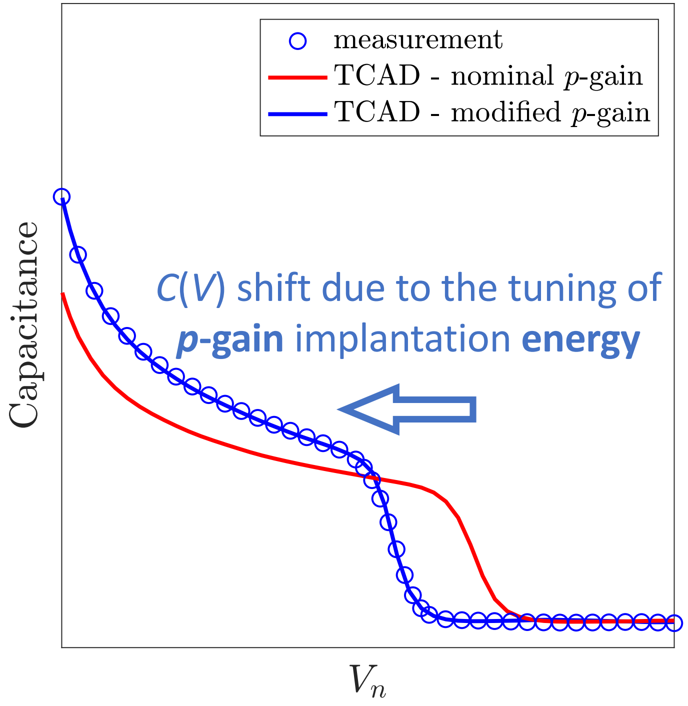
The ARCADIA run-3

Investigations about the **gain** (target: **10 – 30**)



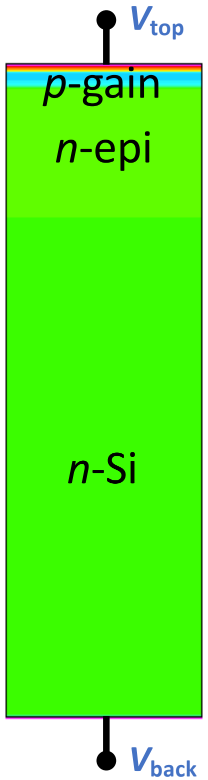
T. Corradino



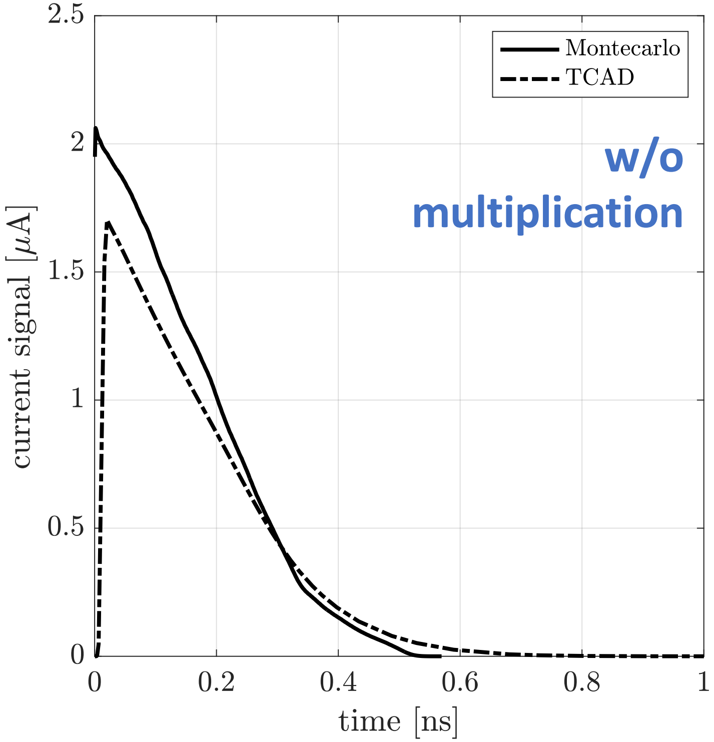
the ***p*-gain energy** has to be decreased by a factor **~2.5** to recover the mismatch

Optimization of numerical tools

Signal simulations w/ and w/o default models (and parameters) for **TCAD** and **Montecarlo**



PRE-optimization

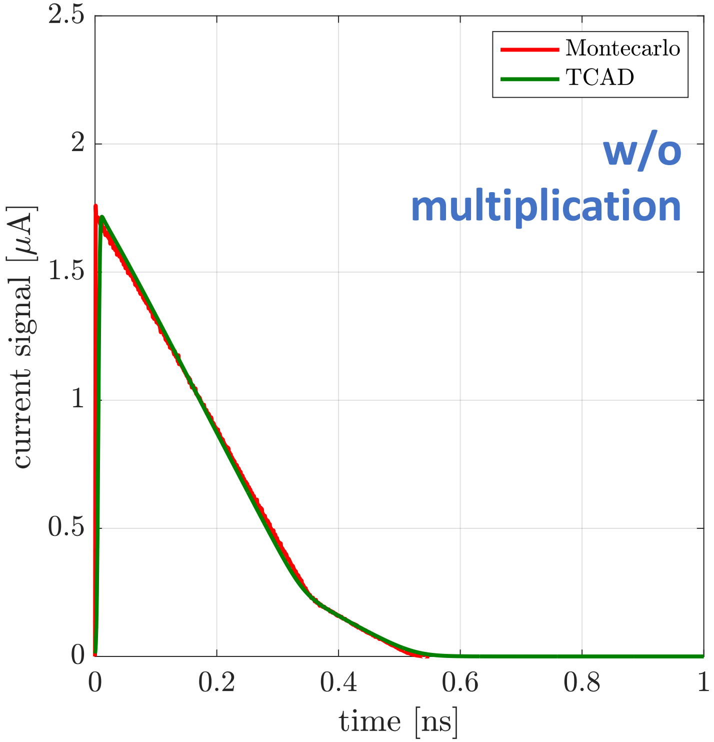


Elements involved in the tuning:

- **Masetti-Canali** mobility model
- transient **timestep** (~ 1 ps)
- **mesh** spacing
- number of **pairs/μm** (~ 80)

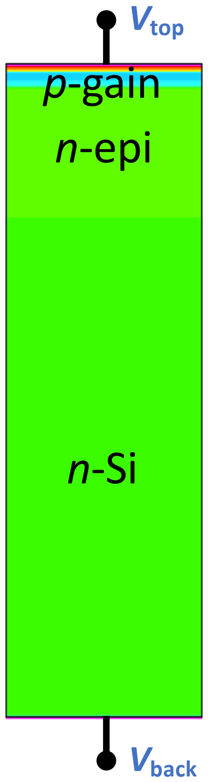
- **extended-Canali** mobility model
- transient **MaxStep** (~ 1 ps)
- **track width**
- number of **pairs/μm** (~ 70)

POST-optimization

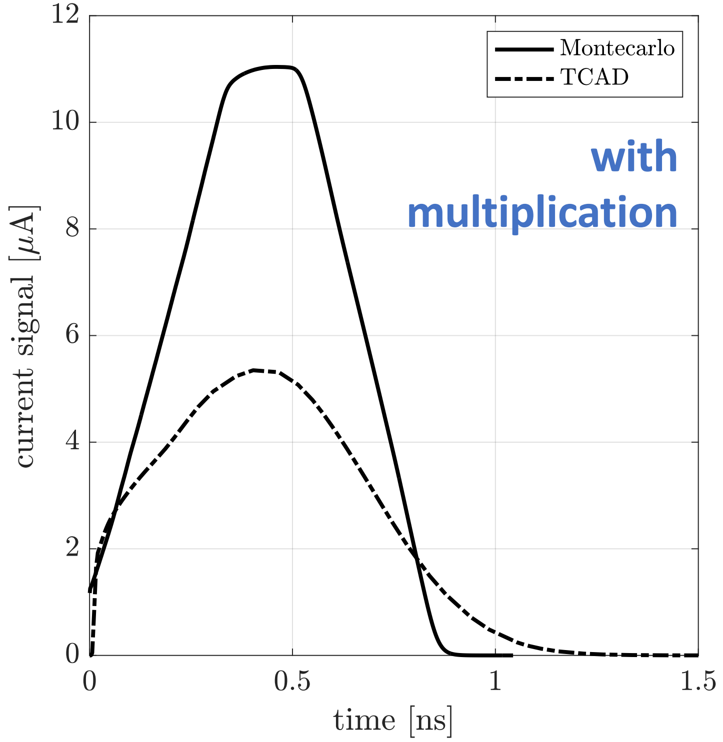


Optimization of numerical tools

Signal simulations w/ and w/o default models (and parameters) for **TCAD** and **Montecarlo**



PRE-optimization

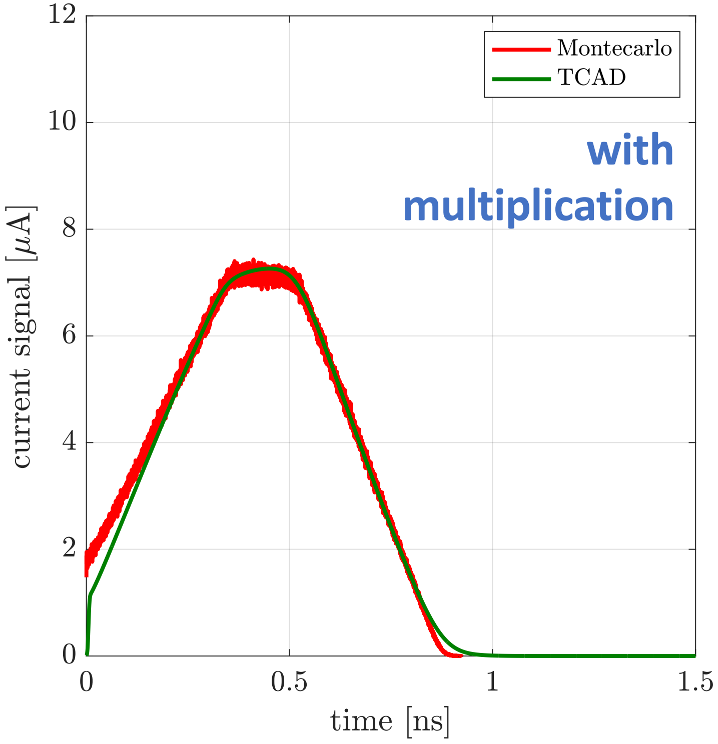


Elements involved in the tuning:

- **Masetti-Canali** mobility model
- transient **timestep** (~ 0.1 ps)
- **mesh** spacing
- number of **pairs/µm** (~ 80)

- **extended-Canali** mobility model
- transient **MaxStep** (~ 0.5 ps)
- **track width**
- number of **pairs/µm** (drastically reduced to get rid of *space-charge effects*)

POST-optimization



Conclusions

- we accumulated a lot of experience in the past years in **designing** and **characterizing** monolithic **CMOS** sensors for particle detection produced with the standard (commercial) technological **110-nm-node**
- the first two runs demonstrated the **robustness** of our **designing tools** (both for electronics and sensor part), the effectiveness of the **LFoundry-INFN** collaboration and the maturity level of the **sensor concept**
- with the last production we investigated and proved the **compatibility** of the **LGAD** technology with the **CMOS** process
- we found the reason behind the **low gain** we observed in run-3 and we are ready to launch a new **short-loop engineering run** with a reasonable splitting of ***p*-gain** implant **doses** in order to cope with the process uncertainties and achieve the target of having CMOS sensors with an **internal gain** between **10** and **30**

Thanks for your attention!