Developments on ARCADIA

State of the art and future perspectives

Marco Mandurrino [1], on behalf of the **ARCADIA Collaboration**

[1] *INFN* Torino

marco.mandurrino@to.infn.it

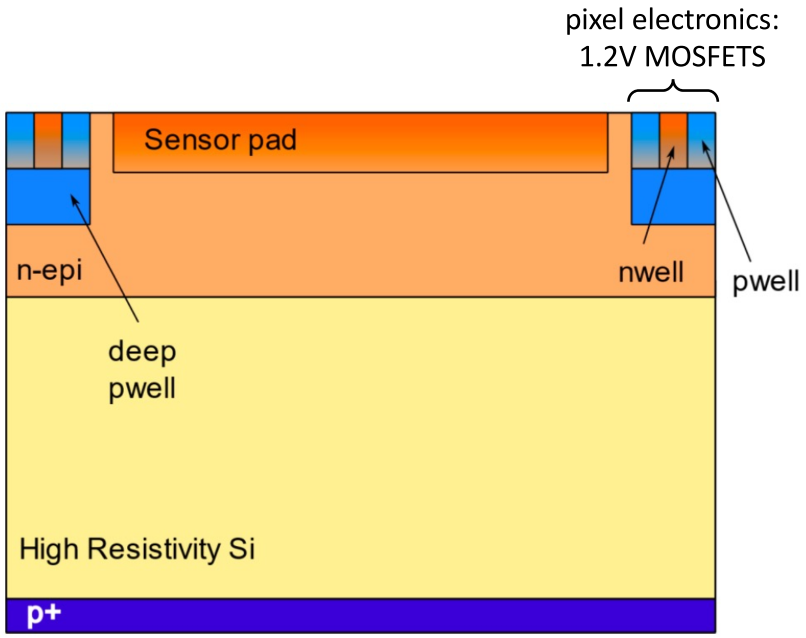
AIDAinnova 3rd Annual Meeting

Mar 18–21, 2024

Catania, Italy

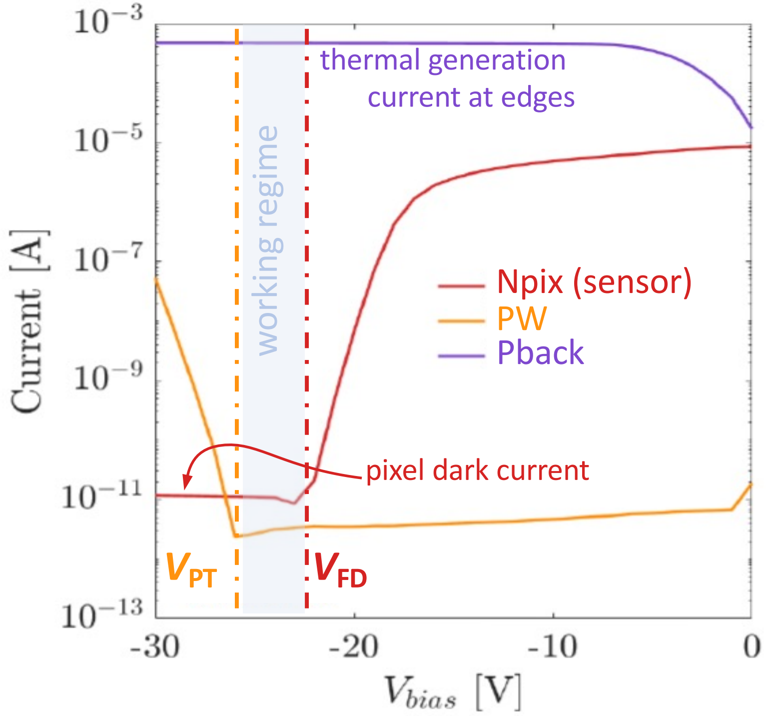
The ARCADIA sensor concept

Fully-depleted Monolithic Active Pixel Sensors



Main constraints:

- **full-depletion** condition
- **edge breakdown** induced by the **topside voltage**
- **punch-through** due to the **backside bias**



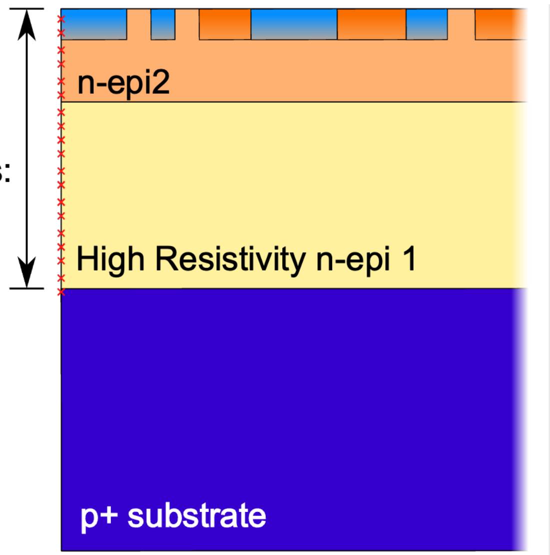
- ***n*-type high resistivity** substrate with ***n*-type epitaxial** active volume
- **110 nm** CMOS process (LFoundry)
- **deep-*p*-wells** shielding *n*-wells with electronics
- **reverse-biased** junction: depletion grows from back to top

Substrates and post-processing

Type 1:

thinning to 100 or 300 µm total thickness

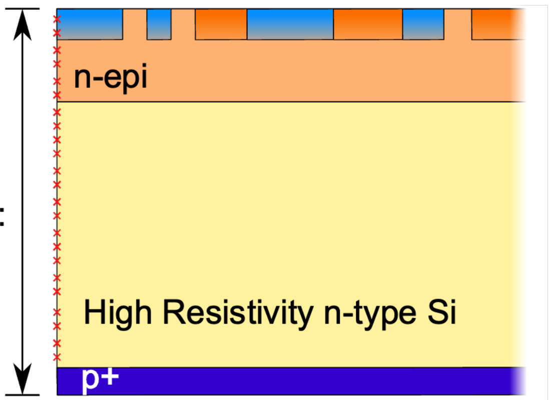
Active thickness: 48µm



Type 2:

thinning, backside ***p***$^+$ **implantation** and laser annealing

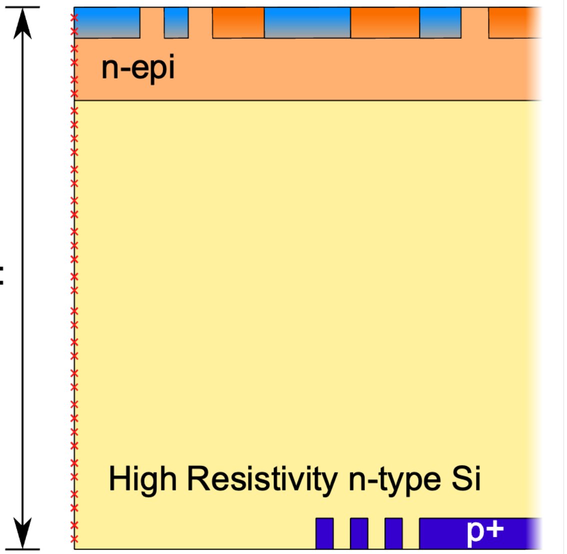
Active thickness: 100µm



Type 3:

thinning, **lithography**, backside ***p***$^+$ **implantation** and laser annealing, **insulators/metal** deposition and patterning

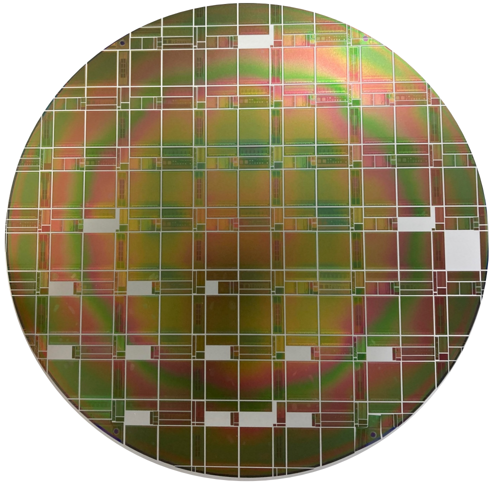
Active thickness: 200µm



First ARCADIA engineering runs

8” wafers

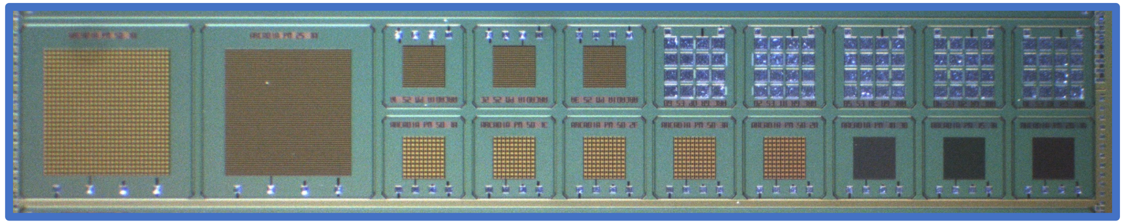
front side



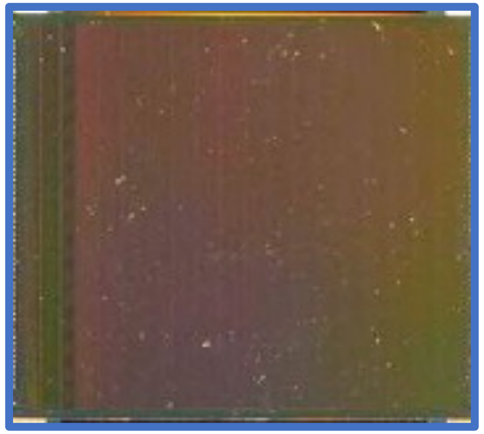
back side (type 3)

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



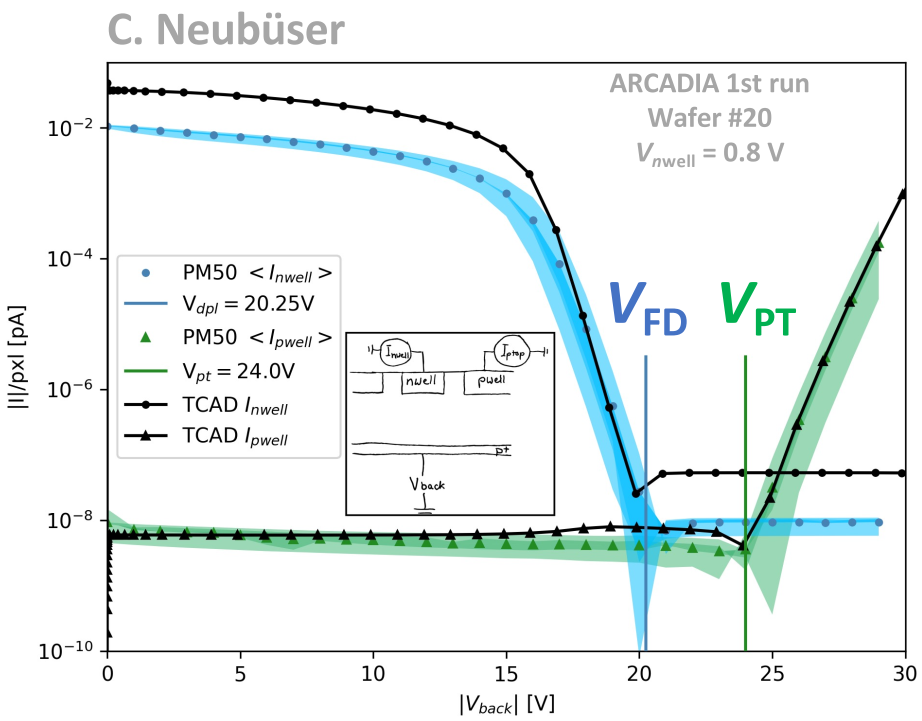
passive test structures block

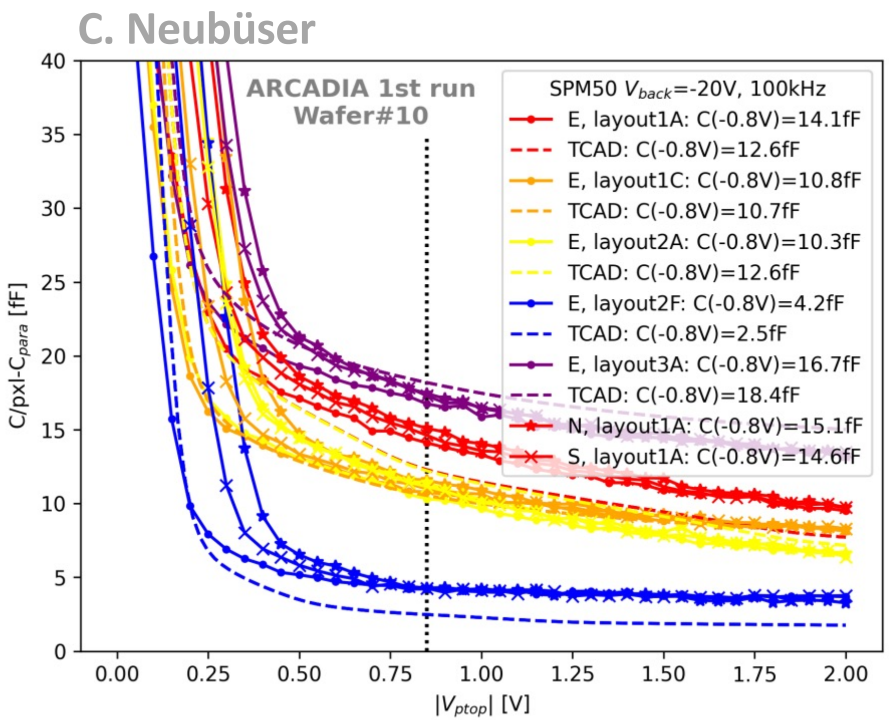


ARCADIA Main Demonstrator

First ARCADIA engineering runs

Electrical characterizations





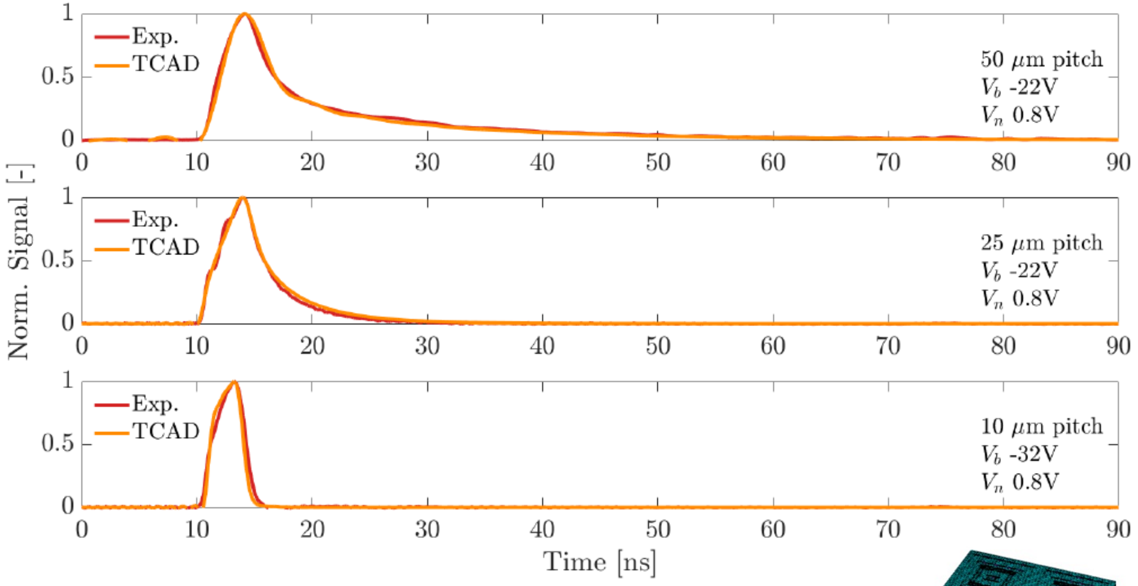
- different **pixel layouts** have been tested
- **intra-** and **inter-wafer uniformity** evaluated
- **TCAD parameters** adjusted on experimental results

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

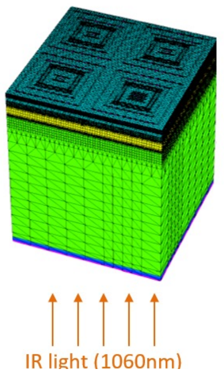
First ARCADIA engineering runs

Dynamic response with laser

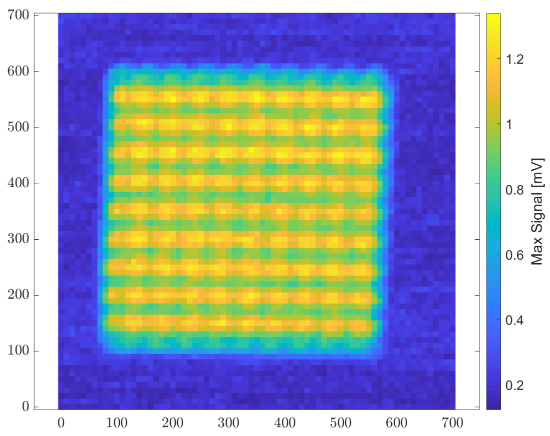
T. Corradino



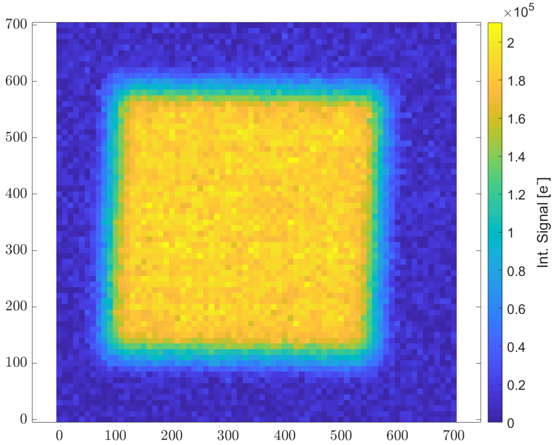
- < **100 ps** FWHM IR laser pulse
- passive **pixel array** test structures
- **100 µm** active thickness
- different **pixel pitch**: **50 µm** - **25 µm** - **10 µm**



signal peak amplitude



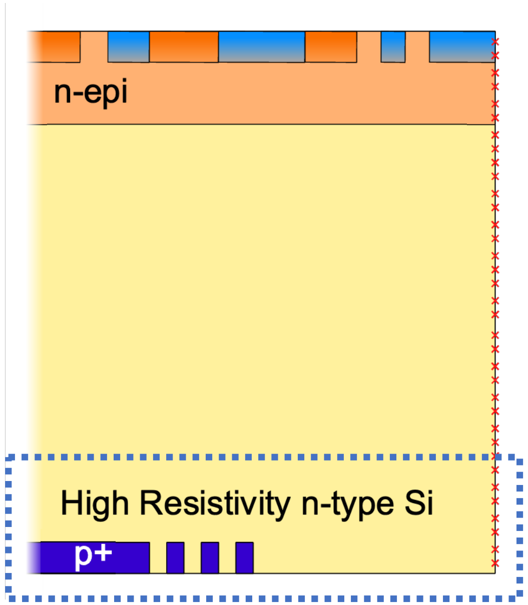
integrated charge



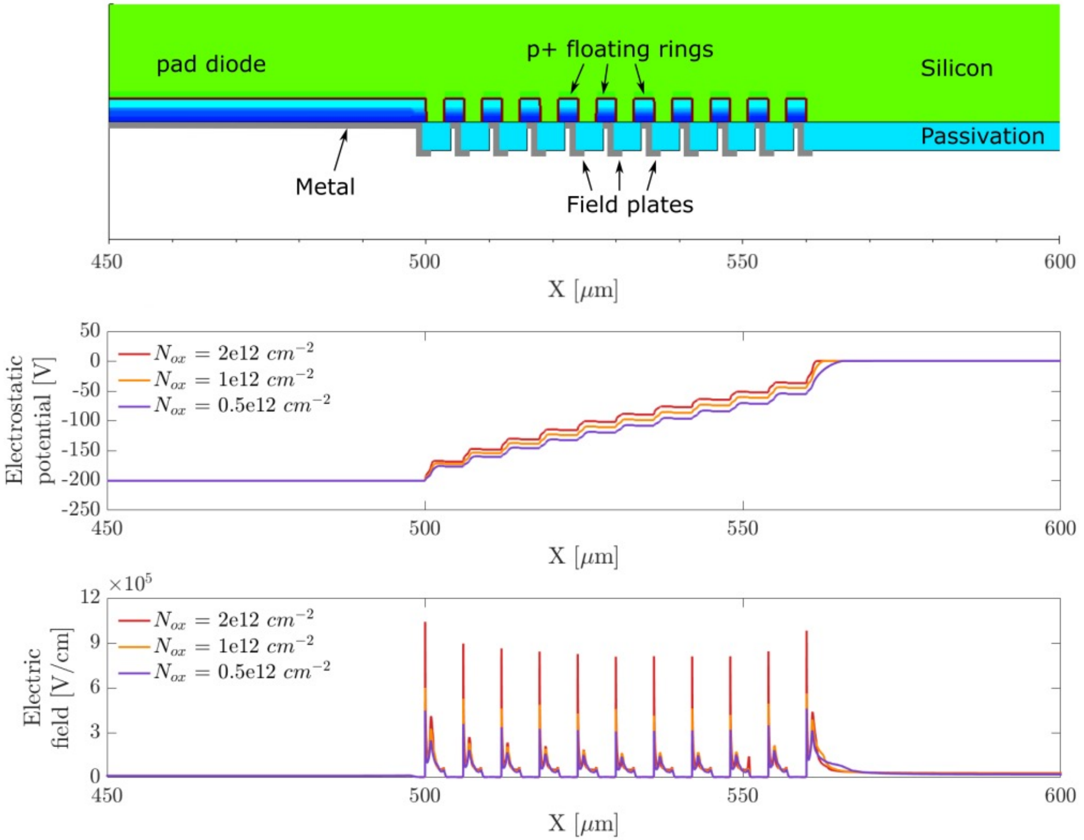
- **10 µm** FWHM focused red laser
- **50-µm-pitch** test structure
- V_{top} **= 0.8 V** and V_{back} **= –22 V**
- **10 µm** steps in *X* and *Y* directions

First ARCADIA engineering runs

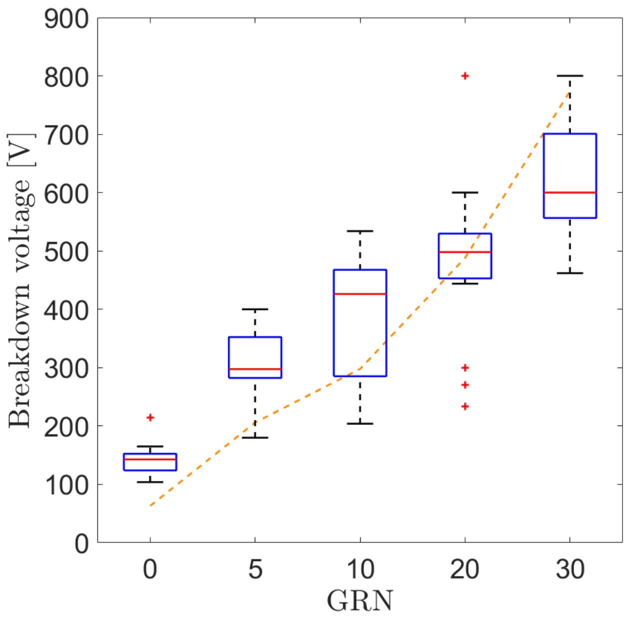
Backside layout optimization (Type 3)



T. Corradino



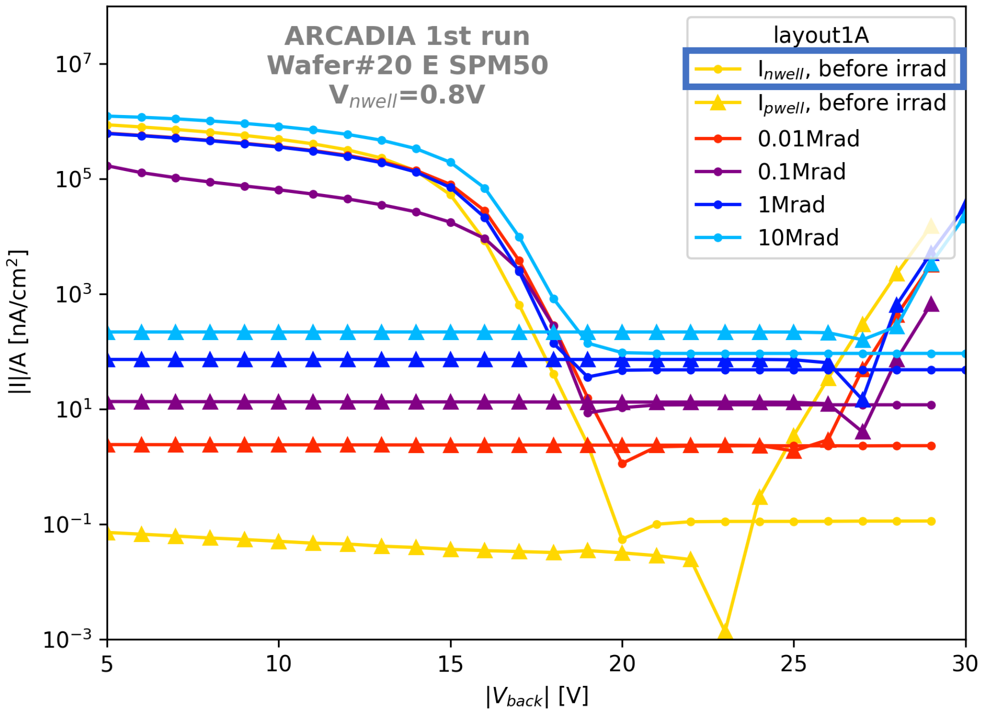
breakdown voltage for different numbers of **GRs**



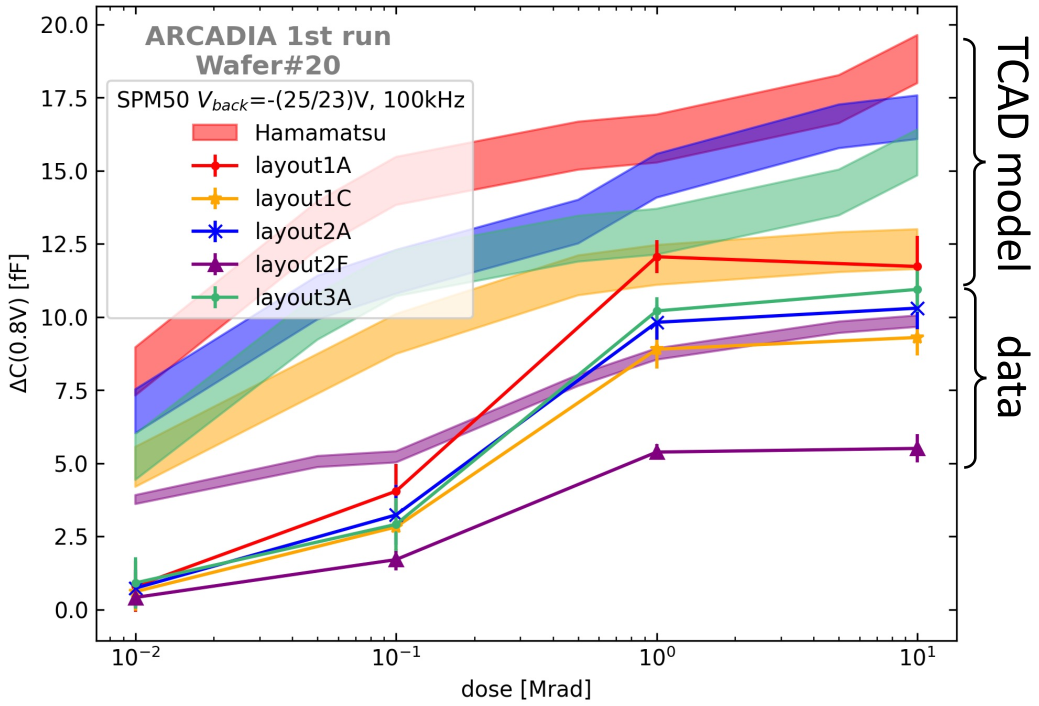
First ARCADIA engineering runs

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

C. Neubüser



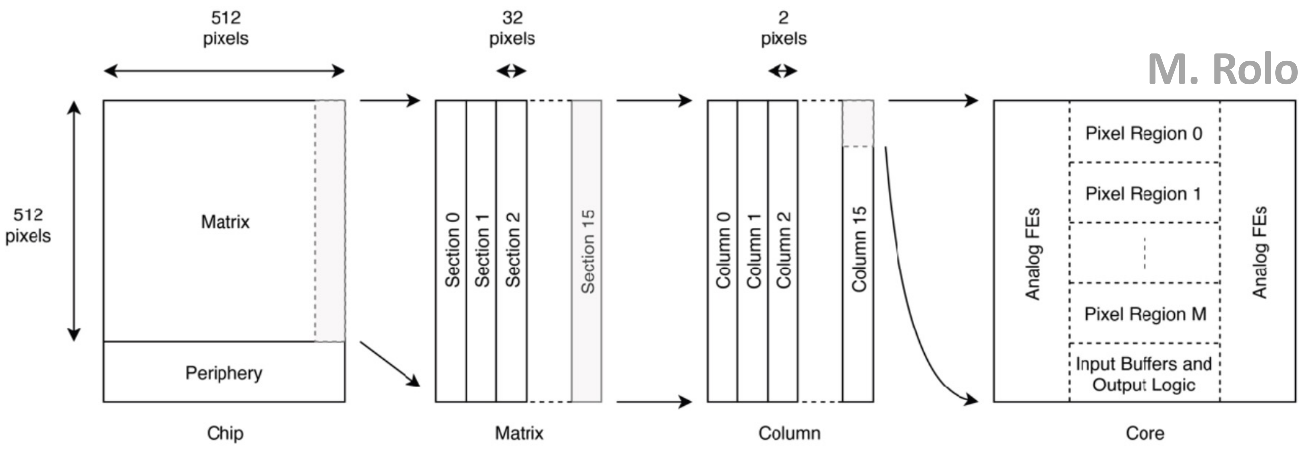
C. Neubüser

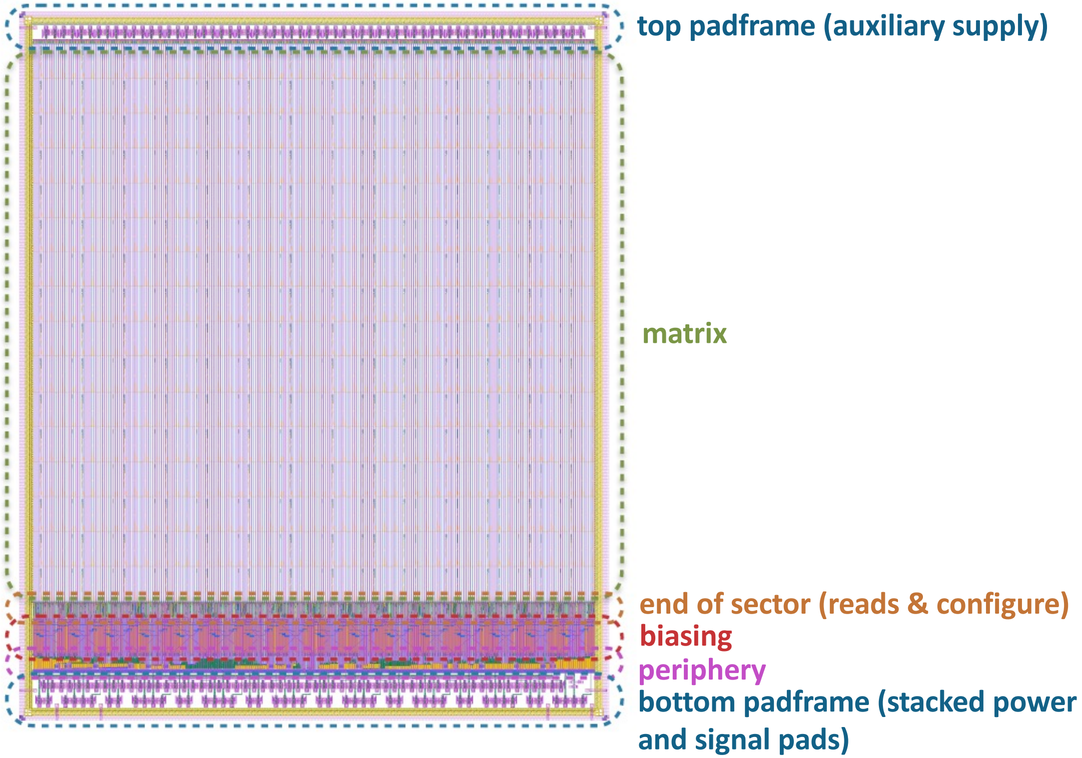


- increase of **pixel leakage** current with **Total Ionizing Dose** (TID) due to **surface generation**
- capacitance post-irradiation overestimated by the Perugia model with Hamamatsu parametrization

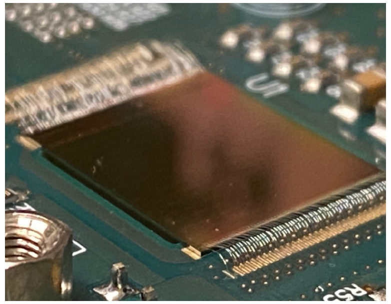
First ARCADIA engineering runs

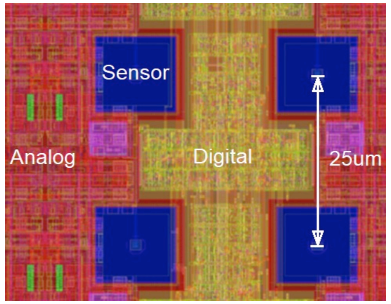
Main Demonstrator - architecture





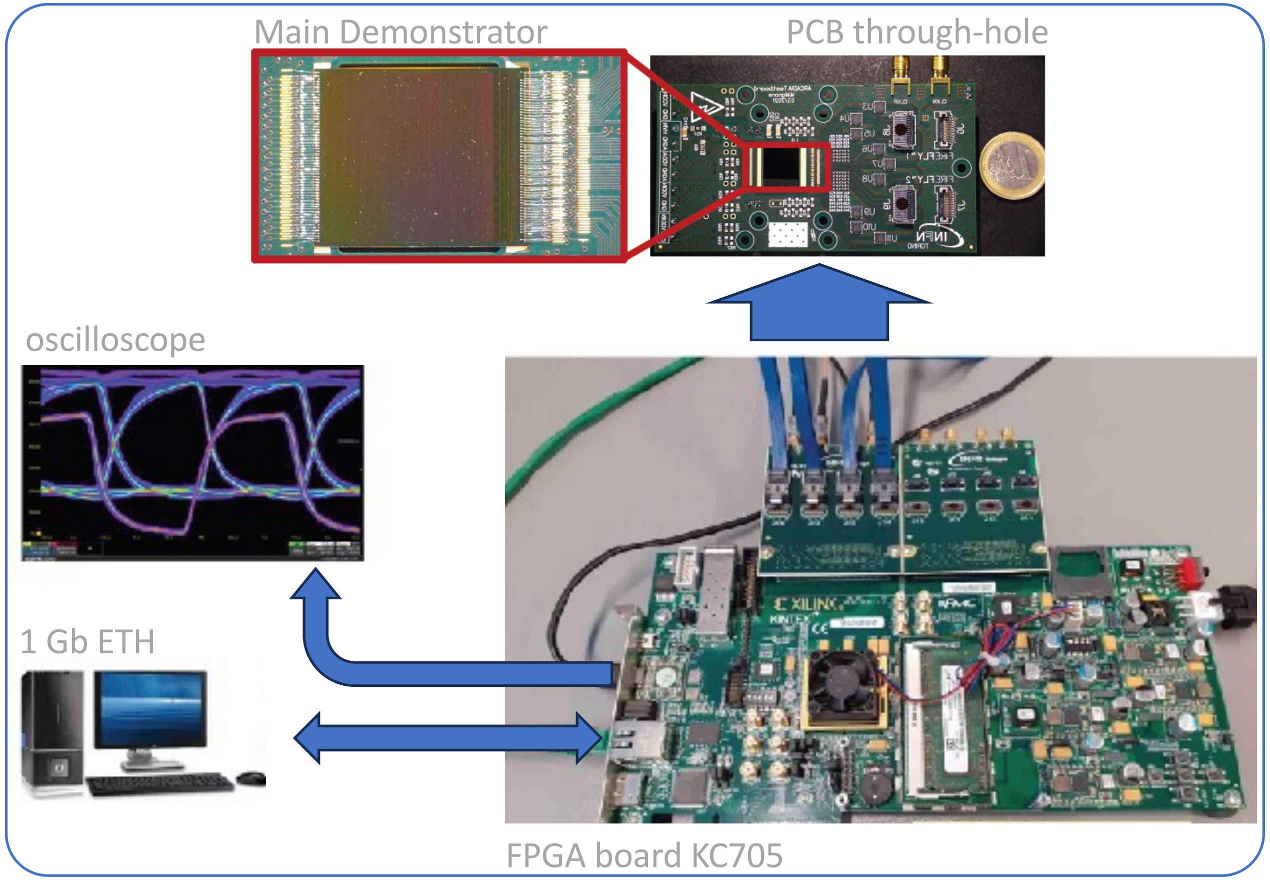
- Pixel **pitch**: **25 µm**
- Array core **area**: **1.28 cm × 1.28 cm** (262144 pixels)
- Electronics: **analog** and **digital**, with in-pixel **threshold** and **data storage**
- Architecture: **event-driven**, with active pixels sending their address to the chip peripheral circuits
- (Low) **power**: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

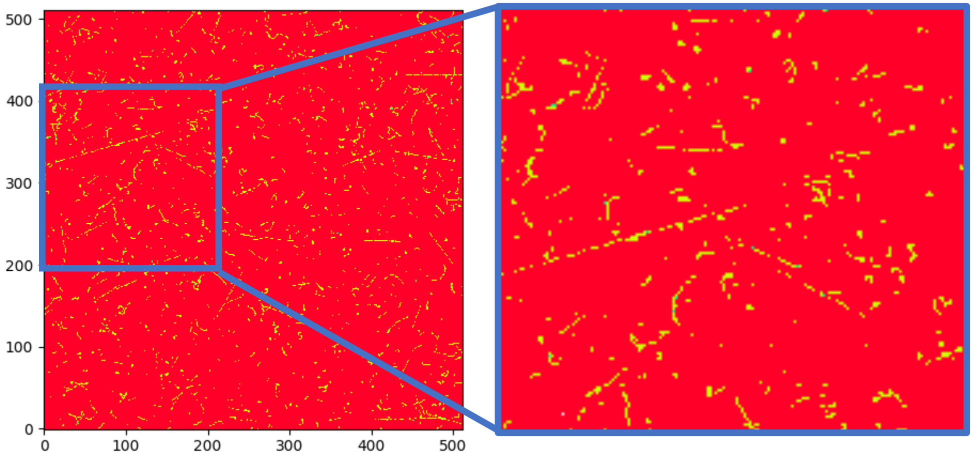




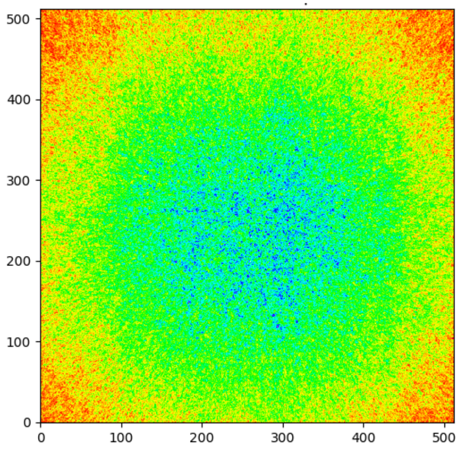
First ARCADIA engineering runs

Main Demonstrator - acquisition setup

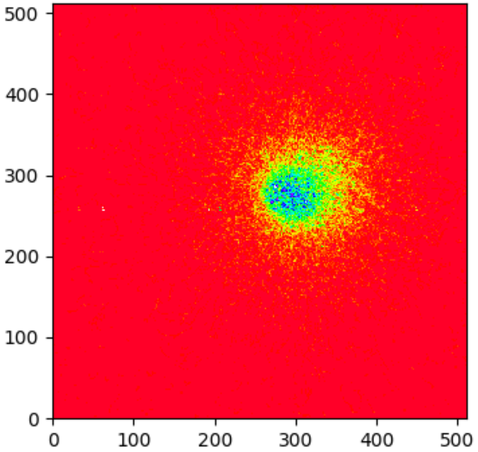




Cosmic rays acquisition (4h)



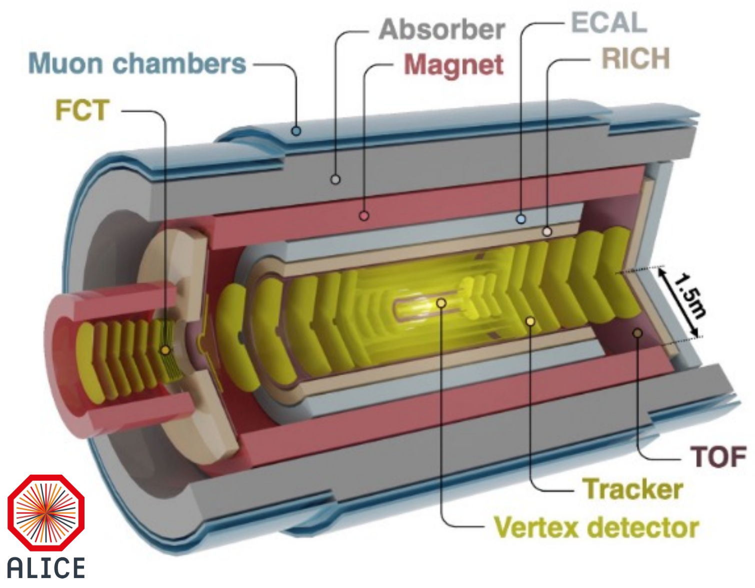
^{90}Sr beta source (1cm^2) 8 mm from the sensor surface



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

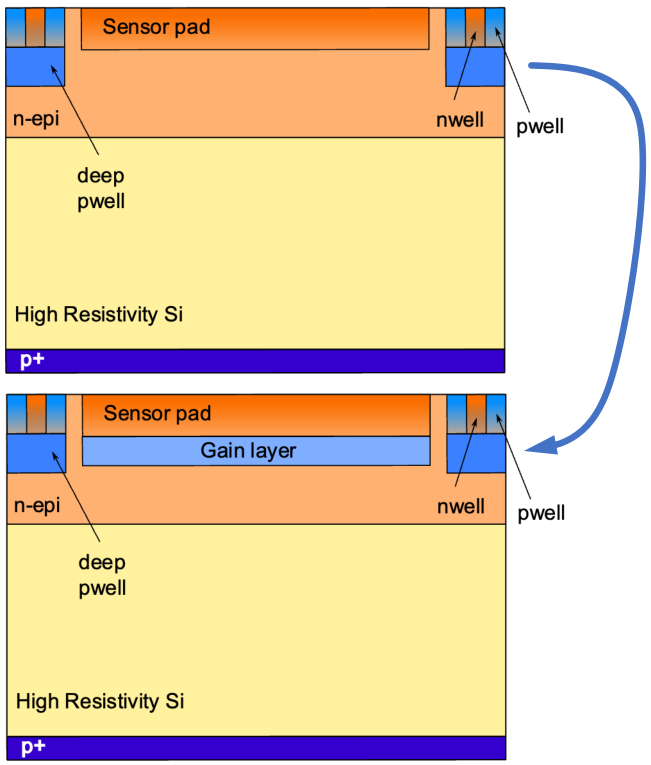
- Total **power consumption**: **10 mW/cm^2** at low event rates
- **Design specification**: **20 mW/cm^2** at rates up to 100 Mevents/cm^2

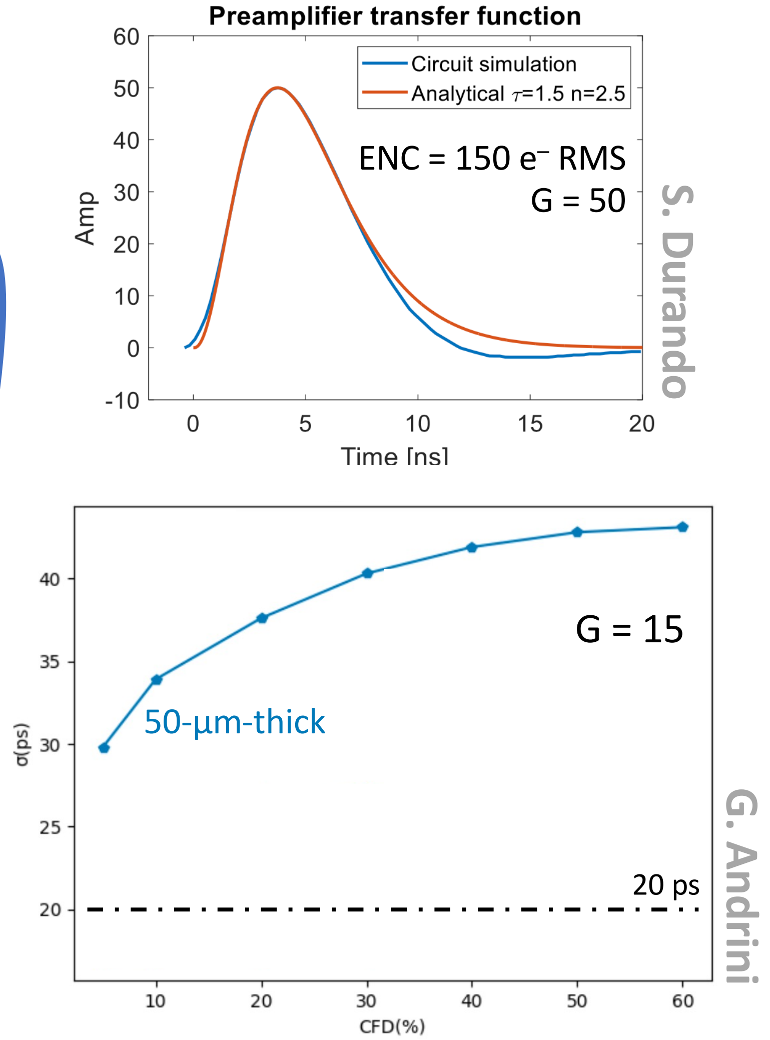
The ARCADIA run-3



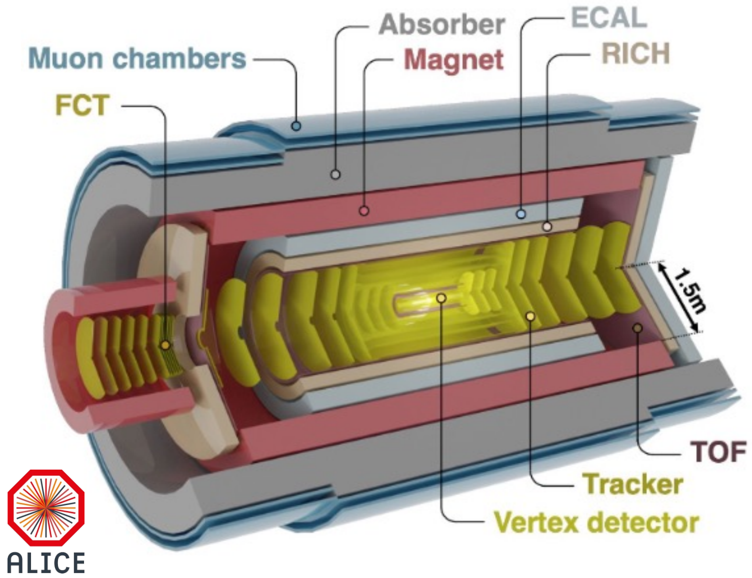
ALICE 3 **TOF** detector:

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



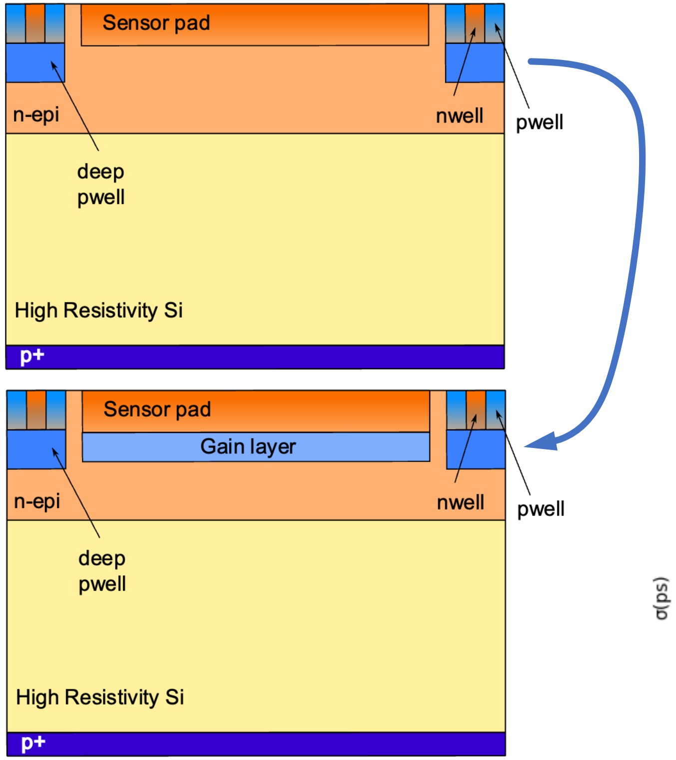


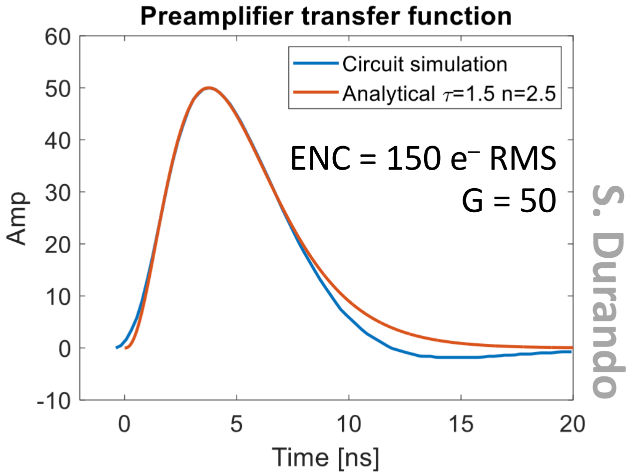
The ARCADIA run-3

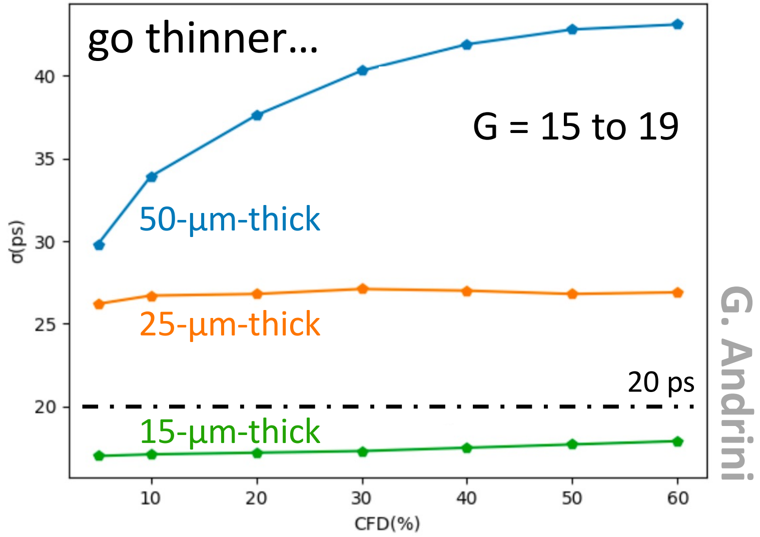


ALICE 3 **TOF** detector:

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

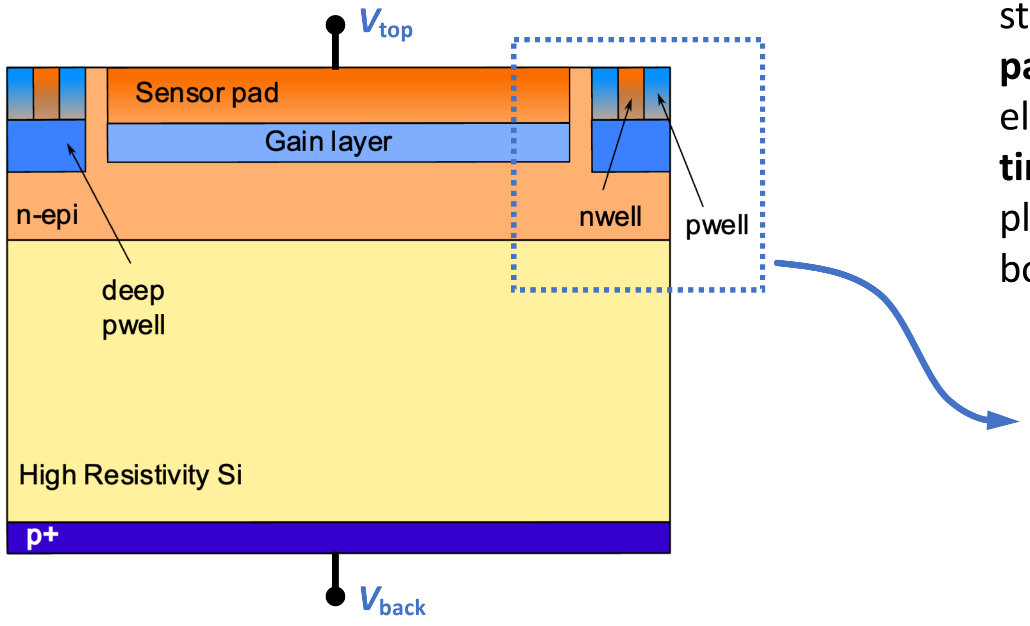






The ARCADIA run-3

Sensor structure and layout

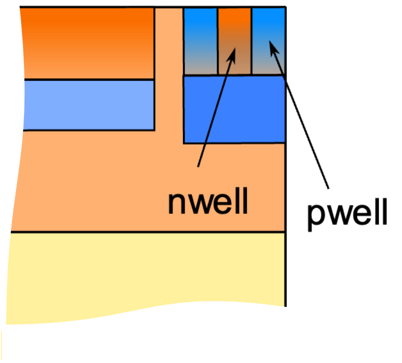


V_{top} (30-40 V) determines the **gain**, while
V_{back} (–30 V) defines the **drift field** in the substrate

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

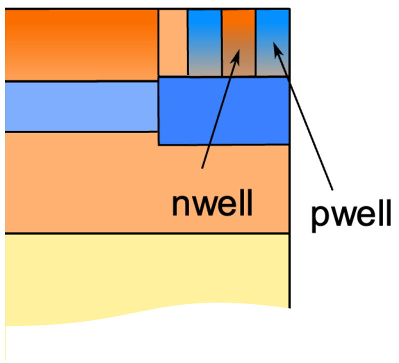
Layout A2:

standard solution: **direct path** to the n^+ collection electrode ⇒ more **uniform time response**; NO multiplication of charges at borders



Layout A1:

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



- 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**

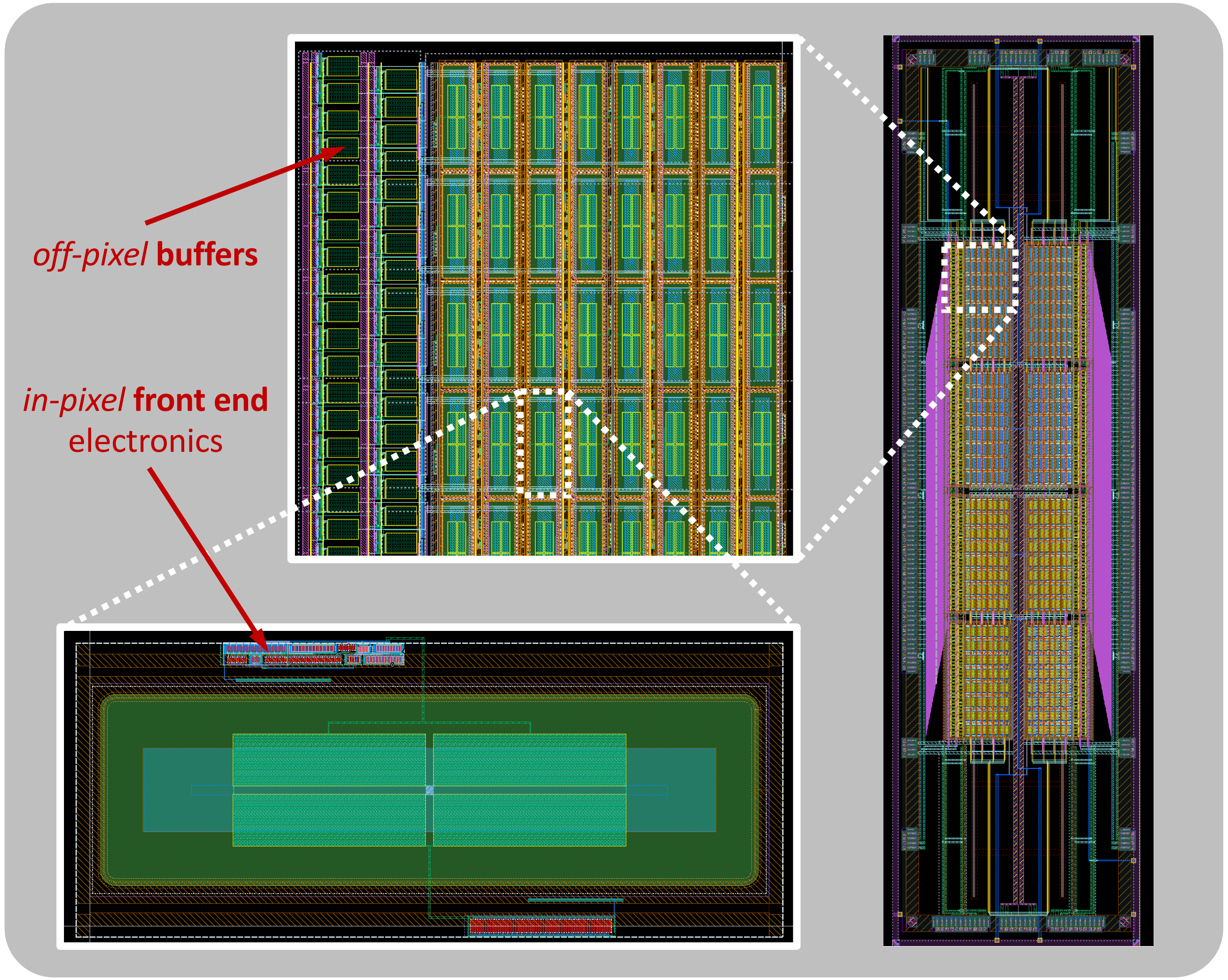
- **8 matrices** (**64 pixel pads** each) implementing different sensor and front-end flavours
- pads of **250 × 100 μm²**
- readout: **64 × 2 analog outputs** on each side
- **rolling shutter** of single matrix readout

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 *off-pixel* buffers (3.3V)

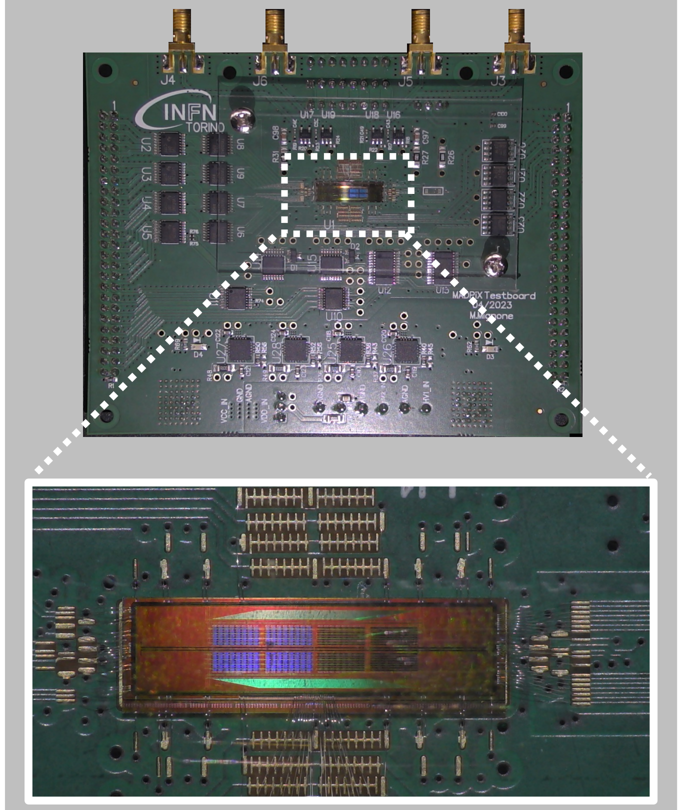
- **AC-coupled** with **FE**
- **Power** consumption: **1.65 mW/ch**



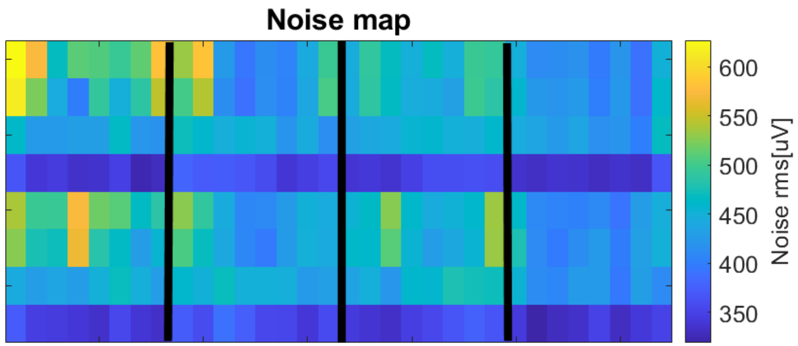
The ARCADIA run-3

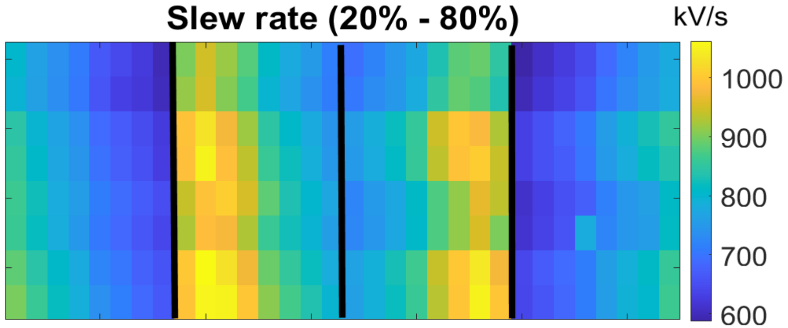
MadPix: first small-scale (**4 × 16 mm²**) demonstrator with **gain** and **integrated electronics**

MadPix testboard



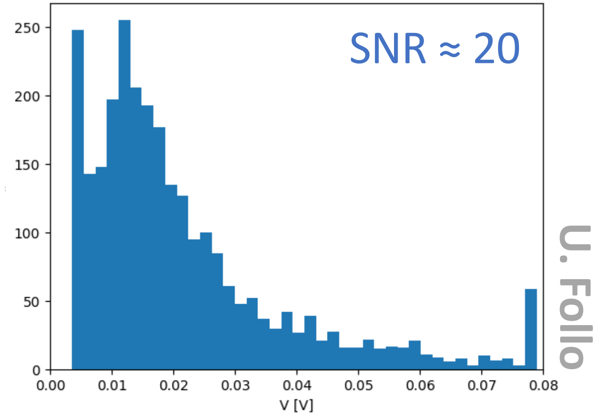
Noise and **slew-rate** characterization with external **test-pulse** injection

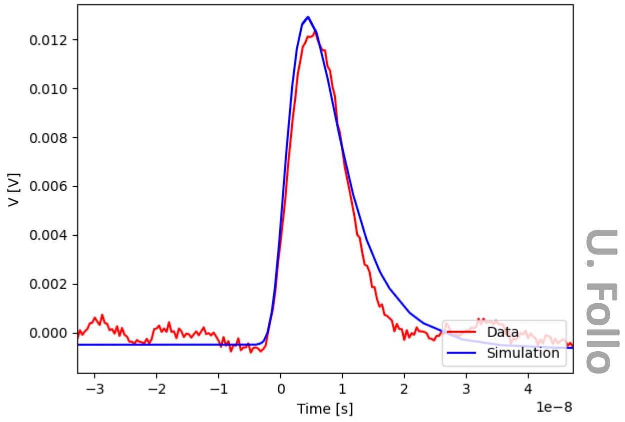




U. Follo

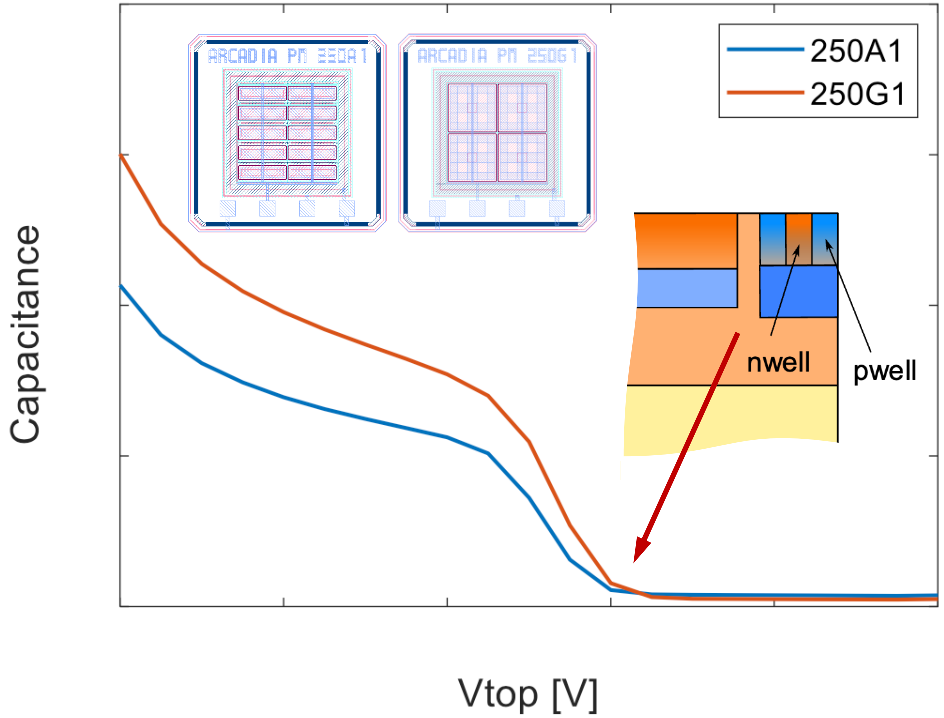
First data with **beta source** (^{90}**Sr**)



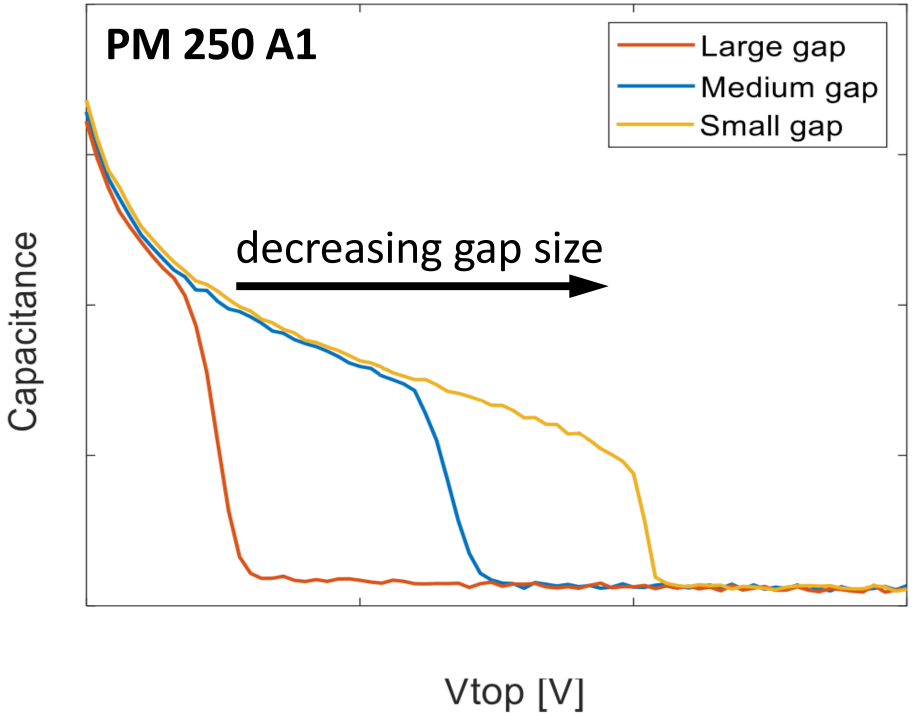


The ARCADIA run-3

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



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

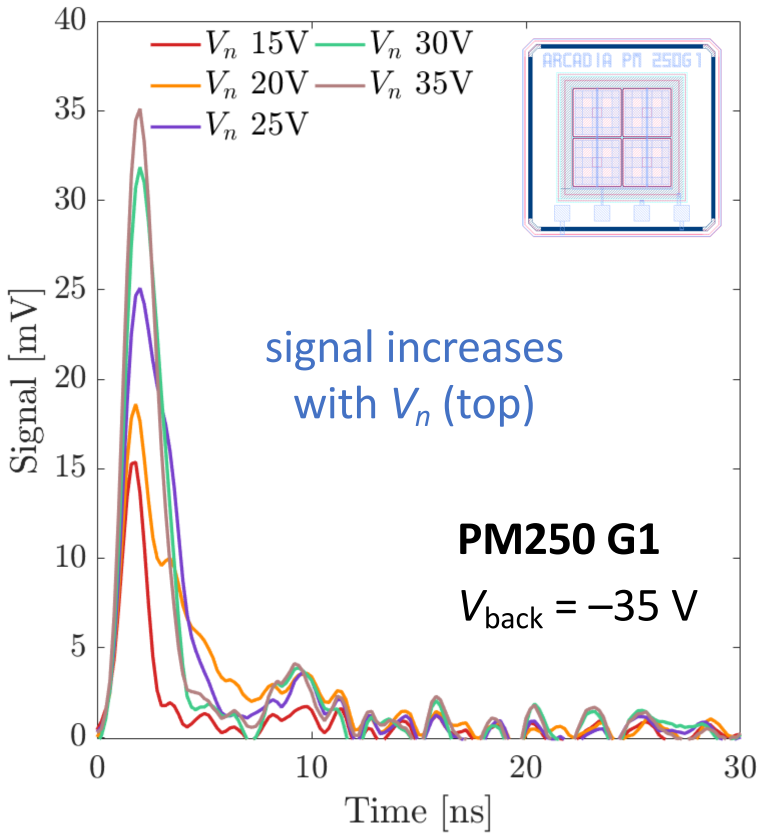


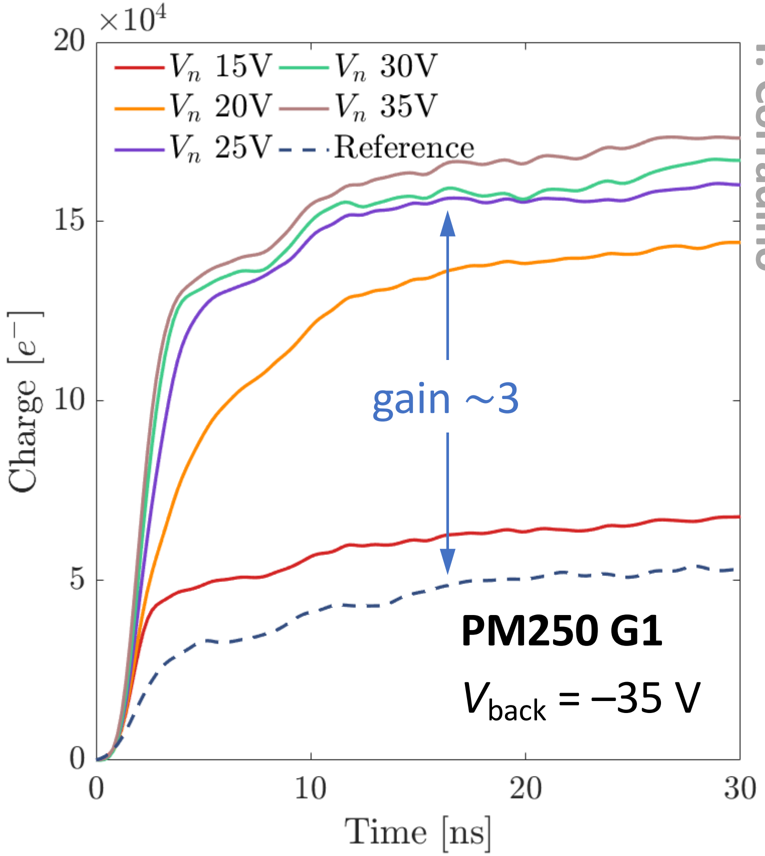
The **knee** observed in the *C*(*V*) curves depends on the **size** of the gap. A **larger gaps** are fully **depleted** at **lower voltage**

The ARCADIA run-3

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

Focused IR laser spot (~10 μm)
Backside illumination

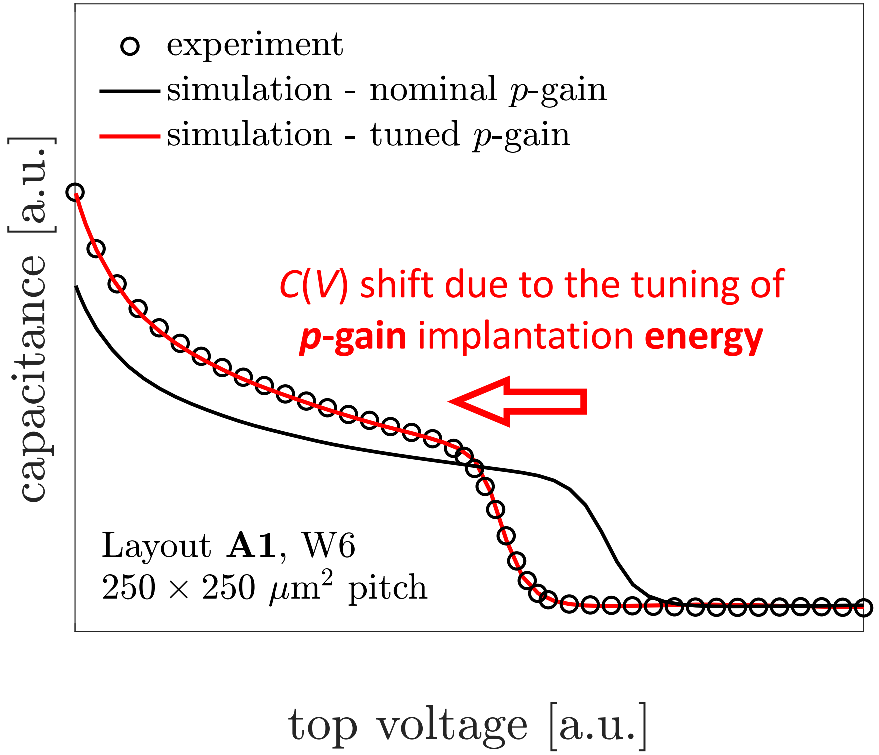




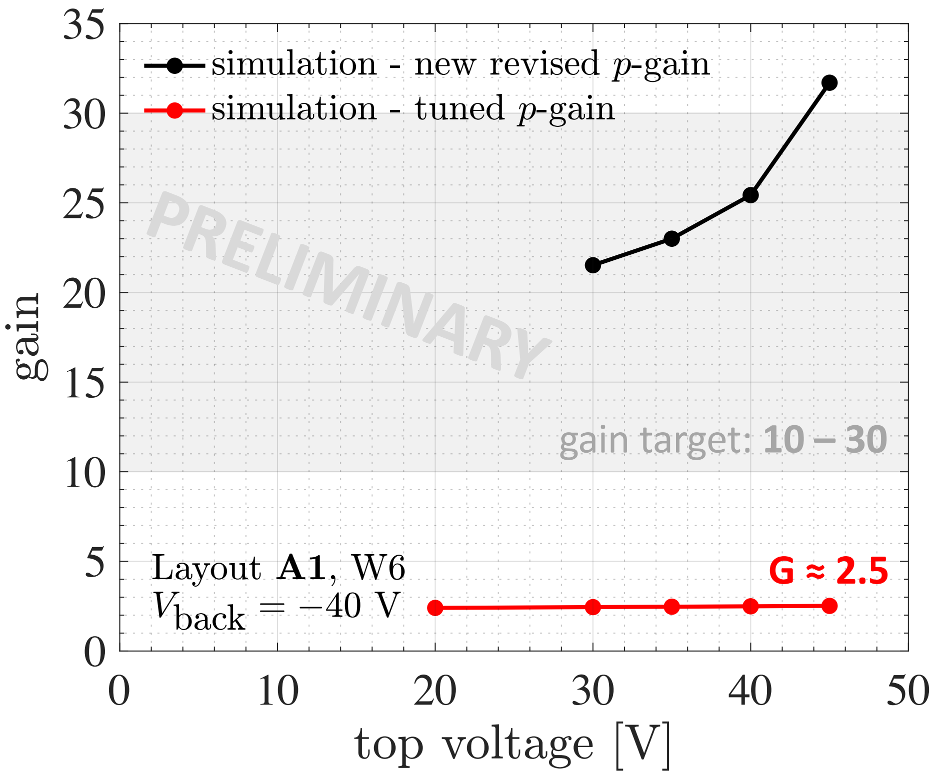
T. Corradino

The ARCADIA run-3

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



the ***p*-gain implant energy** has to be reduced by **~30%** to recover the mismatch



Conclusions

- robustness of **design tools** (both for electronics and sensor part), as well as effectiveness of the **LFoundry-INFN** collaboration and maturity level of the **sensor concept** have been demonstrated by the first two ARCADIA runs
- we proved the **compatibility** of the **LGAD** technology with the **CMOS** process through our last production
- the **gain layer** has been implanted with a **lower energy** than what expected, as confirmed by either measurements and TCAD simulations

… *what's next* ?

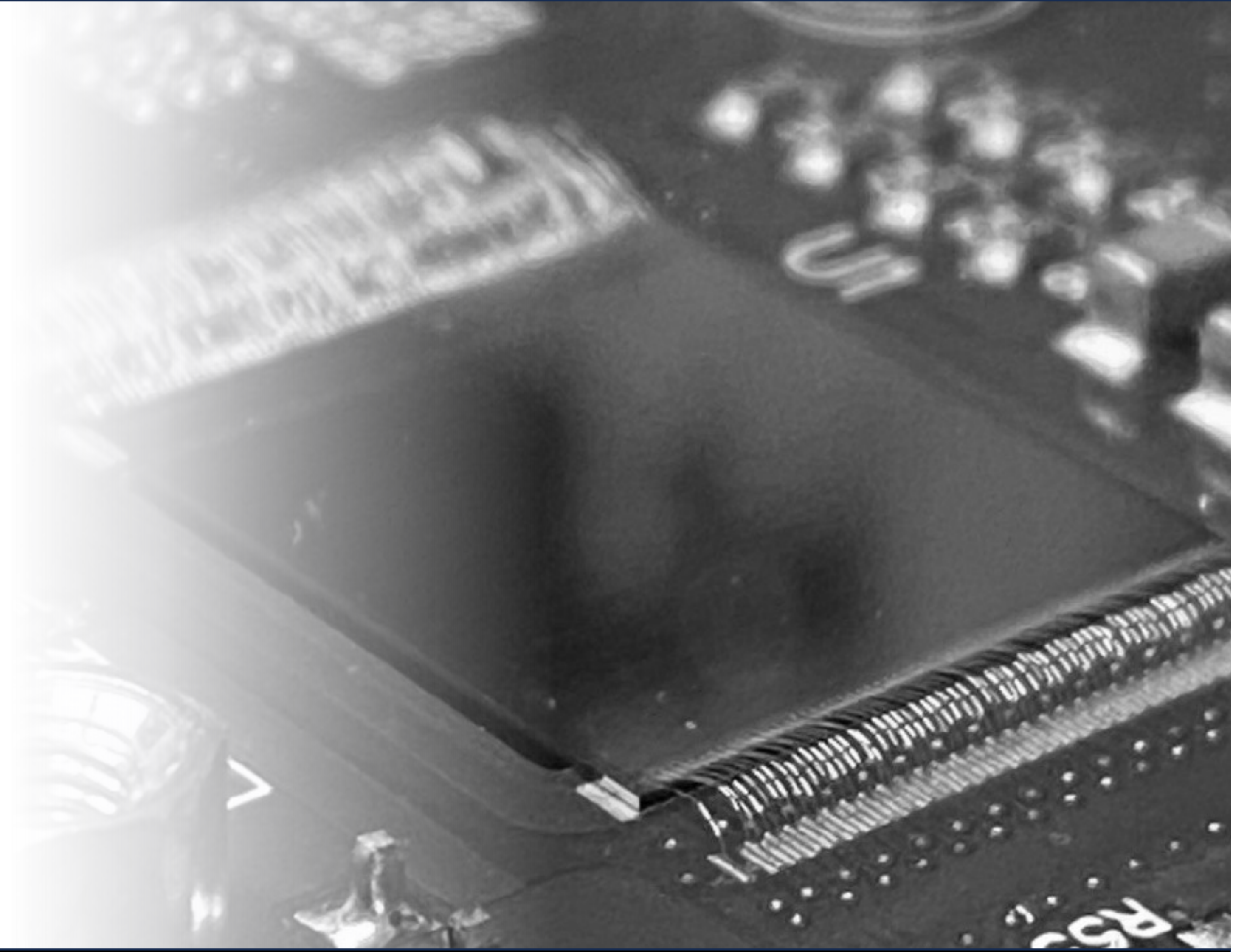
- we are waiting the release of a new **short-loop engineering run** with a different splittings of ***p*-gain** implant **doses** to cope with process uncertainties and achieve the target of having CMOS sensors with **internal gain** between **10** and **30**

Acknowledgments

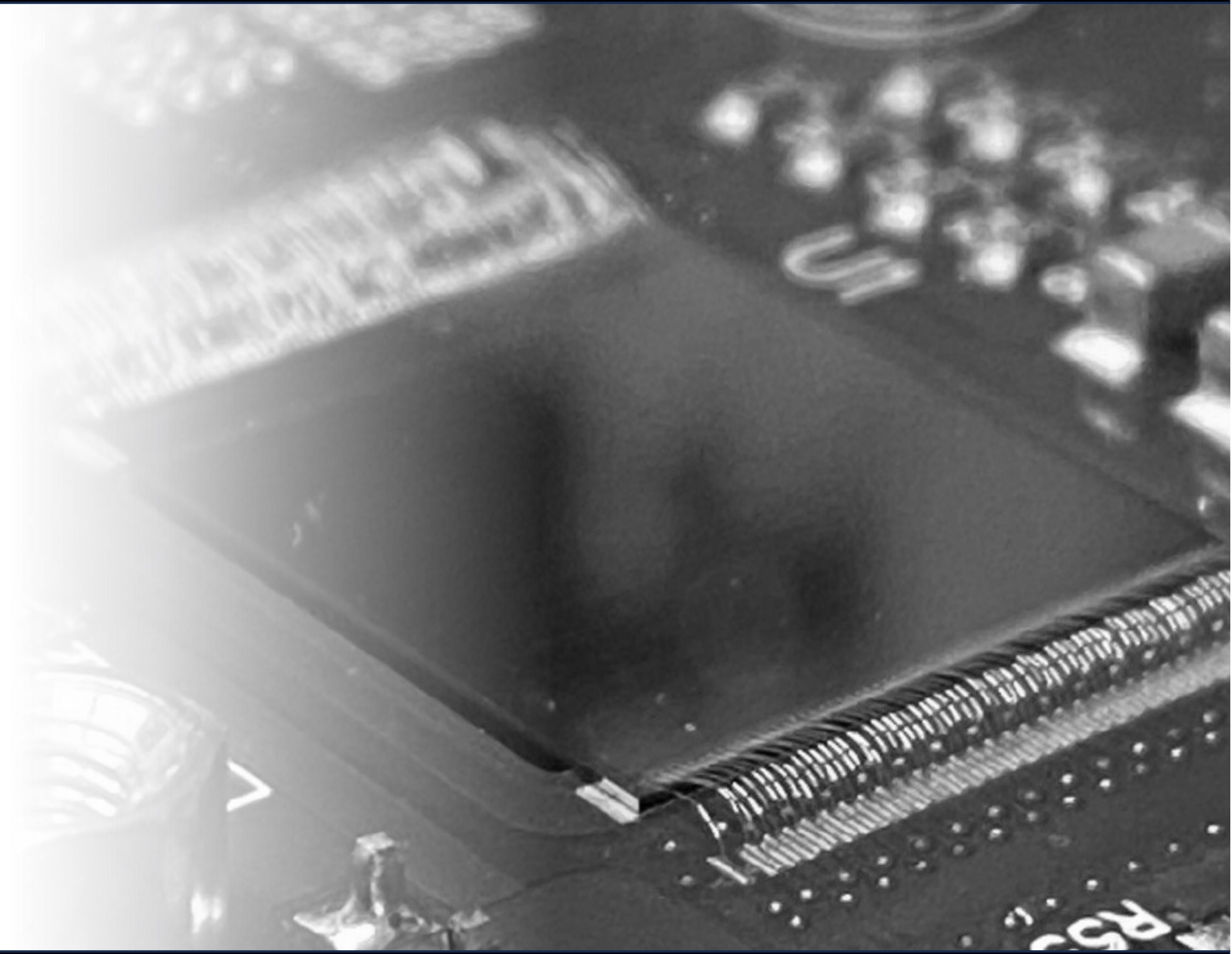
We acknowledge:

- the European Union's Horizon 2020 Research and Innovation programme within the AIDAinnova GA 101004761
- the Italian National Institute for Nuclear Physics (INFN) within the call ARCADIA

Thank you for the attention!



backup



First ARCADIA engineering runs

Pixel characterization

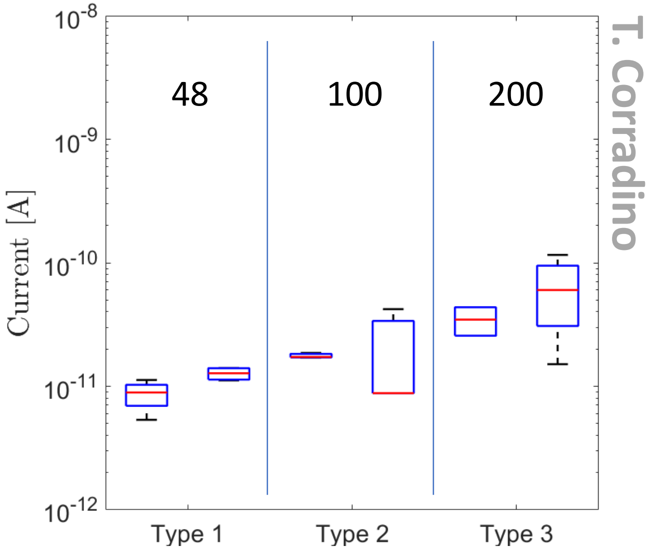
static characteristics

Active thickness (µm)	48	100	200
bias voltage (V)	25	20-35	60-100
dark current density (pA/cm^2)	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

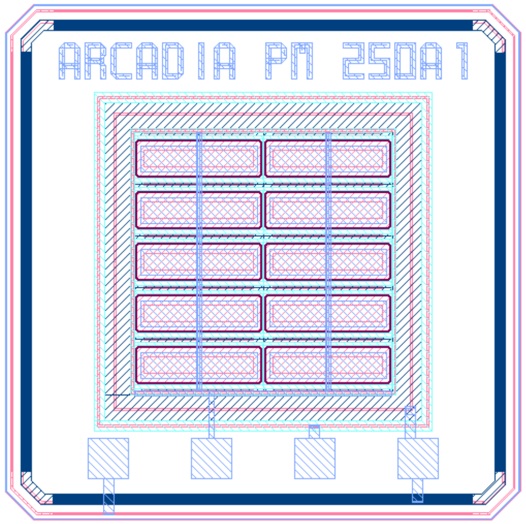
dark currents in **1.5 mm × 1.5 mm pixel** arrays with different active **thicknesses**



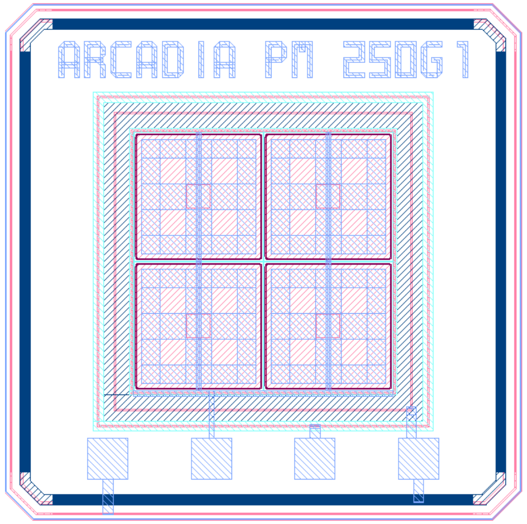
The ARCADIA run-3

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

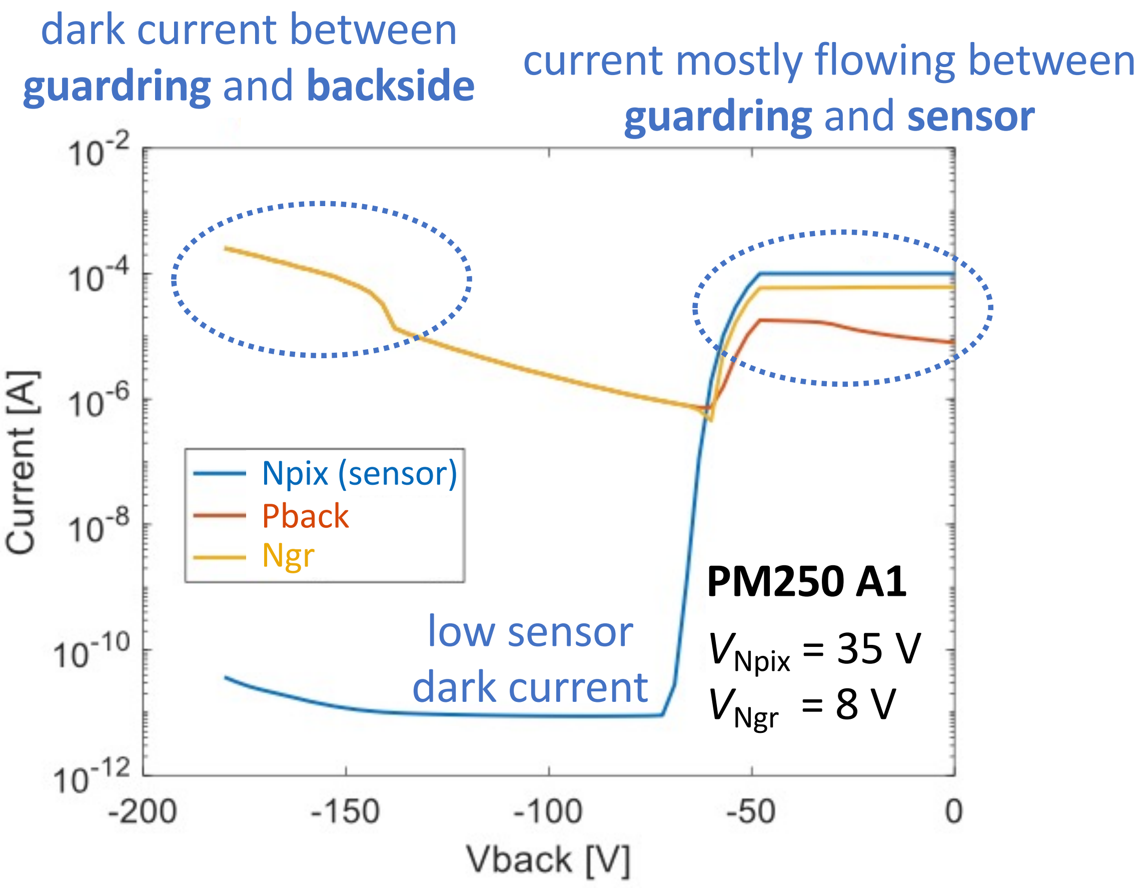
Designed for test at the probe station and with external amplifiers



Rectangular passive pads:
70 µm × 250 µm



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

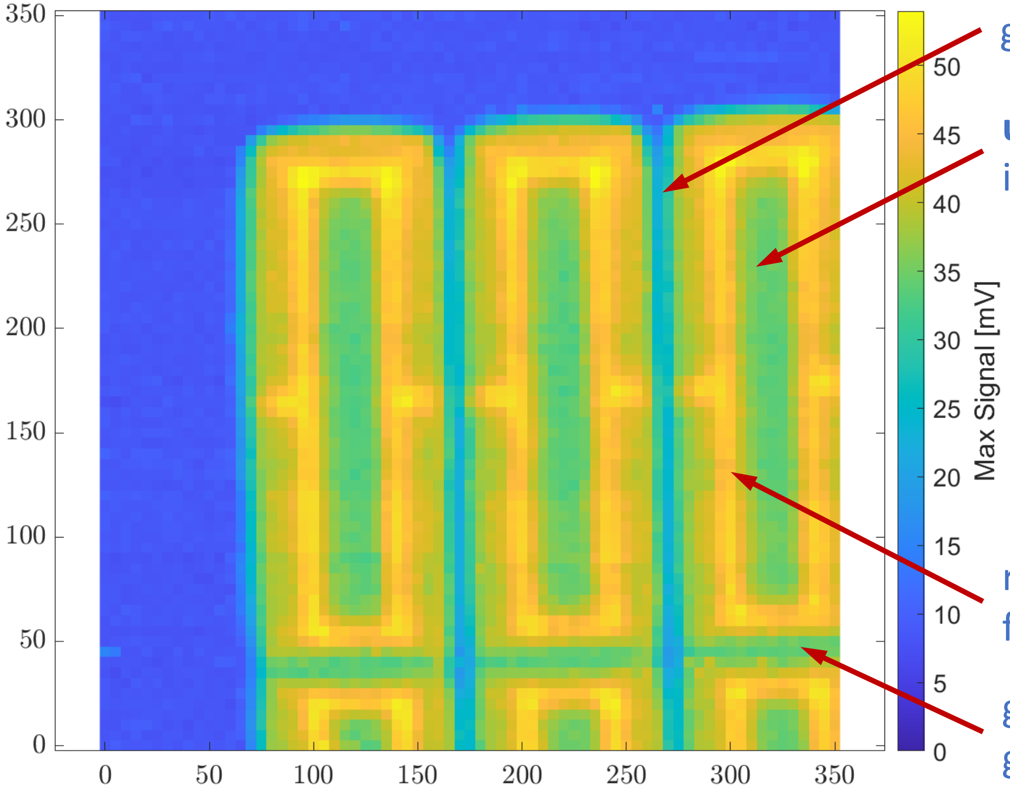


The ARCADIA run-3

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

Focused IR laser spot (~10 µm)
Frontside illumination

Maximum signal amplitude map



gap w/ guard-ring

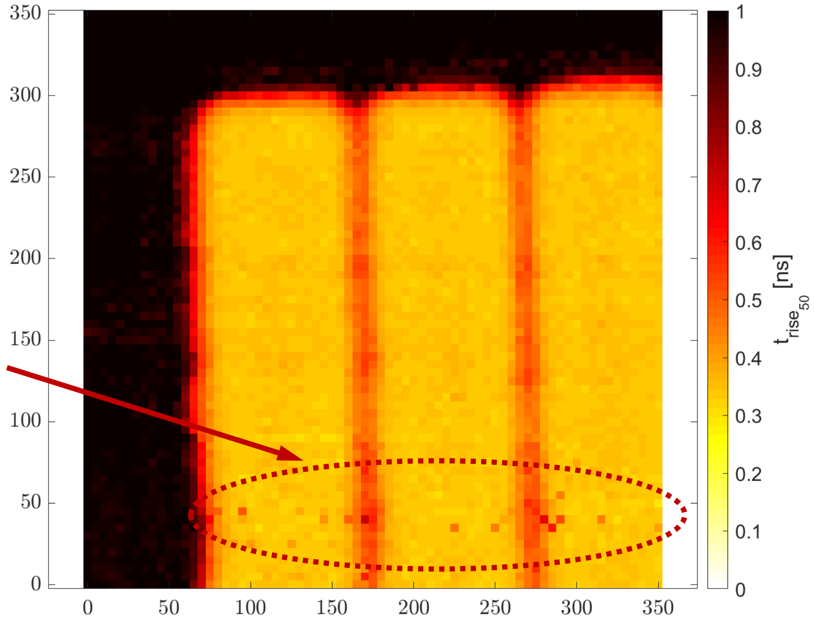
uniform response inside the pad

reflection in the frontside metal

gap w/o guard-ring

T. Corradino

Signal risetime map



no discontinuities at gaps w/o guard-ring

- 70×250 µm^2 **PM250 A1** array
- $V_{pix} = 40$ V, $V_{back} = -35$ V
- Focused laser spot (~10 µm)
- 5 µm motor step

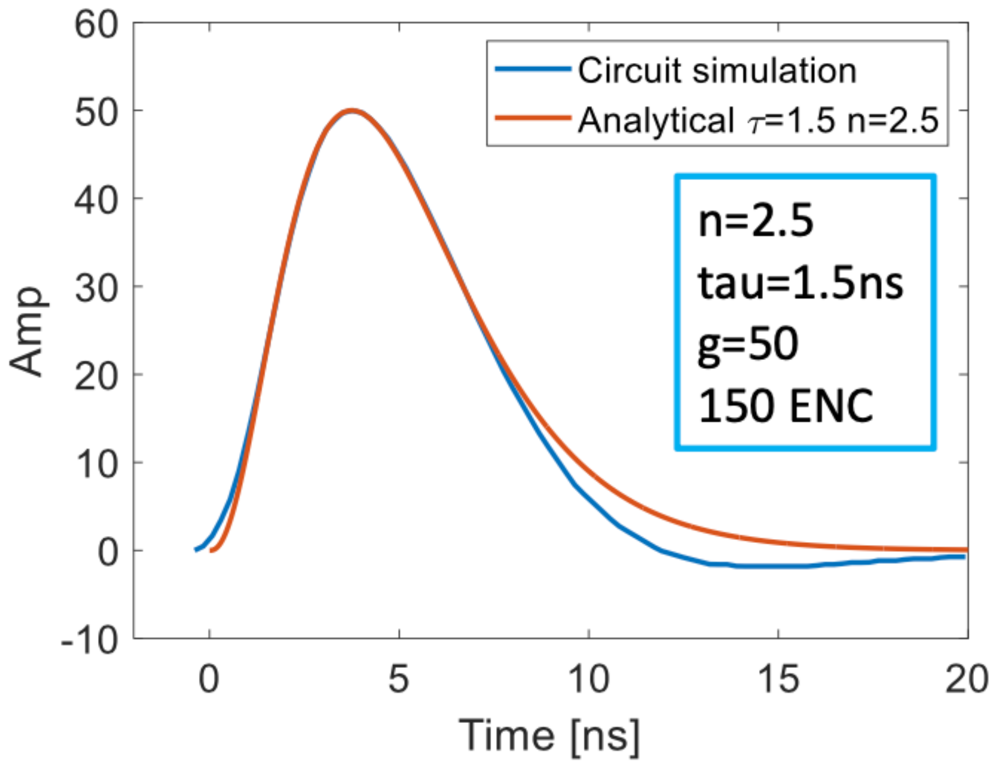
σ_t simulations with MC

Electronics noise impact on the **time resolution**

integrated **pre-amplifier transfer function**

$$f(t) = g \exp(n) \left(\frac{t}{t_p}\right)^n \exp(-t/\tau)$$

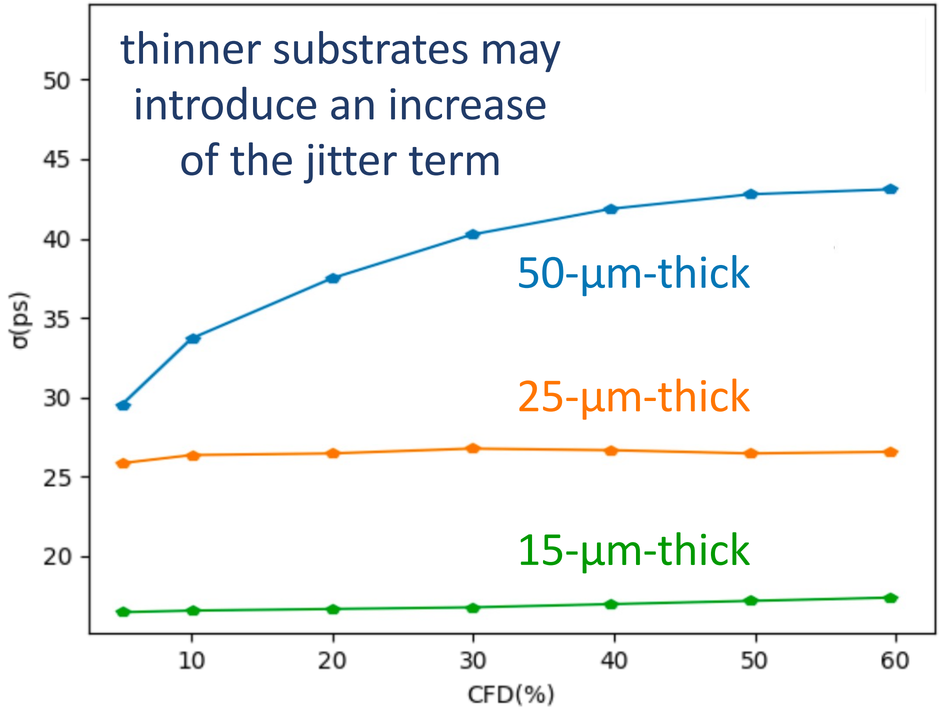
$$t_p = n\tau$$



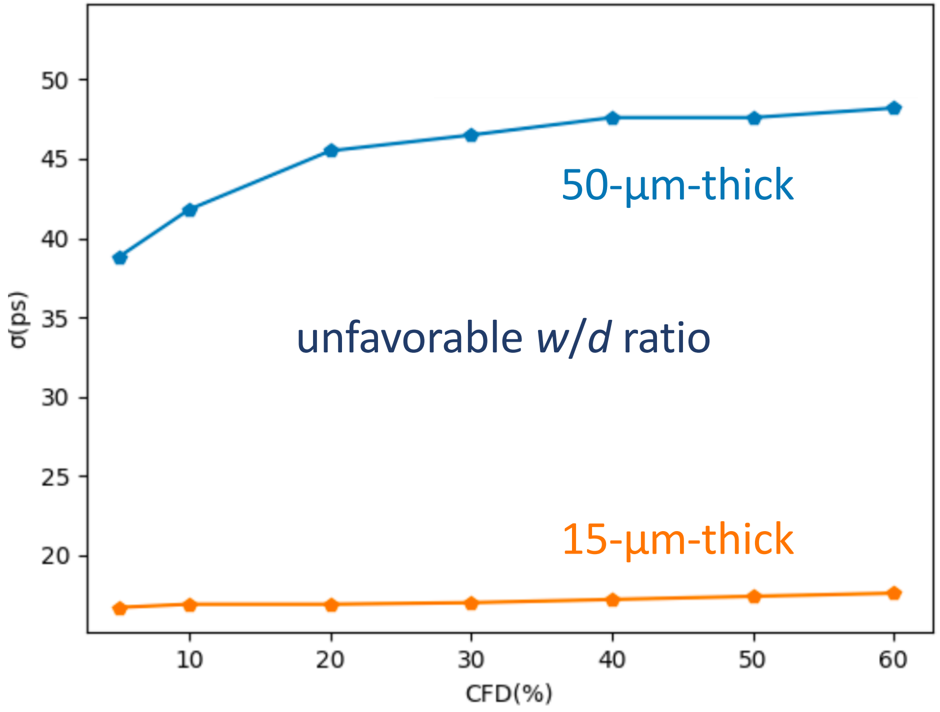
σ_t simulations with MC

Time resolution vs. sensor width

noise: **150 e⁻ RMS**
width: **40 µm**

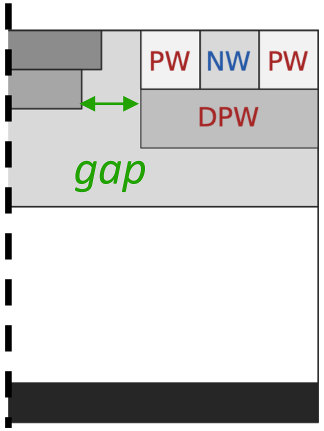


noise: **150 e⁻ RMS**
width: **70 µm**



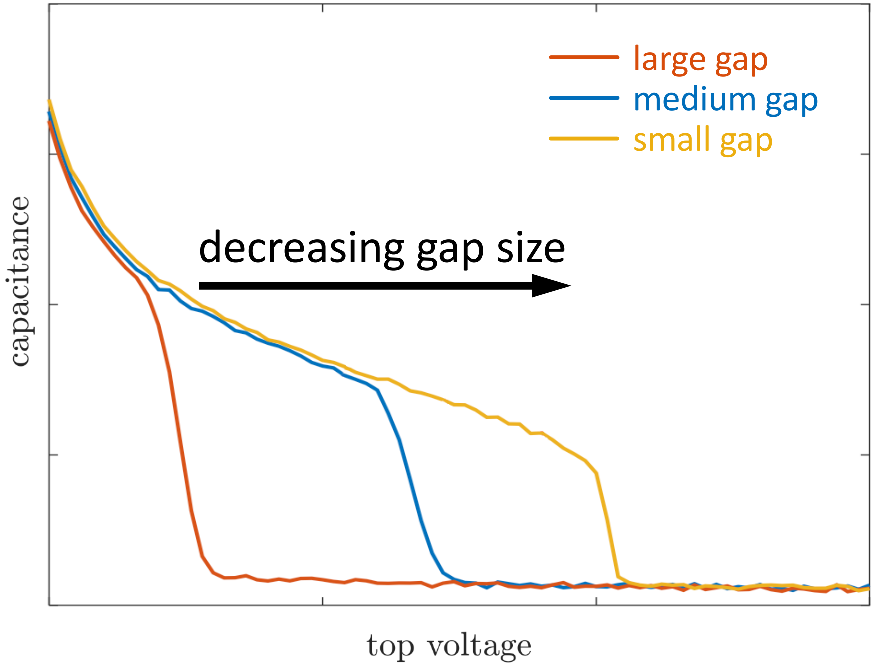
Capacitance vs. bias curves

Layout A2



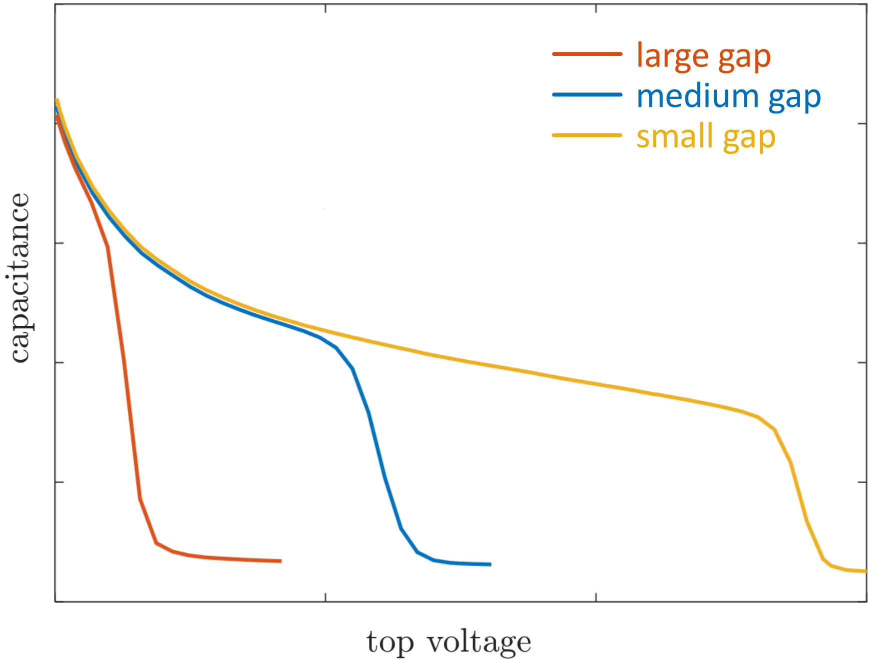
Measurements

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



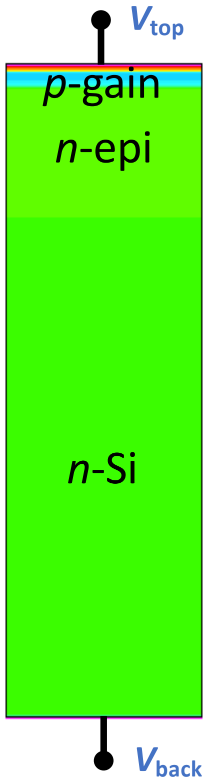
TCAD Simulations

Qualitative agreement. We need to **fine tune** the **lateral spreading** of doping profiles to match the experimental *C*(*V*) characteristics

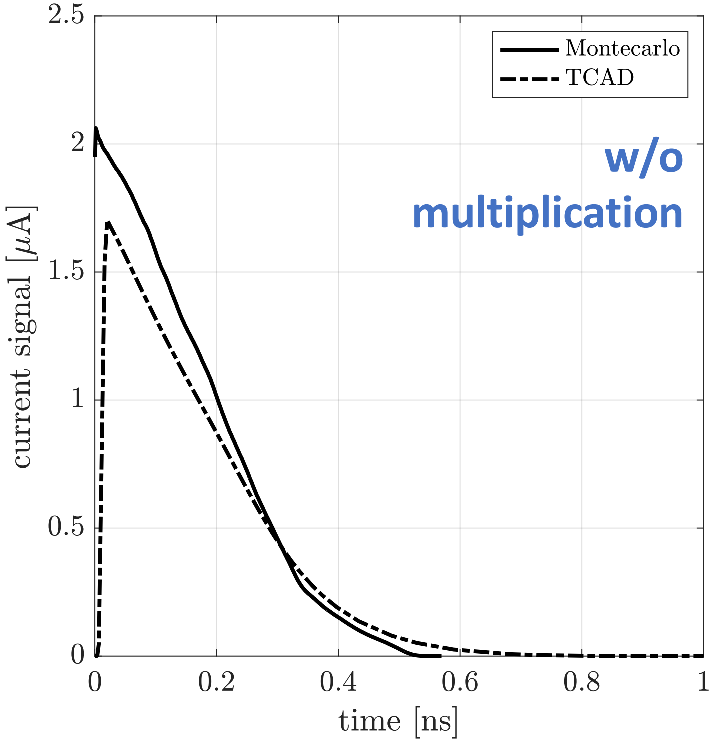


Optimization of simulation tools

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



PRE-optimization

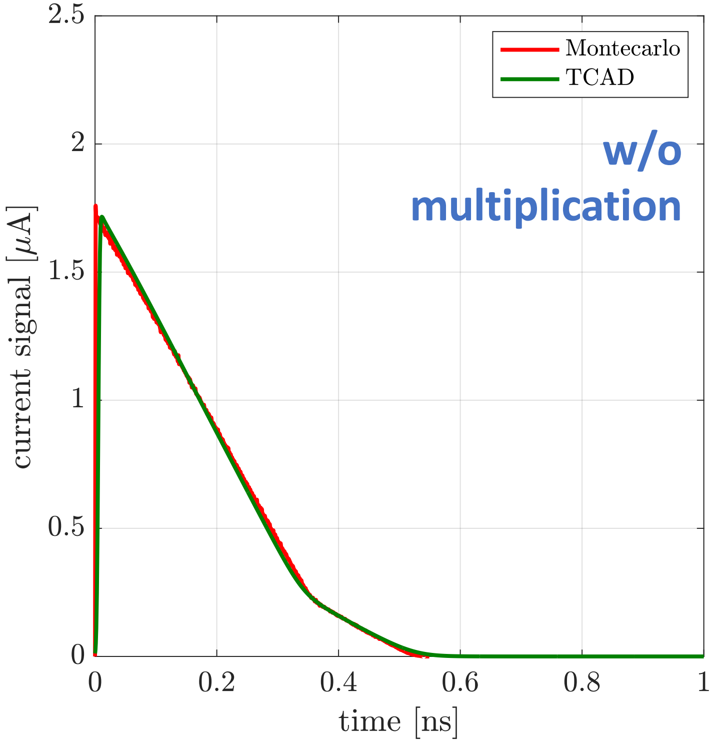


Elements involved in the tuning:

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

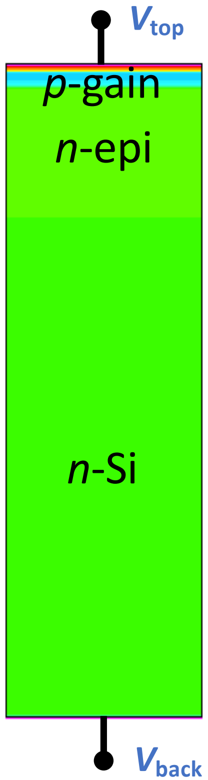
- **extended-Canali** mobility model
- transient **MaxStep** (~ 1 ps)
- **track width**
- number of **pairs/µm** (~ 70)

POST-optimization

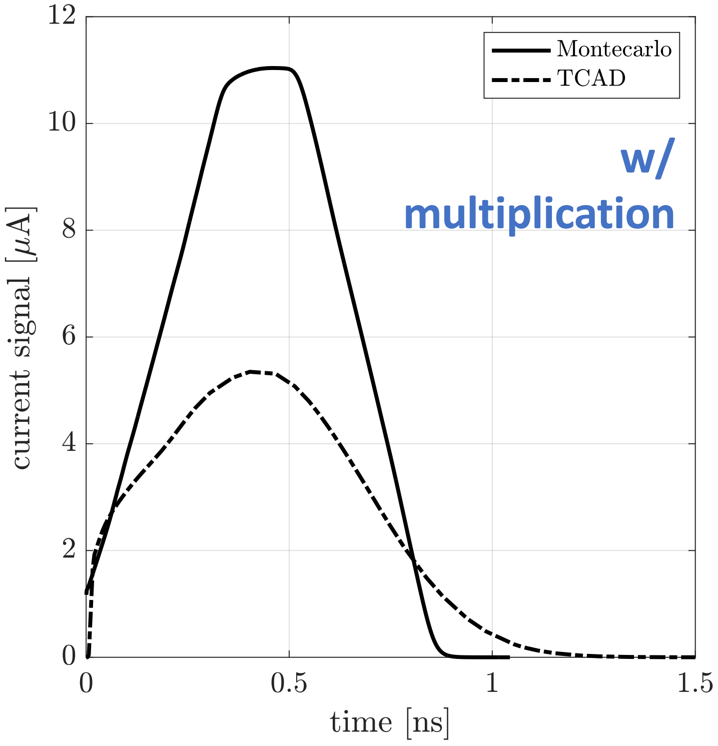


Optimization of simulation tools

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



PRE-optimization

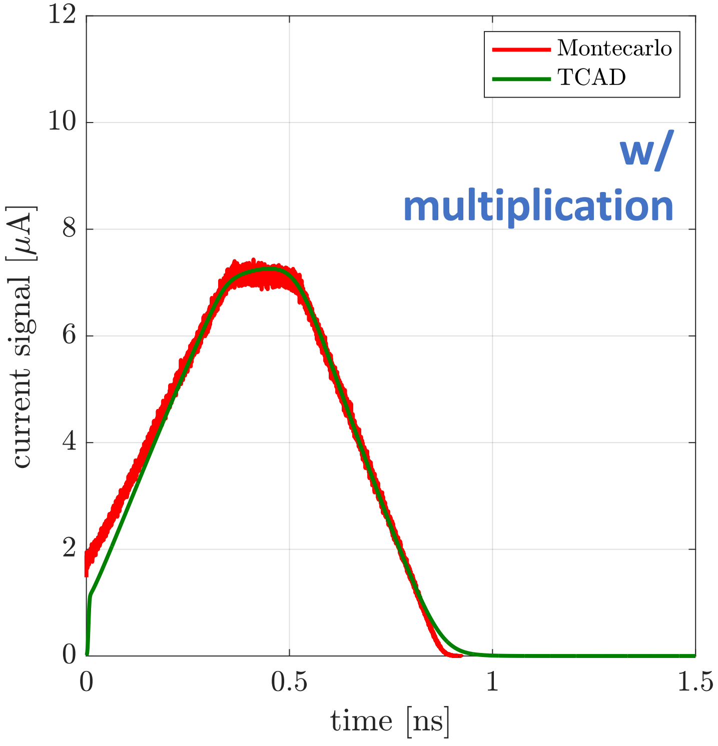


Elements involved in the tuning:

- **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



Space-charge effect

Electric field **screening effect**: (high-energy) **particle injection** from **backside**

Difference between *static* and ***run-time*** updated **field profiles** (in TCAD) during the **transient**