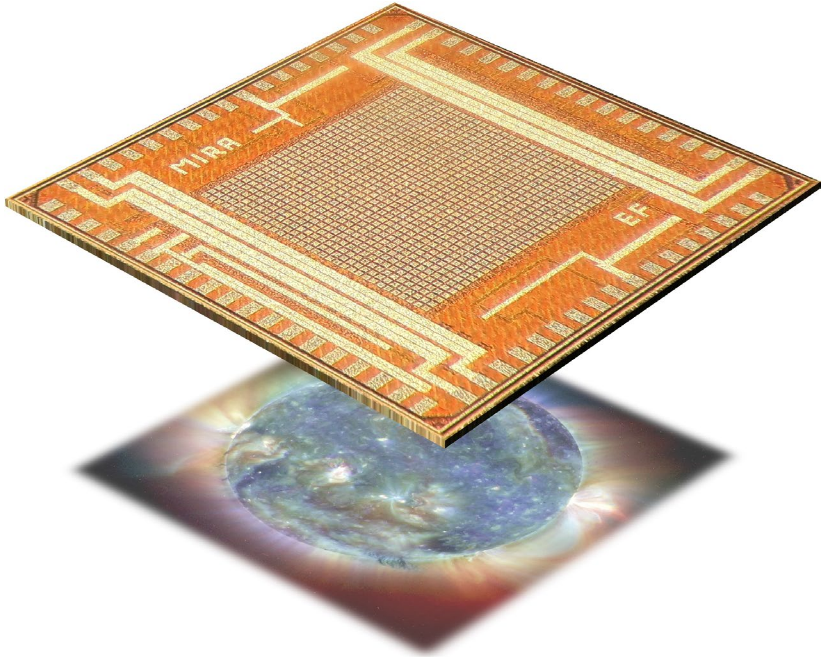

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MIRA: a Low-Noise ASIC with 35 µm Pixel Pitch for the Readout of Microchannel Plates

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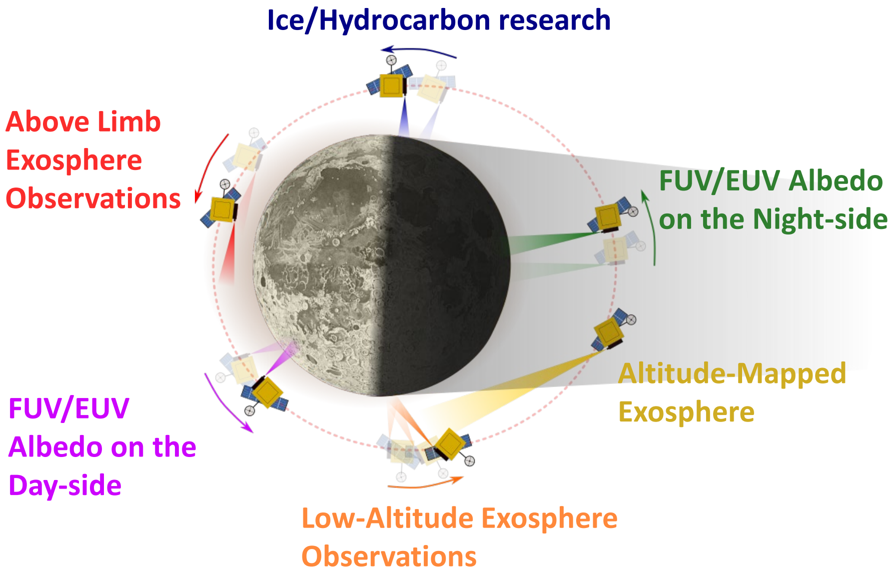
OUTLINE

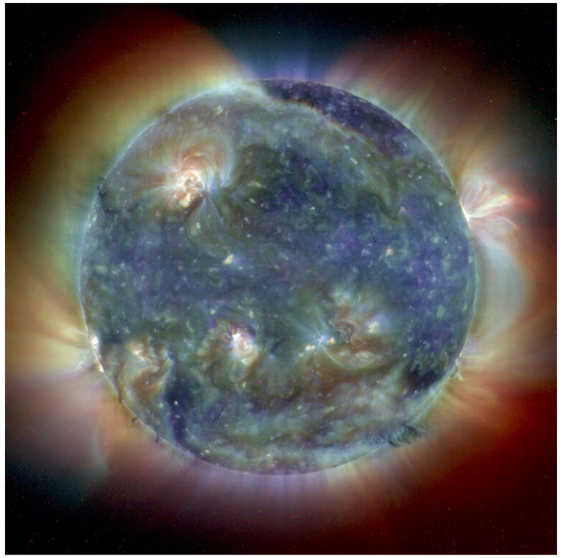
- Ultraviolet Astronomy and Microchannel Plates (MCP) Detectors
- The MIRA readout ASIC for MCPs
- Charge Sensitive Preamplifier
- Pixels summing stage and discriminator
- Charge sharing arbitration
- Experimental results (MIRA I and MIRA II)
- First operation with MCP
- Conclusions and future work

Ultraviolet Astronomy

FUV/EUV Imaging Spectrometry:

- To probe the **exospheres** (direct detection) and the **highest-altitude atmospheres** (through stellar occultation) of planets and satellites, including the **Moon**
- To determine **constituents**, study the atmosphere dynamics, and understand the **formation mechanisms** and the **surface release** processes
- To investigate auroras occurring on **giant planets**



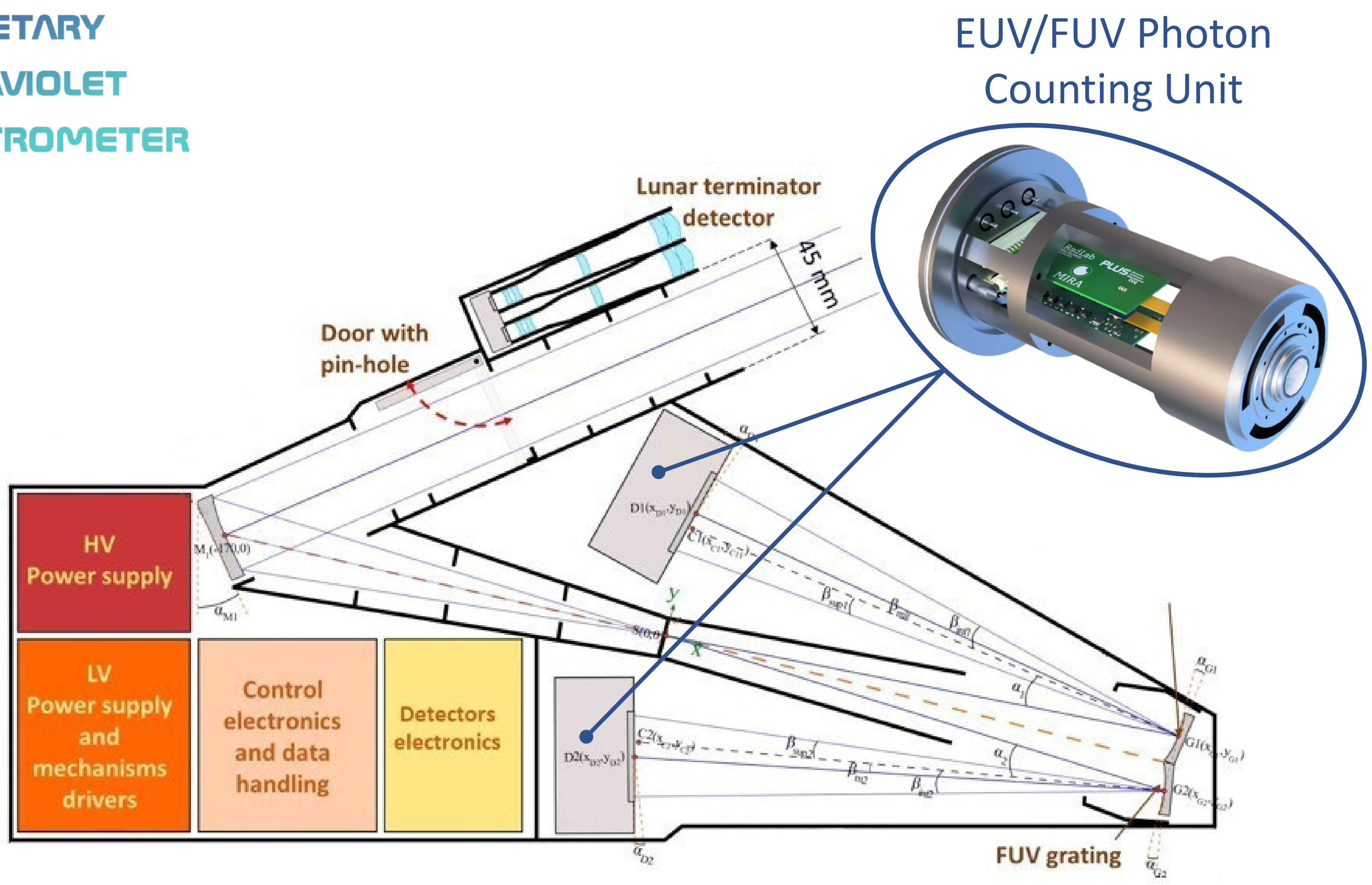


ESA. “Ultraviolet image shows the sun’s intricate atmosphere”

The PLanetary Ultraviolet Spectrometer (PLUS) Project

PLANETARY
ULTRAVIOLET
SPECTROMETER

- Started in **2020**
- PoliMI, CNR, INAF
- Multichannel **FUV/EUV** imaging **spectrometer** for astronomical application
- Improved **detection limit**, **shorter observations** integration time, and in **dynamic range**
- EUV/FUV **MCP-based** photon counting unit for **events counting**



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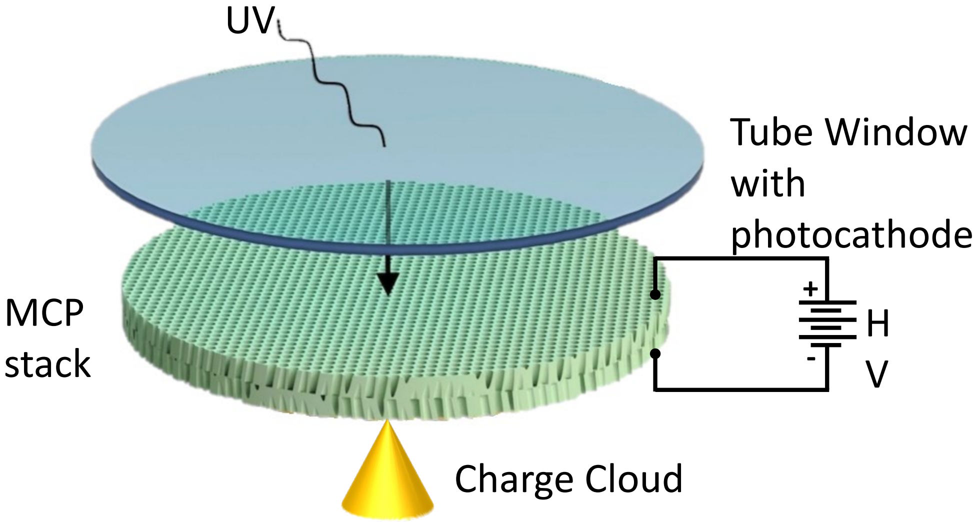
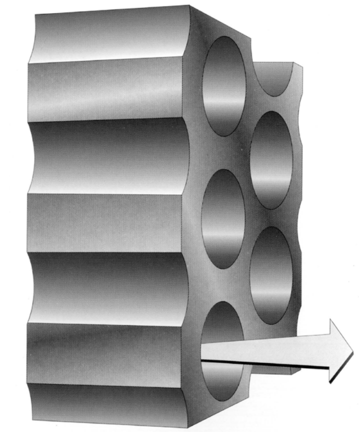
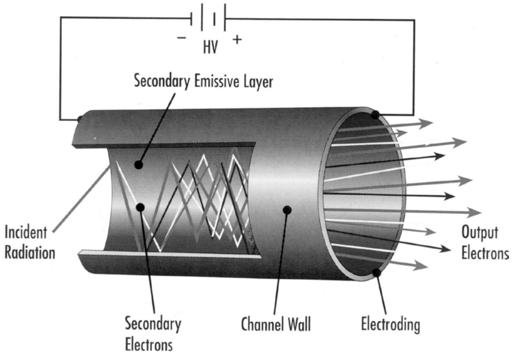
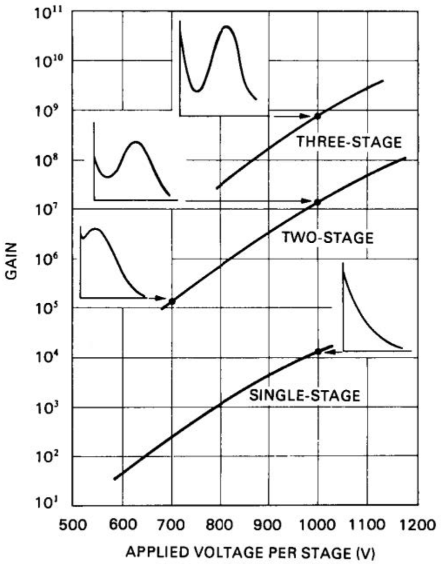
Microchannel Plates Detectors (MCPs)

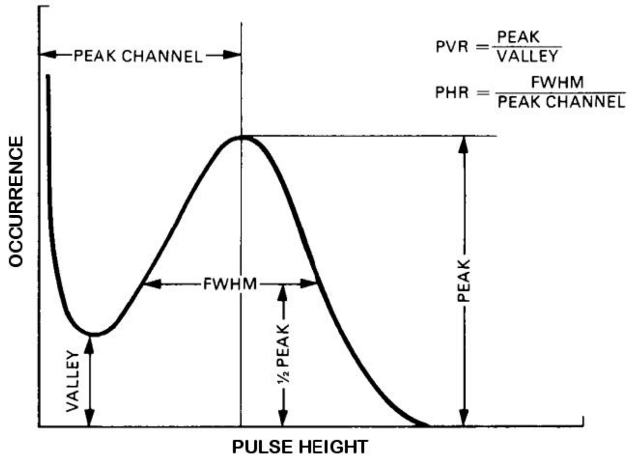
- **High time** resolution (down to 10 ps)
- **High spatial** resolution (down to 10 µm)
- Large **format arrays** (> 1K x 1K pixels)
- Large **sensitive area** size (up to 20 cm)
- Low **dark current** (< 0.5 pA/cm^2 at HV = 1 kV)
- High out-of-band rejection **(solar blindness)**
- **Radiation** hardness and operation at **room temperature**







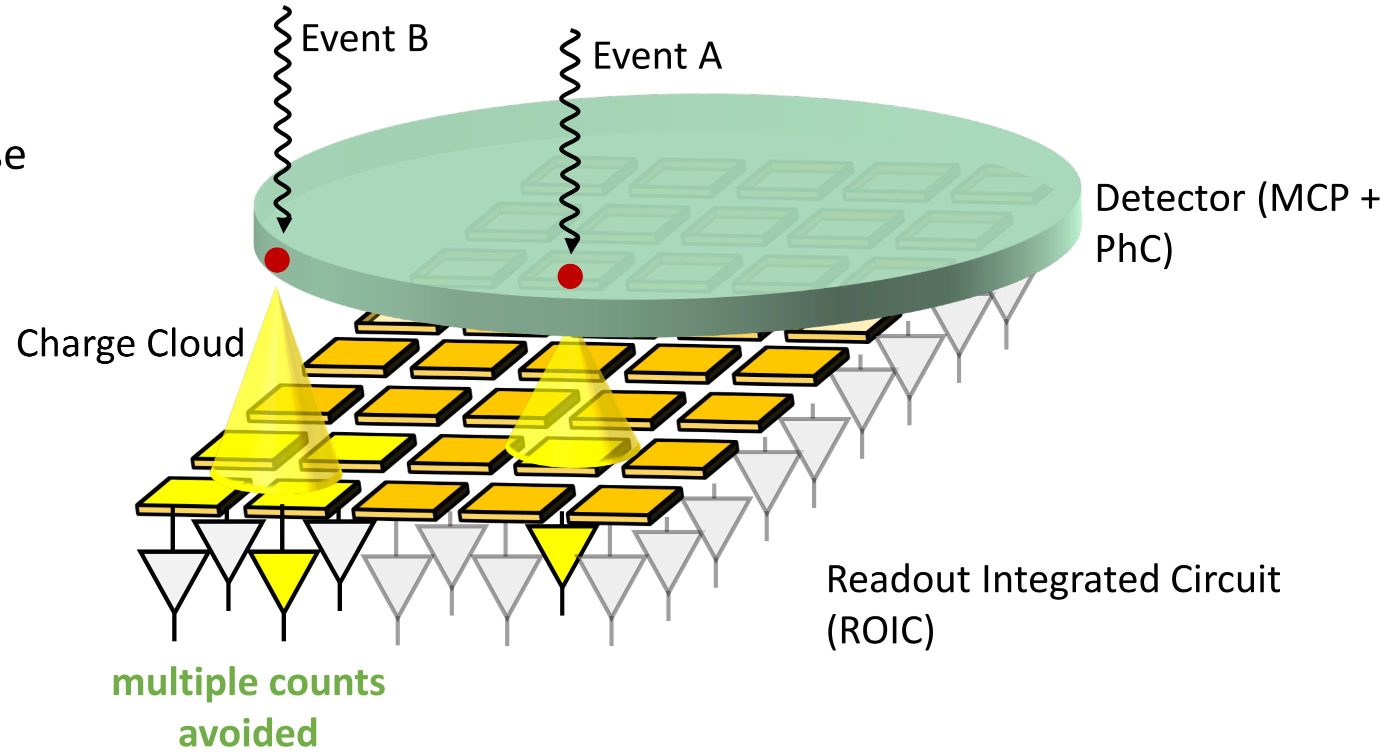




MCP Detector Readout Electronics

Readout Integrated Circuit (ROIC):

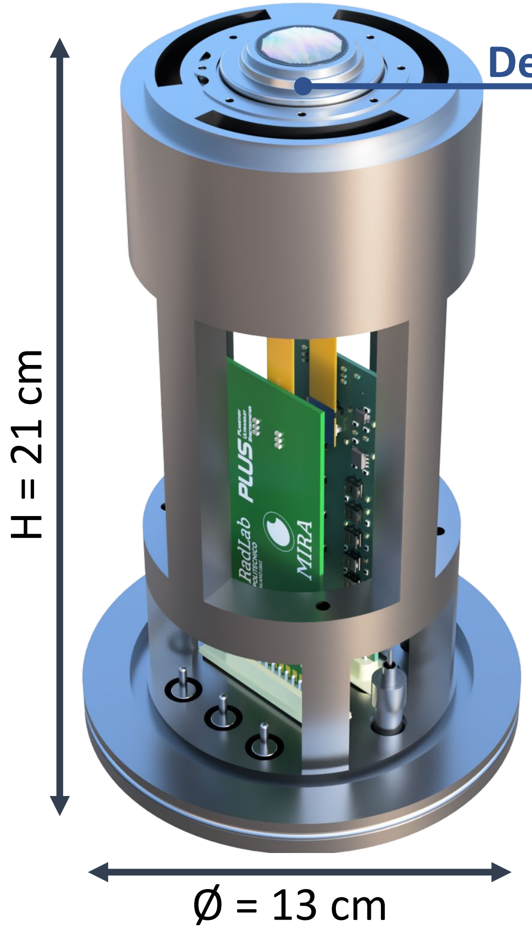
- **Integrated 2D anode** array
- **Analog** and **Digital** circuits to perform pulse processing and events identification
- **Low noise** operation
- **High count rate** capability
- **Zero** dead time
- **Small pixel** size
- **Integrated charge sharing** correction

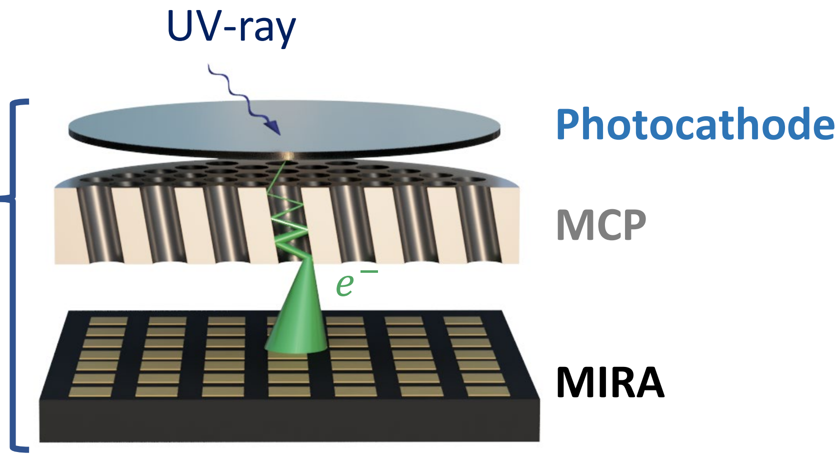


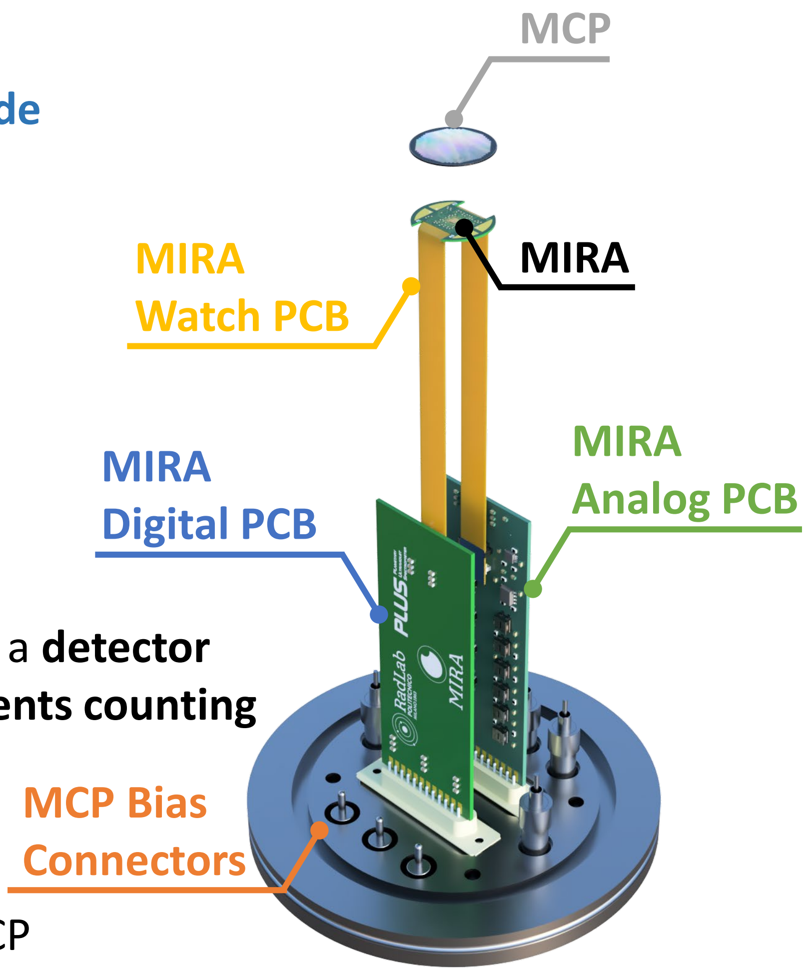
Refs:
J Vallerga *et al* 2014 *JINST* 9 C05055
A.Harwit, wt al., Proc. SPIE, 91541N, 2014

Goal of the project: develop a custom-designed **ROIC** for the readout of **microchannel plates**

The PLUS Photon Counting Unit







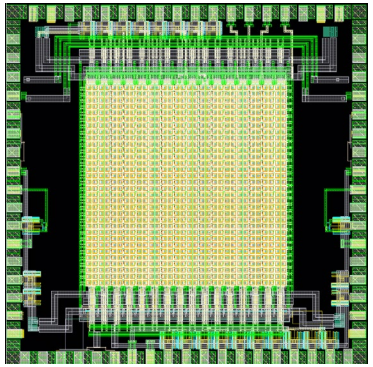
Detector Slot:

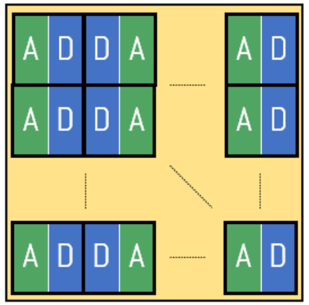
- **23 mm** diameter
- Photocathode and Microchannel Plate (MCP) as a **detector**
- MIcrochannel plate Readout ASIC (MIRA) for **events counting**
- **550 µm gap** between MCP and MIRA

Electronic Readout:

- MIRA Watch PCB to **host** MIRA and **align** the MCP
- MIRA **Digital** and **Analog** PCBs to read out, configure, and bias MIRA

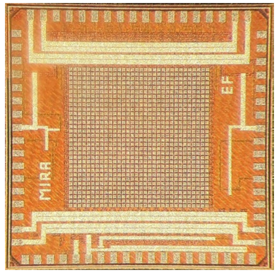
MIRA Development Roadmap (3 years)

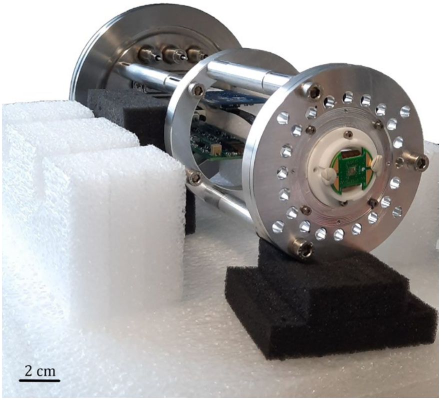




2022

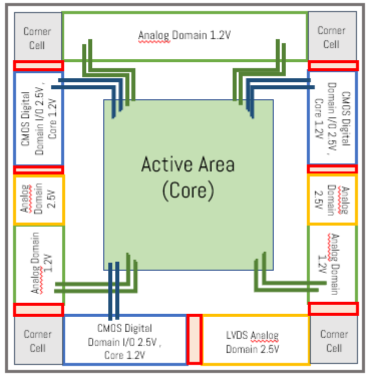
MIRA Acquisition system:
- GUI & RadLab setup & PLUS PCBs design
- MIRA I characterization
- MIRA II tape-out





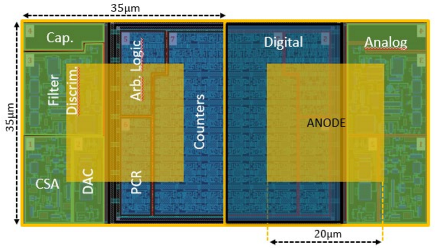
2021

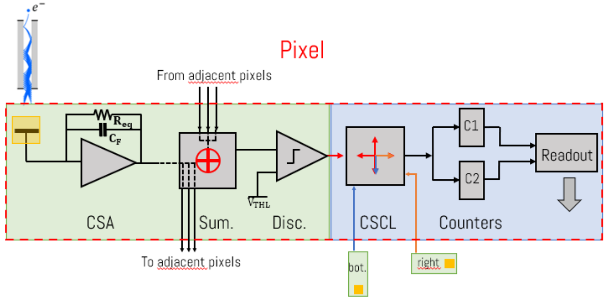
MIRA I:
- Full-chip design
- MIRA I tape-out



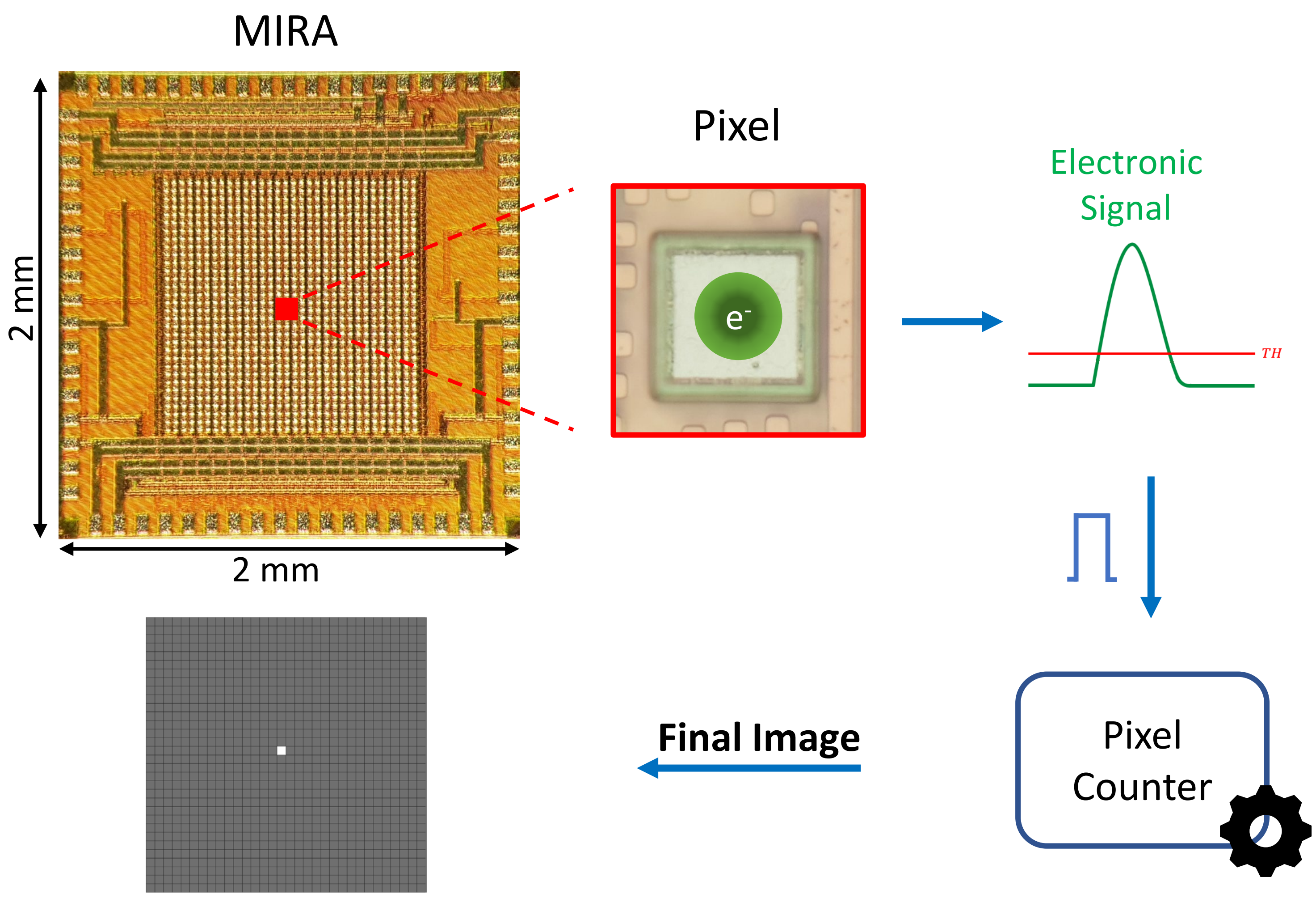
2020

MIRA I design started:
- Requirements
- Pixel schematic & layout design





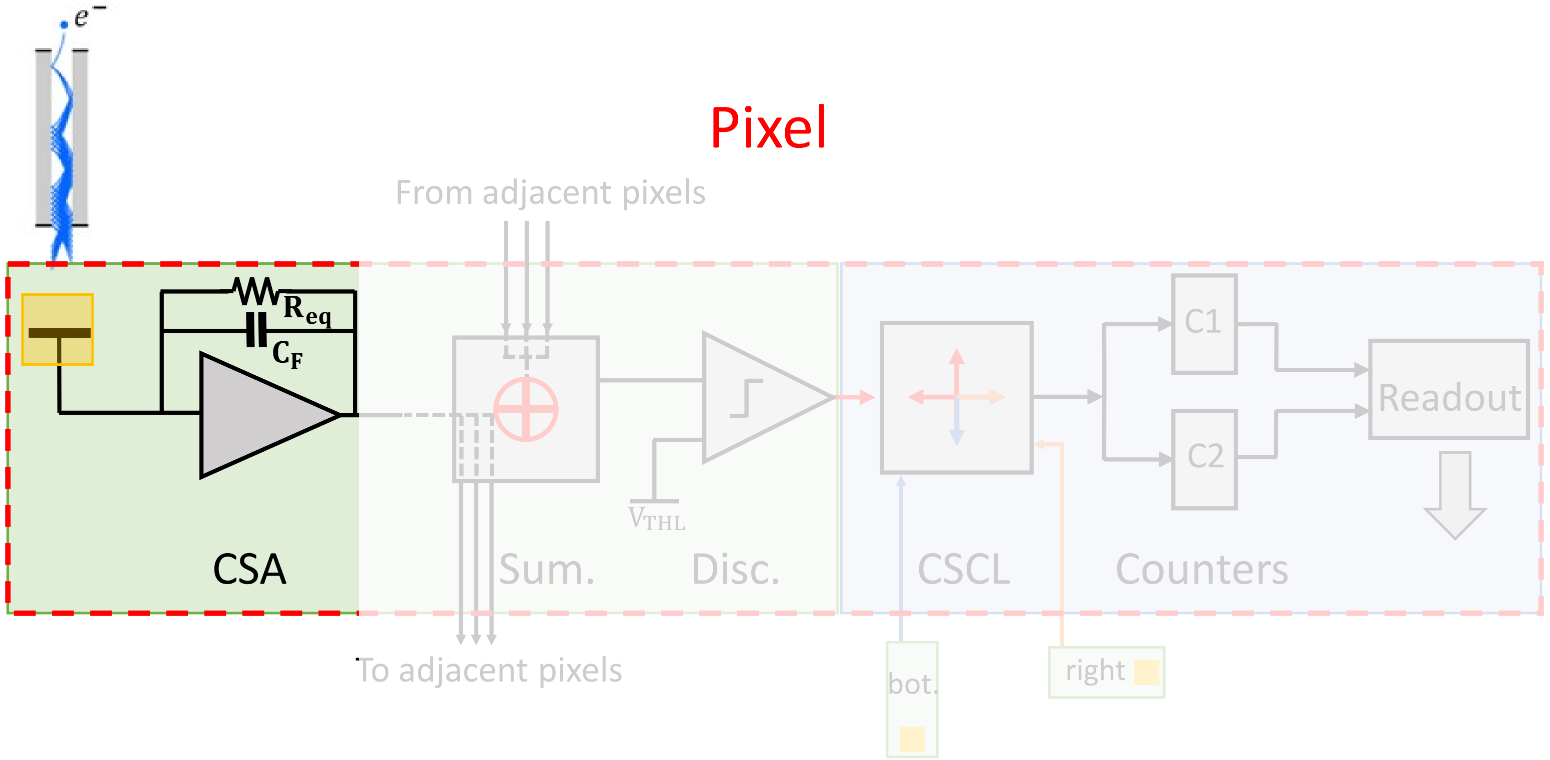
The MIRA ASIC



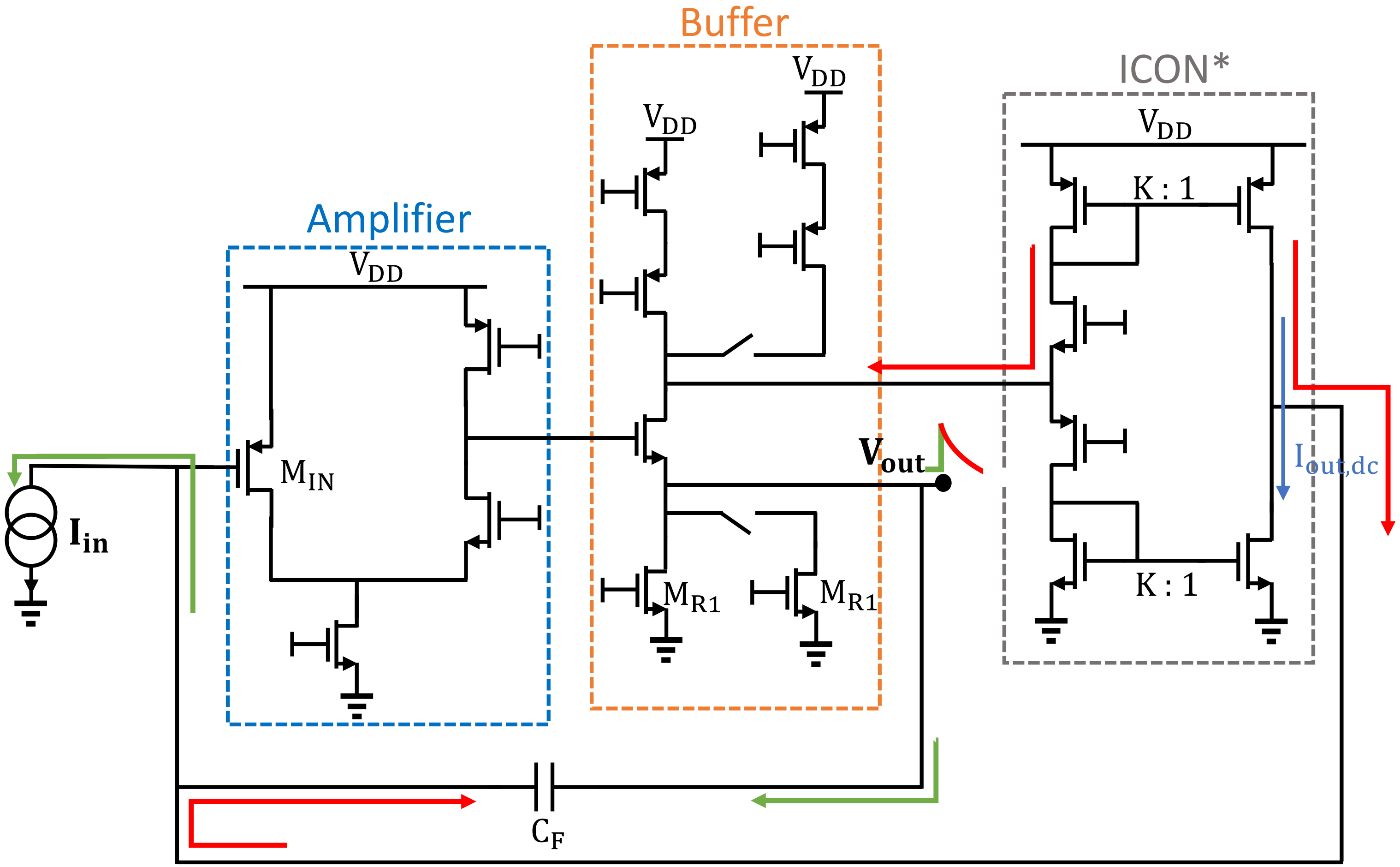
MIRA Purpose and Specs:

- **Collect** the charge cloud with the integrated 2D anode array
- **35µmx35µm** pixel size
- **Low electronics noise (ENC = 20 e^-_{rms})** to operate the MCP at **low gain** and extend its lifetime in space.
- **Charge Sharing** Correction Logic to select a single pixel in charge shared events
- **Counting** capability up to **100kcounts/s/pixel**, zero dead time
- **32x32 pixels** prototype
- TSMC 65nm technology

Pixel Readout Channel

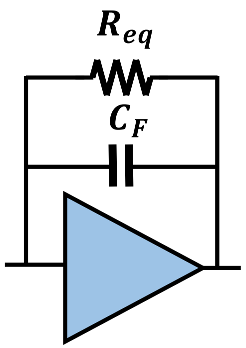


MIRA Charge Sensitive Amplifier (CSA)



MIRA CSA:

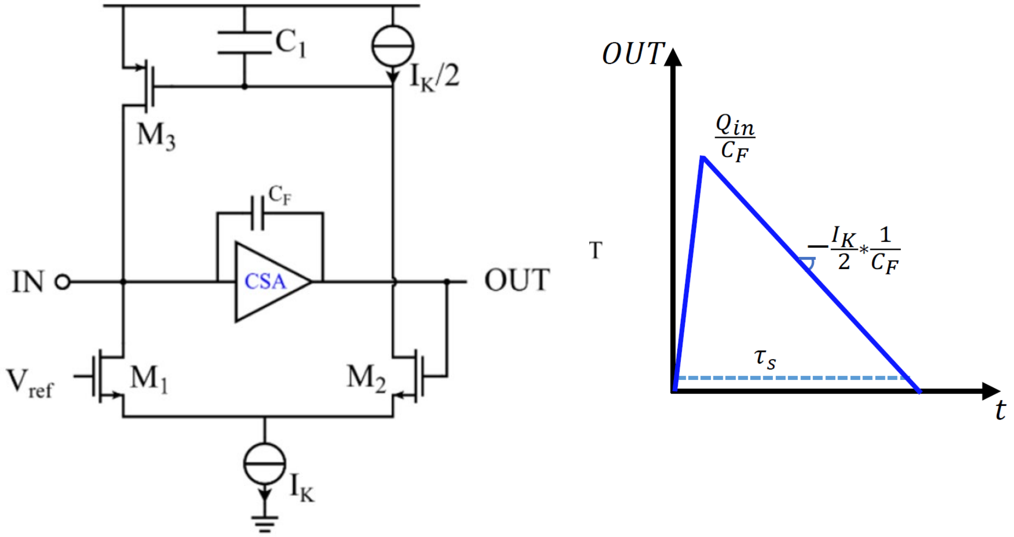
- **Folded Cascode Amplifier**
- **Buffer** → Selectable R_1 for different shaping times: **Fast & Slow Mode**
- **ICON*** → Large feedback resistance $\mathbf{R_{eq} = R_1(1+K)}$ for C_F discharge



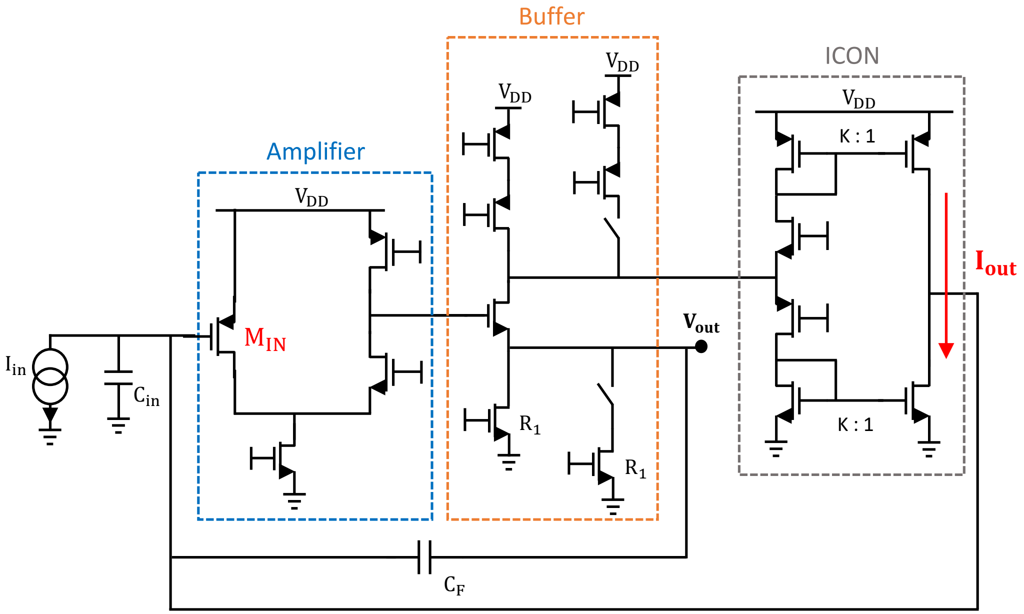
* Refs:
- R. L. Chase, A. Hrisoho, J.-P. Richer: "8-channel CMOS preamplifier and shaper with adjustable peaking time and automatic pole-zero cancellation." Nucl. Instr. and Meth. A, vol. 409, 1998, p. 328–331.
- C. Fiorini and M. Porro, “Integrated RC cell for time-invariant shaping amplifiers”, IEEE Trans. Nucl. Sci., Vol. 51, n°5, pp. 1953 –1960, Oct 2004.

Noise current source vs. pulse duration

Krummenacher*



MIRA CSA

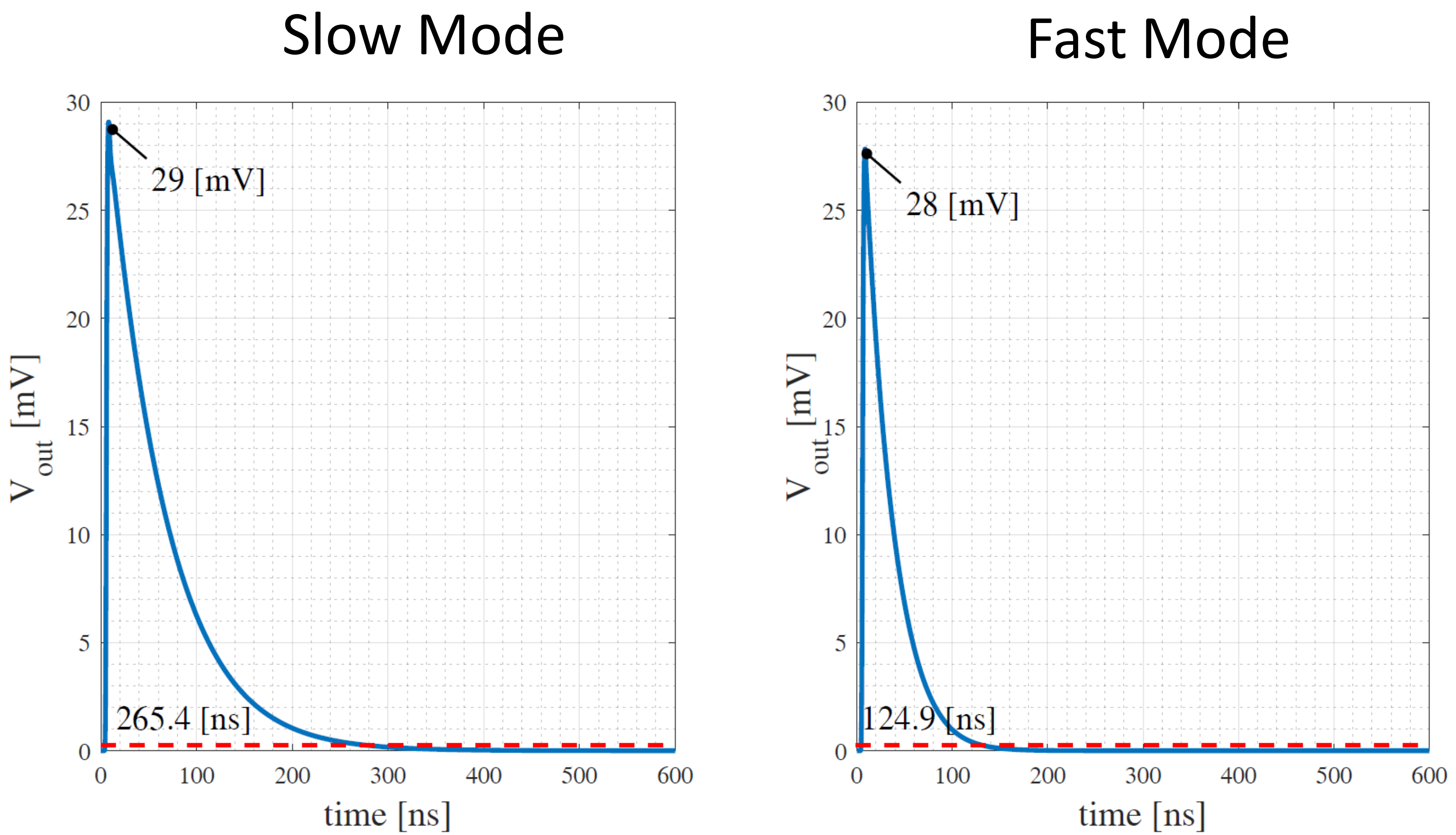


- **Shaping time** $\boldsymbol{\tau_s \propto \frac{1}{I_K}}$
- **Noise current source** $\boldsymbol{\propto I_K}$
- **Dependence** between noise of $\boldsymbol{I_K}$ and shaping time

*Ref: Krummenacher, Francois. "Pixel detectors with local intelligence: an IC designer point of view." Nuclear Instruments and Methods in Physics Research Section A **305.3** (1991): 527-532

- Main **noise current source at the input** $\boldsymbol{\propto I_{out}}$
- **Shaping time** $\boldsymbol{\tau_s \propto KR_1C_f}$
- **No dependence** between noise of $\boldsymbol{I_{out}}$ and shaping time
- Buffer and left-brench ICON noise sources demagnified by a factor K^2 → **negligible**

MIRA CSA Transient Pulse and Noise - Simulations



$\mathbf{Q_{in,MAX}} = 4000\ e^-$

Slow Mode:

- $\mathbf{t_{width}}|_{\mathbf{1\%peak}} = 265$ ns
- $V_{peak} = 29$ mV
- $\mathbf{Q_{in}} = 1000\ e^-$
- $\sigma_{n,vout} = 835\mu V_{rms}$
- $\mathbf{ENC_{CSA}} = 27\ e^-_{rms}$

Fast Mode:

- $\mathbf{t_{width}}|_{\mathbf{1\%peak}} = 125$ns
- $V_{peak} = 28$ mV
- $\mathbf{Q_{in}} = 1000\ e^-$
- $\sigma_{n,vout} = 835\mu V_{rms}$
- $\mathbf{ENC_{CSA}} = 27\ e^-_{rms}$

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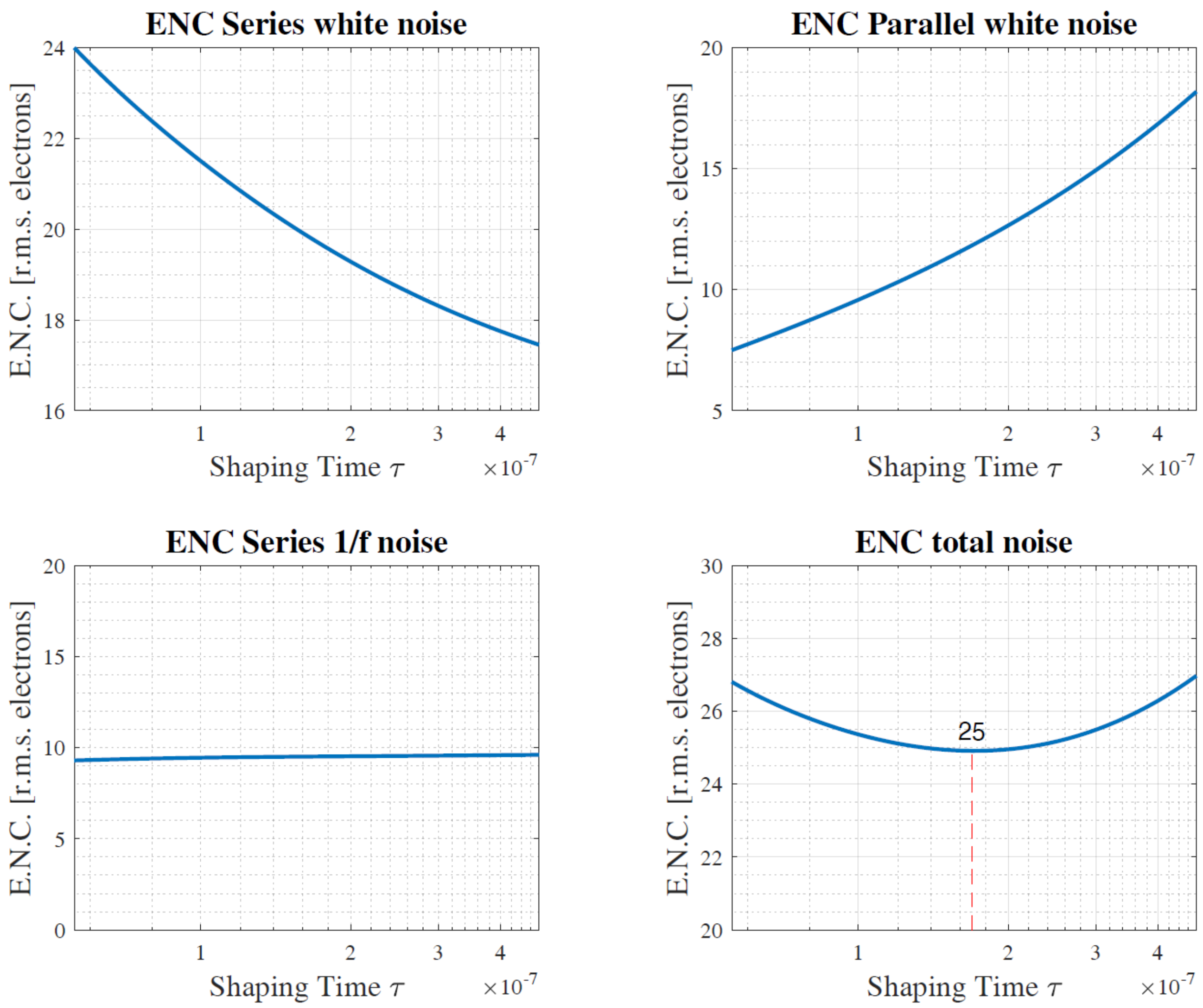
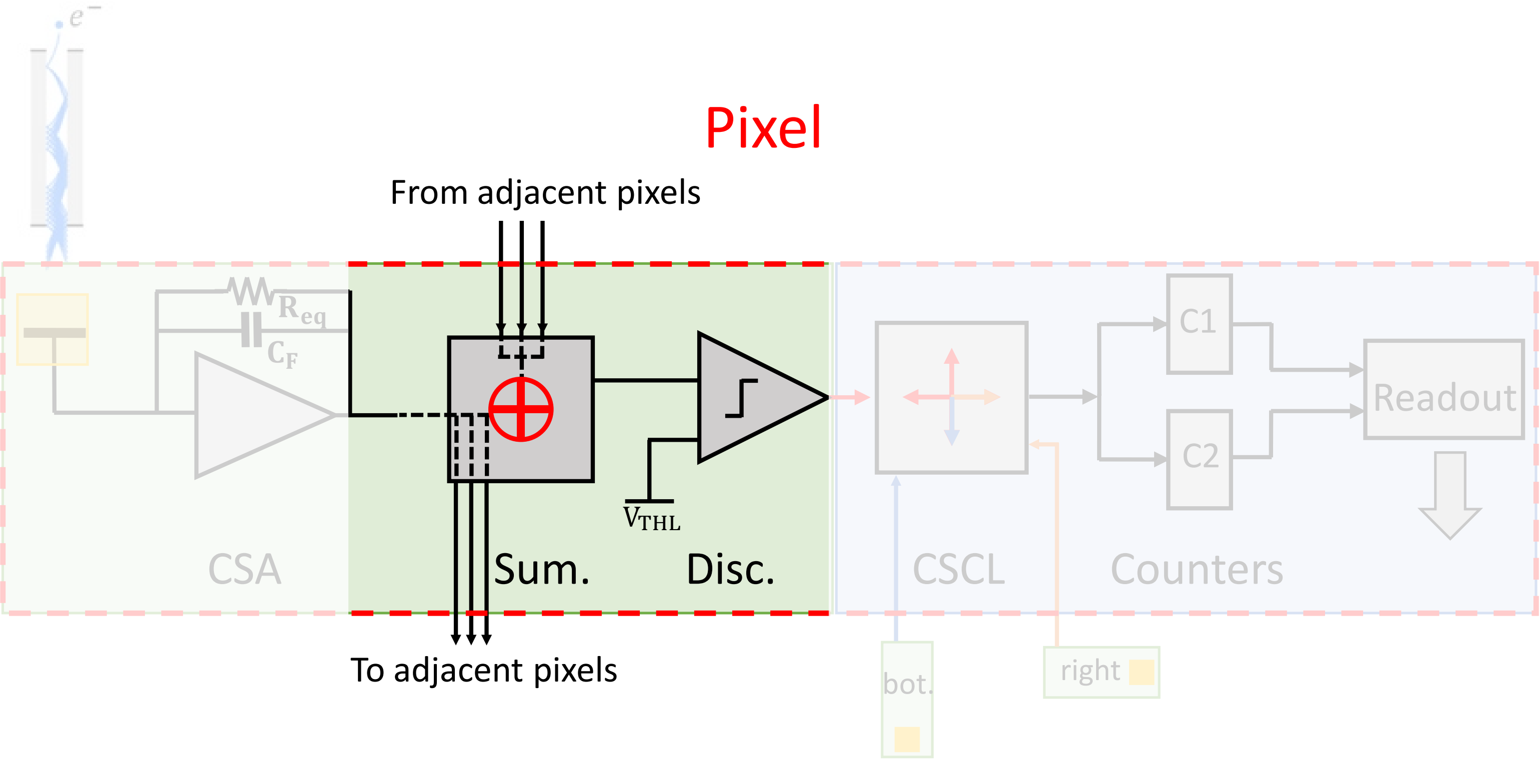
Noise contributions - Simulations



Pixel Readout Channel



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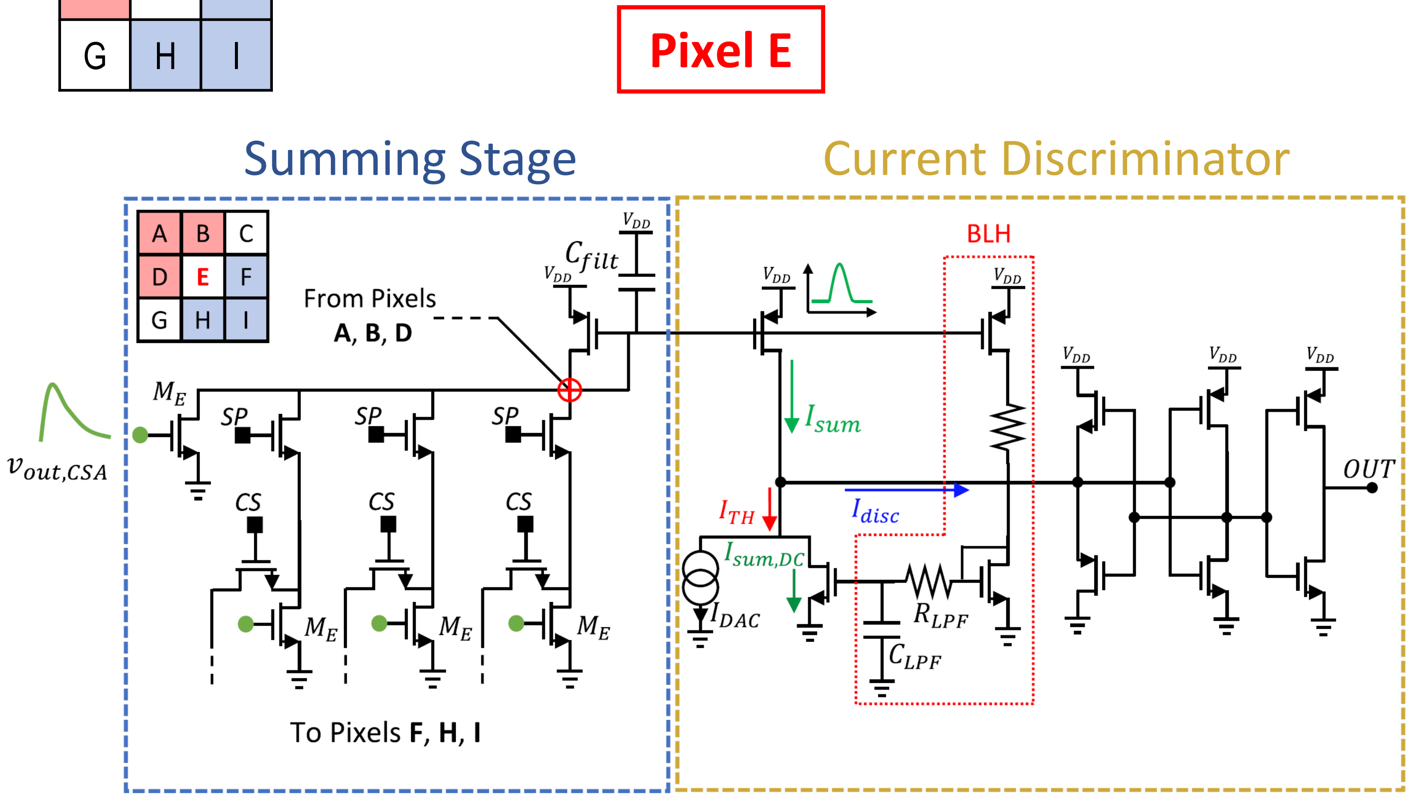
MIRA Summing Stage and Discriminator

A	B	C
D	E	F
G	H	I

*



MIRA Summing Stage:

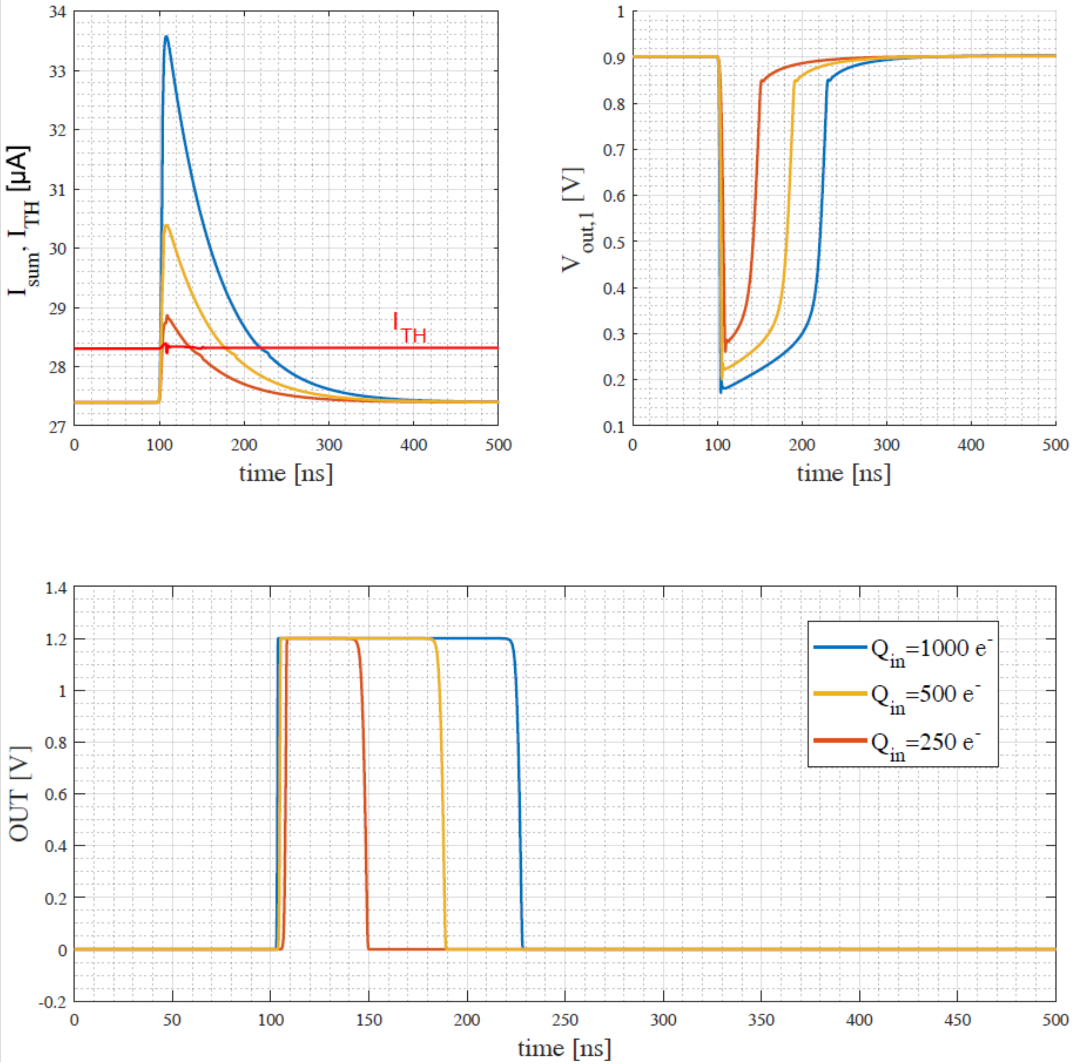
- **Charge Summing Mode (CS)** → Signal sum from adjacent pixels*
- **Single Pixel Mode (SP)** → Gain × 4
- **Low-pass Filtering** on the sum signal → C_{LPF}

MIRA Current Discriminator:

- **Tunable Threshold** → 4-bit DAC + 1 Sign bit
- **DC Feedback (Baseline Holder)**
  → Improves compensation of mismatches

*Ref: R. Ballabriga et al: "The Medipix3 prototype, a pixel readout chip working in single photon counting mode with improved spectrometric performance." IEEE Trans. Nucl. Sci., vol. 54, no. 5, 2007, p. 1824−1829.

MIRA Sum. and Discr. Transient Response - Simulations



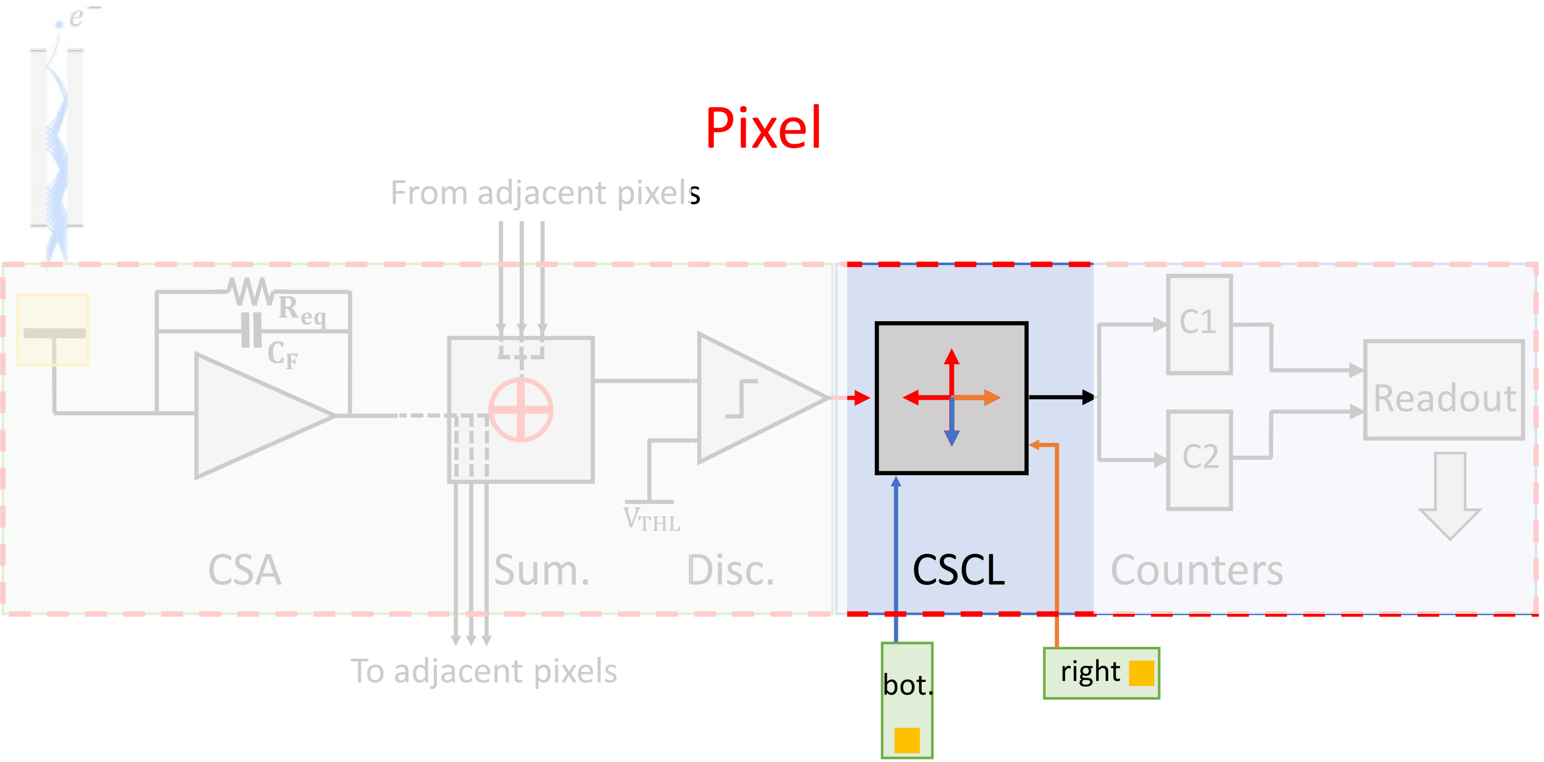
- **ToT strategy: higher** the charge, the **faster** the pulse arrival time and the **longer** its duration

Example:

Q_{in} [e^-]	Rising Edge Arrival Time [ns]	Falling Edge Arrival Time [ns]
1000	3.4	126.25
500	4.1	88.9
250	7.6	47.5

- **Noise after 2nd stage:**
  - **ENC** $= 17\ e^-_{rms}$ in SP and Slow Mode
  - **ENC** $= 18\ e^-_{rms}$ in SP and Fast Mode

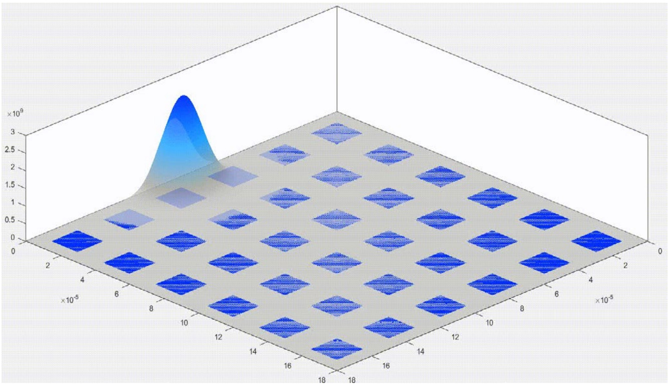
Pixel Readout Channel

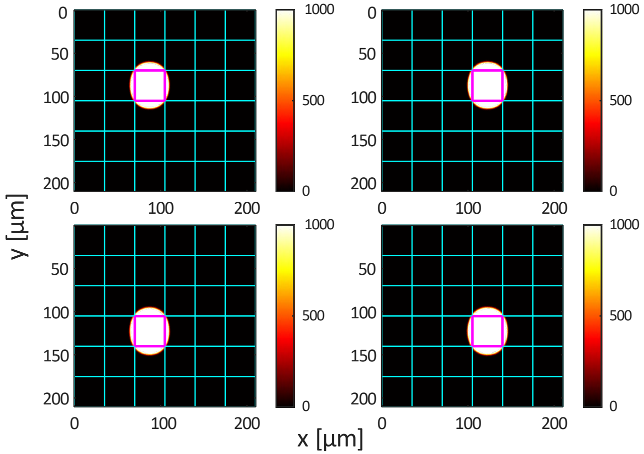


Charge Sharing

Simulation Model:

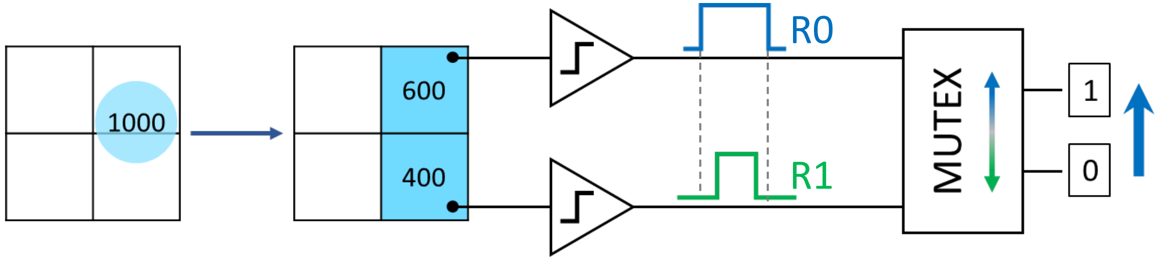
- **Electrons cloud**: $Q_{MCP} = 4000e^{-}$, $\sigma_x = 7\mu m, \sigma_y = 9\mu m$
- Multiple **counts** and a degraded **spatial resolution**
- **Anode size:** $20\mu m$





Charge Sharing Correction:

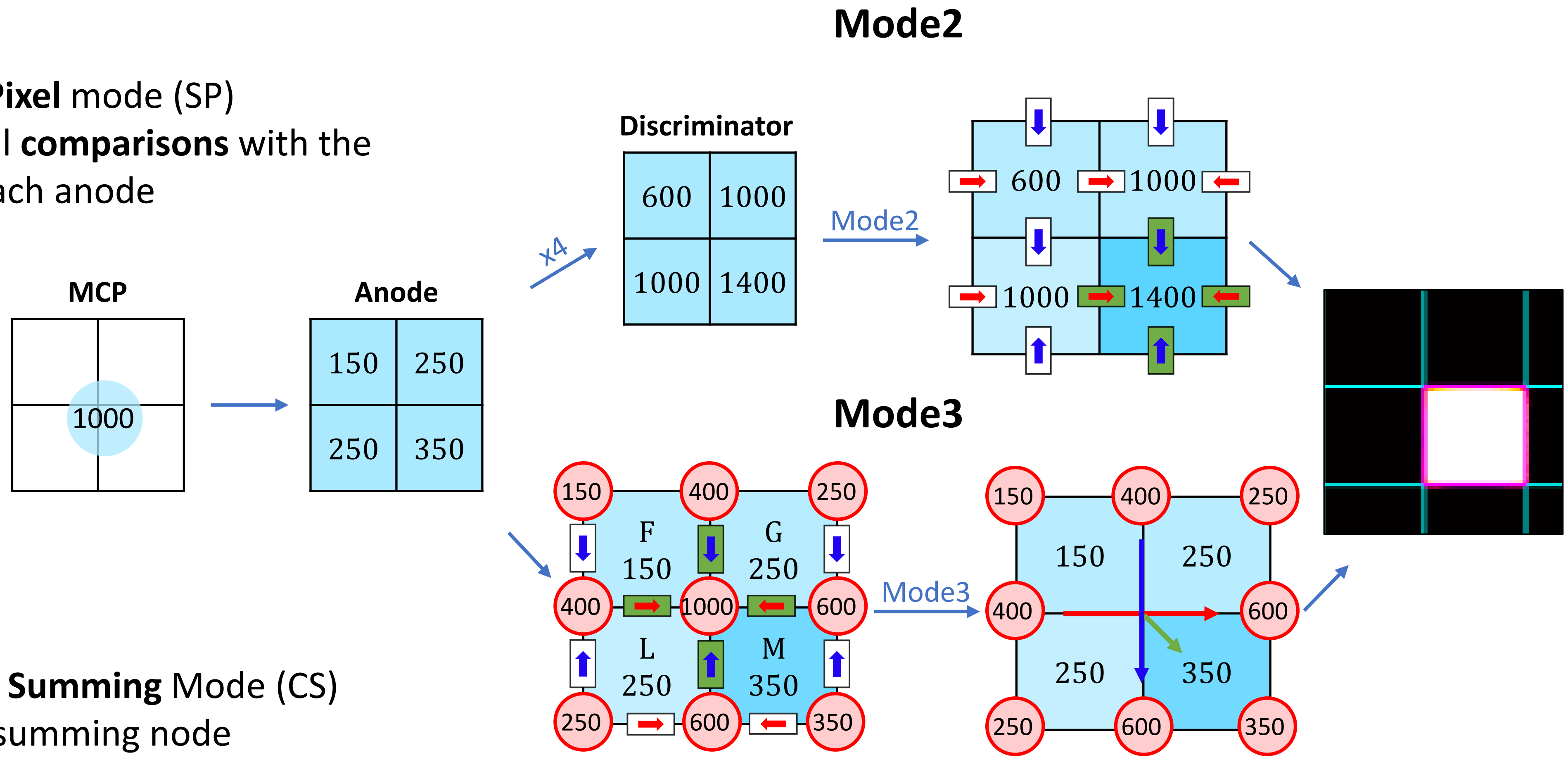
- **Highest** amount of charge identification → MUTEX
- Mutex is based on an **SR latch**
- Several comparisons inside a **cluster** of 2x2 pixels
- **Two** modalities of operations Mode2 and Mode3
- Multiple **counts** avoided and **spatial resolution** recovered



MIRA Charge Sharing Correction Logic

Mode2

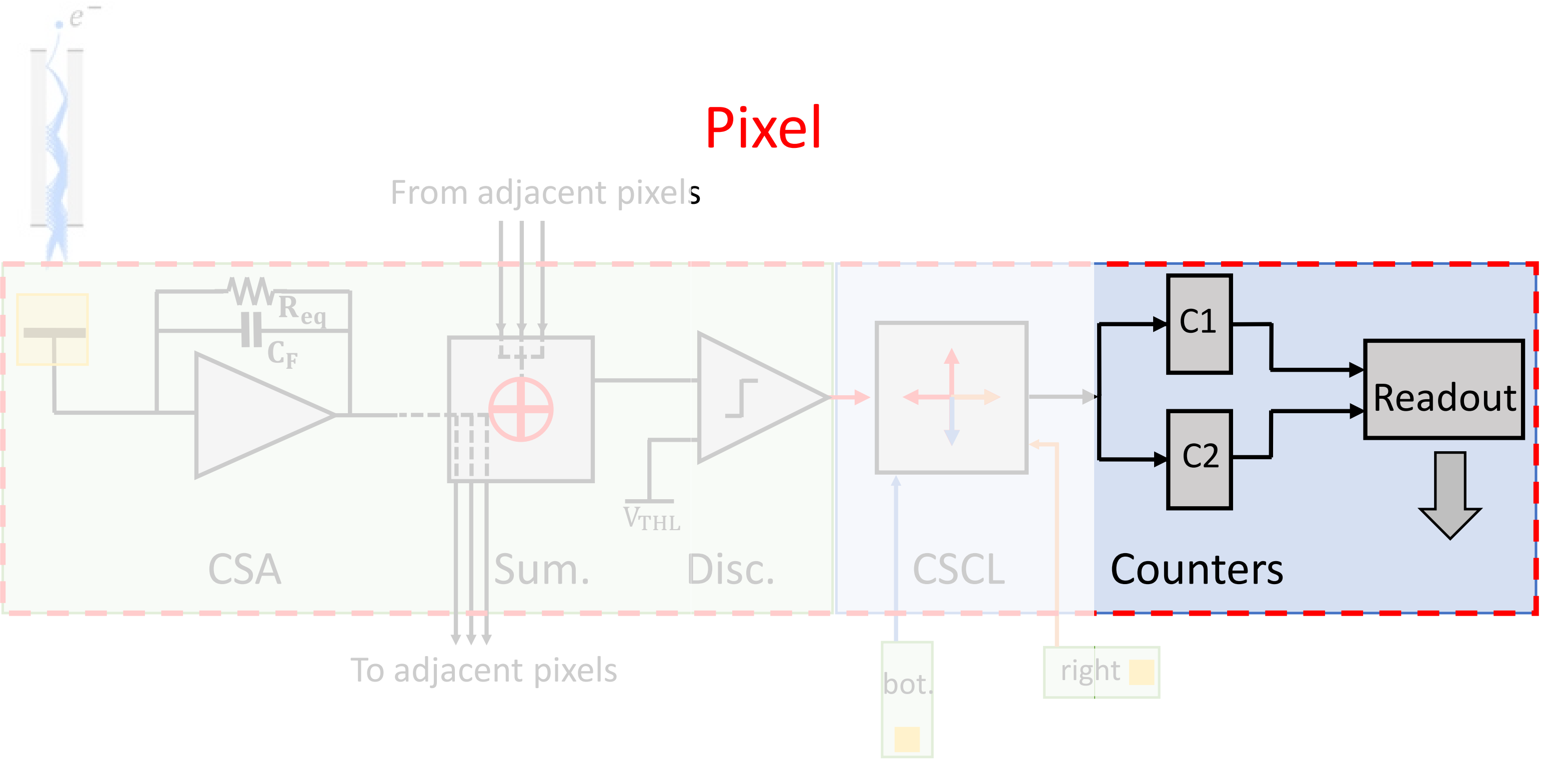
- Filter Stage in **Single Pixel** mode (SP)
- Horizontal and vertical **comparisons** with the charge collected by each anode



Mode3

- Filter Stage in **Charge Summing** Mode (CS)
- **Cluster** identified by summing node
- **Comparisons** made on all pixels in the cluster (including diagonal)

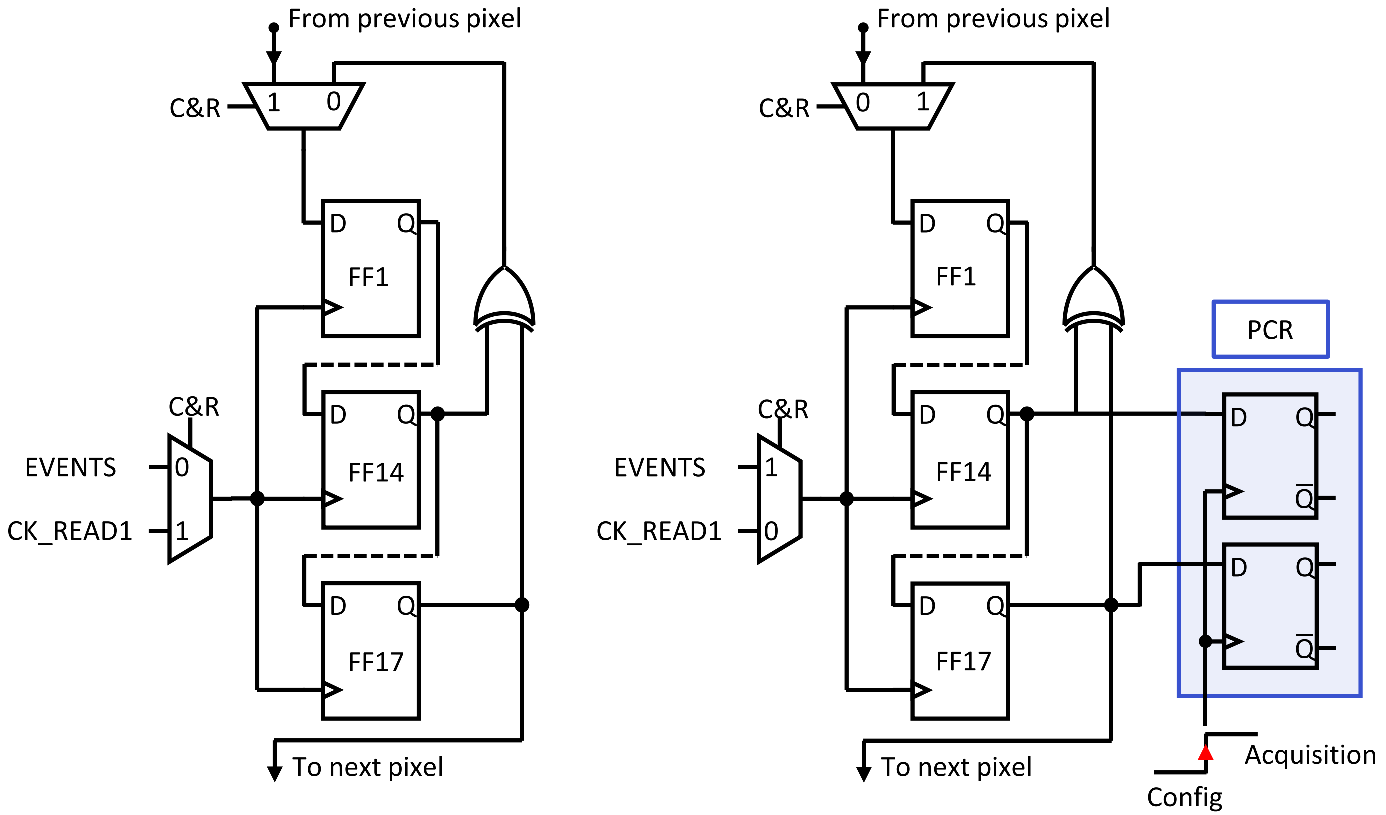
Pixel Readout Channel



Readout Stage - Pixel

Pixel readout stage:

- Two **17-bit counters**
- Implemented as **Linear Feedback Shift Register** (LFSR)
- LFSR acts as a counter or shift register
- **Countinous** counting and reading phases to have **zero dead time**
- **7-bit Pixel Configuration Register** (PCR) to program the pixel



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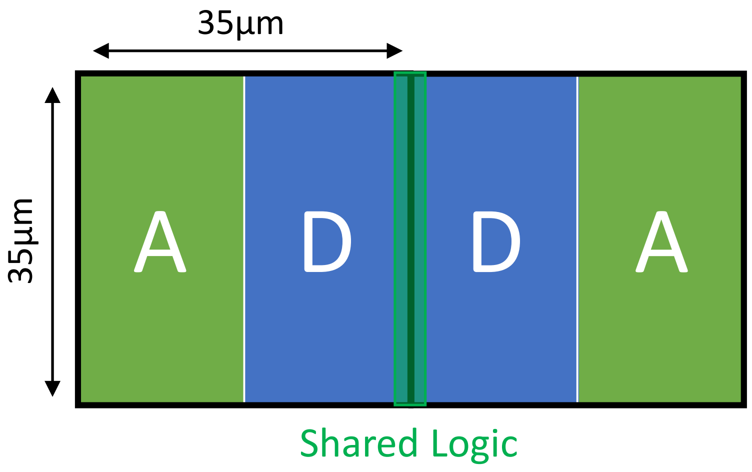
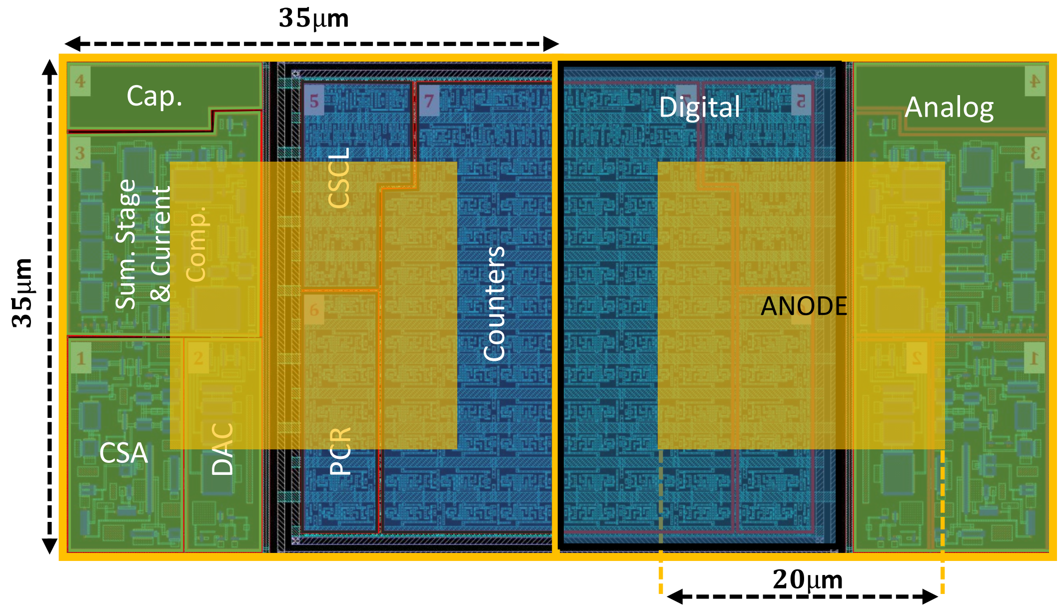
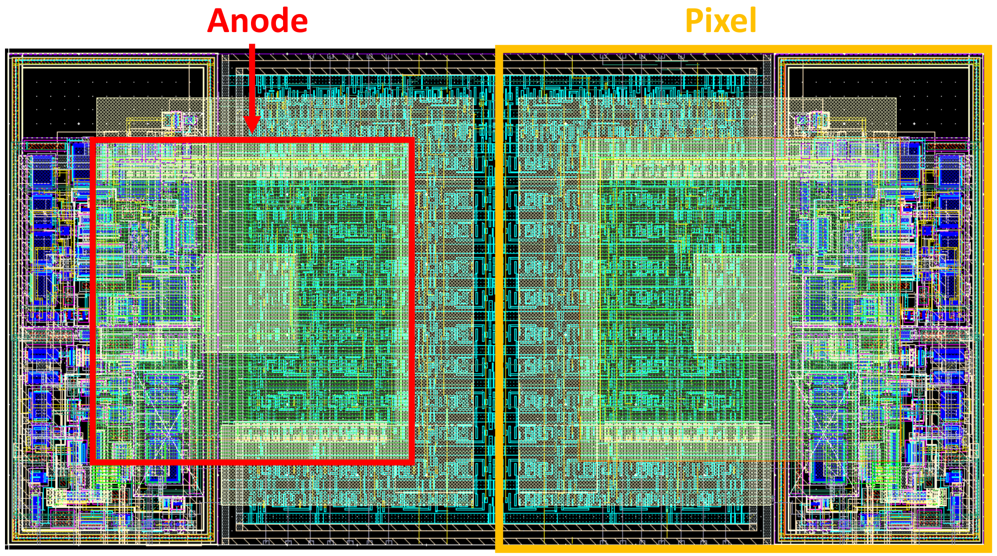
The SuperPixel - Layout







The SuperPixel:

- **Two** mirrored pixels with adjacent digital parts
- **35x35 μm²** pixel size with **20x20 μm²** anode size
- **Half-analog** and **half-digital** pixel
- **Fully-custom** design for **analog** part, **RTL** design and synthesis for **digital part**

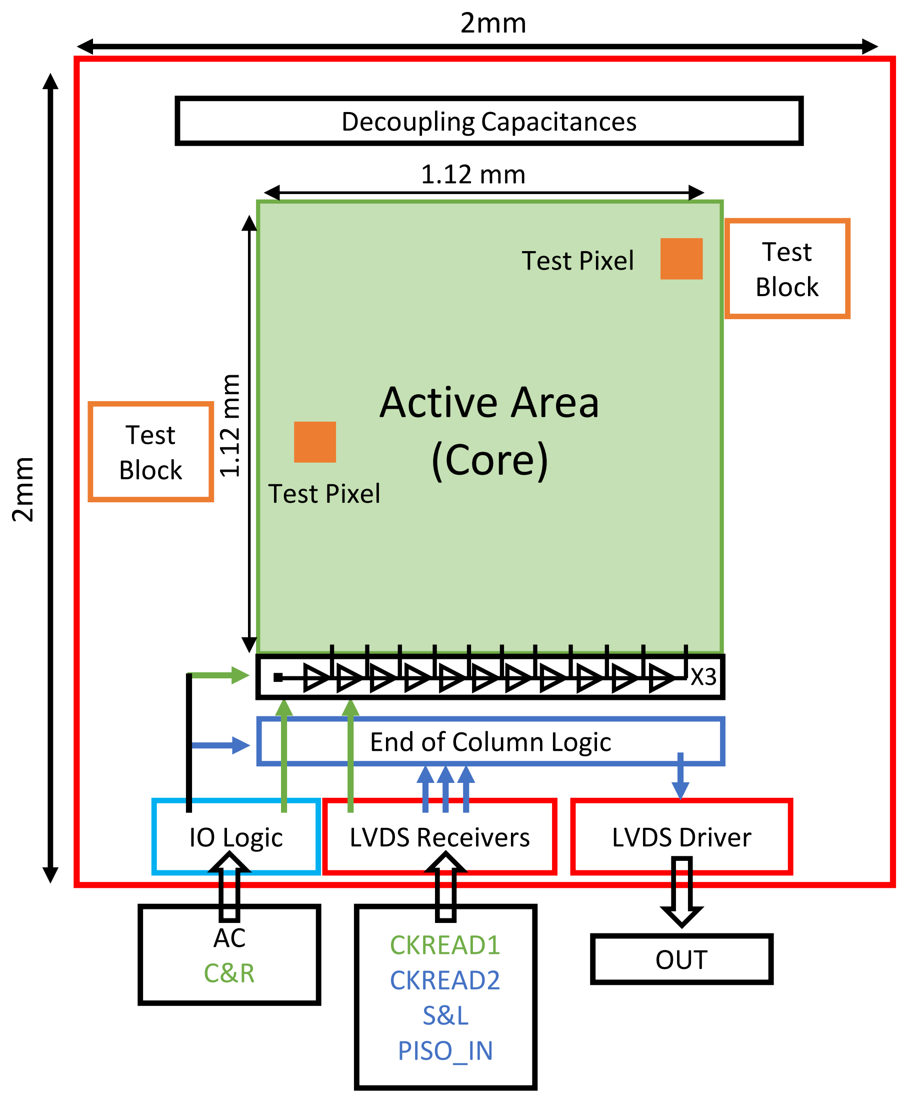
MIRA Layout - Periphery

MIRA first prototype:

- $2x2\ mm^2$ chip **area**
- $1.12x1.12\ mm^2$ **active** area
- **Two** test pixels

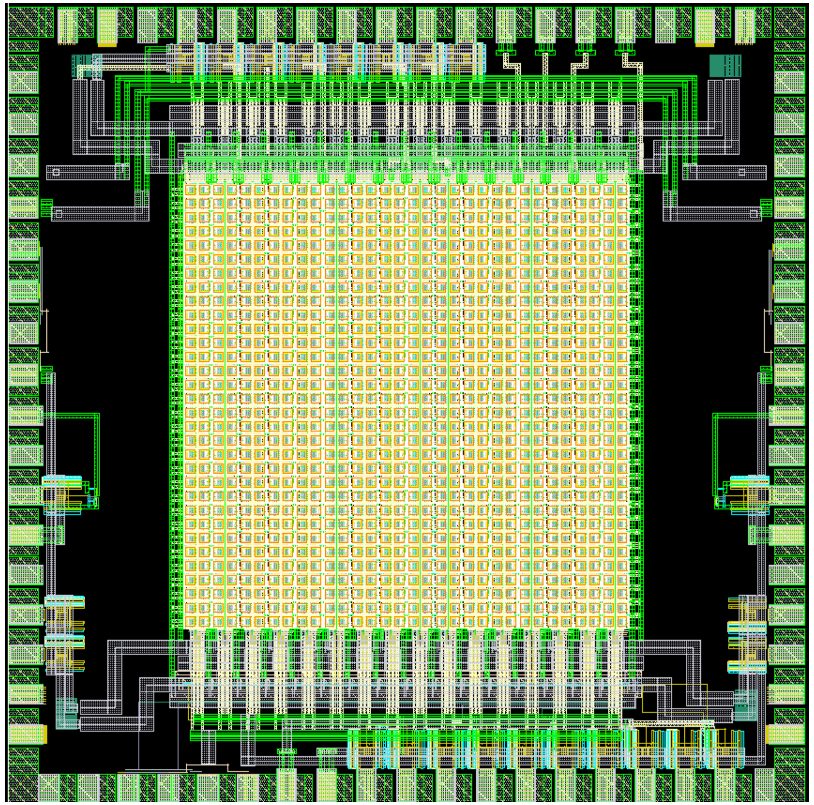
Periphery & Power Domains:

- **Column drivers** for column bus lines
- **EoC** logic and **I/O** drivers
- **LVDS** driver and receivers
- **Two test blocks**
- **Decoupling** capacitances
- **Analog and Digital** power domains
- **Supplies isolation**
- **CUP** structure

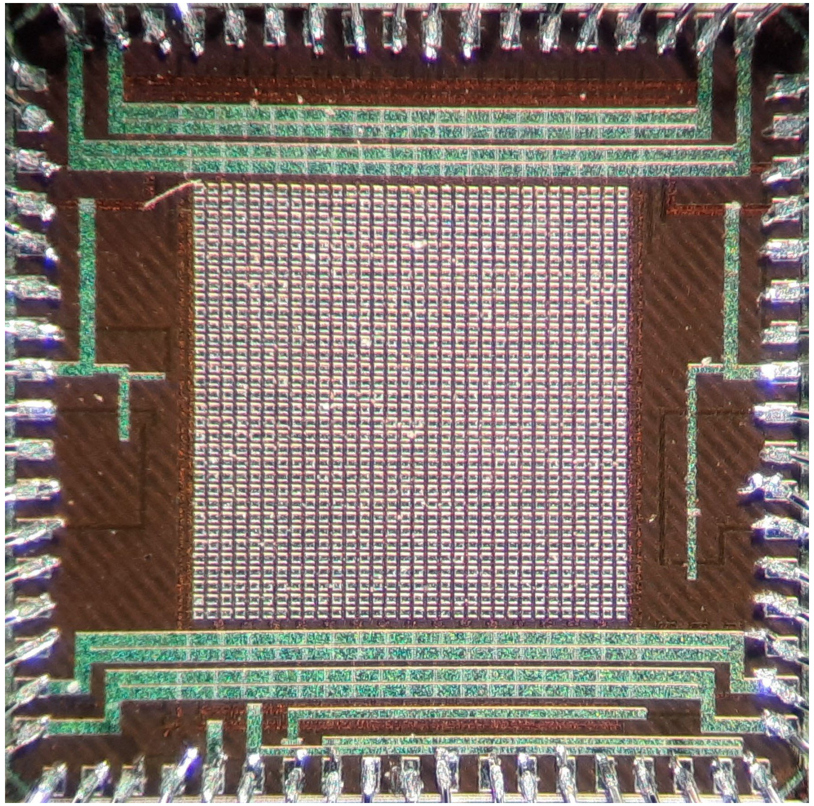


MIRA – First Prototype

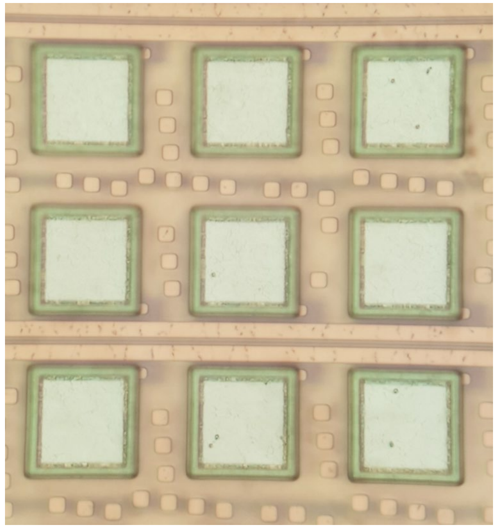
Layout



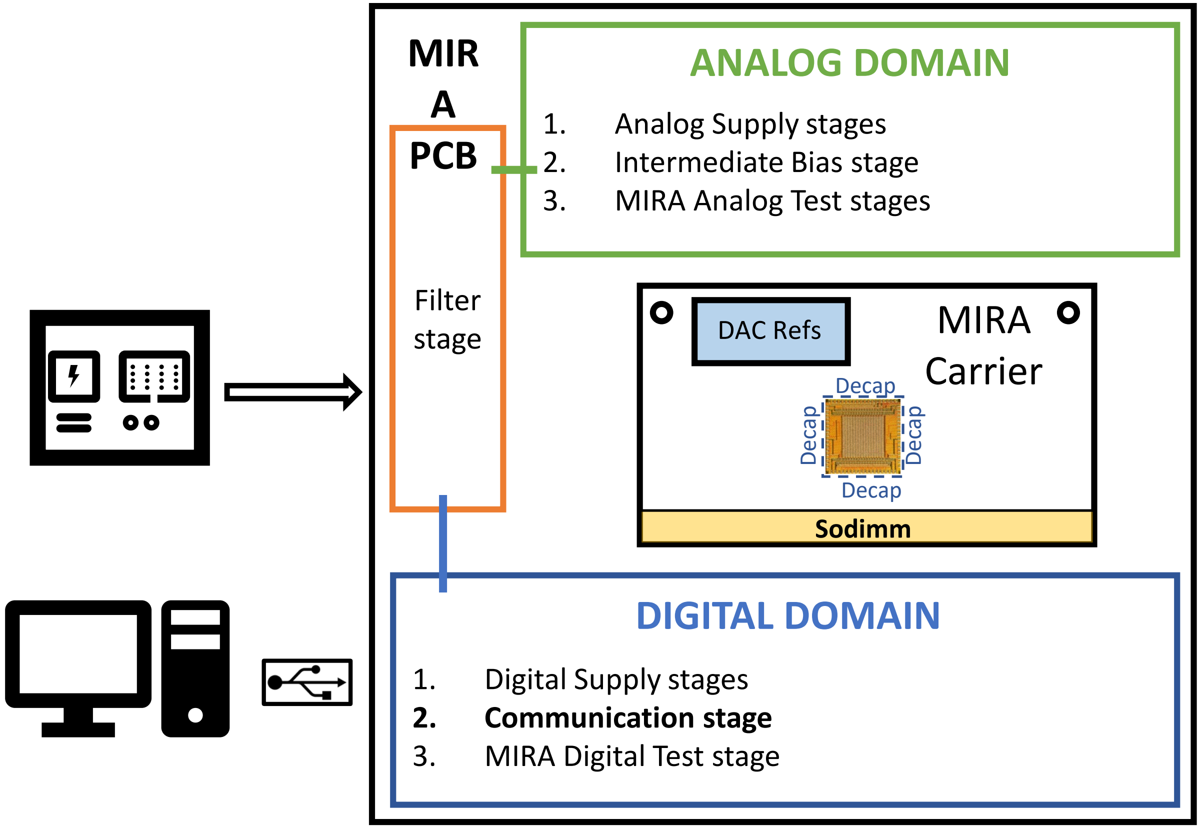
Microscope Image

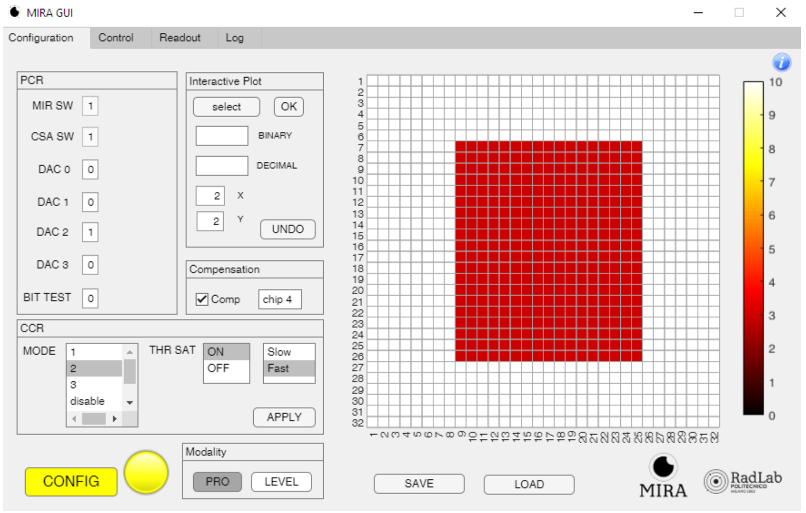


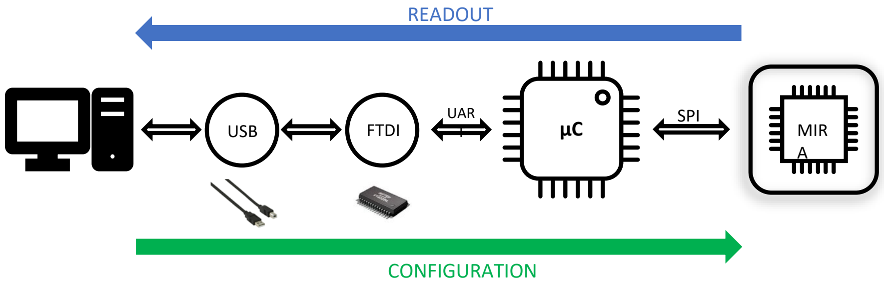
Anodes



MIRA Acquisition System

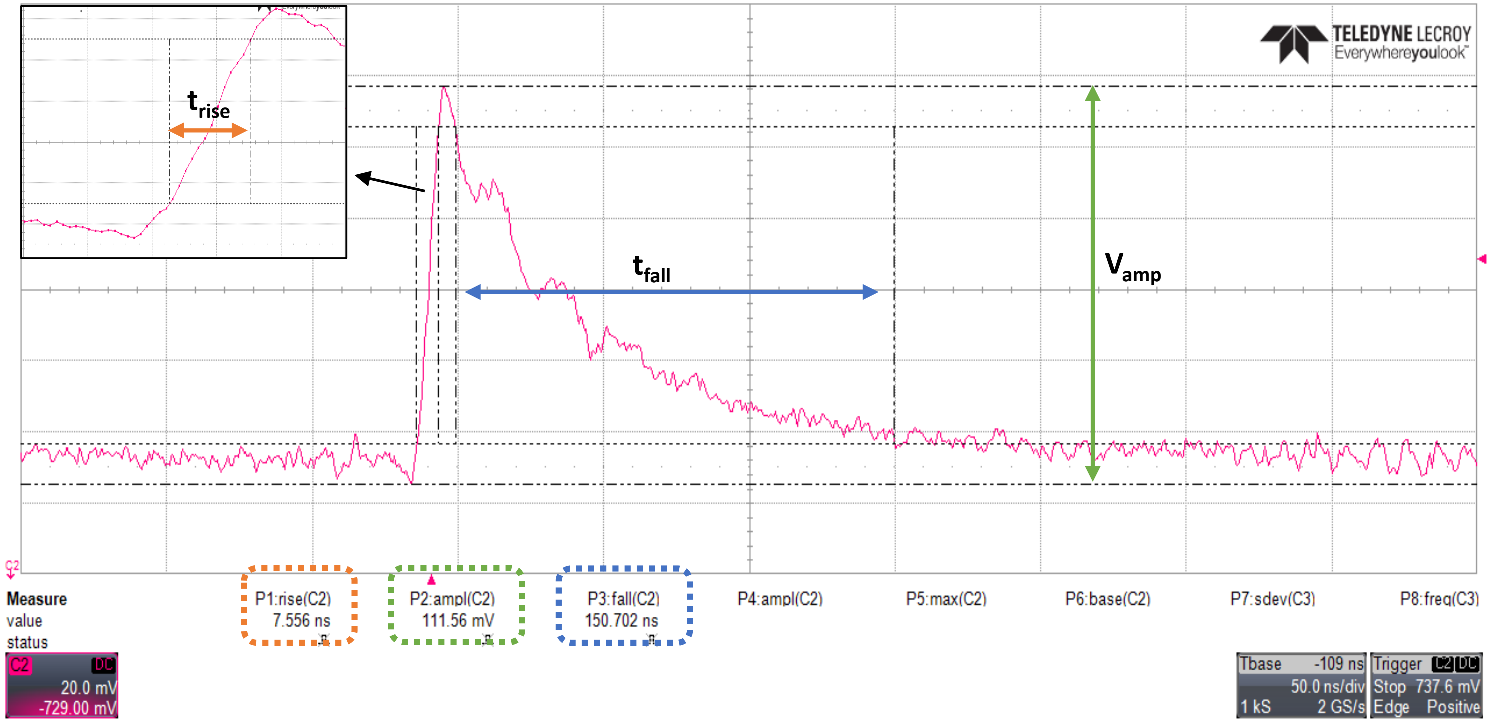


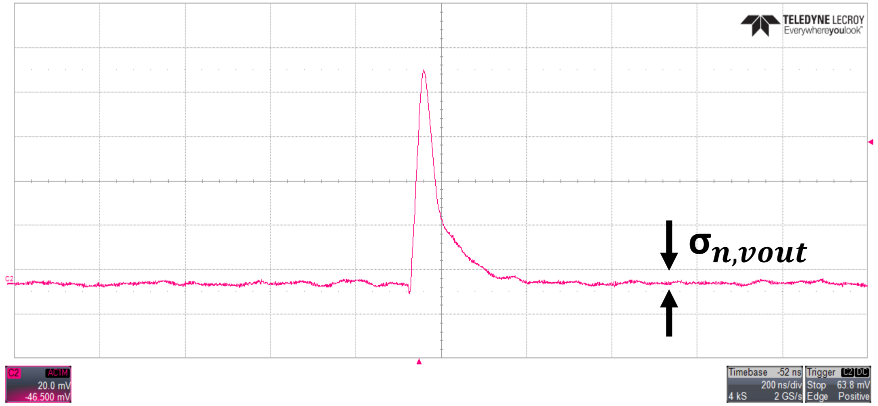




- MIRA PCB to **supply, configure, read** MIRA and monitor the test pixels
- MIRA Carrier to **host MIRA**
- Communication with an external PC through **USB 2.0**
- MATLAB-based **GUI** to show and arrange the **acquired and configuration data** of the MIRA ASIC

MIRA I CSA Transient Response - Measurements





With active probe:

- **Slow** Mode
- $\mathbf{t_{rise}} = 7\text{ ns}$, $t_{fall} = 150\text{ ns}$
- $\mathbf{t_{width}}|_{\mathbf{1\%peak}} = 261\text{ ns}$
- $V_{amp} = 112\text{ mV} \rightarrow \mathbf{Q_{in}} = 4000\ e^-$

With SMA connection:

- $t_{rise} = 22\ ns$
- $\boldsymbol{\sigma_{n,vout}} = 750\ \mu V_{rms}$
- $ENC_{CSA} = \mathbf{27}\ \boldsymbol{e^-_{rms}}$

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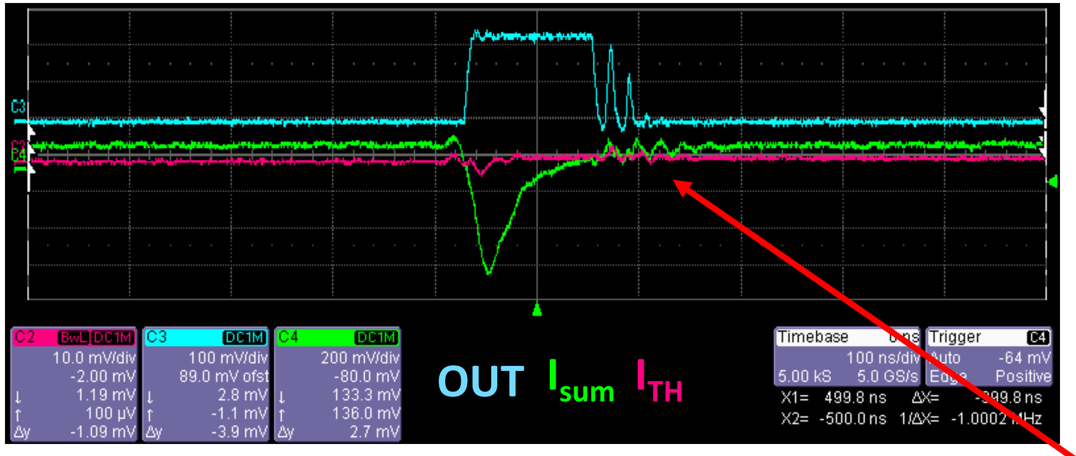
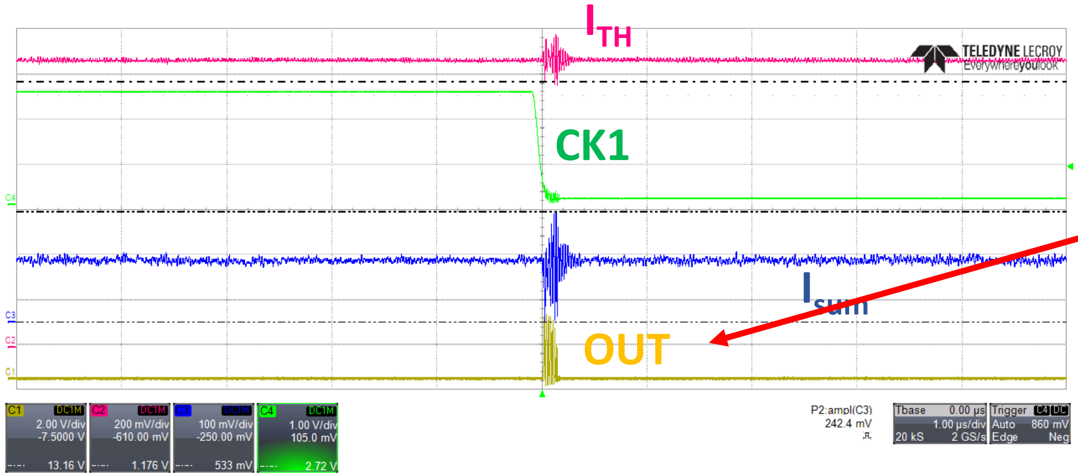
MIRA I Characterization Results

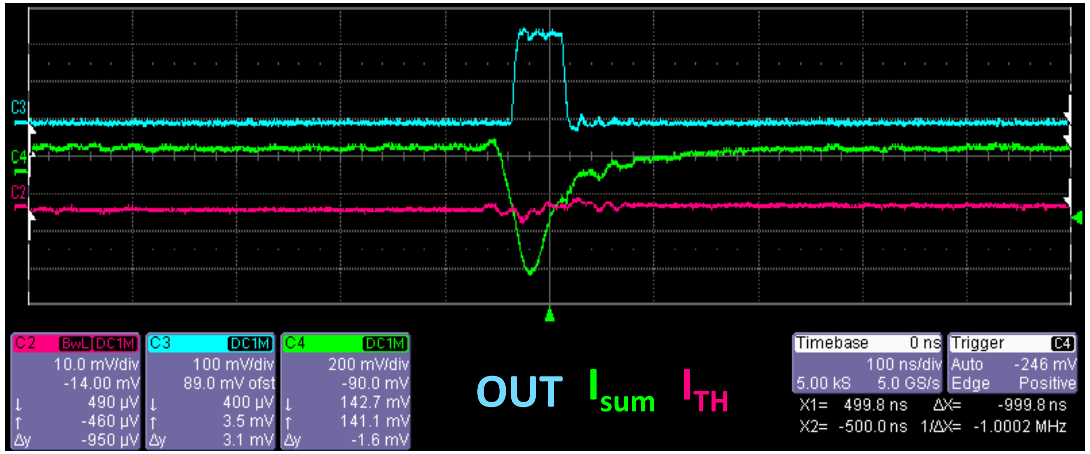
Low Threshold (just above noise)





OUT: current comparator output

High Threshold

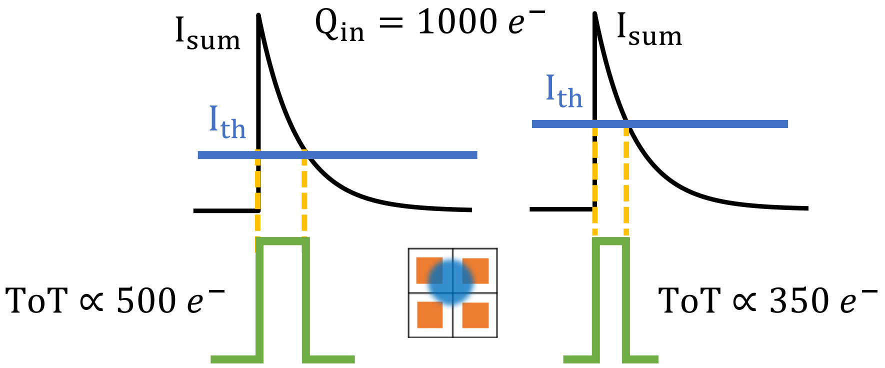


- **Self-triggers in low-threshold** operations
- **Clock (CK1) coupling** causing false counts
- **High-threshold operation** to trigger single events
- Threshold **lower limit**: 500 e^-
- ENC = **20** e^-_{rms}

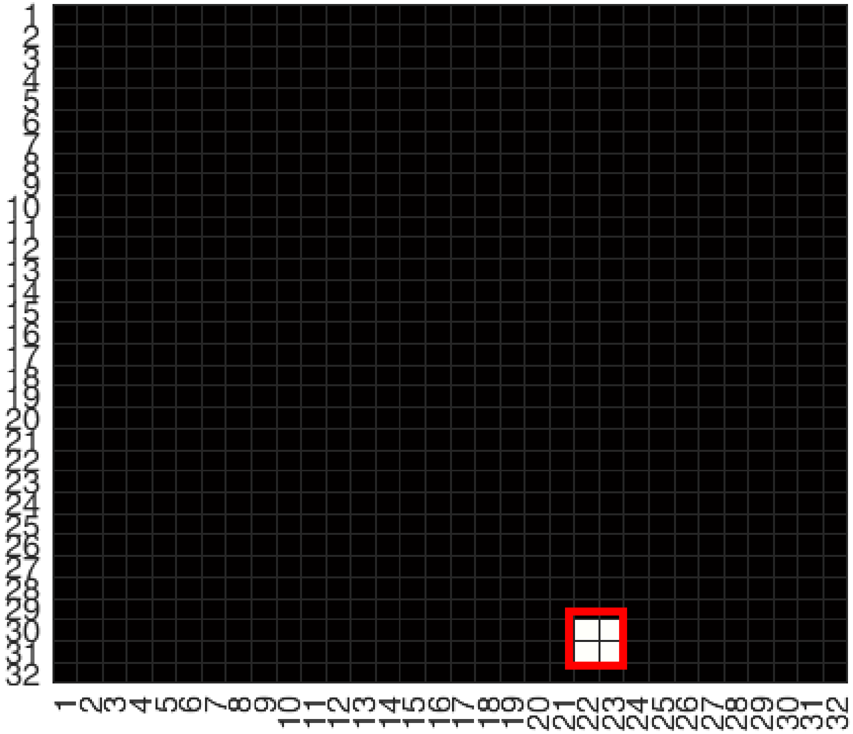
Charge Sharing Correction Logic - Results

Test Setup:

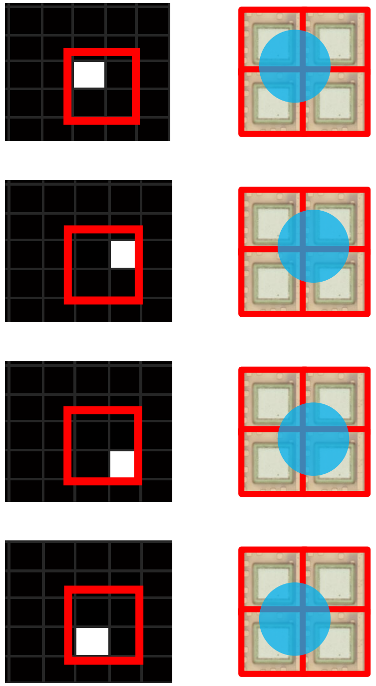
- **Each pixel** stimulated with **same** test signal ($Q_{in,eq} = 1000e^-$)
- **Different** pulse **ToTs** obtained by programming the cluster pixels with **different thresholds**



No Correction



Mode2



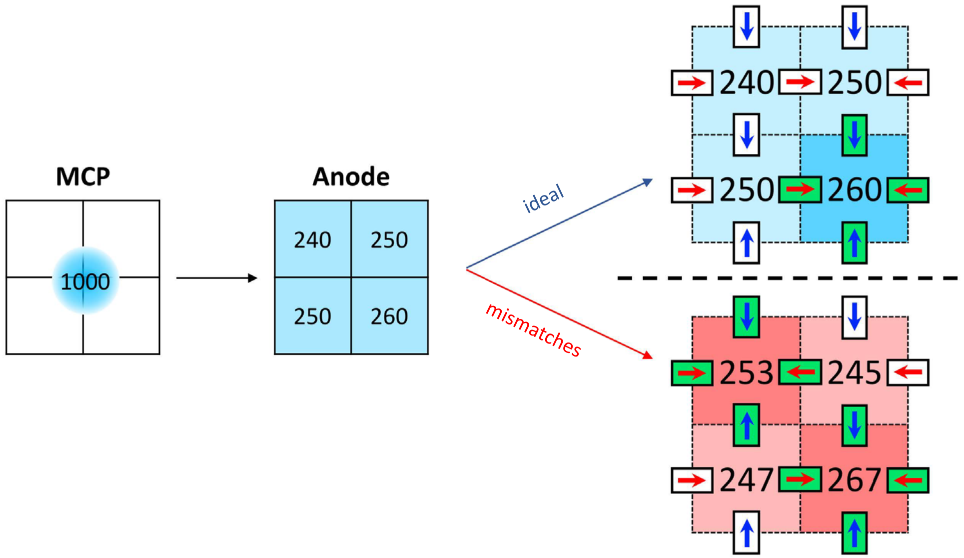
Results:

- Only the pixel with the **highest charge** is counting
- **MIRA CSCL** works as expected
- Multiple pixel **counts** avoided

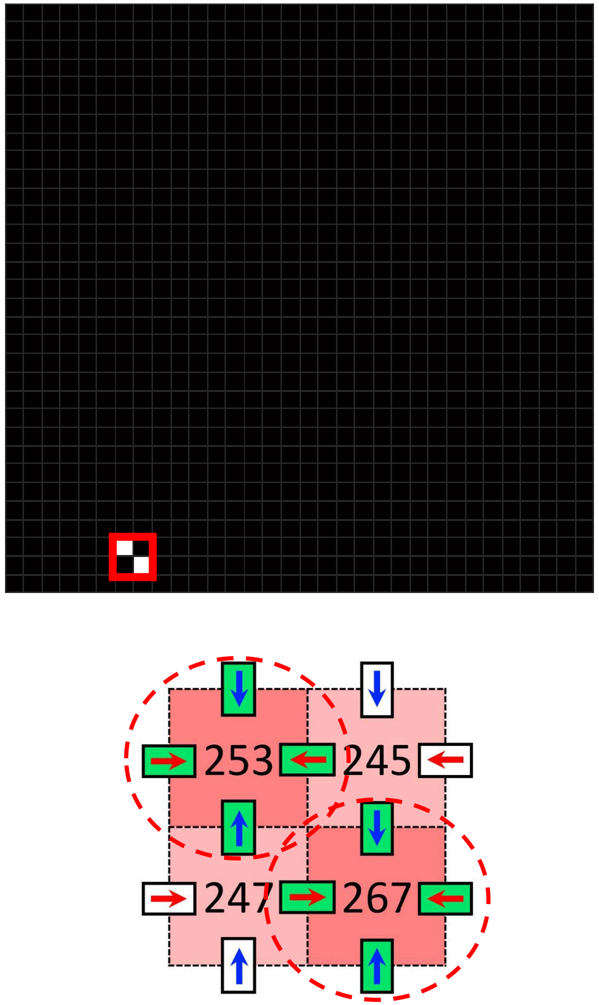
Mode2 vs Mode3

Diagonal double counting:

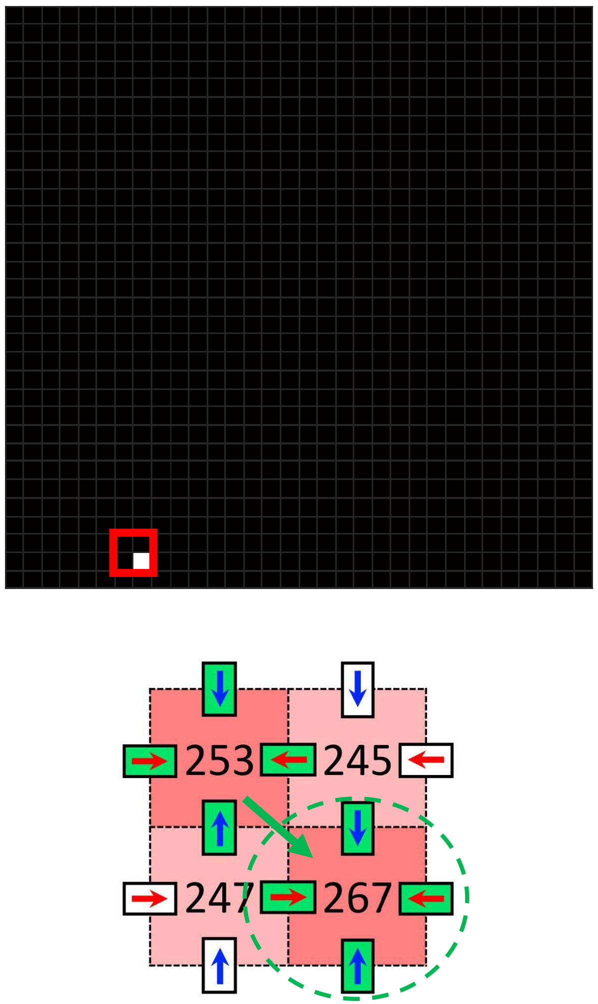
- A **diagonal double counting** may occur in **Mode 2** from a **charge cloud** almost equally shared in the cluster, and **pixels mismatches**
- It results in two diagonally-placed pixels with **longer ToTs**
- **Mode3 solves** it performing diagonal comparisons



Mode2



Mode3



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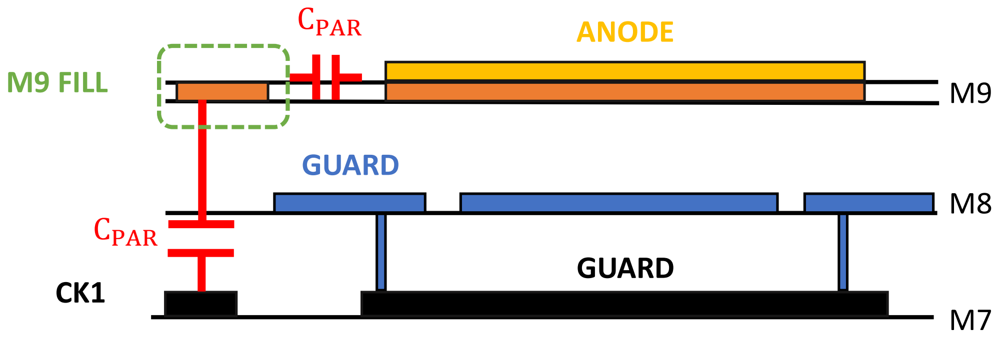
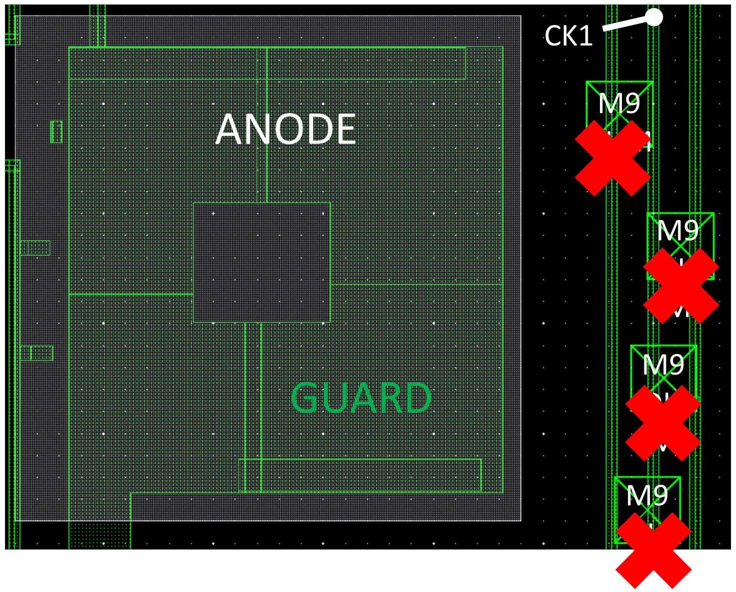
MIRA II – Improvement of Low-Threshold Operation

Clock coupling:

- Parasitic coupling between **clock lines** and **Anode** pad
- Coupling induced by **metal dummies patterns** in M9 (foundry)





Further improvements:

- **Elimination of self-trigger** due to digital pickup on analog pulse
- **Improvement of clock distribution** (configuration and readout issues, not discussed here)

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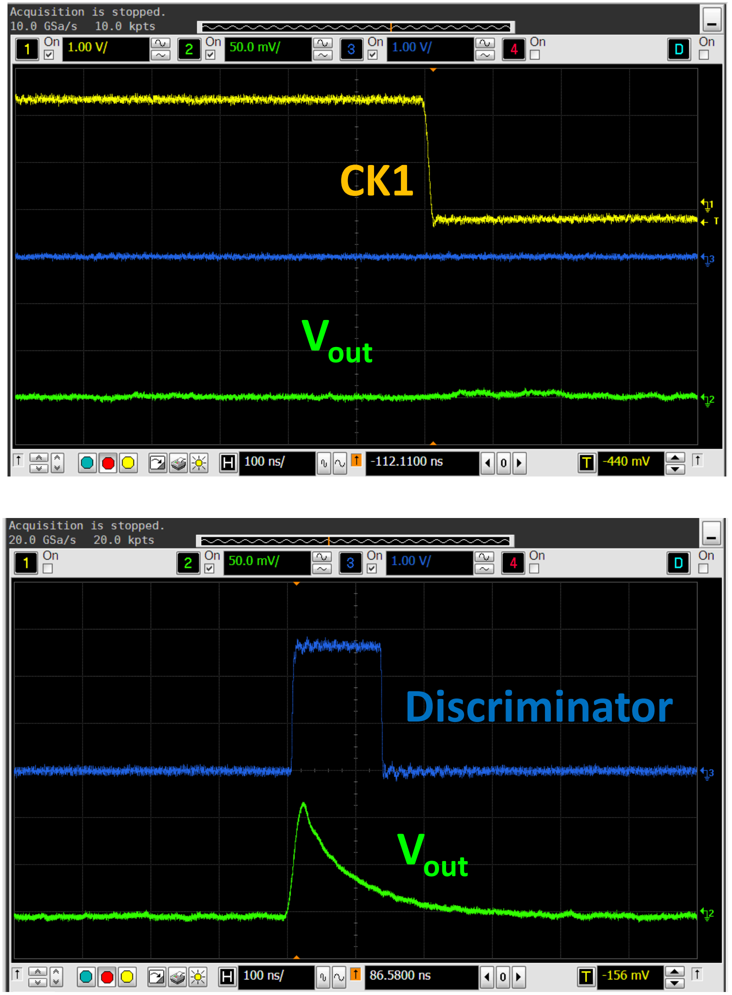
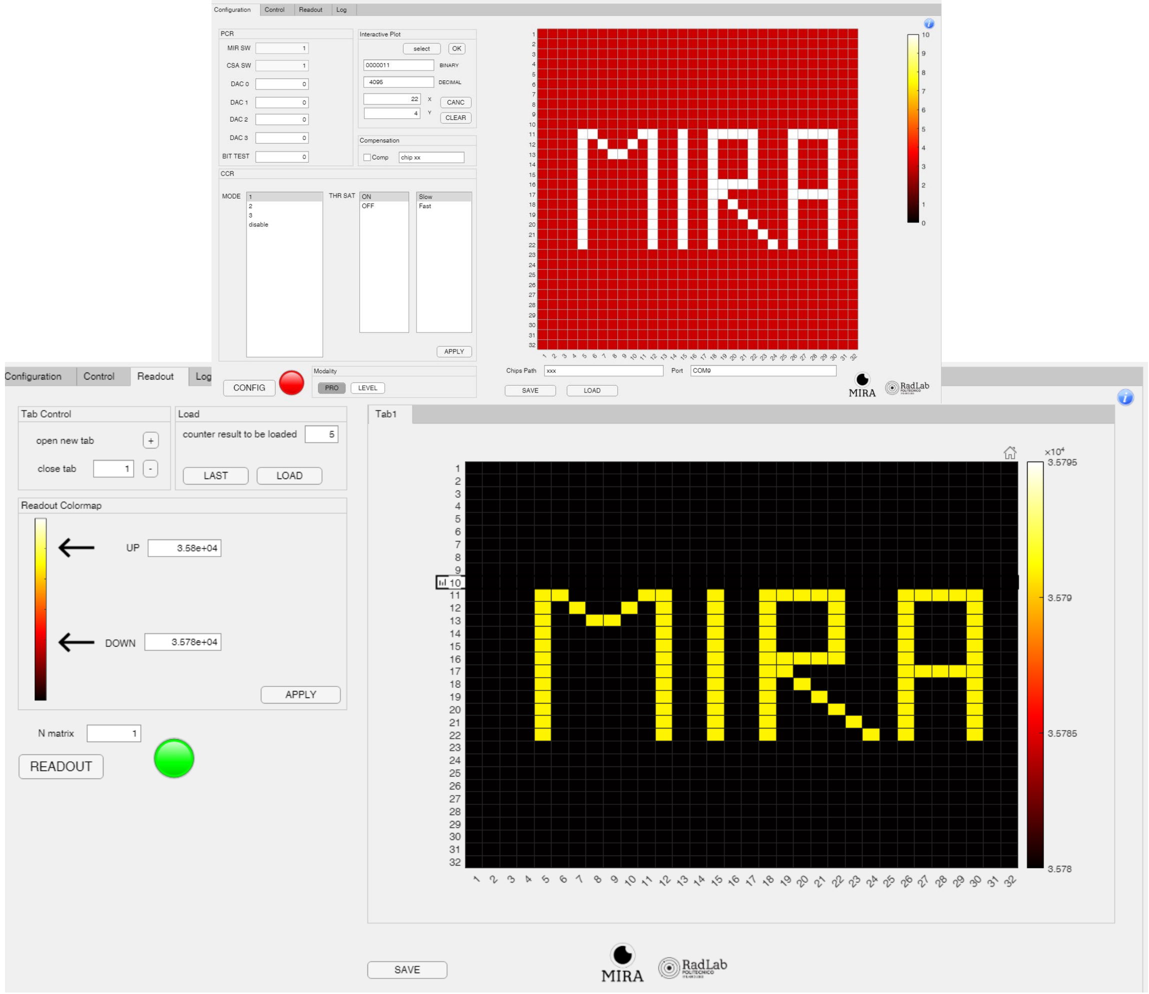
MIRA II –Results

✓ Low-threshold operation



✓ All pixels are configurable and readable



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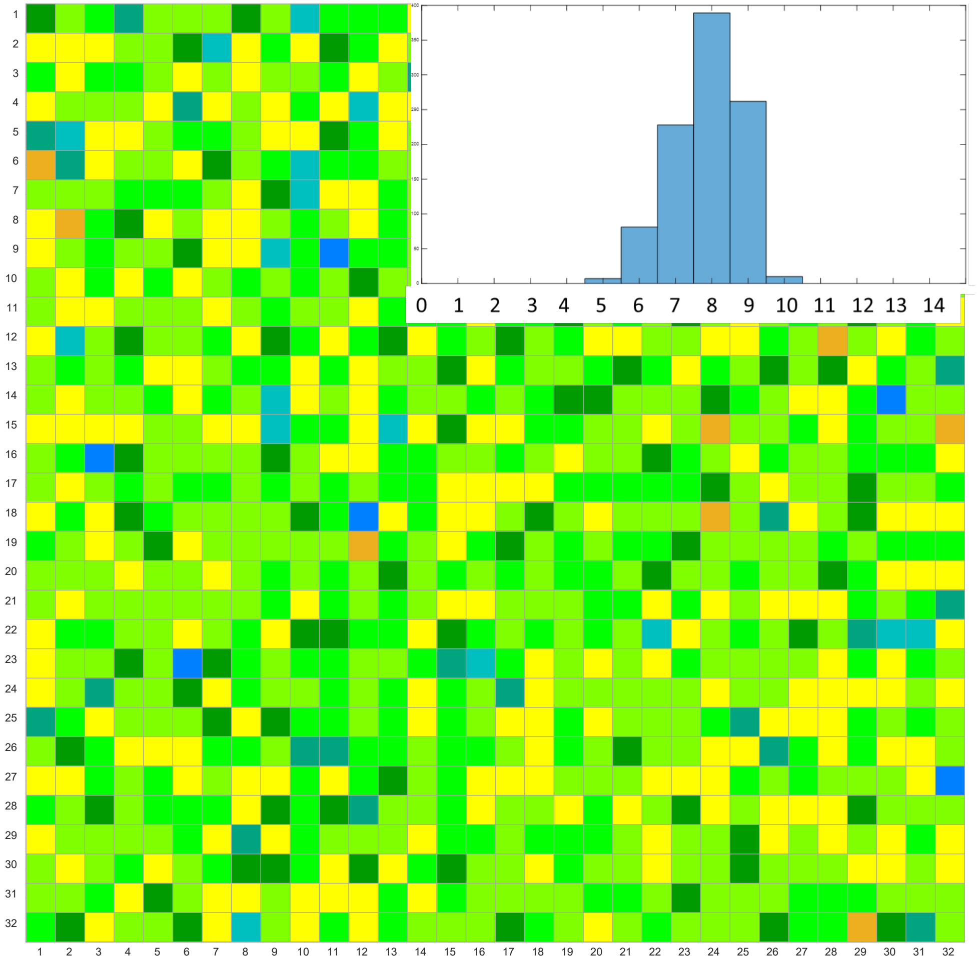
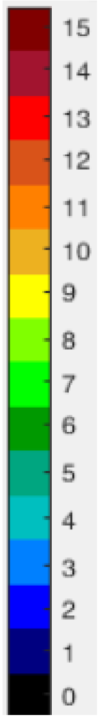
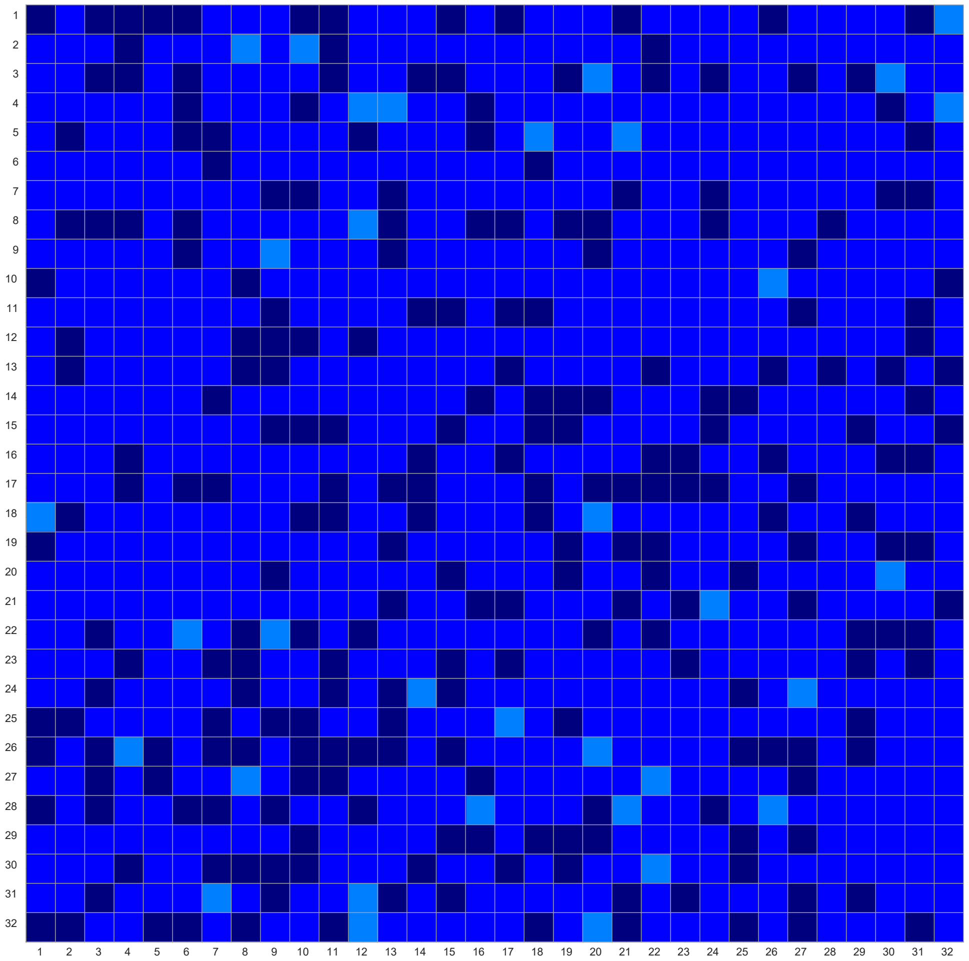
MIRA II – Offset Dispersion and Noise





DACs bits
(1bit ~ 47e-)



Offset dispersion (before calibration)

Noise threshold distribution after Offset calibration

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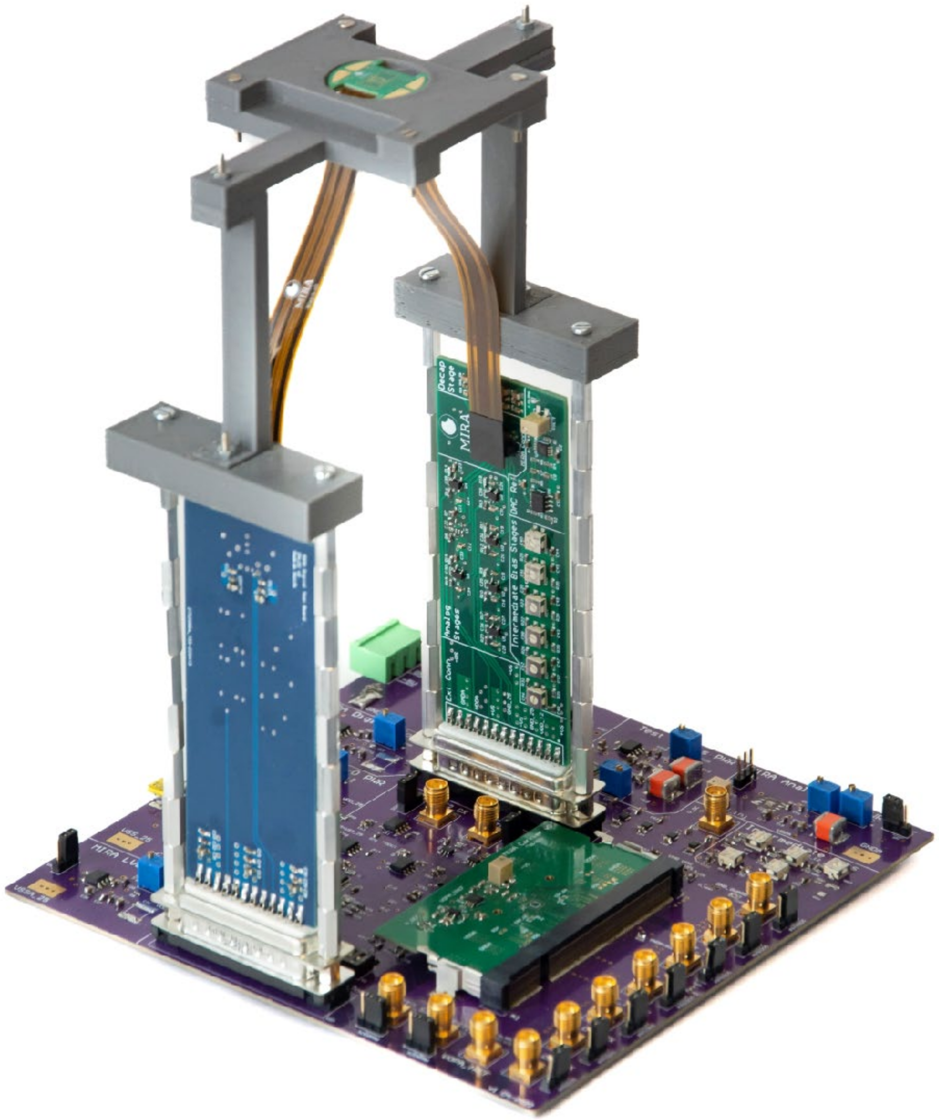
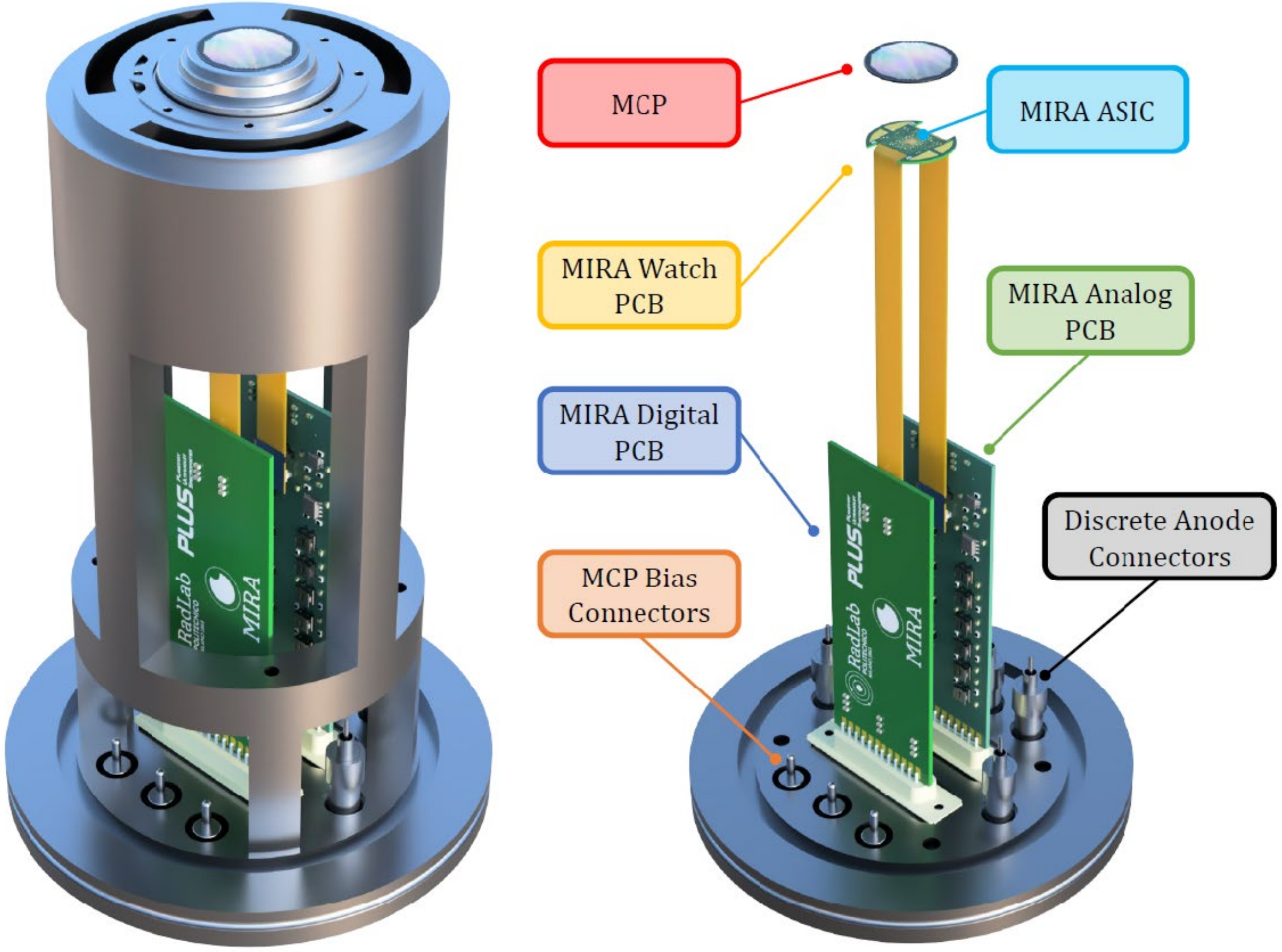
MIRA ASIC assembly in the MCP system





PLUS Planetary Ultraviolet Spectrometer

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MIRA MCP detector integration

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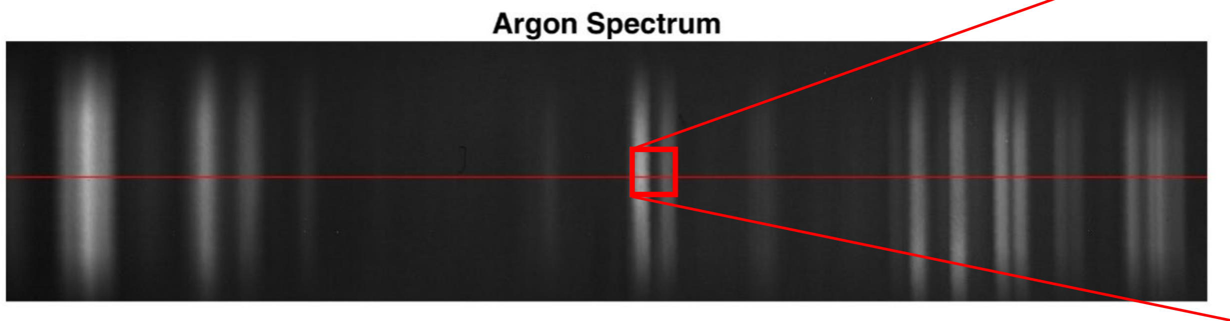
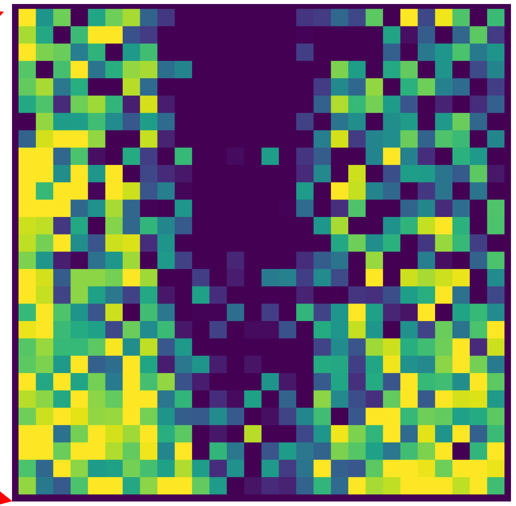
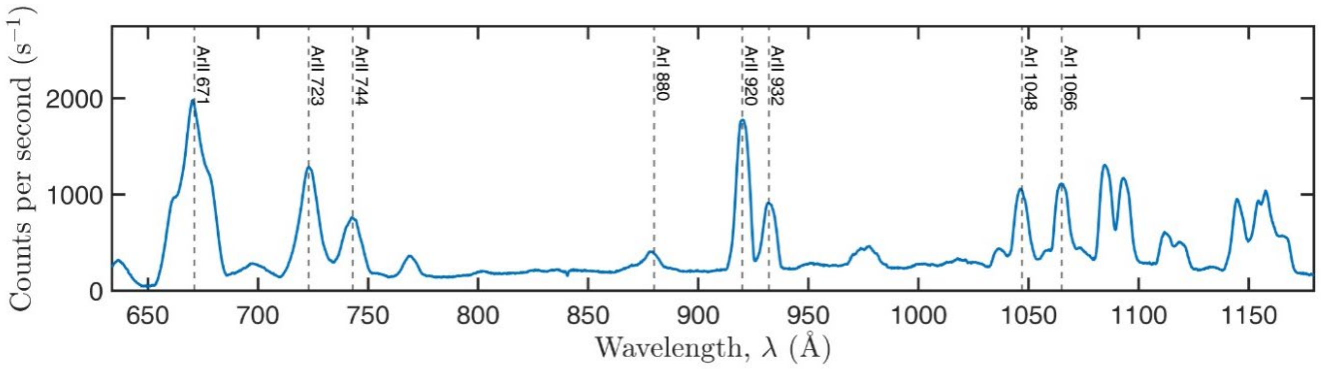
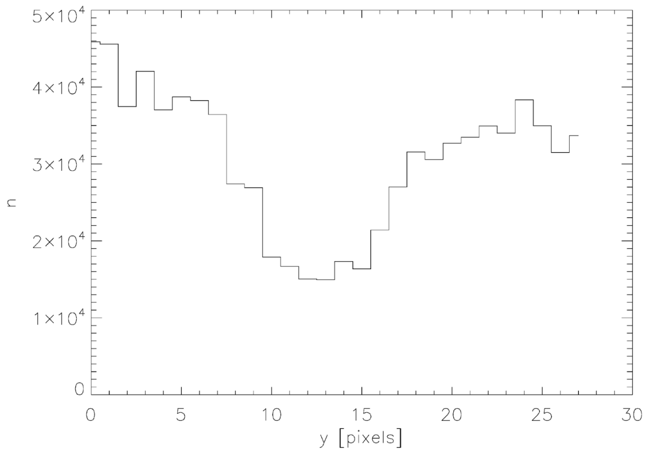
MIRA MCP detector acquisition









Conclusions and future work

MIRA ASIC developed for the readout of MCP for space applications:

- TSMC 65 nm technology
- 32 x 32 pixels, in a chip area of 2 mm x 2 mm, Active area of 1.12 mm x 1.12 mm
- Pixel size of **35 μm**
- **Low noise → ENC $\simeq$ 20 e^{-}_{rms}**
- **MIRA II** prototype integrated with MCP

Future Developments:

- Extended characterization of the PLUS photon counting unit and MIRA II in the PLUS spectrometer with a UV source
- Revision of power consumption (presently ~ 150μW/pixel)
- Increase of ASIC pixels matrix (e.g. 256×256 pixels) and possible sub-pixel spatial resolution
- Possible extension of application for solid-state detectors?

PLUS PLANETARY ULTRAVIOLET SPECTROMETER

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