Fermilab

Tower Semiconductor

SLAC NATIONAL ACCELERATOR LABORATORY

FERMI NATIONAL ACCELERATOR LABORATORY

October 21, 2026

Toward a fast and Low-Glow Sub-electron Readout with Monolithic Skipper-CMOS sensor

Agustin Lapi on behalf of Claudio Chavez

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U.S. DEPARTMENT of ENERGY

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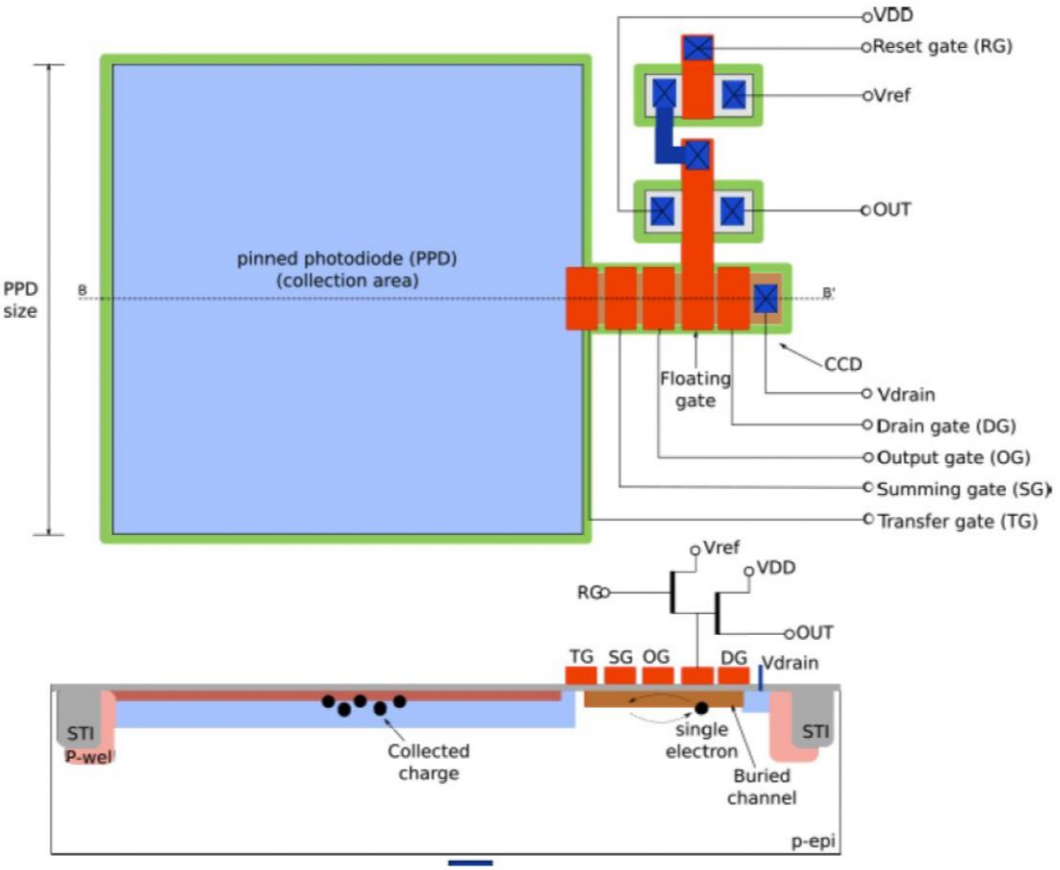
FERMILAB-SLIDES-26-0243-ETD

01

Device and readout system overview

4T CMOS with CCD

CMOS and Pixel structure based on Tower Semiconductor 180 nm CIS process



Pin-Photodiode for light collection

CCD structure charge-coupled to PPD

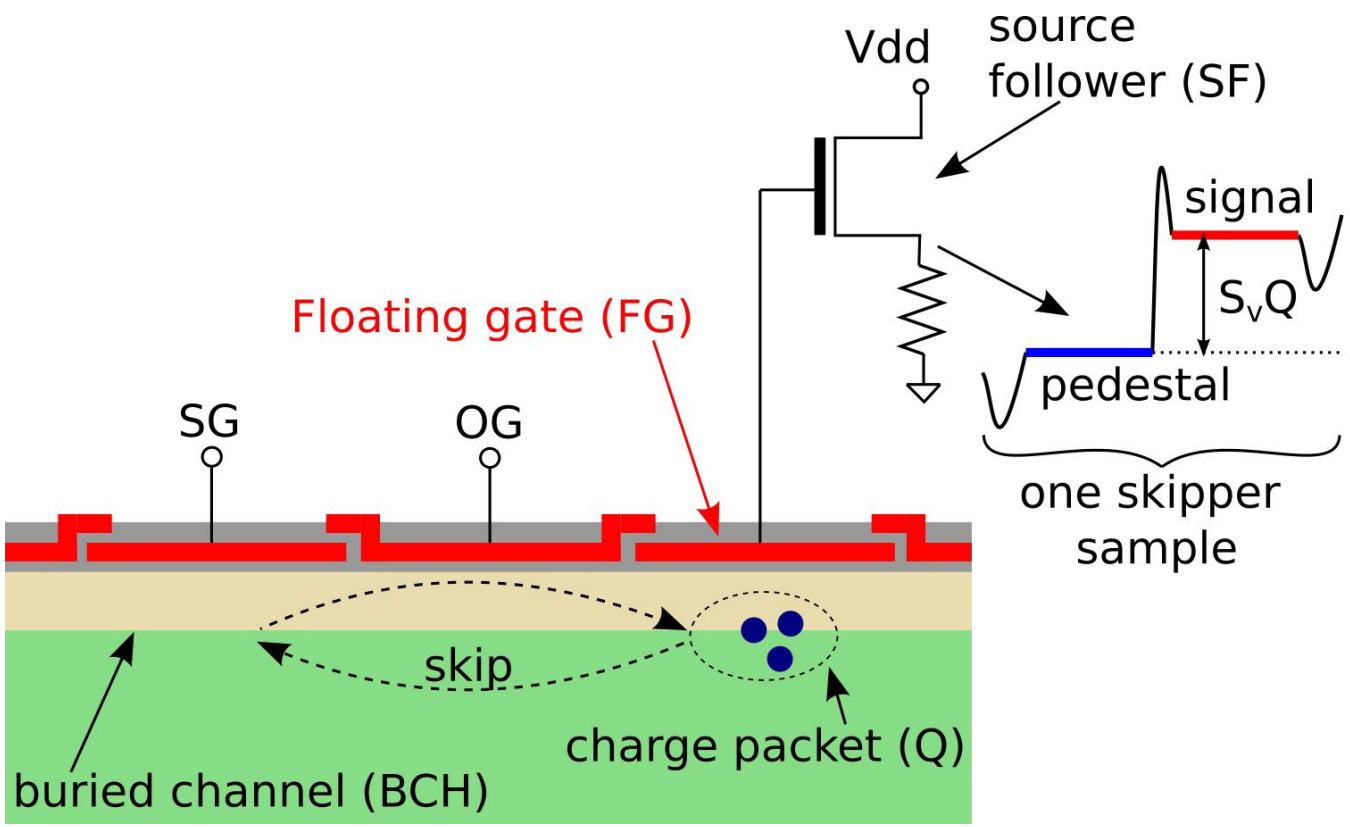
Floating gate for non-destructive multiple readouts

- Expected conversion gain ~100 µV/e-.
- Expected single sample noise <1e-.

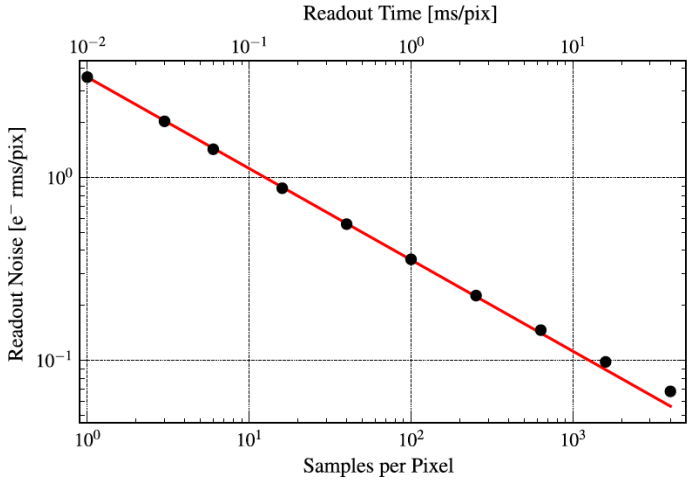
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Device and readout system overview

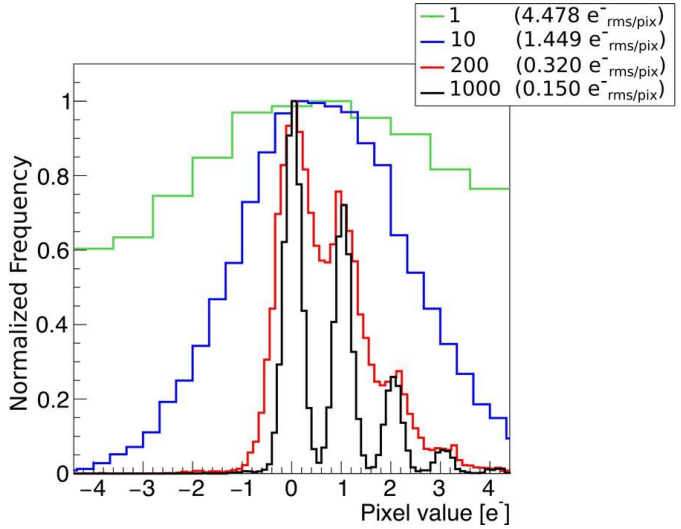
Non-destructive readout and noise



- Multiple non-destructive measurements (N) of the same charge packet.



Noise goes down by 1/sqrt of N

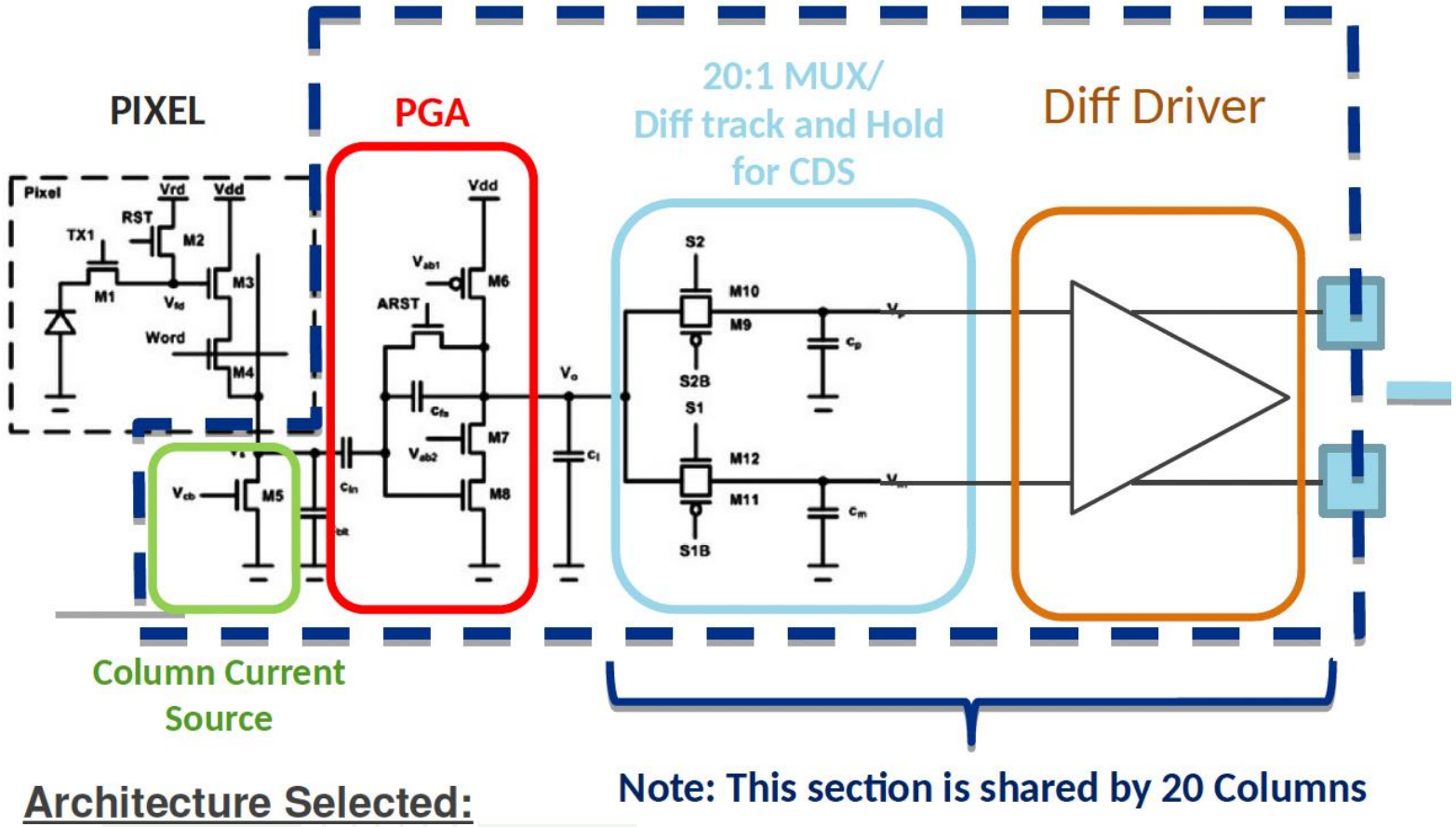


Pixel histogram approaches to a discrete values histogram as noise goes down

Device and readout system overview

- SAMPLE sequence:
  - Clamp pedestal level with S1
  - Clamp signal level with S2
  - Measure the difference

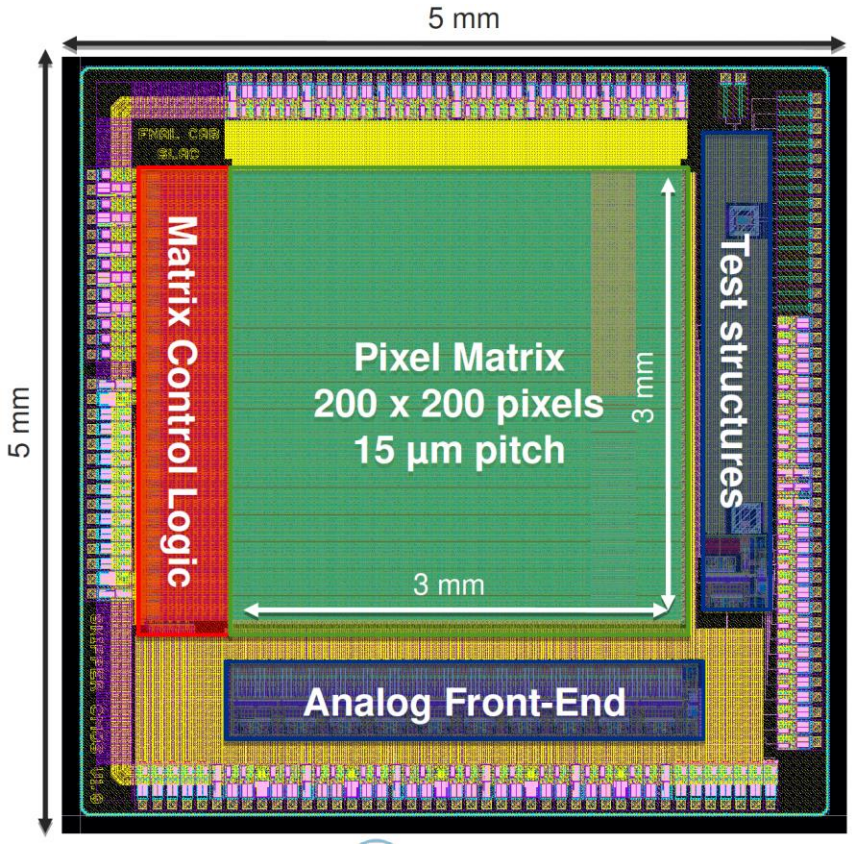
- Current source configurable 1µA to 8 µA.
- Programable Gain Amplifier (column amplifier) 1 to 64 V/V.

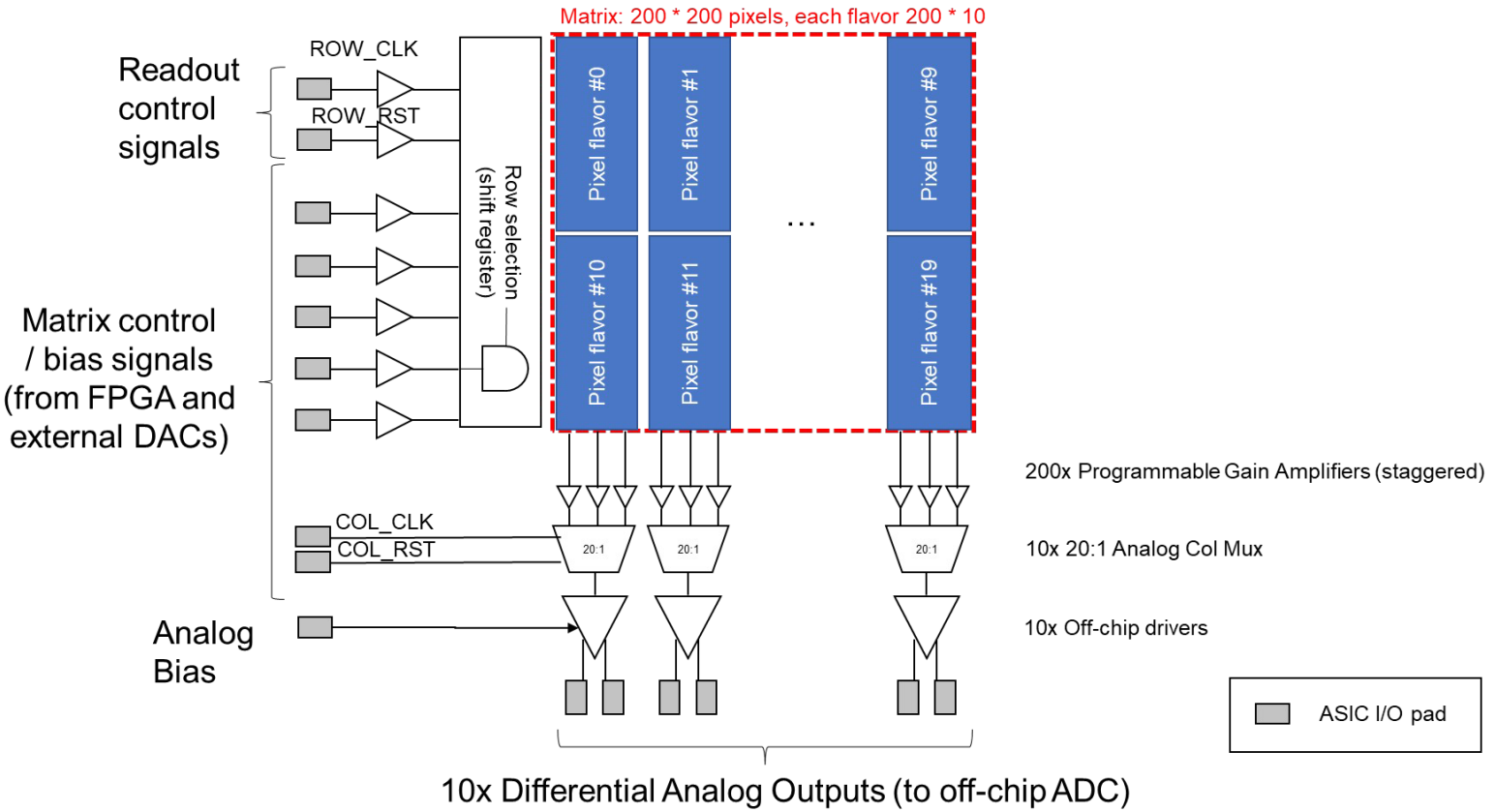


Architecture Selected:

- This is the circuit for the selected pixel.

Device and readout system overview





- Pixel gates control are digital.
- Pixels controlled thru level-shifers.
- 20 pixel flavors (different PPD, gate and transistor sizes)

Device and readout system overview

Previous results (2023)

Stand-alone pixel structure successfully demonstrated by Agustin Lapi.

Charge transfer from PPD

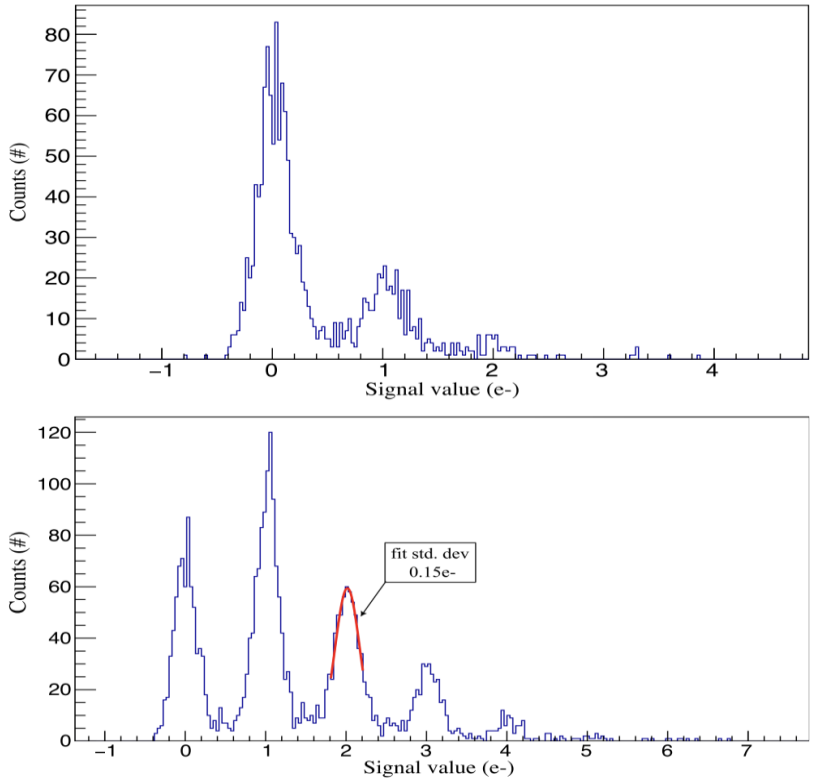
Successfully transfer charge from PPD to floating gate through charge-coupled CCD structure

Non-destructive readout

Up to 3000 skips tested

Sub-electron noise

0.15 e^- rms noise achieved



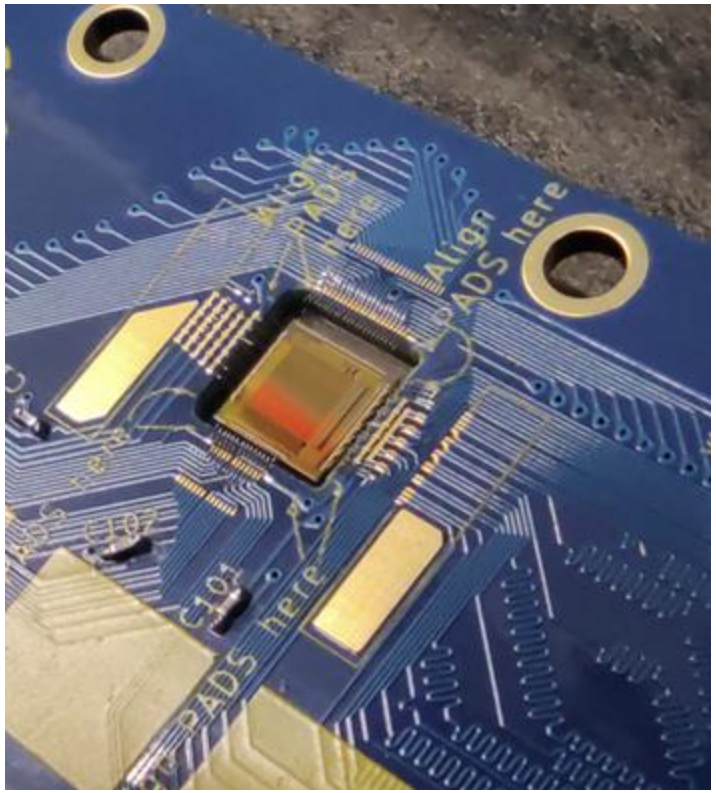
Stand-alone pixel test structure successfully demonstrate by Agustin Lapi [https://doi.org/10.1109/TED.2024.3463631]

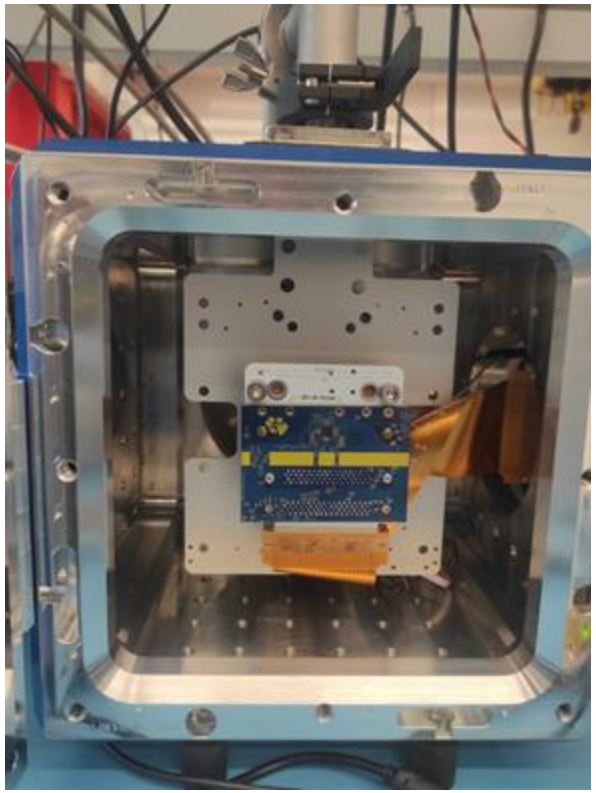
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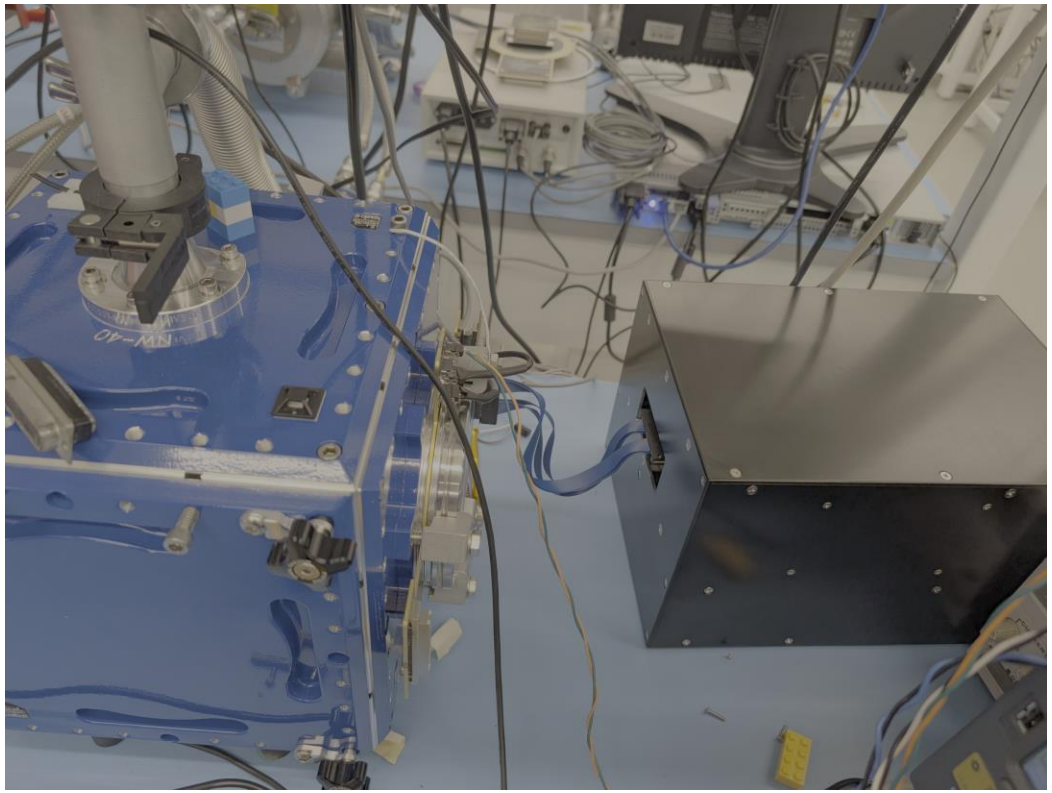
Device and readout system overview

Test Setup

- Operating under vacuum (1E-5 torr), at a 125 K temperature.
- STA Archon Controller, 12 MHz ADC.







02

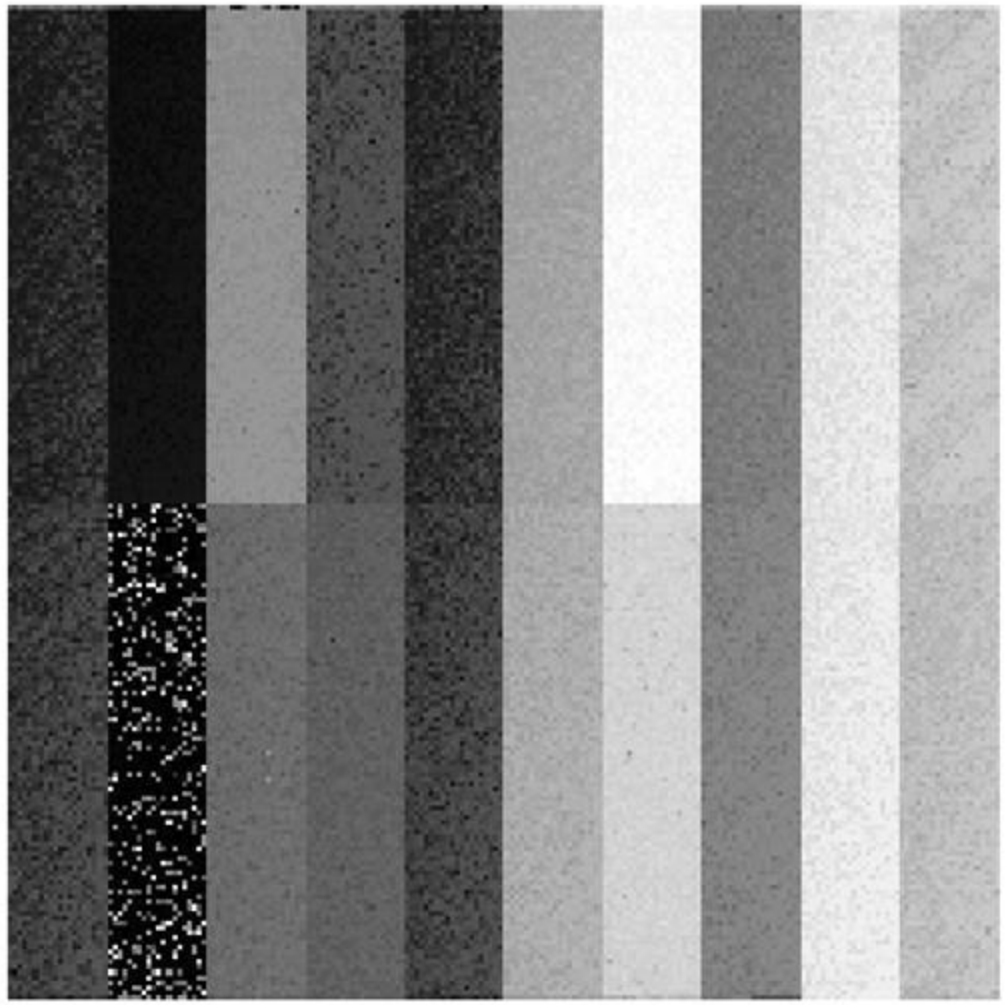
Preliminary tests

Preliminary tests

First full matrix acquisition parallel readout (scale optimized for contrast)

- Pixel selection logic ✅
- Analog front-end ✅
- Programable gain amp ✅
- BIAS current source ✅
- Readout sequence and softw. ✅

- The flavors have different response (100 x 20 pix region).
- Some of them seem not be working (saturated).
- **Each pixel has its own baseline.**



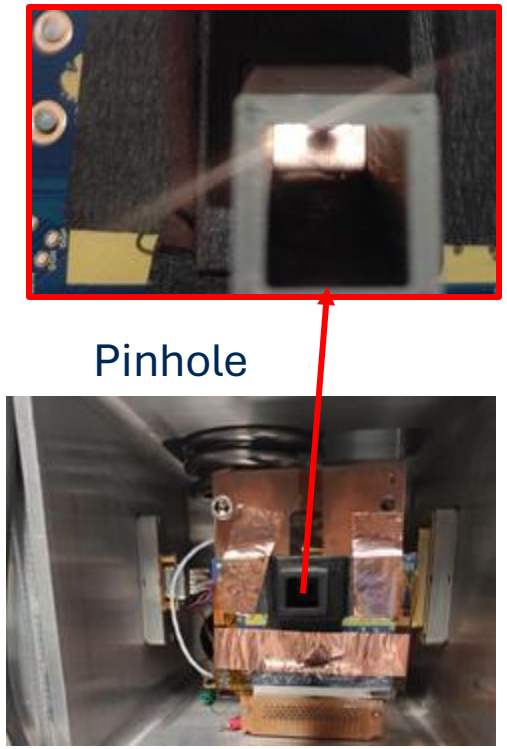
Full matrix image, no light, room temp.

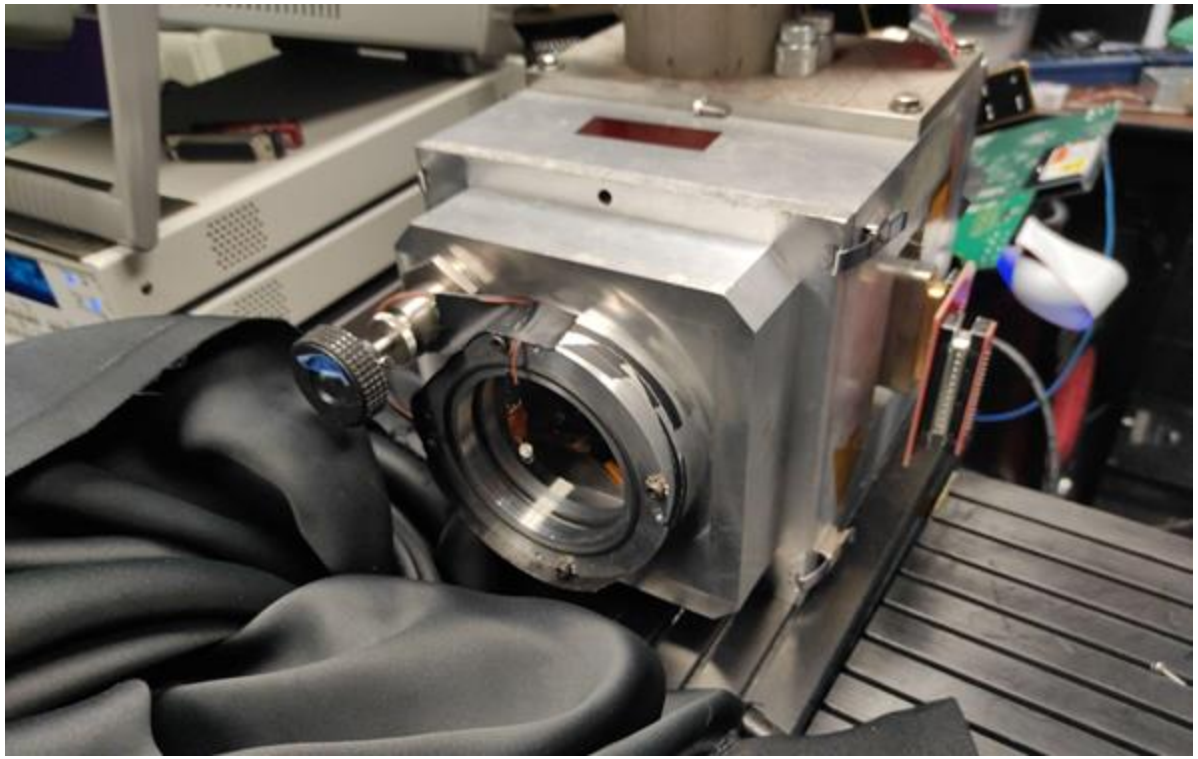
Preliminary test

Imaging

Improvised Pin-hole camera.

- LED placed in front of the windows.

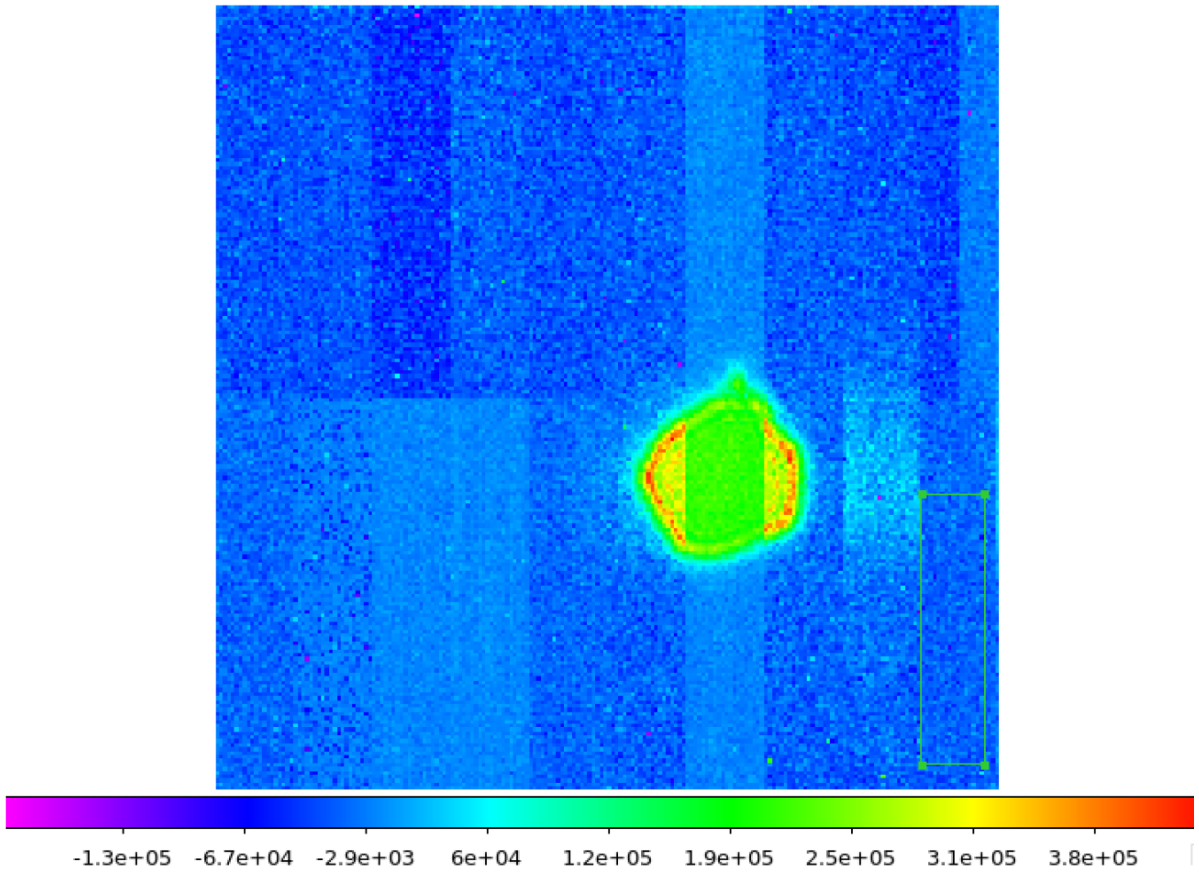




Preliminary test

Imaging

Pin-hole projection, verifying Sk-cmos imaging capability.



Full matrix image, illuminating the pin hole with a LED, single sample (N = 1), operation temperature 200 K

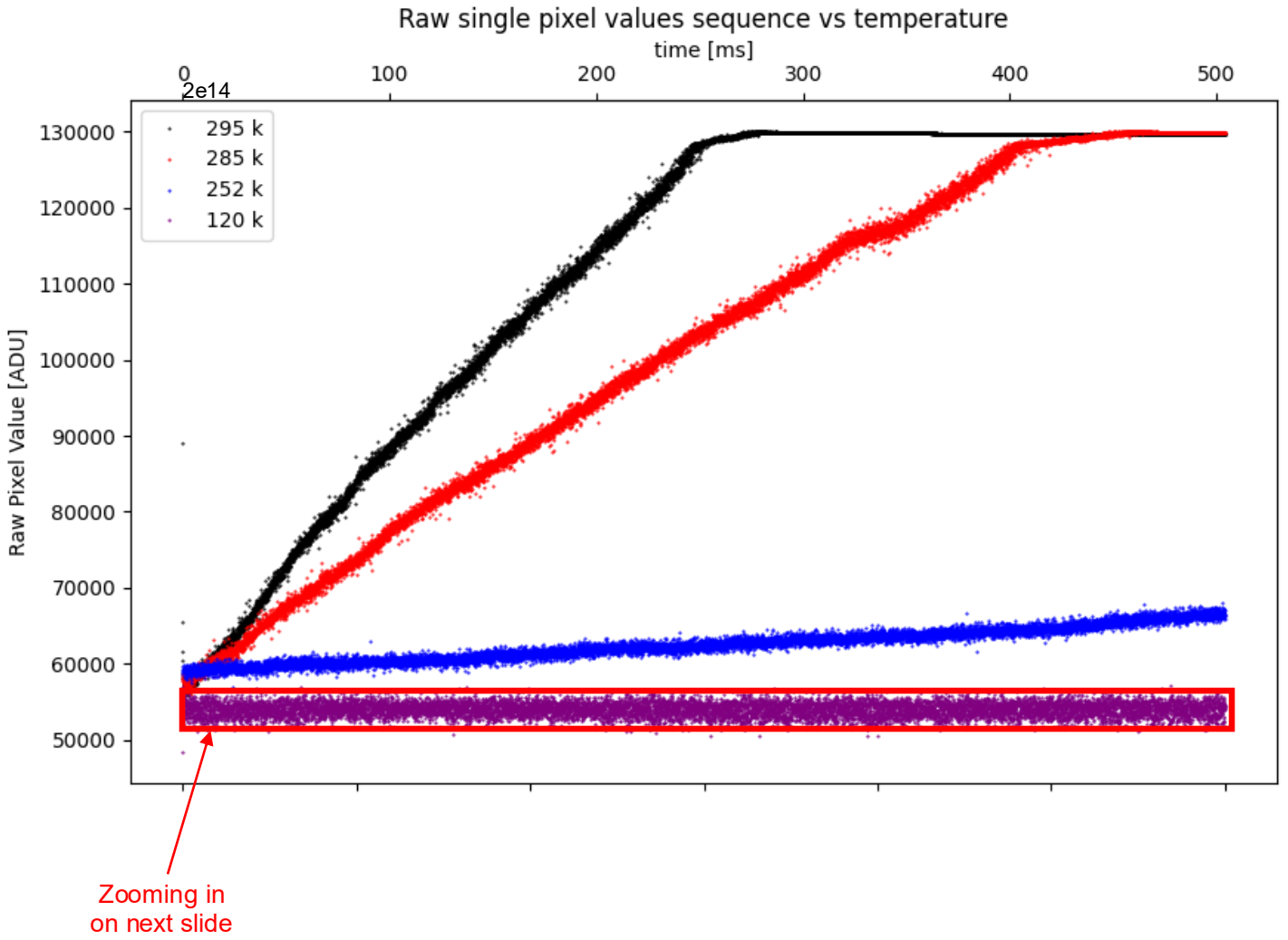
03

Single pixels level test within the matrix

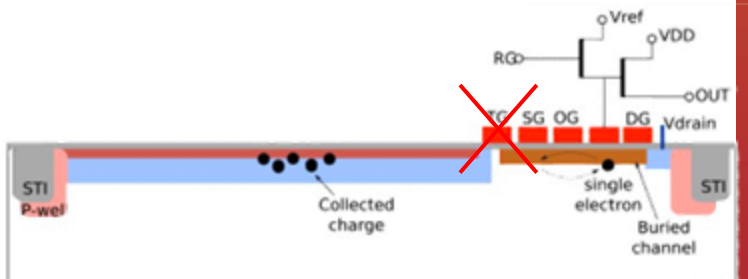
Single pixels test within the matrix

Floating gate drift

Single pixel, No transfer from PPD, continuous sampling, Column amplifier gain 25 V/V, single skip



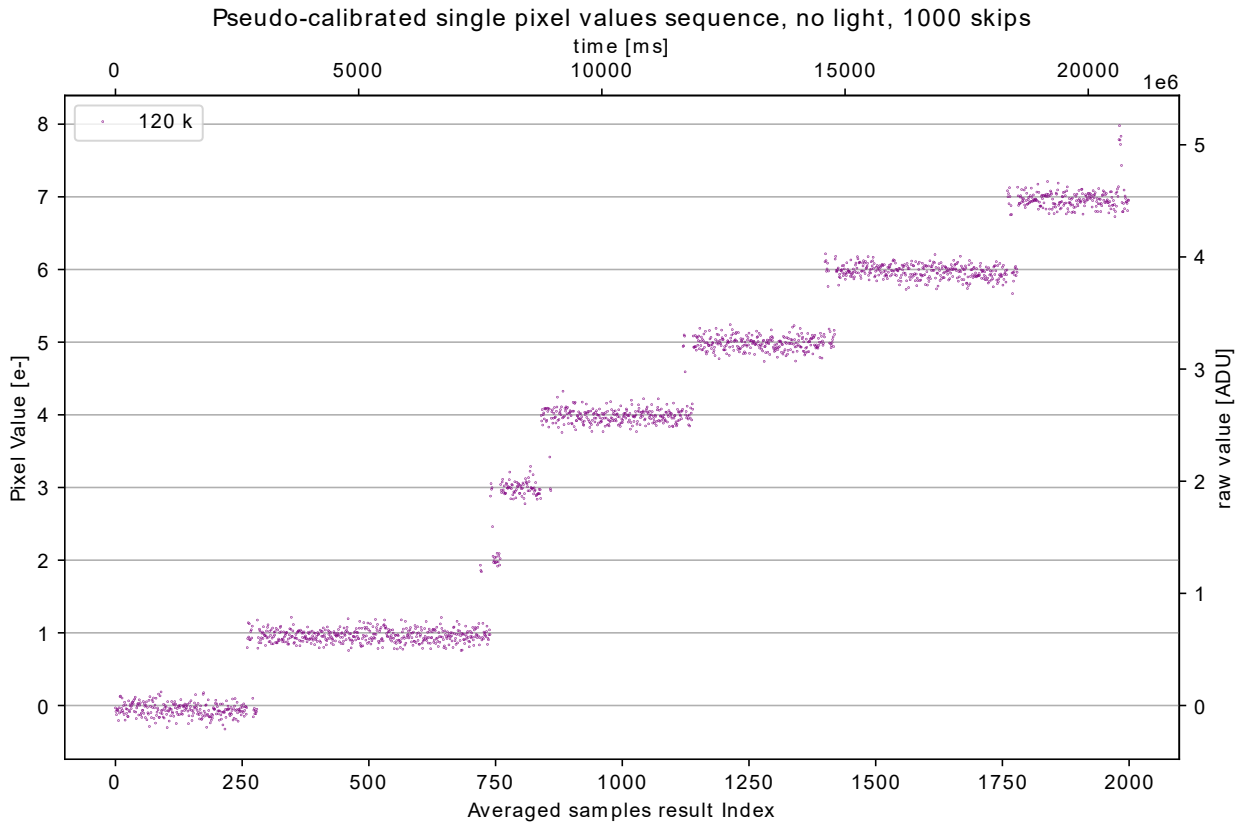
- Drift depends on temperature.
- At room temp the ADC gets saturated quickly.



Single pixels test within the matrix

Pseudo-calibration at pixel level.

Single pixel, NO transfer from PPD, continuous sampling, Column amplifier gain 25 V/V



NOISE ~0.087 e⁻

- Considering the first step as 0 e⁻ and using image conversion gain G_i=660000 ADU/e- (36 uV/e-)

Raw value = BZERO + Gi * Charge

Precise estimation of **BZERO** and **G_i** needed

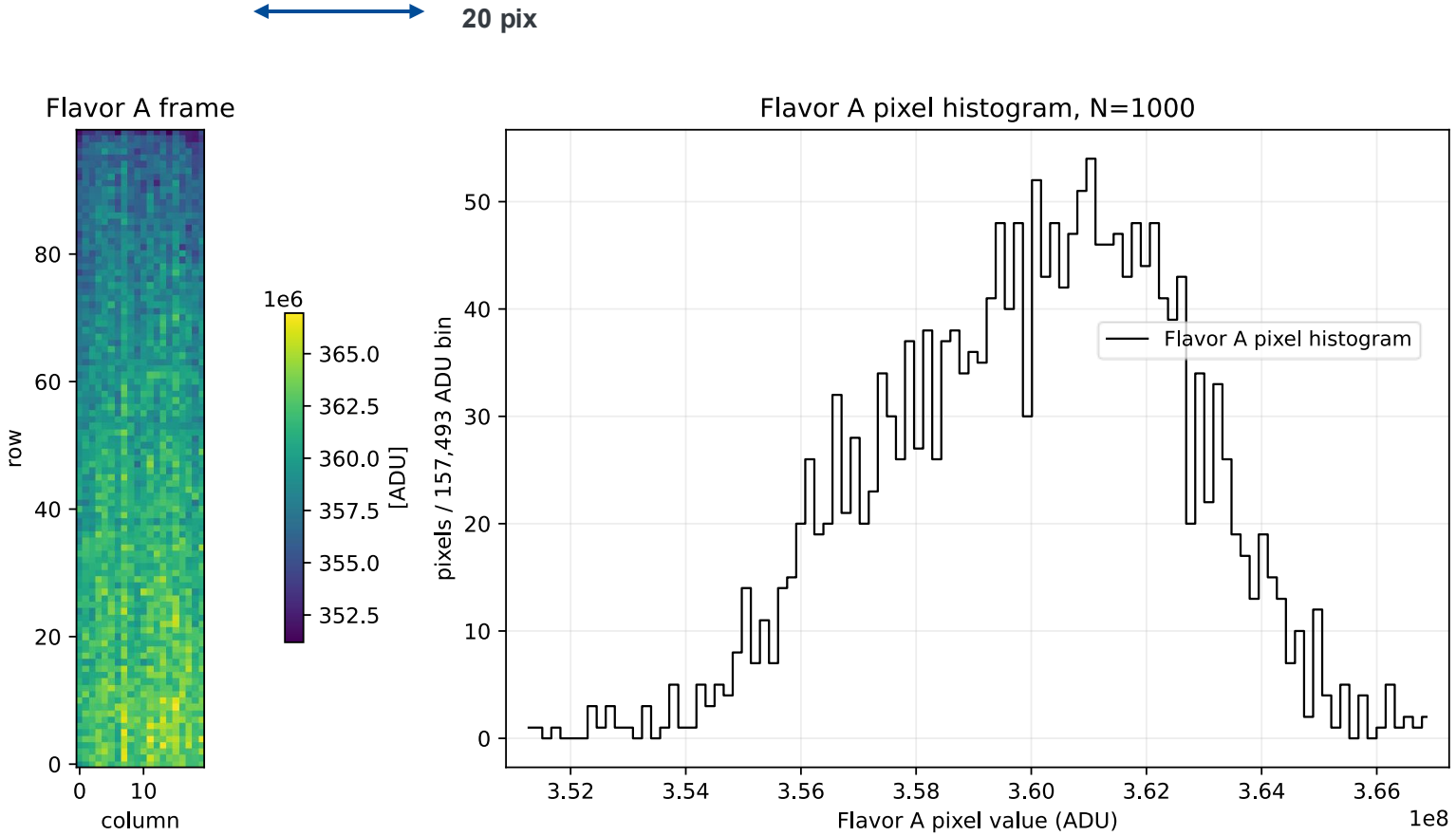
03

Matrix level image test

Matrix image test

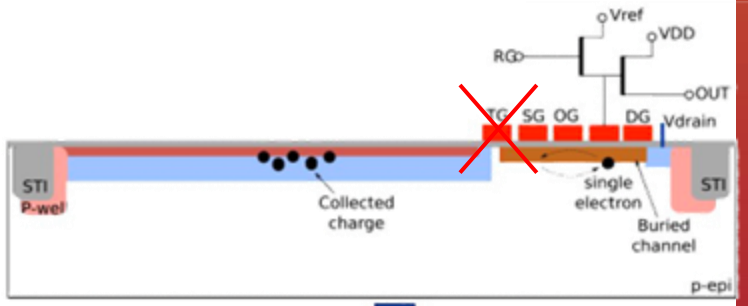
Raw frame

Flavor A Matrix, NO transfer from PPD, normal images 1000 skips, Column amplifier gain 25 V/V



- BZERO mismatch among pixels prevents sub-electron resolution without fine calibration

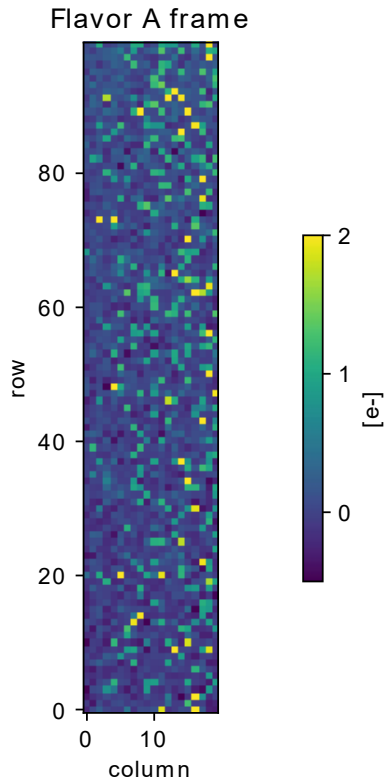
Raw value = BZERO + Gi * Charge

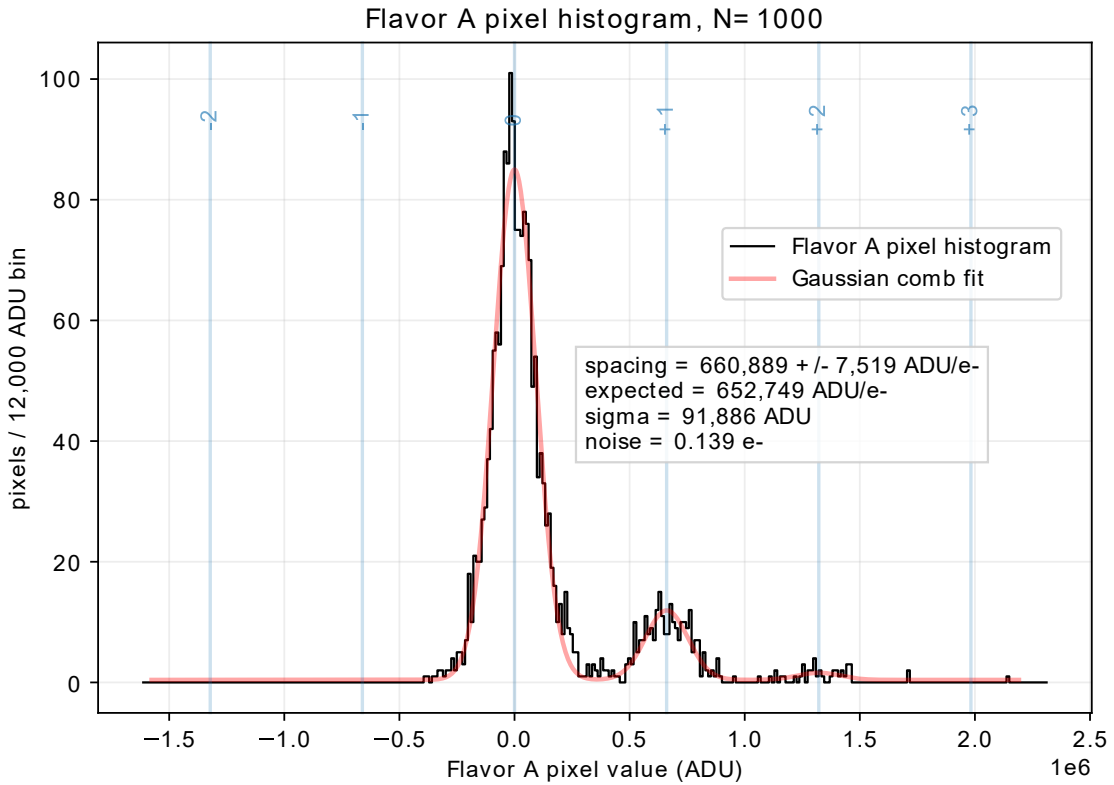


Matrix image test

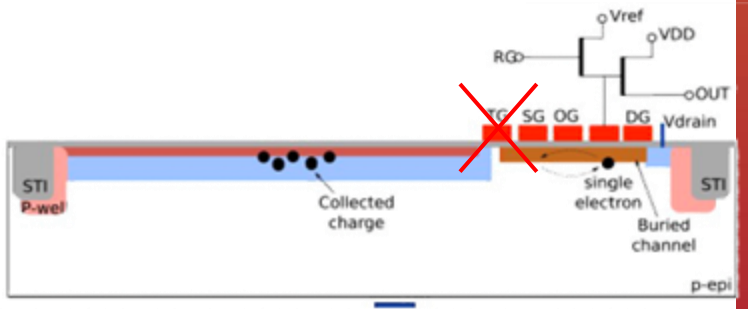
Calibrated frame (Preliminary)

Flavor A Matrix, NO transfer from PPD, single frame 1000 skips, Column amplifier gain 25 V/V





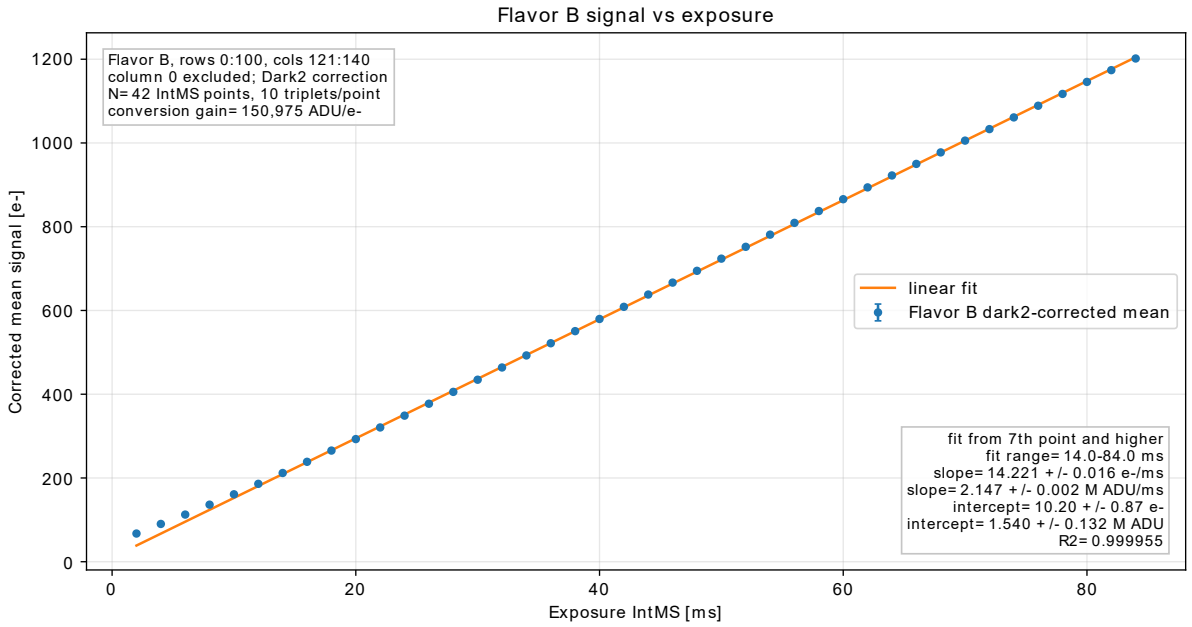
- Once we apply master bias substraction, single photon resolution becomes evident.
- Flavors Convertion Gain varies from 32 to 36 uV/e-,
- 0.13 to 0.15 e- rms at N=1000, 10 us/pix

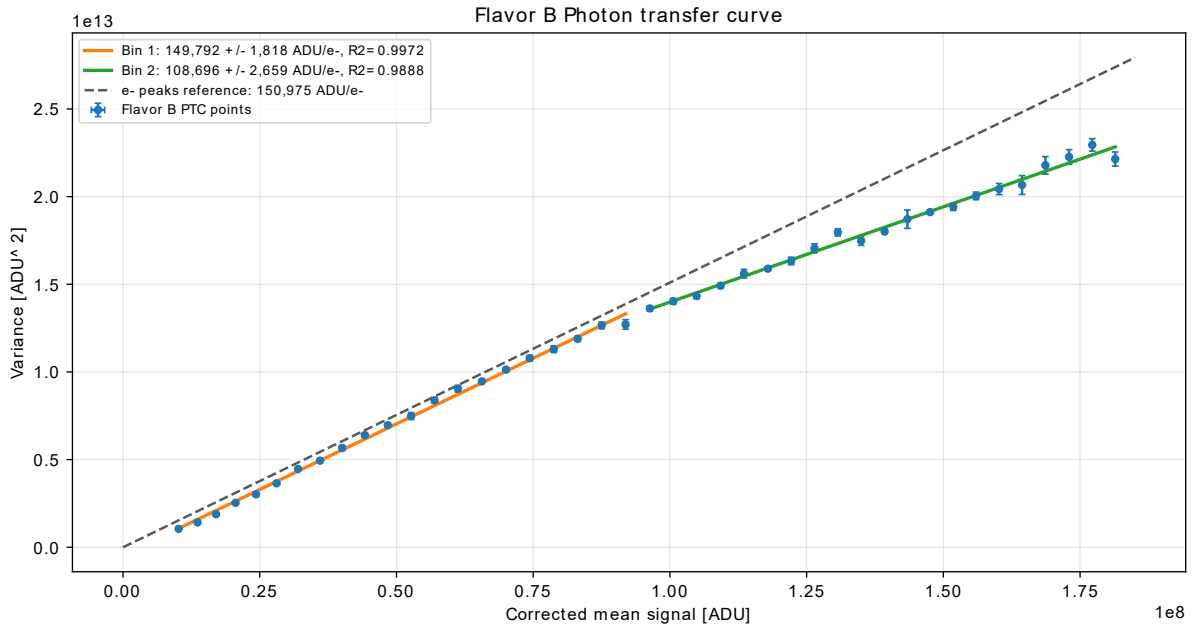


Matrix image test

Photon transfer curve and low light response (Preliminary)

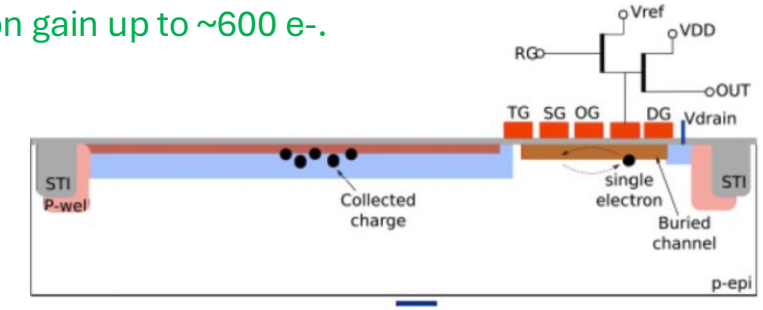
Flavor B, Column amplifier gain 7 V/V. LED inside dewar, no windows with transfer from PPD





- Values increase with exposure as expected.
- LED timing controlled from Archon.

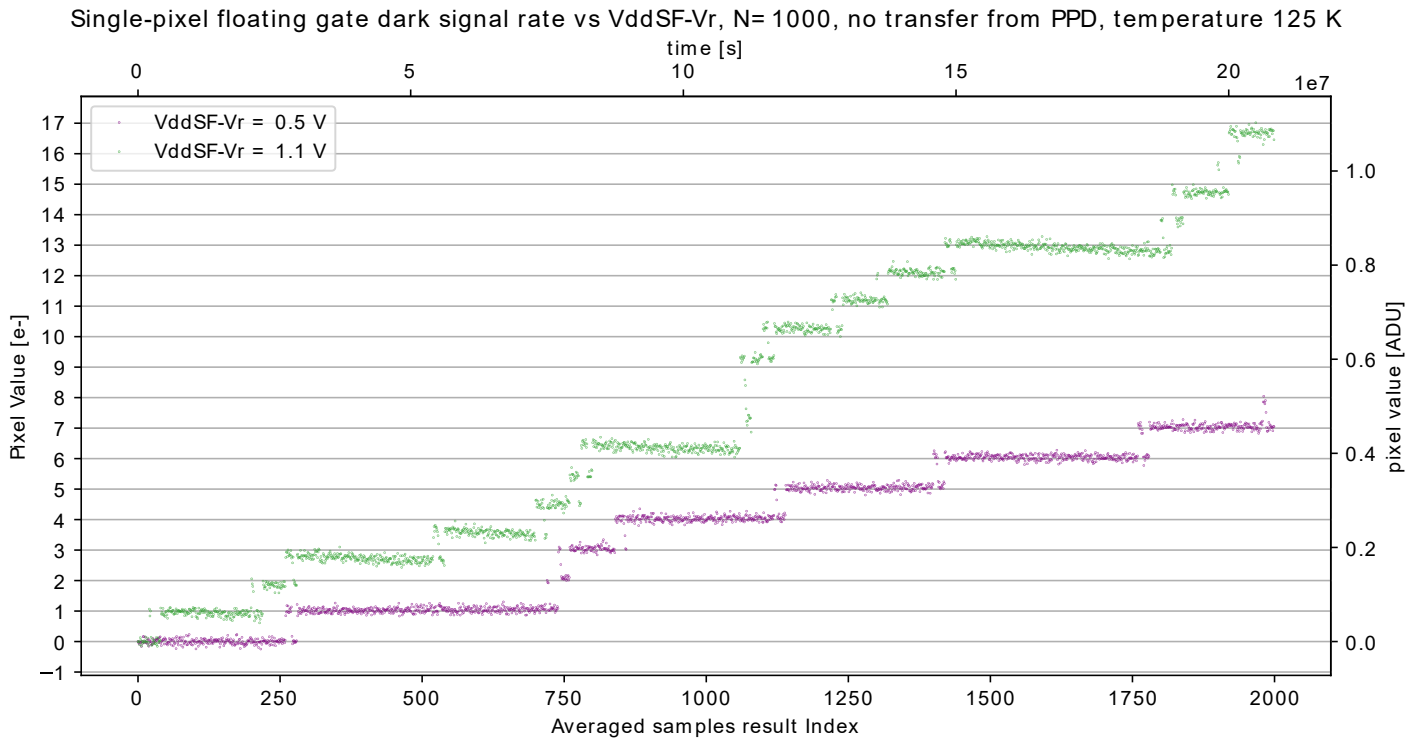
- PTC conversion gain agrees with the sub-e histogram conversion gain up to ~600 e-.

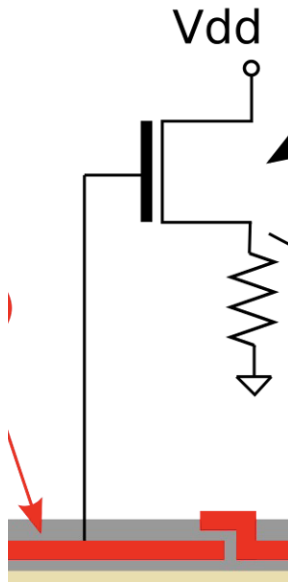


Matrix image test

Glow control (Preliminary)

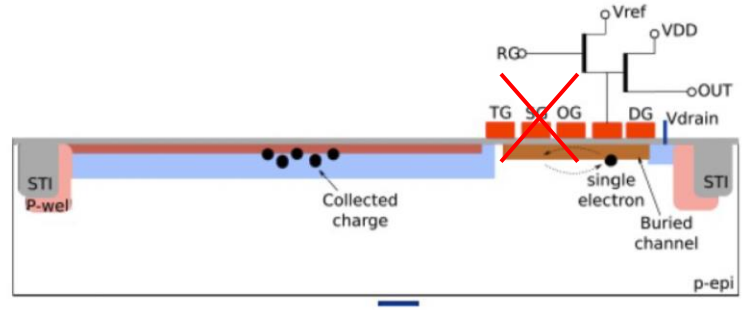
Flavor B, Column amplifier gain 25 V/V. Source Follower drain to source voltage effect.





- DECREASING Vds of source followers to minimun usable to lower the glow at each pixel.
- Low temperature to 120k/125 k for low DC.

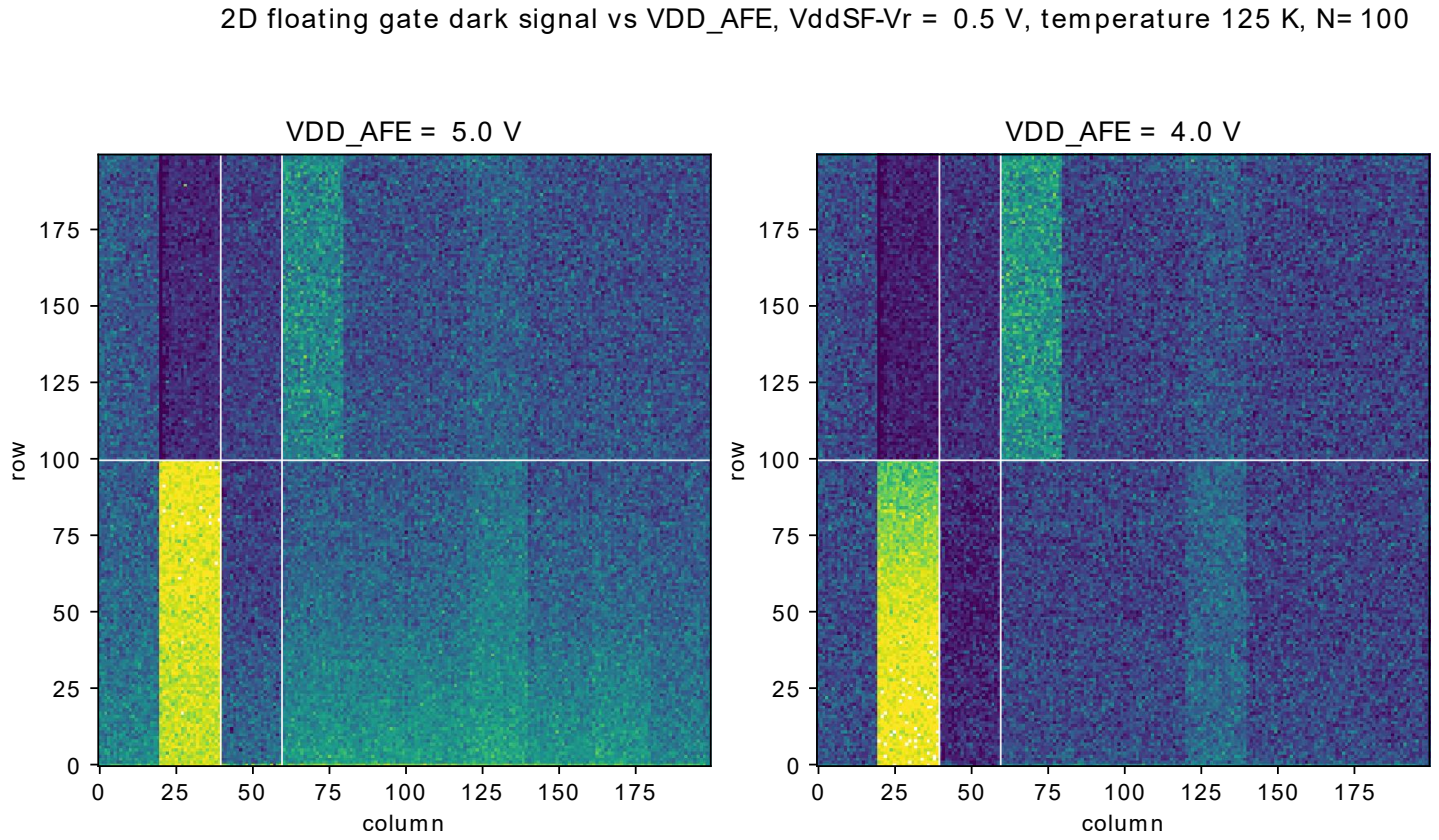
- Mitigating the glow is **critical** when there are **40,000** amplfifiers.

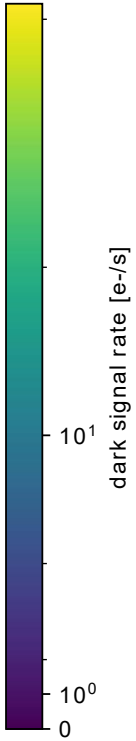


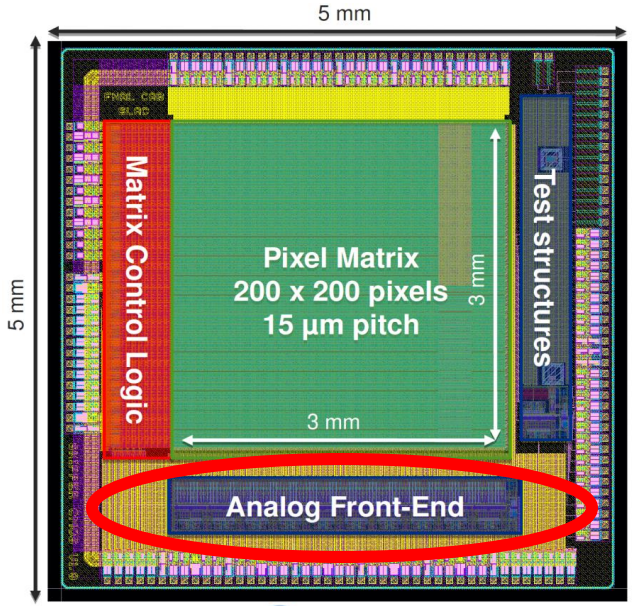
Matrix image test

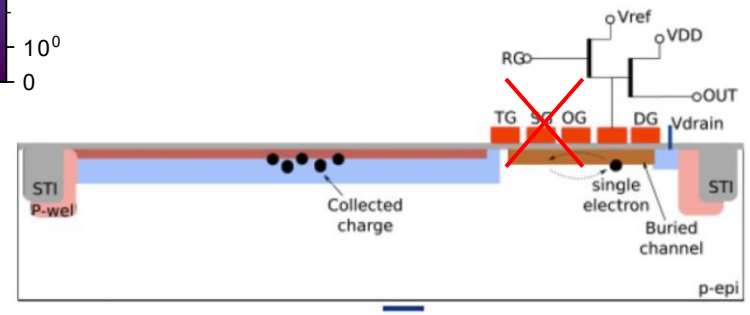
Glow control (Preliminary)

Analog front-end glow for different voltages.









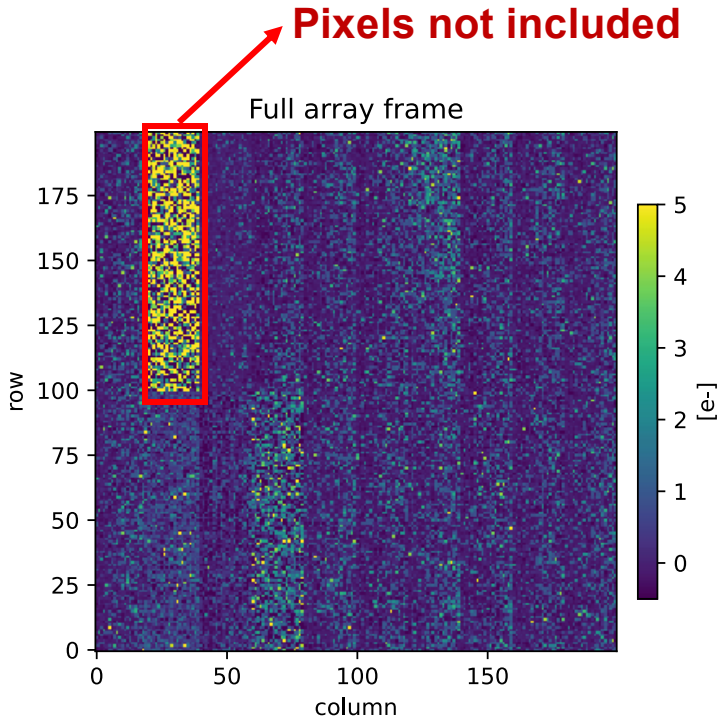
- **Acumulation rate decreased with VDD_AFE= 4V**

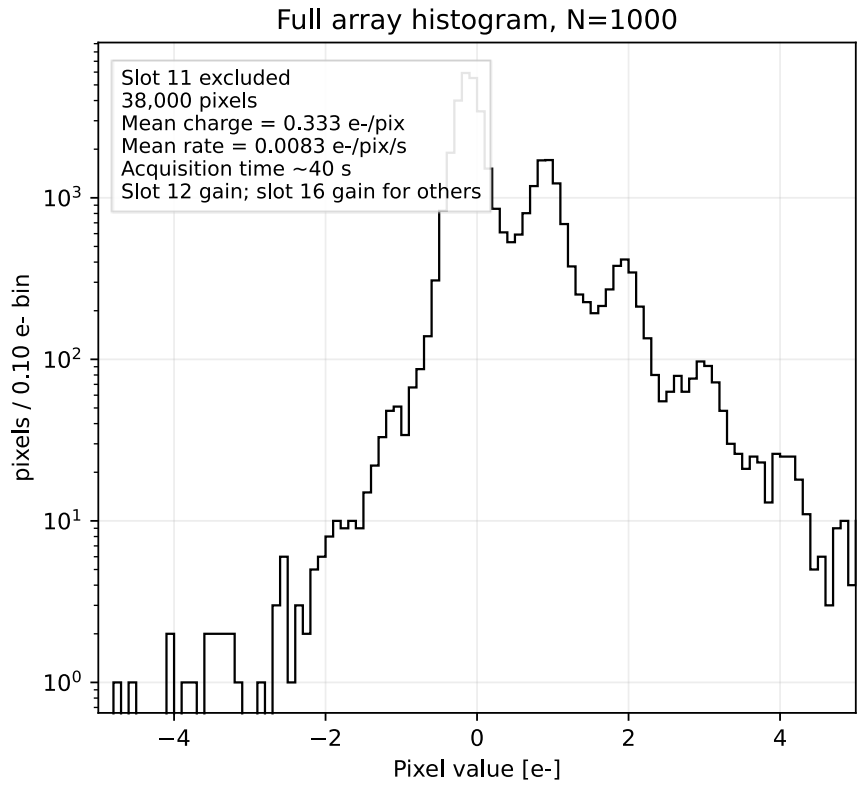
- DECREASING Analog front end voltage reduces the glow coming from there.

Matrix image test

Glow control (Preliminary)

Calibrated full sub-electron noise frame. Final glow contribution from output stage and analog front end per frame, 0s exposure + transfer from PPD.

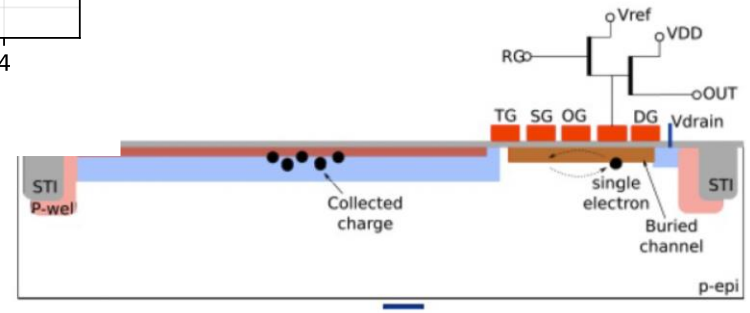




- ~0.33 e-/pix is added per frame by the AFE, pixel source follower glow and DC.
- Equivalent rate of ~0.008e e-/pix/s in a 40 s adquisition.
- Some flavors have higher DC/glow.

- **38,000 amplifiers included.**

- Pixels on the left of the 0e- peak are caused by incomplete zero correction.



Key takeaways

- Single electron resolution
  - Demonstrated at both, single pixel and complete array level, 0.13 e- at N=1000, 10 us per sample.
  - 0.13 e- rms /0.1 fps could be achievable in an 1Mpix sensor with fully column-parallel CMOS architecture.
- Evidence of high transfer efficiency from PPD for charge packet up to ~800 e-
- Low glow operation
  - Successfully demonstrated using a combination of BIAS optimization and readout schemes.
  - Measured dark signal rate (DC + glow) in dark frames of 0.008 e-/pix/s.

Next steps

- Plan next iteration
  - Identity best flavor
  - Possible change from rolling shutter to global shutter
- Parallel test and characterization at SLAC National Accelerator Lab.
- Test with readout ASIC sprocket3 to demonstrate future 3D stacking.



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Thanks!

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- cchavez@fnal.gov

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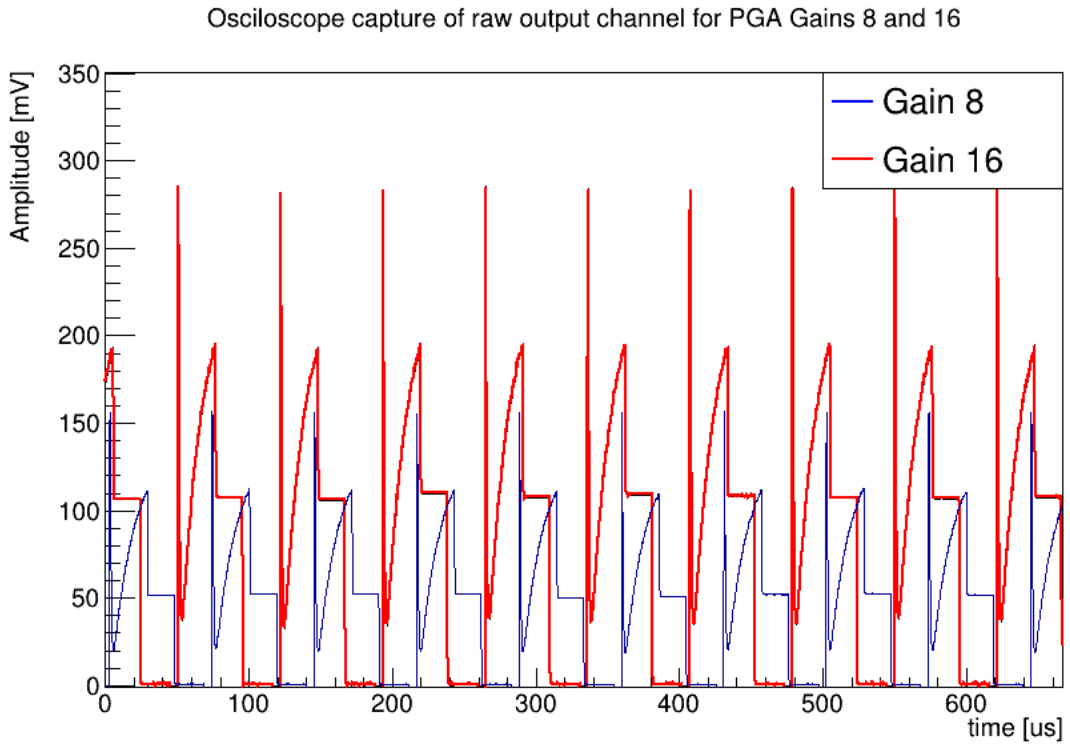


04

Additional information

Preliminary test

PGA test, oscilloscope captures of an output channel

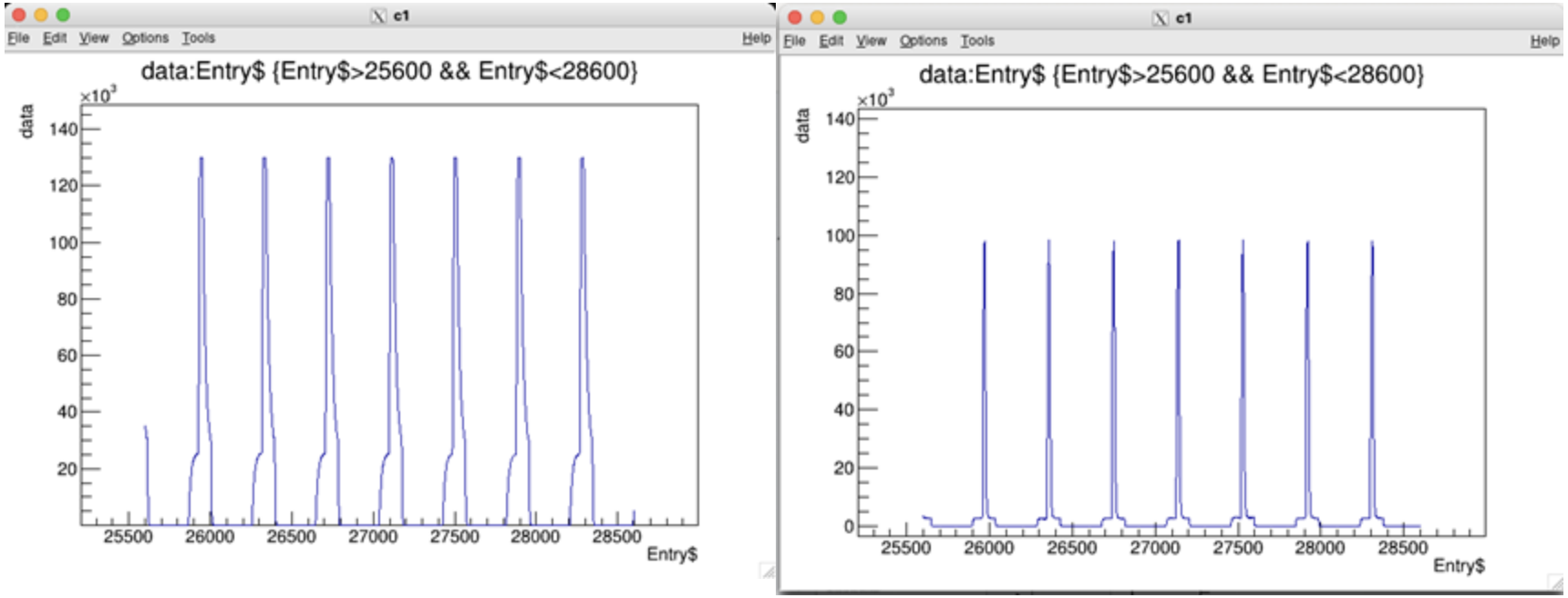


Preliminary test

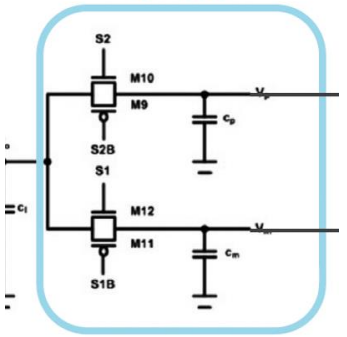
Cds Capacitors test, oscilloscope captures of an output channel

Cds sel (11)

Cds sel “8” (00)

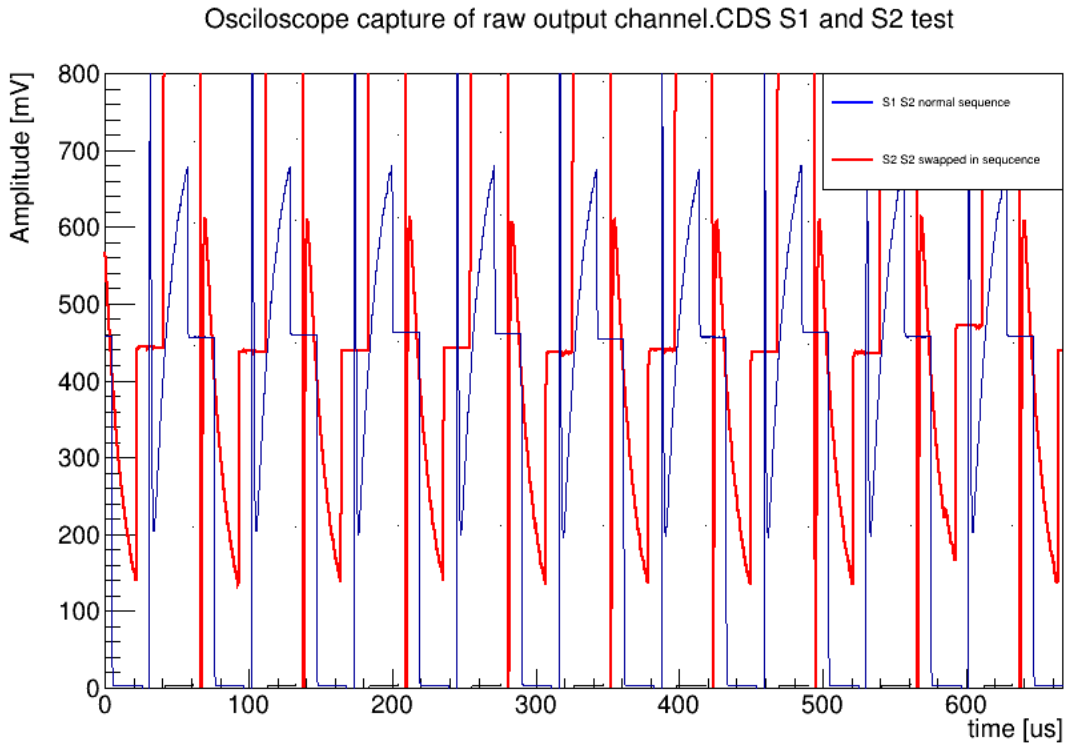


20:1 MUX/
Diff track and Hold
for CDS

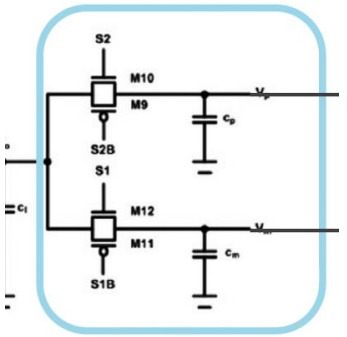


Preliminary test

S1 S2 track & hold test, oscilloscope captures of an output channel

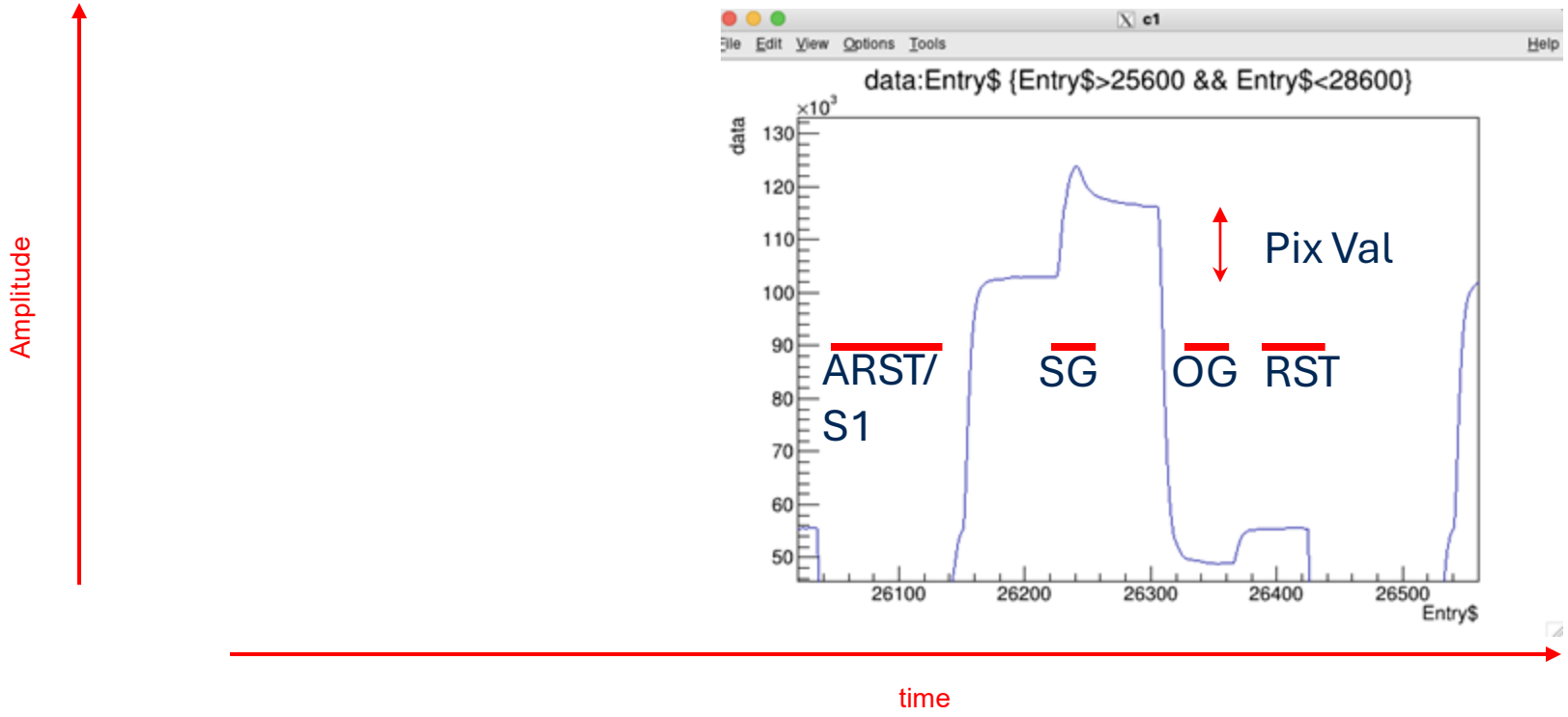


20:1 MUX/
Diff track and Hold
for CDS



Preliminary test

Gates control test, , oscilloscope captures of an output channel



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Preliminary test

Idc measurement (output source follower bias)

For idc sel (-155 C)

00: 147 uA

01: 588 uA

10: 297 uA

11: 1192 uA

For idc sel (-135 C)

00: 155 uA

01: 618 uA

10: 312 uA

11: 1240 uA

For idc sel (-9 C)

00: 188 uA

01: 755 uA

10: 379 uA

11: 1521 uA

Idc sel (Nominal)

00: 200 uA

01: 800 uA

10: 400 uA

11: 1600 uA

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Preliminary test

Imaging with the sk-cmos

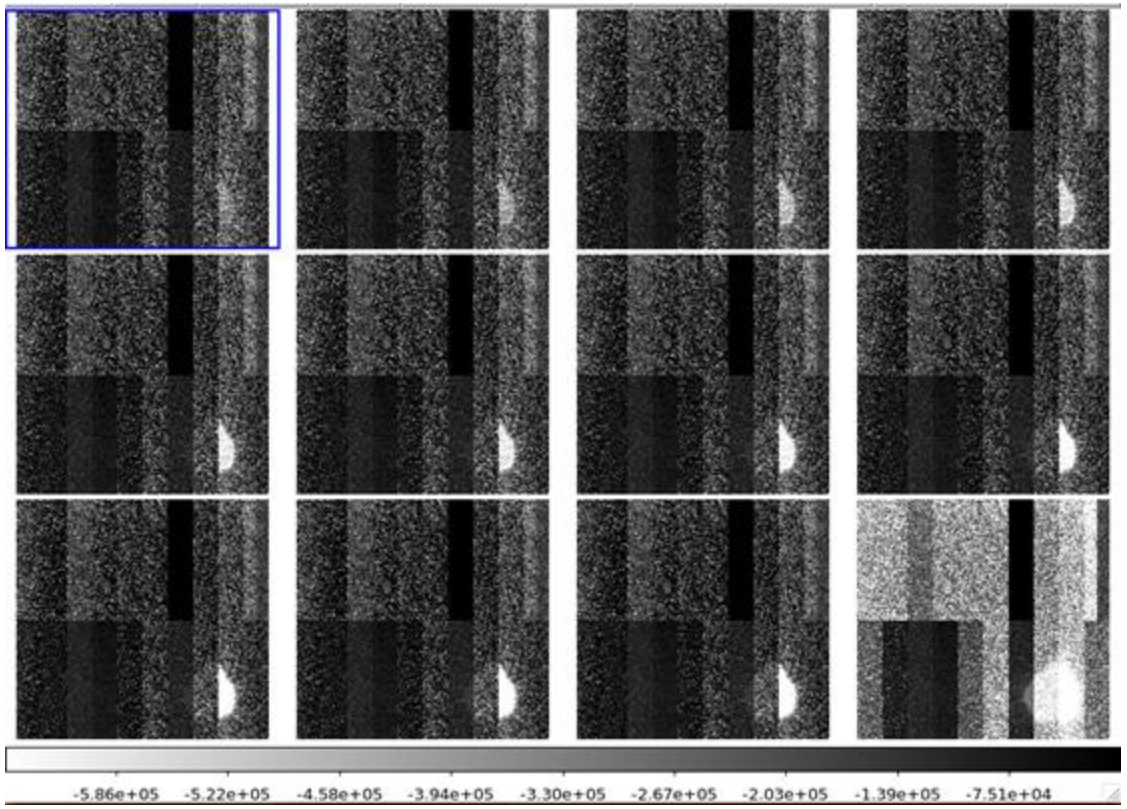
Wafer 1, LED fixed varying exposure , PGA gain 1, single skip

Expose and then read (not compatible with rolling shutter)

10,20,30,40 ms

40,50,60,70 ms

80,90,100, 250 ms



Read:

- Select Row:
  - Select column:
    - Dump FG/OG **X**
    - Transfer from PPD **X**
    - sample N times, dump
  - Go to next column
- Go to next row

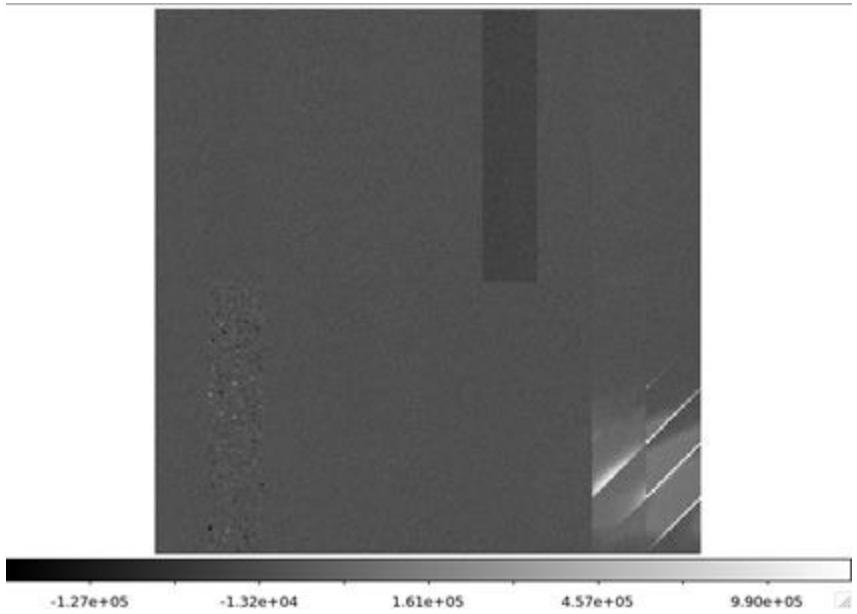
Full matrix images with Pin Hole with LED at fixed positions, different exposures. Single sample, Temp 200 k

Preliminary test

Imaging with the sk-cmos. Sequencer correction

Wafer 1, moving led around

- Sequencing fixed, selection logic, PGA, CDS tested ok!
  - The column selector was not going back to 0 after processing the last column



Malformed image due to a mistake in the sequencer

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Single pixels test within the matrix

Issues at low temp



On, idle



On, readout



off

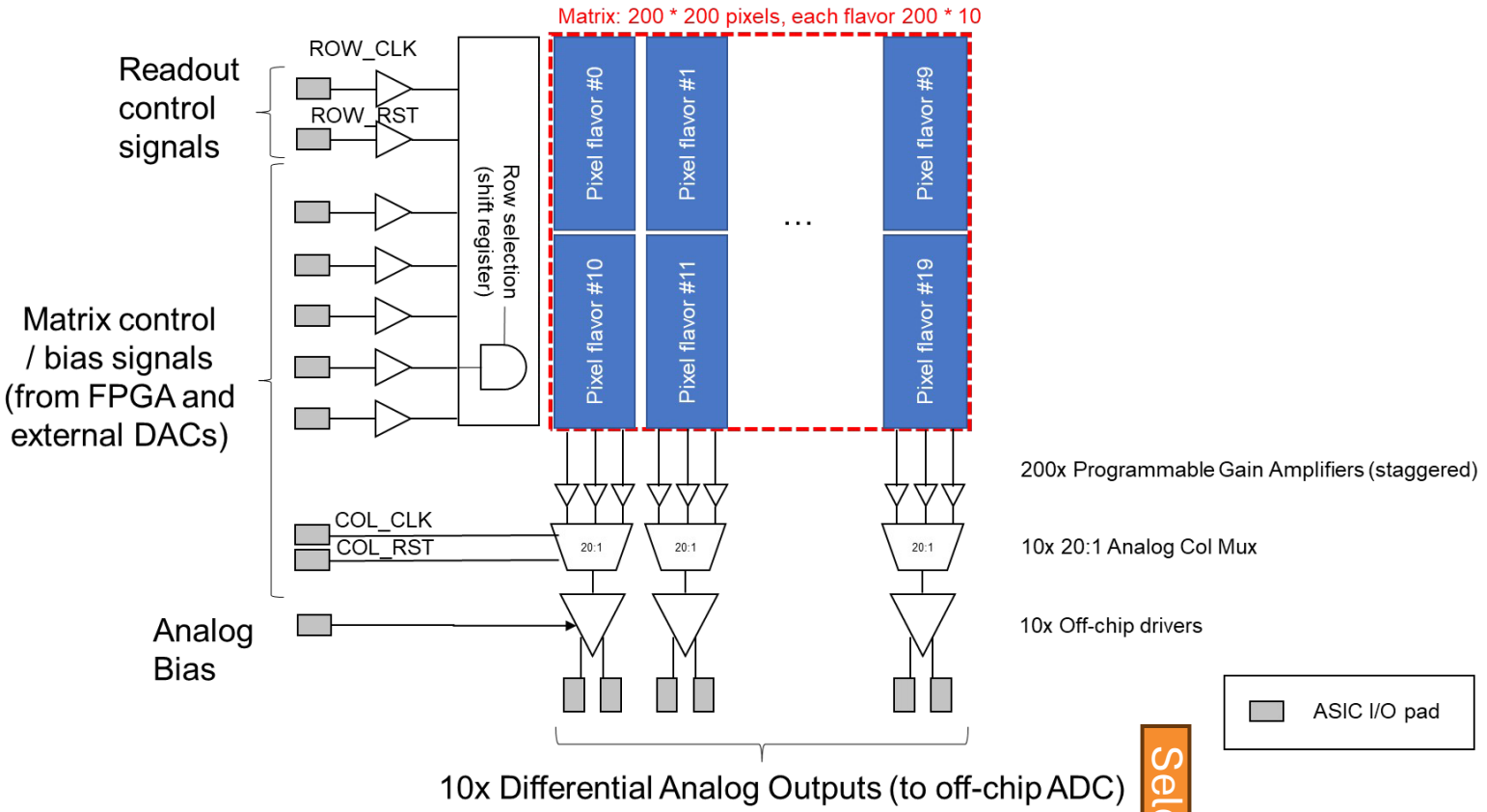
- The chip PTAT shuts down at low temperature. It starts failing below 180 K
- We use the STARTUP pin in HIGH all the time to keep them working.

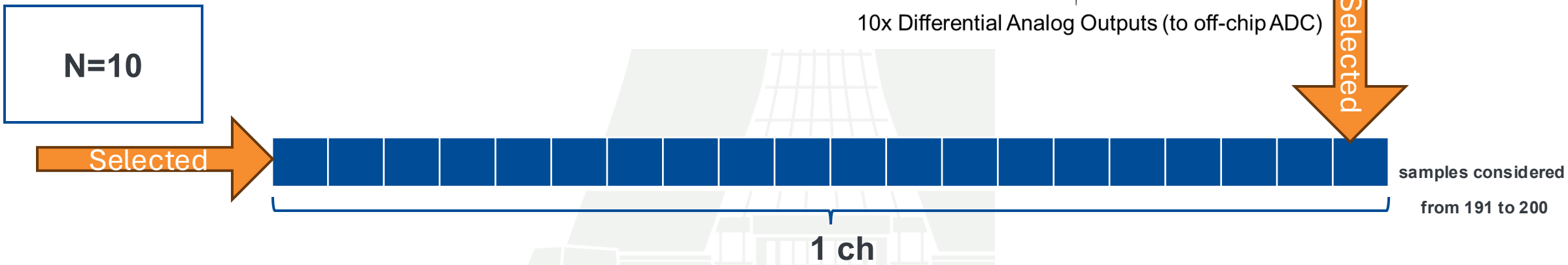
Device and redout system overview

Readout sequence

- Read:
  - Select Row
    - Select column
      - Dump FG/OG
      - Transfer from PPD, sample N times, dump
    - Go to next column
  - Go to next row

NON-DISTRUCITVE READOUT MUST WORK IN ORDER TO READ THE WHOLE MATRIX

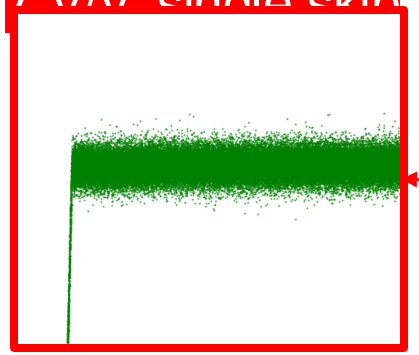


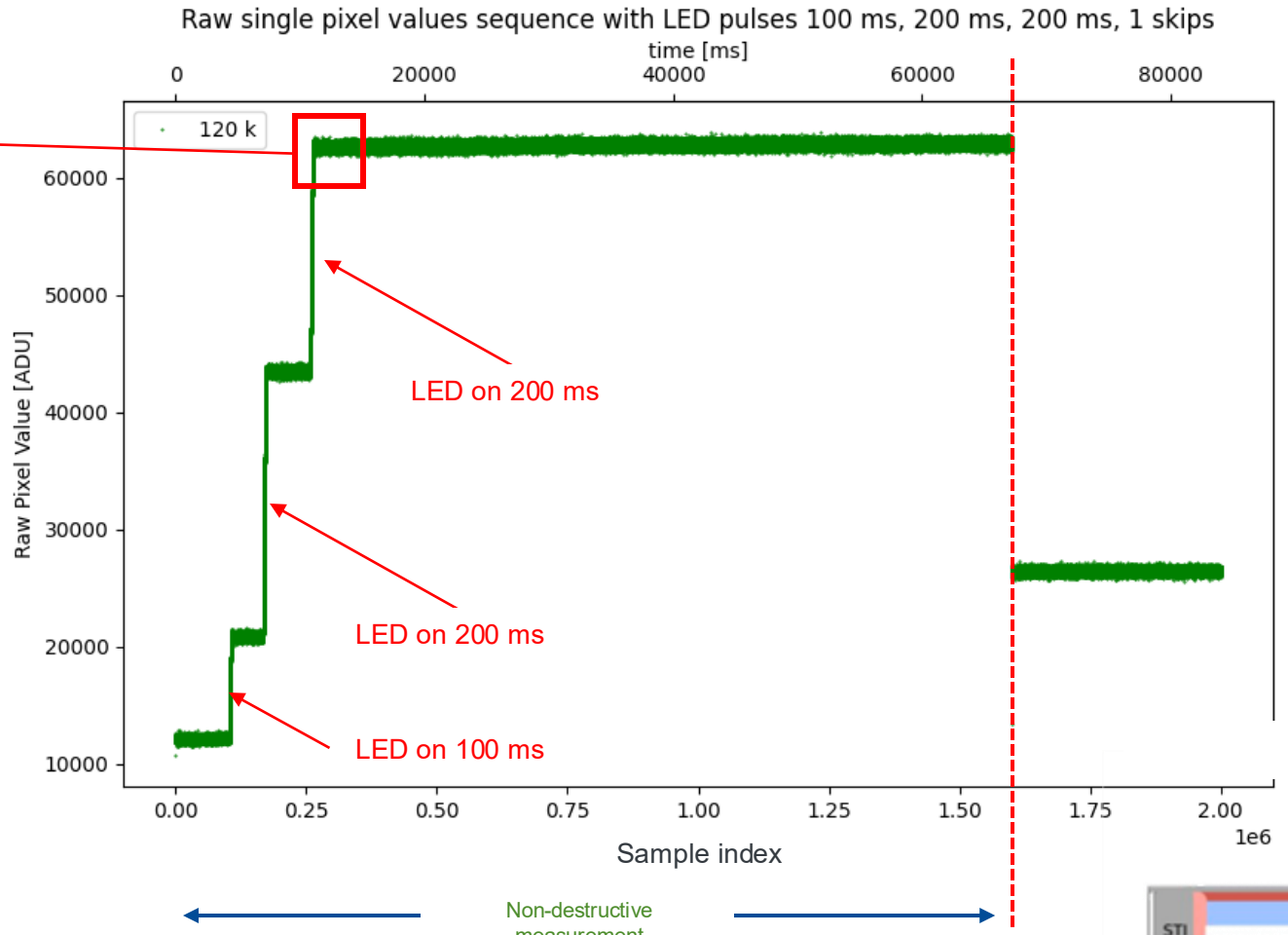


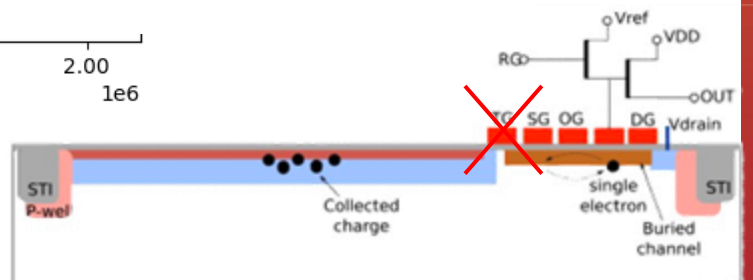
Single pixels test within the matrix

Placeholder subheading (optional)

Wafer 1, SINGLE PIXEL, NO transfer from PPD, continuous sampling, Column amplifier gain 7 V/V, single skip



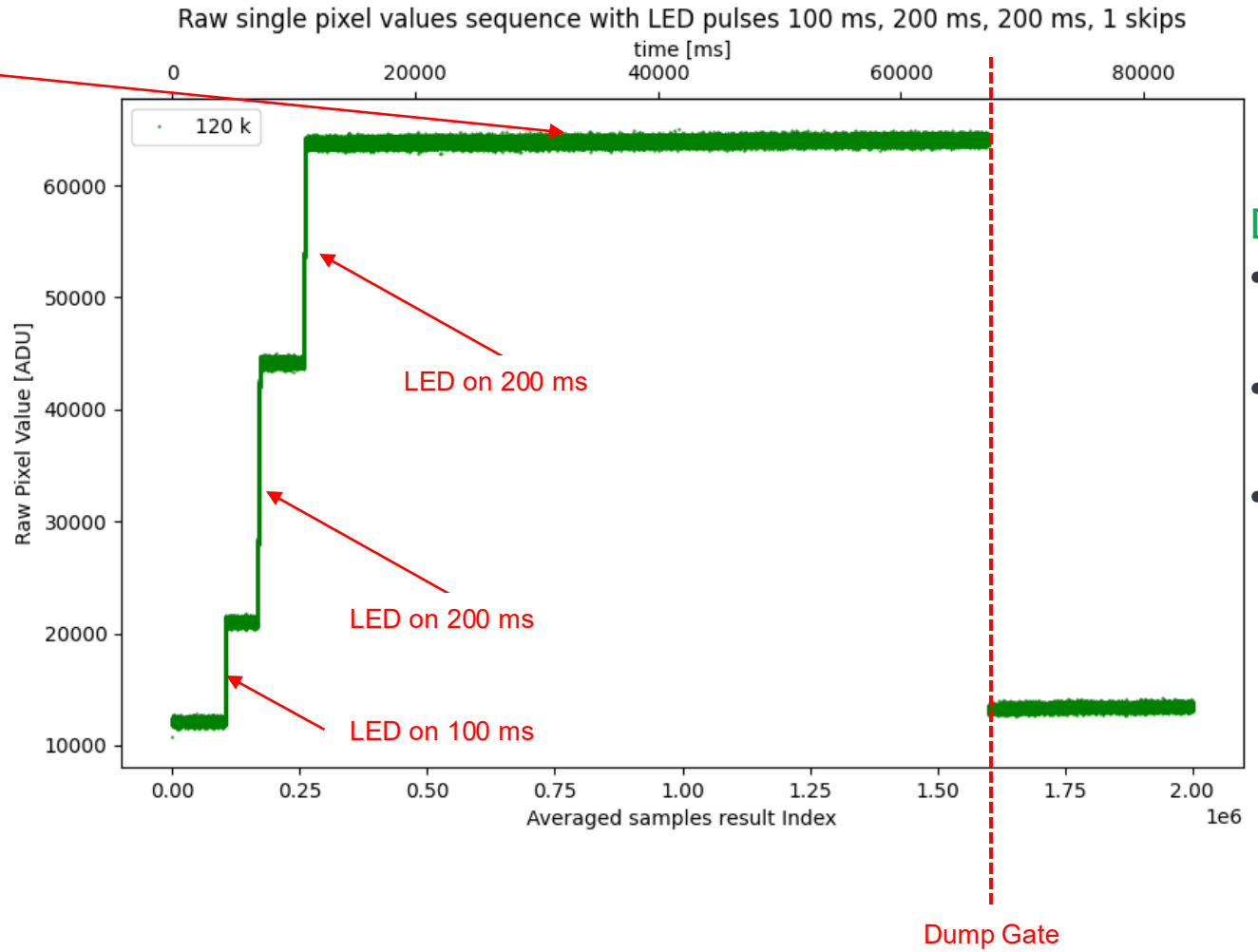




Single pixels test within the matrix

Improving dumping

Wafer 1, SINGLE PIXEL, NO transfer from PPD, continuous sampling, Column amplifier gain 7 V/V, single skip



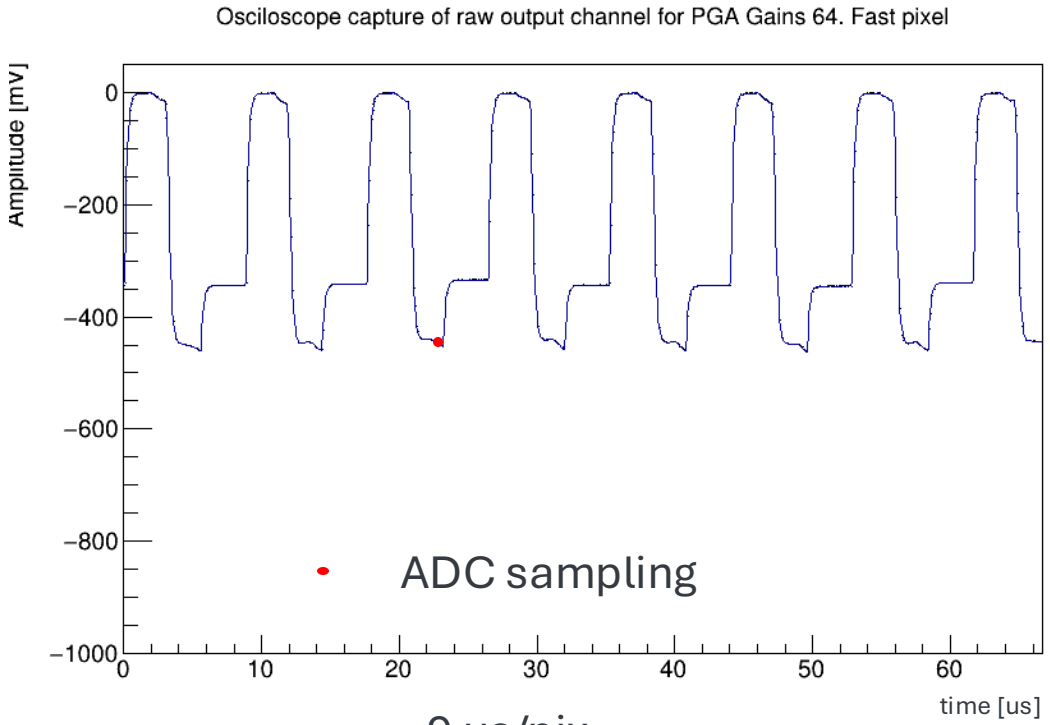
Dumping improved

- Higher voltage for Vdrain. (7 V)
- Higher voltage for DG high level (5.5 V)
- Multiple dumping cycles (100 times)

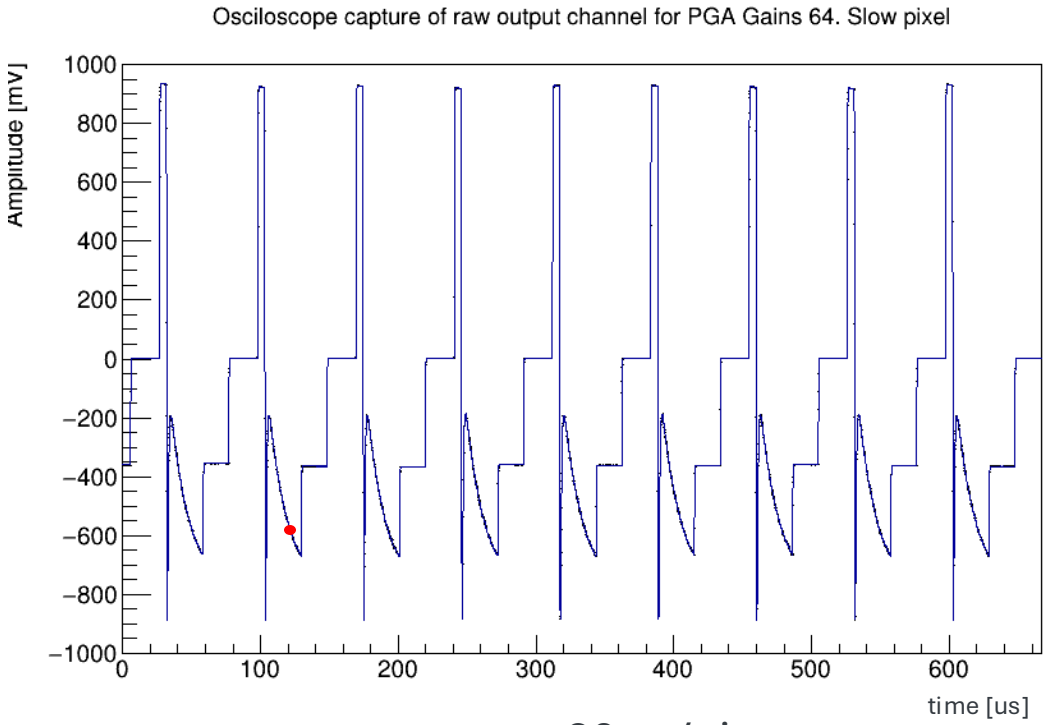
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Single pixels test within the matrix

Speed considerations, oscilloscope captures of an output channel



~9 us/pix



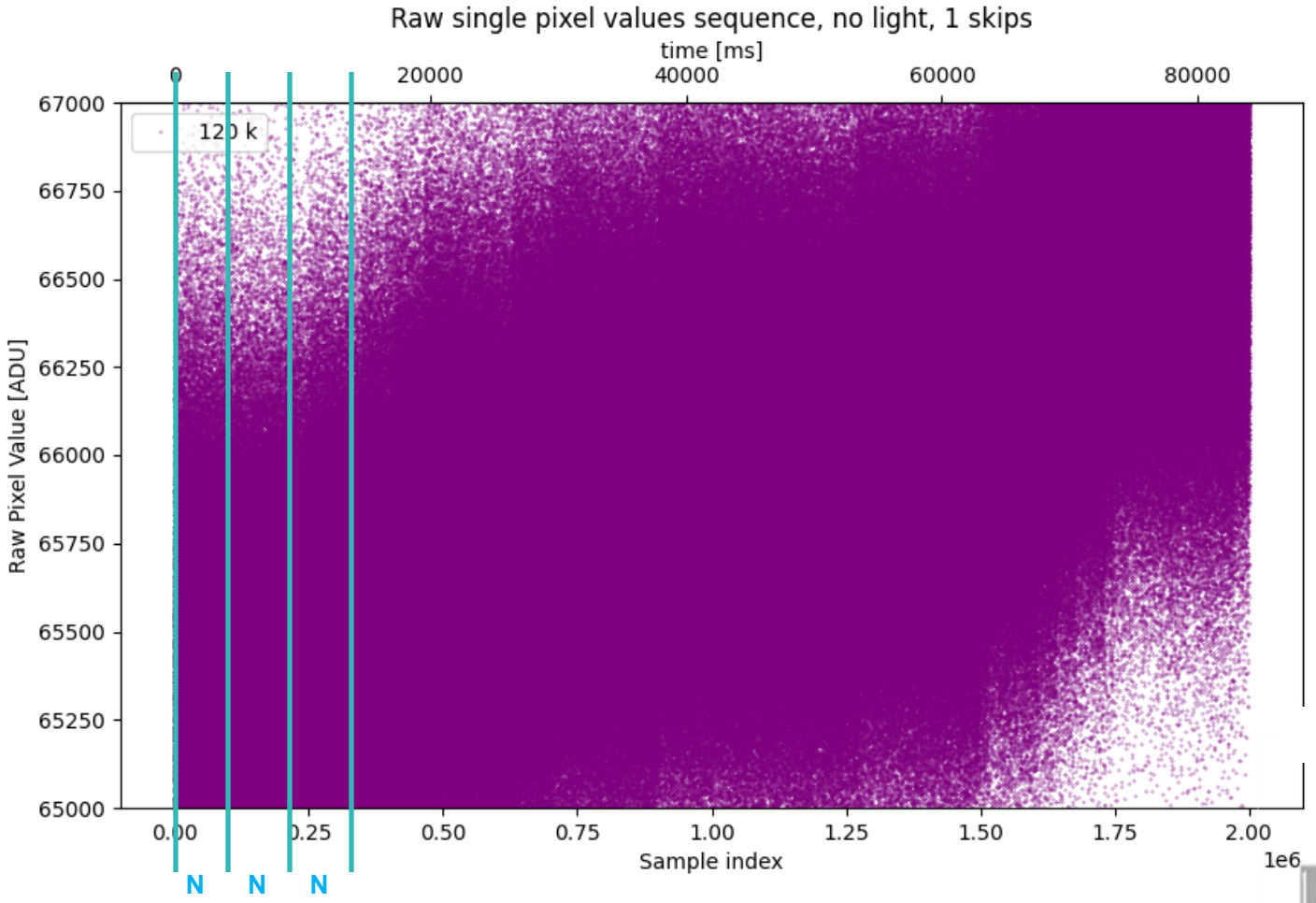
~80 us/pix

- Speeds of up to ~ 10 us/pixel possible but all the test were performed using the slow pixels. Noise increases slightly at fast speed but that can be due to non-optimal ADC timing.
- This readout system cannot go below 10 us/pixel. It's not a limit set by the Sk-cmos chip

Single pixels test within the matrix

Single pixel skipping

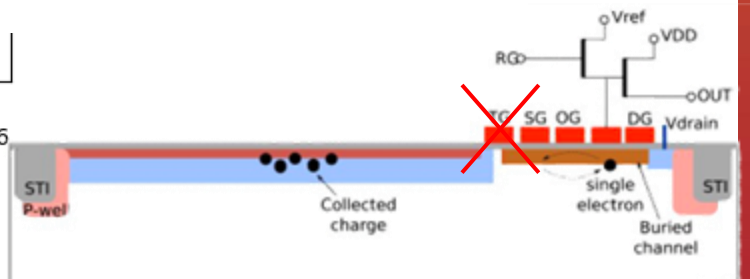
Wafer 1, SINGLE PIXEL, NO transfer from PPD, continuous sampling, Column amplifier gain 25 V/V



N= # Skips

NO LED pulses

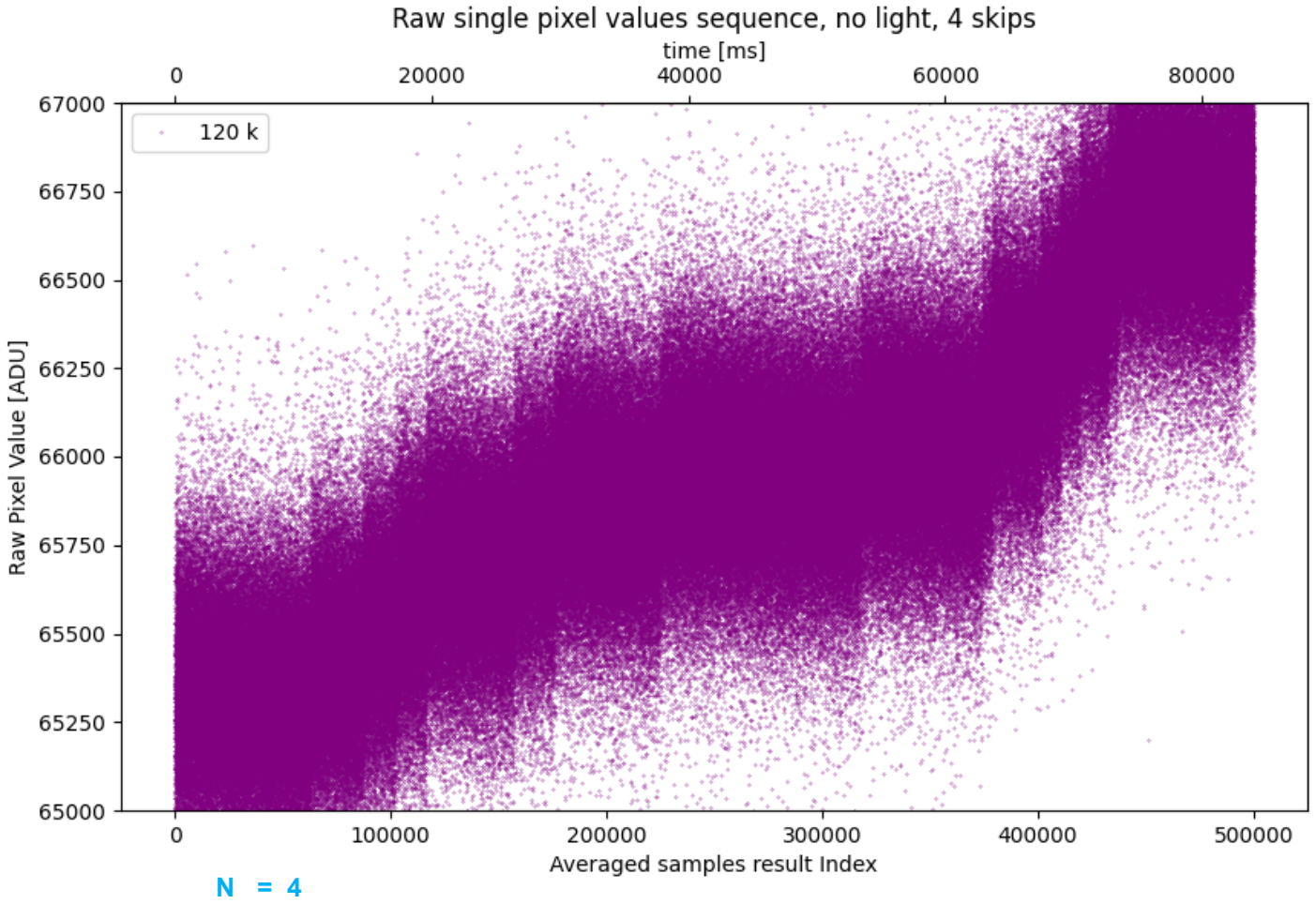
- Take **N** points and get the mean value and plot the result as new point.
- This is equivalent to a pixel with N skips. Since we are using the same pixel.



Single pixels test within the matrix

Single pixel skipping

SINGLE PIXEL, NO transfer from PPD, continuous sampling, Column amplifier gain 25 V/V



N = 4

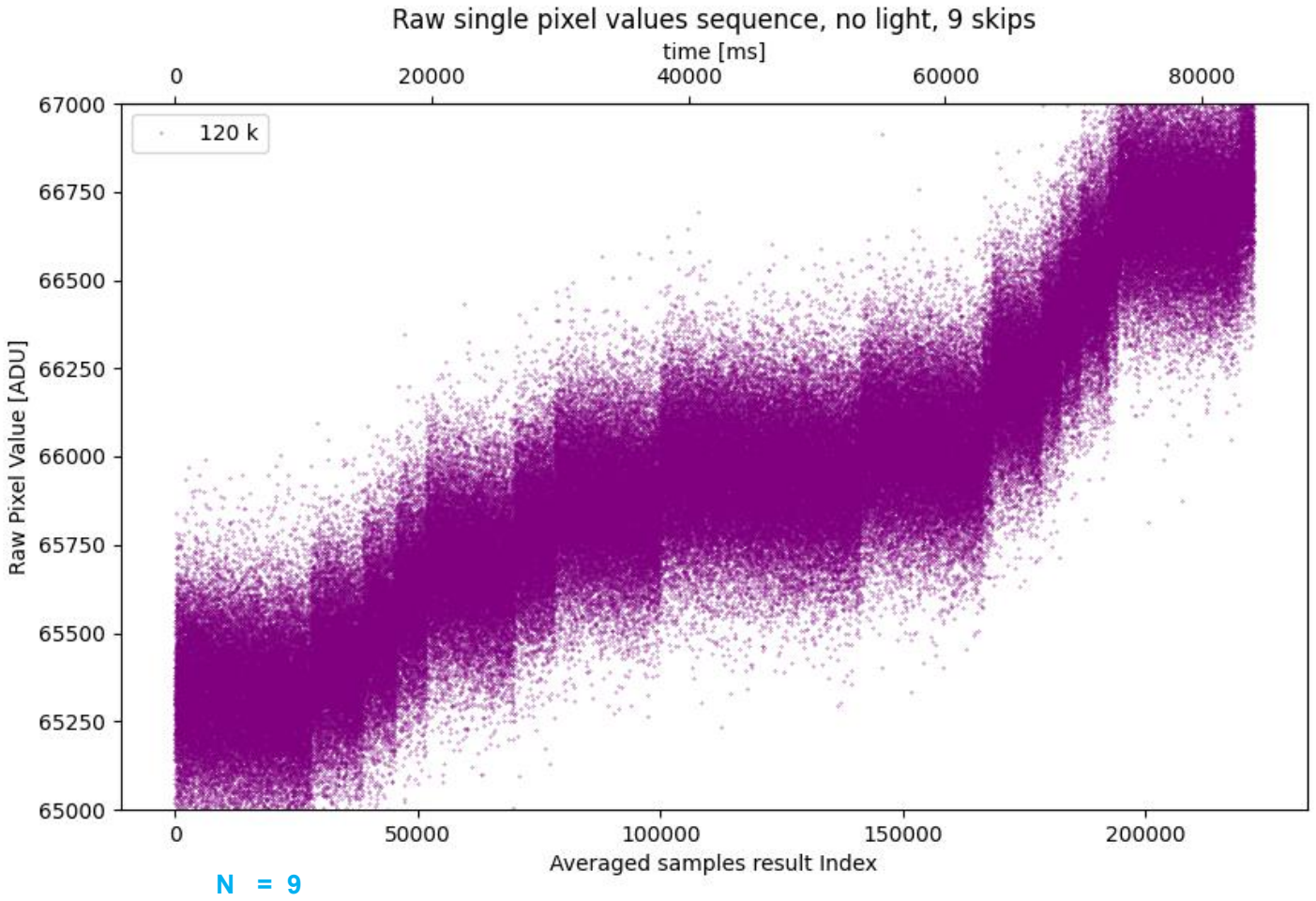
NO LED pulses

- Each point is the result of averaging N points from the previous plot.
- Dispersion gets lower.--> Noise gets lower.

Single pixels test within the matrix

Single pixel skipping

SINGLE PIXEL, NO transfer from PPD, continuous sampling, Column amplifier gain 25 V/V



N = 9

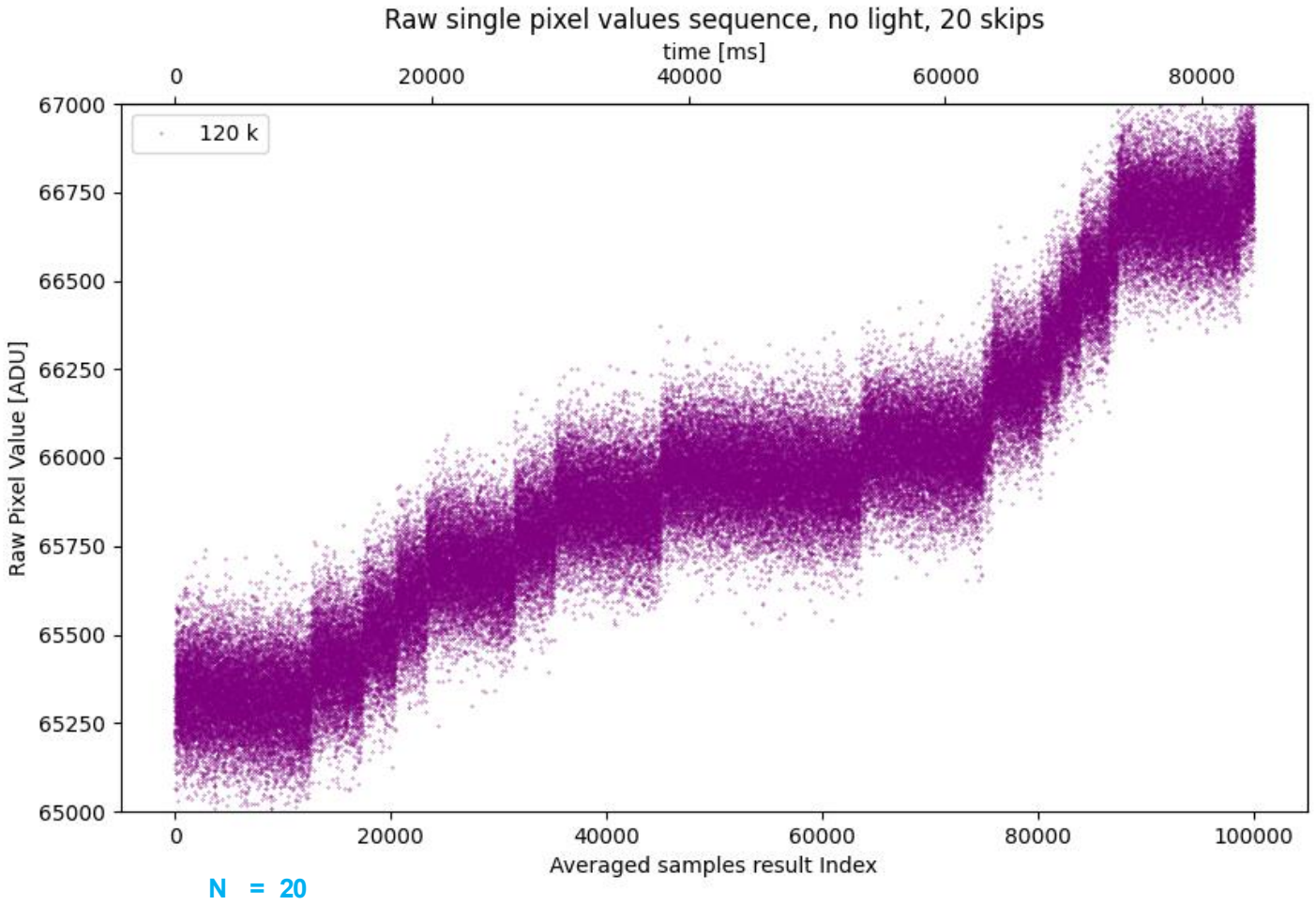
NO LED pulses

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Single pixels test within the matrix

Single pixel skipping

SINGLE PIXEL, NO transfer from PPD, continuous sampling, Column amplifier gain 25 V/V



N = 20

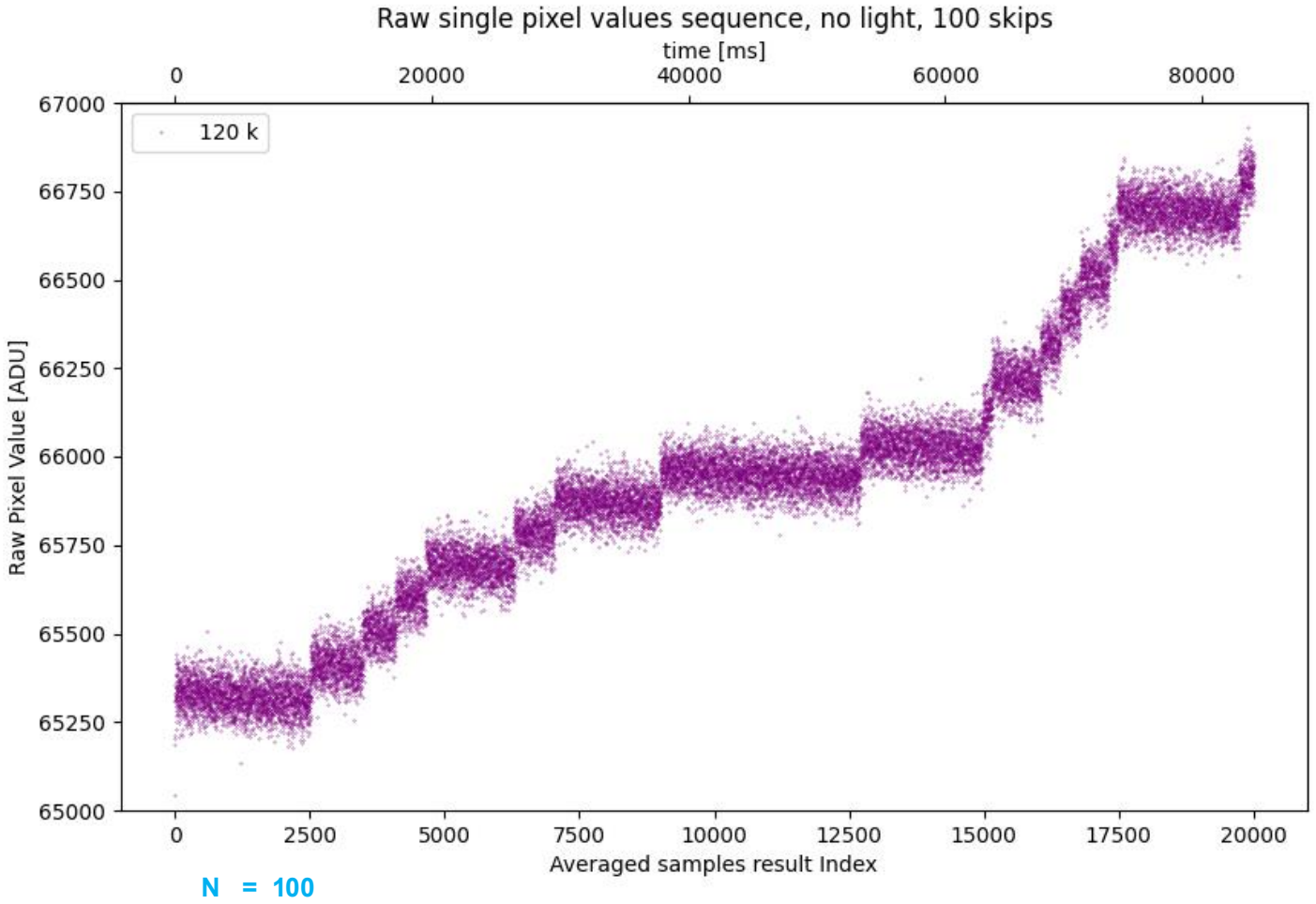
- A clear discretization appears as noise keeps going down.

NO LED pulses

Single pixels test within the matrix

Single pixel skipping

SINGLE PIXEL, NO transfer from PPD, continuous sampling, Column amplifier gain 25 V/V



N = 100

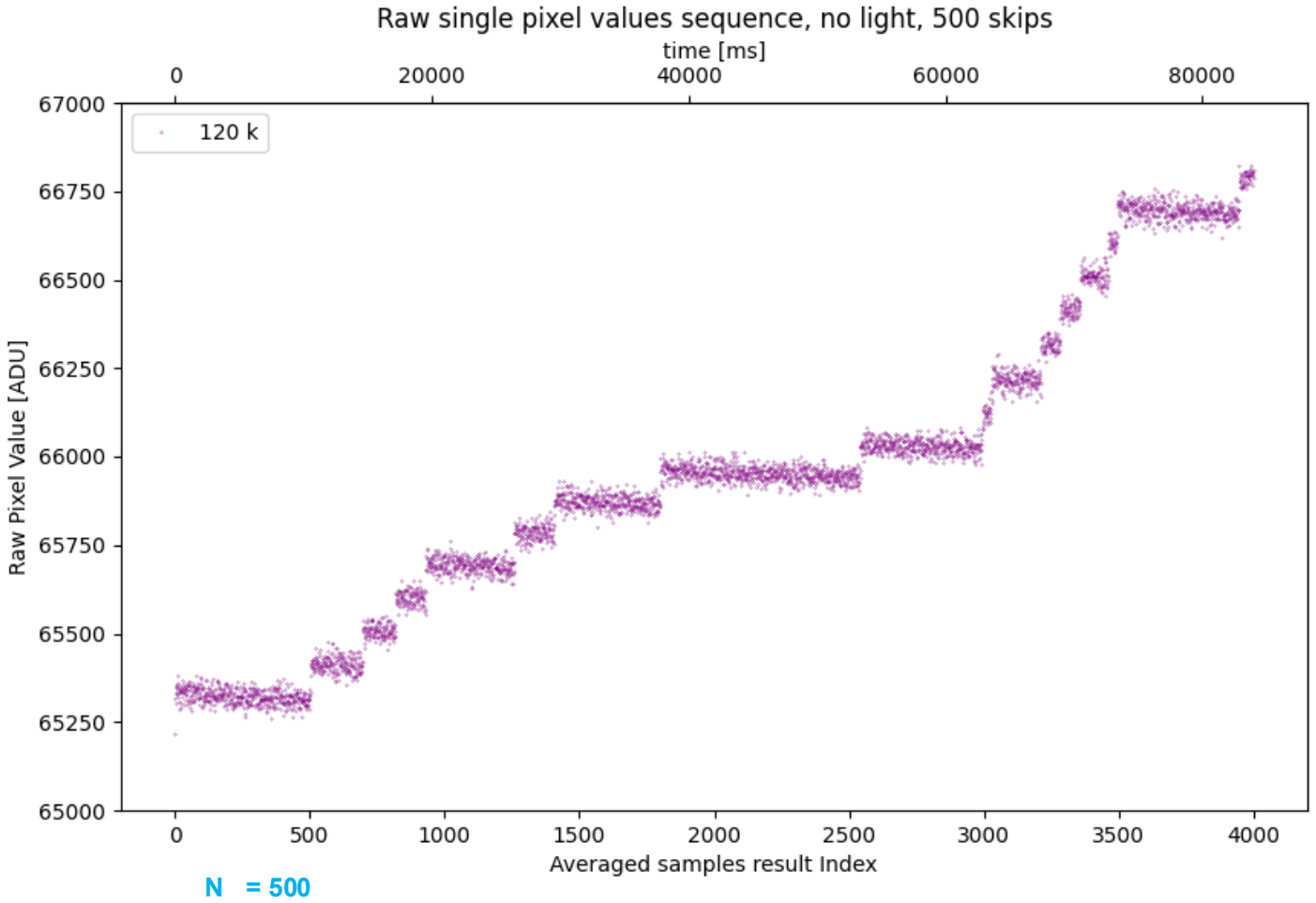
NO LED pulses

- Now the drift looks clearly as discrete steps

Single pixels test within the matrix

Single pixel skipping

SINGLE PIXEL, NO transfer from PPD, continuous sampling, Column amplifier gain 25 V/V



N = 500

Sub-electron noise unlocked

NO LED pulses

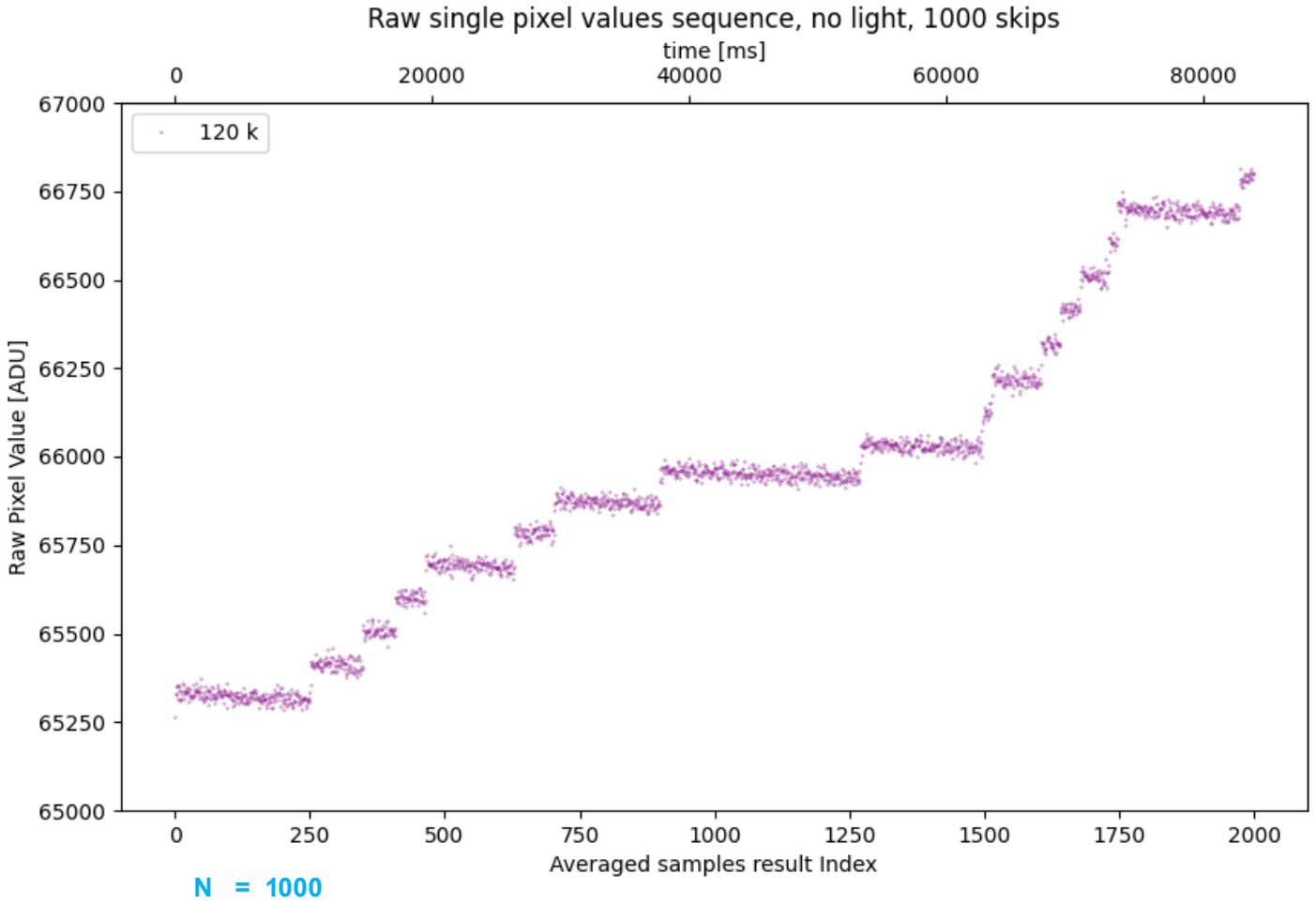
- What we are seeing is the DC of the floating gate bulding up, electron by electron.

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Single pixels test within the matrix

Single pixel skipping

SINGLE PIXEL, NO transfer from PPD, continuous sampling, Column amplifier gain 25 V/V



N = 1000

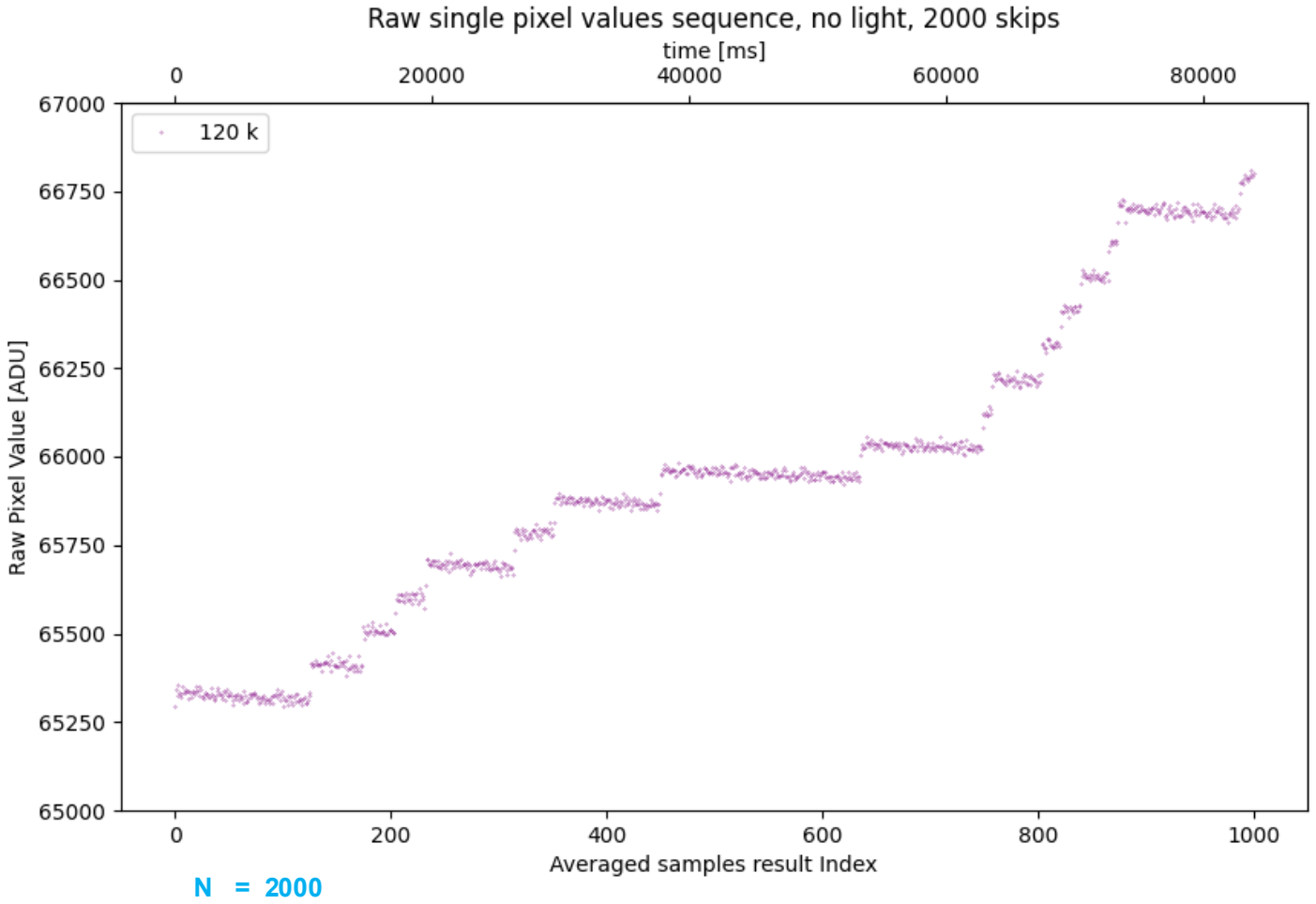
NO LED pulses

- The output is completely discrete. This is sub-electron noise.

Single pixels test within the matrix

Single pixel skipping

SINGLE PIXEL, NO transfer from PPD, continuous sampling, Column amplifier gain 25 V/V



N = 2000

NOISE 0.096 e-

NO LED pulses

- Distance between consecutive steps is the image conversion gain G_i.
- Following the electronic chain we get the Floating gate conversion gain G_i=32 µV/e-

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