

The H2M Monolithic Pixel Detector Prototype

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Detector R&D Retreat
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HELMHOLTZ



H2M (Hybrid-to-Monolithic) Pixel Detector Prototype

Common design and testing effort between:

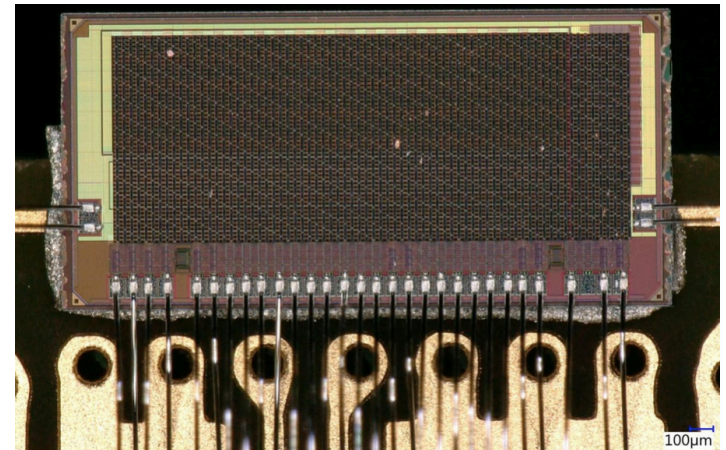
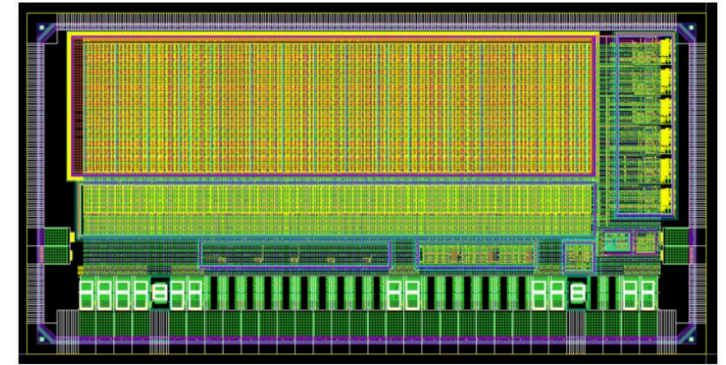
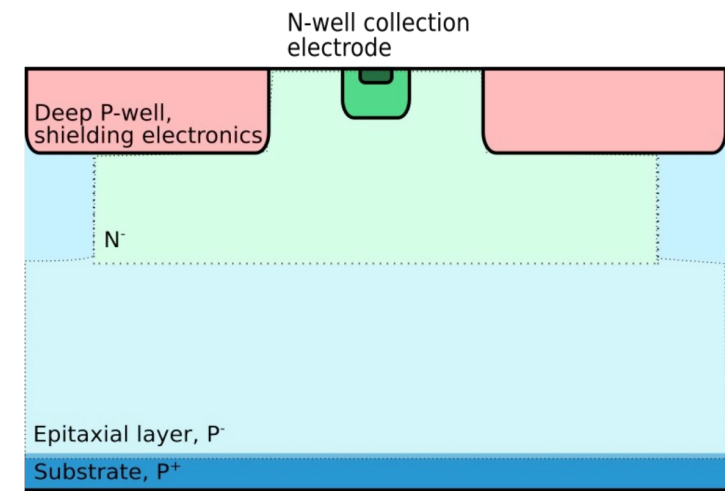


Development goals:

- Study the challenges of porting a known **hybrid pixel detector architecture** into a **monolithic chip**
- Exercise digital-on-top design flow and methodology in monolithic process
- Design and test a compact digital cell library

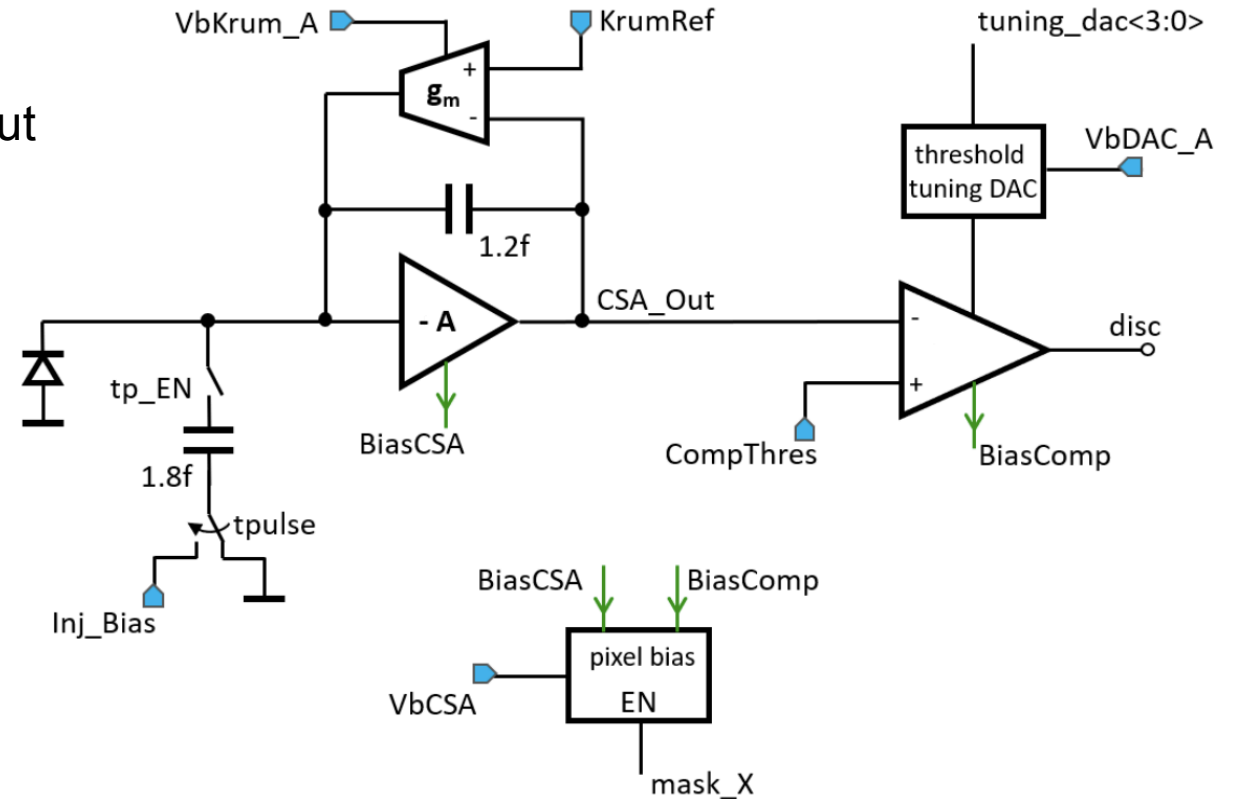
Sensor Layout

- Monolithic pixel sensor designed and fabricated in 65 nm CMOS imaging process
 - Pixel matrix: 64×16 pixels
 - Pixel pitch: $35 \mu\text{m}$
 - Total sensitive area: $2.24 \times 0.56 \text{ mm}^2$
 - Relatively thin epitaxial layer
 - Sensor: n-gap layout
- N-gap layout
 - Additional n-doped layer with gaps around pixel edge
 - Ensure charge collection from pixel edges and corners
 - $2.5 \mu\text{m}$ gap size



Pixel Analog Front-End

- Charge-sensitive amplifier (CSA)
 - Gain stage and Krummenacher feedback
 - Test pulse injection via capacitance at CSA input
 - Bias set via 8-bit global DAC
- Continuous-time threshold comparator
 - Global threshold via 8-bit DAC in periphery
 - Per-pixel threshold tuning with a 4-bit DAC, global bias DAC to adjust tuning step size
- Mask bit to disable and power down pixel
- Comparator output processed by digital pixel logic



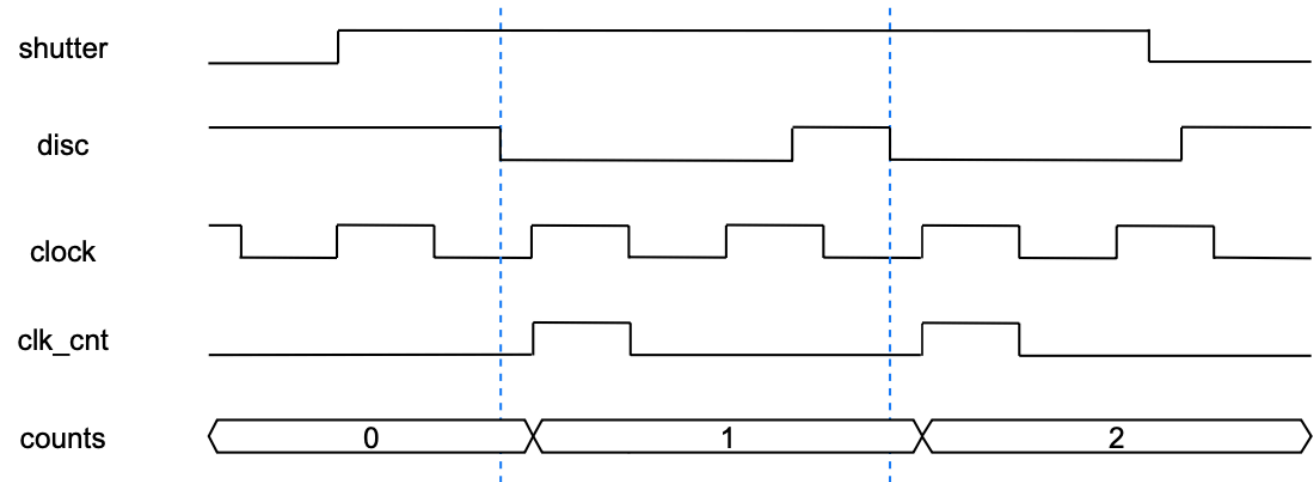
Pixel Digital Logic

8-bit in-pixel counter with 4 different acquisition modes:

- Frame-based acquisition modes
 - Active window defined by external shutter signal
 - Time of arrival (ToA)
 - Time over threshold (ToT)
 - Photon counting
- Triggered binary readout

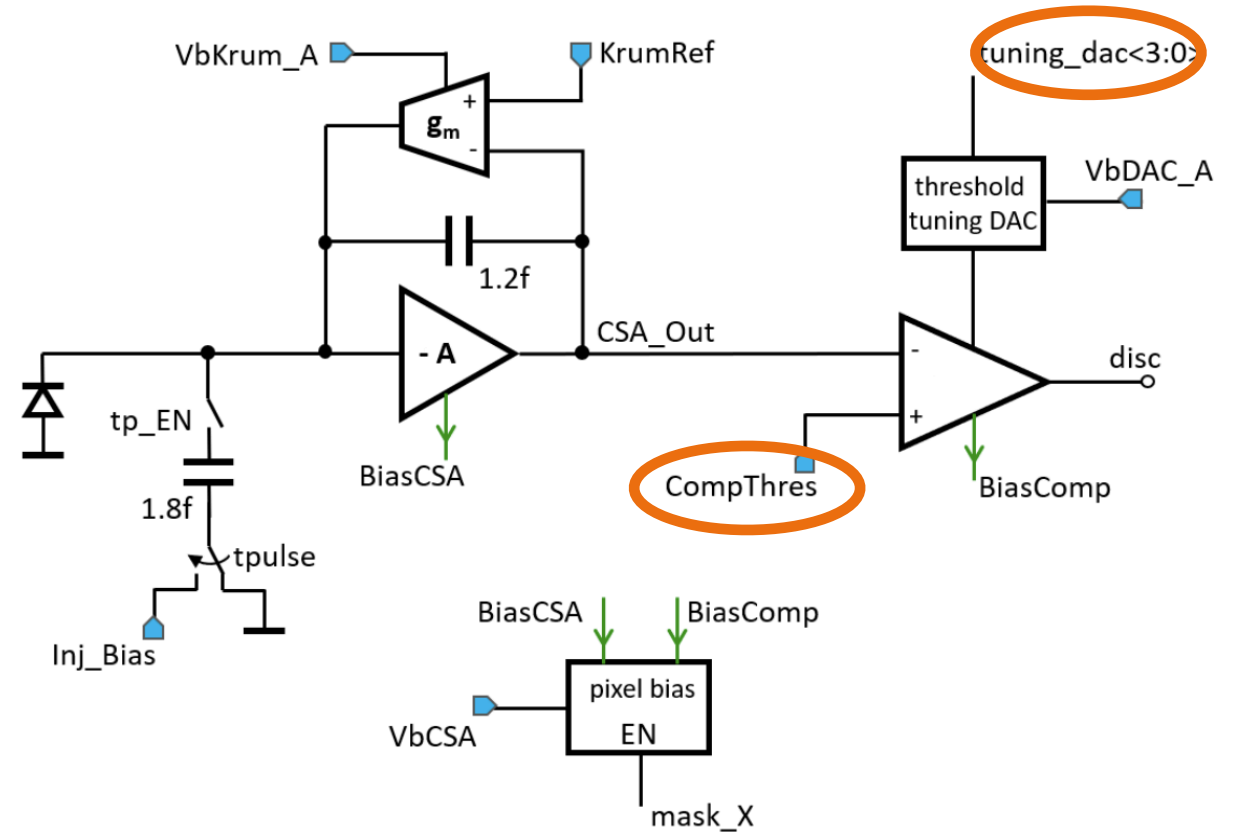
Photon counting mode:

- Triggering on discriminator falling edge
- Counts number of threshold crossings i.e. CSA output exceeds comparator threshold



Noise Based Pixel Trimming

- Scanning of pixel threshold for different pixels
→ per-pixel *tuning_dac*
- **Aim:** optimize *tuning_dac* settings for minimal threshold dispersion
- Scan of comparator threshold (CompThres)
 - Photon counting mode
 - Number of threshold crossings increase close to pixel baseline
 - Maximum of distribution marks baseline
- Repeat threshold scan for all *tuning_dac* settings



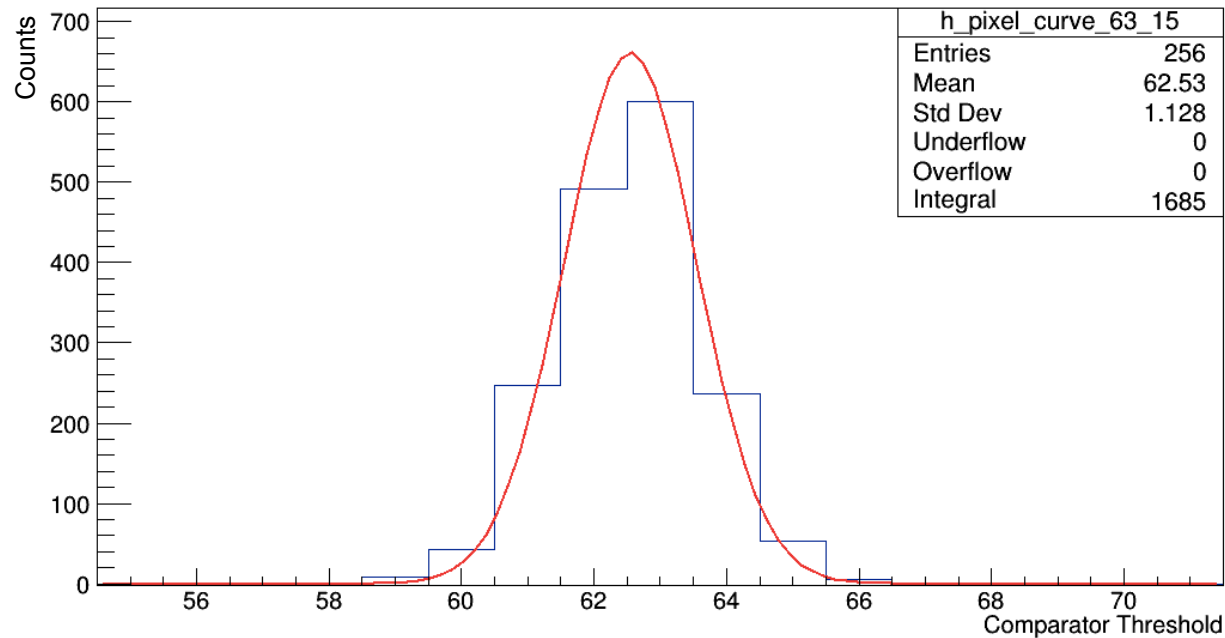
■: provided from periphery

→: distributed on pixel level

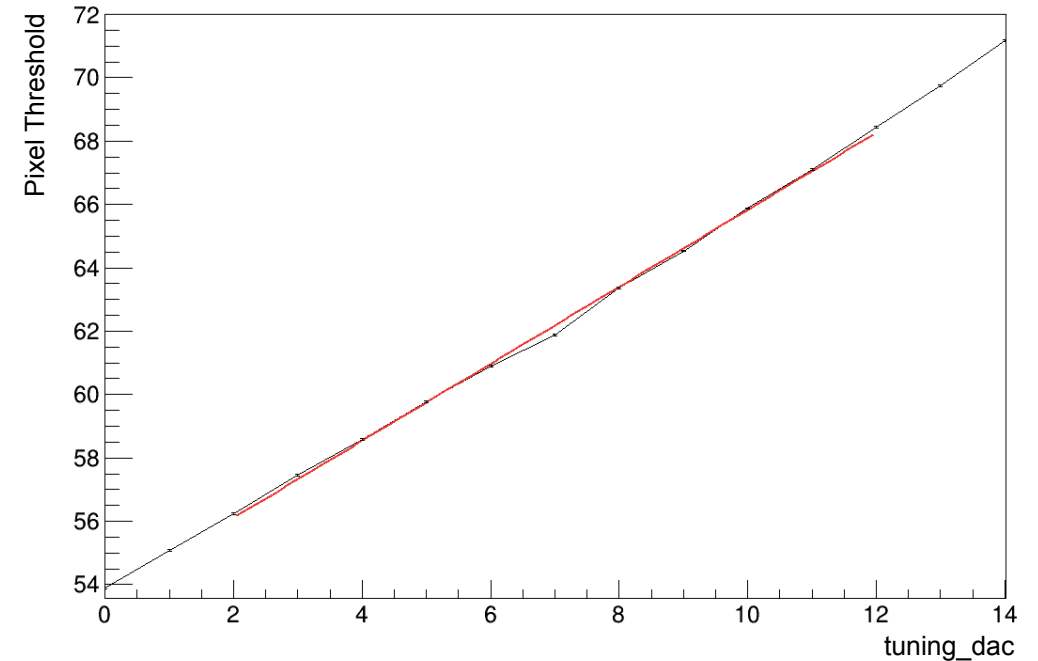
Analysis of Noise Scans

- Gauss fit for all pixels and *tuning_dac* settings to find individual pixel threshold
- Select trimming target within threshold range of all pixels
- Find matching *tuning_dac* setting via linear fit considering the standard error of the mean $SEM = \frac{\sigma}{\sqrt{N}}$
- Create mask file with *tuning_dac* settings for different pixels

Pixel 1023: *tuning_dac* = 7, bias voltage: -1.2 V



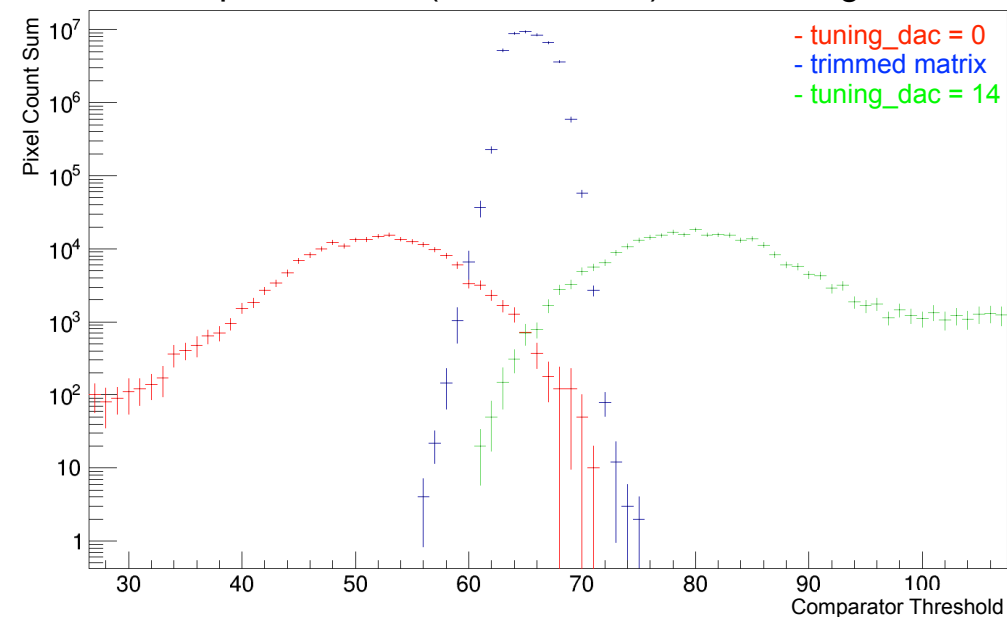
Pixel 1023, bias voltage: -1.2 V



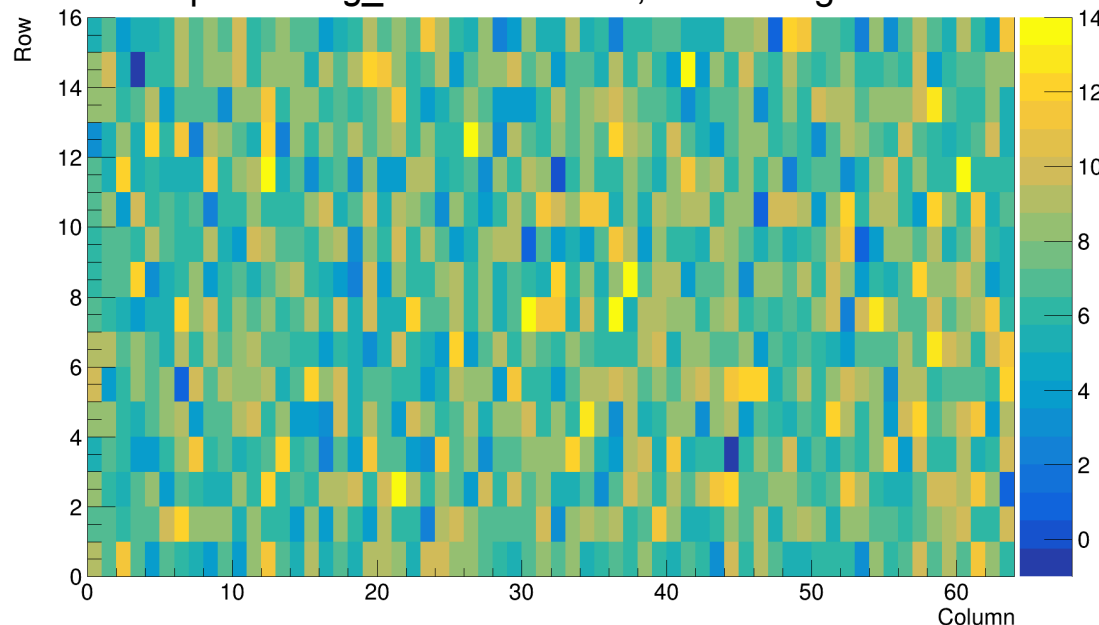
Trimmed Pixel Matrix

- Scan of comparator threshold shows steep distribution with small standard deviation around trimming target
- Trimming: no trends in pixel matrix observable
- *tuning_dac* distribution makes use of full dynamic range
- Approximately 0.5% of the pixels are not tuneable

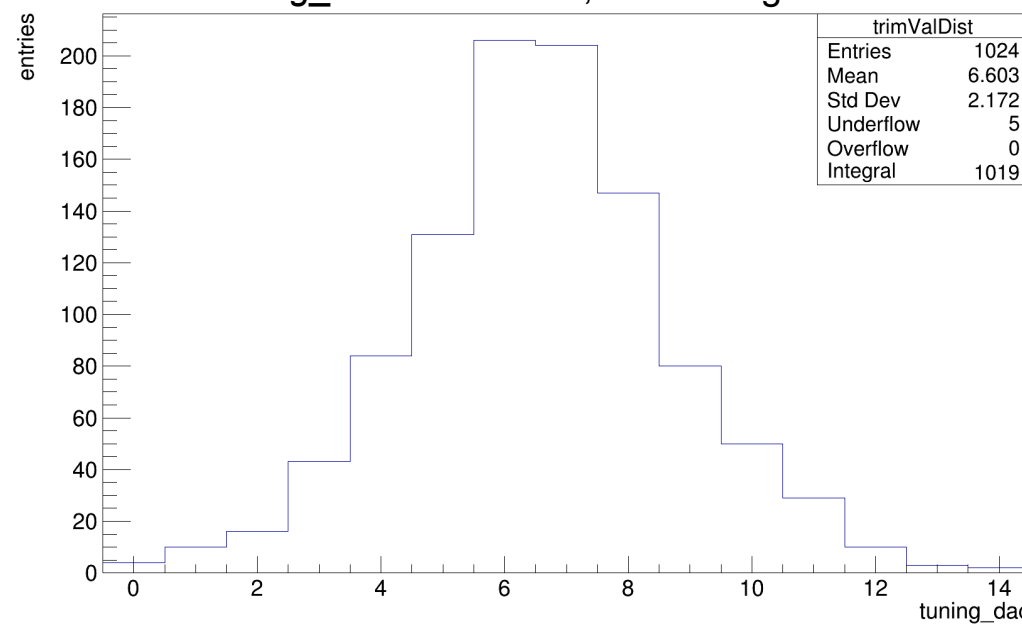
Sum of pixel counts (whole matrix), bias voltage: -1.2 V



Map of *tuning_dac* distribution, bias voltage: -1.2 V

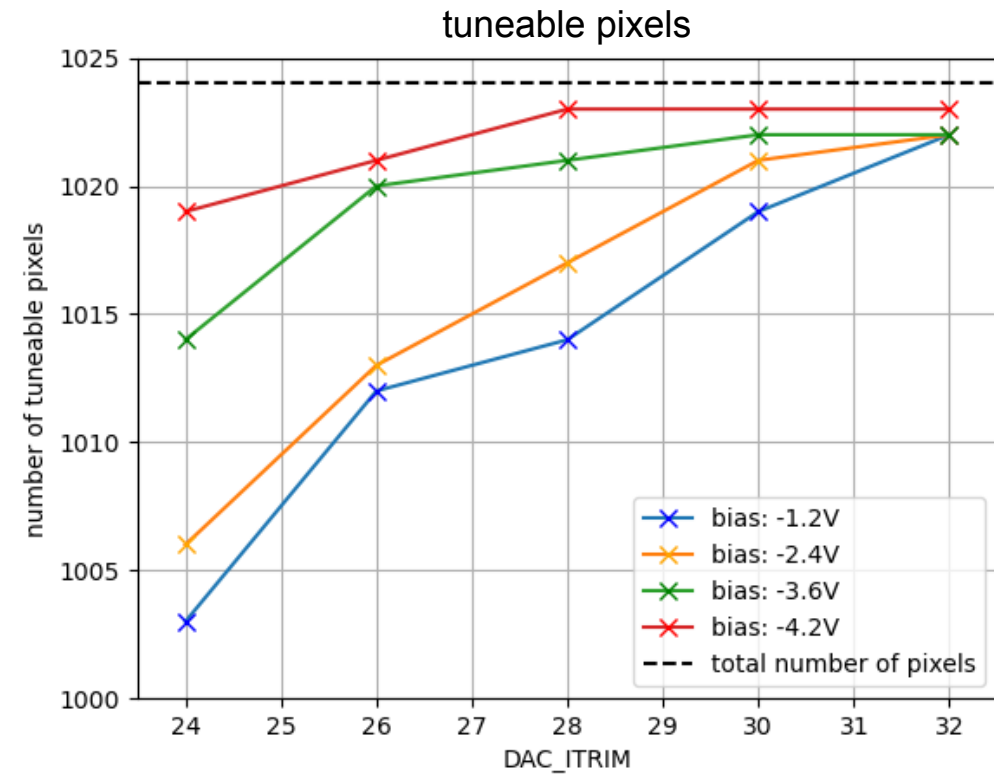
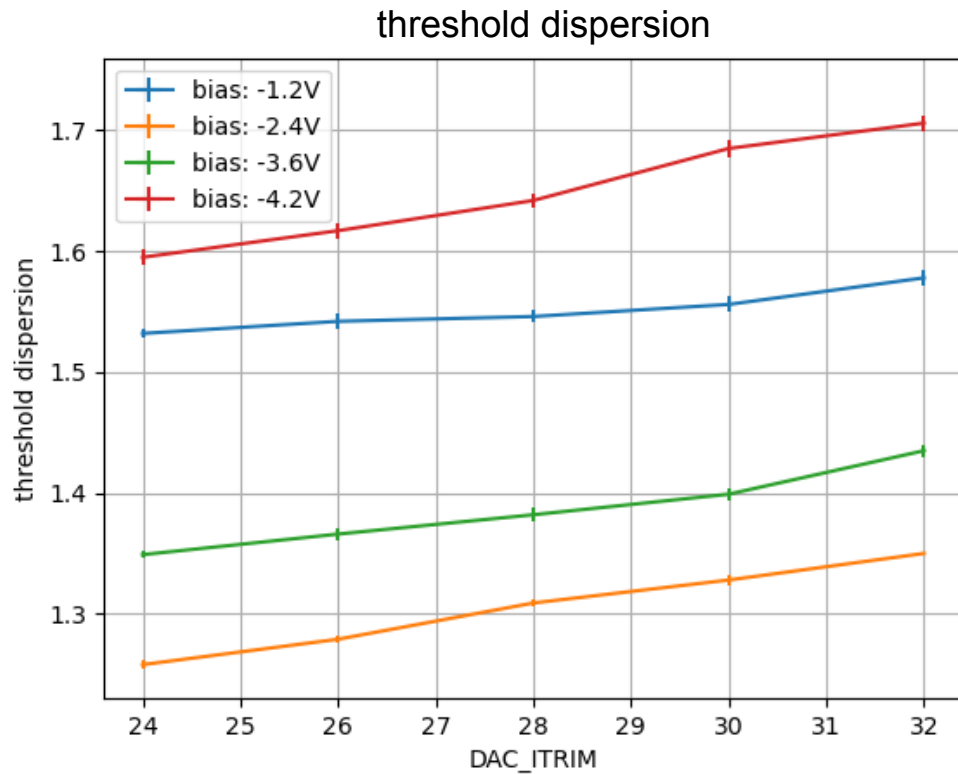


tuning_dac distribution, bias voltage: -1.2 V

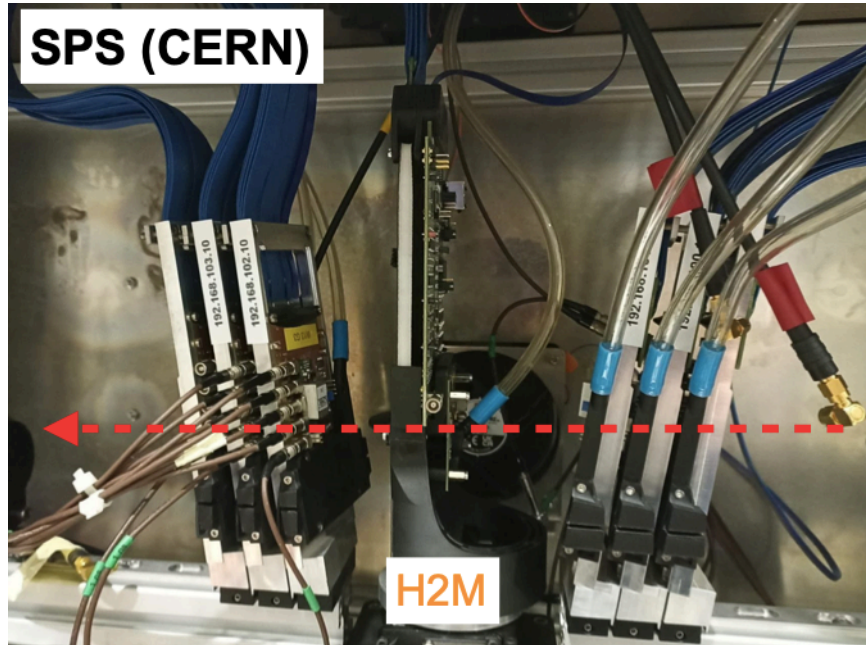


Global Biasing DAC_ITRIM Optimization

- Variation of *tuning_dac* bias current to adjust tuning step size by changing the pixel slope
 - ⇒ affects range covered by *tuning_dac* settings, amount of tuneable pixels and threshold dispersion
- Compromise between low threshold dispersion and high amount of tuneable pixels
- Choose operation point for different bias voltages based on these results

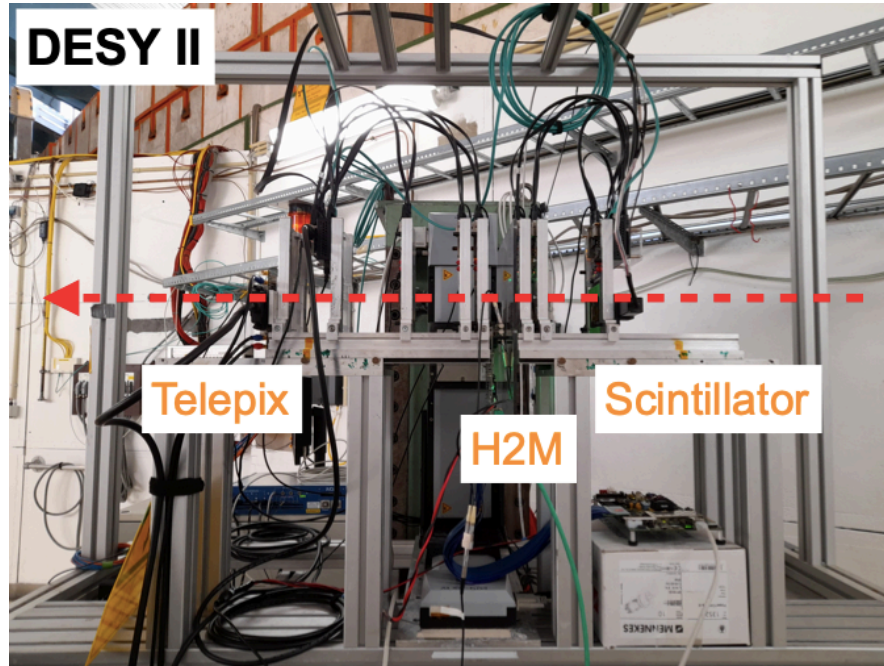


Test Beam Campaigns



SPS @ CERN

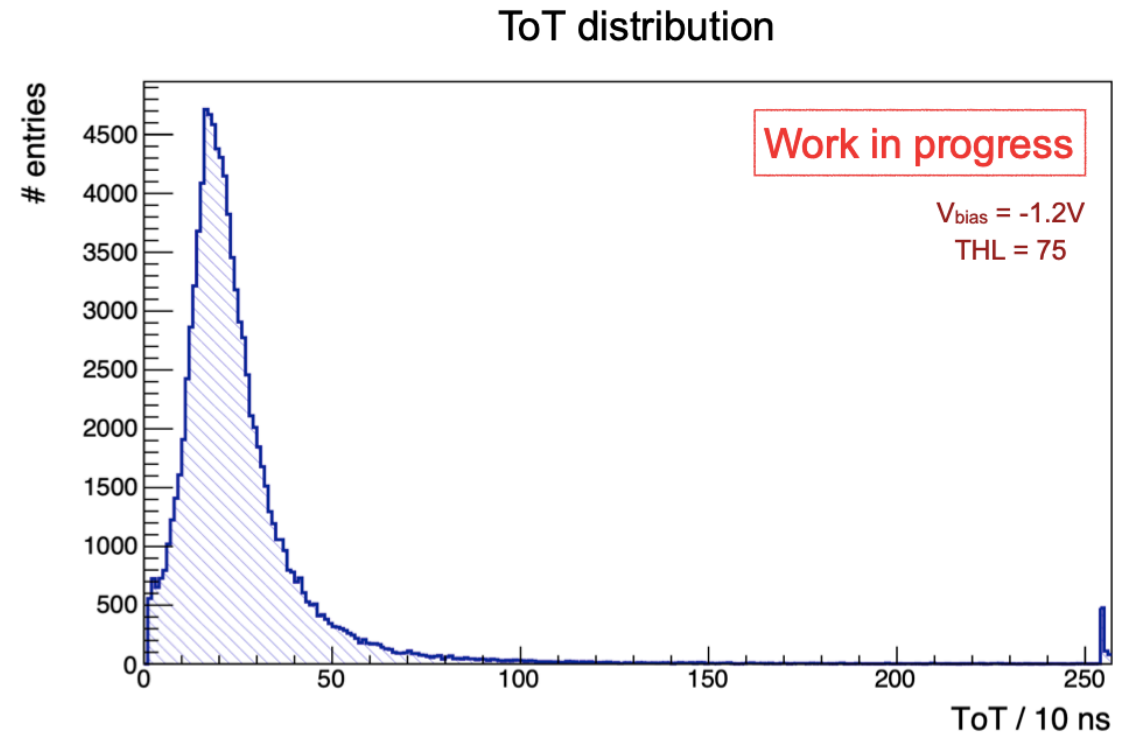
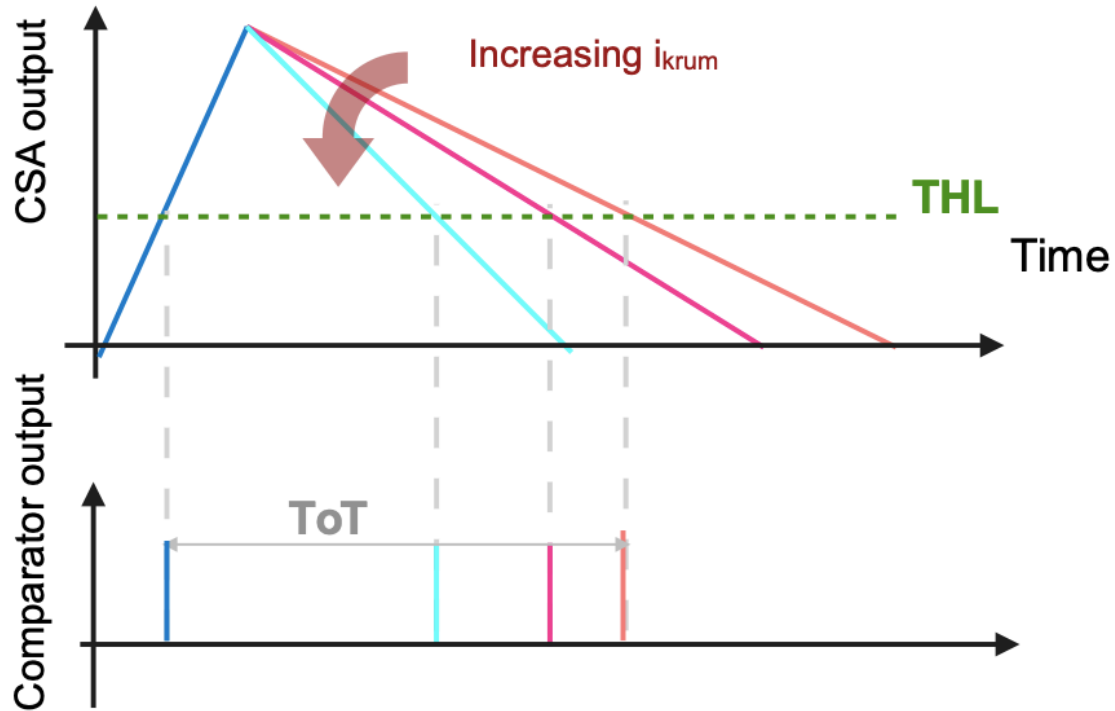
- Beamline H6, 120 GeV/c charged pions
- Timepix3 reference telescope
 - Pointing resolution $\sim 1.8 \mu\text{m}$
 - Track time resolution $\sim 1 \text{ ns}$



DESY II

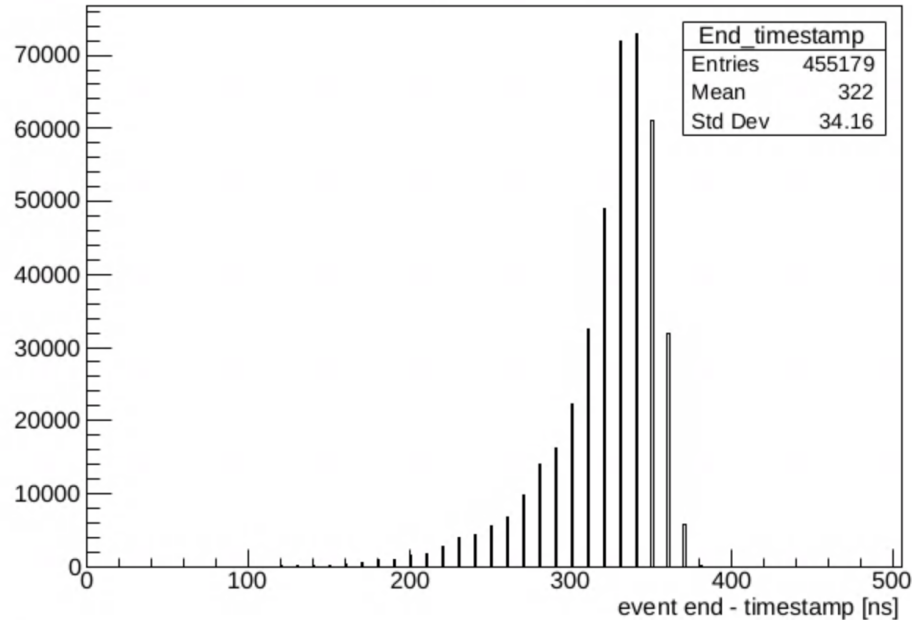
- Beamline 22, electron beam with $\sim 4.8 \text{ GeV}$
- Alpid reference telescope
 - Pointing resolution $\sim 3 \mu\text{m}$

ToT Distribution

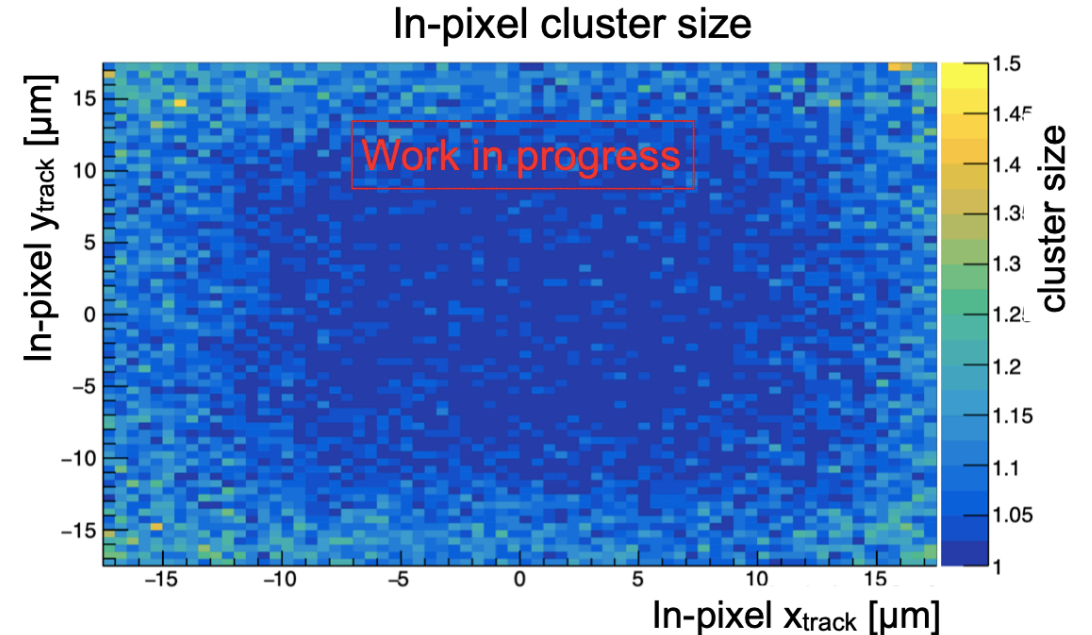


- Return to baseline adjusted with Krummenacher current
→ ToT distribution used to tune Krummenacher current
- Analysis ongoing for data at different bias voltages and hit detection thresholds

ToA and Cluster Size Distribution



- Event end: shutter window closed with trigger signal (coincidence of Telepix and scintillator)
- Timestamp: hit in H2M
- Time resolution ≈ 34.16 ns
- Tail in distribution due to time walk

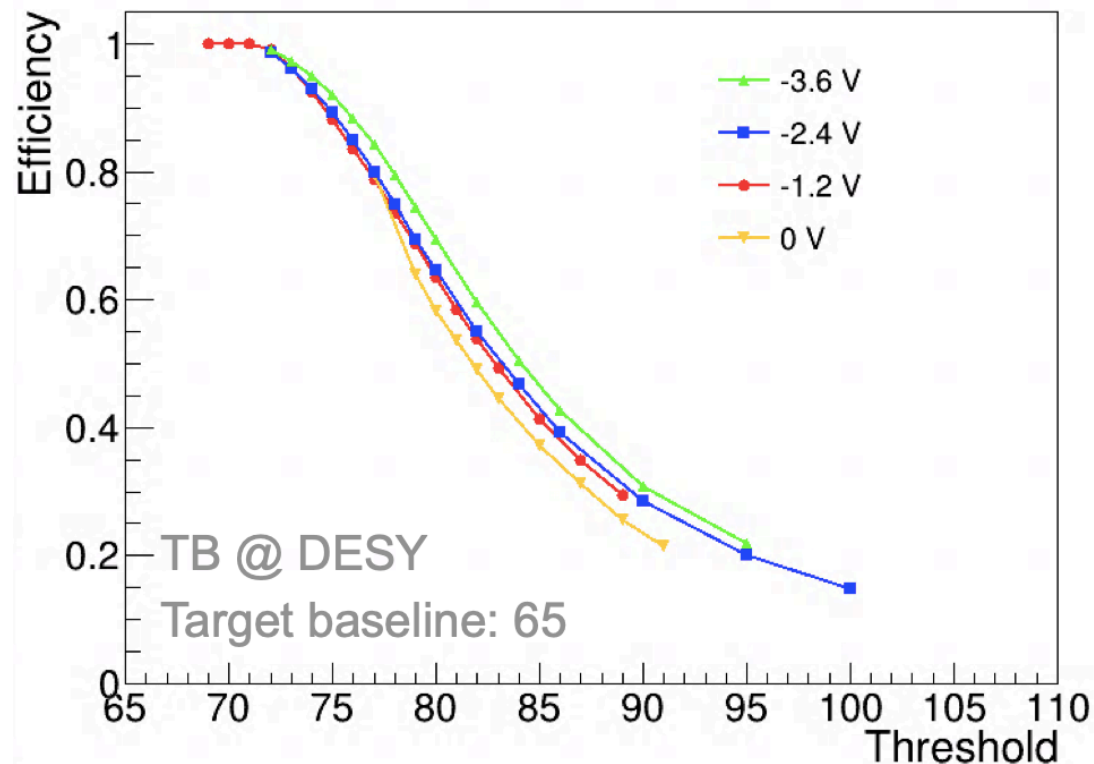
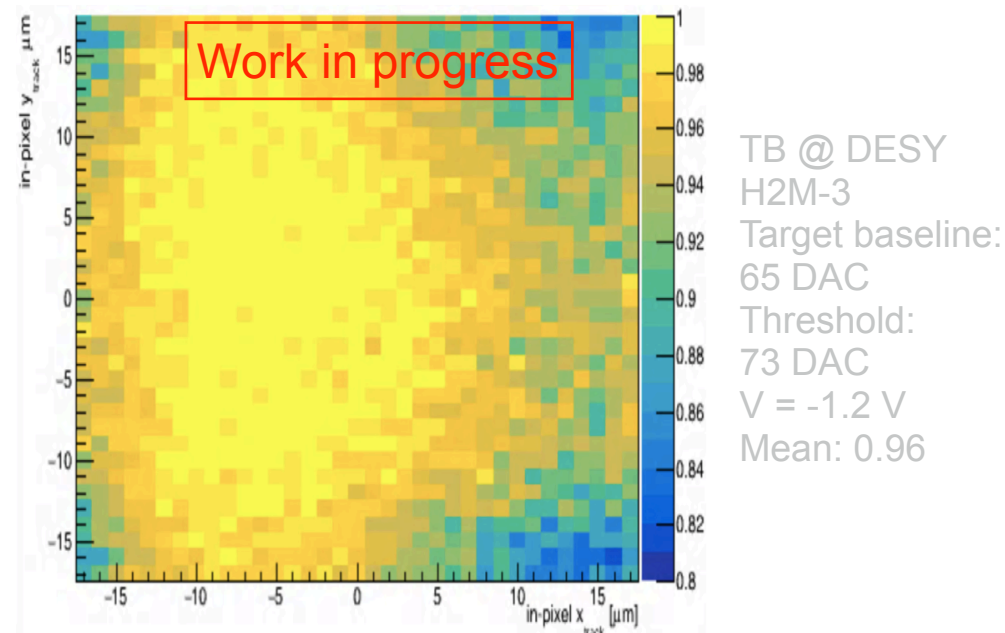


- Dominated by cluster size 1
- Larger cluster size in edges and corners due to charge sharing

In-Pixel Efficiency Map

$$\text{Efficiency} = \frac{\text{tracks with an associated cluster}}{\text{tracks with and without associated cluster}}$$

- Unexpected in-pixel efficiency pattern observed
 - For different bias voltages (less pronounced at larger bias voltage)
 - At different hit detection thresholds
 - In both tested assemblies (H2M-2 and H2M-3)
 - During test beams at SPS and at DESY II
- Seems to be related to the position of the analog and digital part of the front-ends



Summary & Outlook

Summary

- Full hybrid design ported into monolithic chip in 65 nm CMOS imaging process
- Successful first laboratory measurements
 - Implementation and optimization of pixel trimming procedure
 - Chip features work as intended
- First test beam campaigns at SPS and DESY II
 - Chip DAQ works as intended
 - ToT and ToA modes successfully tested
 - Integration with reference planes and trigger signal

Outlook

- Front-end parameter optimization
- Charge calibration for the test beam characterization of the used samples
- Testing of photon counting mode and triggered binary readout
- Further analysis of test beam data for different acquisition modes
- Studies of efficiency patterns
- Comparison of test beam results and simulations

Thank you!



Contact

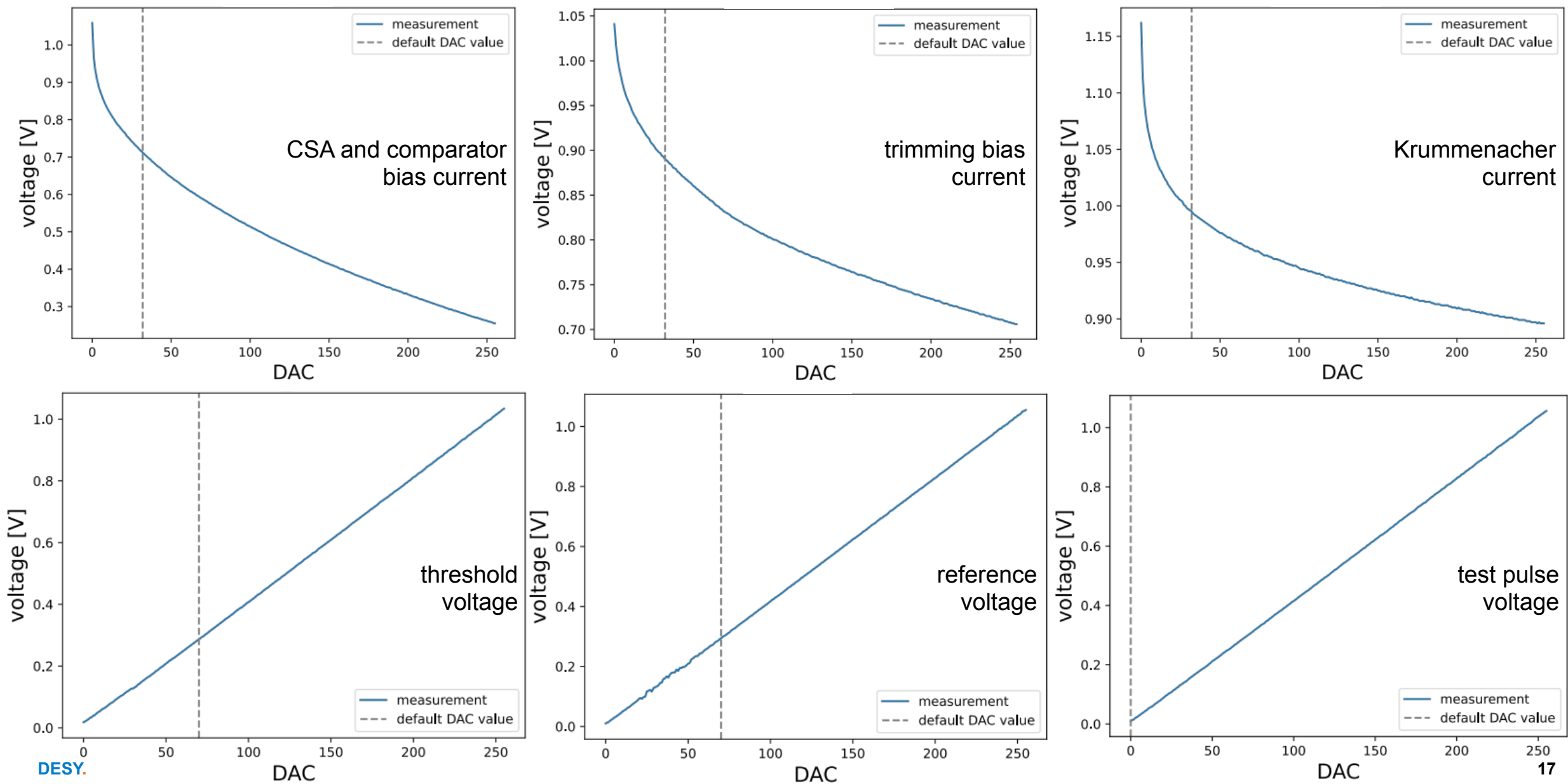
Deutsches Elektronen-
Synchrotron DESY
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Judith Schlaadt
Tangerine
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Backup Slides

DAC Scans - Expected Behaviour Observed

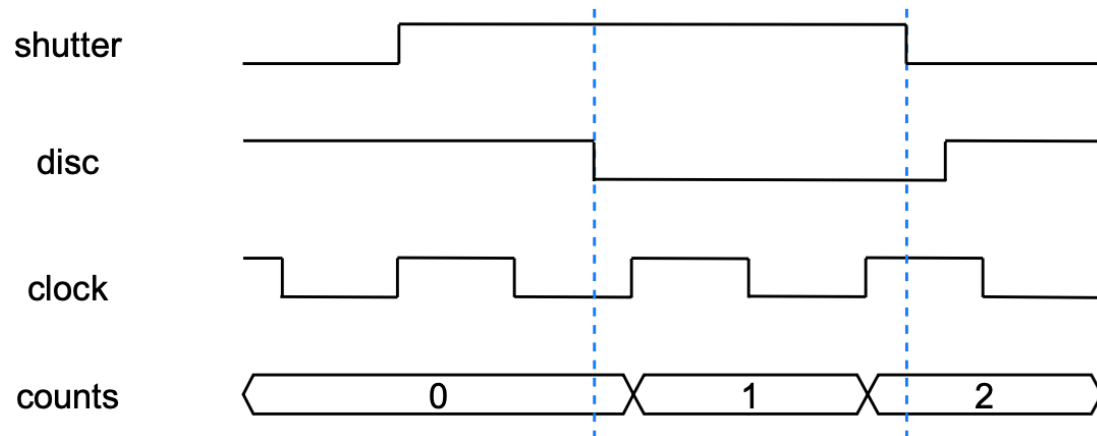
S. Ruiz Daza



Frame-based Acquisition Modes

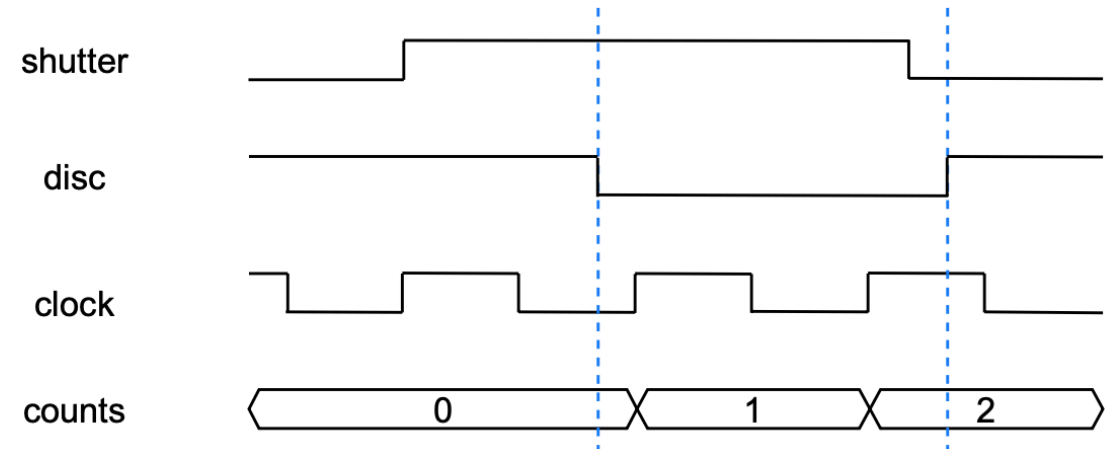
Time-of-arrival (ToA)

- Triggering on discriminator falling edge
- Counts number of acquisition clock cycles until shutter window closes
- 100 MHz acquisition clock: 10 ns binning



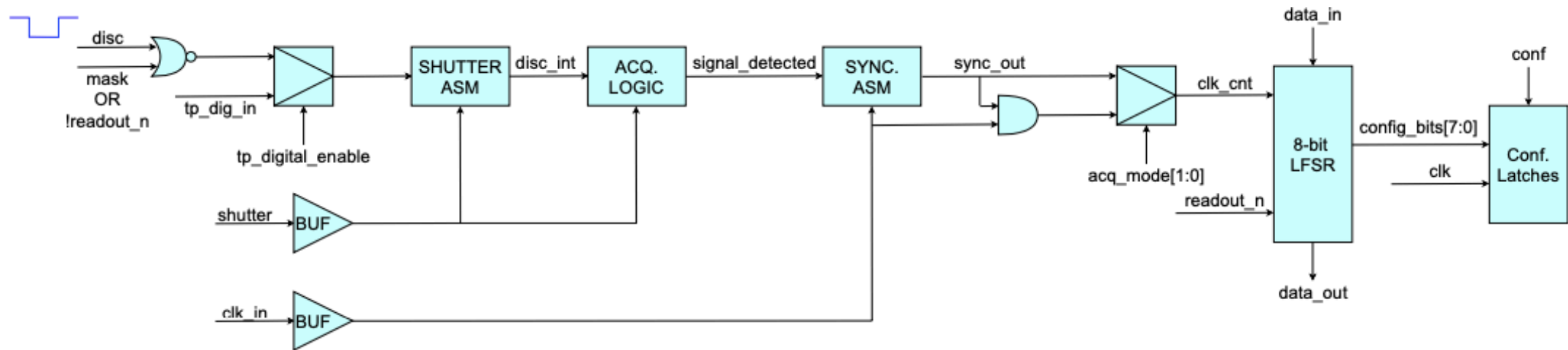
Time-over-threshold (ToT)

- Triggering on discriminator falling edge
- Counts number of acquisition clock cycles until discriminator signal rising edge
- ToT $\sim$ collected charge (after calibration)



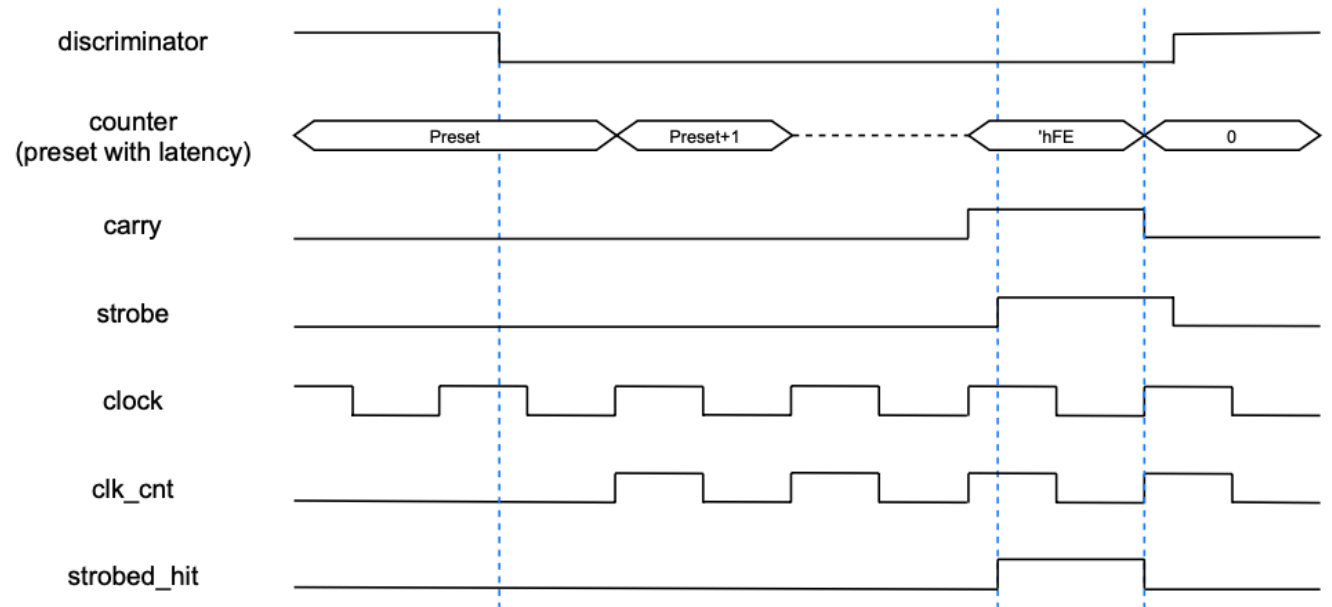
Pixel Digital Logic: Frame-based Acquisition Modes

- Discriminator output: readout or masking
- Digital test pulses: enabling overwrites discriminator output
- Shutter asynchronous state machine (ASM): discards trigger outside of shutter window
- Acquisition logic (ACQ. LOGIC): produces signal based on used acquisition mode
- Synchronising logic (SYNC. ASM): synchronises signal to acquisition clock
- Counting → data stored in 8-bit linear-feedback shift register (LFSR); 8-bits for pixel configuration
 - Readout: 8-bits shifted from top to bottom of column
 - Configuration: 8-bits shifted from bottom to top of column and set to pixels



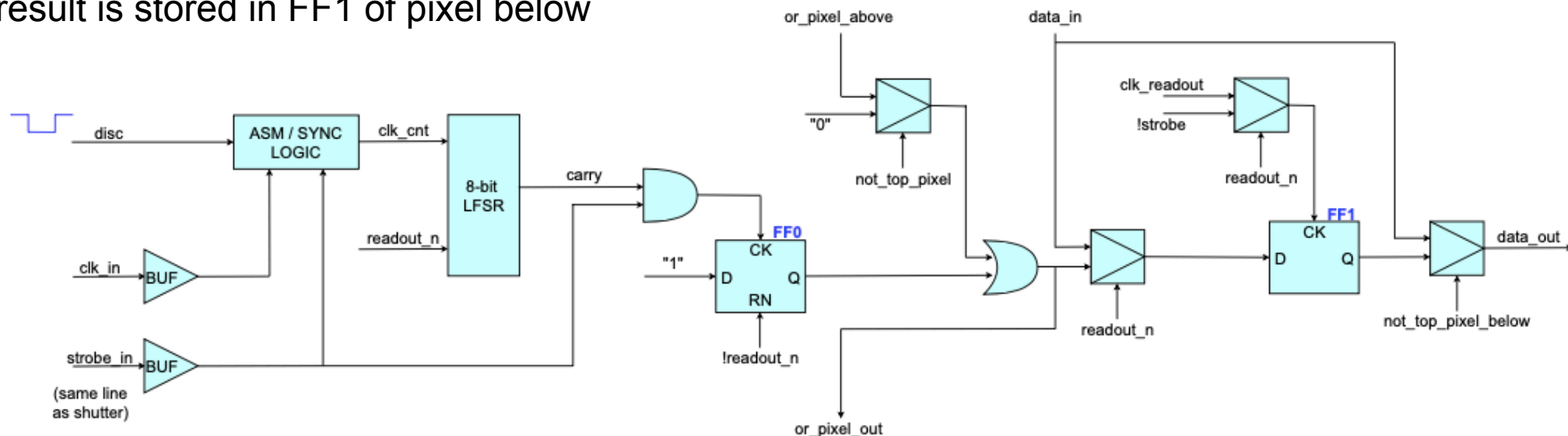
Triggered Binary Readout

- Counter preset with trigger latency value
- Triggering on discriminator falling edge
⇒ starts counter at preset value
- Carry signal produced as soon as counting reaches overflow
- External strobe signal provided, synchronised with acquisition clock
- Hit: carry and strobe signal in coincidence
- Variable configuration: pixel stores its own hit or combines data from group of pixels



Pixel Digital Logic: Triggered Binary Readout

- External strobe signal is distributed analogously to shutter signal
- Hit when carry and strobe signal are in coincidence: flip-flop (FF0) is set
 - ⇒ Result registered to flip-flop (FF1) after delay (one clock cycle after strobe signal rises)
 - ⇒ Readout of FF1
- Possible to combine information of several pixels via not_top_pixel configuration of pixel below:
 - not_top_pixel = 0: hit will be stored in FF1 and read out
 - not_top_pixel = 1: FF0 is input to FF0 of pixel below; information of both pixels is ORed and result is stored in FF1 of pixel below



Tuning DAC

Mapping

- Implemented in peary
- *tuning_dac* 0: most negative comparator offset voltage
- *tuning_dac* 7: zero comparator offset voltage (no shift)
- *tuning_dac* 14: most positive comparator offset voltage

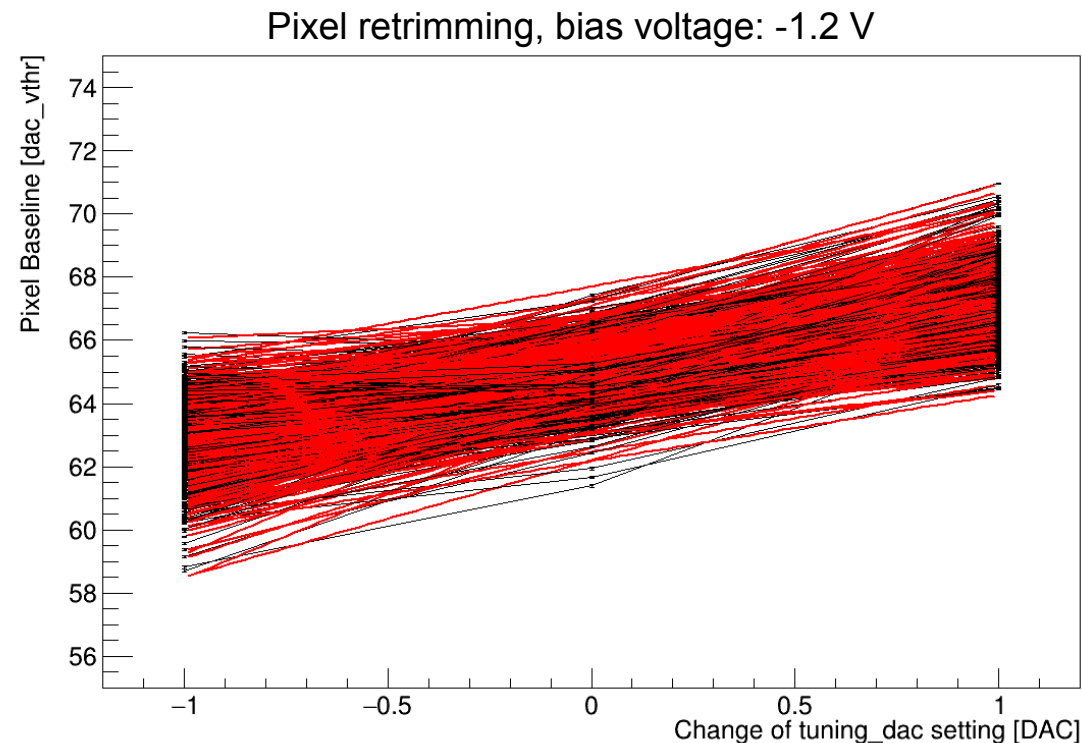
Threshold *tuning_dac* control bits for DAC_ITRIM 82 nA

tuning_DAC				DAC#	Comp. current (nA)	Comp. offset voltage (mV)
<0>	<1>	<2>	<3>			
0	0	0	0	0	+370.6	+41
0	1	0	0	2	+318.8	+35
0	0	1	0	4	+266.4	+29
0	1	1	0	6	+213.8	+23
0	0	0	1	8	+161.0	+17
0	1	0	1	10	+107.8	+12
0	0	1	1	12	+54.3	+6
0	1	1	1	14	0	0
1	1	1	1	15	0	0
1	0	1	1	13	-54.3	-6
1	1	0	1	11	-107.8	-12
1	0	0	1	9	-161.0	-17
1	1	1	0	7	-213.8	-23
1	0	1	0	5	-266.4	-29
1	1	0	0	3	-318.8	-35
1	0	0	0	1	-370.6	-41

Pixel Retrimming

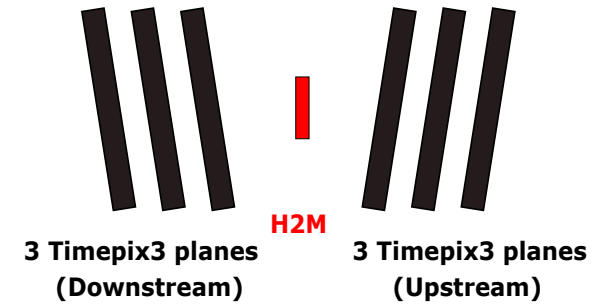
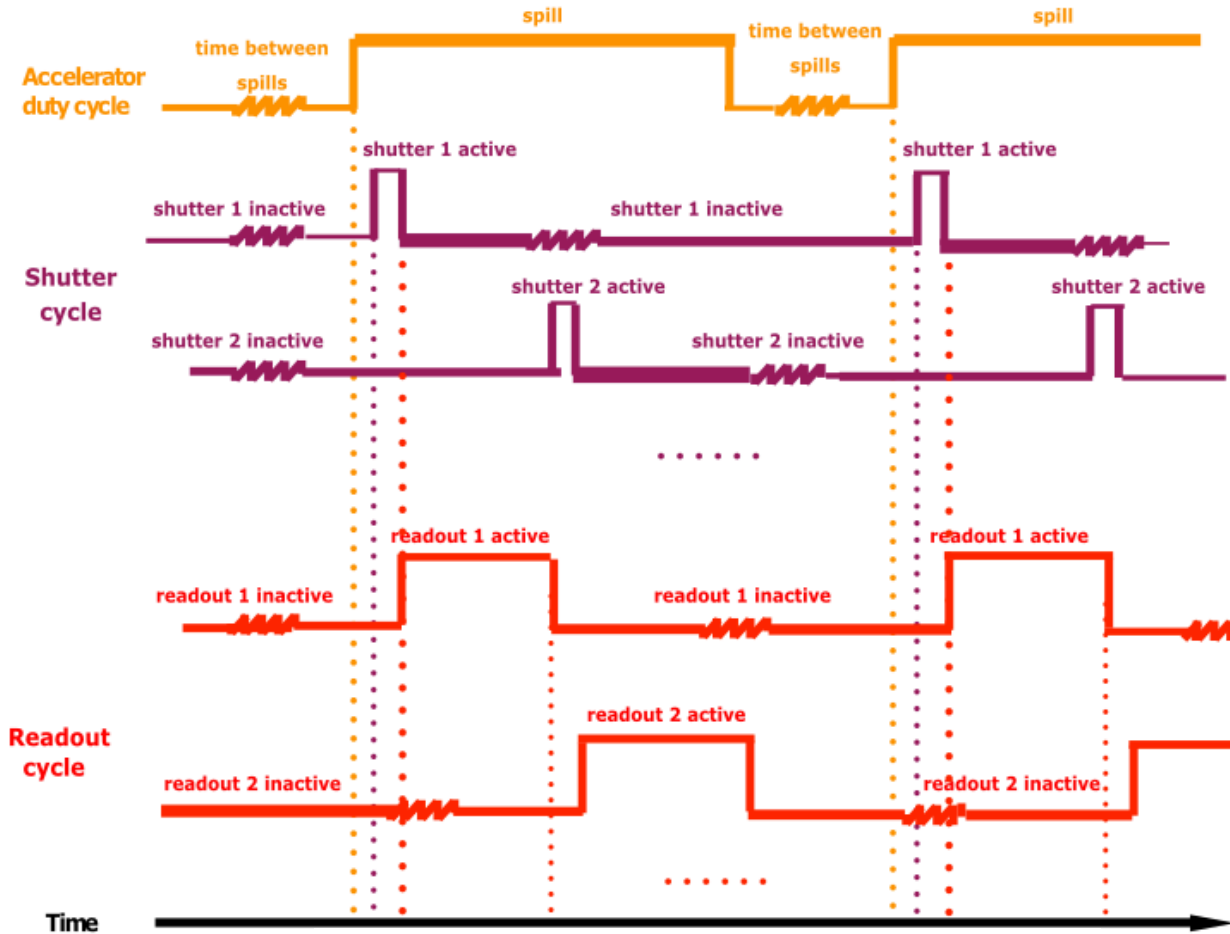
Re-evaluation of fractions of the matrix:

- Performing two more noise scans with *tuning_dac* settings above and below the initial setting
- Combine these information and redo linear fit for all pixels in “region of interest”
 - ⇒ changes *tuning_dac* setting for approximately 40% of the pixels
- Retrimming only slightly reduces threshold dispersion
 - ⇒ indicates stable voltage supply within pixel matrix



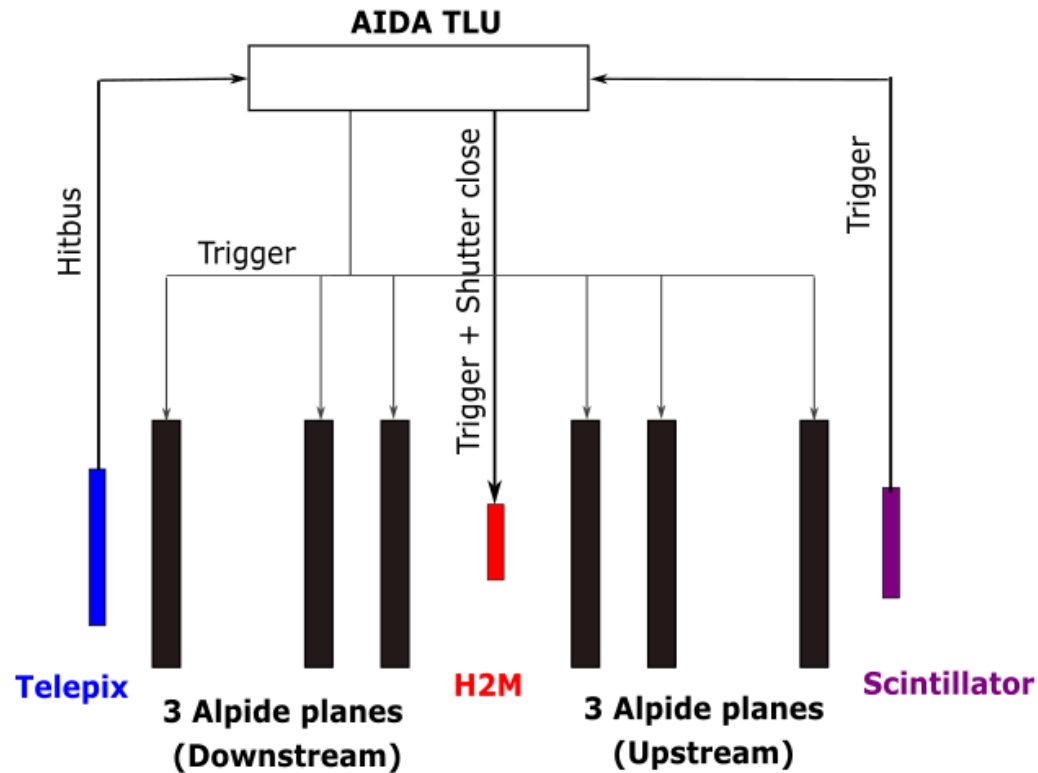
Method	Mean	Standard Deviation
Lin. Fit	66.28	1.63 ± 0.01
Retrimming	65.35	1.57 ± 0.01

Test beam measurements @ SPS



- **Trigger Logit Unit (TLU):** provides global clock (40 MHz) and T0 for the telescope and DUT.
- **H2M:**
 - ToT mode
 - Gated with **SPS spill signal**
 - **Shutter window** of 150 μs
 - **Readout time** $\sim 500 \mu\text{s}$
- **Timepix3:**
 - In data-driven mode
 - Selecting region of interest (ROI)

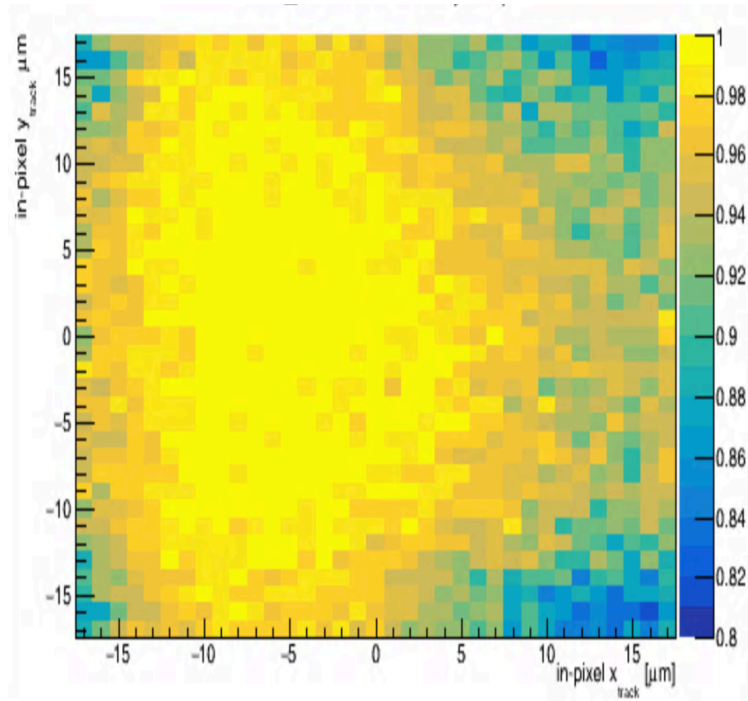
Test Beam Measurement @ DESY



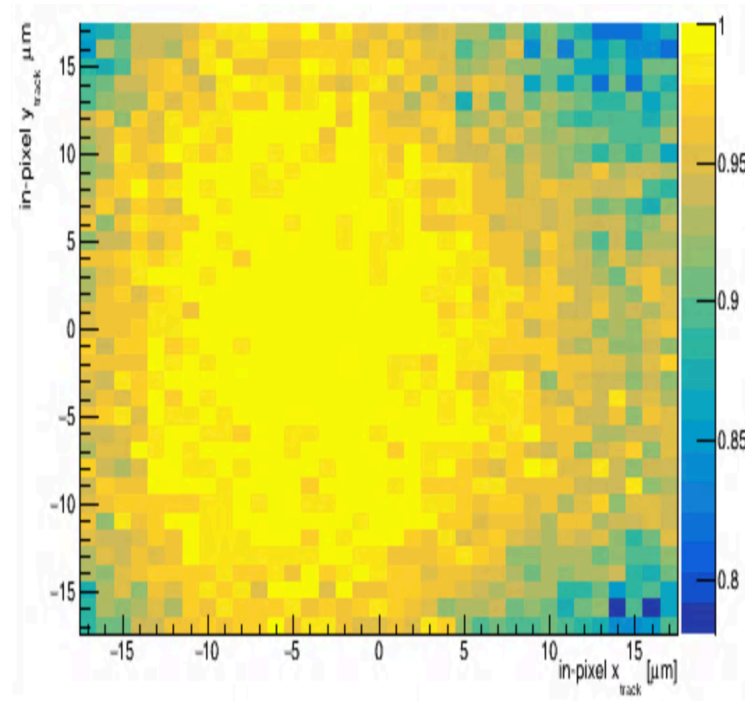
- **Trigger Logit Unit (TLU):** provides global clock (40 MHz) and T0 to all devices.
- **Trigger signal:**
 - Coincidence of **Telepix** AND **scintillator**
 - ROI defined on Telepix
- **H2M:**
 - ToA mode
 - **Shutter opened** after previous readout
 - **Shutter closed** with trigger signal
 - **Readout time** ~ 500 μ s

In-pixel efficiency maps: threshold = 73

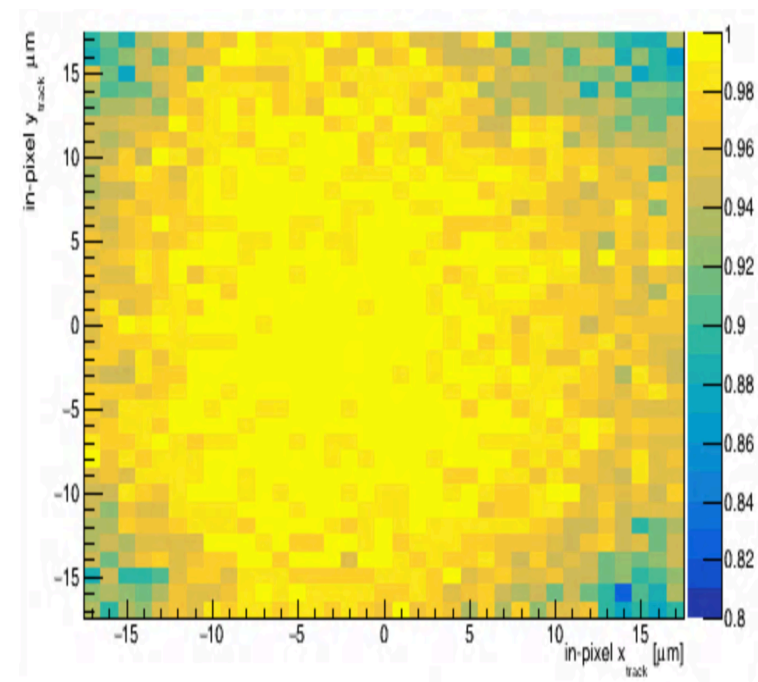
V = -1.2 V, Mean efficiency: 0.96



V = -2.4 V, Mean efficiency: 0.96



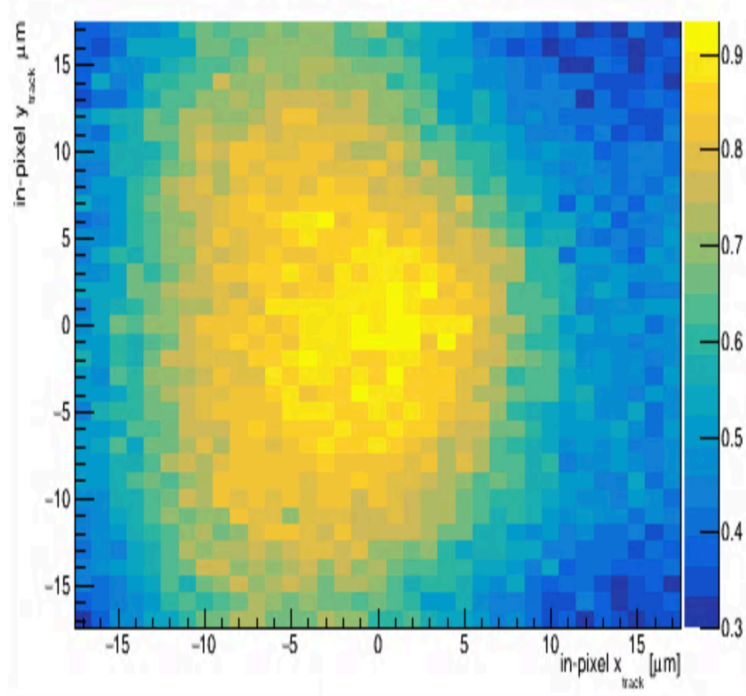
V = -3.6 V, Mean efficiency: 0.97



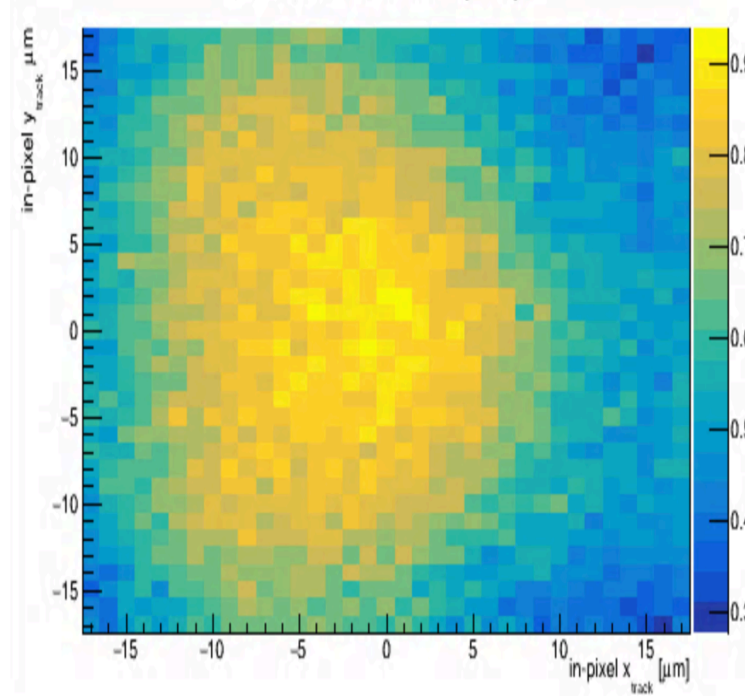
- Pattern less visible at higher bias voltages

In-pixel efficiency maps: threshold = 80

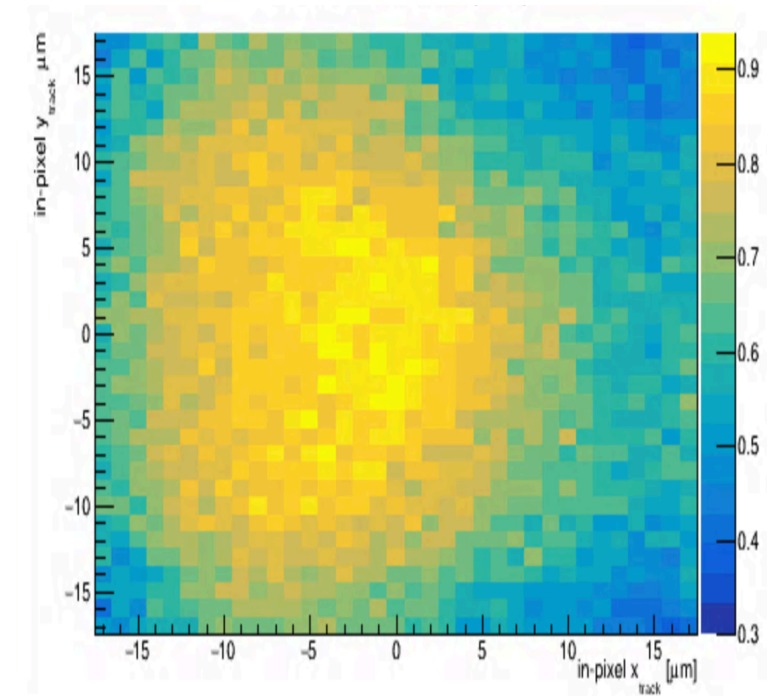
V = -1.2 V, Mean efficiency: 0.63



V = -2.4 V, Mean efficiency: 0.65



V = -3.6 V, Mean efficiency: 0.69



- Pattern still visible at higher bias voltages

Caribou Data Acquisition System

