An SEU-Immune Self-Tuned Pixel Chip Architecture
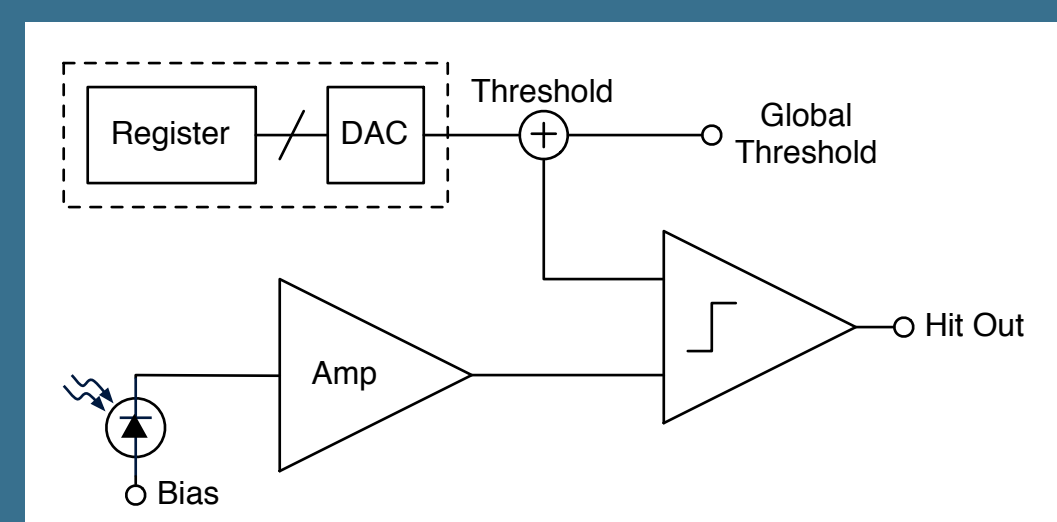
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ATLAS EXPERIMENT

Generalised Pixel Architecture

Pixel calibration:
- Adjust for variability of transistors → per pixel programmable threshold
- Requires pixel to store calibration data, which is susceptible to SEUs
- Transistor characteristic changes with temperature and ionising dose
- Threshold stability over time major challenge in HEP experiments

Untuned

Tuned
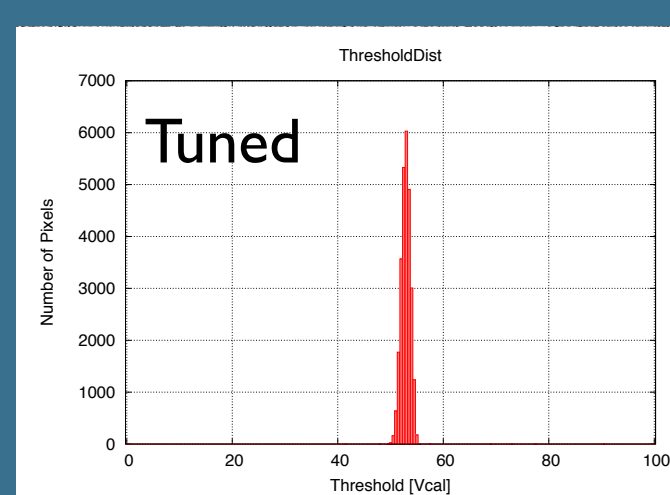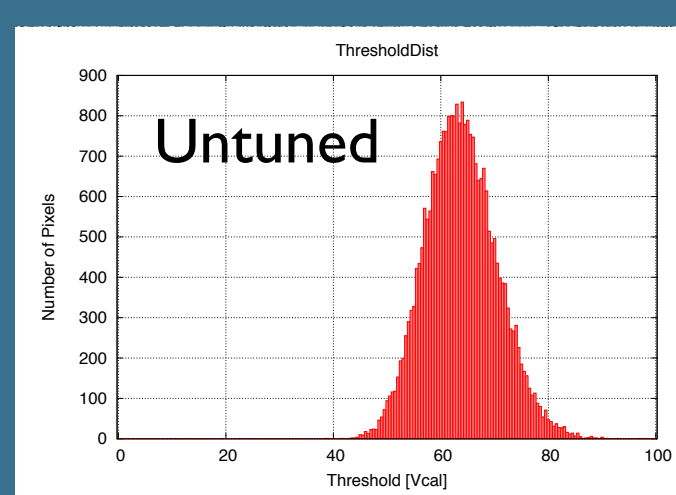
Application

Next RD53 ASIC:
- Readout chip designed by the RD53 collaboration for the ATLAS and CMS Pixel detector at the HL-LHC
- Self-tuning pixel architecture very attractive solution to circumvent frequent retuning of pixels
- Automatically tunes to lowest possible threshold

Motivation

ATLAS Pixel detector:
- Detuning due to ionising dose
- Required constant adjustment and retuning of the detector
- Undesired for operation

ATLAS Phase 2 Upgrade:
- Higher dose → faster detuning
- Pixel density does not allow for adequate SEU protection
> Requires constant reconfiguration and retuning of Front-End

ATLAS Pixel Preliminary

200 krad   600 krad   1 Mrad

FE65-P2
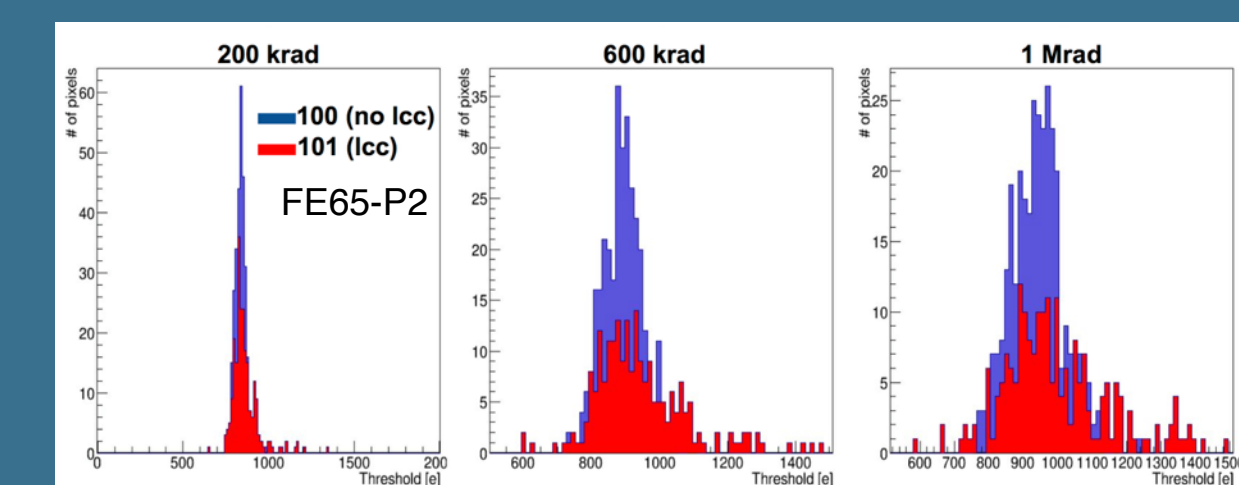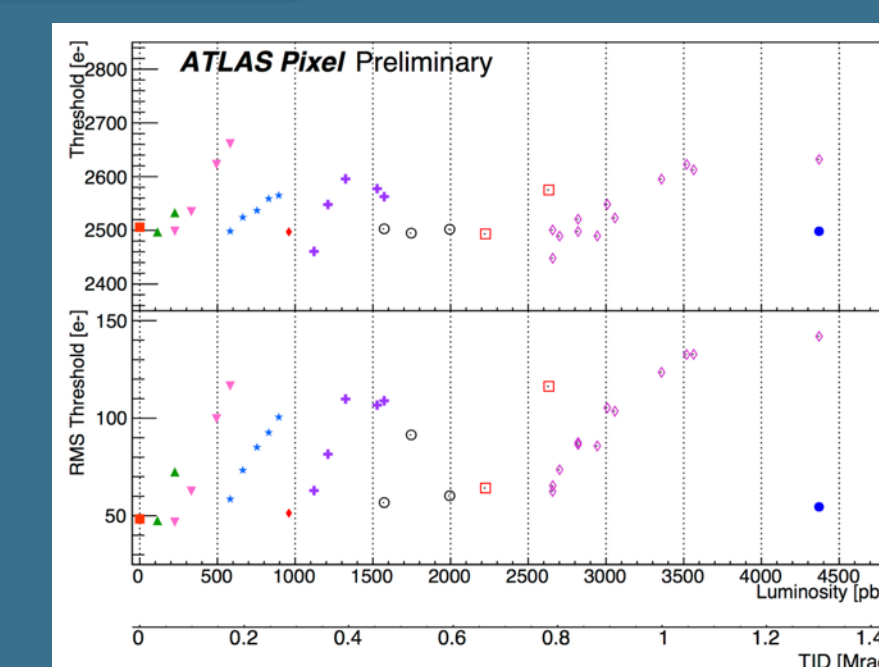
Self-Adjusting Threshold Mechanism

Real-time threshold measure:
- Noise hit rate will decrease exponentially with threshold
> Noise hit rate can be used as indirect measure of threshold

Drive Clock
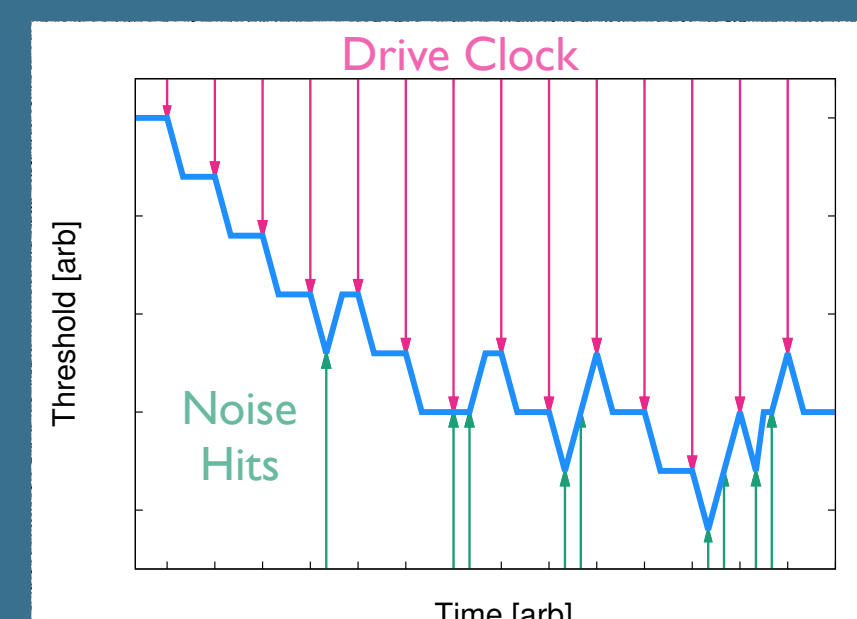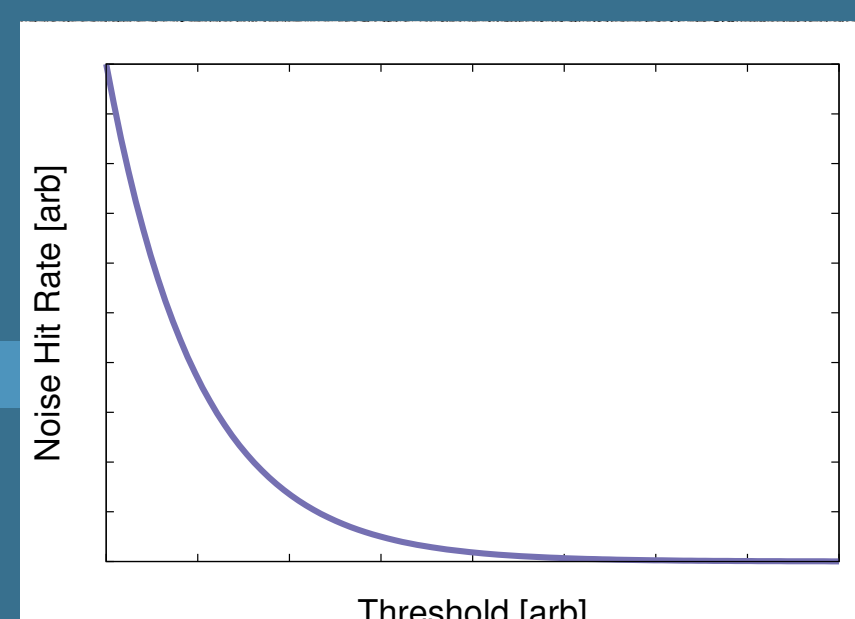
Noise Hits

Self-adjusting threshold:
- Decreases the threshold at a constant rate (drive clock)
- Increases threshold if it registers a noise hit
- Distinguish noise from particles hits:
  - Noise hits are isolated (99.9%)
  - Particles will produce hits in adjacent pixels
> Pixel will be kept at a constant noise hit rate → automatically adjusts for SEUs and changes in the transistor characteristic

Digital Implementation
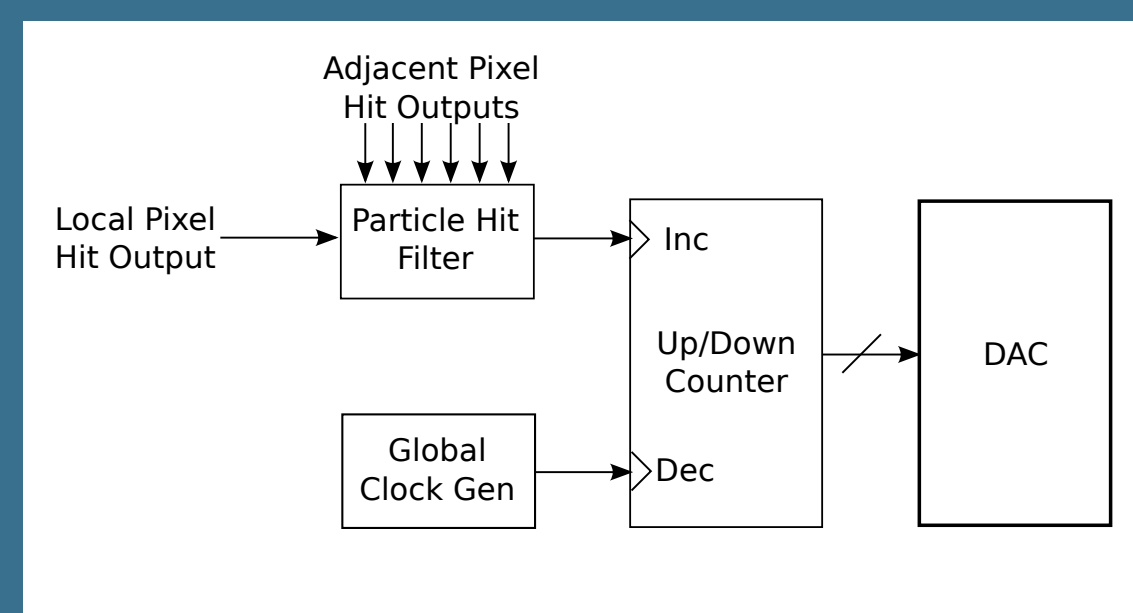
- Replace register with up/down counter
- The counter is decremented by a global (slow) clock
- The counter is incremented if the pixel fired due to an isolated hit (as determined by some combinatorial logic)
- Retains traditional functionality
- Takes up more digital real estate

Analog Implementation
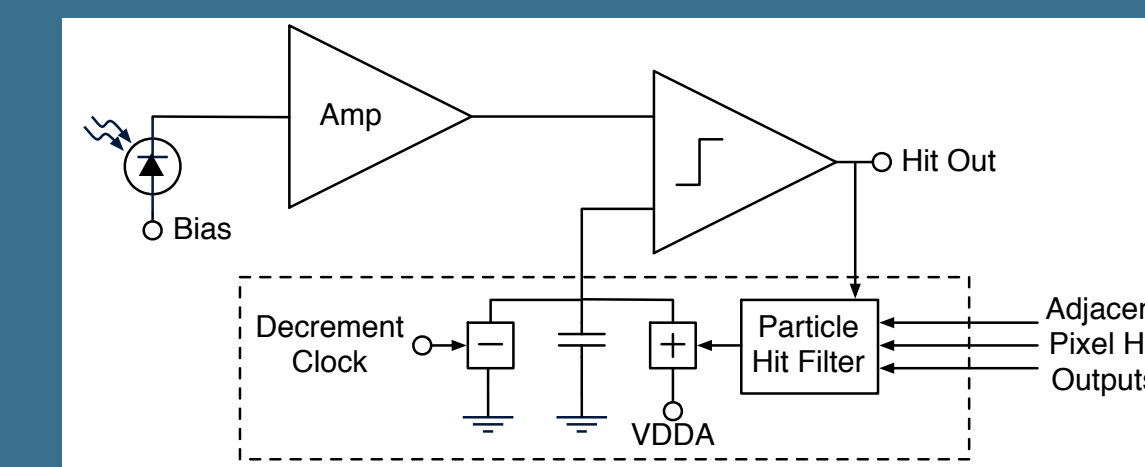
- Replaces DAC and register
- Uses two charge pumps to generate threshold voltage on a capacitor
- Charge is decreased by a global pulse
- Charge is increased by pulse from filter logic
- Frees up digital real estate, but is not externally programmable and capacitor will need to be fairly large
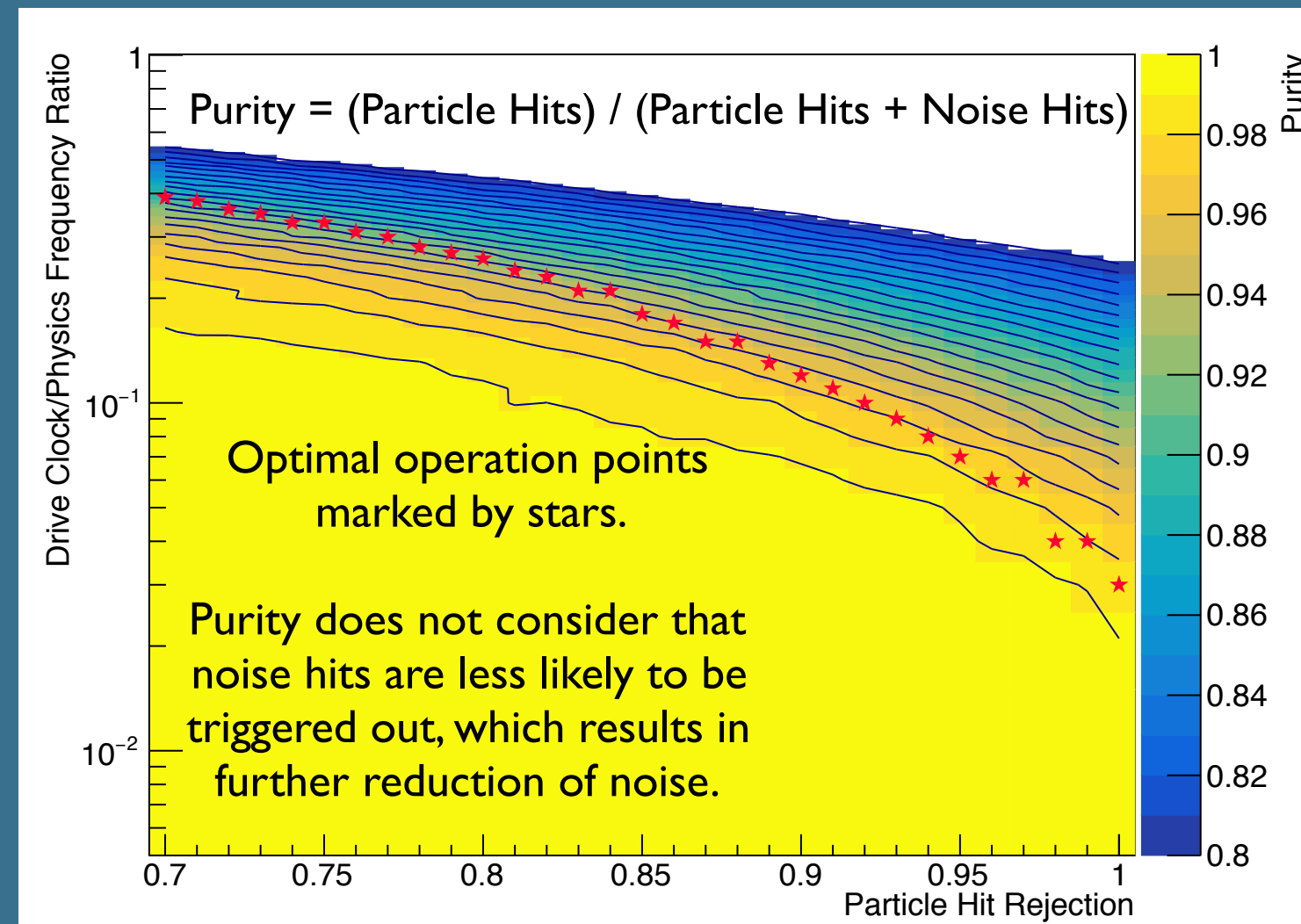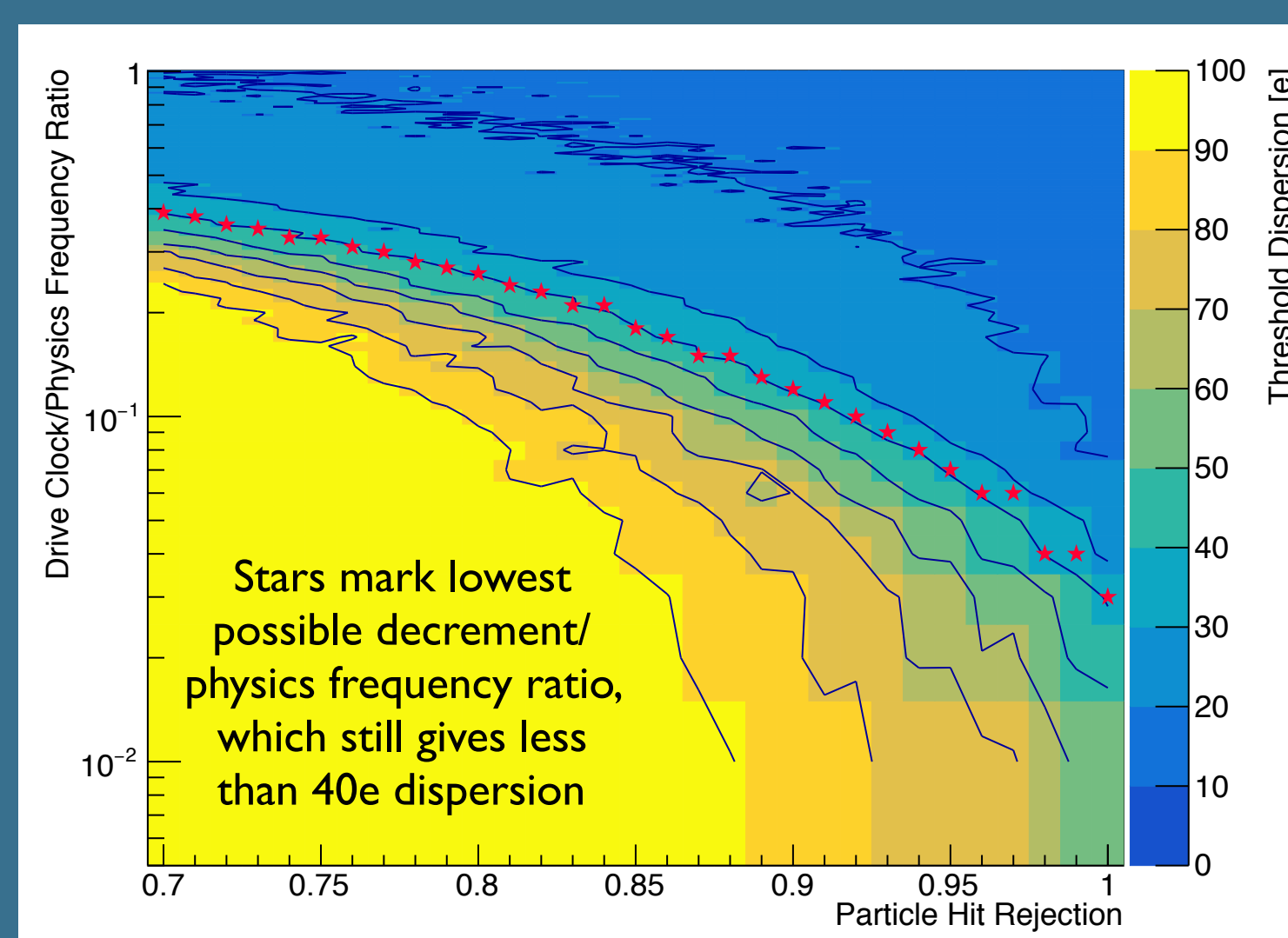- Does not allow manual tuning

Simulation
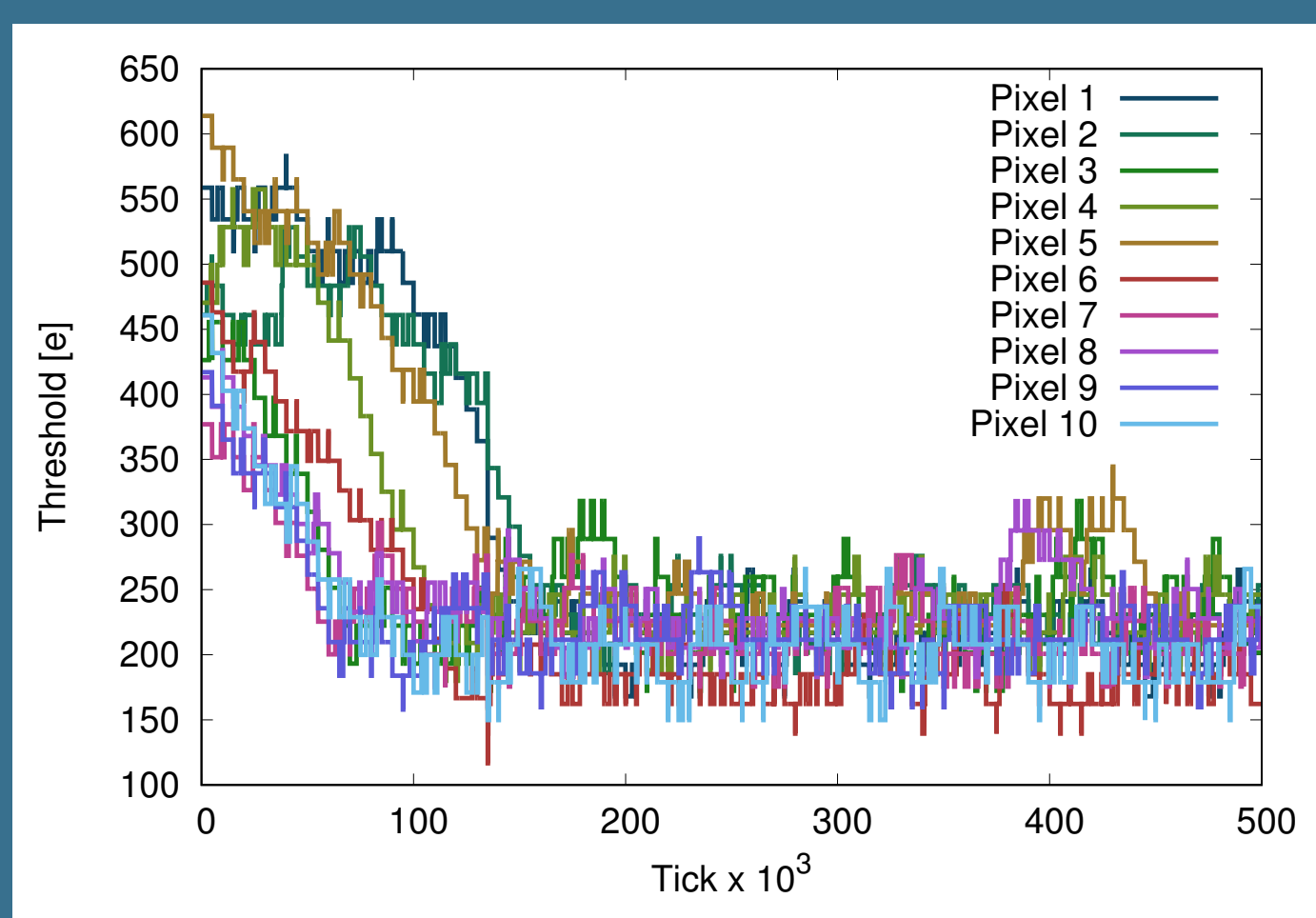
Considerations:
- Simulation results shown in the following have input parameters close to what we expect in the ATLAS Phase 2 Upgrade
- The particle hit filter will not reject 100% of real hits, which results a percentage of particle hits increasing the threshold
- Noise hit acceptance might not be 100%
- The target noise hit rate must be larger than rate of real hits passing filter
- Threshold dispersion of all pixels should be below 40e sigma (a value currently achieved by traditional tuning)

Input parameters:
- Simulate pixel population of $\mathcal{O}(10000)$ pixels
- Each pixel has the following parameters:
  - Base threshold (gaussian distributed): 500e ± 100e
  - Equivalent Noise Charge (gaussian distributed): 50e ± 10e
  - Local threshold step size (gaussian distributed): 25e ± 2e
- Global parameters:
  - Particle hit rate: 10^{-3} per tick per pixel
  - Drive clock: 10^4 per tick
  - Particle hit filter efficiency: 90%
  - Noise hit acceptance: 100%
  - Base threshold step: 25e

Simulation Results

Stars mark lowest possible decrement/physics frequency ratio, which still gives less than 40e dispersion

Purity = (Particle Hits) / (Particle Hits + Noise Hits)

Optimal operation points marked by stars.

Purity does not consider that noise hits are less likely to be triggered out, which results in further reduction of noise.

Step size mean:
- Minor increase due to 'bit-bubble'
- Step size has to be tuned to the specific chip needs

$f(x) = 0.842 x + 11.784$

$f(x) = 0.227 x + 30.943$

Step size sigma:
- Only unrealistically large values produce a negative effect
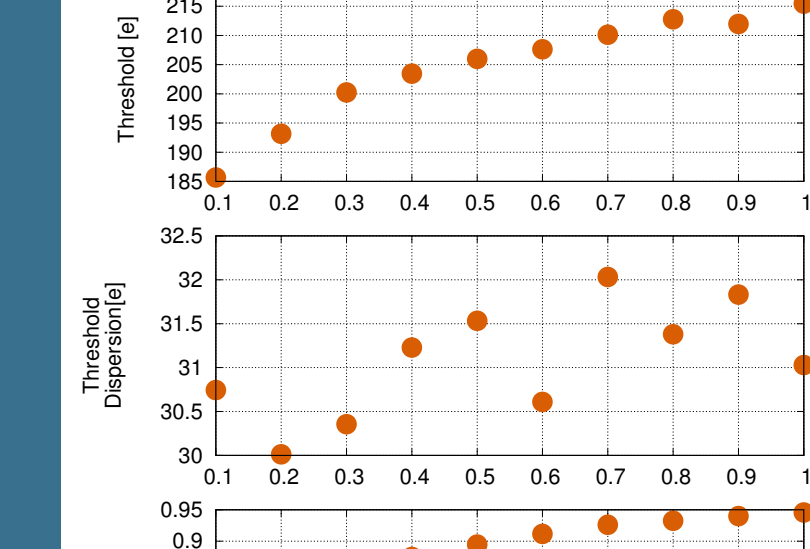
Noise Mean:
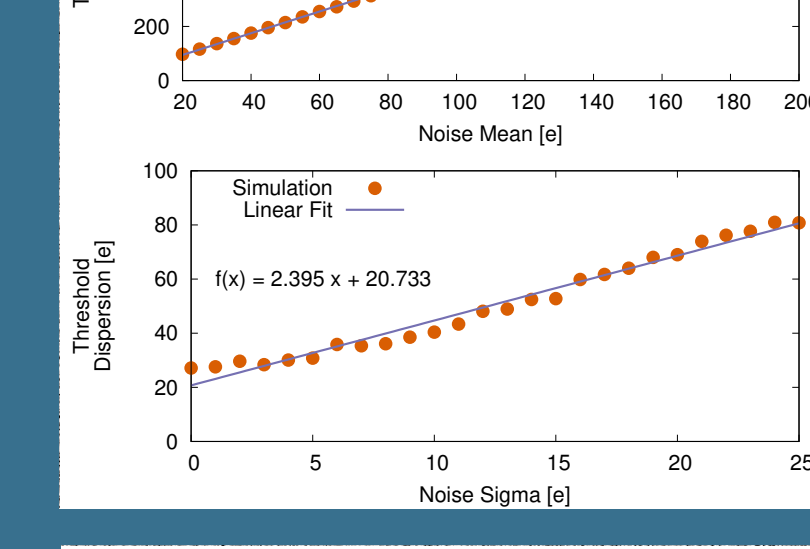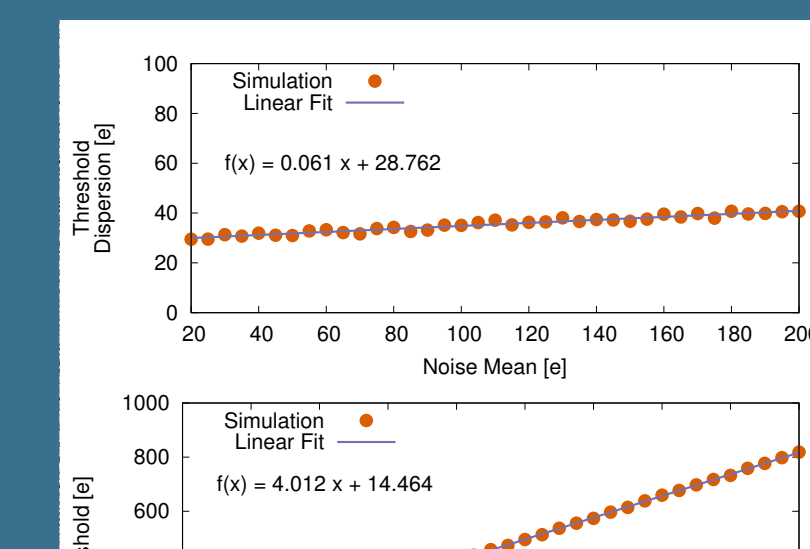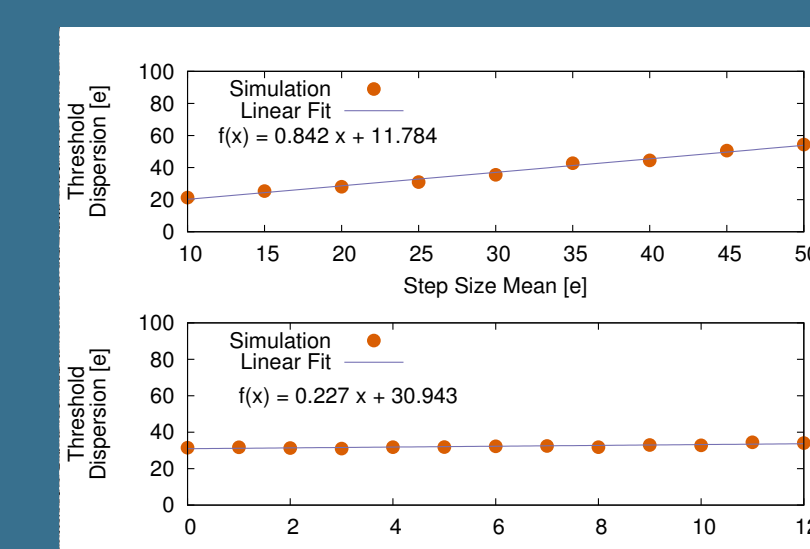- Higher noise mean will result in higher threshold for the same desired noise hit rate
- Has only minor effect on threshold dispersion

$f(x) = 0.061 x + 28.762$

Noise Sigma:
- As noise is used as the threshold reference, it has strong effect on the threshold dispersion
- But noise sigma proven to be uniform over the whole module because it is
- Dominated by input transistor, which is large and therefore not suffering from mismatch

$f(x) = 4.012 x + 14.464$

$f(x) = 2.395 x + 20.733$

Noise hit acceptance:
- Correlated noise hits occur more often than expected from measured noise hit probabilities, likely due to crosstalk
- Correlated noise hits would be identified as particle hits and disregarded
> Effect on self-adjusting threshold mechanism would be that it sees a lower than actual noise rate
> Results in a lower threshold, which in return would have an affect on the purity, due to the increased noise hit rate
- Exponential dependency of noise hit rate on threshold means that there is only little change down to 50% acceptance
- Acceptance can be assumed to be in the region of 99% and higher

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