First results from the HEPAPS4 Active Pixel Sensor

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Outline of the talk

- Active Pixel Sensors – an introduction
- The HEPAPS4 sensor
- Basic characterisation
  - Noise components and reset behaviour
  - Photon Transfer Curve
  - Linearity
  - Dark current
  - First test beam plots (very preliminary)
- Summary

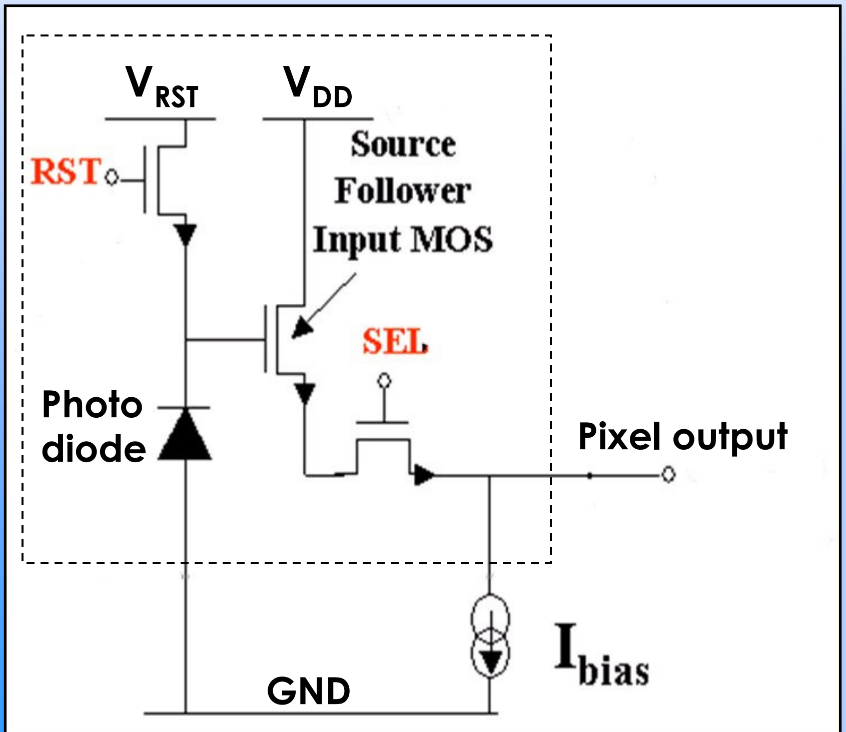
Active Pixel Sensors – Introduction

- Silicon sensor technology based on industry standard CMOS processes
- Monolithic: Sensing volume and amplification implemented in the same silicon substrate
- Similar 'use case' as CCDs
- Photonic applications:
  - Biological/medical applications, HPDs, digital cameras, …
- Envisaged HEP applications
  - Linear collider vertex detector (~10^9 channels)
  - Linear collider calorimeter (Si/W, ~10^{12} channels)

Active Pixel Sensors – Principle of Operation

Simplest design of APS: 3MOS pixel

- Photo diode
- Reset MOS (switch)
- Select MOS (switch)
- Source follower MOS



Functional description

- Photo diode: n-well in the p-type epilayer of the silicon
- Charge collection:
  - e-h pairs from ionising radiation
  - Diffusion of charge in epi-layer
  - Collected by the diode by the built-in field in the pn-junction
- In-pixel circuitry built in p-well.
- Collected charge changes the potential on the source follower gate $V_G = Q_{PD}/C_{PD}$
- Gate voltage changes the transconductance
- Pixel selected by the select MOS
- Output voltage = V_{DD}-g_{ds}*I_{Bias}

Active Pixel Sensor - Cartoon

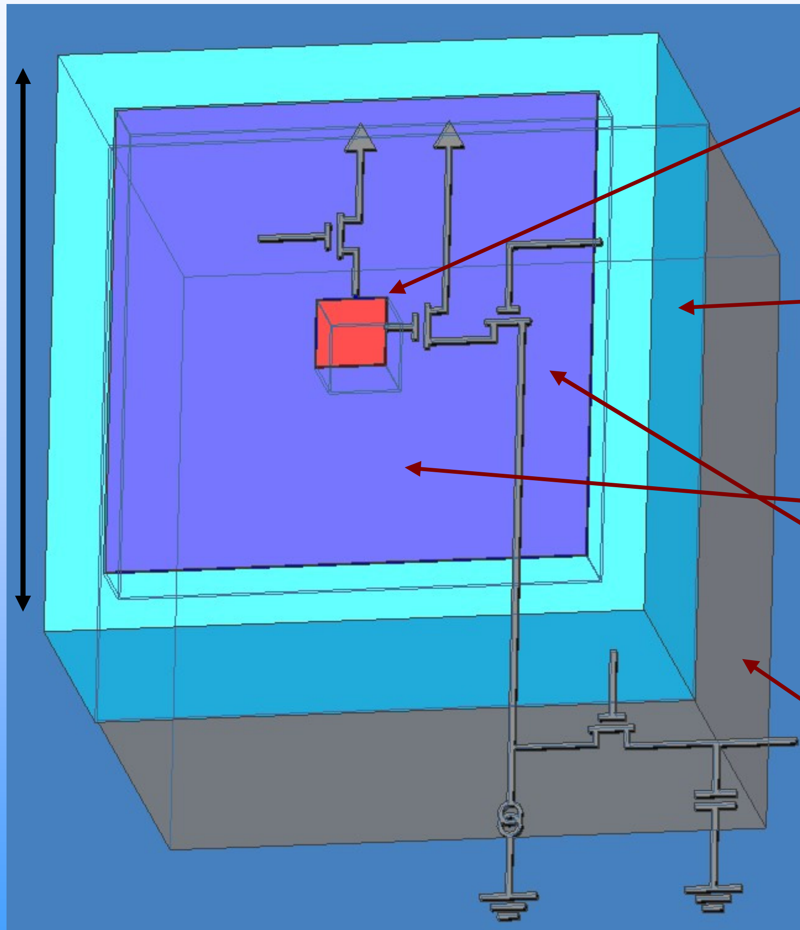


Photo diode (n-well)

- pn-junction with p-epi
- 1-several diodes of varying sizes in different designs.

Epi-layer (5-25 µm)

- Active volume of the device
- Expected MIP: 400-2000 e^-

p-well

- For in-pixel circuitry

In-pixel circuitry

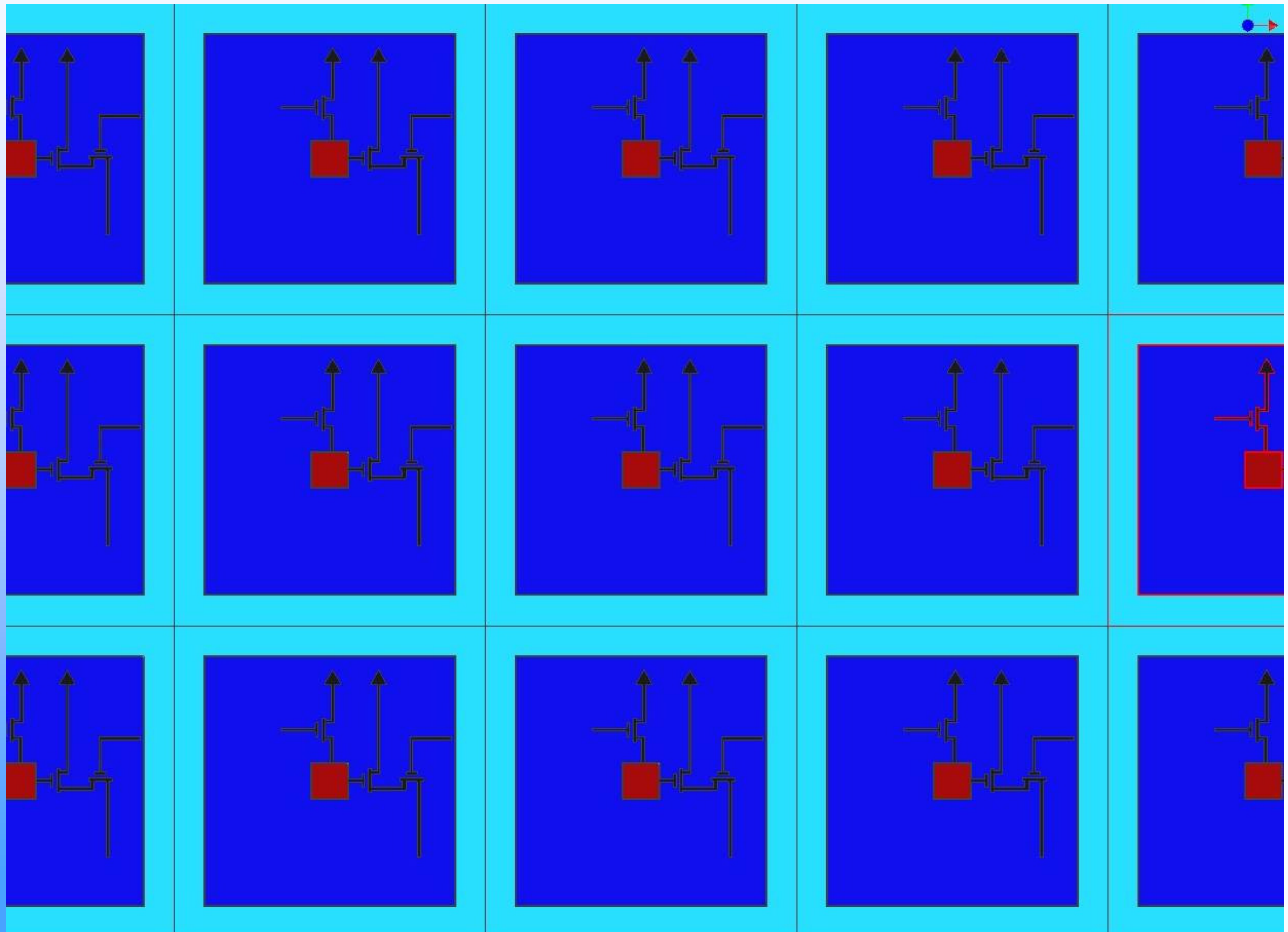
- NMOS transistors

Silicon bulk (10-700 µm)

- Can be thinned as much as mechanical stability allows

* Typical values found in different designs

Cartoon – array of active pixels

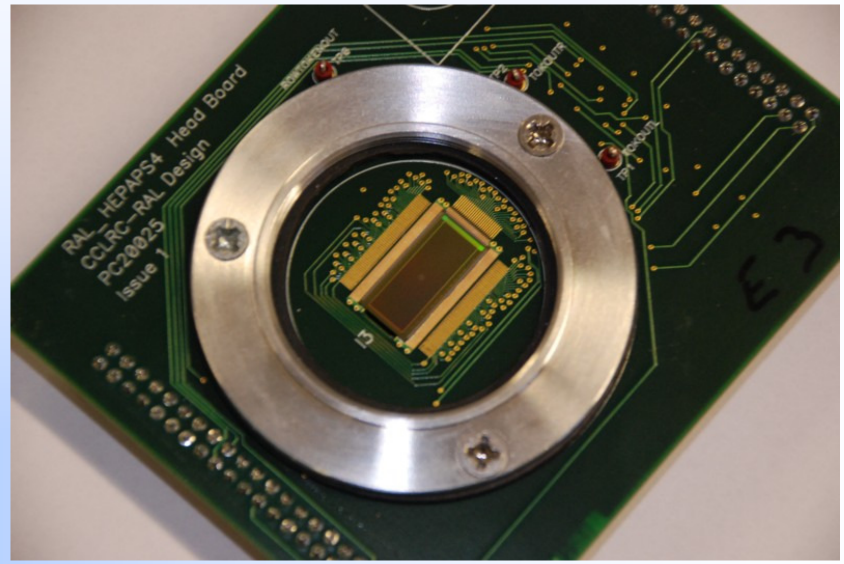


(non-judgemental) pros and cons

- Only uses the epi-layer as active volume
  - Quite small signal (compared to hybrid pixel devices)
  - Can be thinned to minimise material
- But S/N is what counts
  - Intrinsically very low noise
  - Fight other noise components
- Radiation hardness
  - Relies on diffusion for charge collection (no bias voltage)
  - No charge shifting (as in e.g. CCDs)
- Compared to LHC style sensors
  - Relatively slow read-out speed
  - Very low power consumption (saves services!)
- Cost
  - Si sensors relatively expensive per m^2
  - Standard CMOS process
  - Saves integration costs

The HEPAPS4 – large area sensor for HEP applications

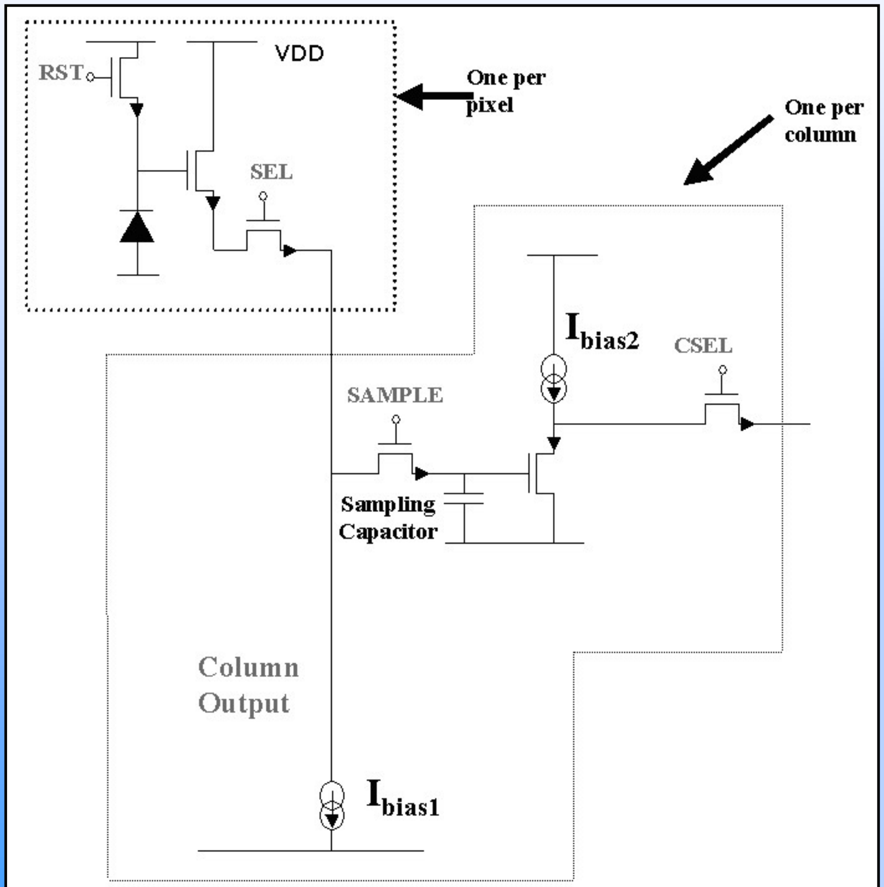
- Fourth in series designed at RAL
- Selected most promising design in HEPAPS2
- Basic parameters
  - 15x15 μm^2 pixel size
  - 384x1024 pixels
  - 20 μm epi-layer
  - 1 MIP = 1600 e$^-$ spread over several pixels
- Three different design variants:



Design	Diode size	From simulations	
		gain	noise
2 diodes in parallel	3x3 μm^2	11 μV/e$^-$	45 e$^-$
4 diodes in parallel	1.7x1.7 μm^2	10 μV/e$^-$	47 e$^-$
Single diode (enclosed geometry transistors)	1.7x1.7 μm^2	16 μV/e$^-$	37e$^-$

Results presented here are from the single diode design

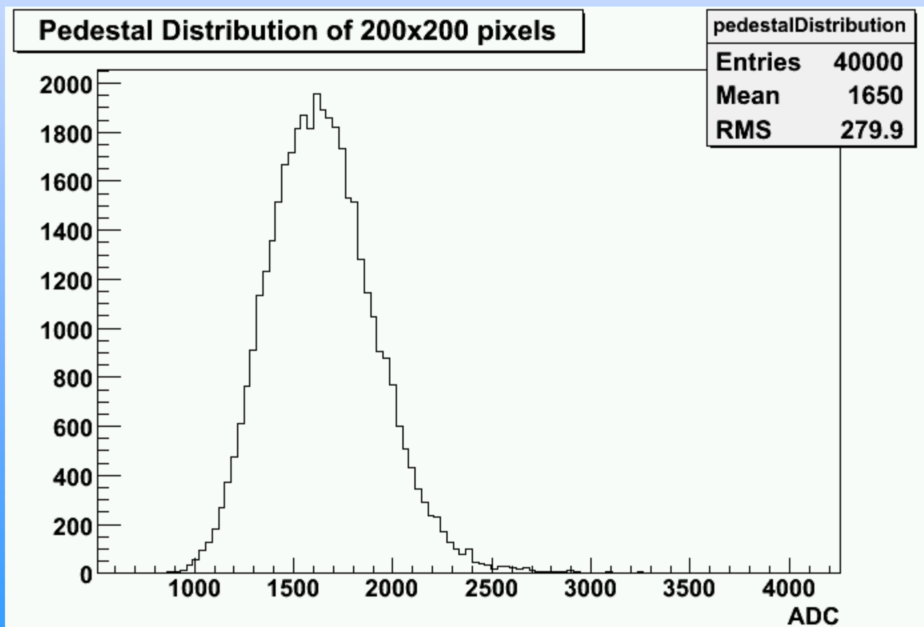
HEPAPS4 operating principle



- 3MOS APS pixel as described previously
- Loop over all rows, select one at a time.
- Sample the signal on to a capacitor for each column
- Loop over columns, read out the value through four independent output drivers
- Reset the row
- Rolling shutter: Continuously cycle through pixels to read-out and reset

Noise components

Fixed Pattern Noise
- Gain Variation
- Pedestal variation
  - 280 ADC or ~1400e$^-$ for HEPAPS4
- Removed by subtracting:
  - Pedestal frame from dark measurement
  - Two adjacent frames



Reset noise
- As described on next slide
- Can be removed by Correlated Double Sampling
  - Sample the reset value before charge collection
  - Can be done in H/W or (partially) offline

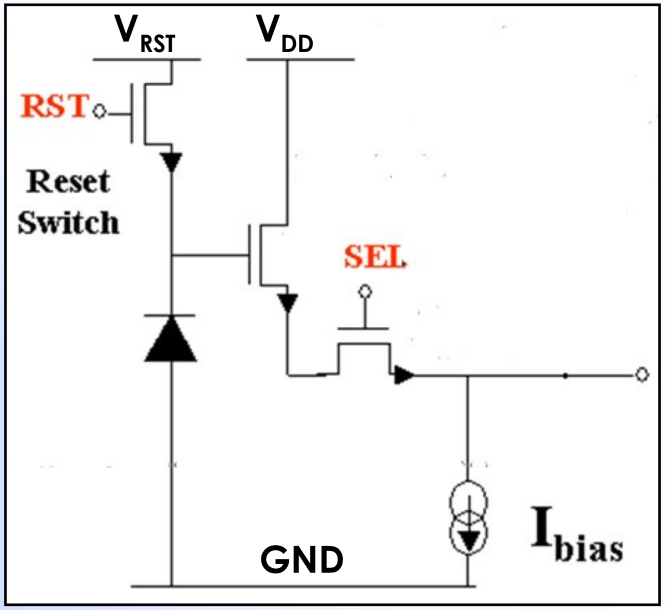
Dark Current
- Leakage current in the photo diode
- Depends on the Average offset = I_{leak}
  - Shot Noise = sqrt(I_{leak})

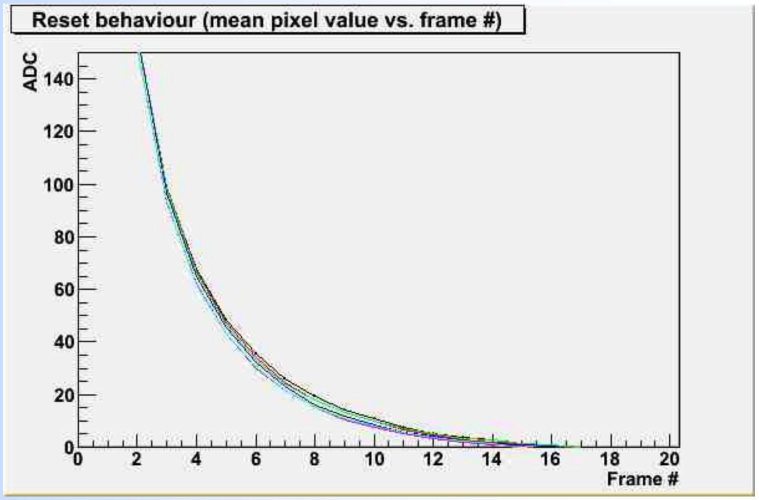
Common mode noise
- Can be partially subtracted

Read noise
- The fundamental noise of the chip

Pixel Reset Behaviour

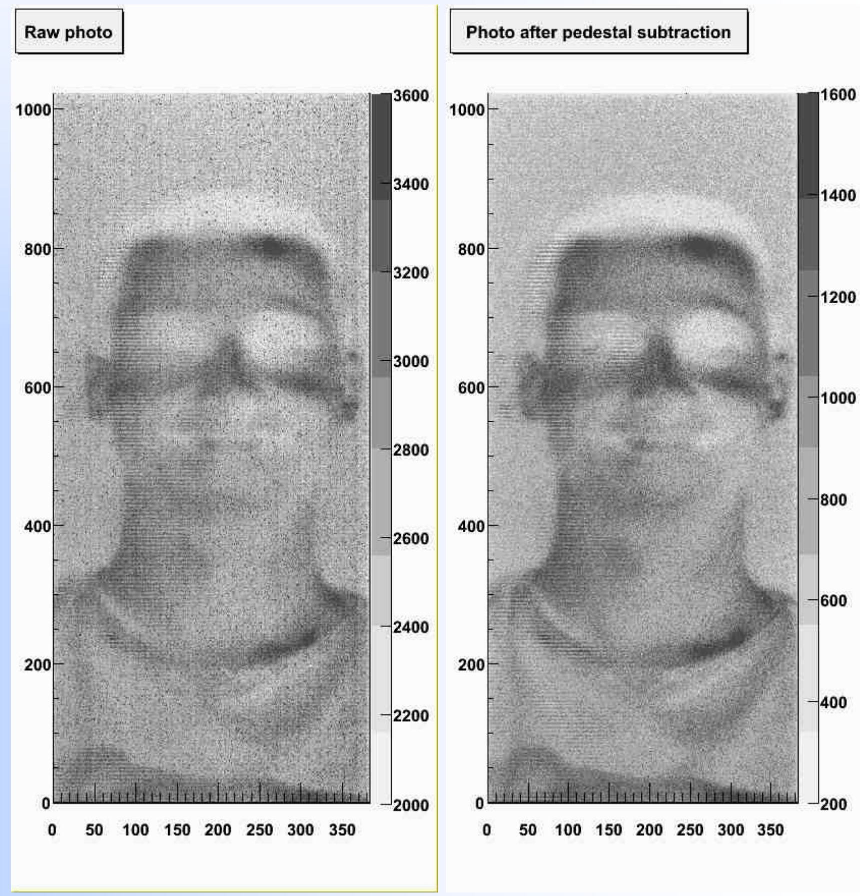
- Pixels are reset by asserting a signal on the Reset Switch
- The charge collecting node is set to the reset voltage V_{RST}
- Soft Reset: $V_{RST} = V_{DD}$
  - Less reset noise
- Hard Reset: $V_{RST} < V_{DD}$
  - Less image lag
  - Decreases dynamic range
- Plot shows HEPAPS4 reset from fully saturated with soft reset operation ($V_{RST}=V_{DD}$).



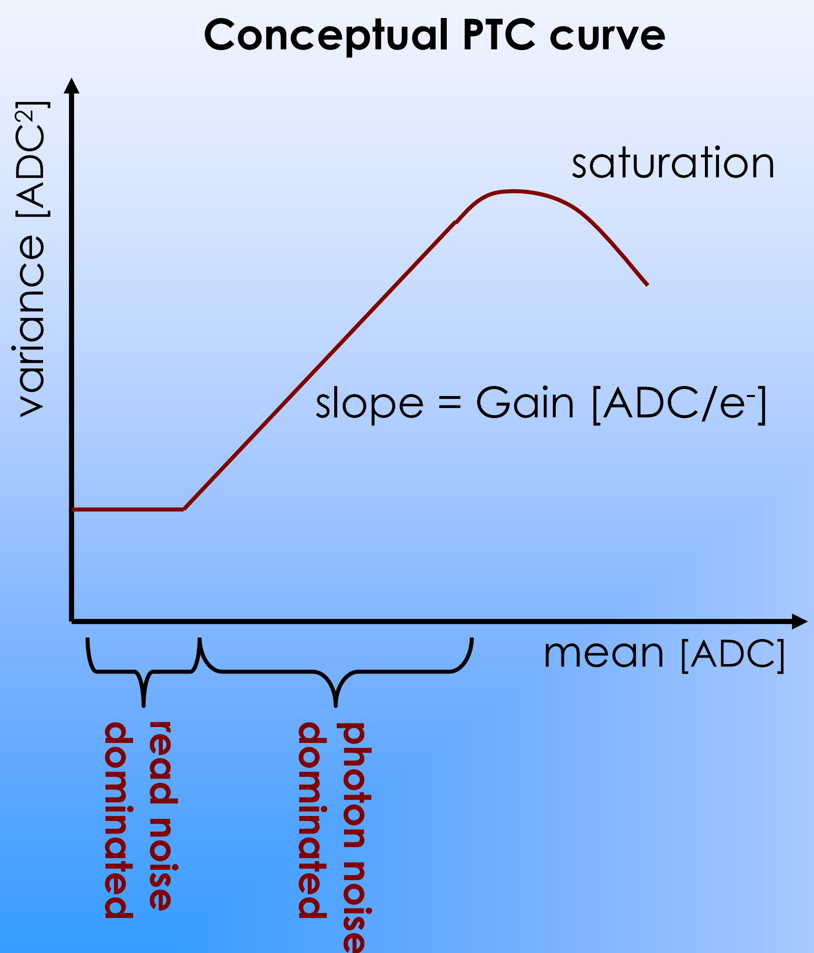


HEPAPS4 as imaging sensor

- APS sensor also used in digital cameras
- HEPAPS4 becomes a B/W 400 kpix camera
- Plots show visually the effects of pedestal subtraction



Photon Transfer Curve (PTC) – Basic Principle



Shine light on the sensor and increase the illumination gradually

- Plot signal variance vs. mean
- Read noise will dominate for low intensities, but:

Mean: $S_{ADC} = G \cdot n_e$

Variance: $\sigma_{ADC}^2 = (G \cdot \sigma_e)^2$

- # of photons per pixel is a Poisson process $\sigma_e^2 = n_e$
- Hence in the region dominated by photon noise

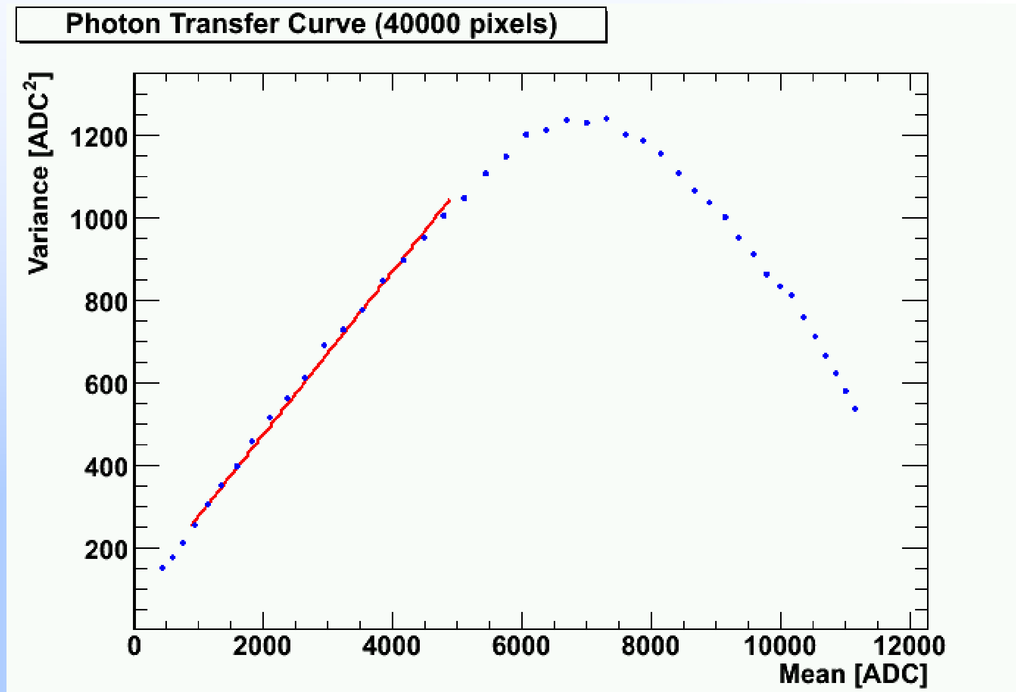
$$\frac{\sigma_{ADC}^2}{S_{ADC}} = G$$

Photon Transfer Curve - Results

- Read out a region of 200x200 pixels
- Subtract pedestal frame
  - Calculate mean signal per pixel
- Subtract two adjacent frames:
  - Removes fixed pattern noise
  - Calculate variance per pixel

Assume constant gain 1000-5000 ADC

- Slope gives gain = 5.1 e^-/ADC
- Noise floor not shown, since it is dominated by systems noise
- Saturation starts after 6000 ADC

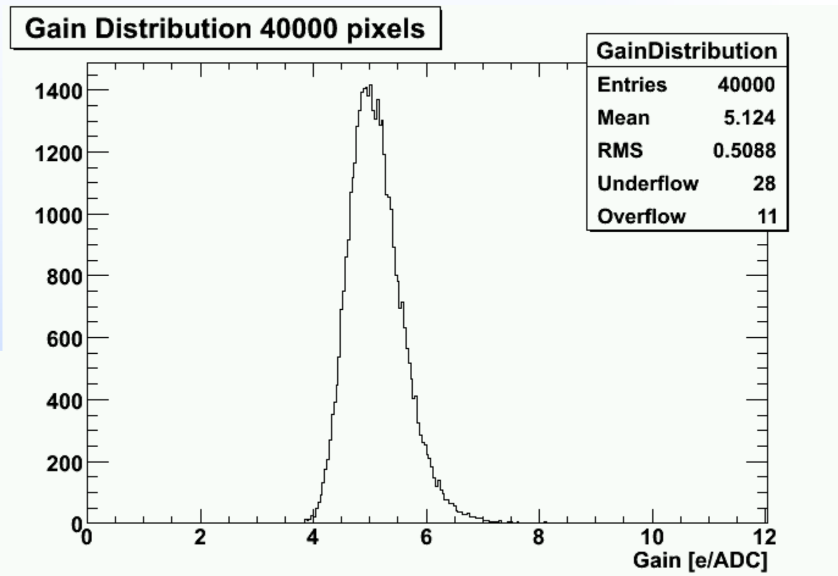


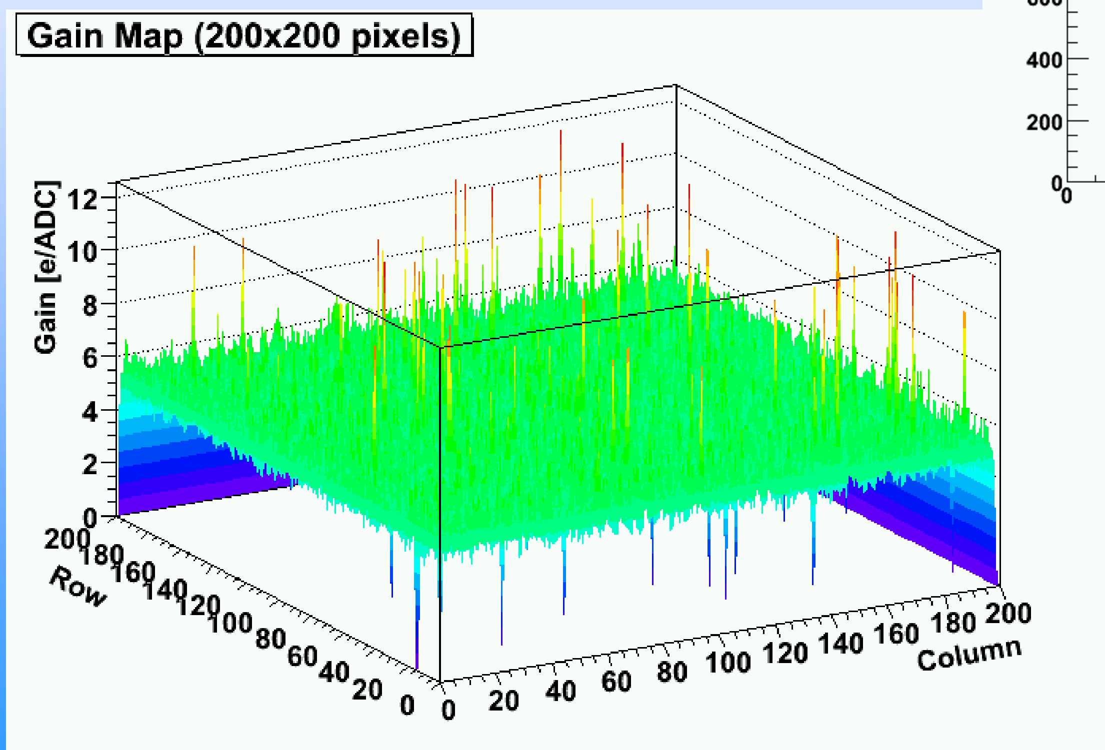
Average variance vs. average mean for 40000 pixels

Expected value from design: 7.8 e^-/ADC

Photon Transfer Curve – Gain Distributions

- Same analysis for 40 000 pixels
- 800 frames to calculate mean and variance
- Fit slope for each pixel

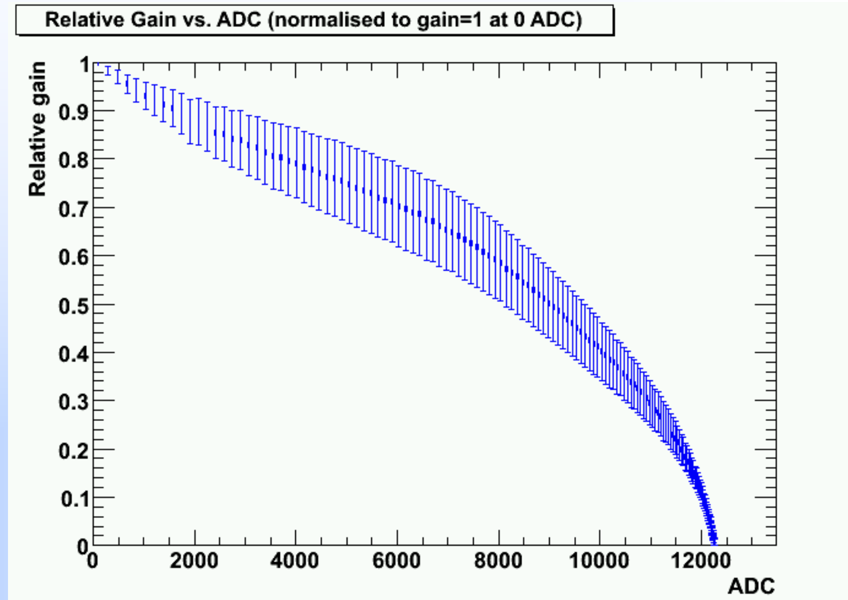


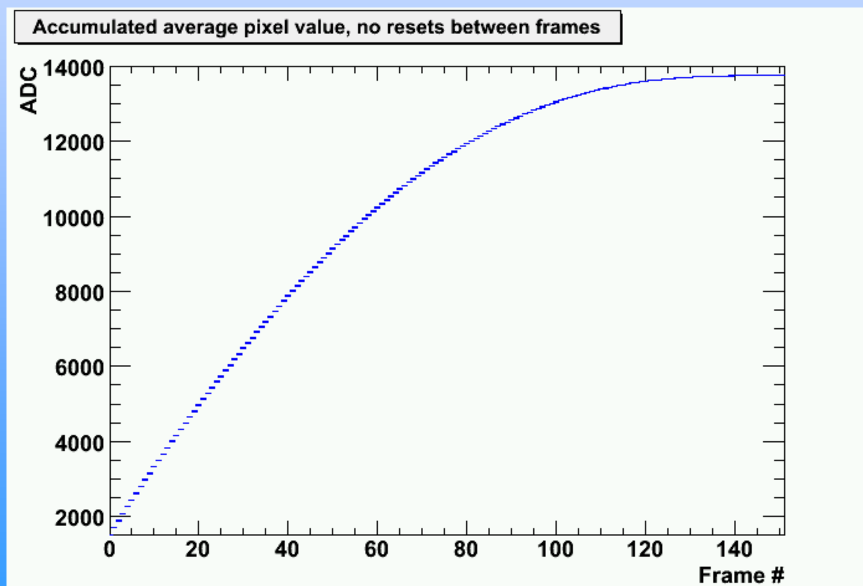


- Gain = 5.1
- Gain RMS = 0.51
- # pixels with gain:
  - < 3 e-/ADC: 41pix
  - > 8 e-/ADC: 90 pix

Linearity

- Non-linearity arises from
  - Change in sense node capacitance when charged
  - Non-linearity of source follower
- Measurement method:
  - Constant, low illumination
  - Continuous acquisition of frames
  - No reset between frames

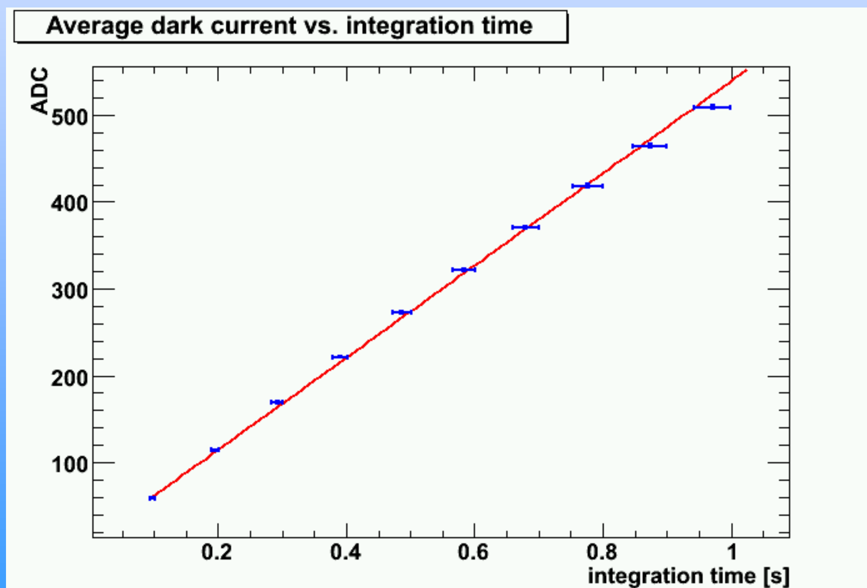




- Relative gain is the derivative of this curve, normalised to the gain at 0 ADC
- Relative gain > 90%
  - 0-1640 ADC
  - 0-8360 e$^-$
- Relative gain > 80%
  - 0-3780 ADC
  - 0-19300 e$^-$

Dark Current

- Dark current is leakage current in the photo diode
- Method:
  - Readout two consecutive frames without reset between the frames
  - Subtract the two frames to remove pedestal and fixed pattern noise
  - Vary the integration time

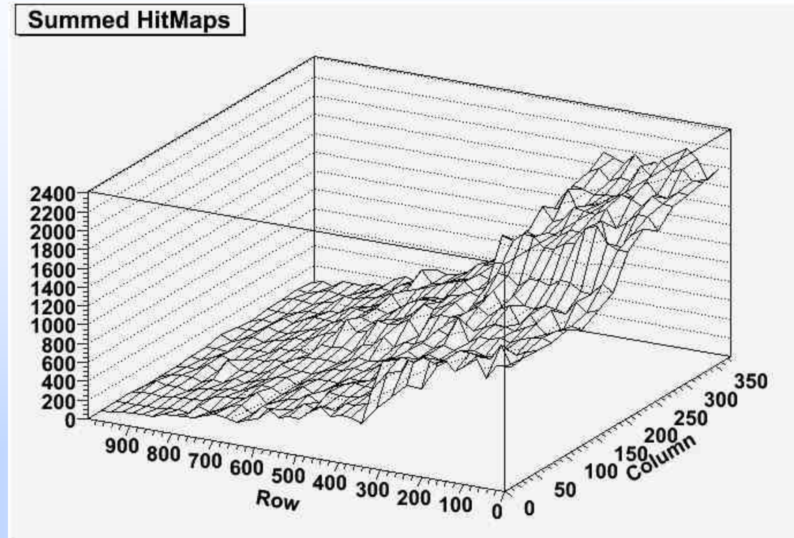


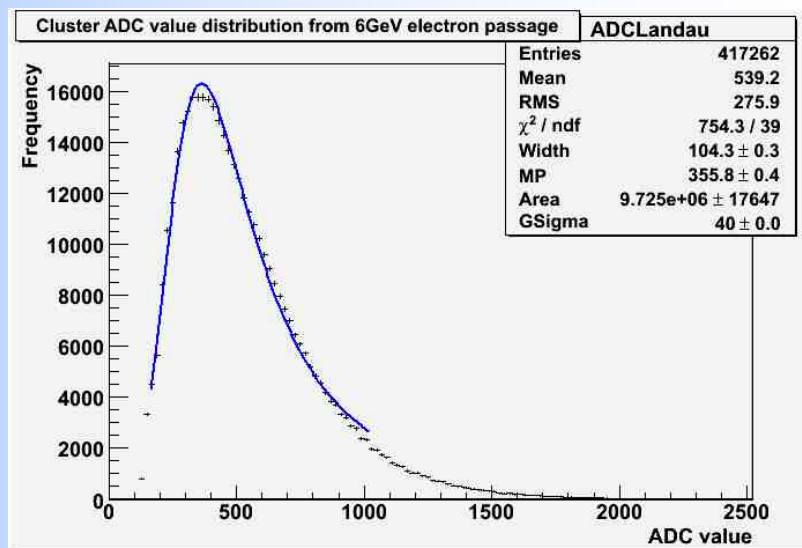
Linear fit to the curve

- Slope 530 ADC/s = 2700 e^-/s
- Pixel size 15x15 μm^2
- I_{dark} = 0.2 nA/cm^2

First Test Beam Plots

- Test beam at DESY: 6GeV electrons
- Combined with ISIS pixel sensor
- Configuration of sensor slightly different from photonic measurements in the lab
- Analysis in progress
- Two ‘muse-bouche’ plots:
  - Hit map: accumulation of reconstructed clusters
  - Landau: Cluster charge in ADC values





Summary

- Active Pixel Sensors are an attractive technology for certain applications in HEP
  - The principle of operation
- HEPAPS4 – a large area APS designed for HEP applications
- First results from the characterisation:
  - Gain 5.1 e-/ADC with an RMS of 0.5 e^-/ADC over 40k pixels
  - 90% of gain up to 8400 e^-
  - 80% of gain up to 19300 e^-
  - Dark current 2700 e^-/s per pixel
- Two preliminary plots from the beam test