Experimental results with Cherwell MAPS sensors

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Outline

Introduction

- Monolithic Active Pixel Sensors (MAPS) are a potential technology for vertexing, tracking and digital calorimetry in HEP.
- Now being adapted for LHC upgrades.
- Our designs used in many other areas:
  - HMRM : Radiation monitoring in space.
  - Sophia : Single Photon Avalanche Detectors.
  - Achilles : Transmission Electron Microscope.
  - Lassena : X-ray imaging.
  - PImMS : Pixel imaging Mass Spectroscopy.
  - Kirana : Ultra High Speed Imaging Sensor (5 MHz).

URL : STFC CMOS Sensor Group or see backup slides

Monolithic Active Pixel Sensors (MAPS)

- Low Cost: 0.18 μm CMOS, mature industrial process.
- Low Power: low voltage and absence of standing currents.
- Low Material: very thin overall (30-50 μm).
- Radiation Tolerance: MAPS in excess of $>$ 10 Mrad.
- High Granularity: pixel sizes down to $\sim$1 μm.

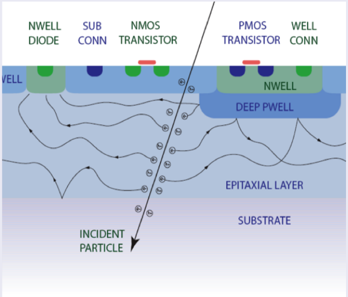
Additional Features developed

- Deep p-well: improved charge collection: [Ballin, J et al., Sensors 2008, 5336-5351].
- High resistivity epitaxial layers: rad. hard, improved charge collection.
- 4T structures: in-pixel structures (strixels), correlated double sampling (CDS), improved S/N, low power (10μW/pixel): [Coath, R et al., IEEE Nuclear Science, 57, 2490-2496 (2010)].
- Stitching: 12 cm $\times$ 12 cm structures: [Bohndiek, S et al., IEEE Nuclear Science, 56, 2938-2946 (2009)].

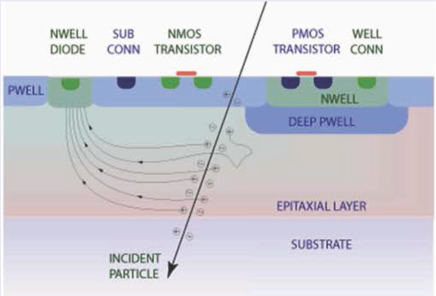
Deep P-well and High Resistivity Epitaxial layers

- PMOS N-well competes with N-well diode, resulting in inefficient regions of the pixel. Deep P-well shields N-well; charge channeled back into epitaxial layer; increased charge collection efficiency over whole pixel.
- High Resistivity Epitaxial Layer: faster charge collection, reduced charge spread, and increased radiation hardness.

CMOS P-well



High Resistivity Epitaxial

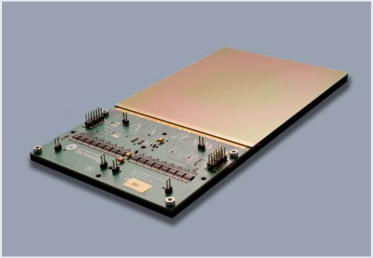


4T, Stitching, and Strixels

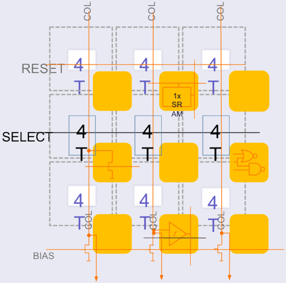
4T CMOS

Readout and charge collection node are now separated. Lower noise, in-pixel correlated double sampling (CDS), higher gain.

Example of stitching



In-pixel Electronics - Strixels

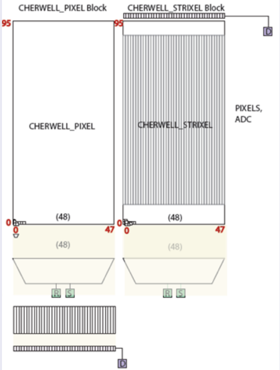


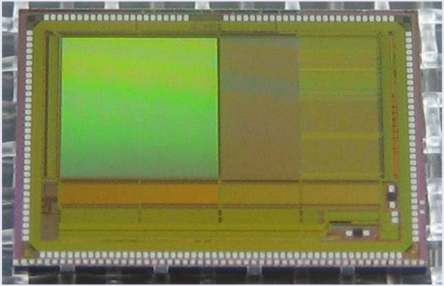
- Use islands of electronics in pixels. Comparators, amplifiers, ADCs, trims,...etc.
- Avoid having dead regions; potentially faster.

Cherwell 1 - Calorimetry/Tracking/Vertexing

Various formats, originally designed for Linear Collider

1. Reference: 48×96 $25\,\mu\mathrm{m}$ pixels with 10-bit ADC at column base.
2. Strixel: 48×96 $25\,\mu\mathrm{m}$ pixels with 10-bit ADC embedded in pixel.



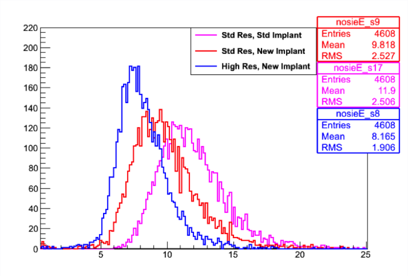


Reference and Strixel can be read out with an external ADC.

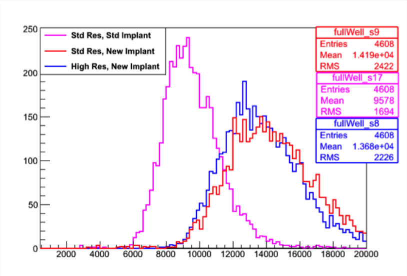
Characterisation

- Std. Res.; Std. Res. + Low Vt; High Res. + Low Vt

Noise (e^-)



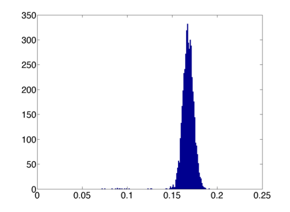
Full well (e^-)



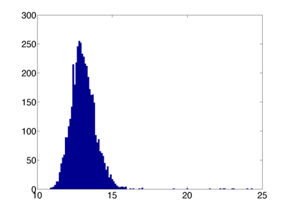
- Low V_t and high resistivity epitaxial layer successfully reduces noise and increases S/N.
- Low noise 8-12 e^-; good gain 0.17 ADCs/e^- or 51$\mu V/e^-$; full well 14700 e^-.

Noise and gain variation within a Std. Res. sensor

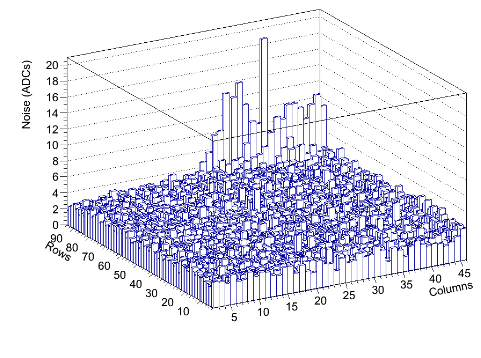
Gain (ADC counts/e^-)



Noise (e^-)

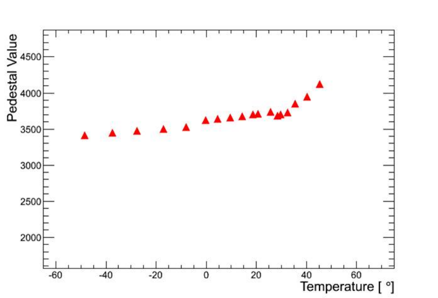


Noise (ADC counts)

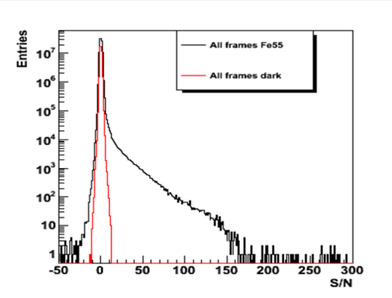


Good gain and noise consistency across pixels

Temperature Stability



^{55}Fe Signal-to-Noise



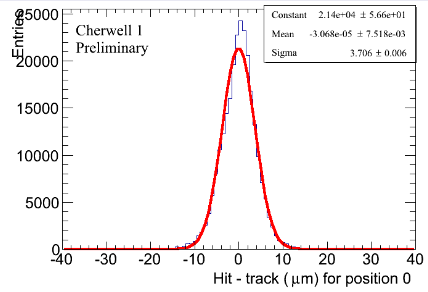
Preliminary results

- Temperature Stability $< 0.01\%/^{o}$C between -50 to 50 ^{o}C.
- Signal-to-Noise > 130.

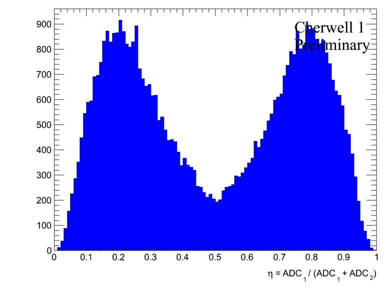
Hit Efficiency and Resolution from CERN test beam

- First align sensors to within $\sim 0.5\,\mu\mathrm{m}$.
- SVD fit to clusters along a road without sensor under consideration.
- No corrections for non-linear charge sharing ($< 1.5\,\mu\mathrm{m}$); multiple scattering ($< 0.5\,\mu\mathrm{m}$); and tracking resolution ($\sim 1 - 2\,\mu\mathrm{m}$).
- Hit efficiency $\gtrsim$ 99.7%.
- Hit resolution $3.7\,\mu\mathrm{m}$ without corrections achieved.

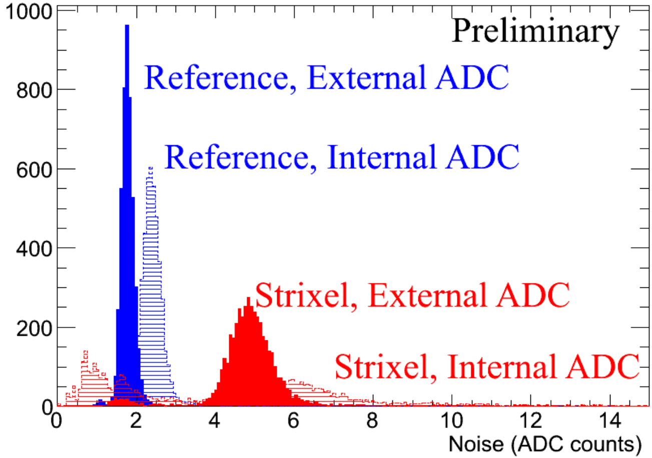
Hit resolution achieved



Charge Sharing

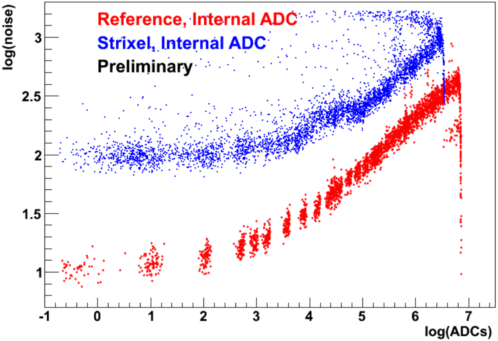


First look at strixels - Noise



- Internal ADCs add some noise
- Strixel noise twice Reference noise but still $< 20e^-$.

First look at strixel performance - Photon Transfer Curve

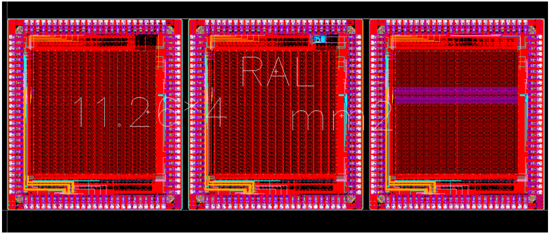


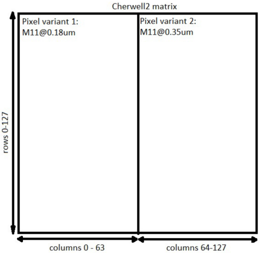
- PTC curve allows us to understand read noise (y-intercept), shot noise (mid range), fixed pattern noise (high range), gain (gradient), and number of electrons collected (turn over point).
- Strixel is noisier than Reference and response is less uniform but all other functions are good. Strixels with ADCs are working.

Cherwell 2 - ALICE Inner Tracker System prototype

- 3 variants, (2 x all digital, 1 x analogue readout).
- In-pixel circuitry, 128×128 $20\,\mu\mathrm{m}$ pitch pixels.
- Predicted: Gain $\sim 30\mu V/e^-$, linear full well 6,000 e^-, noise $\sim 25e^-$, power 11 $\mathrm{mW}/\mathrm{cm}^2$.

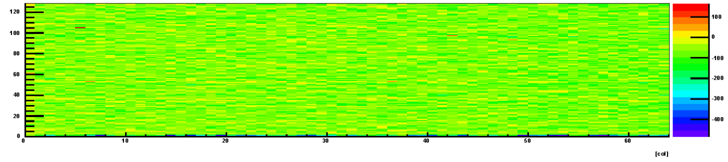
- Source Followers in $0.18\,\mu\mathrm{m}$ and $0.35\,\mu\mathrm{m}$ versions (tests rad. hardness.).
- Characterization on-going.
- Only Analogue tested so far
- Hope to test at CERN in October



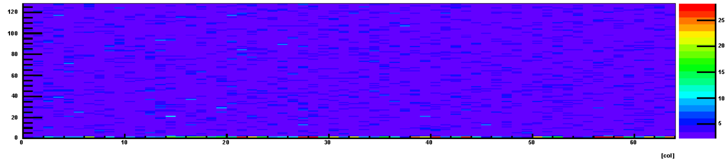


Cherwell 2 - Preliminary Noise and Pedestal Scan

Pedestals Distribution - ADCs



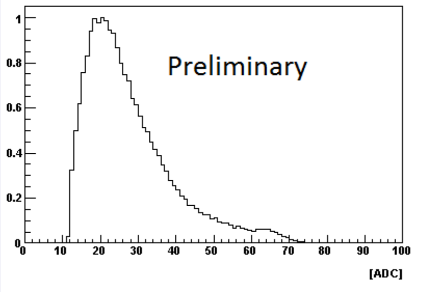
Noise Distribution - ADCs



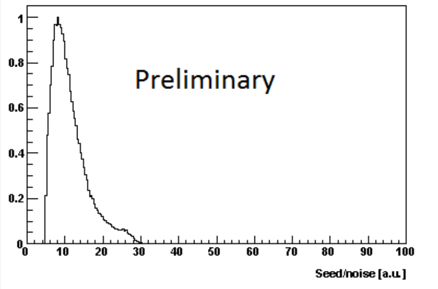
- No unexpected features although noise is too high, $\sim 45e^-$.
- Due to layout problem, integration time increased from 30 μs to 14 ms.

Cherwell 2 - Preliminary ^{55}Fe

^{55}Fe response



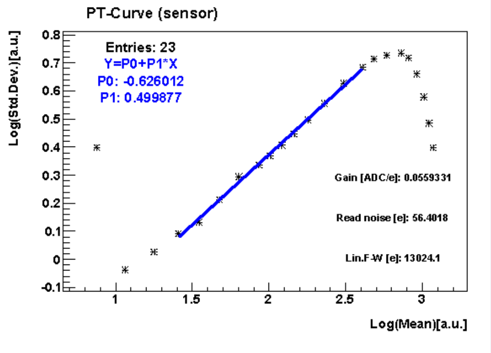
Signal to Noise



- Noise a little higher than predicted, $\sim 45e^-$.
- Gain lower than predicted $\sim 20\mu V/e^-$.
- Investigating readout chain and biasing.

Cherwell 2 - Preliminary PTC Scans

0.18 μm Source Follower version



- PTC averaged over all pixels.
- Noise slightly higher than predicted, $\sim 45e^{-}$.
- Lower gain than expected $\sim 0.055ADC/e^{-}$.
- Linear full well $\sim \times 2$ predicted value.

Cherwell MAPS Conclusion and Future

Cherwell 1 - Linear Collider prototypes

- Exceeding design goals: hit efficiency ($\gtrsim$ 99.7%) and resolution (3.7 $\mu\mathrm{m}$) looking good for future vertex and tracking devices.
- Strixel blocks with ADCs are working.

Cherwell 2 - ALICE prototypes

- Integrated into SRS readout system. Some readout problems.
- Characteristics not quite as predicted - could be biasing/calibration
- Preliminary characterisation to be completed over summer.

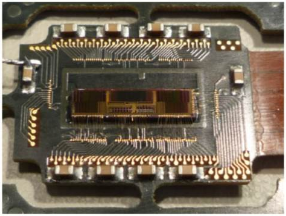
Cherwell 3 and OverMOS - HL-LHC prototypes

- Cherwell 3 : Lower power but faster. Pixel masking.
- OverMOS : Adaptations for LHC upgrades.
- Test beam later this year with Cherwell 1, 2 and 3.

Backup - HMRM and Sophia

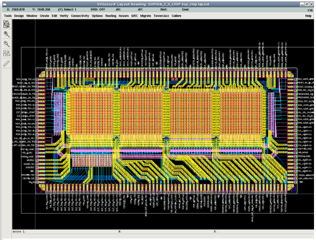
Highly Miniaturised Radiation Monitor

- Sensor size : 50x50 μm, 250 μm thick, 10.3 mm by 2.4 mm.
- Low noise, rad tolerant, designed for ESA.
- To be launched on Tech Demo Satellite.



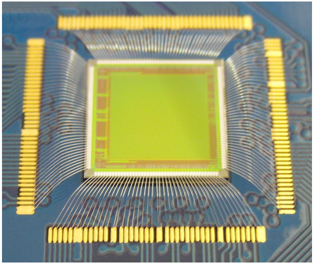
Single Photon Avalanche Detectors

- 0.18 μm CMOS, alternative to APDs and CCDs.
- Targetting FLIM, 3D imaging, astronomy, PET and mass spectroscopy.
- Photon Detection Probability up to 27%
- Timing resolution: 0.5 ns FWHM.



PImMS 1 & 2 - Pixel Imaging Mass Spectroscopy

- Based on TPAC.
- Event-based time-stamping pixel sensor.
- 382×382 $70\,\mu\mathrm{m}$ pixels.
- 80MHz, $12.5\,\mathrm{ns}$ time resolution.
- 12 bit timestamp storage.
- 4 registers per pixel for multiple event detection.
- Per pixel trim, mask and comparator.
- Analogue readout for focusing and event size measurement.
- Gadolinium thin film coating used in neutron imaging.

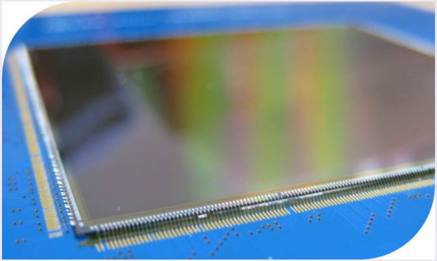


PiMMS 1 camera

Achilles for TEM and Lassena for X-ray imaging

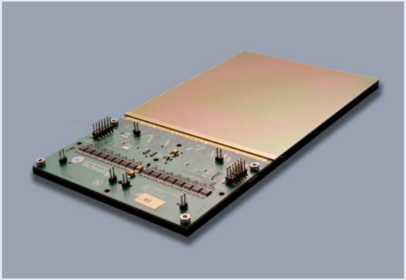
Transmission Electron Microscope

- 4096 x 4096 14 $\mu\mathrm{m}$ pixels
- Sensor Size: 61 mm x 63 mm
- Analogue output, 40 fps.
- Radiation Hard to 20 Mrad.



X-ray Imaging

- 2800 x 2400 50 $\mu\mathrm{m}$ pixels.
- 139.2 $\mathrm{mm} \times$ 120 mm.
- Analogue output, 30 fps.
- 3-side buttable with minimal dead space.



Kirana - Ultra High Speed Imaging Sensor

- 924×768, 30 μm pixels.
- Die size: 32.5×25.5 mm.
- CDS, in-pixel storage.
- Continuous readout at 1,180 fps.
- Burst mode: 180 frames at 2 MHz (but sensor will work at 5 MHz).
- Gain: $80\mu V/e^-$.
- Full well: $11{,}700e^-$.
- Commercialised (Specialised Imaging).