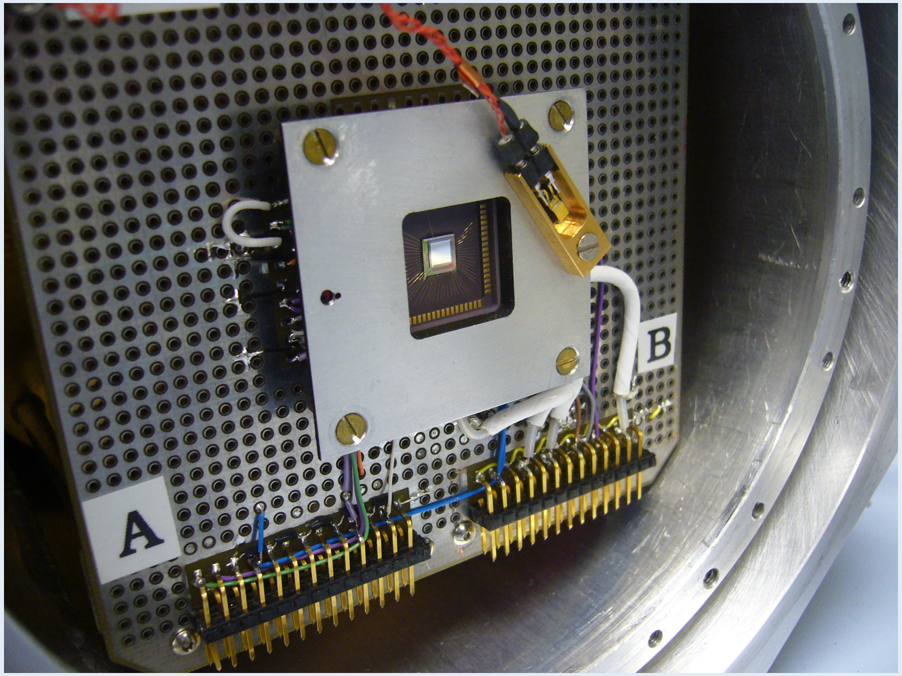
The Speedster-EXD: A New Event-Driven Hybrid CMOS X-ray Detector



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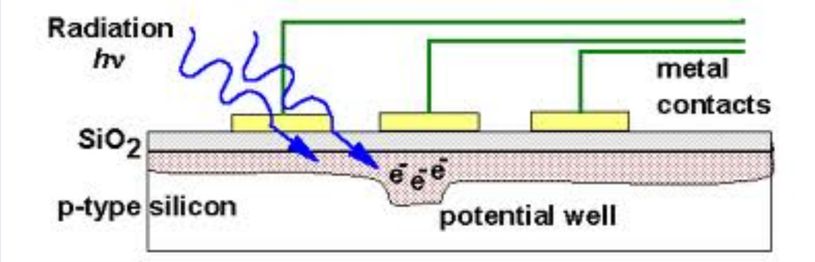
Fermi Summer School

Outline

- Background to X-ray Detectors and Current Technology
- Advantages of Hybrid CMOS
- Future Space Missions and Science Motivations
- Speedster-EXD Detector
- Future work

X-ray Detection in Silicon

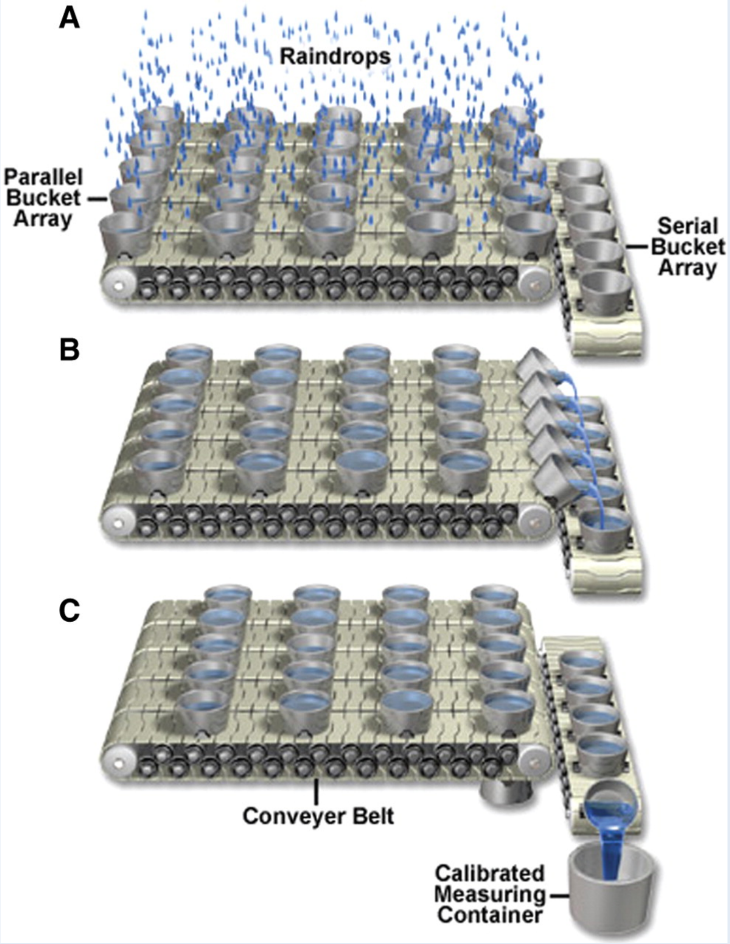
- X-ray photons cause multiple electron hole pairs (~0.5keV – 20keV).
- Gives us spectral information to make an "Imaging Spectrograph"



Silicon Detection Schematic

X-ray CCDs

- Current X-ray missions, such as Chandra and XMM, currently use CCDs.
- CCDs have faired very well producing excellent energy resolution and very low read noise.
- However, with the higher collecting area of future X-ray missions, CCDs will not have fast enough readout times and will suffer from pile-up.



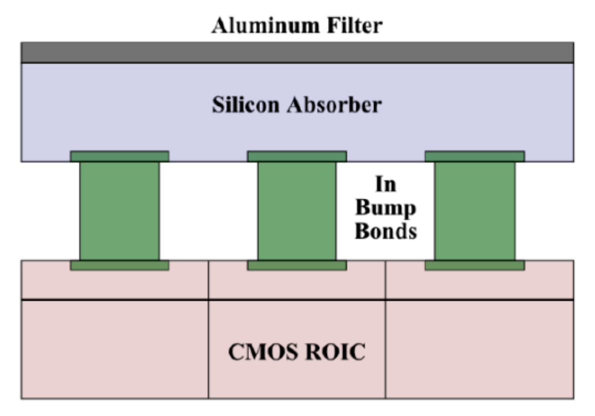
Credit: http://cshprotocols.cshlp.org/

Hybrid CMOS Detectors

- Individual pixels can be read out and constrain the source of interest before too many photons saturate a pixel.

- The silicon absorber array is responsible for photon-to-charge conversion via photoelectric absorption

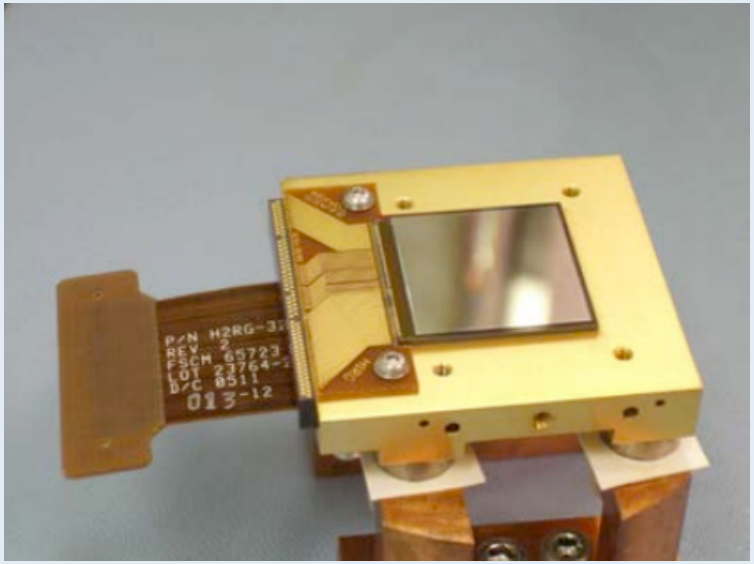
- The CMOS Readout IC (ROIC) functions as a charge-to-voltage converter and a signal processor.



Schematic cross-section of a hybrid CMOS detector

Hybrid CMOS X-ray Detectors (HCDs)

- Hybrid CMOS detectors currently have many advantages over current X-ray CCD's including:
  - – Faster readout times to avoid pile-up (necessary for future high-throughput missions such as the Future X-ray Surveyor)
  - – More radiation hard
  - – Use less power



HCD currently in our lab

Future X-ray Missions

- Current proposed X-ray space missions are high-throughput and have large collecting areas (up to 30X Chandra).
- Some missions (e.g. SMART-X and/or Future X-ray Surveyor) call for high spatial resolution (0.5”).
- The larger detector area has driven the need for a new X-ray detector to keep up with the amount of X-rays that will be detected.

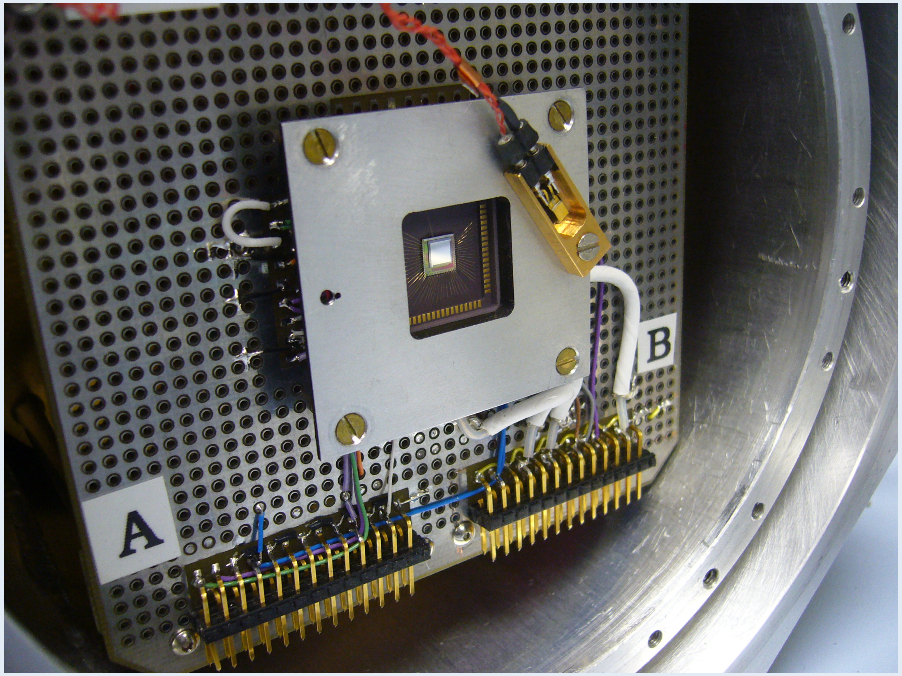
Artist Impression of the Athena Mission

Future Mission Science Goals

- Evolution of large scale structure by mapping the structure of hot gas trapped in galaxy clusters
- AGN feedback and cycles of matter and energy (even at high z) by looking at temperature maps of AGN.
- Super massive black holes and their environment up to z>6
- Study of blazars and bright X-ray binaries
- Studies of the WHIM

Speedster-EXD Hybrid CMOS X-ray Detector

- 64 x 64 pixel^2 prototype detector with 40μm pixel pitch fabricated by Teledyne Imaging Systems.



Speedster-EXD detector in dewar bread board

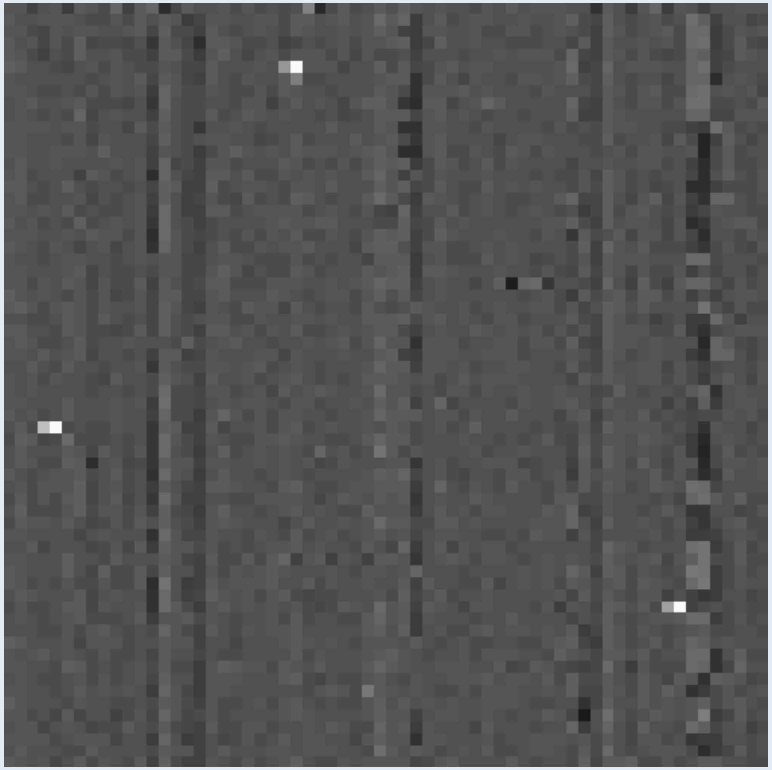
Speedster-EXD Hybrid CMOS X-ray Detector

- Improved Features include:
  - **Low noise, high gain CTIA amplifier** to significantly reduce IPC. The CTIA amplifier is held at a constant voltage during integration time to prevent signal spreading.
  - **In-pixel Correlated Double Sampling** (CDS) subtraction to reduce reset noise.
  - **Four Gain Modes** to optimize either full well capacity or energy resolution.
  - **10kHz frame rate**
  - **In-pixel comparator** to allow sparse readout.

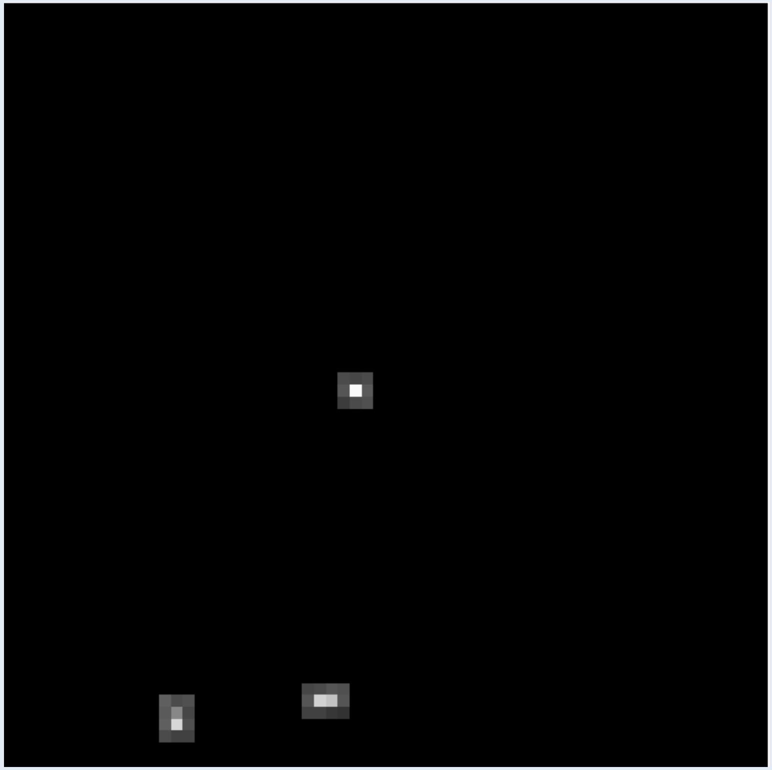
Sparse Readout

- One of the key features of the Speedster-EXD is sparse readout, the ability to read out only pixels that contain X-ray charge.
- The user defines a global threshold for the in-pixel comparator and only pixels that exceed this threshold are read out.
- Sparse readout can be run in two modes including single pixel readout and 3x3 readout.

Sparse Readout



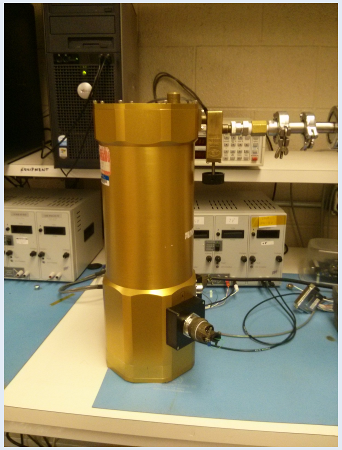
Full Frame Readout Mode:
Comparator threshold set below the noise floor



3x3 Sparse Readout Mode:
Comparator threshold set above the noise floor

Experiment Set Up

- Tested two Speedster-EXD detectors (17014 and 17017).
- Pump the detector chamber down to below 10^{-6} Torr and cool the detector to 150K using liquid nitrogen.
- Use an ^{55}Fe radiation source, which produces Mn Kα (5.9keV) and Kβ (6.4keV) X-rays and Po source, which excites an Al disc to produce Al Kα (1.49 keV) X-rays.

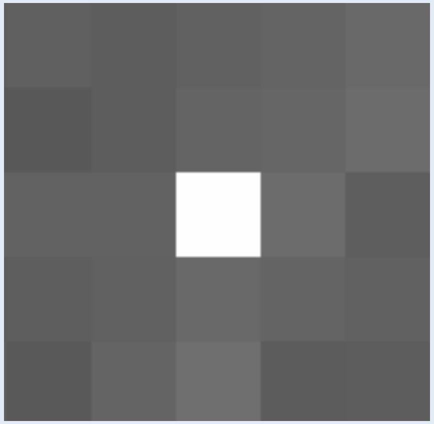


IR Labs HDL-5 Dewar

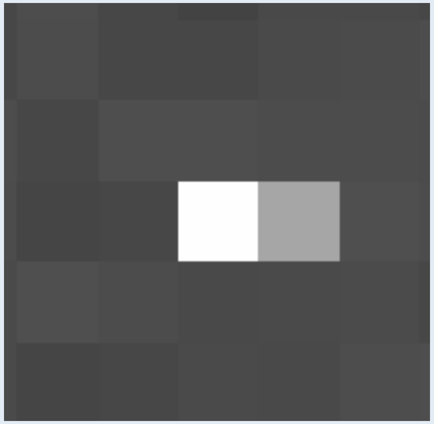
Speedster located in "Cube" Test Stand

X-ray Data Reduction

- Used 5σ (where σ is the read noise) as primary threshold to find X-ray events and make sure the pixel is a local maximum.
- Use 3σ as secondary threshold to "grade" events, where σ is the read noise.
- Use single pixel events (grade 0) and singly split events (grade 1-4).



Single Pixel Event or Grade 0 event

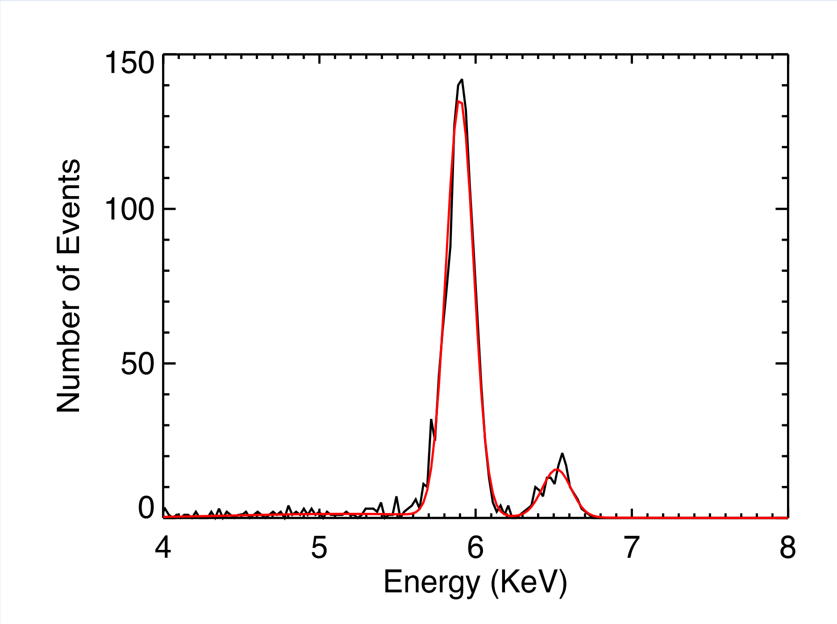


Split Event or Grade 1-4 Event

Energy Resolution

(^{55}Fe Source Full Frame Readout Mode)

- We fit multiple Gaussians to the measured spectrum and calculate ΔE/E where ΔE = Full Width Half Max (FWHM).
- We measure the best energy resolution to be **ΔE/E = 3.5%** with **FWHM = 206 eV** using single pixel events in a high gain mode.

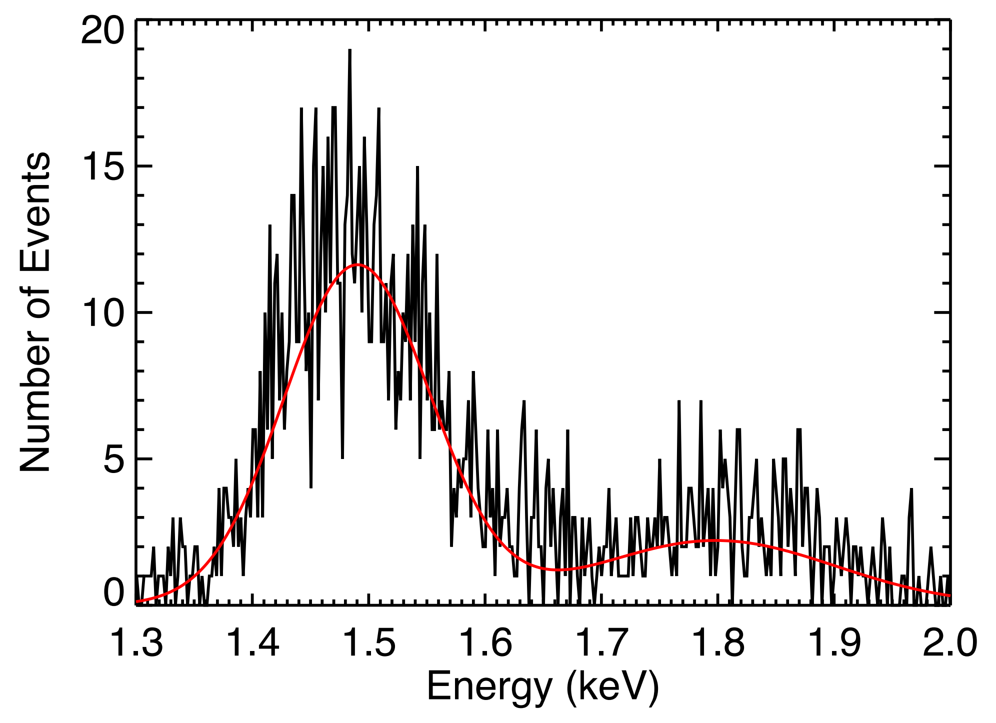


FPA17014

Energy Resolution

(Full Frame Readout Mode Single Pixel Events)

Aluminum Source (1.49 keV)

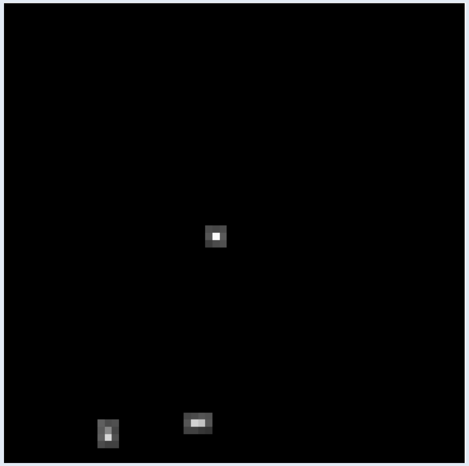


ΔE/E = 10.0% (FWHM = 148eV)

Energy Resolution

(^{55}Fe Source 3x3 Sparse Mode)

- Use Sparse 3x3 mode in order to properly grade events.
- We measure the best energy resolution to be **ΔE/E = 4.2%** with FWHM = 247 eV in the highest gain mode, using single pixel events on FPA17014.



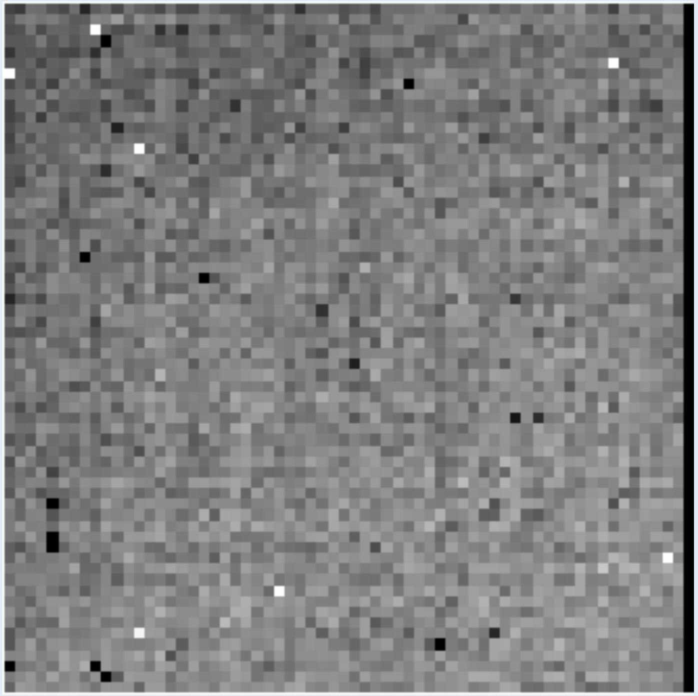
3x3 Sparse Read Out Mode

Gain Variation

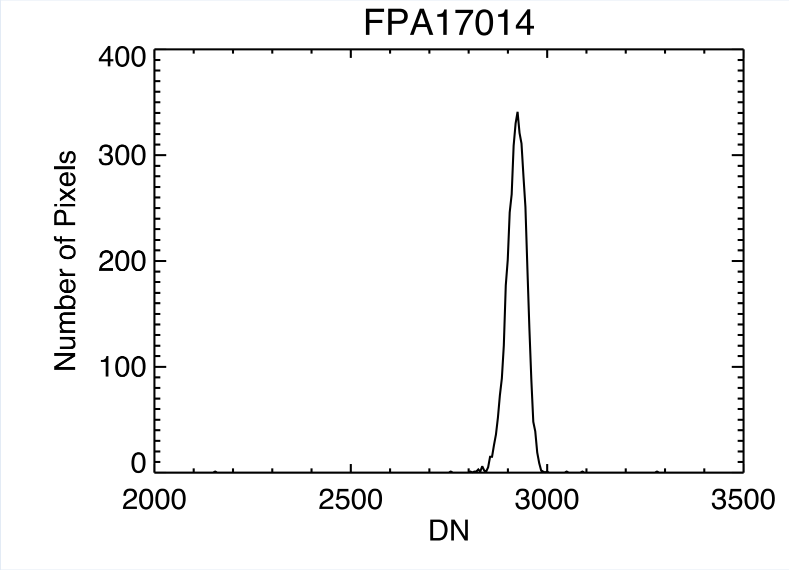
- Gain variation is caused by slight differences in the gain constant (e-/DN) on amplifiers on a detector.
- We exposed each pixel to around 10,000 Mn Kα events by taking ~30 million images in about 17 hours to ensure good statistics.
- We were able to create a gain variation map for each detector.

Gain Variation

FPA17014



Gain Variation = 0.80% ± 0.03%

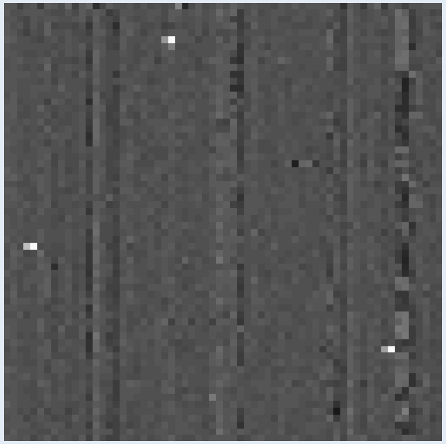


Speedster-EXD Conclusion

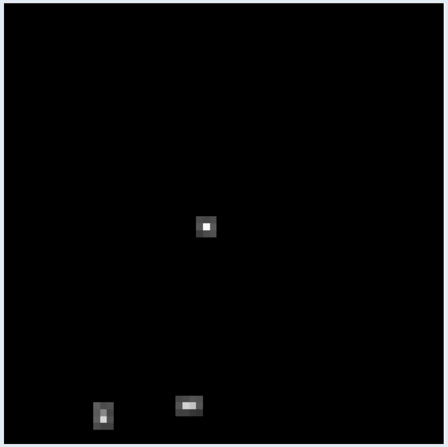
- We find the Speedster-EXD and its sparse circuitry to be fully functional.
- We measure energy resolution as low as **ΔE/E = 3.5%** in Full Frame Readout mode and **ΔE/E = 4.2%** in Sparse 3x3 mode at 5.89keV and **ΔE/E = 10.0%** at 1.49keV.
- We also find the **IPC to be 0.25%** in neighboring pixels, which is a significant improvement over our previous generation detectors.
- We measure the gain variation to be as low as **0.80% ± 0.03%.**

Future Work

- We are developing a small pixel detector (~15μm) that uses the CTIA amplifier to eliminate IPC and meet requirements for 0.5” angular resolution optics (X-ray Surveyor and/or SMART-X).
- We are also scaling up the Speedster-EXD design (40μm pixel pitch) to a larger detector (512x512) to meet requirements for Athena-like optics (1”).



Full Frame Readout Mode



3x3 Sparse Readout Mode