Design and optimization of multi-pixel transition-edge sensors for X-ray astronomy applications

PE-59

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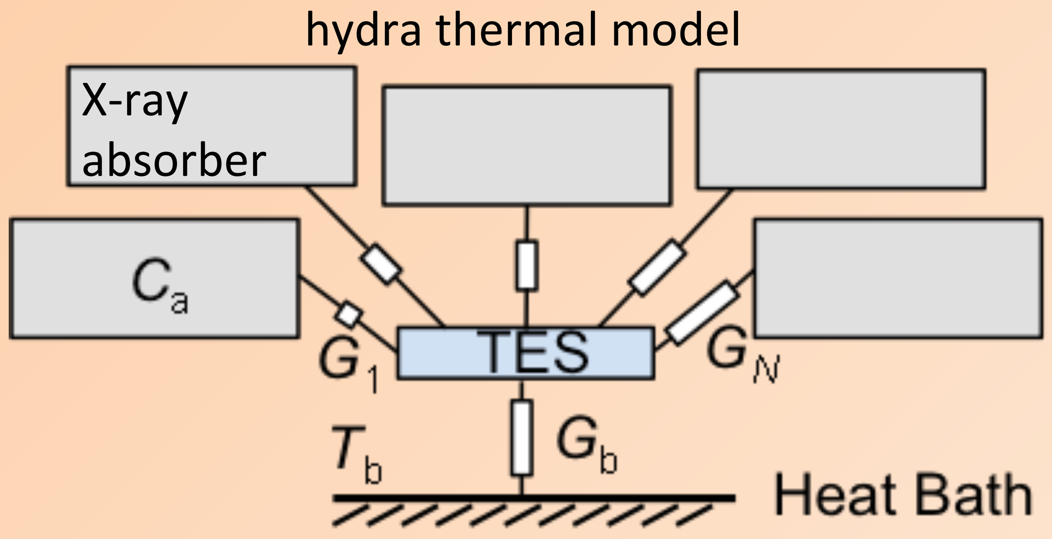
ABSTRACT: *Multi-pixel transition-edge sensors (TESs), commonly referred to as 'hydras', are a type of position sensitive microcalorimeter that enables very large format arrays to be designed without commensurate increase in the number of readout channels and associated wiring. In the hydra design, a single TES is coupled to discrete absorbers via varied thermal links. The links act as low pass thermal filters that are tuned to give a different characteristic pulse shape for x-ray photons absorbed in each of the hydra sub pixels. In this contribution we report on the experimental results from hydras consisting of up to 20 pixels per TES. We discuss the design trade-offs between energy resolution, position discrimination and number of pixels and investigate future design optimizations specifically targeted at meeting the readout technology considered for Lynx.*

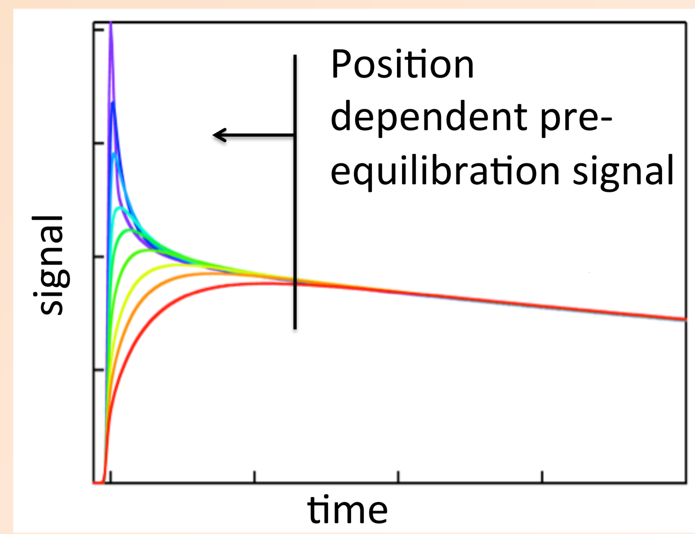
hydra thermal model



(1) Multi-absorber 'hydra' concept

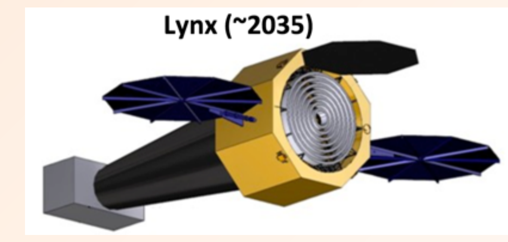
- Multiple absorbers with different thermal coupling G to 1 readout sensor.
- Sensor could be transition-edge sensor (TES) or magnetically coupled calorimeter (MCC) – here we focus on TES readout.
- Position dependent pulse-shape from thermal diffusion.
- Designed to increase array coverage with fewest TESs.
- Reduces focal-plane array complexity, lower heat loads, less wiring, fewer readout channels.

Measured pulse shapes for hydra with 9 individual absorbers



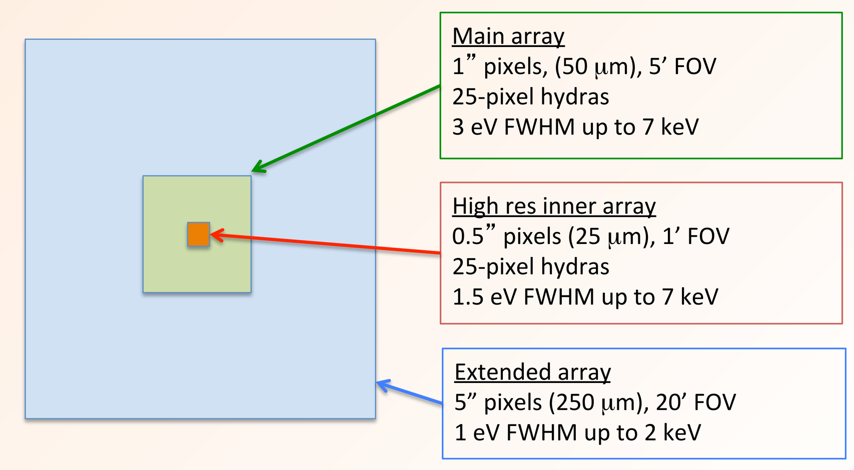
(2) Hydra development for Lynx

- Developing hydras with up to 25-pixels for proposed future x-ray astronomy applications such as 'Lynx', a large mission concept under study by NASA for the Astro-2020 Decadal Survey.



- Proposed instrument combines a ~ 0.5 arc-second x-ray optic with a micro-calorimeter spectrometer incorporating ~ 100,000-pixel array, with spectral resolution better than 5 eV full-width-at-half-maximum (FWHM) in the energy band 0.2-10 keV. The array will be read out using microwave multiplexed rf SQUIDs.
- Lynx microcalorimter array layout is still under formalism but could incorporate different regions optimized for different angular resolution, energy resolution and count-rates.

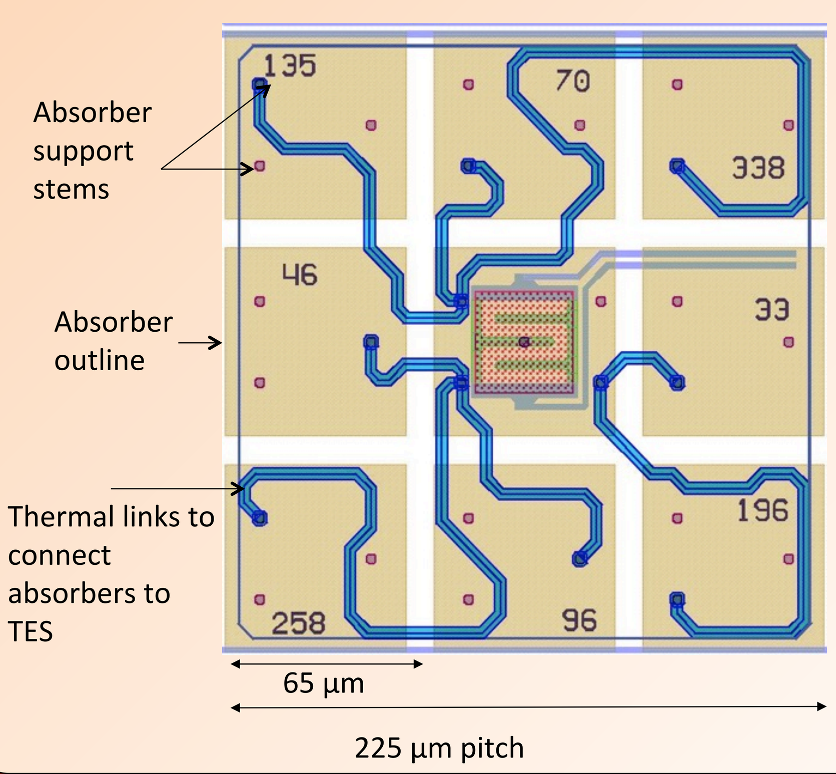
Example hybrid array concept under study for Lynx, which could combine single pixels and hydras in one array. *(See Bandler et al. PE-46 for further details on Lynx)*



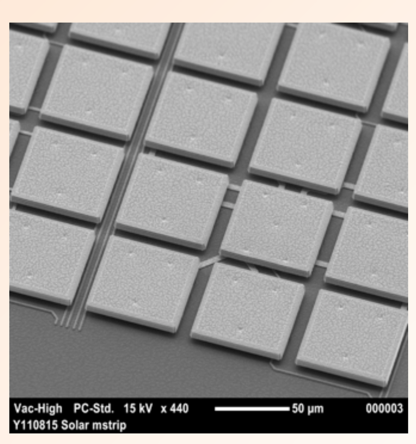
3) 4 and 9-pixel hydras

- Arrays presented here are small-pixel designs < 75 μm pitch for high angular resolution.
- 8 x 8 arrays of 4 and 9 pixel hydras have been developed.
- 35×35 μm² Mo/Au bilayer TES.
- 65×65 μm² electroplated Au x-ray absorbers, 5 μm thick. Provides 98% absorption at 6 keV.
- Absorbers are cantilevered above substrate and TES for high fill factor.
- Fabricated on thick Si wafers with embedded Cu heat sink layer.
- ~ 500 nm Au thick, few μm wide links couple the TES to the absorbers.

9-pixel hydra layout



9-pixel hydra SEM

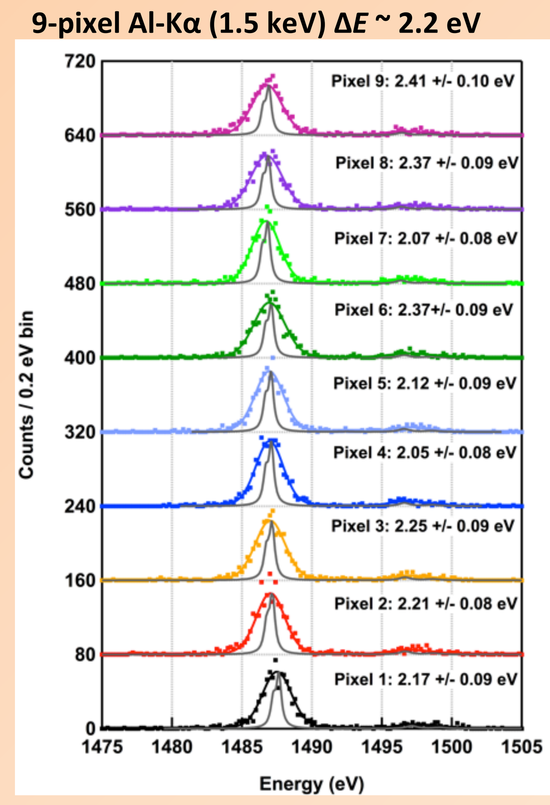


- $T_C \approx 55$ mK
- $C \approx 0.4$ pJ/K, 4 pixels
- $C \approx 1.0$ pJ/K, 9 pixels

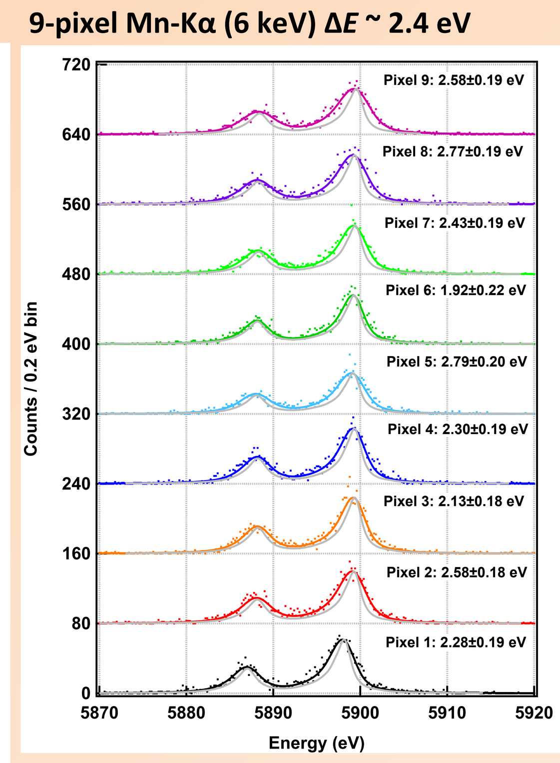
4) 4 and 9-pixel hydra Energy Resolution

- ΔE scales approximately with √(number of pixels).
- $\Delta E_{\text{single pixel}}$ ~ 0.9 eV at 1.5 keV.
- 9 pixel Hydra $\Delta E_{\text{FWHM}} \approx 2.2$-3.4 eV all 9 pixels for E = 1.5-8 keV
- 4 pixel Hydra $\Delta E_{\text{FWHM}} \approx 1.4$-2.2 eV all 4 pixels for E = 1.5-6 keV.
- Excellent resolution consistent across all pixels and consistent with expectations.

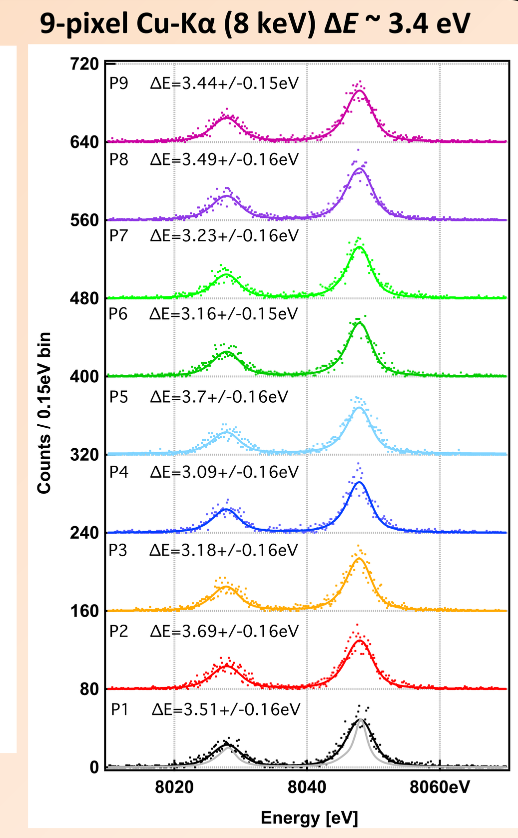
9-pixel Al-Kα (1.5 keV) ΔE ~ 2.2 eV



9-pixel Mn-Kα (6 keV) ΔE ~ 2.4 eV



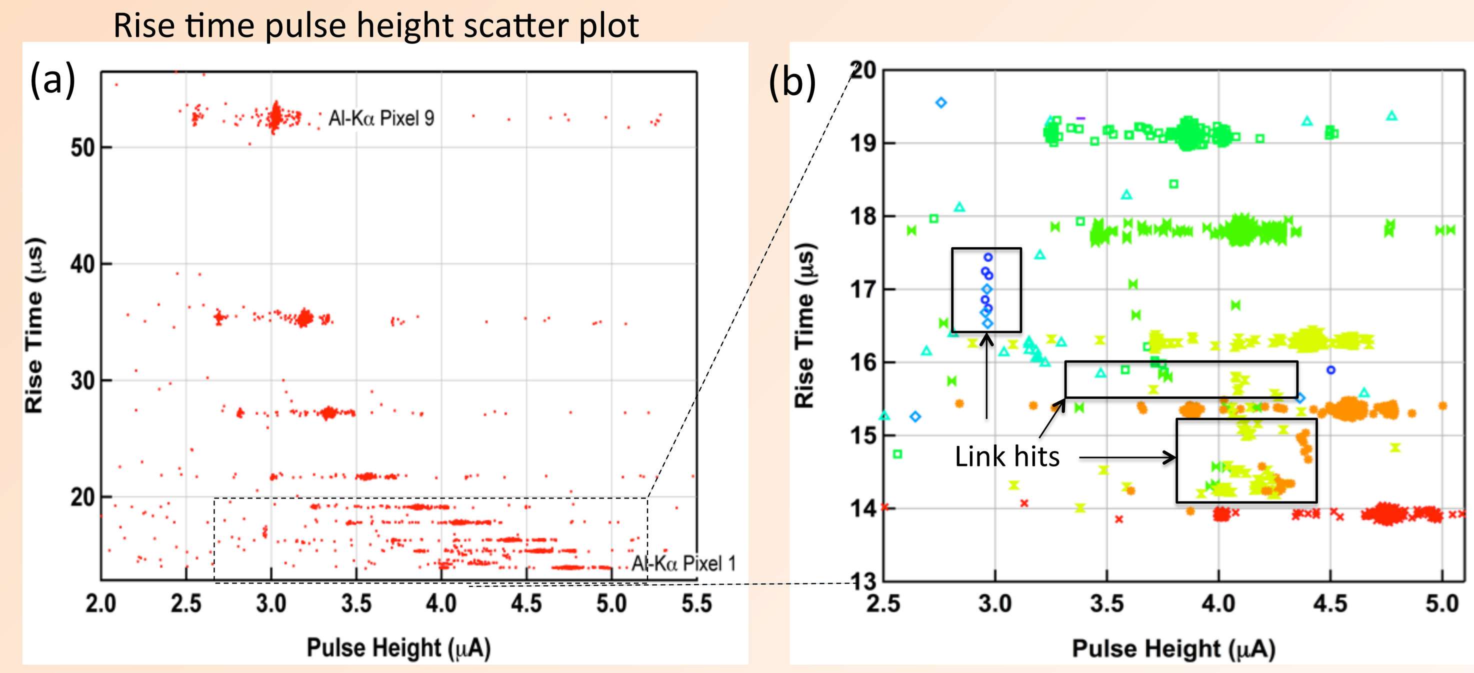
9-pixel Cu-Kα (8 keV) ΔE ~ 3.4 eV

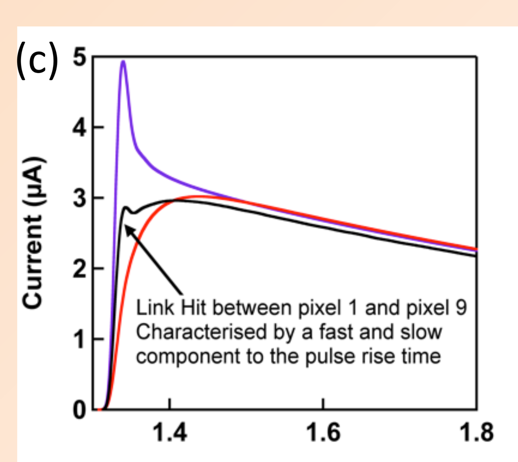


5) Position Sensitivity

- Position determined from rise-time.
- Thermal links designed using a finite element model to calculate the pulse shapes and noise.
- Position sensitivity decreases as energy decreases ($\Delta x \propto 1/E$).
- Position discrimination demonstrated down to ~ 1 keV for both 4 and 9 pixel designs.
- Simulations suggest sensitivity should be good down to a few 100 eV.
- Pulse shapes match well with numerically simulated.
- Hits in exposed links between absorbers have been identified.
- Low T_C resulted in excellent ΔE but relatively slow decay times (ms). Thus these particular detectors are excellent for lower count-rate X-ray astronomy applications.

Rise time pulse height scatter plot





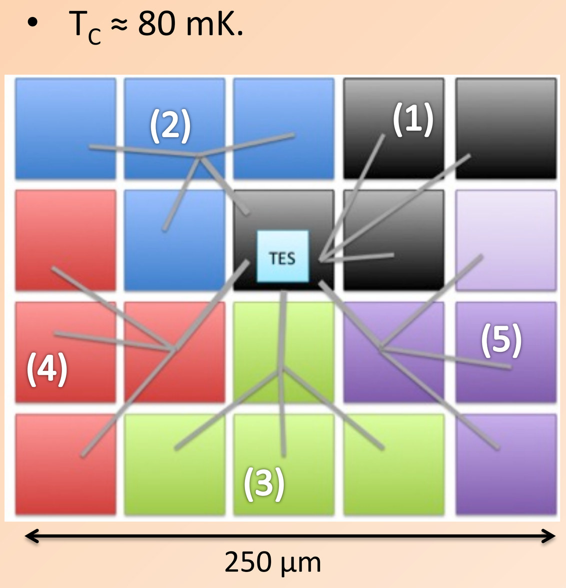
a) 9-pixel Hydra pulse-height versus rise-time for Al-Kα. All 9 pixels are well separated.

b) Expanded view of just the 1st 5 pixels. Events in the boxes in between the main populations are thought to be due to hits in the exposed links between the absorbers. The energy splits between the two absorbers giving rise to a different characteristic pulse shape. χ^2 template matching between template pulse shapes and raw data can also be used determine position and helps highlight link hit events, which can then be removed from the data. This is color and symbol coded based on the best fit between the different templates and the raw data. Link hit events have different pulse shapes and usually have high χ^2 and different pixel allocations compared to rise-time.

c) Average pulse shape for an event absorbed in the exposed link between pixels 1 and 9 (black line). Shown for comparison are the average pulses shapes for pixel 1 (purple) and 9 (red). The link hit shows a fast and slow component to the rise time because the energy splits between the two absorbers.

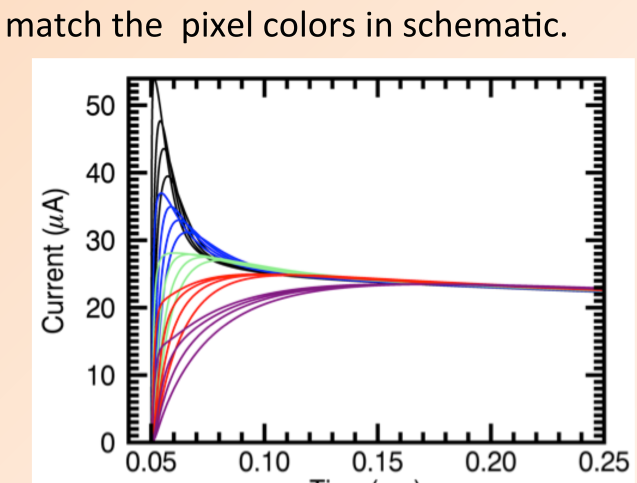
6) 20-pixel hydra design

- Extending designs to develop the first prototype 20-pixel hydras.
- These designs utilize a hierarchical structure using trunks and branches that make it easier to design and lay out, but require more complex position discrimination algorithms.
- 1st design iteration consisting of 5 clusters of 4 absorbers, where each cluster is individually coupled to the TES (schematic below).
  - The absorbers are 4.2 μm Au on a 50 μm pitch
  - TES is 25x20 μm²
  - $T_C \approx 80$ mK.

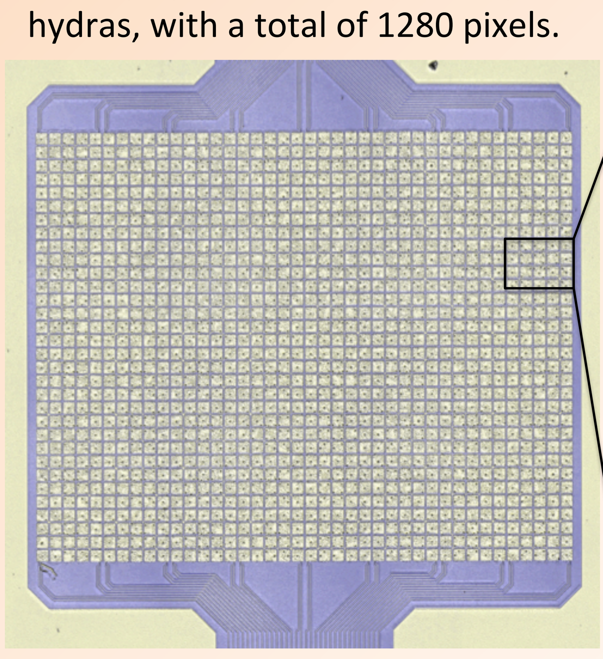


20-pixel hydra schematic showing hierarchical link structure.

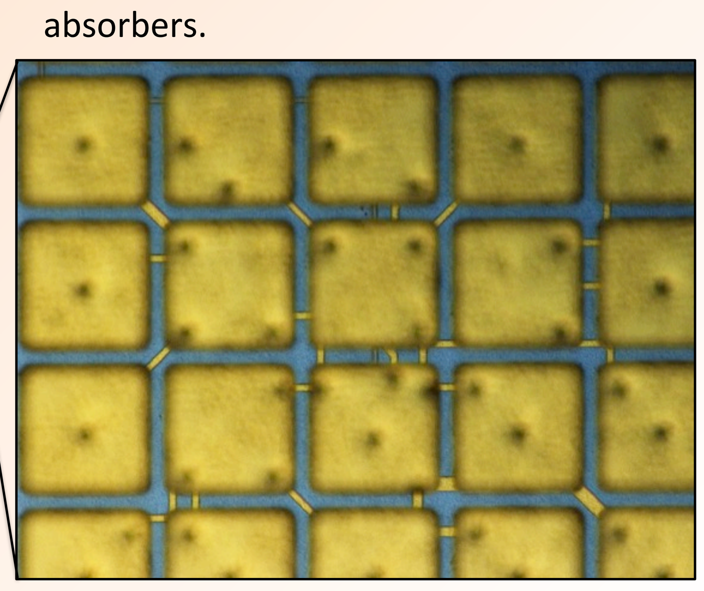
Simulated pulse shapes for a 20-pixel hydra design. Pulses are color-coded to match the pixel colors in schematic.



Photograph of 8x8 array of 20-pixel hydras, with a total of 1280 pixels.



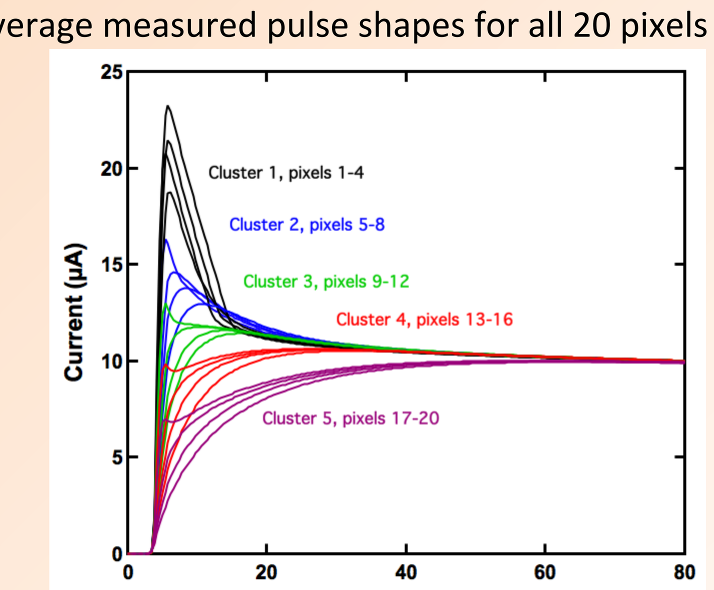
Close-up photograph of single hydra, the metal links are visible in between absorbers.

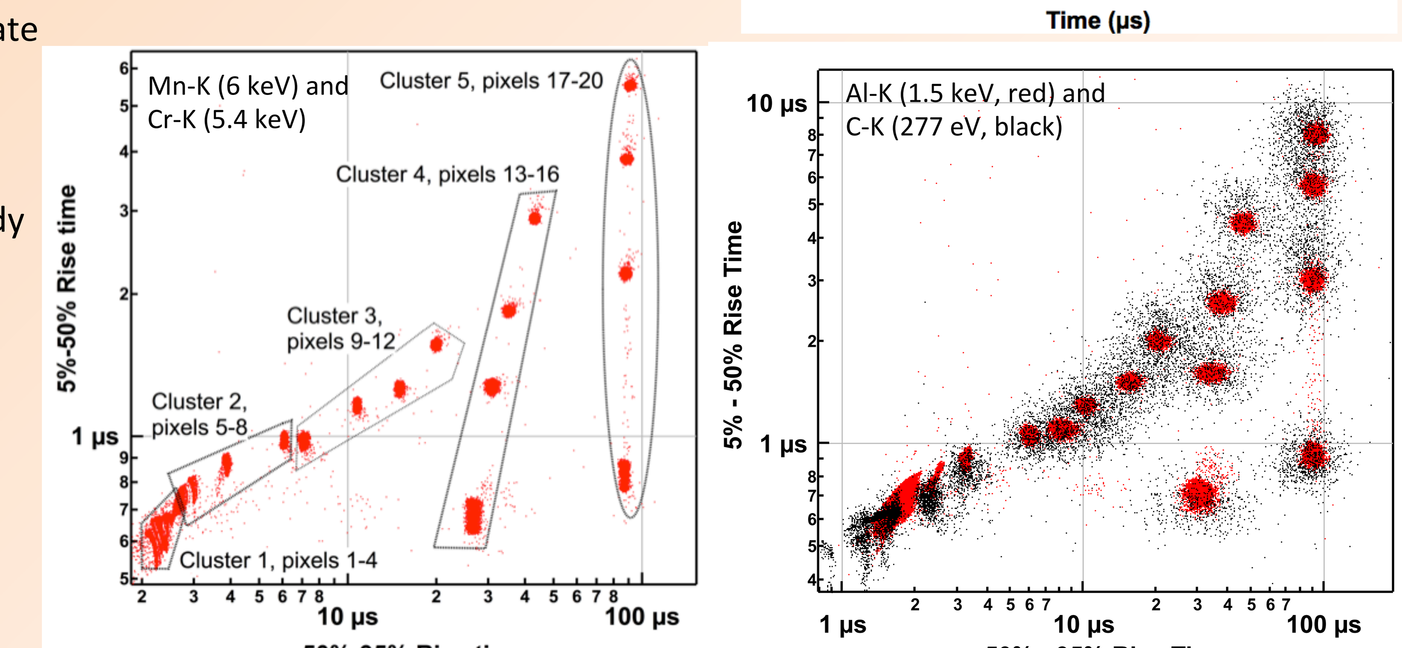


7) 20-pixel hydra results

- Measured average pulse shapes (right) qualitatively agree with simulations.
- The 5 clusters each with 4 pixels have different characteristic pulse shapes.
- Additional pole in rise time requires 2nd metric for parameterizing pre-equilibration signal. Different algorithms under study for determining optimum position.
- Example shown here uses 2 rise time metrics: τ_1, determined from 5-50% and τ_2, from 50-95% of the pulse peak. Two X-ray data runs at different energies:
  - Mn-K (6 keV) and Cr-K (5.4 keV).
  - Al-K (1.5 keV) and C-K (277 eV).
- Good position discrimination demonstrated on most pixels down to < 1.5 keV.
- However, due to very fast rise time and low sampling rate (only 4 data points on rise of fastest pixels), position confusion occurs between fastest pixels (cluster 1).
- ΔE_{FWHM} evaluated a Cr-K using crystal monochromator.
- **<ΔE_{FWHM}> = 3.39 ± 0.18 eV** including all 20 pixels, already surpassing 5 eV goal for Lynx.
- Future plans include:
  - Extend design to 25-pixels for Lynx baseline design.
  - Optimize design to match fastest pixel with microwave mux readout bandwidth.
  - Test large scale arrays with multiplexed microwave mux readout.
  - Design hydras with 25 μm pixel pitch to better match Lynx 0.5 arc-second goal.

Average measured pulse shapes for all 20 pixels





Rise-time scatter plots of τ_1 versus τ_2 for two different data sets at different x-ray energies indicated in the figures.