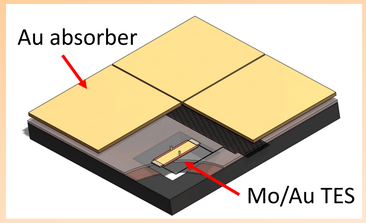
Development of the Microcalorimeter Array for the Line Emission Mapper (LEM) X-Ray Probe

Stephen J. Smith*, J.S. Adams, S.R. Bandler, J.A. Chervenak, R.S. Cumbee, F.M. Finkbeiner, J. Fuhrman, S.V. Hull, R.L. Kelley, C.A. Kilbourne, F.S. Porter, K. Sakai, N.A. Wakeham, E.J. Wassell, S.H. Yoon – *NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA.* **stephen.j.smith@nasa.gov*

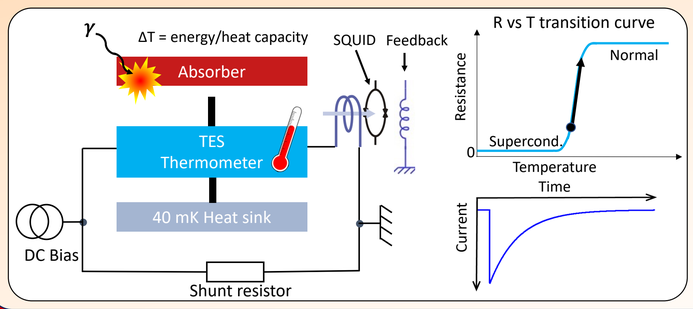
1. Introduction

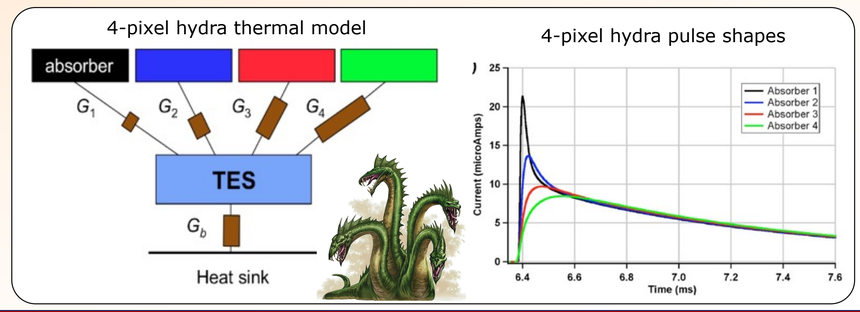
- The Line Emission Mapper (LEM) is a probe-class mission concept developed by SAO and NASA and is currently under review for a potential Phase-A study [1,2].
- LEM will provide unprecedented insight into the physics of galaxy formation, including stellar and black-hole feedback and flows of baryonic matter into and out of galaxies.
- LEM incorporates an X-ray optic with 10" angular resolution and a large-format microcalorimeter array with a 15" pixel pitch over a 33' field-of-view (FOV).
- An anti-coincidence detector behind array will distinguish cosmic-ray background particle events from the science photons (see poster by S. Hull).
- We present an overview of the baseline microcalorimeter detector and describe the status and plans for continued development.

2. Transition-Edge Sensors and Hydras

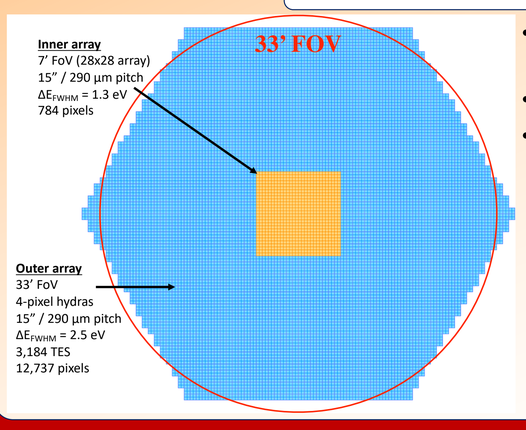


- Transition edge sensors (TES) measure heat from thermalization of an X-ray.
- Superconducting film biased in superconducting-to-normal transition.
- Uses SQUID based Time Division Multiplexed (TDM) readout.
- Hydra = 1 TES connected to multiple absorbers.
- TES-to-absorber thermal coupling tuned to give different pulse shape for hits in each absorber.
- Position determined from pulse rise-time.
- Enables extremely large numbers of pixels without commensurate increase in system complexity.





3. LEM Microcalorimeter Design



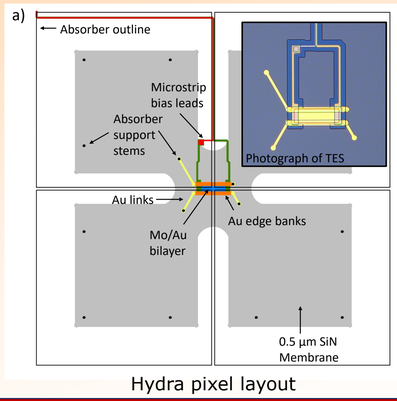
- LEM microcalorimeter is a 'hybrid array' of single-pixel TESs + 4-pixel hydras.
- 14k pixels in total (4k TES)
- Read out with 69 channels of Time Division Multiplexing (TDM) with 59 TESs (+ 1 dark pixel) per channel.

Key performance requirements

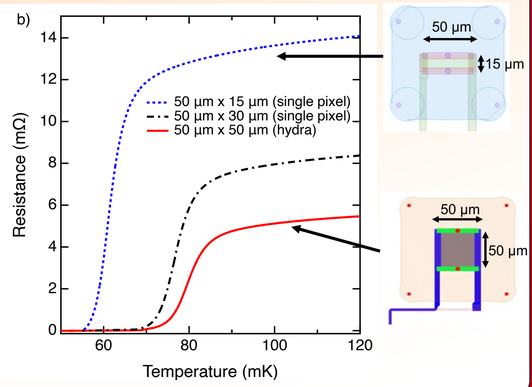
Parameter	Requirement
Energy range	0.2 to 2 keV
FoV	30 arcmin diam.
Angular resolution	18 arcsec
Energy resolution (inner/outer)	1.3/2.5 eV (FWHM) at 1 keV
Energy scale (absolute/relative)	1 eV/0.25 eV at 0.5 keV

4. Pixel Optimization for LEM

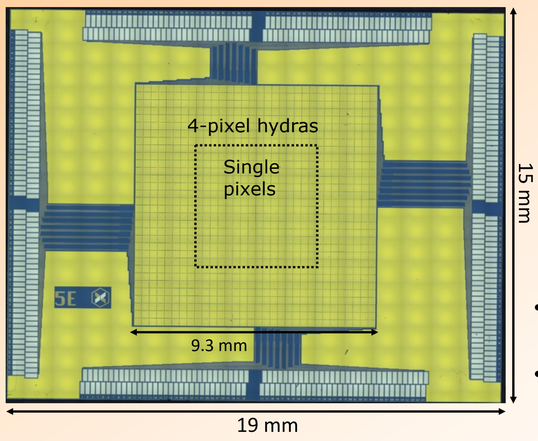
- TES/array design leverages Athena/X-IFU technology [3].
- LEM pixels are optimized for improved ΔE over lower energy range.
- Reduce T_C from 90 ->55 mK: $\Delta E \propto T^{1.5}$.
- Change absorber composition from 6 μm Bi/Au to 0.54 μm Au: $\Delta E \propto C^{0.5}$.
- LEM baseline TES is (50 x 15) μm^2 and has x250 reduced magnetic field sensitivity compared to X-IFU pixels.

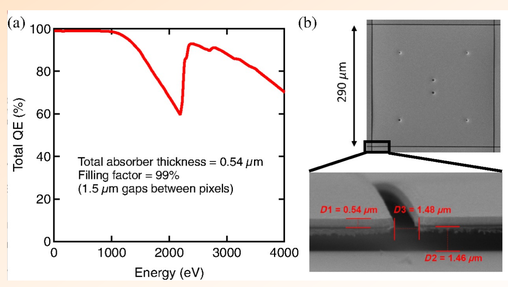


Hydra pixel layout



5. LEM 1k Demonstration Arrays

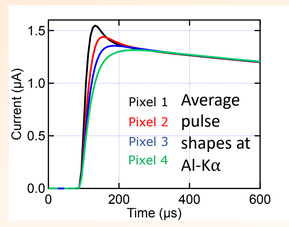


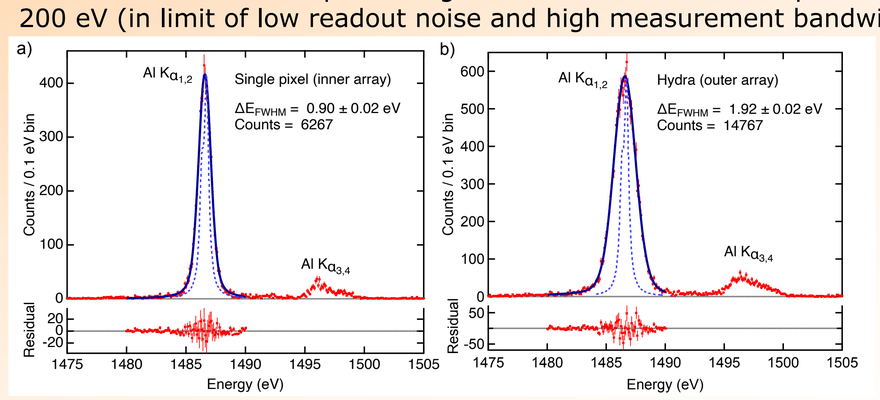


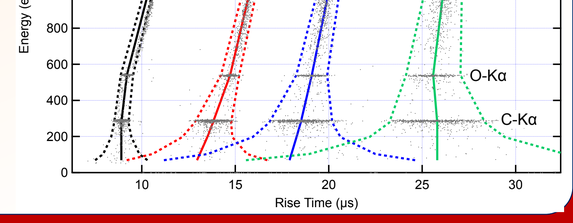
- Absorbers provide ~100% stopping power at 1 keV and 99% fill-factor.
- SEM of test absorber deposition shown right.
- 1k-pixel high fidelity array (not full scale).
- 50x15 μm^2 TES pixels, 290 μm pixel pitch, 0.54 μm thick Au absorber.
- Array is fully wired within interior, and 250 pixels connected to bond-pads.
- Arrays used to test different pixels designs and verify performance [3,4].

6. Measured Spectral Performance

- Measured ΔE at an energy of 1.5 keV (Al-Kα) on hydra and single pixel detectors [4].
  - ΔE_{FWHM} = 0.90±0.02 eV in single pixel device.
  - ΔE_{FWHM} = 1.92±0.03 eV in hydra (all 4 pixels combined).
  - (ΔE_{p1} = 1.90±0.04 eV, ΔE_{p2} = 1.93±0.04 eV, ΔE_{p3} = 1.92±0.04 eV ΔE_{p4} = 1.92±0.04 eV) => meets performance requirements.
- Measured rise-time vs pulse-height demonstrates intrinsic position sensitivity to below 200 eV (in limit of low readout noise and high measurement bandwidth).

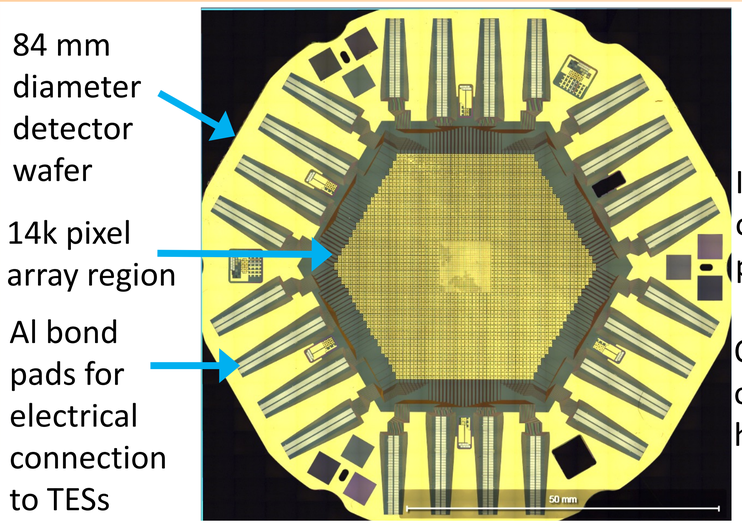


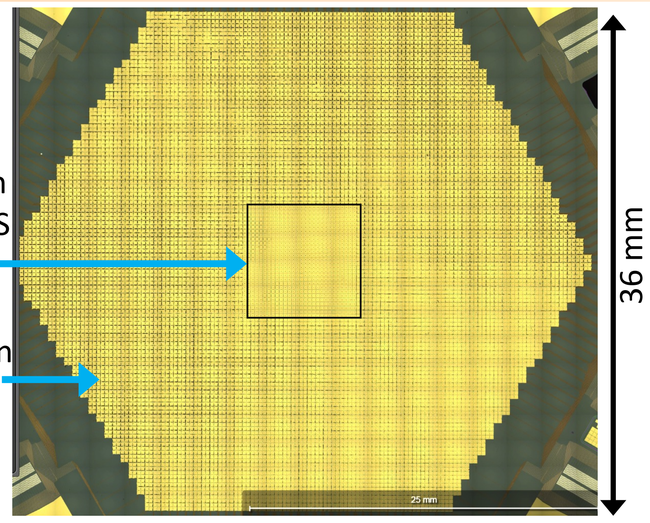




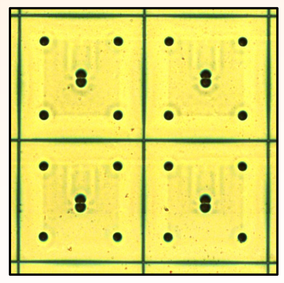
7. Full-Scale prototype LEM Arrays

Photograph of full-scale prototype LEM detector with 14k pixels.

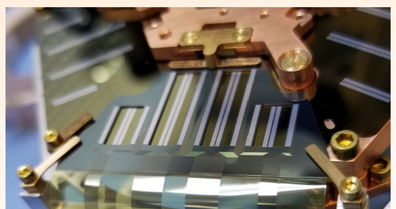




- 1st full-scale 'high-fidelity' LEM arrays (14k pixels) now fabricated and will be tested soon (shown left).
- Array has flight-like mechanical and electrical interfaces. (design compatible with flight focal-plane assembly).
- Pre-cursor to engineering model design.



Zoom-in of 4 pixels with 0.54 μm thick Au absorbers on 290 μm pitch. The 6 black dots are absorber support columns



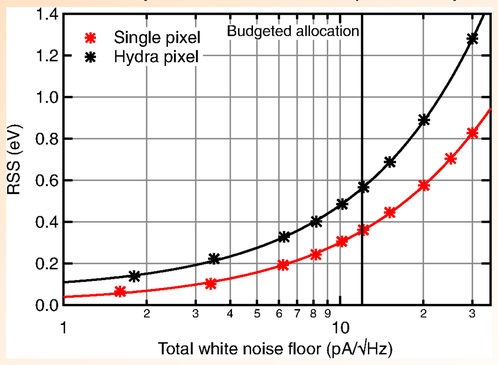
Test set-up for screening high-fidelity arrays (Athena array shown). Similar set-up will be used for testing LEM arrays.

8. Resolution Budget

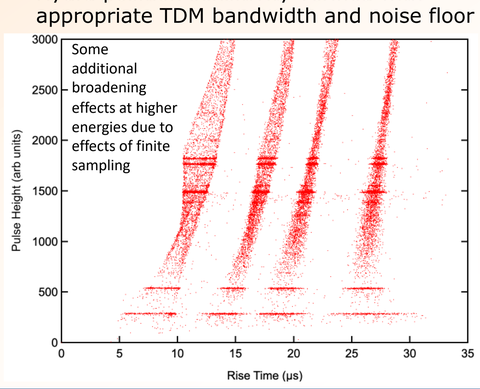
- Detailed resolution budget for both single pixels and hydras established [3] (see Table right).
- Detector is largest contribution followed by readout noise.
- Impact of TDM readout noise and measurement bandwidth on energy/position resolution confirmed.

Parameter	Single pixel (eV)	Hydra (eV)
Detector	0.95	2.02
Readout	0.46	0.68
Aperture cylinder	0.16	0.49
Gain drift	0.41	0.45
Cross-talk	0.15	0.15
MXS centroiding	0.30	0.30
Other contributors	0.18	0.20
Current best estimate (CBE)	**1.20**	**2.27**
Unspecified margin	0.49	1.06
Total (CBE+margin)	**1.30**	**2.50**

Predicted energy resolution contribution from TDM readout noise (based on measured pixel SNR).

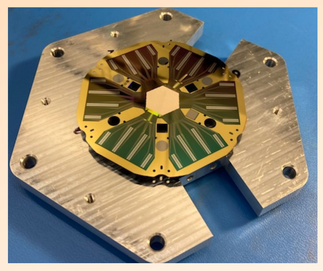


Hydra position sensitivity verified with appropriate TDM bandwidth and noise floor

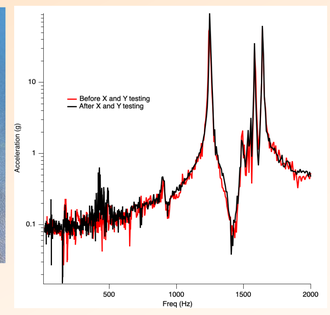


9. Plans for Continued Maturation

- Continued TRL-6 maturation plans include:
  - Test arrays with LEM TDM chips.
  - Verify vibration tolerance of the array on sub-assembly to launch loads (completed already on similar Athena arrays, see Figs. a-c).
  - α-particle tests to verify fidelity of heat sinking and immunity to particle background (completed already on similar Athena arrays, see Fig. d).
  - Integrated system-level demonstration of partial LEM detection chain. Including high-fidelity versions of the detector, SQUID cold electronics, harness and room temperature electronics (implemented with differential readout).

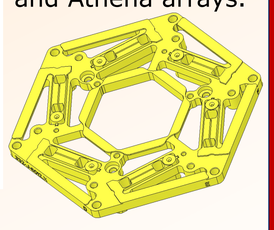


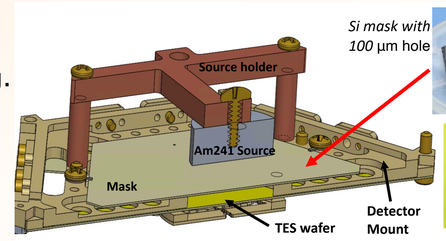
a) Vibration test set-up showing Athena array epoxied to dummy mount.



b) Laser vibrometer measurement of frequency response of wafer

c) Flight-like mount that will be bused for high-fidelity vibe tests of LEM and Athena arrays.





d) Test set-up for alpha-particle background testing.

References

[1] D.J. Patnaude et al., "*Line Emission Mapper: an X-ray probe mission concept to study the cosmic ecosystems and the physics of galaxy formation*," JATIS. 9(4) 041008 (2023).

[2] S.R. Bandler et al., "*Line emission mapper microcalorimeter spectrometer*," JATIS 9(4) 041002 (2023).

[3] S.J Smith et al., "*Development of the microcalorimeter and anticoincidence detector for the Line Emission Mapper x-ray probe*," JATIS. 9(4) 041005 (2023).

[4] N.A Wakeham et al., "*Characterization of a hybrid array of single and multi-absorber transition-edge sensor microcalorimeters for the Line Emission Mapper*," JATIS. 9(4) 041006 (2023).