NSENSE: Non-destructive Statistical Estimation of Nanoscale Structures and Electronics

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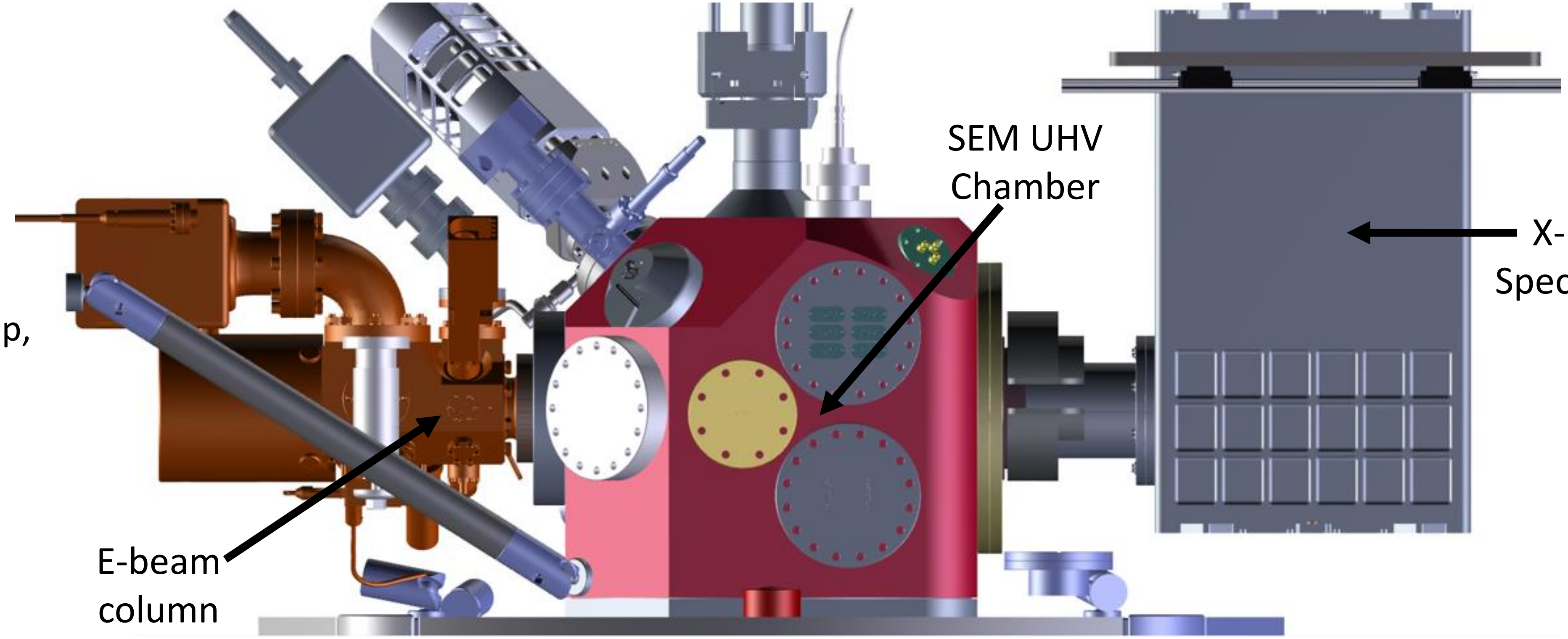
National Institute of Standards and Technology (NIST), Boulder, CO

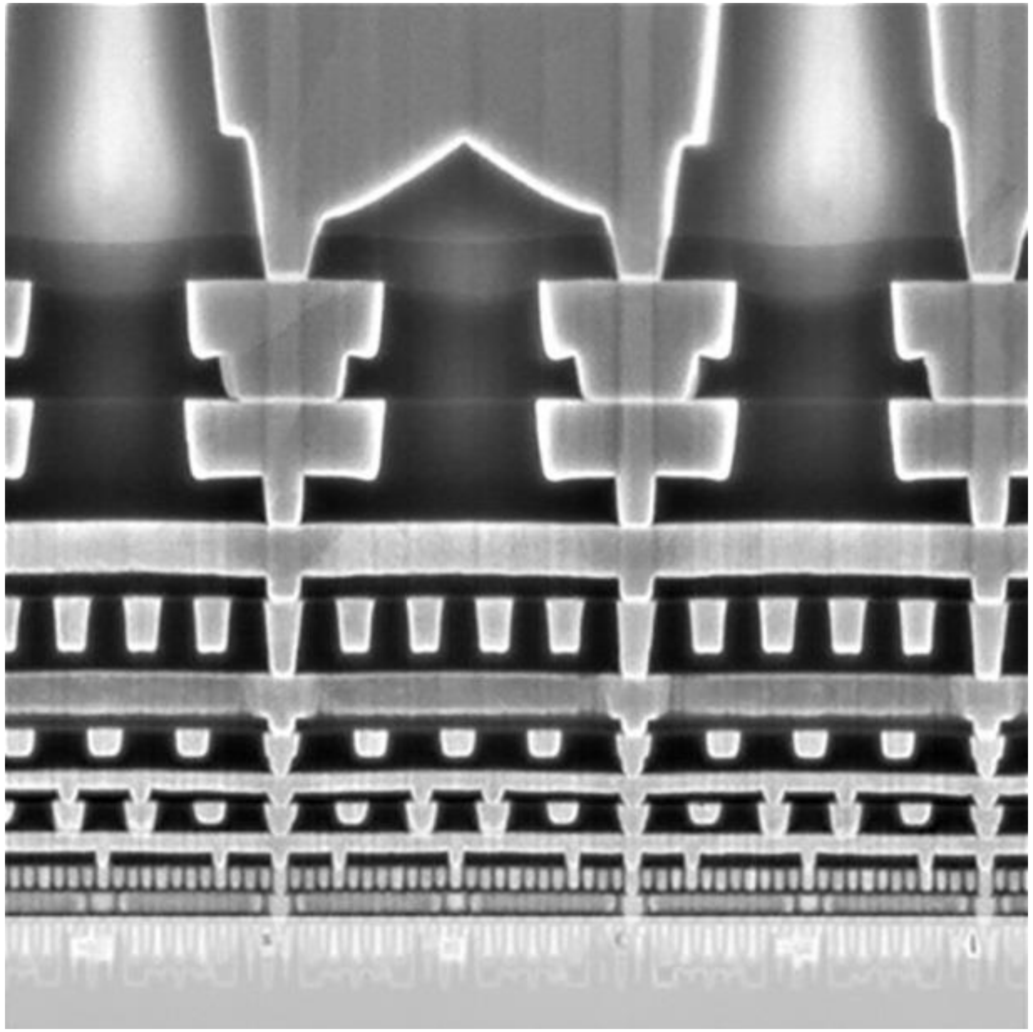
Collaboration between BAE Systems, NIST Quantum Sensors Group, and Orsay Physics



Project Goals

- State of the art integrated circuits (ICs) have been getting increasingly complex with extremely small feature sizes (~10 nm) and many fabrication layers.
- Although patterning these features can be done with advanced lithography techniques, imaging embedded features can be much more difficult.
- Advanced x-ray imaging techniques must be developed to map 10 nm scale features in a timely manner.
- Ideally, such techniques would be non-destructive to the IC and can be performed with a tabletop instrument.

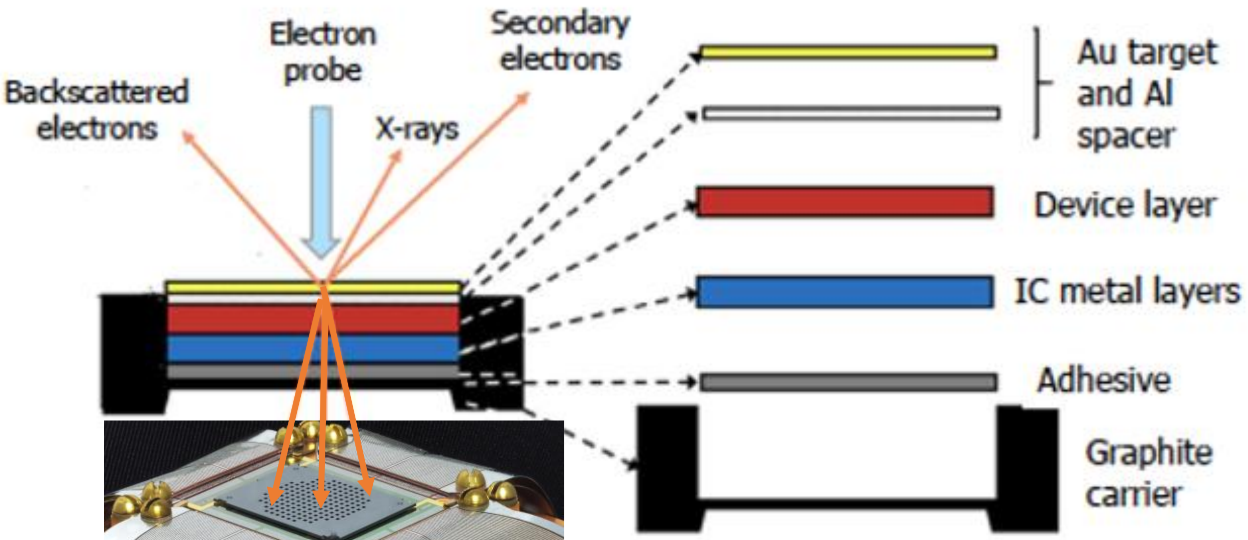
Intel 10 nm interconnects

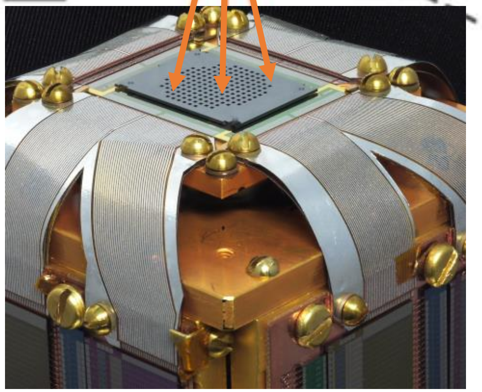


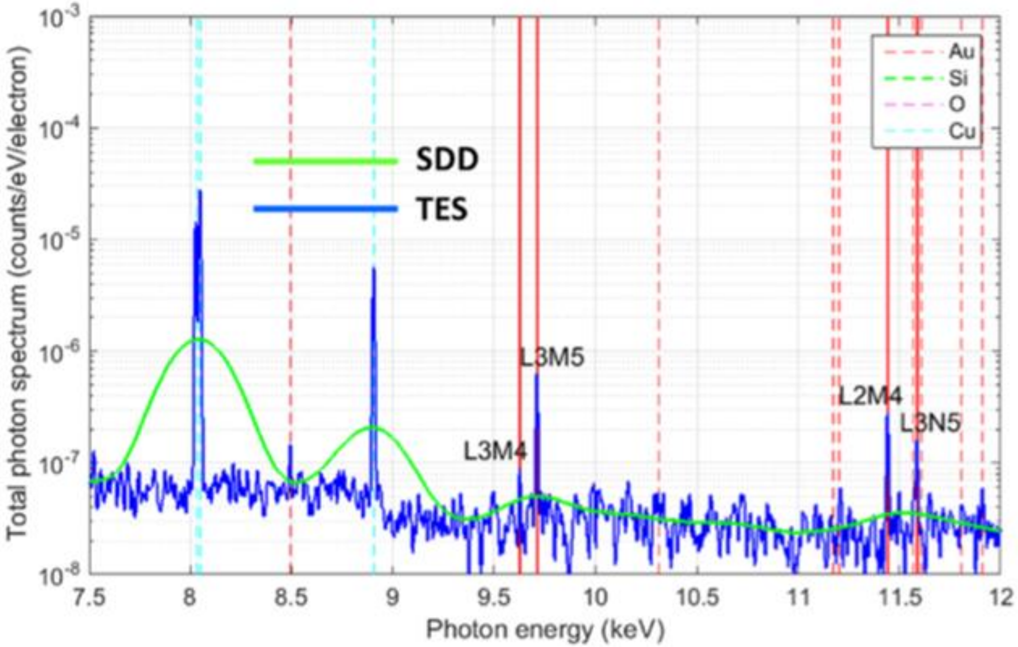
https://en.wikichip.org/w/images/2/22/intel_interconnect_10_nm.jpg

How do TES calorimeters fit into all of this?

NSENSE approach: perform tomography on IC under test using a tightly focused SEM electron beam as the source and a TES microcalorimeter array for x-ray detection.







1. Pixelated array – Simultaneously probe multiple x-ray paths through sample, large active area.
2. High x-ray collection efficiency – maximize count rate, reduce time needed for a tomographic scan.
3. High resolving power over a broad (~10 keV) energy range - maximize SNR at emission lines used for tomography.

Phased Approach

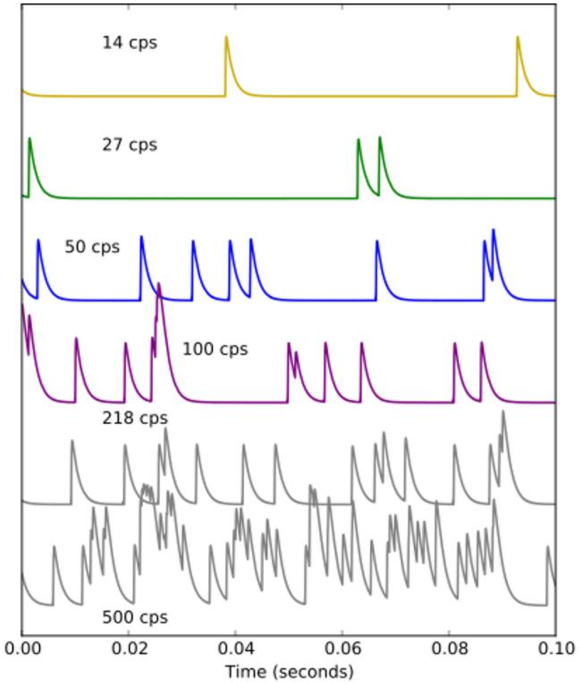
- **Phase 1**: Prototype 240 pixel TES instrument, prioritize achieving best spatial resolution (~10 nm) over imaging speed.
- **Phase 2**: Scaled up 3,000 pixel TES instrument using microwave SQUID multiplexing, expected throughput increase of 1000x, main goal of increasing imaging speed while maintaining spatial resolution.
- **Phase 3**: Full scale instrument with 10,000 or more TES microcalorimeters, further increase imaging speed.

Phase 1 TES Optimization

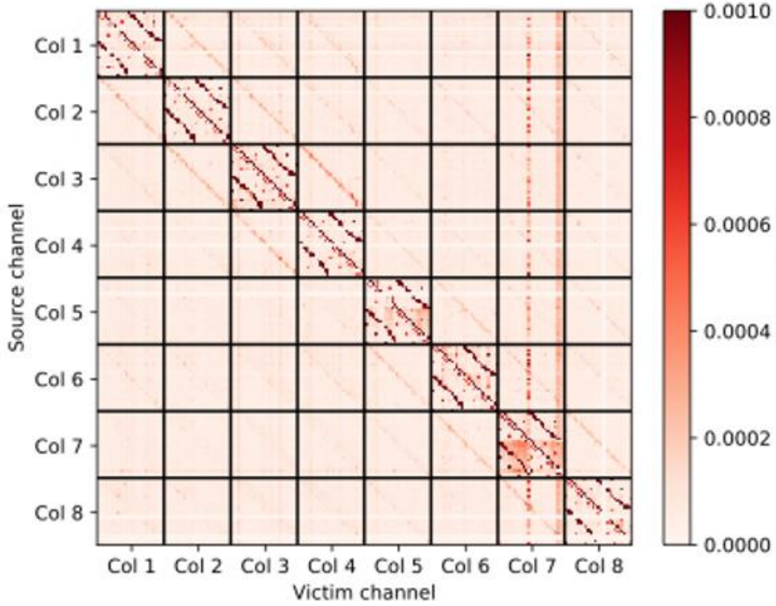
- Unlike NIST's typical X-ray TES spectrometers, optimizing for energy resolution at extremely high count rates.

Issues at high detection rates

Pulse Pileup



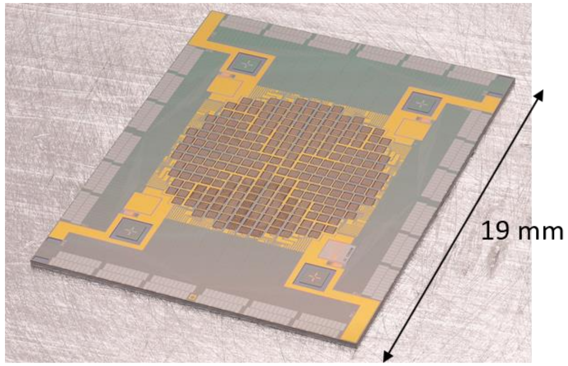
Crosstalk



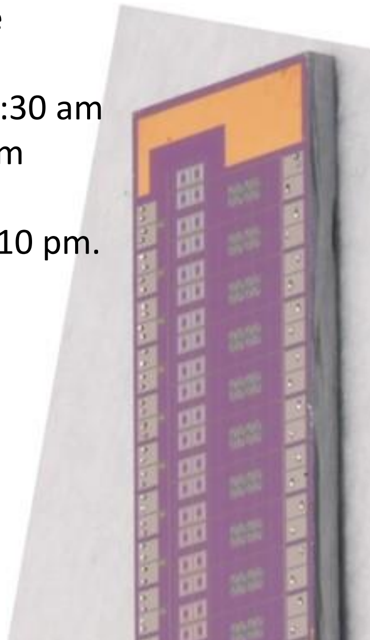
Changes for NSENSE

Detector Array:

Increase speed of detectors in standard 240-TES to meet 200 cps/pixel target.



Talks by Joe Fowler on Thursday, 8:30 am and Malcolm Durkin on Monday, 6:10 pm.



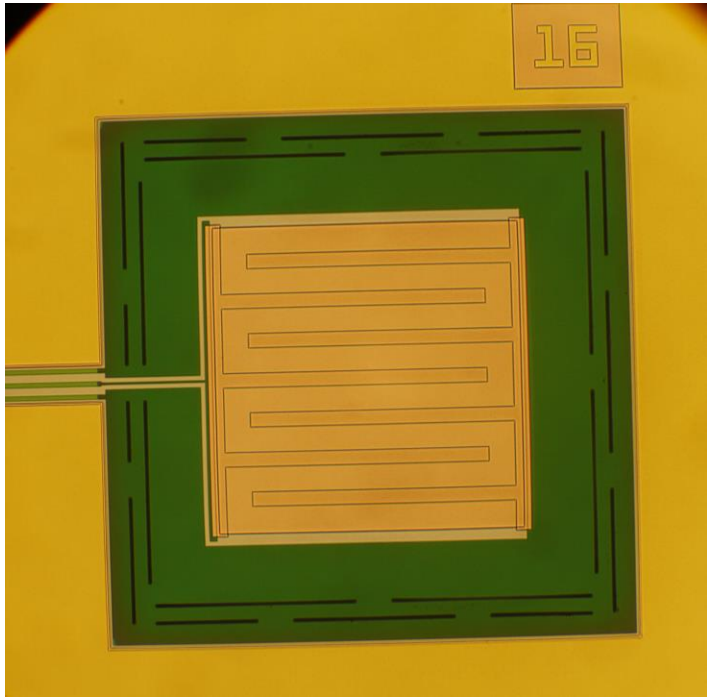
Multiplexing Chips:

Increase slew rate limit by decreasing the coupling by 2.5x.

Fast TES Design

$$\frac{2}{\tau_{\pm}} = \frac{R_{sh} + R(1+\beta)}{L} + \frac{1 - \frac{\alpha}{n}(1 - (\frac{T_{bath}}{T})^n)}{C/G}$$

1. Decrease thermal time constant: C/G
   - Decrease heat capacity by adjusting material type or mass of structures on TES island
   - Increase perimeter of TES
   - Fewer/smaller membrane perforations
   - Increase TES critical temperature
2. Change TES R(T,I) transition shape

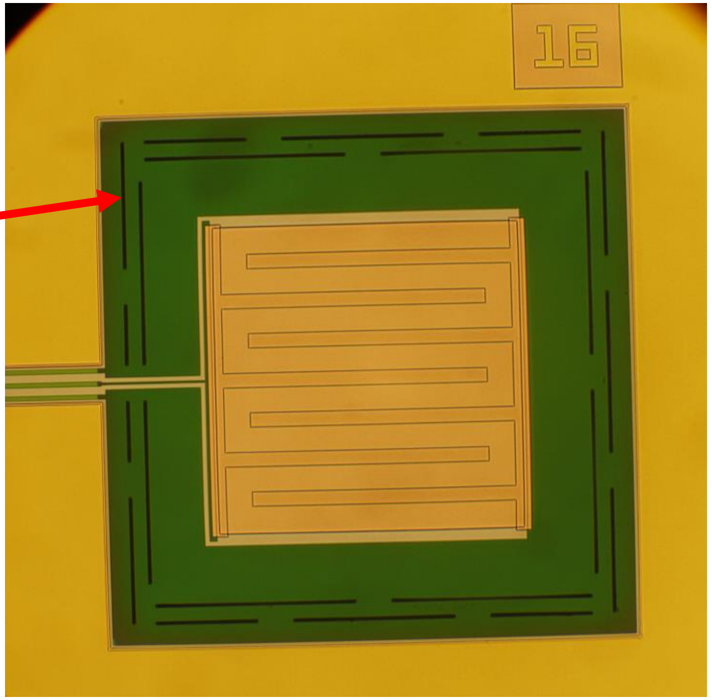


C. Pappas et al., Proceedings of GOMACTech (2019)

Fast TES Design

$$\frac{2}{\tau_{\pm}} = \frac{R_{sh} + R(1+\beta)}{L} + \frac{1 - \frac{\alpha}{n}\left(1 - \left(\frac{T_{bath}}{T}\right)^{n}\right)}{C/G}$$

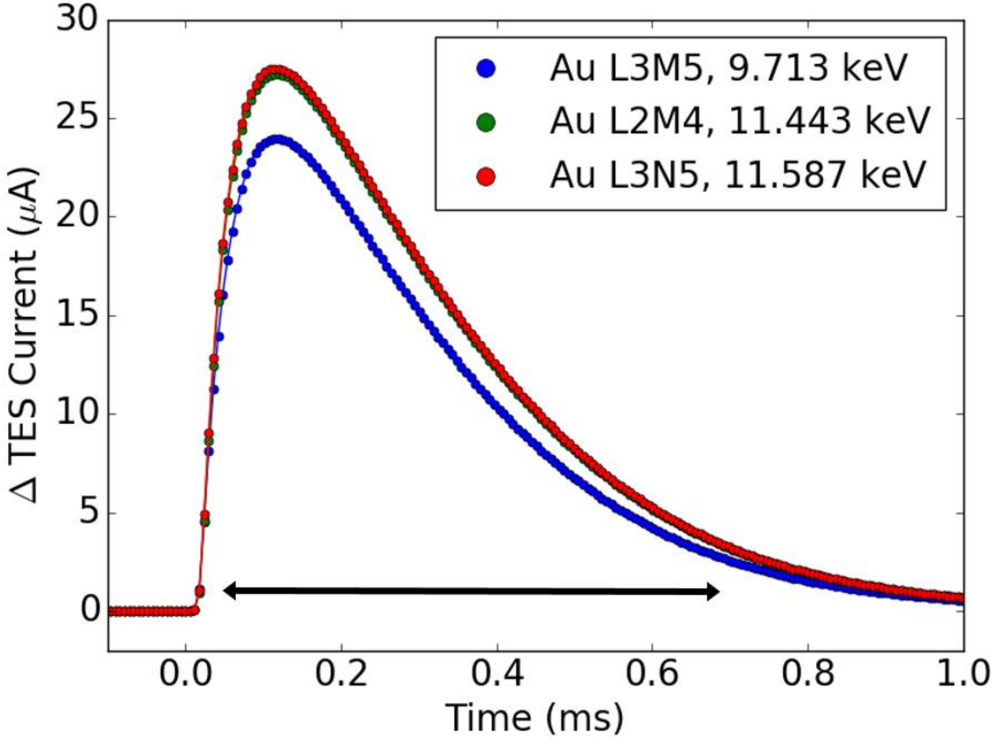
1. Decrease thermal time constant: C/G
    - Decrease heat capacity by adjusting material type or mass of structures on TES island
    - Increase perimeter of TES
    - Fewer/smaller membrane perforations
    - Increase TES critical temperature → Tc=130 mK
2. Change TES R(T,I) transition shape



C. Pappas et al., Proceedings of GOMACTech (2019)

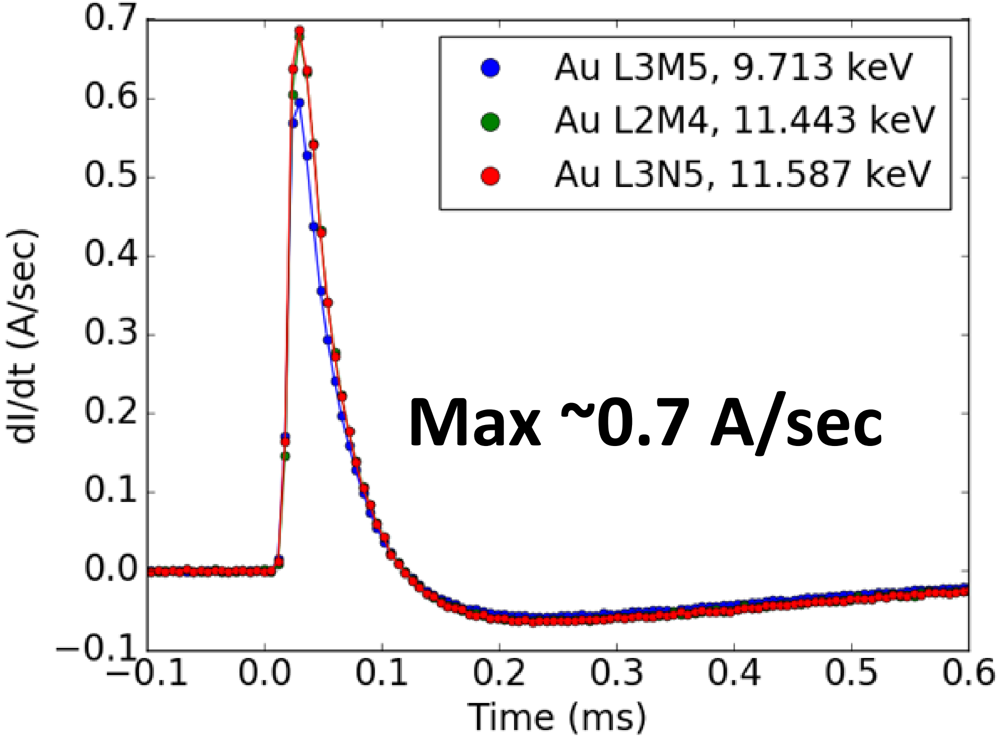
NSENSE Array Measured Au L-line Pulses

TES Current vs. Time



Pulse duration (dead time): 710-740 µs

Slew Rate vs. Time



Maximum measured slew rate below ~0.9 A/sec NSENSE TDM limit

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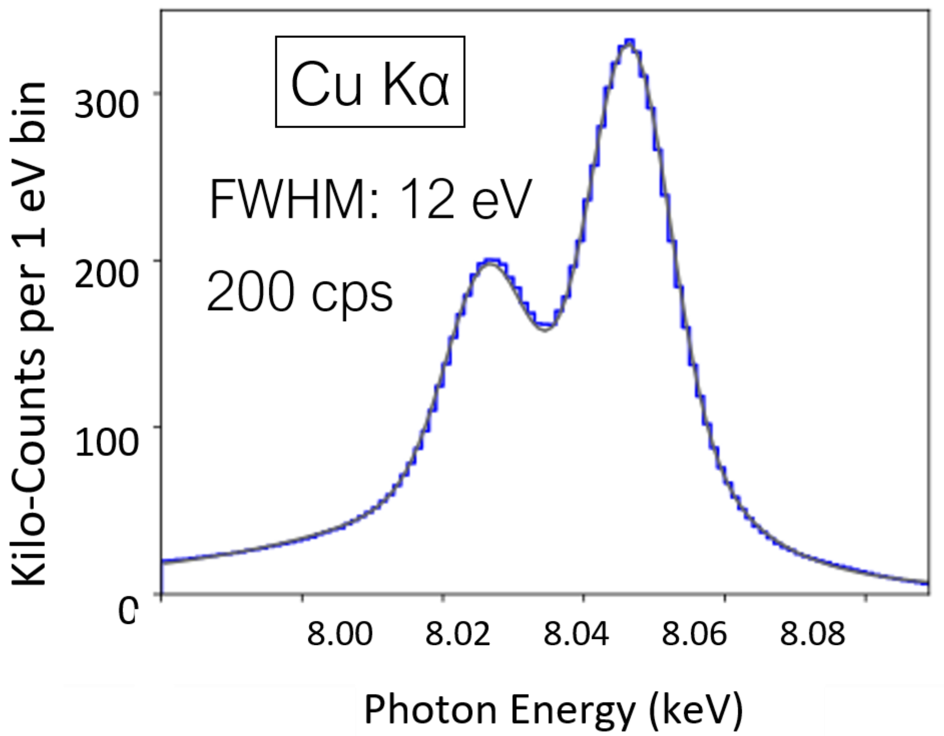
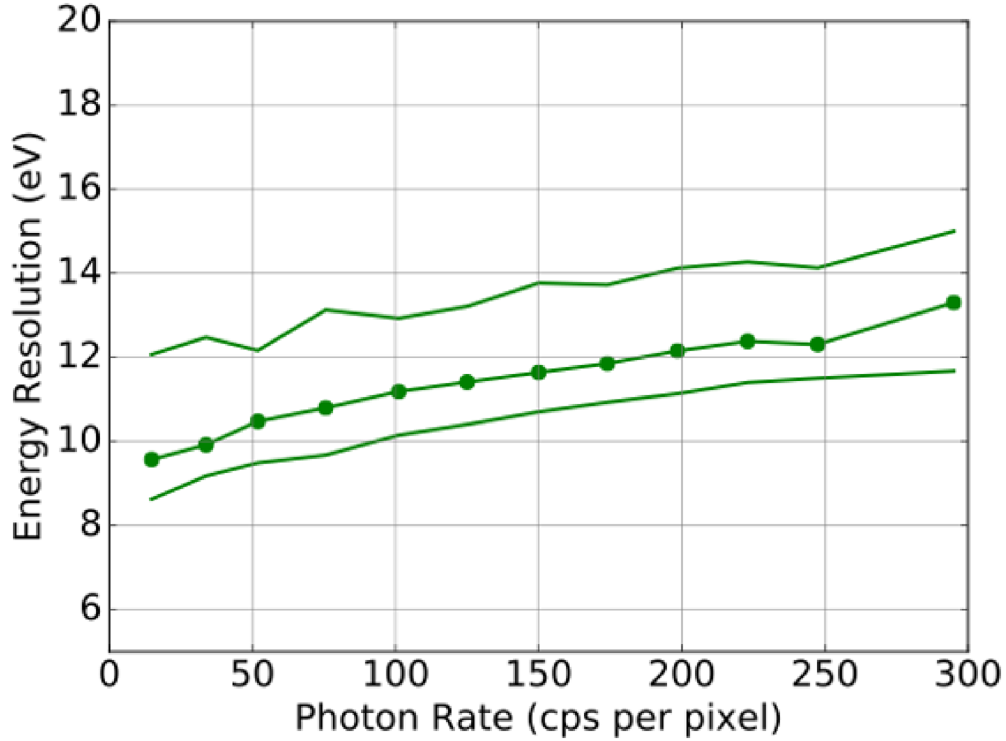
Energy Resolution Scaling

200 cps/pixel Cu Kα Spectrum

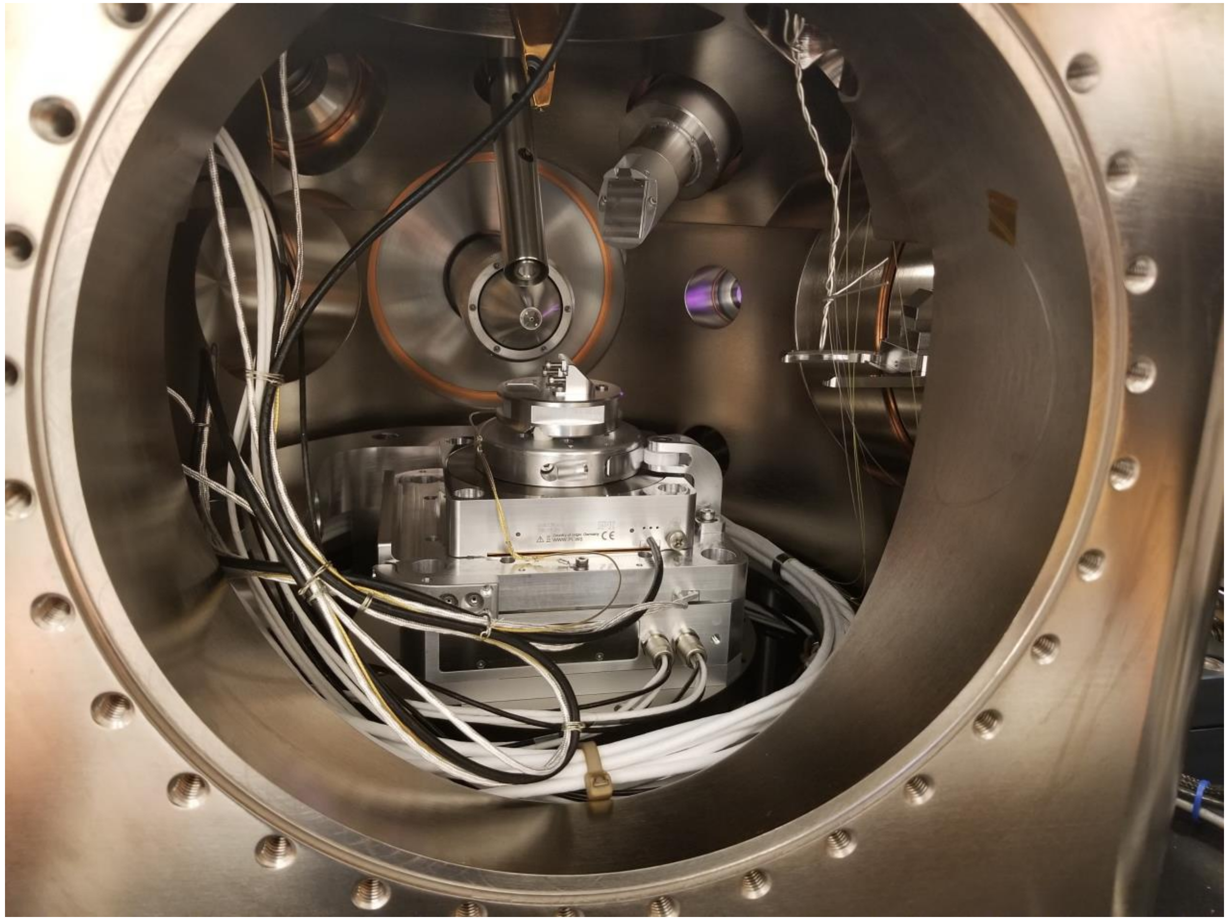


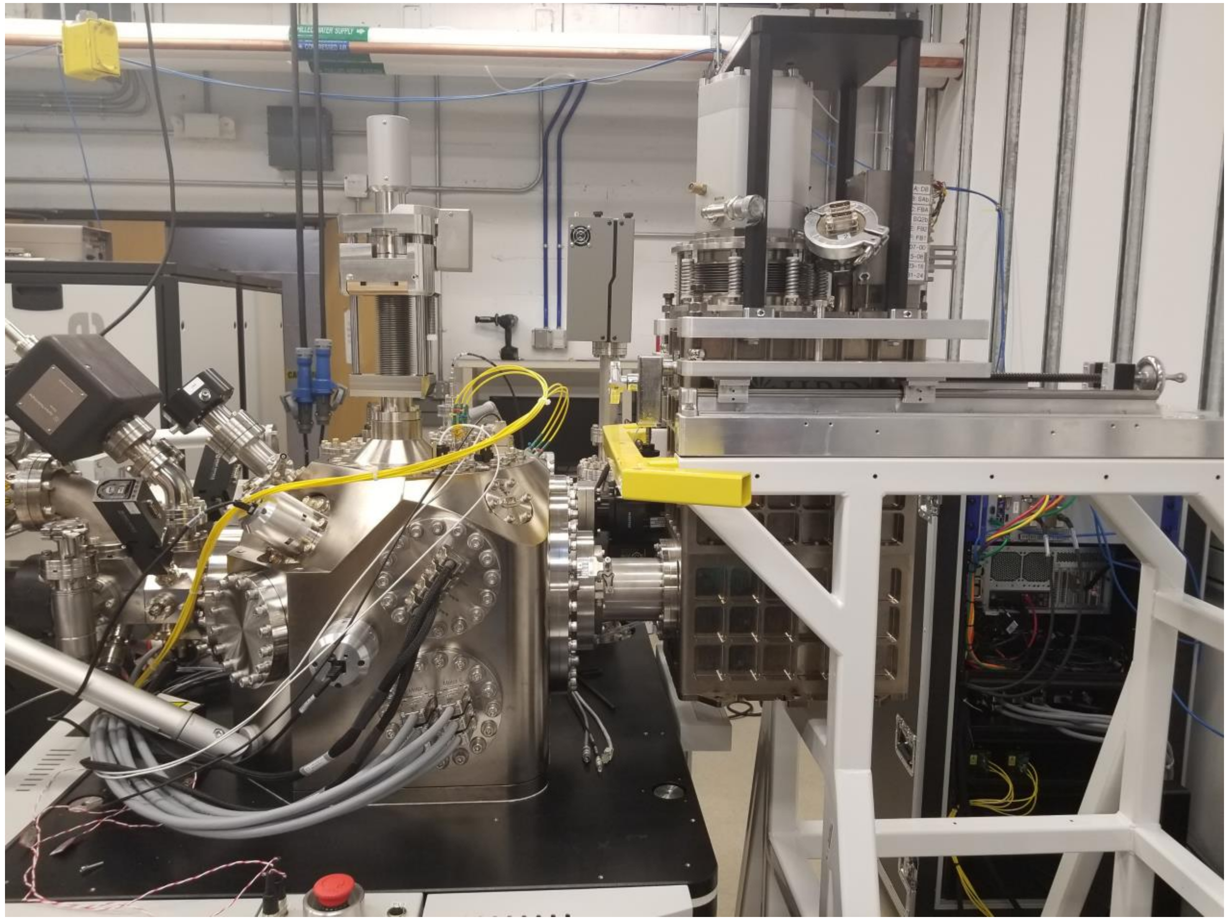
ΔE vs. Count Rate



Energy resolution meets high rate NSENSE goal of 20 eV!

TES Spectrometer Integration





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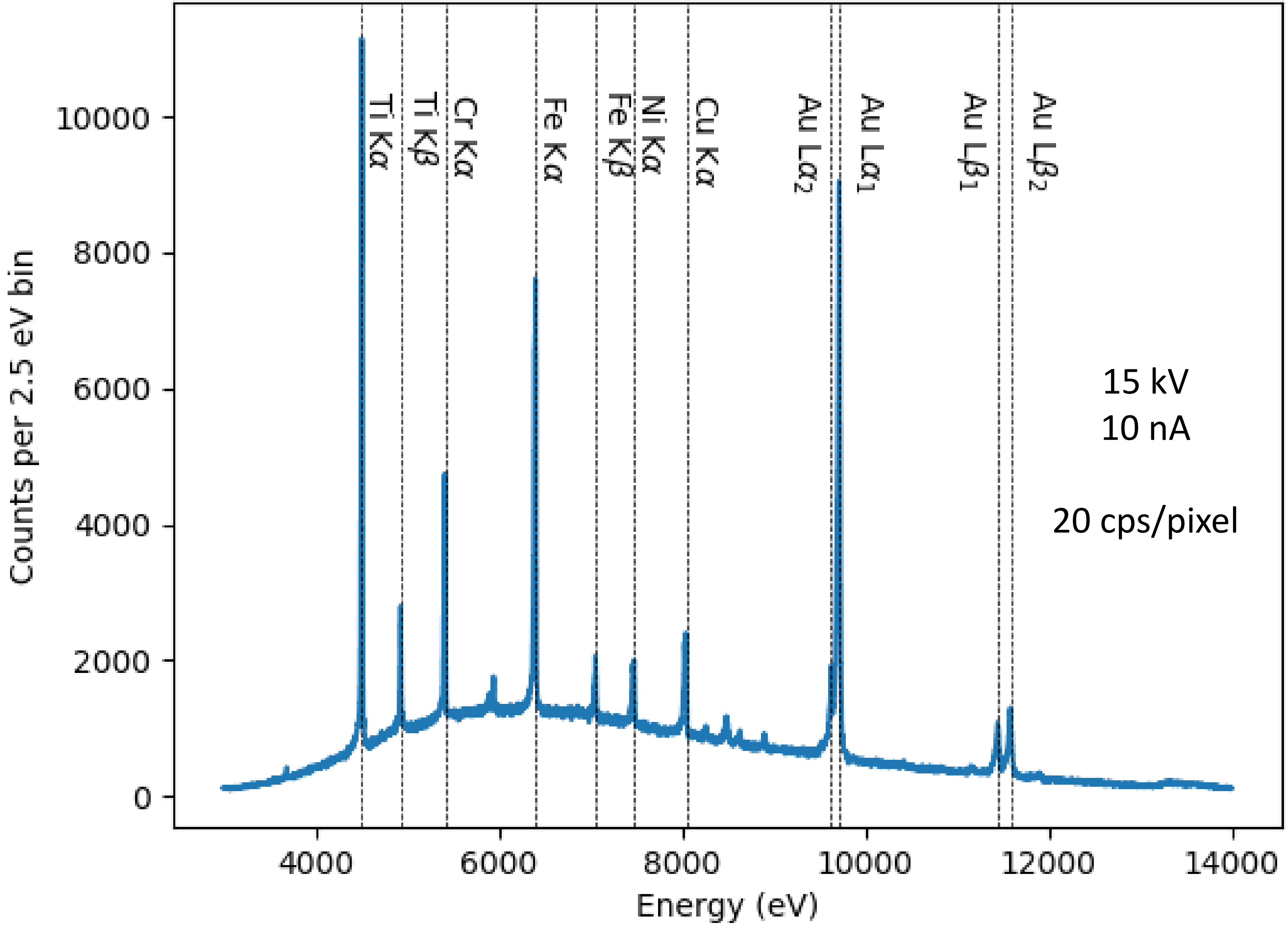
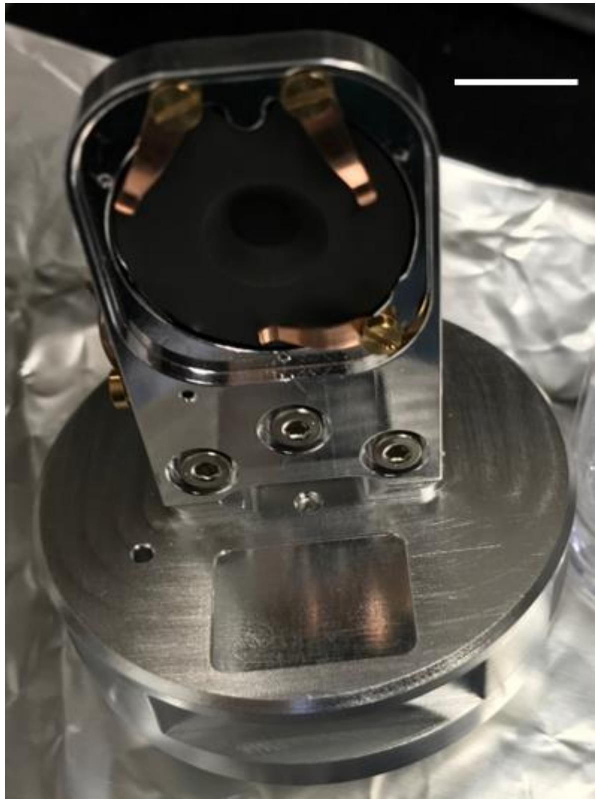
First Light Spectrum!



- Au from 50 nm target layer
- Ti from 2, 10nm adhesion layers
- Fe, Ni, and Cr from stainless steel, likely from both the sample holder and UHV chamber walls.
- Cu from mounting clips and wiring.

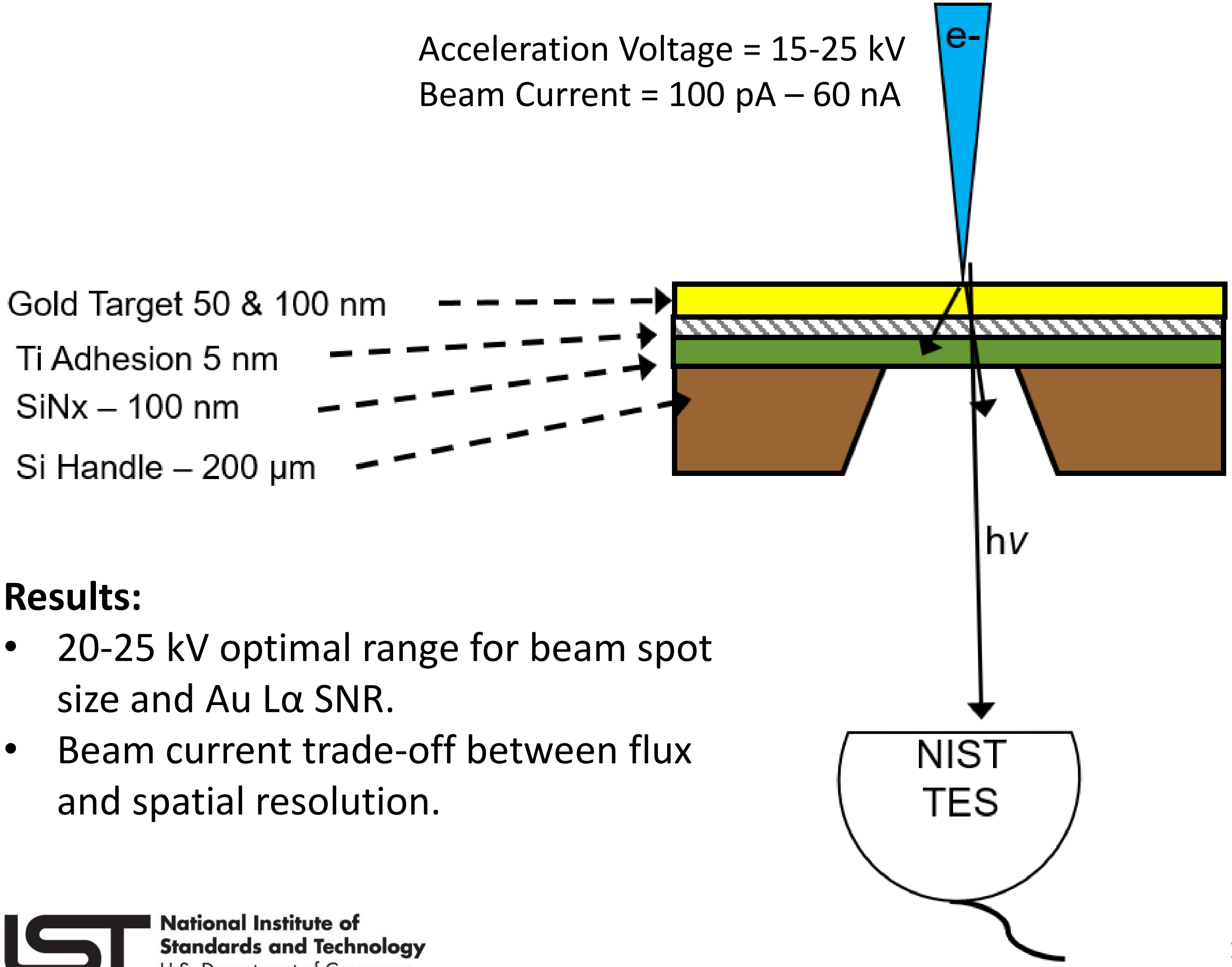


System Characterization Measurements

Expected Scaling Relations:

- **Count rate**: increases linearly with beam current and target thickness (eventually saturates), also increases with acceleration voltage.
- **Beam spot size**: decreases with acceleration voltage, but increases with beam current and target thickness.
- **SNR**: Depends on line energy, expect best efficiency when beam energy is 2-3x the line energy.

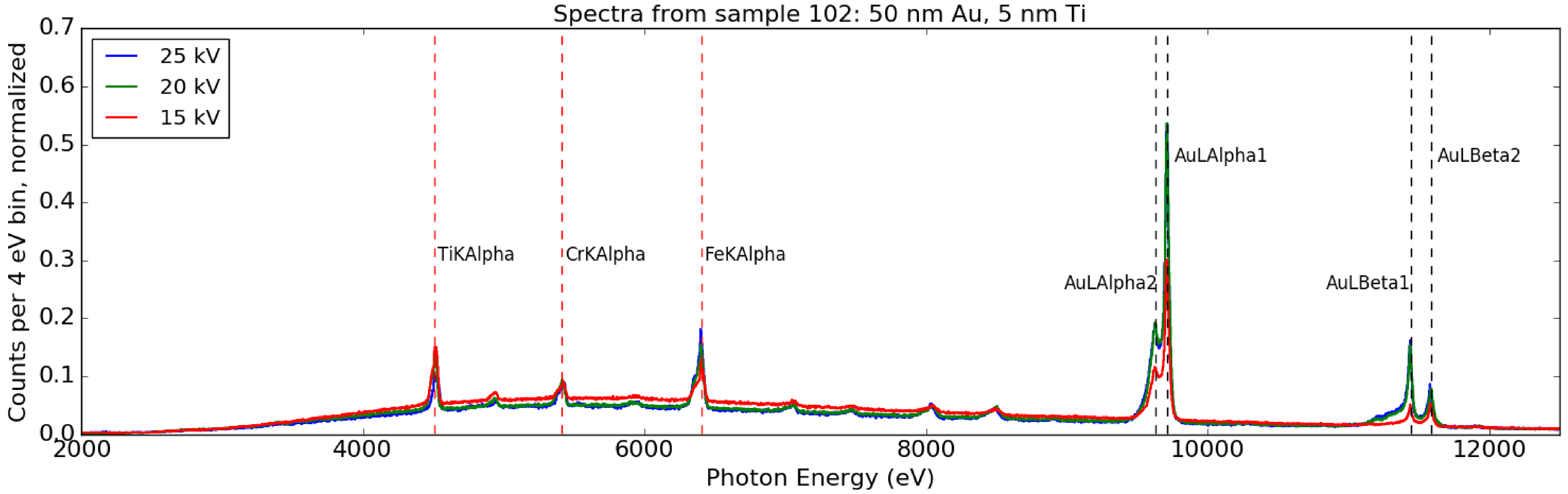
Acceleration Voltage = 15-25 kV
Beam Current = 100 pA – 60 nA



Results:

- 20-25 kV optimal range for beam spot size and Au Lα SNR.
- Beam current trade-off between flux and spatial resolution.

System Characterization Example



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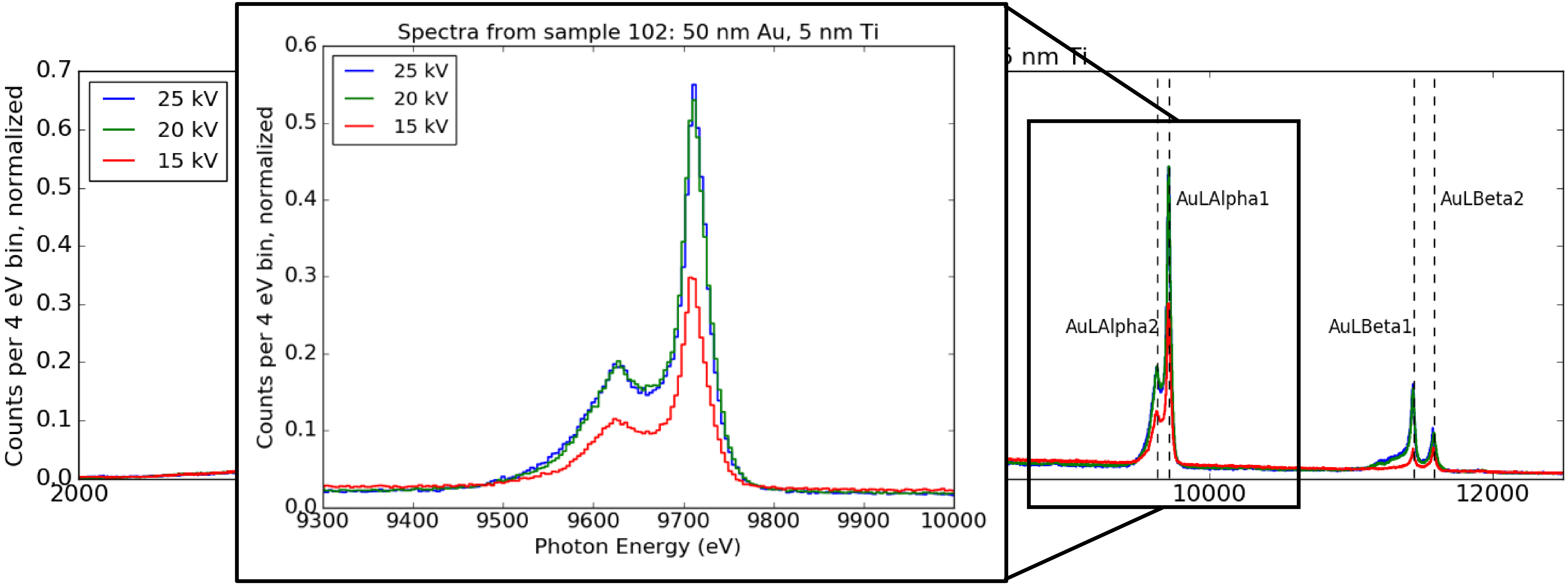
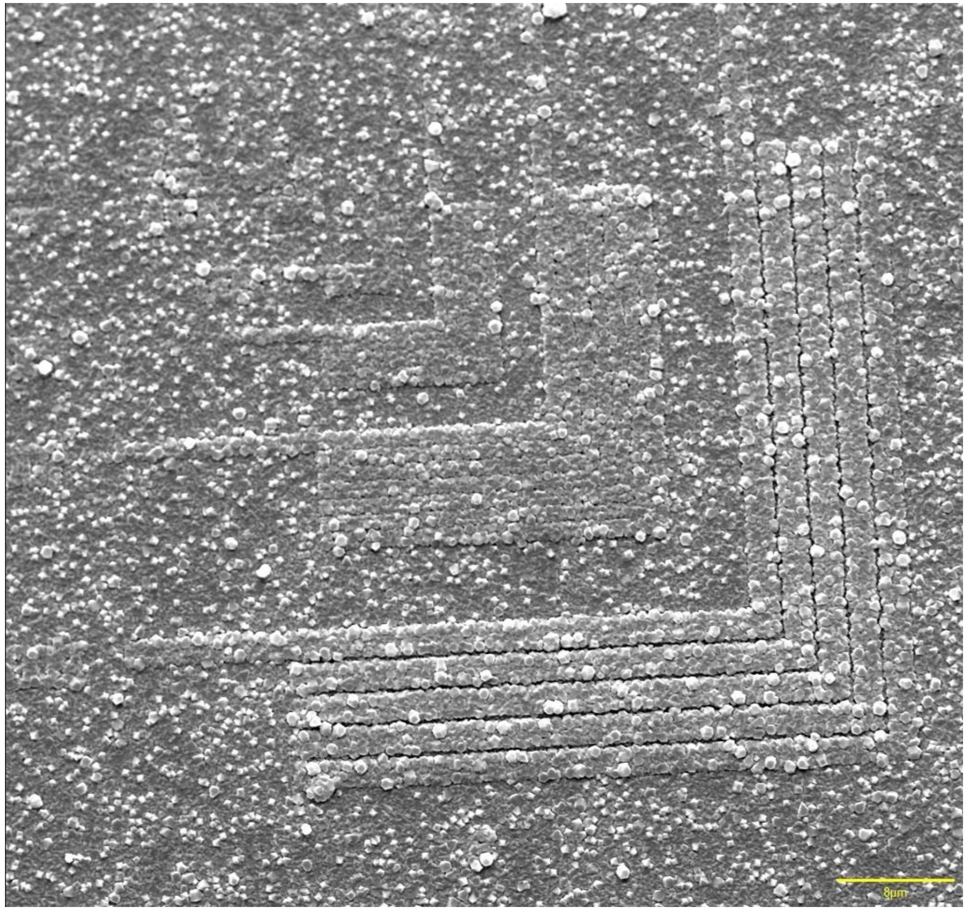
System Characterization Example

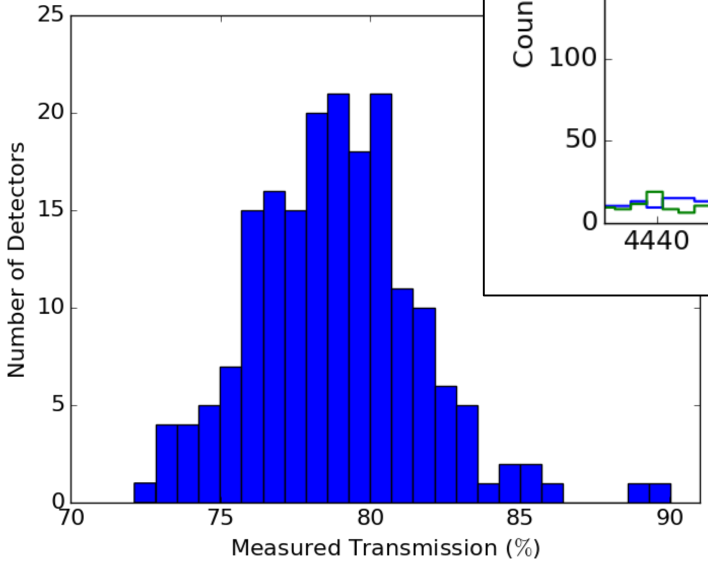


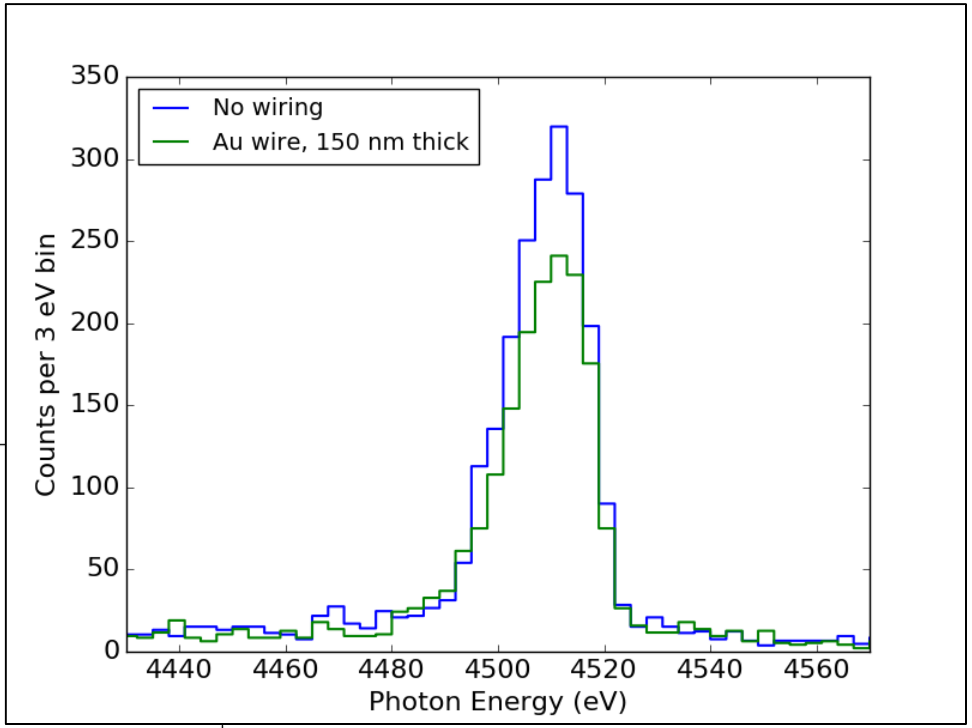
Contrast Tests and Initial Scans



Sample: 150 nm thick Au structures.

Target: 1 um Al spacer, 75 nm Au, 125 nm Ti.





Measured contrast ratios of ~25-30%

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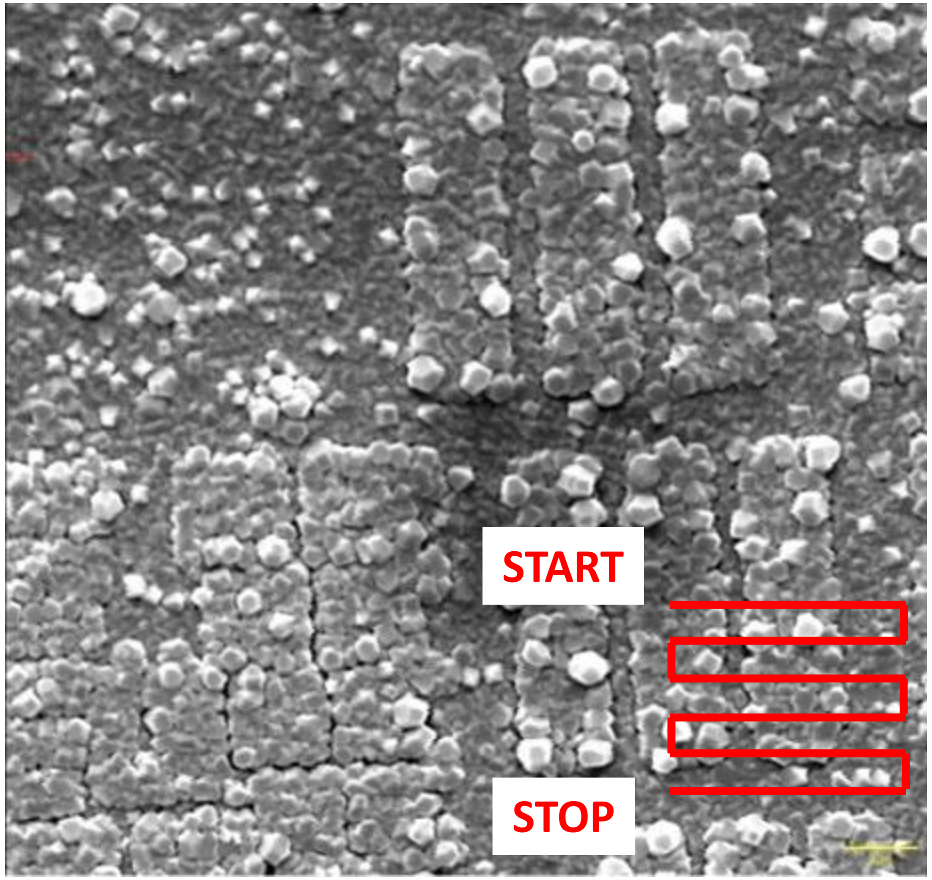
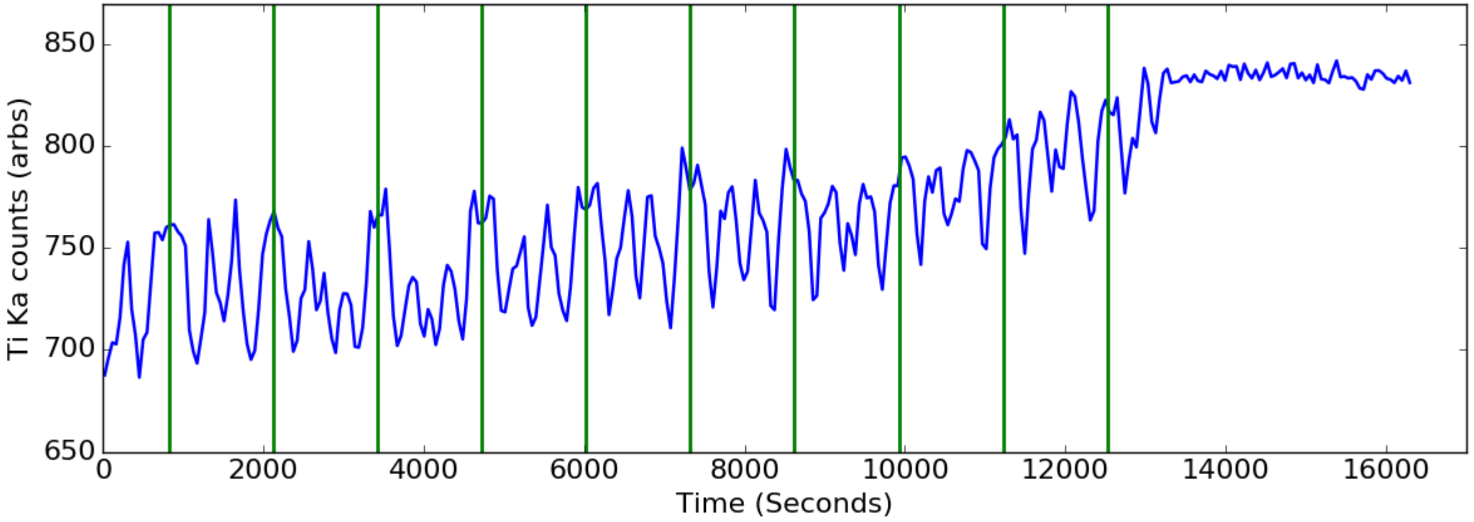
Contrast Tests and Initial Scans

Green lines indicate step across line and back





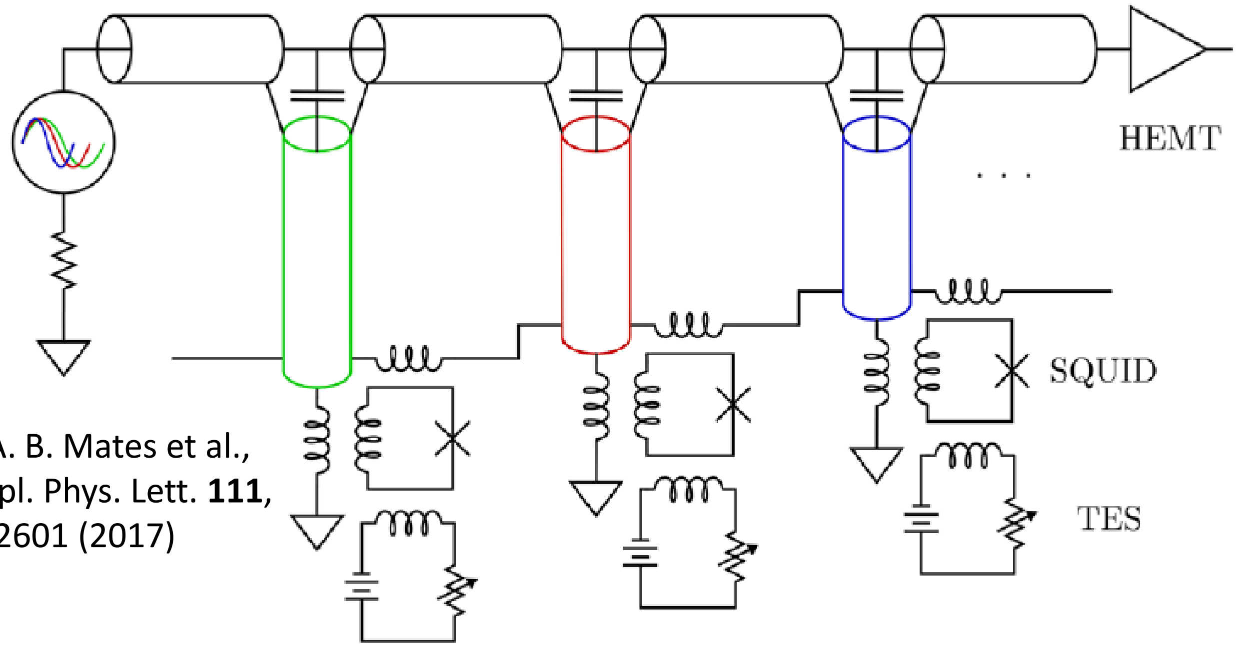
- Bar widths 550 nm.
- 20x20 dwell locations, 100 nm steps, 30 s dwells, 2.5 s step times.
- Essentially 20 line scans at different vertical positions.
- Coadded across all detectors, averages across ~130 nm.

2nd Generation Instrument Scaling

Bluefors Dilution Refrigerator

Continuous operation and increased cooling power, allowing for larger arrays of lower T_C detectors

µMUX Readout Architecture



J. A. B. Mates et al., Appl. Phys. Lett. **111**, 062601 (2017)

Increased readout bandwidth (4 GHz) to facilitate larger and faster TES arrays, common microwave transmission line also reduces wiring complexity.

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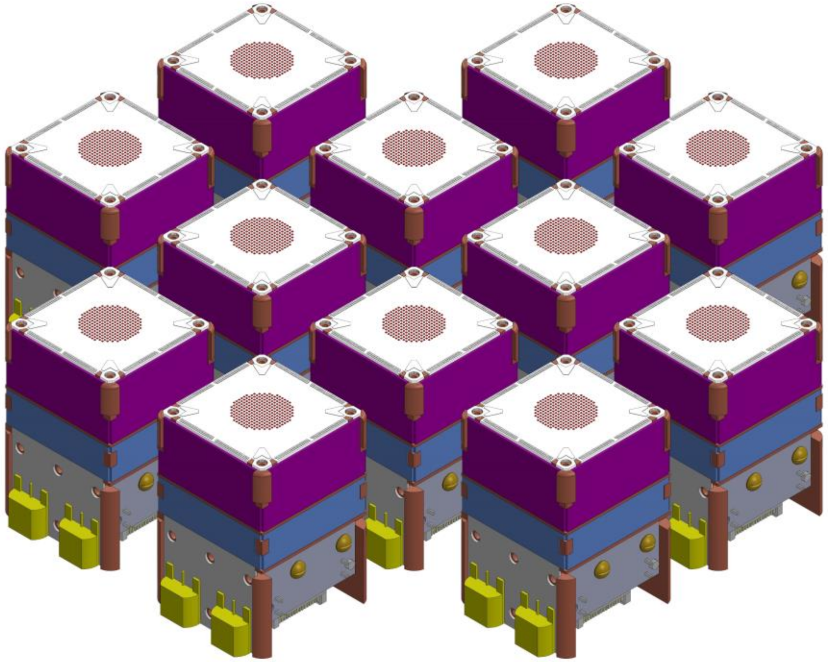
Scaling array size and detector speed

Number of Detectors

Talk by Abby Wessels on Friday, 9:15 am



Modular “micro-snout” design, simplifies scaling to large numbers of pixels. Generation 2 instrument would house 12 micro-snouts = 3000 TESs

Detector Speed

$$\frac{2}{\tau_{\pm}} = \frac{R_{sh} + R(1+\beta)}{L} + \frac{1 - \frac{\alpha}{n}\left(1 - \left(\frac{T_{bath}}{T}\right)^{n}\right)}{C/G}$$

Will increase detector speed by a factor of 10 in a similar fashion as was done for optimizing the Phase 1 RAVEN detectors.

- The increased bandwidth of µMUX readout allows us to make much faster detectors that would have been unusable with our current TDM architecture due to slew rate limitations.
- Throughput improvement will depend on being able to increase the source strength

Improvements from lowering T_C

Ignoring β dependence

$$\Delta E \approx \sqrt{\frac{CT_c^2}{\alpha}\sqrt{\frac{1}{1-(T_b/T_c)^n}}}$$

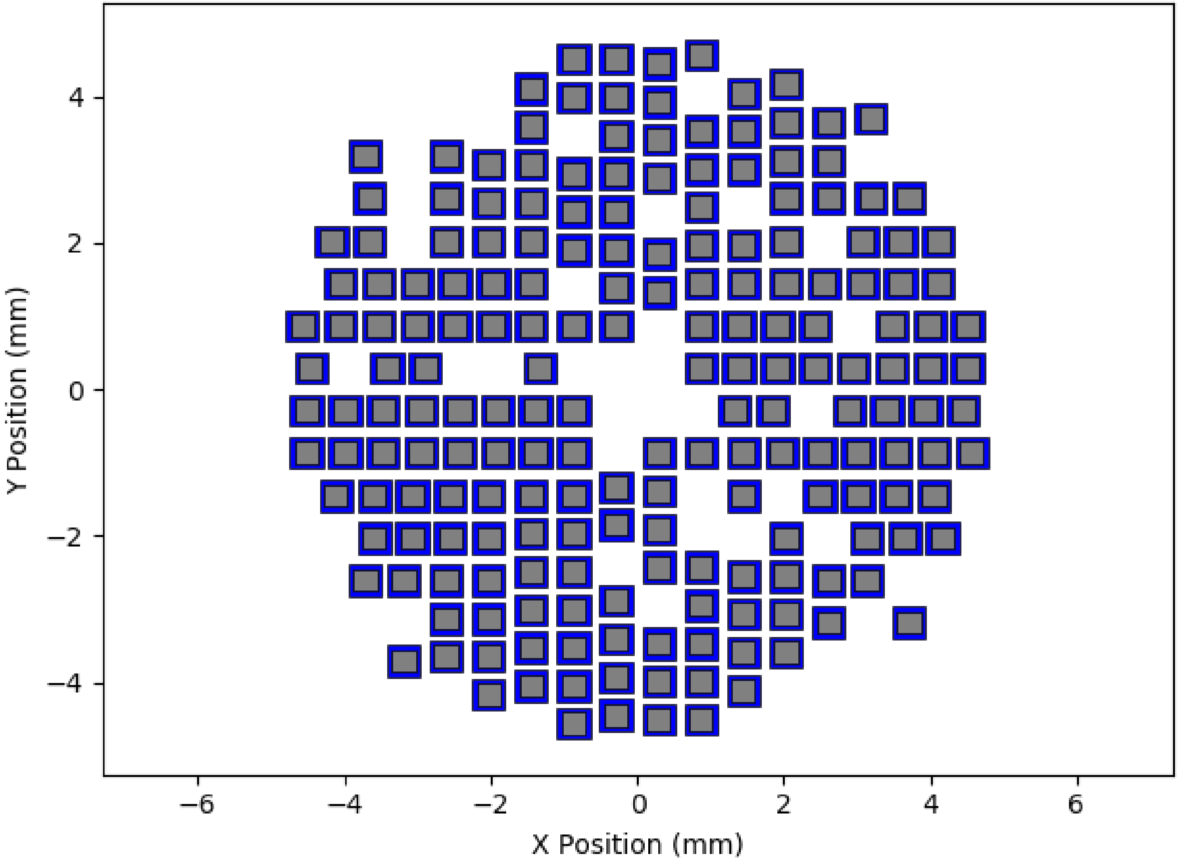
Linear TES model with constant dynamic range

$$E_{max} \approx \frac{CT_c}{\alpha}$$

$$\Delta E \approx \sqrt{E_{max}}\sqrt{\frac{T_c}{\sqrt{1-(T_b/T_c)^n}}}$$

T_b sufficiently low

$$\Delta E \propto \sqrt{T_C}$$

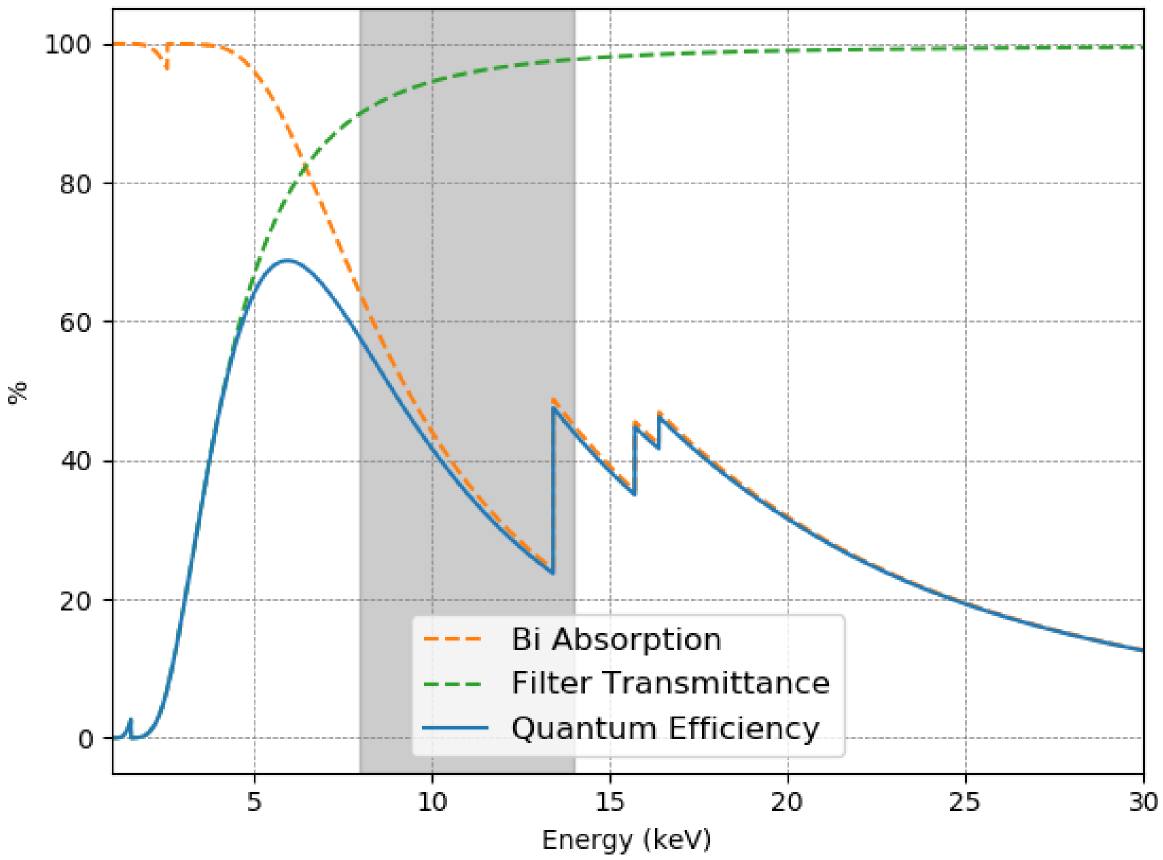


Potential for up to a factor of 2 improvement in resolution, increasing the SNR of spectral features used for tomography

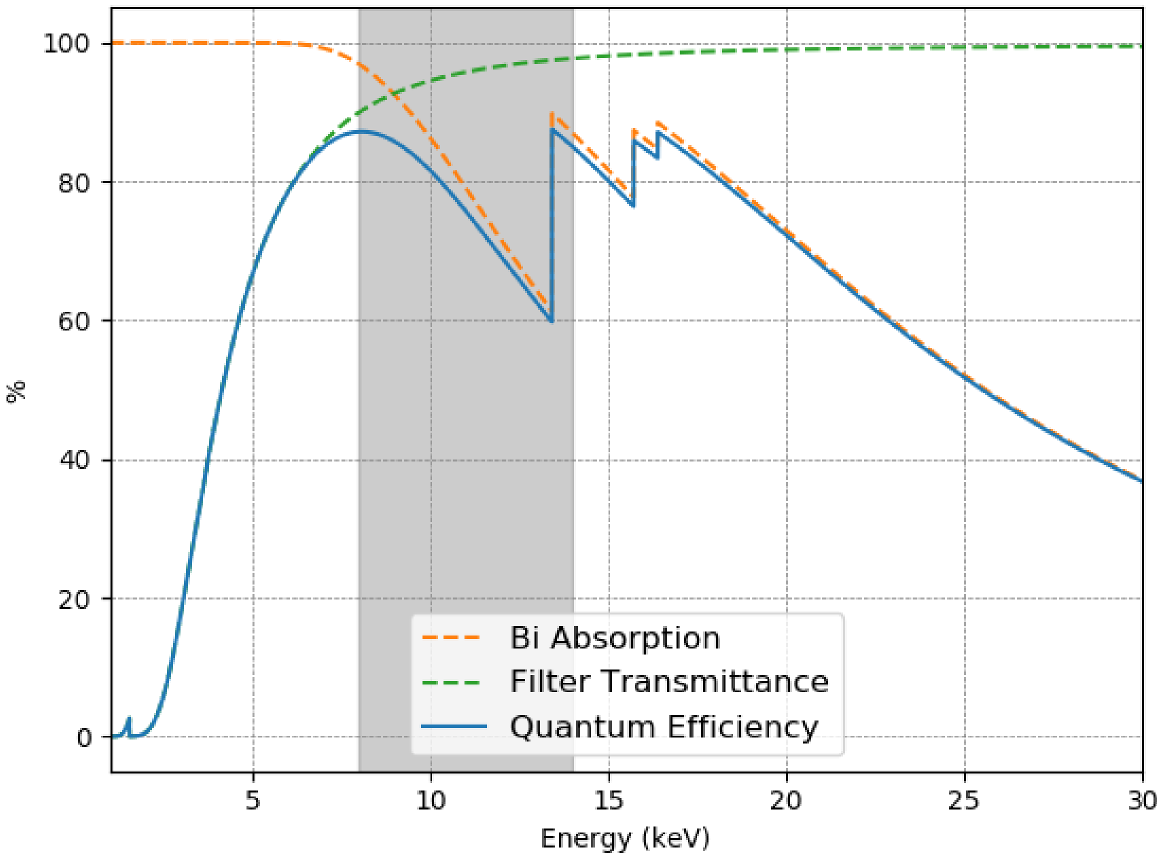
Also allows us to increase detector size, ~2-4x collection area improvement

Thicker Bi absorber (~2x improvement)

Current Bi absorbers, 4.4 um thick



Electroplated Bi absorbers, 15 um thick



Talk by Joel Weber on Wednesday, 12:15 pm

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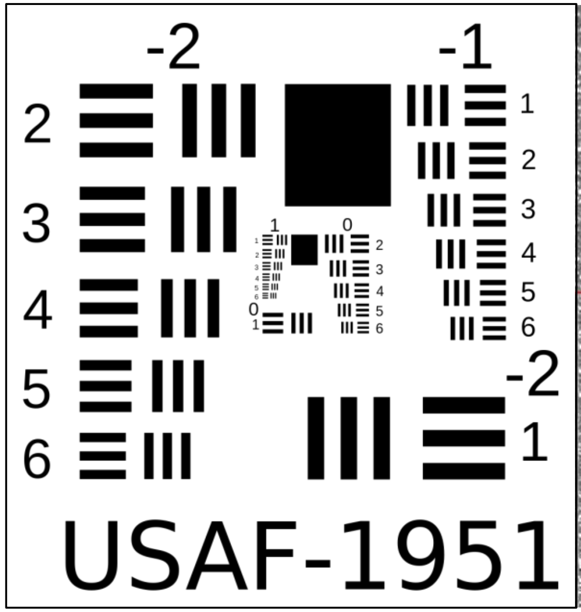
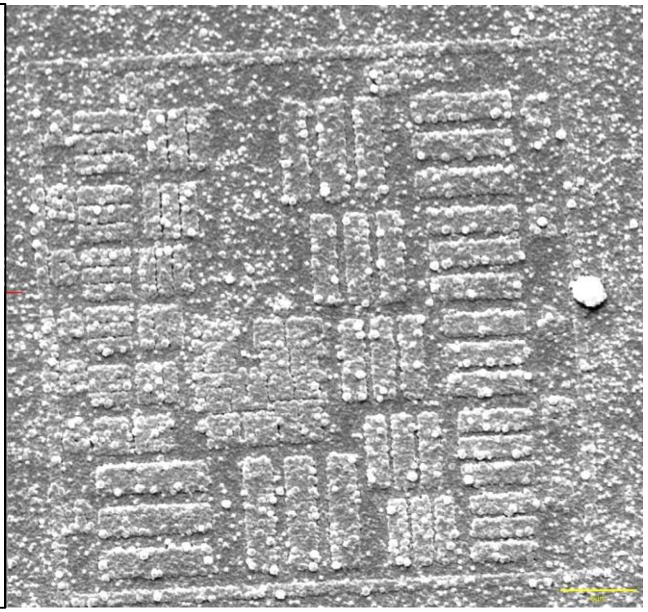
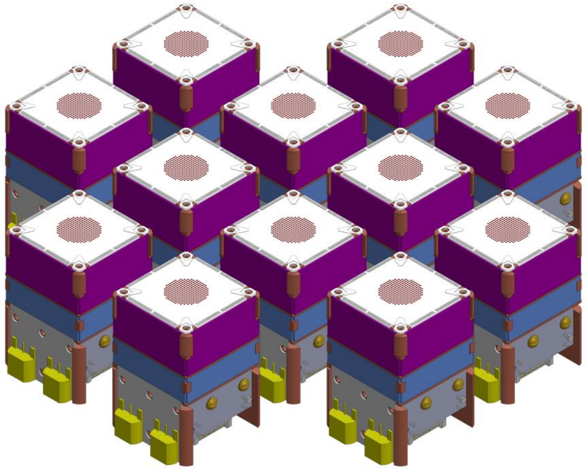
Next Steps

- Continue scans on 2 dimensional structures. Reduce system vibrations/noise sources and determine best achievable spatial resolution.
- Begin scans of more complicated ICs with varying numbers of structural layers and feature sizes.
- Begin design of 2nd generation instrument cryostat, readout, and detectors.







Thank you!

This work was funded through IARPA's Rapid Analysis of Various Emerging Nanoelectronics (RAVEN) research program.

Paul Szypryt is supported by a National Research Council (NRC) Postdoctoral Fellowship.