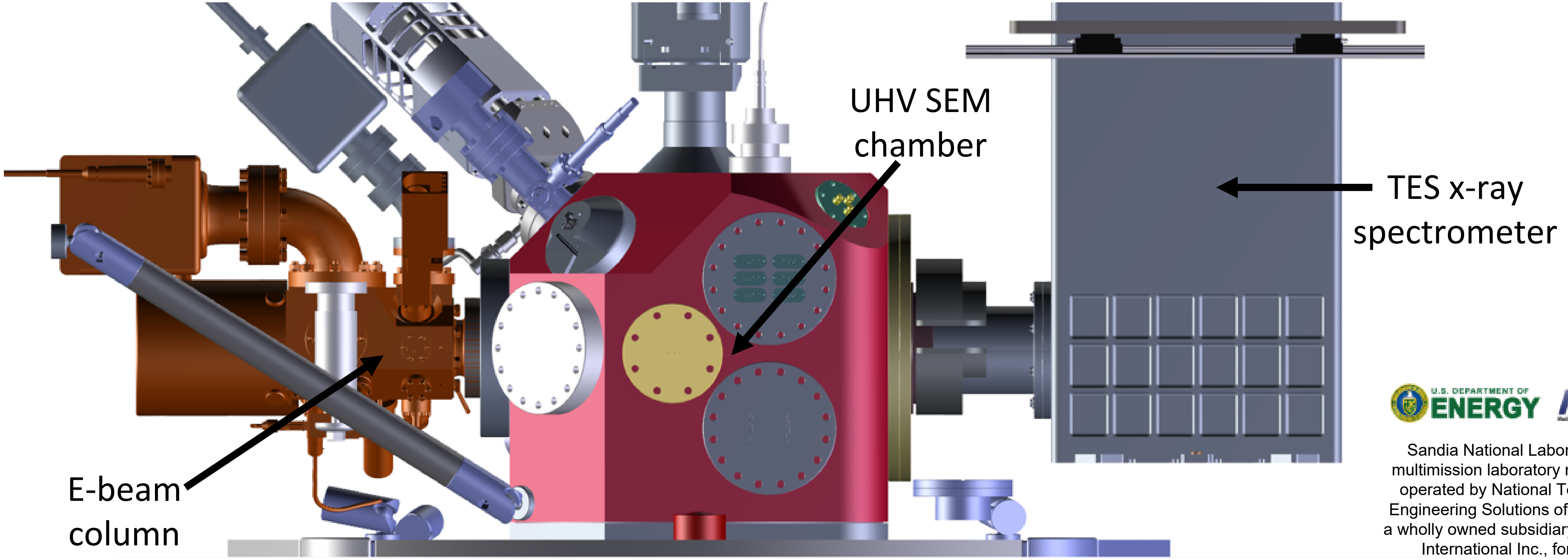
SAND2022-13093C

Implementing transition-edge sensors in a tabletop x-ray CT system for imaging applications

Paul Szypryt

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



National Institute of Standards and Technology

Our Team

National Institute of Standards and Technology (NIST)

- Bradley K. Alpert, Daniel Becker, Douglas A. Bennett, W. Bertrand Doriese, Malcolm Durkin, Joseph W. Fowler, Johnathon D. Gard, Jozsef Imrek, Zachary H. Levine, John A. B. Mates, Luis Miaja-Avila, Kelsey M. Morgan, Nathan Nakamura, Galen C. O'Neil, Nathan J. Ortiz, Carl D. Reintsema, Daniel R. Schmidt, Daniel Swetz, Paul Szypryt, Joel N. Ullom, Leila Vale, Joel C. Weber, and Abigail L. Wessels

Sandia National Laboratories

- Amber L. Dagel, Gabriella Dalton, J. Zachariah Harris, Edward S. Jimenez, Daniel McArthur, Kyle R. Thompson, Christopher Walker, and Jason W. Wheeler

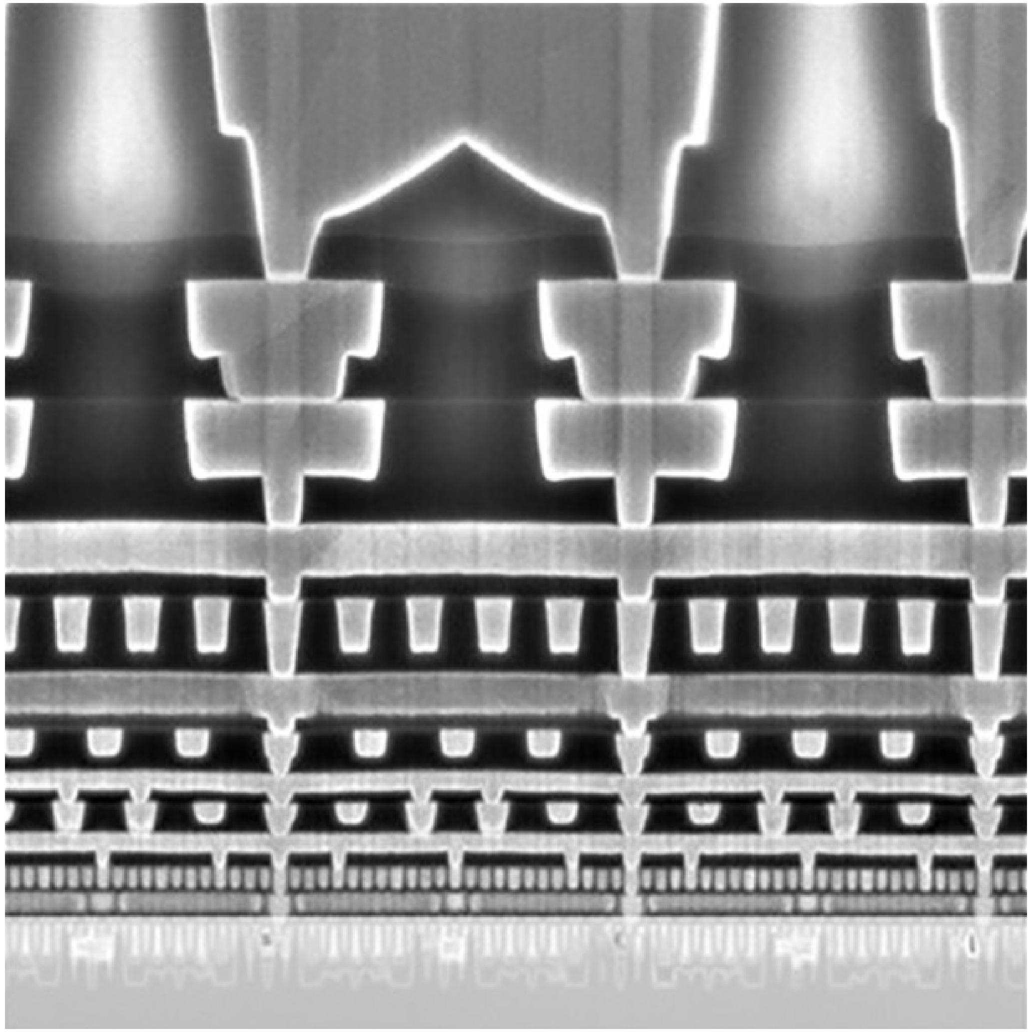
Orsay Physics

- Julien Alberto, Damien Griveau, Jeremie Silvent, and others

Motivation

- 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 subsurface features can be much more difficult.
- Advanced x-ray imaging techniques must be developed to map 10 nm scale features in a timely manner. Goals here would include defect analysis, detection of unknown/unwanted structures, etc.
- Ideally, such techniques would be non-destructive to the IC and can be performed with a tabletop instrument.

Intel 10 nm interconnects

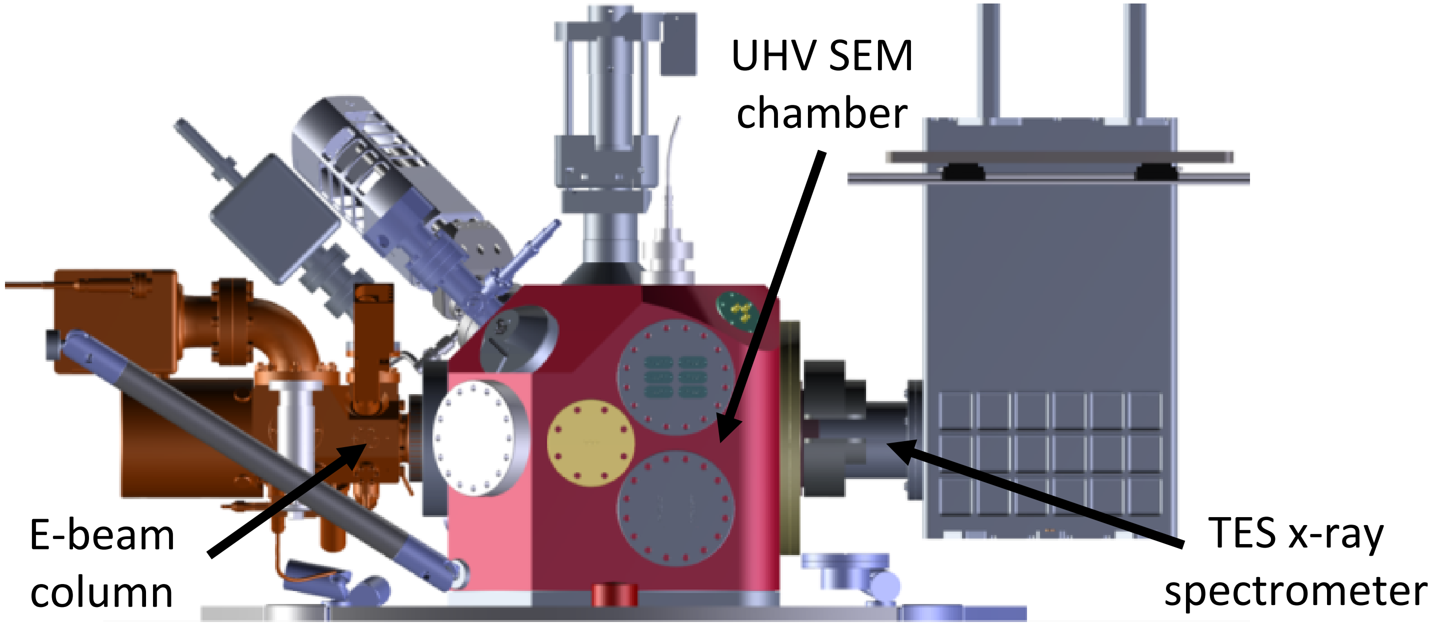


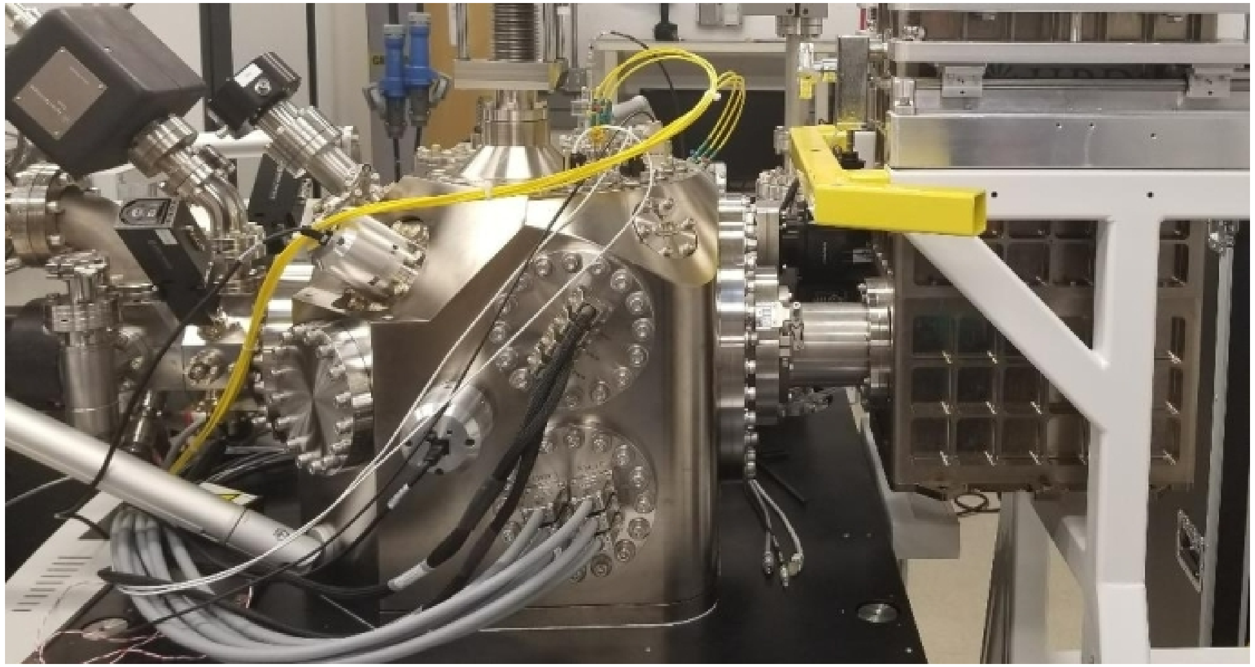
https://en.wikichip.org/wiki/File:intel_interconnect_10_nm.jpg

Instrument

The **TOM**ographic **C**ircuit **A**nalysis **T**ool (**TOMCAT**) consists of the following key components:

- **S**canning **E**lectron **M**icroscope (**SEM**)
  - Electron beam confined to 100 nm spot or better
- Specially designed metal target deposited directly on the circuit under test
  - Small x-ray spot size close to sample providing high magnification
  - Can achieve sub-beam resolutions using nanopatterned targets
- **T**ransition-**E**dge **S**ensor (**TES**) x-ray spectrometer
  - Energy-resolved (part per thousand) single photon detection
  - Pixelated array, utilizing spatial information





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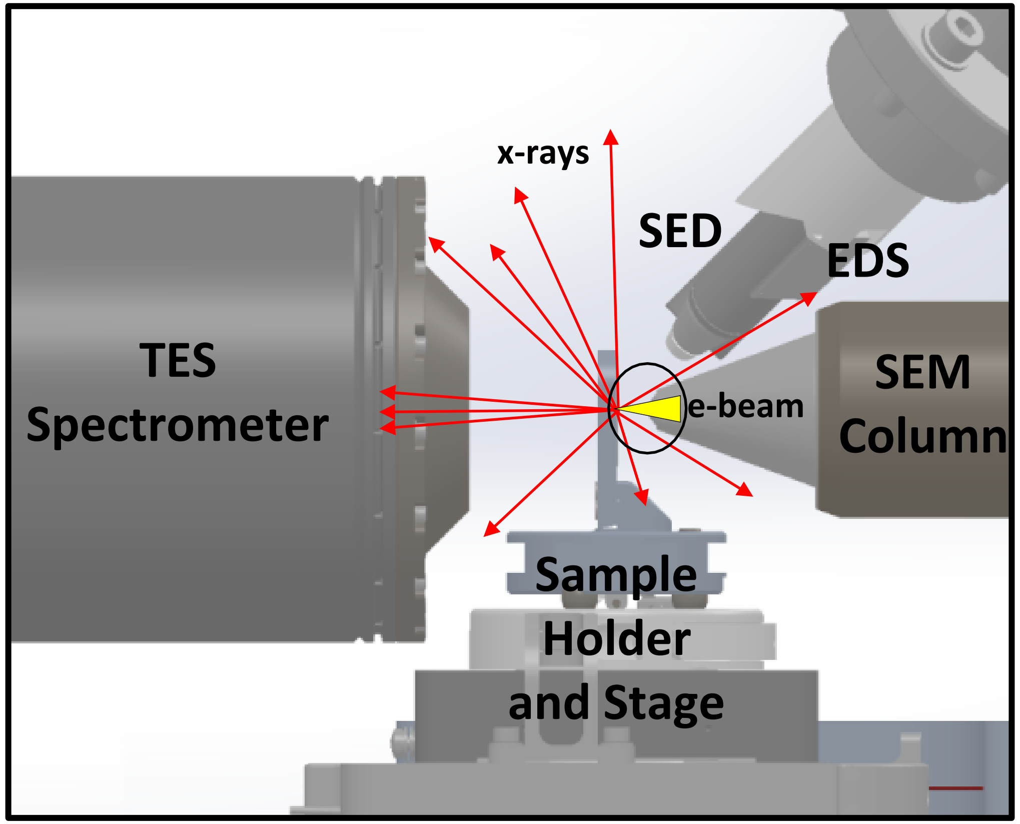
Approach



Layer	Material	Nominal thickness	Measured thickness
(orange)	Si	275 um	
(purple)	Ti	70 nm	
(yellow)	Si3N4	2 um	
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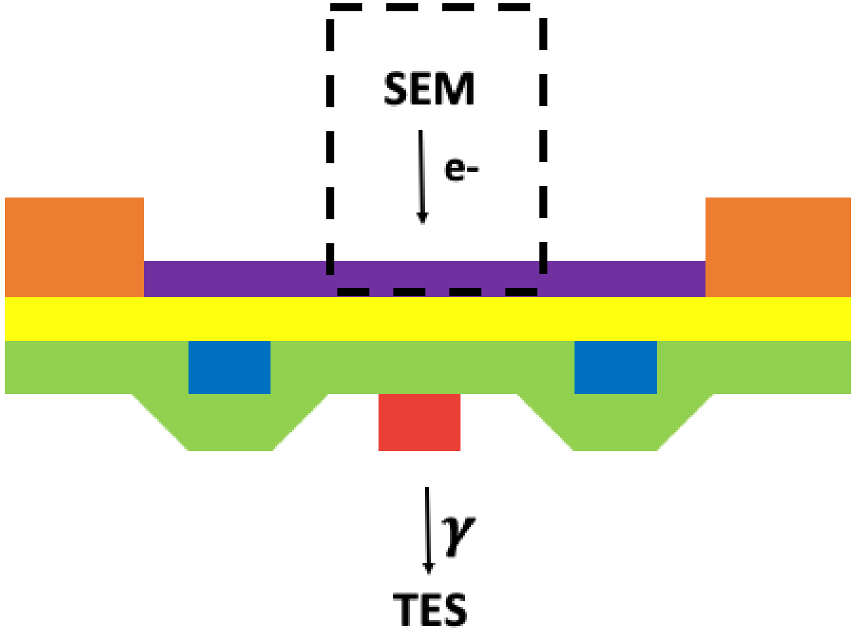

1. Use focused electron beam from scanning electron microscope (SEM) to excite characteristic, traceable x-rays in a target layer.
2. X-rays travel through the sample and the intensity is attenuated depending on the x-ray energy and materials in the sample.
3. Transmitted x-rays are detected with a TES x-ray spectrometer, and the energy resolution is used to discern target x-rays from Bremsstrahlung and other background radiation.
4. The sample stage or electron beam is stepped to get a 2D attenuation map. Data from different sample rotations are then combined to perform a tomographic inversion and generate a 3D image.

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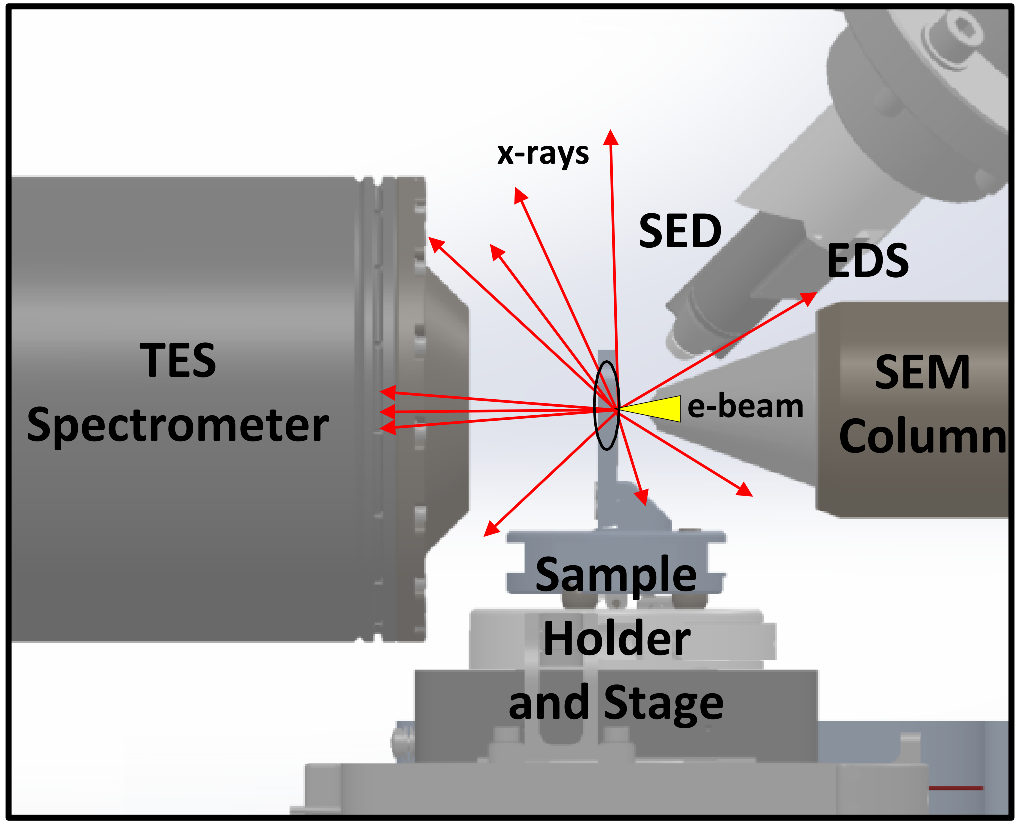

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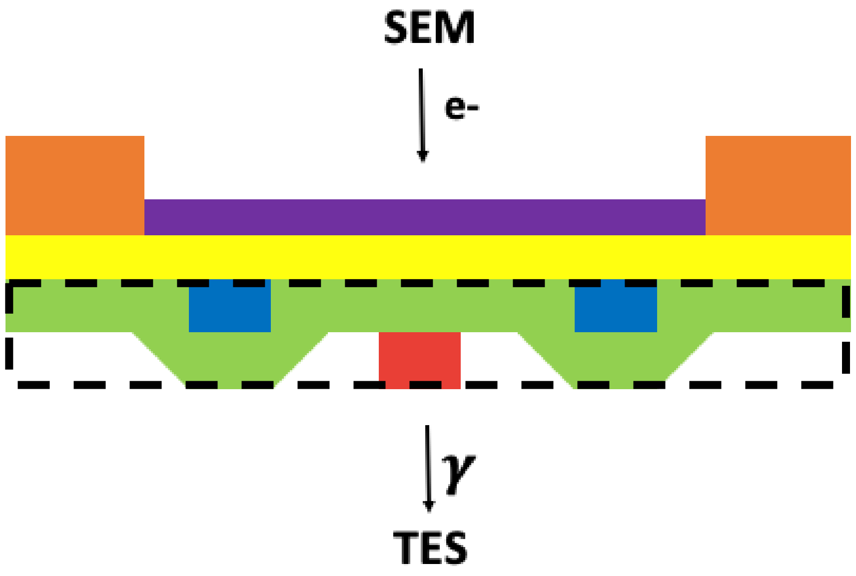

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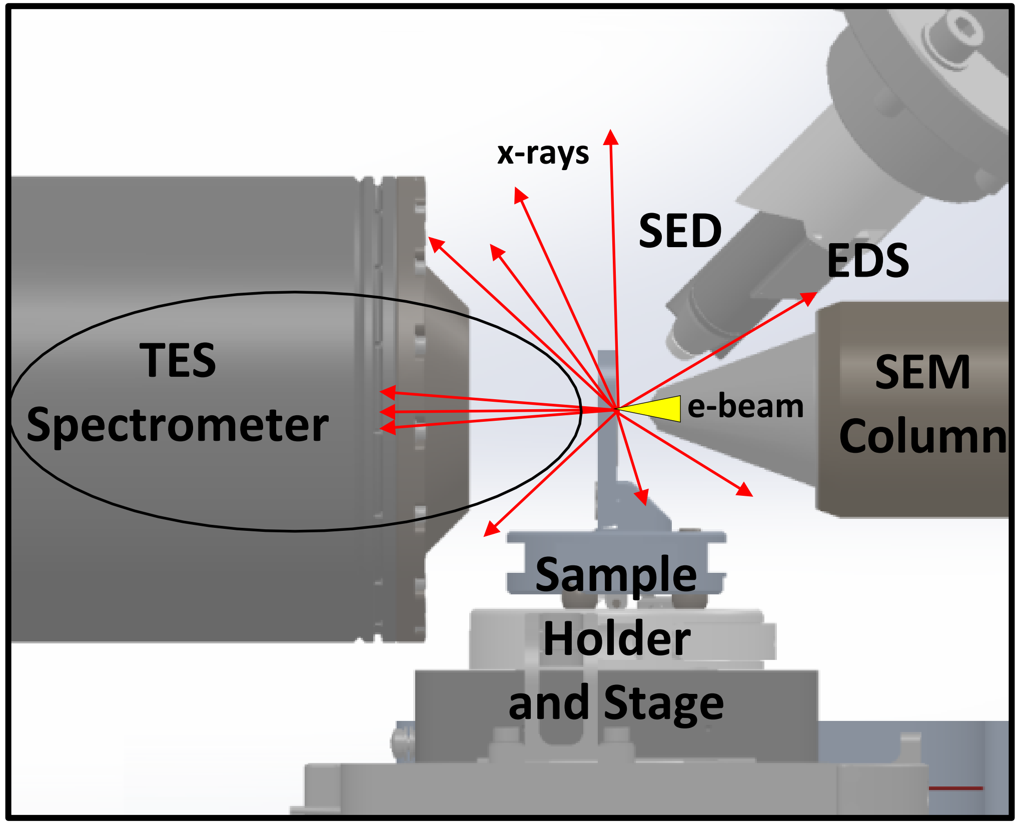

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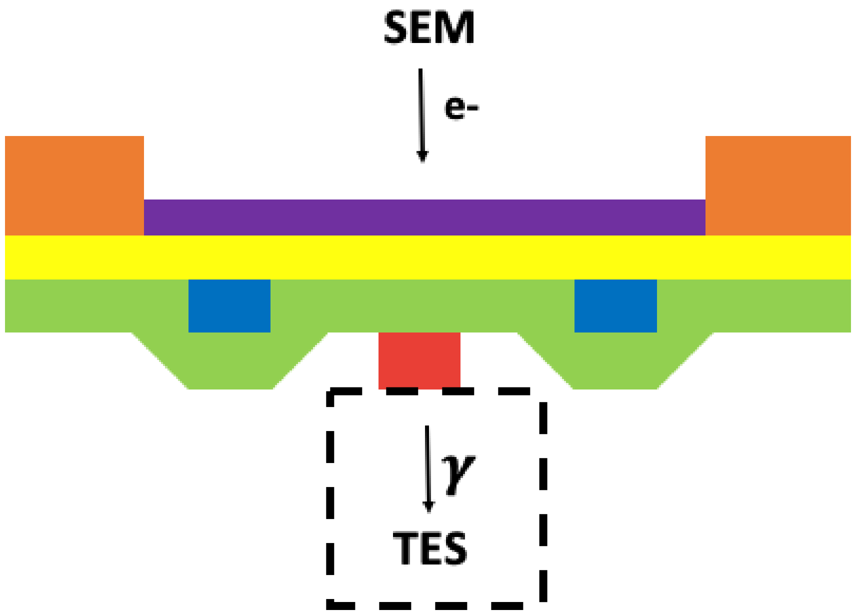

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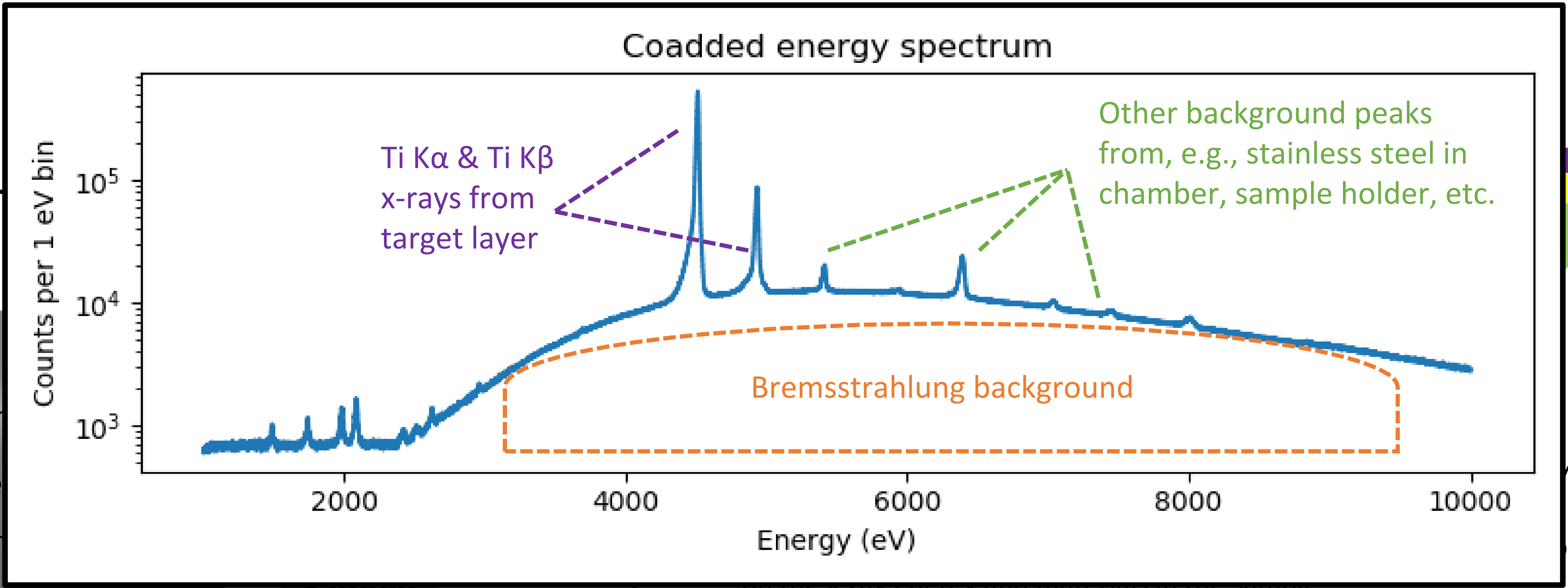

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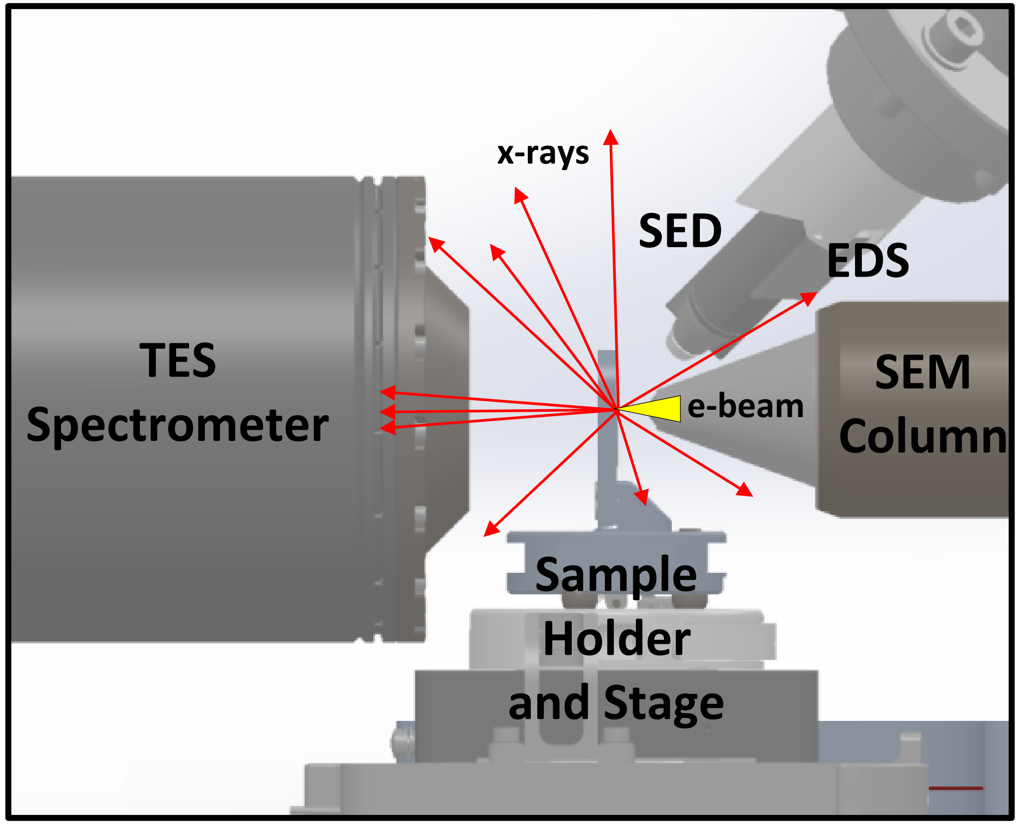

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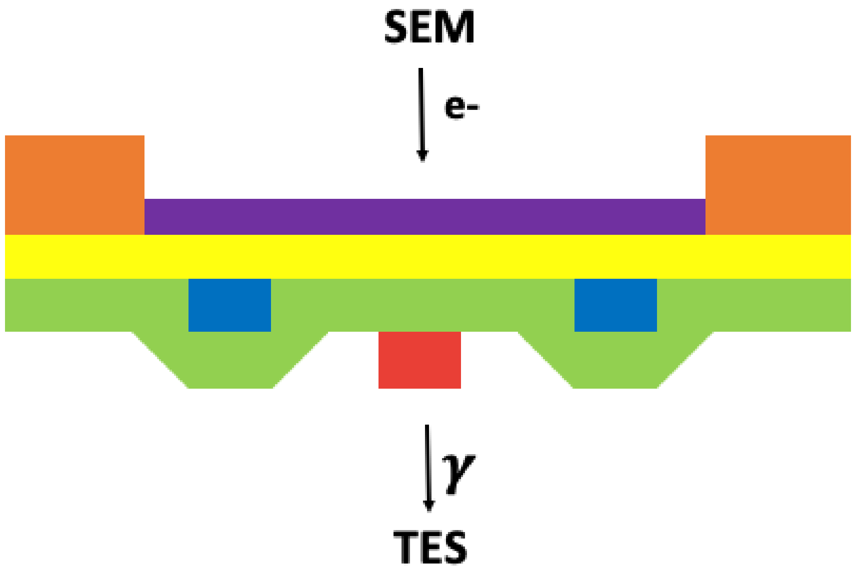

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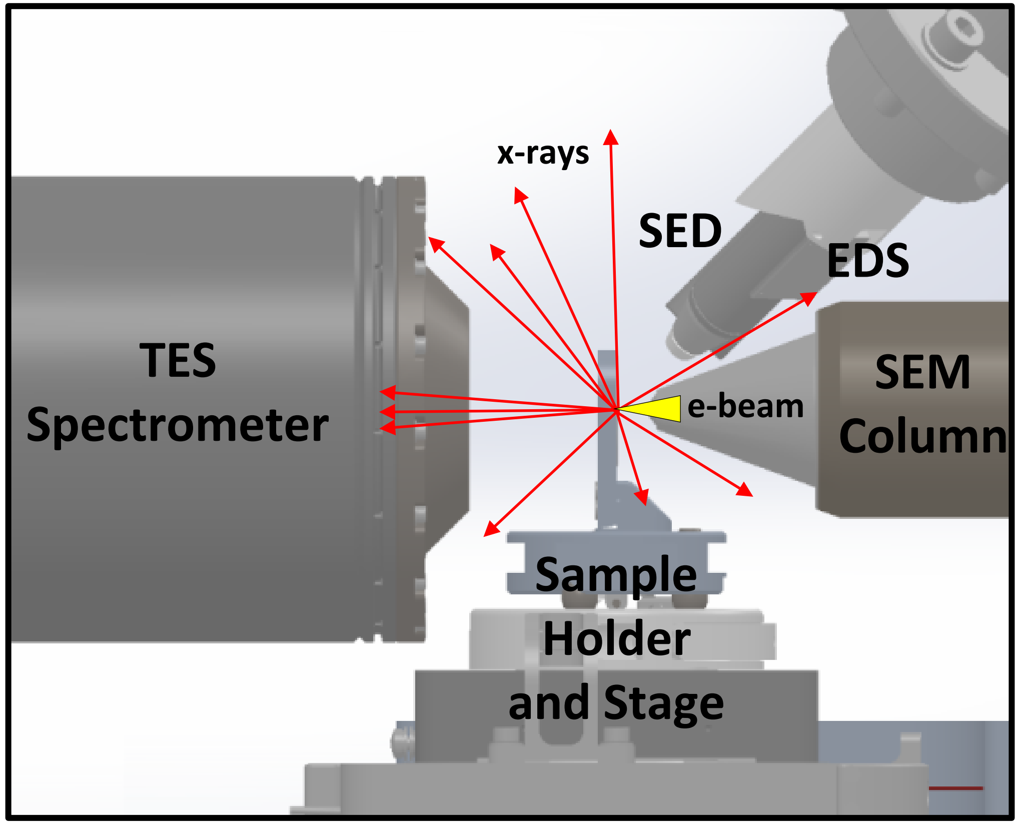

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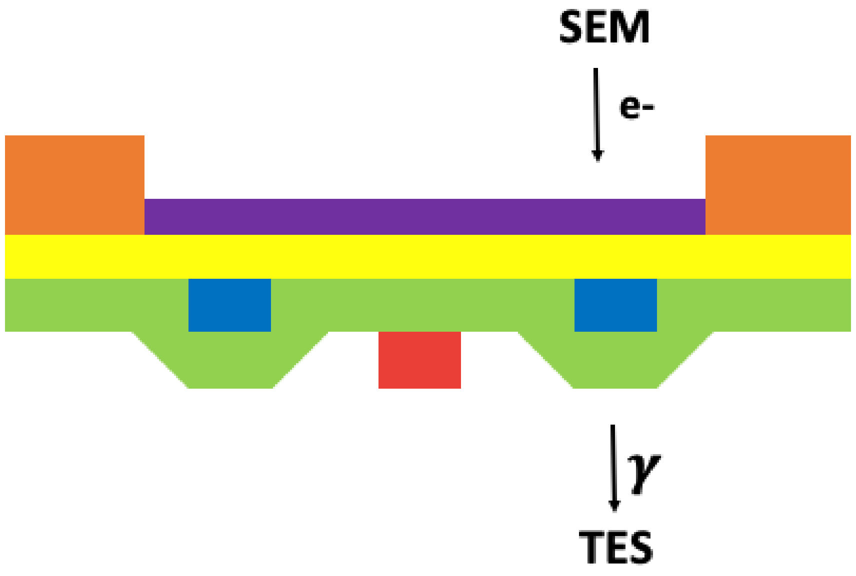

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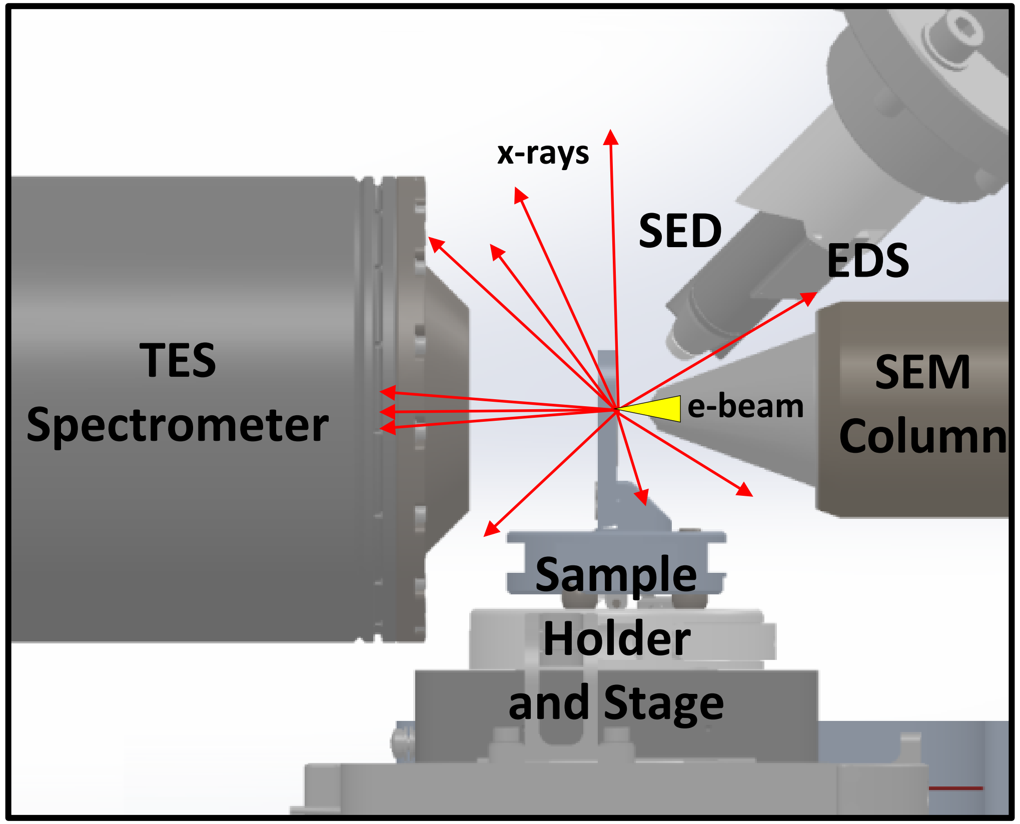

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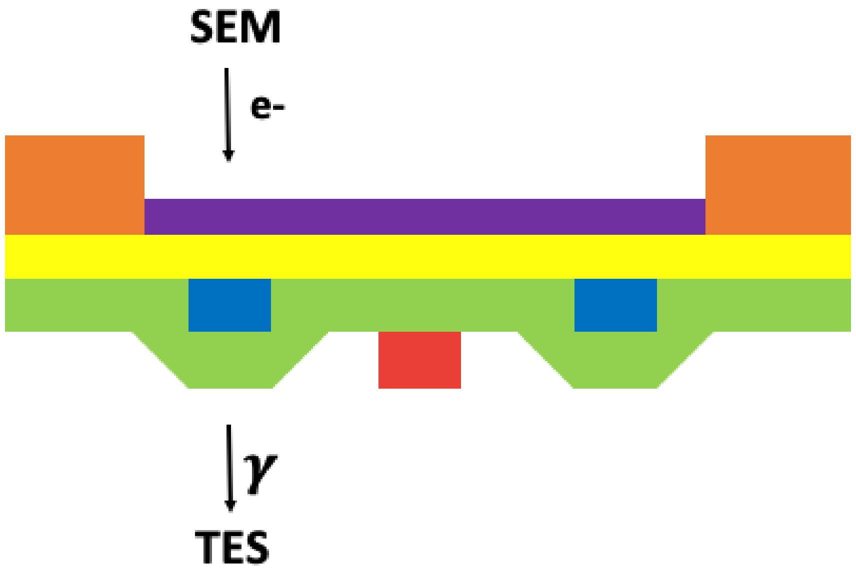

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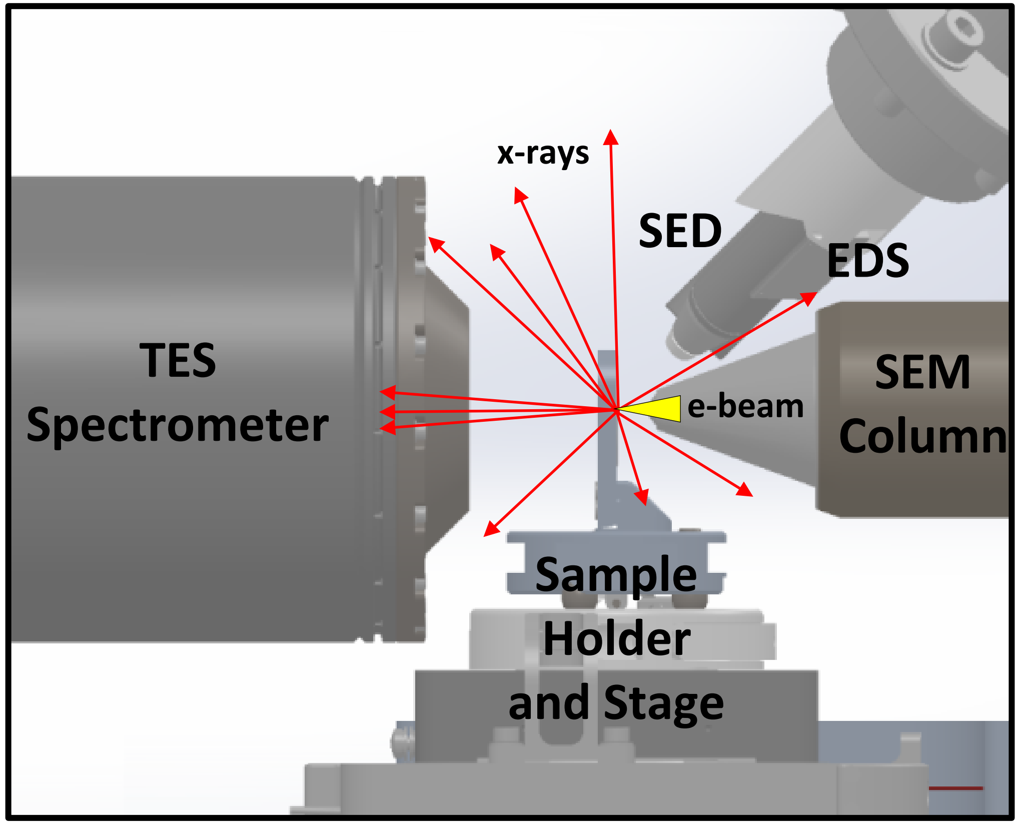

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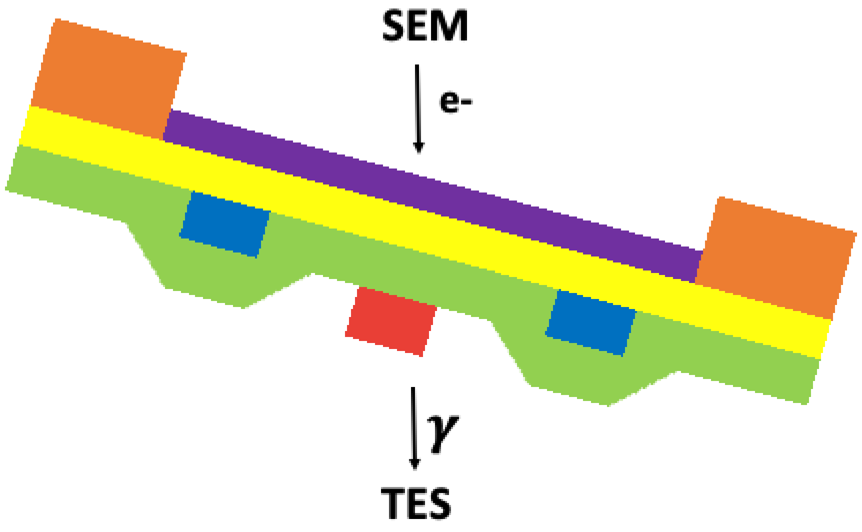

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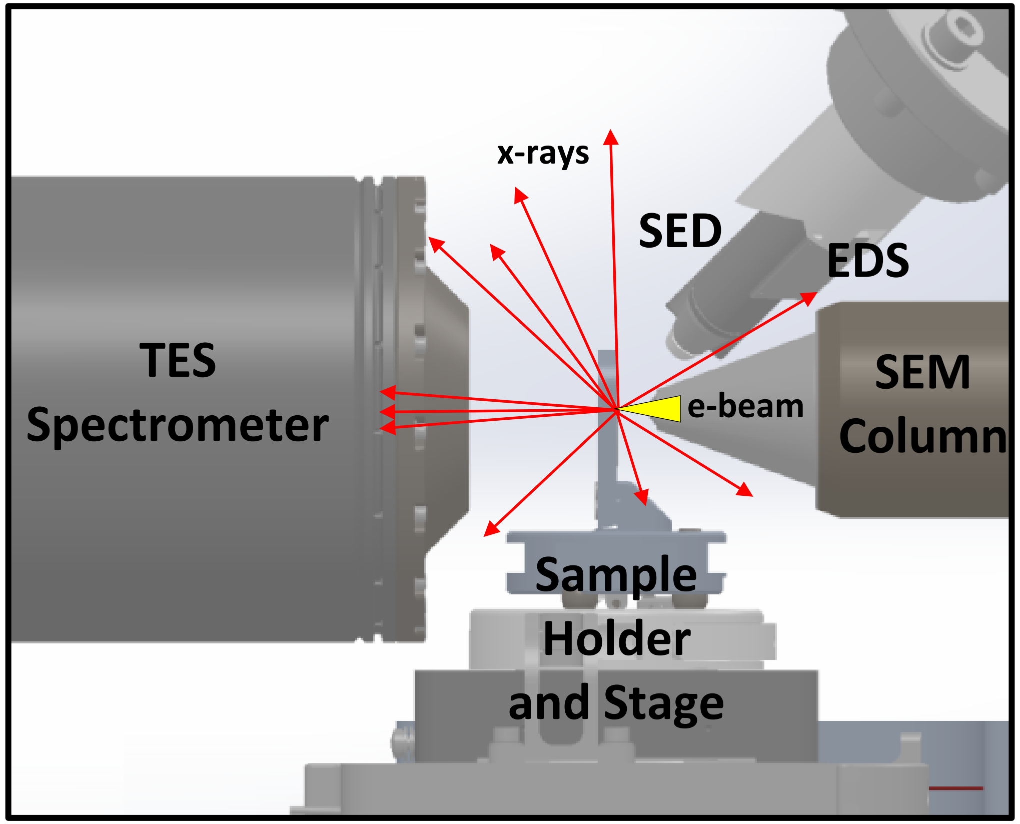

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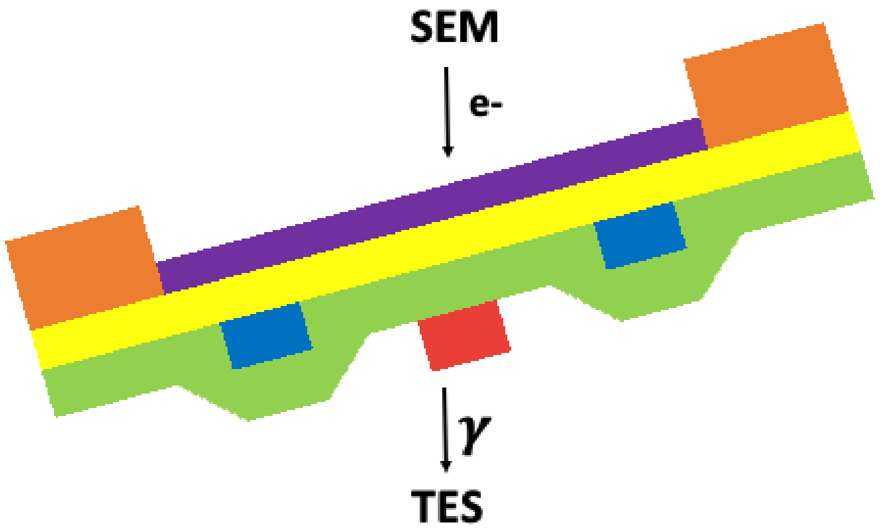

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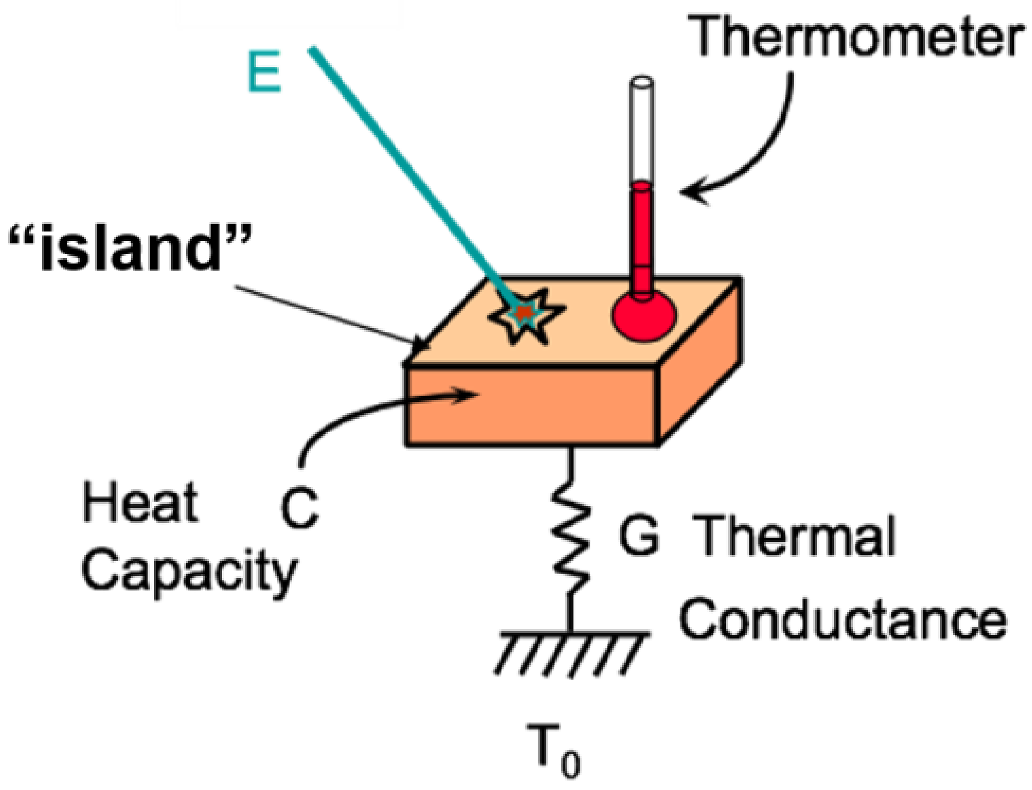
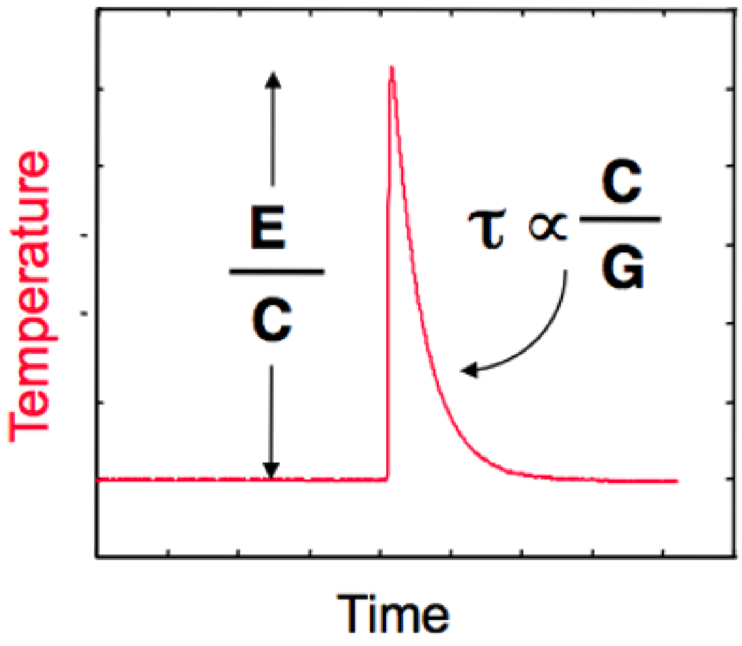
Microcalorimeter principles of operation



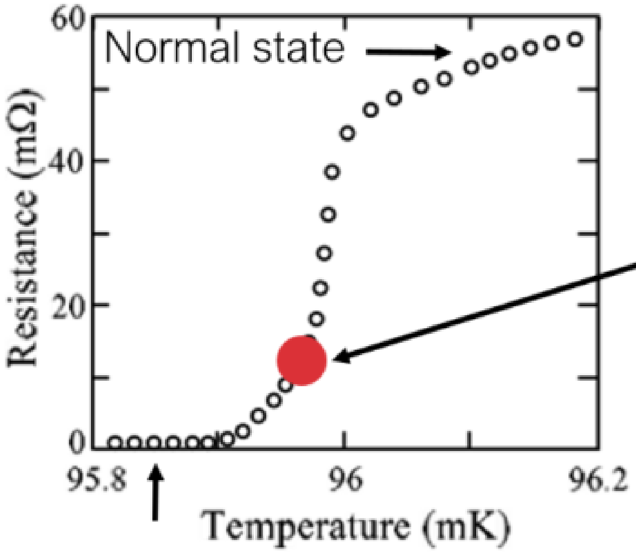


Temperature ~100 mK

Thermometer = Transition-Edge Sensor (TES)

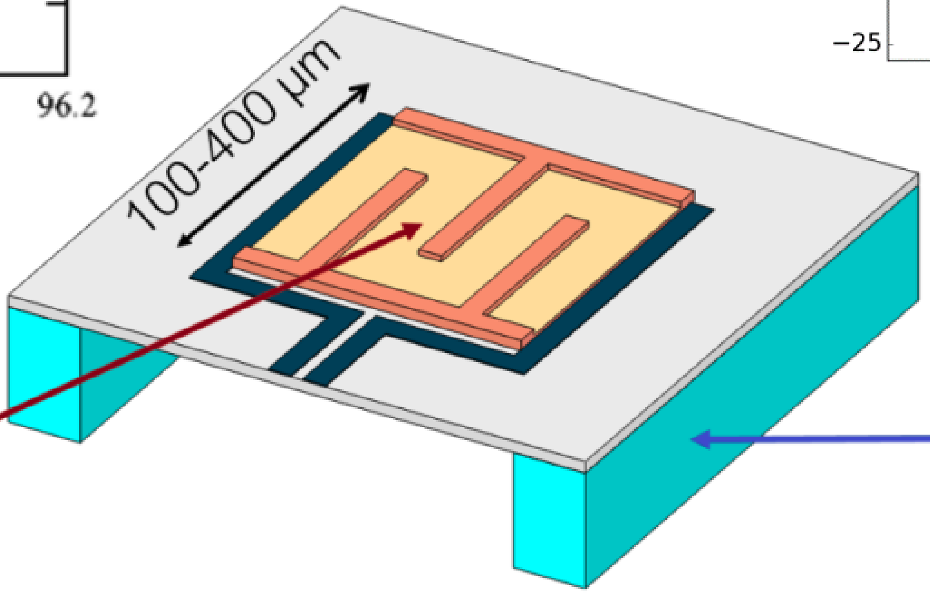
$\delta E \sim \sqrt{4k_B T^2 C}$ ~1 eV

TES physics

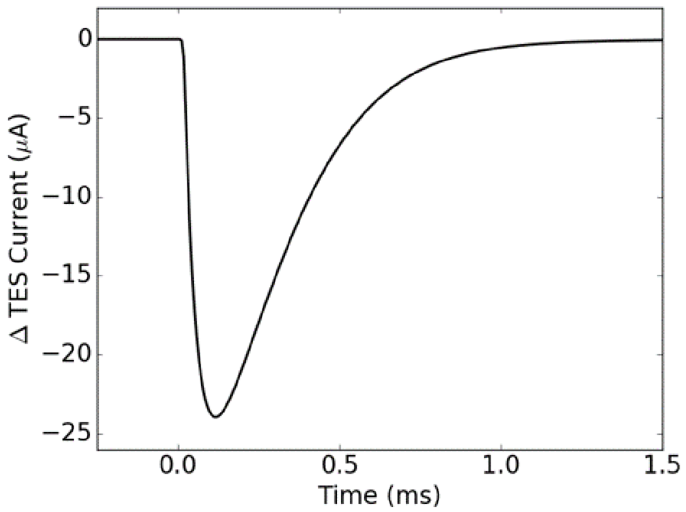


Voltage-bias
Onto Transition

Superconducting
State



Tc ~100 mK

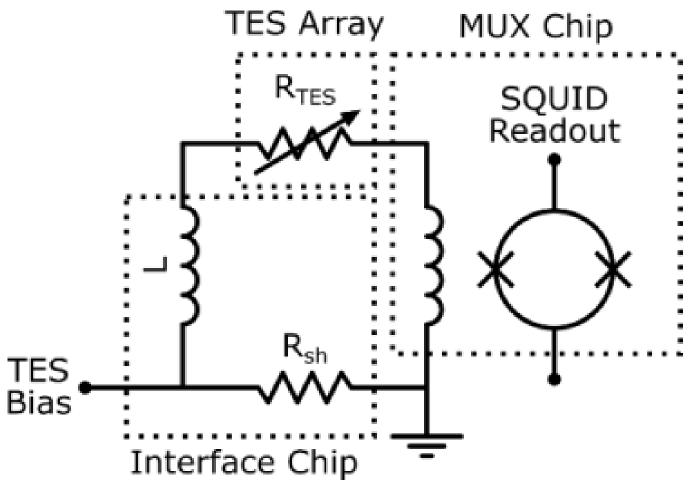


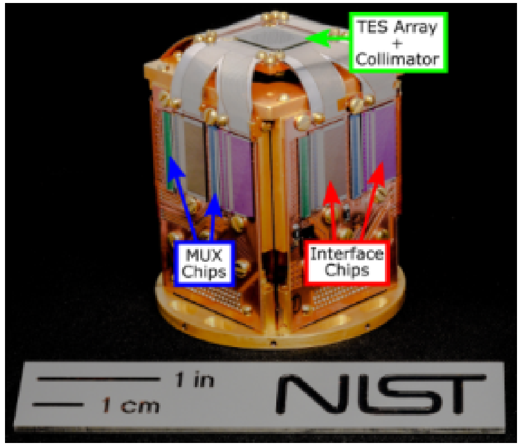
Absorber coupled to TES to detect high energy x-rays, decoupled optimizations!

Tbath < 100 mK

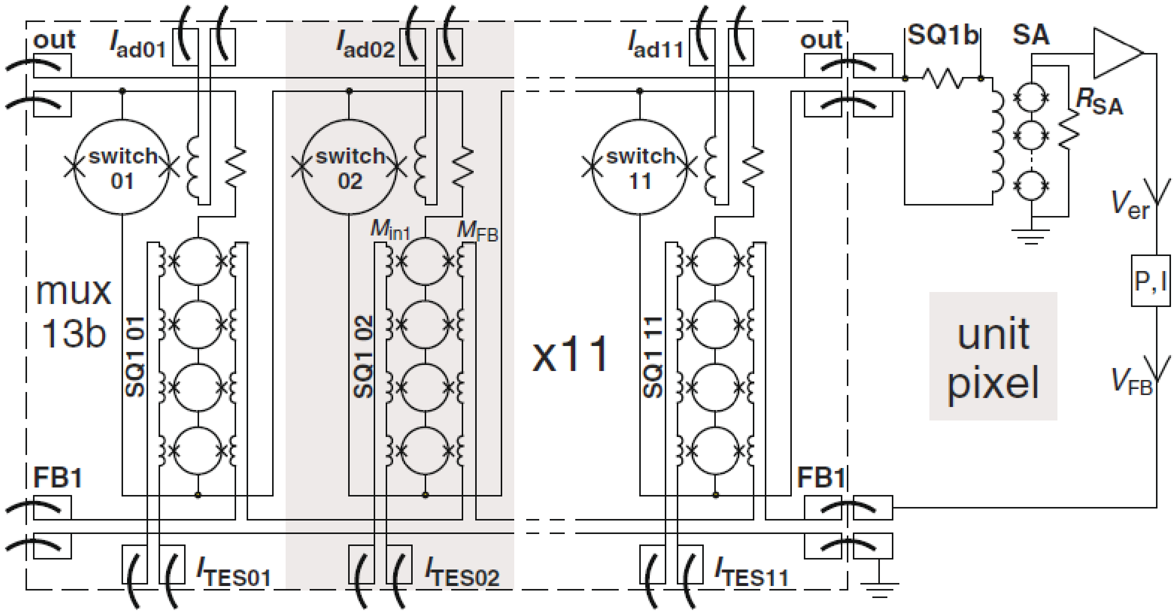
Readout electronics and multiplexing

Often read out and multiplexed using superconducting quantum interference devices (SQUIDs)



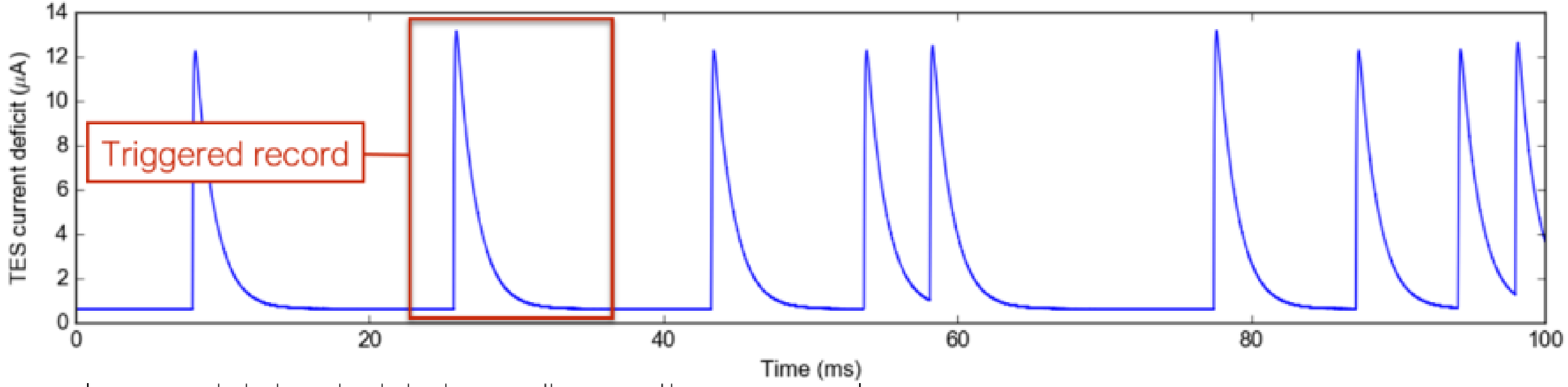


Adapted from Szypryt et al., 2019, https://doi.org/10.1063/1.5116717

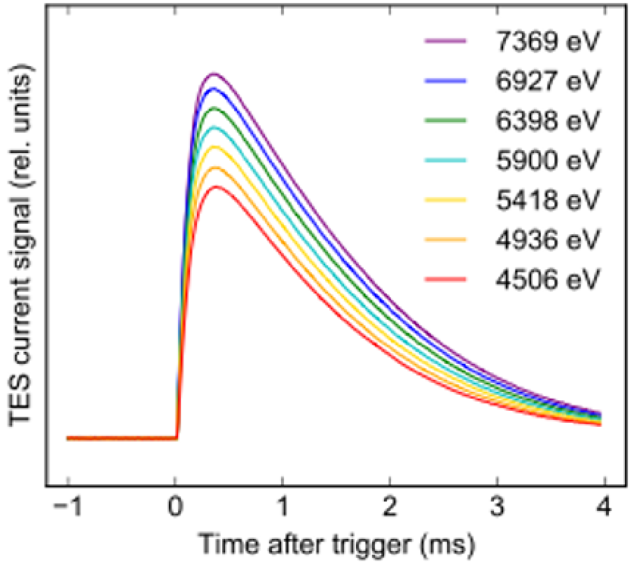


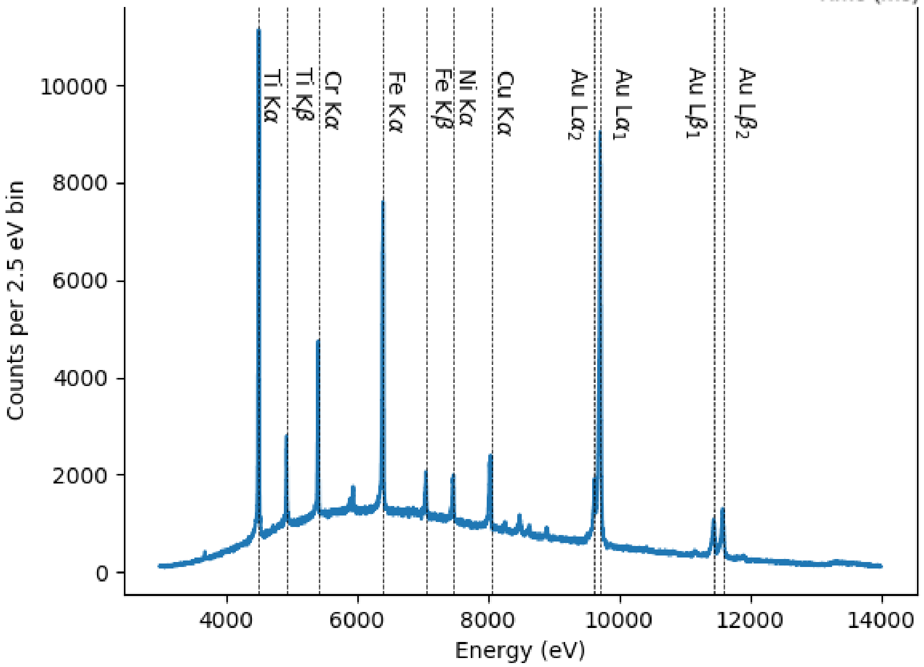
Time-division multiplexing (TDM) scheme, in which 'rows' of detectors are addressed sequentially, and multiple 'columns' of detectors are read out in parallel. Typical array sizes of 200 or more TES microcalorimeters!

Data acquisition and analysis

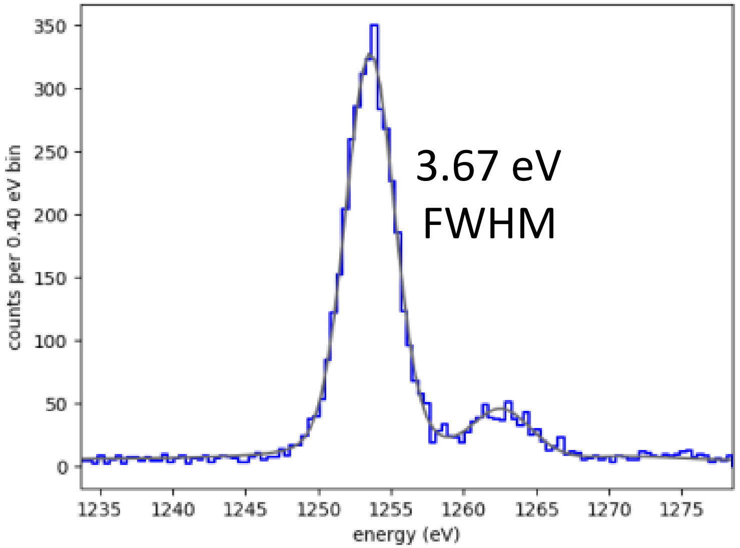


Pulse height estimates x-ray energy





Broadband spectrum of Au and Ti samples in stainless steel chamber



Mg Kα Fit

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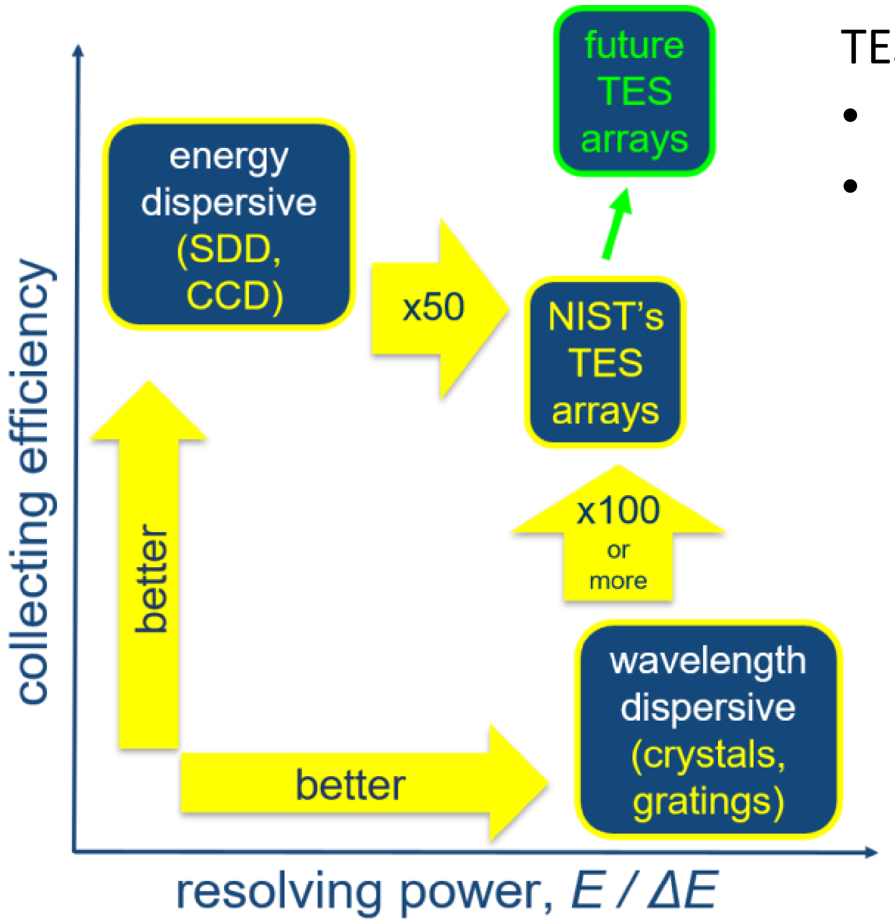
Advantages over traditional x-ray detectors



TES x-ray calorimeters are interesting because of their combination of:

- Collection efficiency comparable to energy dispersive detectors
- Energy resolution comparable to wavelength dispersive detectors

<u>Most useful so far for:</u>

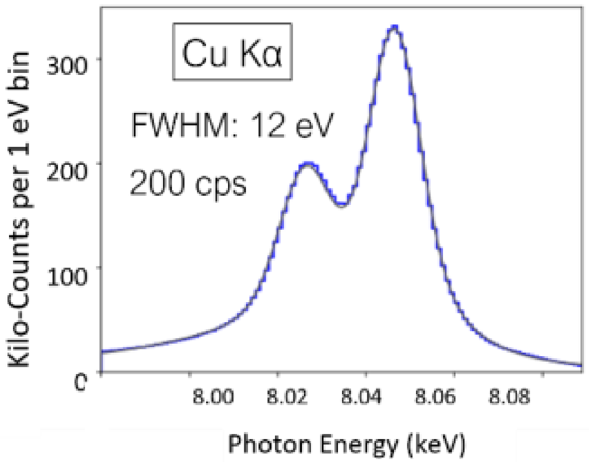
- Photon-starved experiments
  - Dilute samples
  - Time-resolved
- Broadband synchrotron measurements
- Tabletop spectroscopy (line metrology, EBIT, chemical/nuclear composition analysis, etc.)
- Radiation-sensitive samples

TOMCAT 240-pixel spectrometer

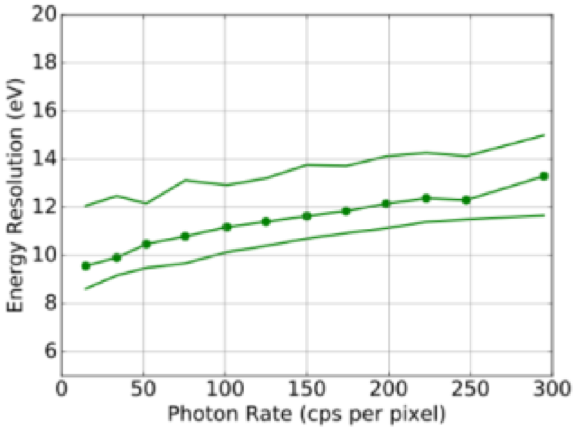
- Uniquely optimized for high count rates rather than purely energy resolution
- Single photon detection of x-rays up to about 12 keV.
- Measured energy resolution of 12 eV at Cu Kα (8 keV) and rates of 200 counts per pixel per second
- ~1 μs x-ray arrival time resolution

Cryostat integrated with SEM

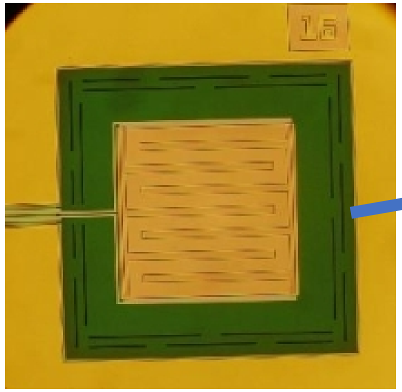
Cu Kα fit

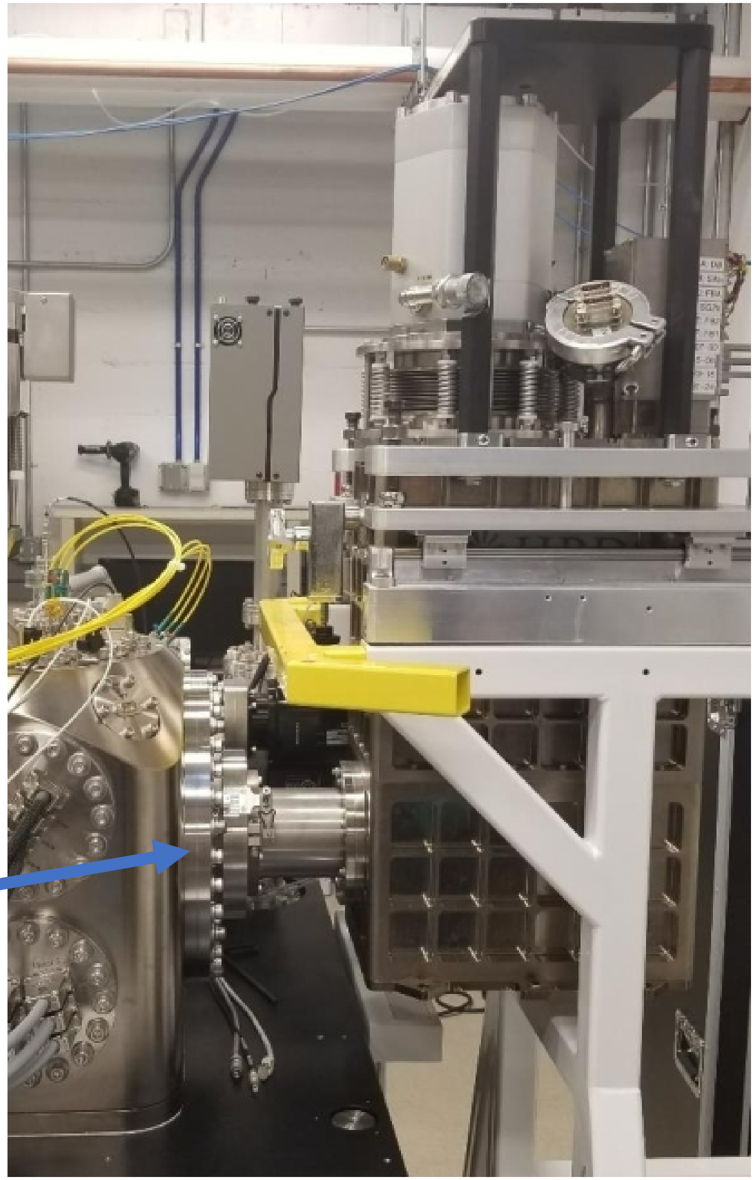


ΔE vs. Count Rate



Single TES microcalorimeter





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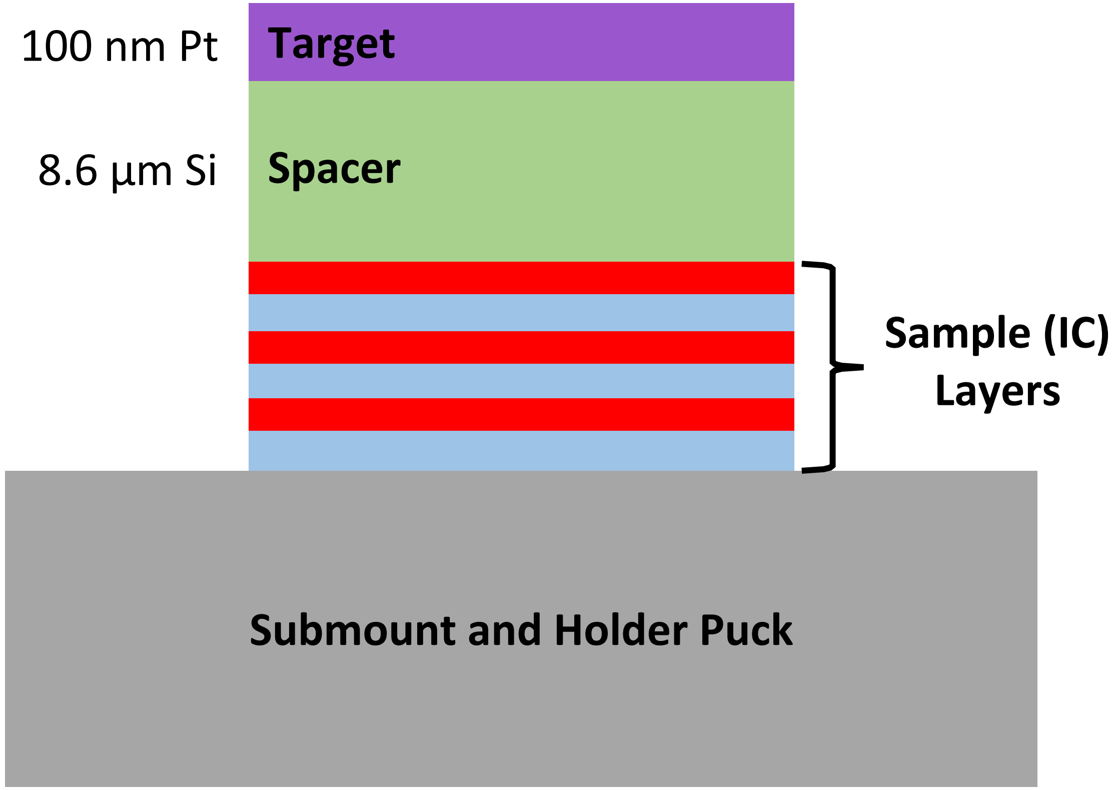
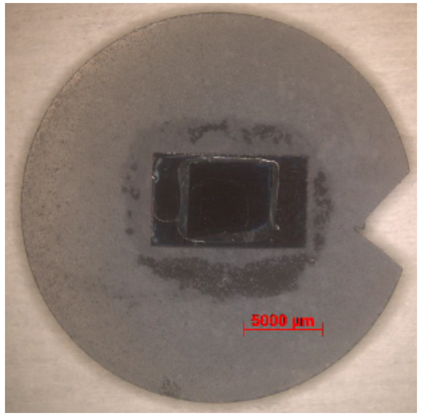
Sample preparation

- In first proof of concept measurement, started with IC at the 130 nm technology node. Sample consists of 3 via and 3 metal layers.
- Thinned backside Si of sample down reduce x-ray attenuation. Remaining thickness (8.6 µm) set to match desired magnification.
- Single metal slab target layer, using 100 nm Pt to get good contrast of expected circuit features.
- Also using 60 um glassy carbon submount for structural support and windowed graphite puck for sample holder mounting



Dummy sample frontside



Backside

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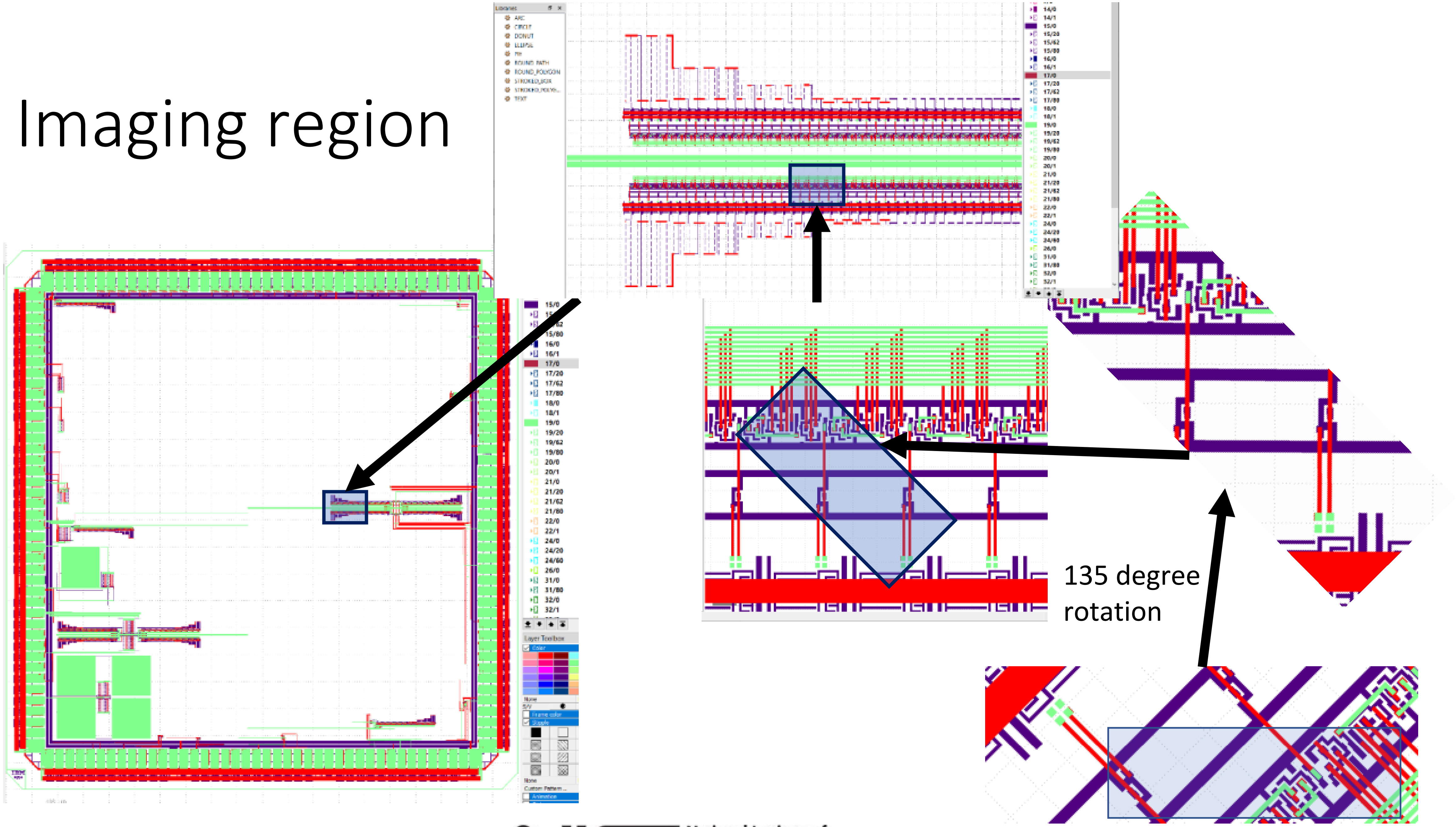
Imaging region



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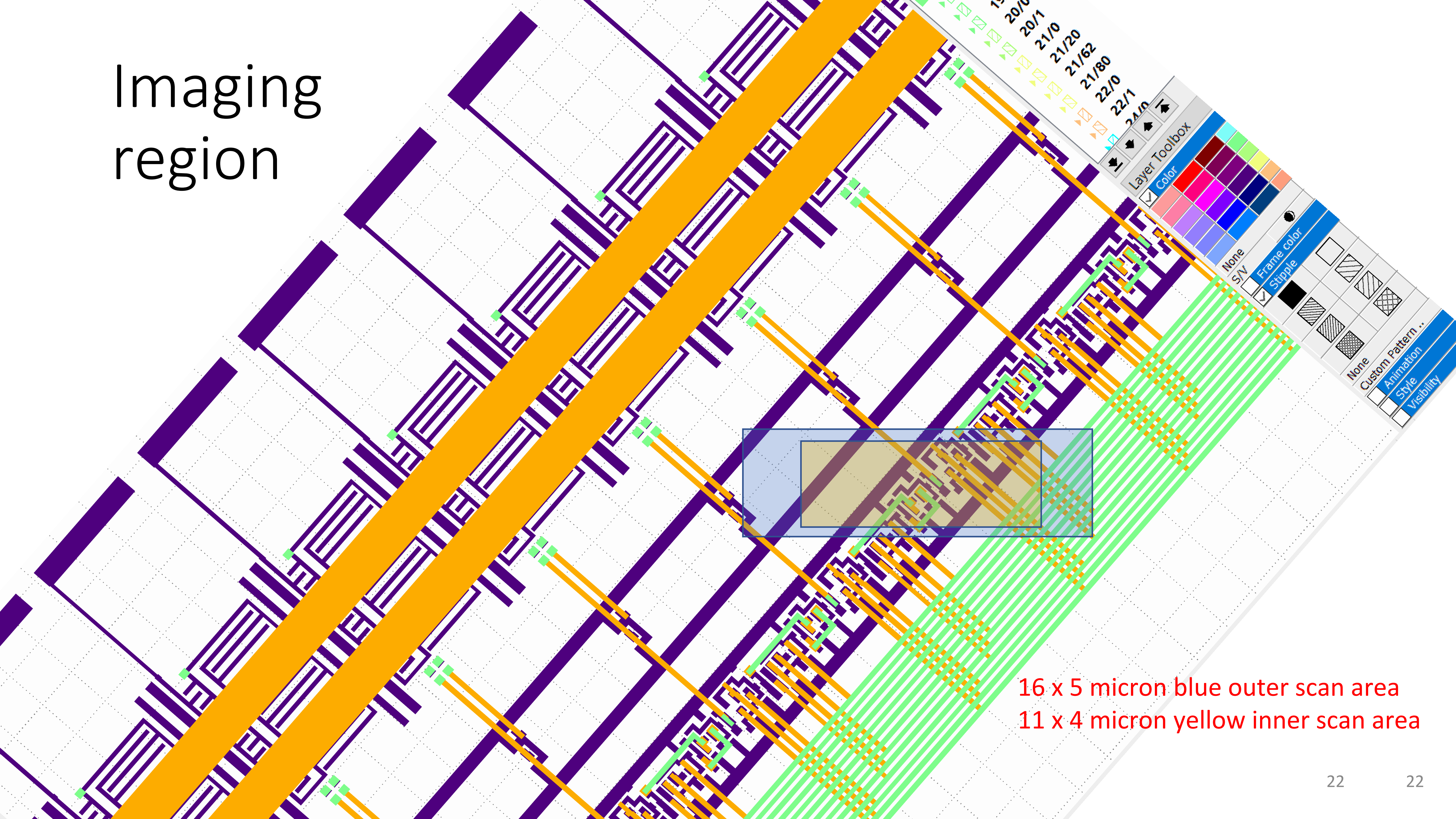
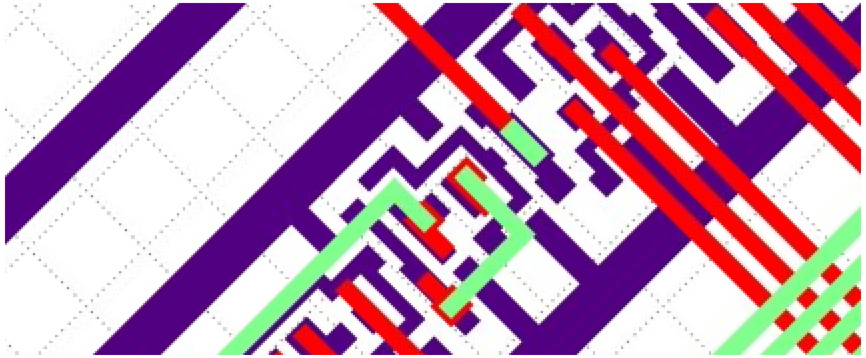


16 x 5 micron blue outer scan area
11 x 4 micron yellow inner scan area

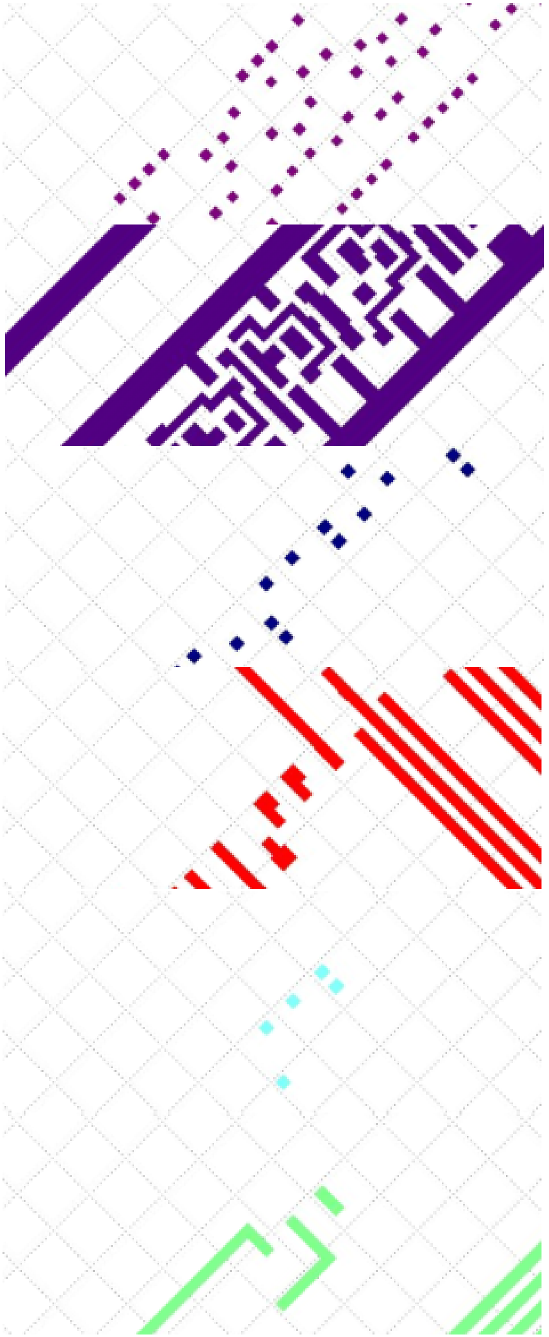
22

Expected structure



3 metal layers connected by vias
Minimum feature in IC = 160 nm vias

First via layer



Metal layer 1

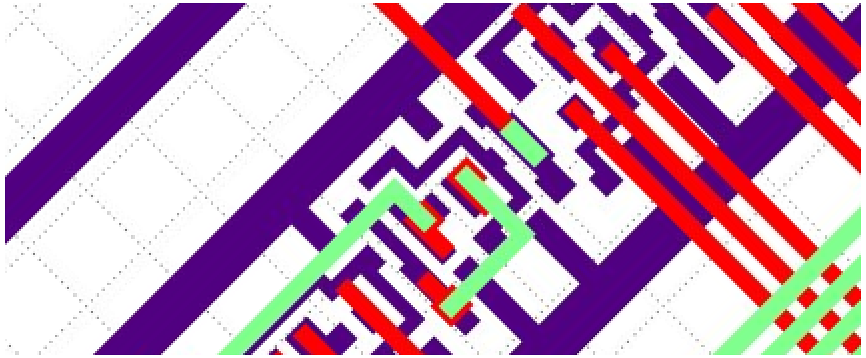
Via layer

Metal layer 2

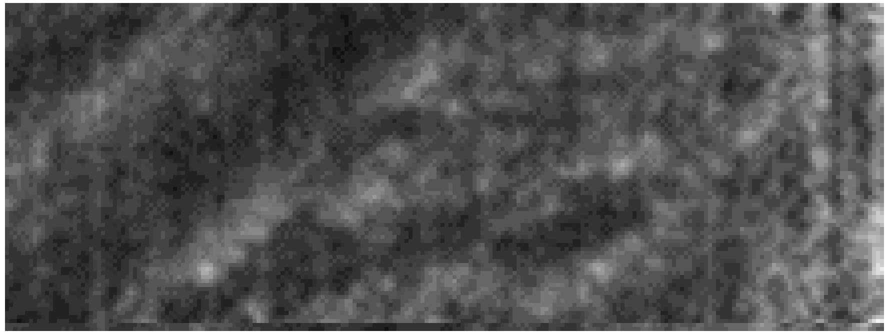
Via layer

Metal layer 3

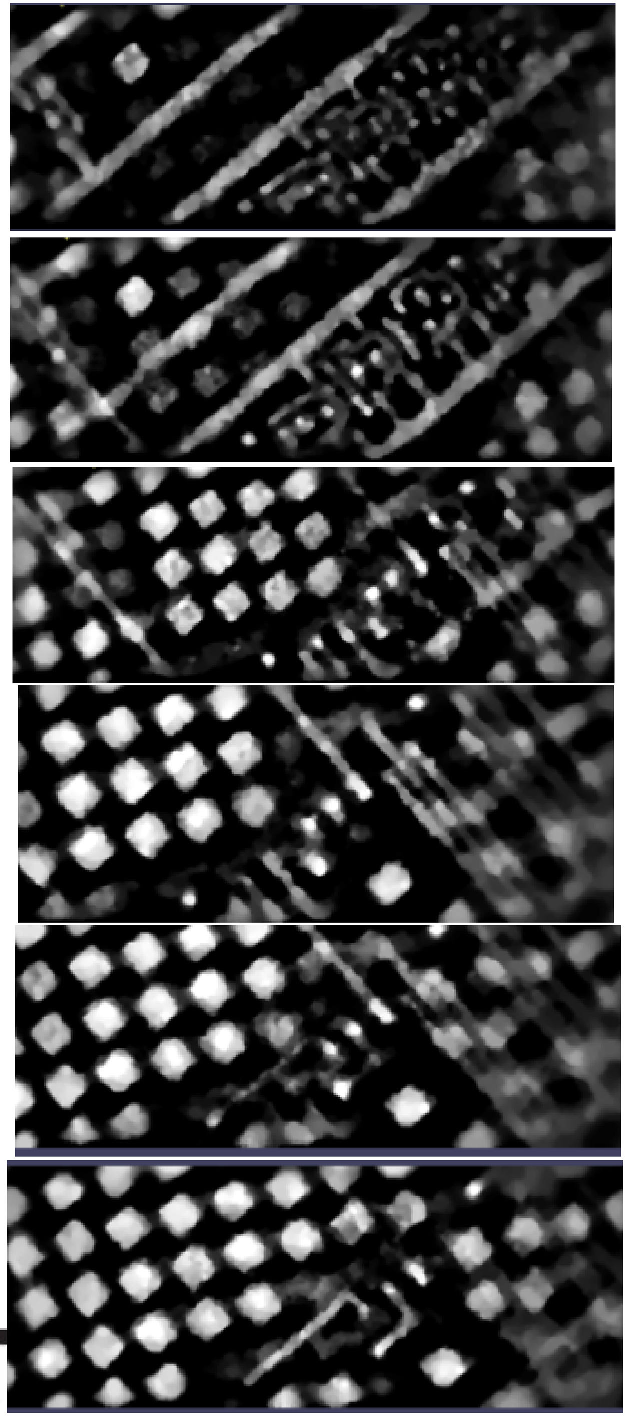
Reconstructions

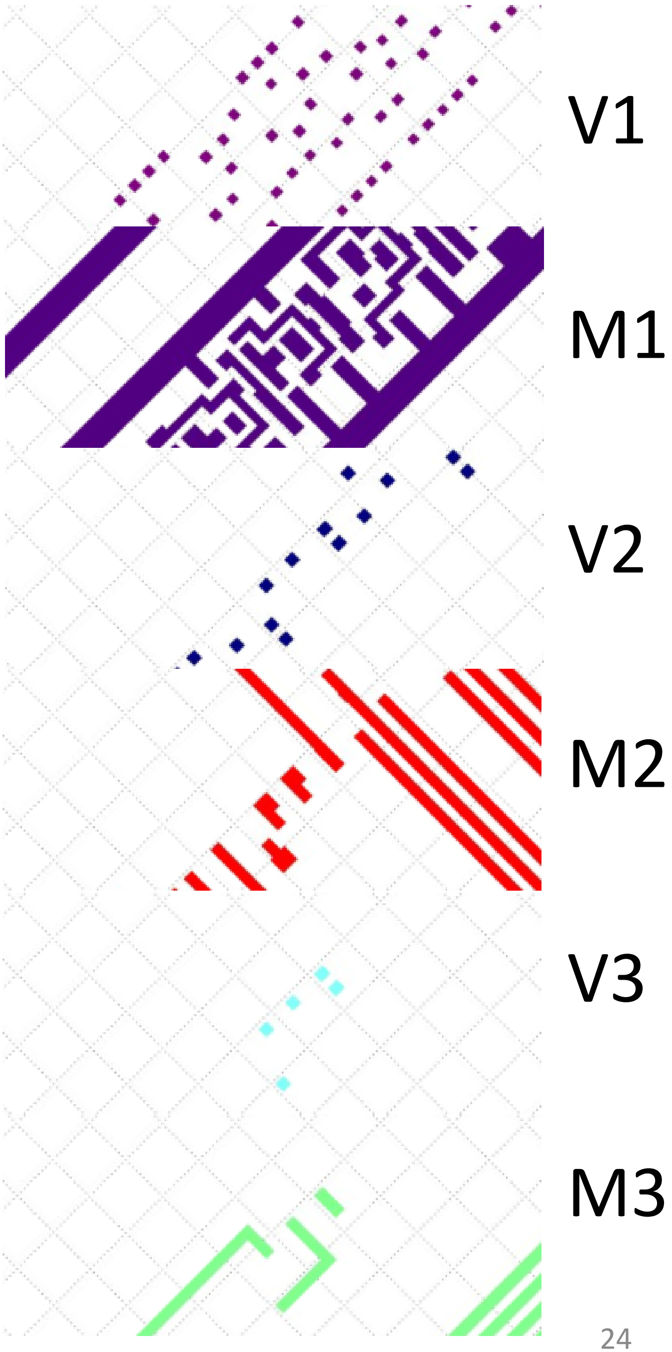


3 metal layers connected by vias
Minimum feature in IC = 160 nm vias

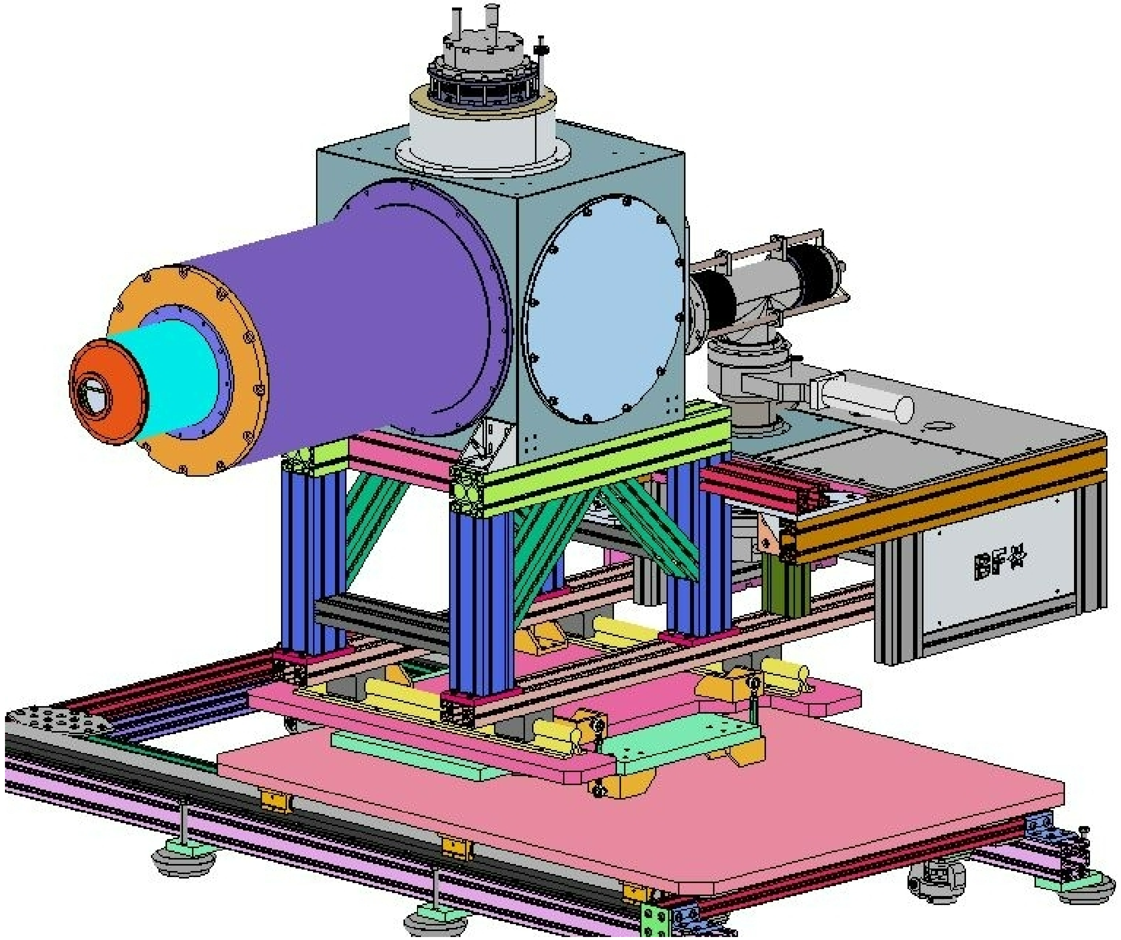


CMP fill (Cu diamonds) not shown in GDS
40x40x80 nm voxels
Lateral resolution sufficient to resolve all features





3,000-pixel TES instrument

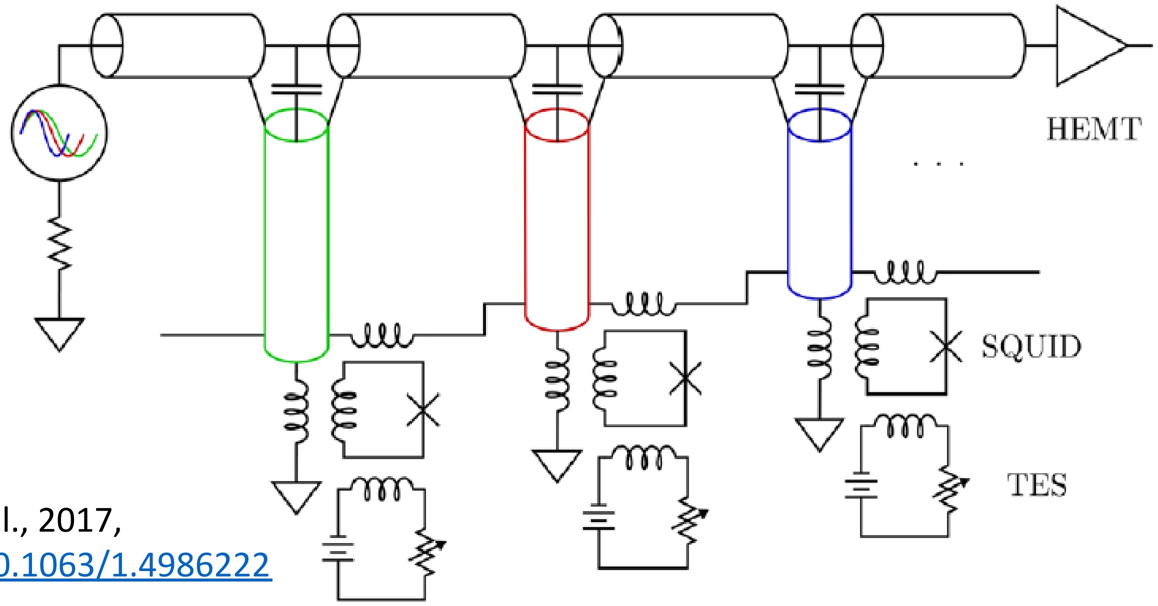


Primary improvements:

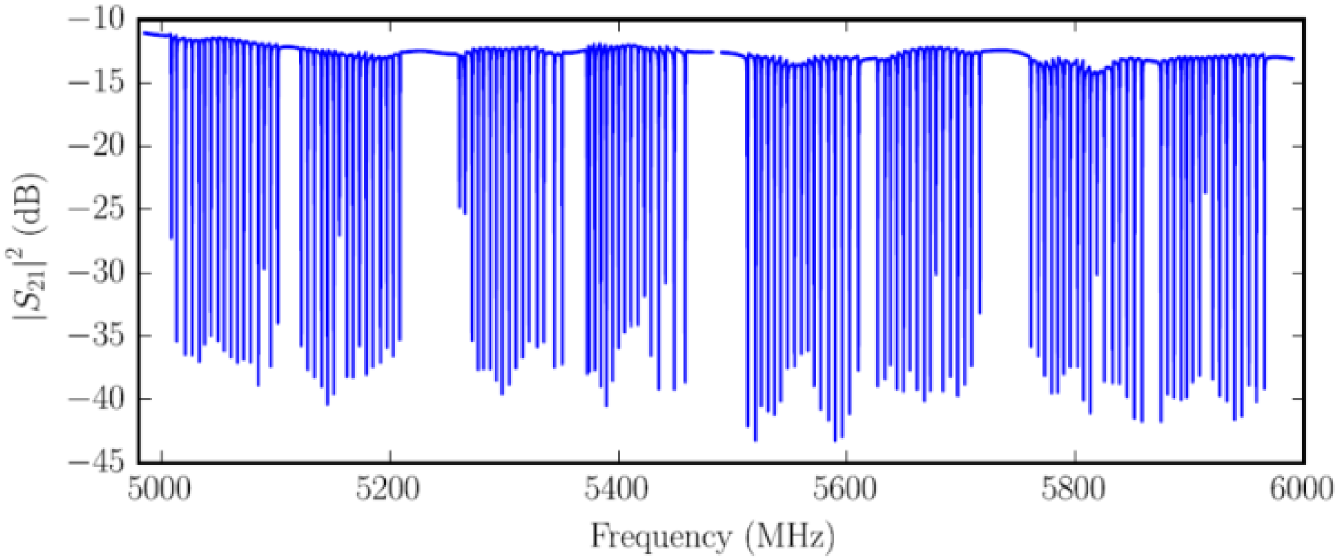
- 3000 TES x-ray microcalorimeters designed to operate 4-10x faster than the current detectors.
- Microwave SQUID multiplexer readout, which enables the detector count and speed increases.
- Dilution refrigerator to support increased heat loads of larger detector/readout array, continuous operation.
- Modular 'microsnout' detector & readout assemblies for simpler build up of the array, scalable design.

Detector speed and microwave SQUID multiplexer readout

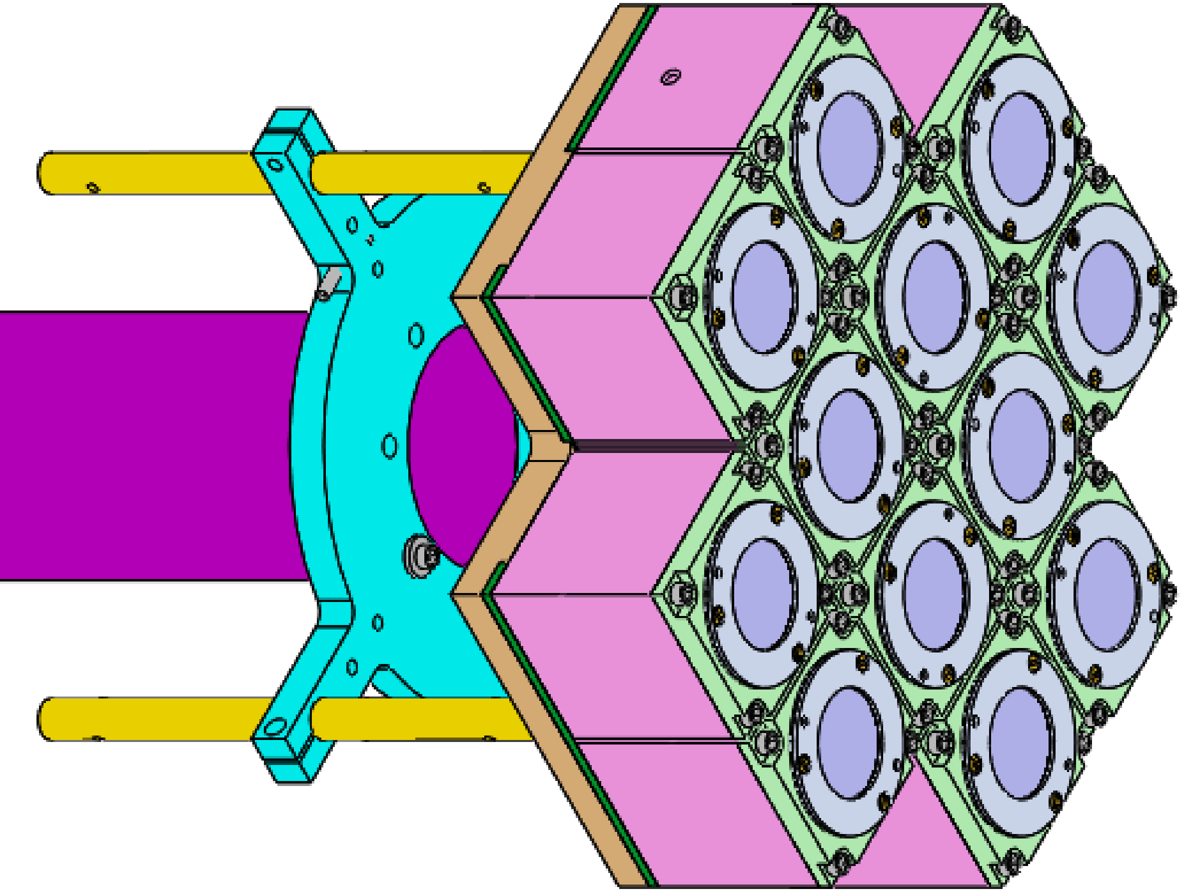
- Increasing detector speed by adjusting heat capacity and thermal conductivity, aiming for a count rate limit of ~1000 cps/detector before output rate starts becoming saturated.
- Using 1 MHz resonator width, enough bandwidth to account for increased detector speed.
- 6 independent readout channels, each with 4 GHz bandwidth, 500 detectors per readout channel.

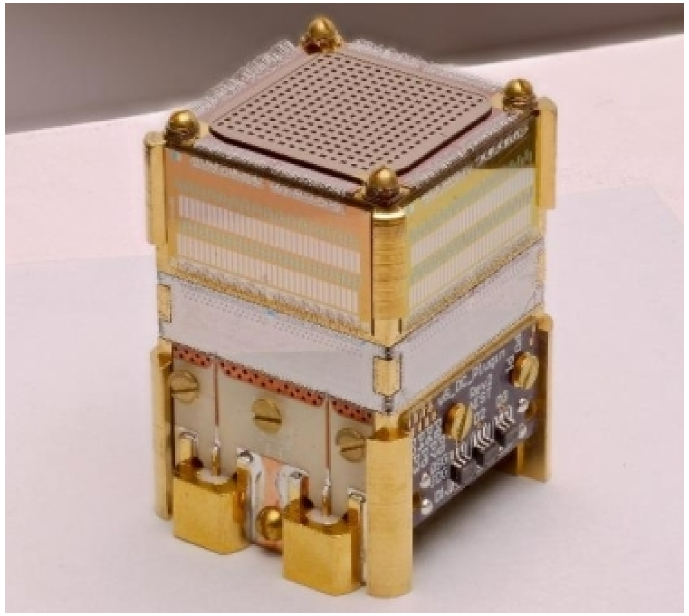


J. A. B. Mates et al., 2017, https://doi.org/10.1063/1.4986222



'Microsnout' design

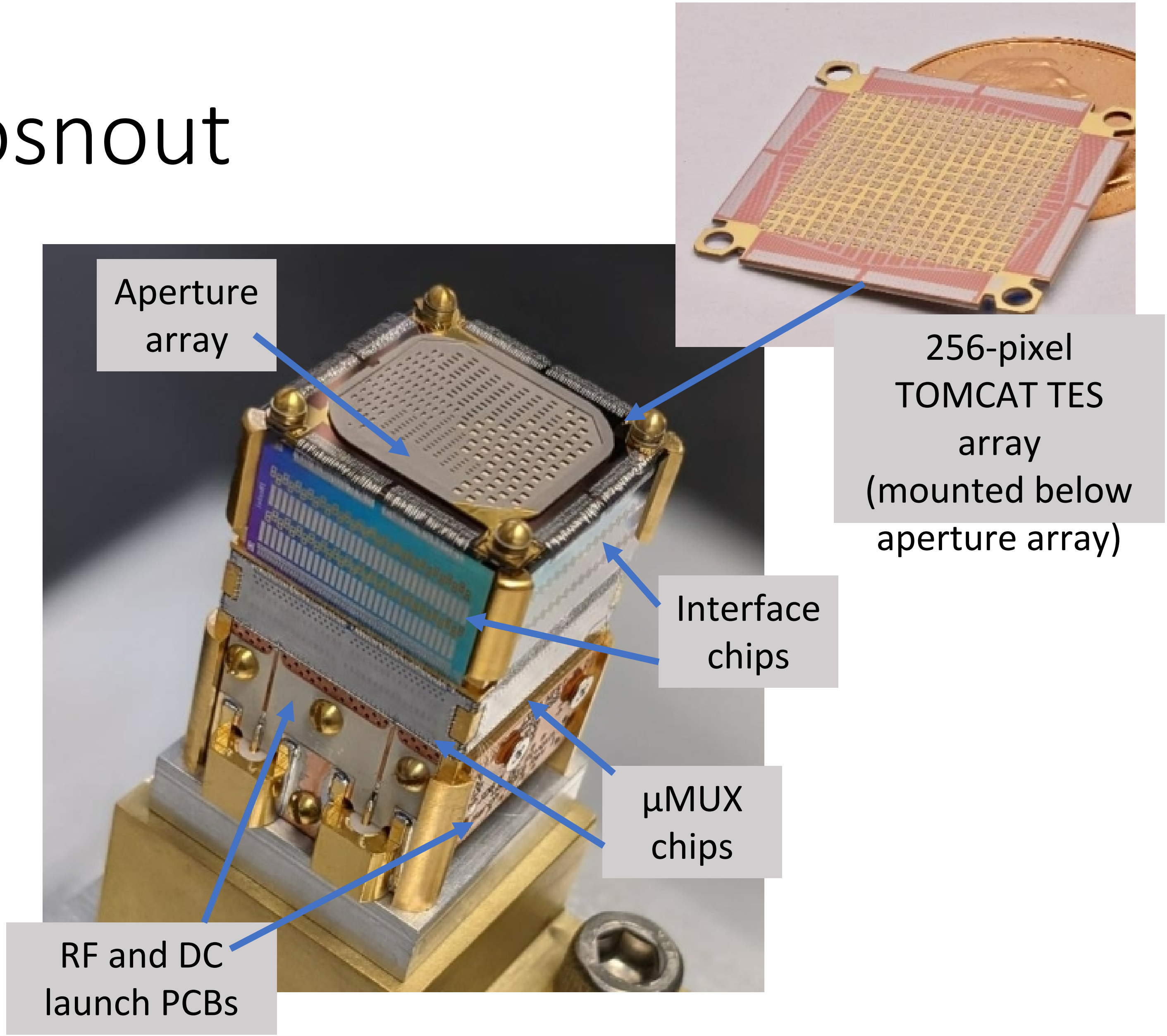




- Each microsnout is designed to house 250 TES x-ray microcalorimeters and associated RF-SQUID readout circuits.
- Modular design, can easily scale the number of microsnouts in the instrument, as limited by cryostat/SEM space constraints.
- Nominal design for this instrument includes 12 microsnouts = 3000 detectors.

Anatomy of a microsnout

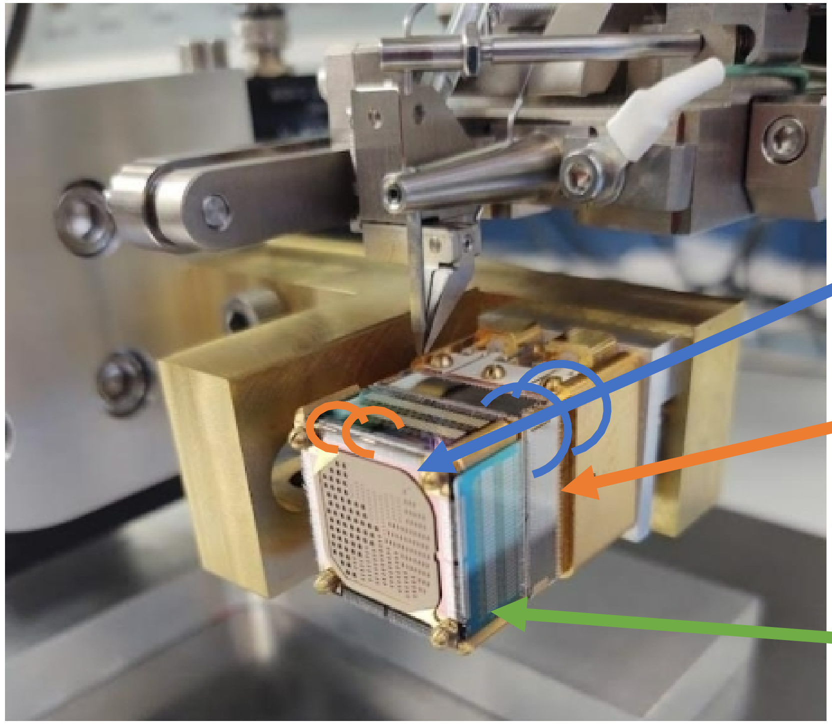
- Each microsnout package contains the following chips:
  - 4x µMUX chips
  - 4x interface chips
  - 1x detector array
  - 1x aperture array
  - RF launch board
  - PCB for detector bias and flux ramp signals
  - 1,000+ wire bond connections



Readout connections

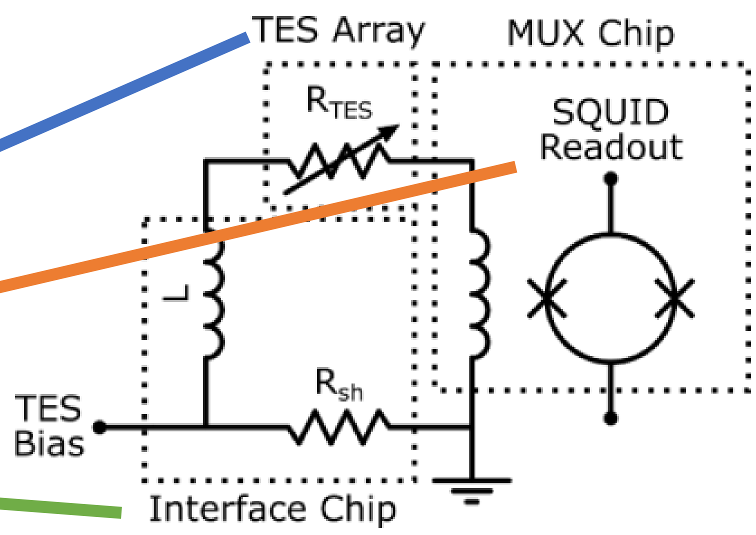
Complete 12 microsnout system will use:

- 6x RF line pairs
- 1x flux ramp line
- 48x detector bias lines

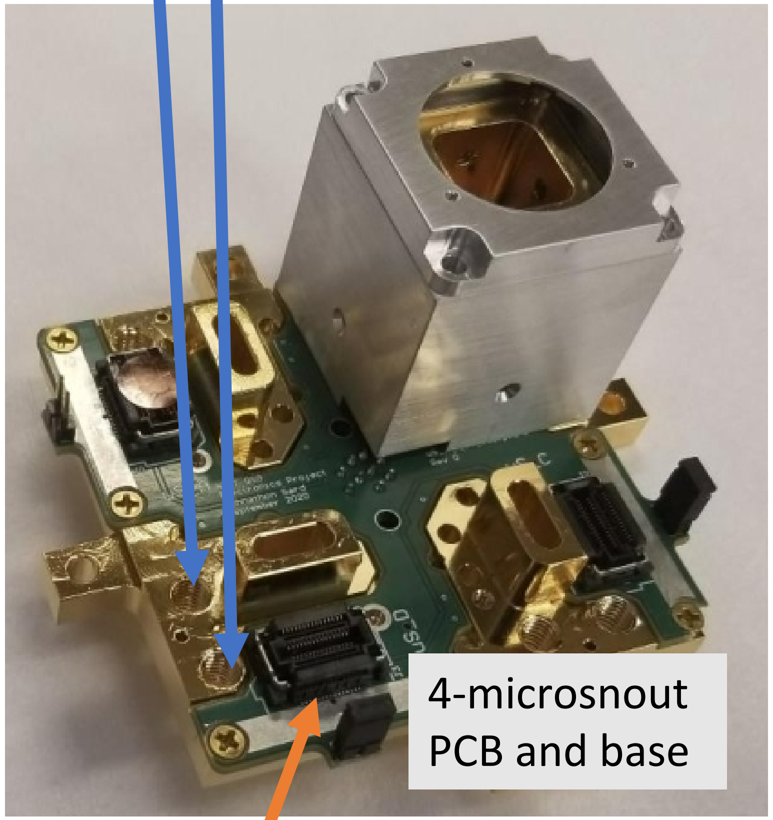


Around the corner wire bonding

Single TES circuit diagram



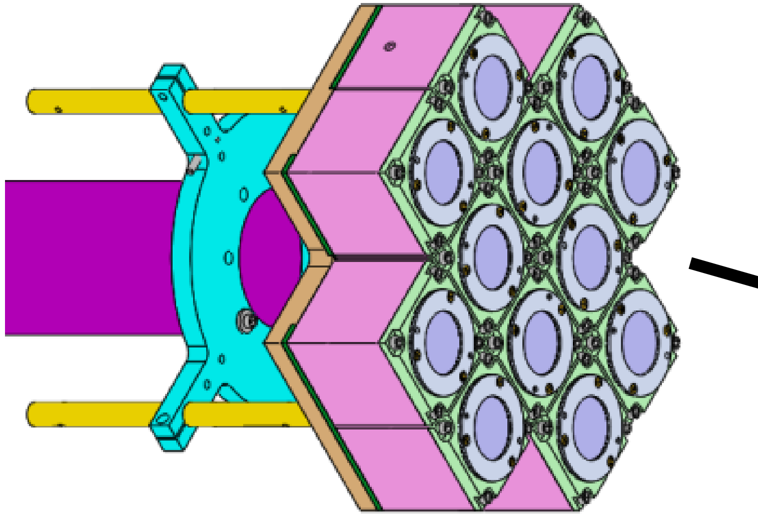
SMP connectors for RF lines



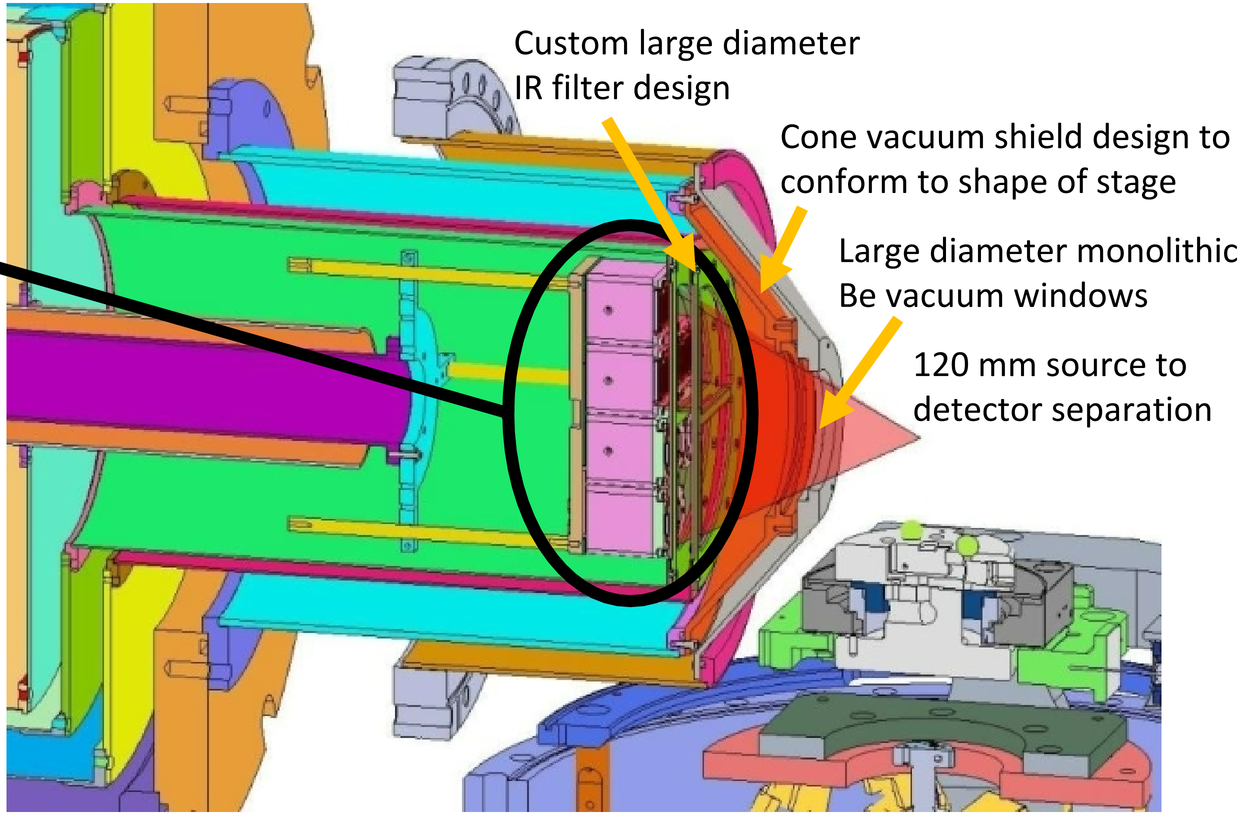
30-pin socket strip connector for DB and FR

Cryostat/SEM mechanical design

12-microsnout assembly

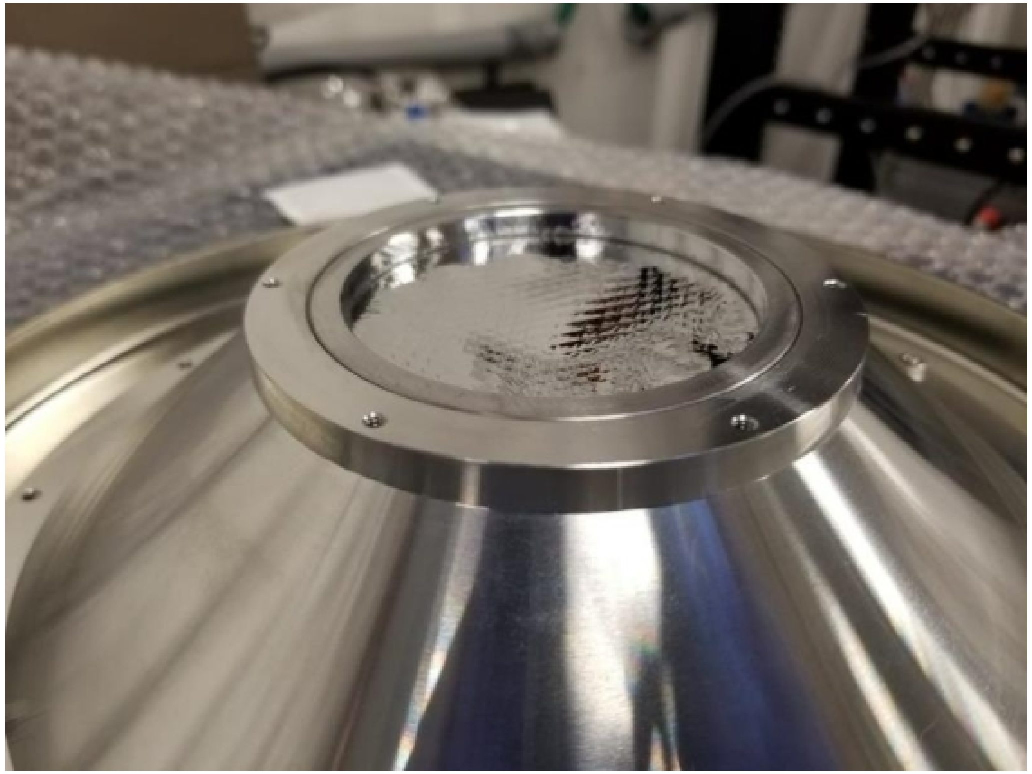


- Developed vacuum shell and IR radiation and magnetic field shields that can accommodate 12 microsnouts.
- Cone shape to match the shape of the SEM stage, minimize distance between the x-ray source and the detectors to maximize solid angle.

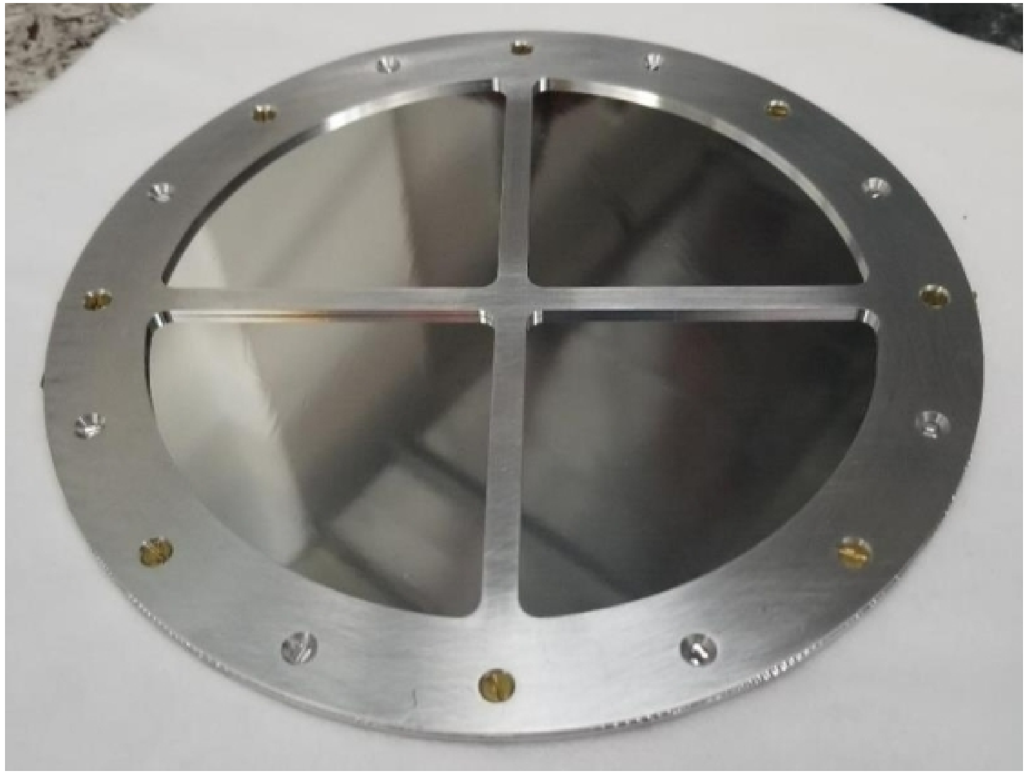


Cryostat and SEM chamber internal views

Windows and filters



Al with C fiber mesh backing vacuum windows already delivered, to be used prior to receiving final Be windows.



Robust IR filter containing ~100 nm of Al and 1 mil Kapton backing, high transmission for x-ray energies important for TOMCAT.

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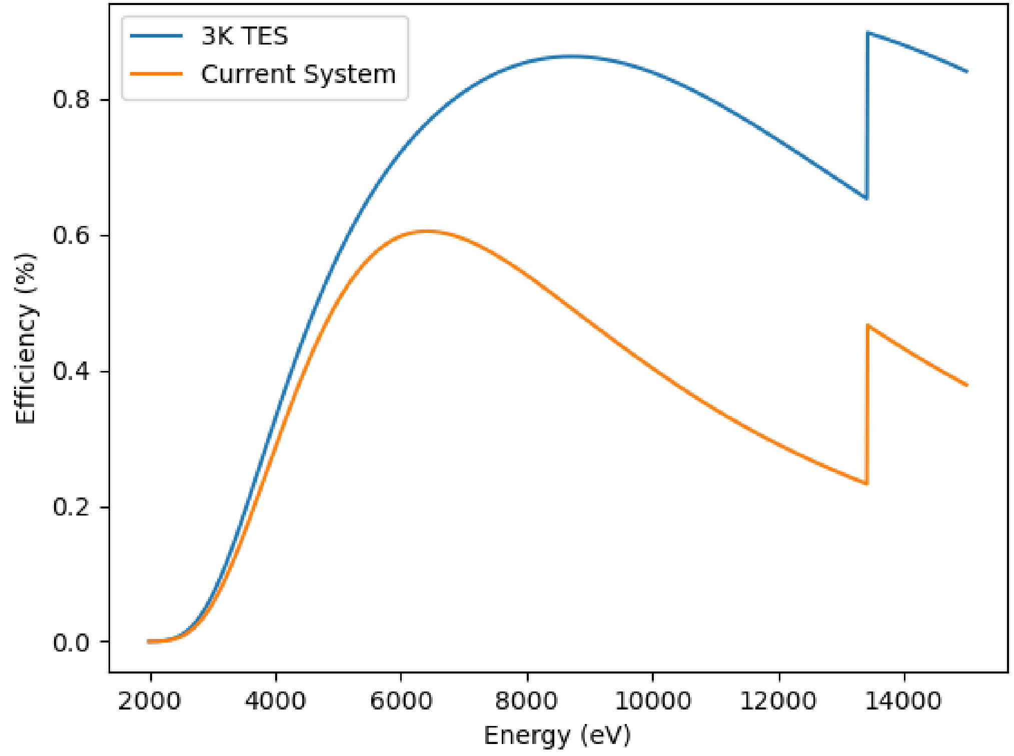
Expected imaging speed improvements

- Increase due to larger array size: $\mathbf{256 \times 12/240 = 12.8}$
- Increase due to larger absorber area: $(398 \times 528)/(350 \times 350) = \mathbf{1.7}$
- Increase due to thicker absorbers and new windows/filters = **2.0 near 10 keV (Pt Lα)**
- Reduction due to increased separation between detectors and source: $\sim(75/120)^2 \approx \mathbf{0.4}$

Expected imaging speed increase with existing SEM: $\sim\mathbf{20}$.

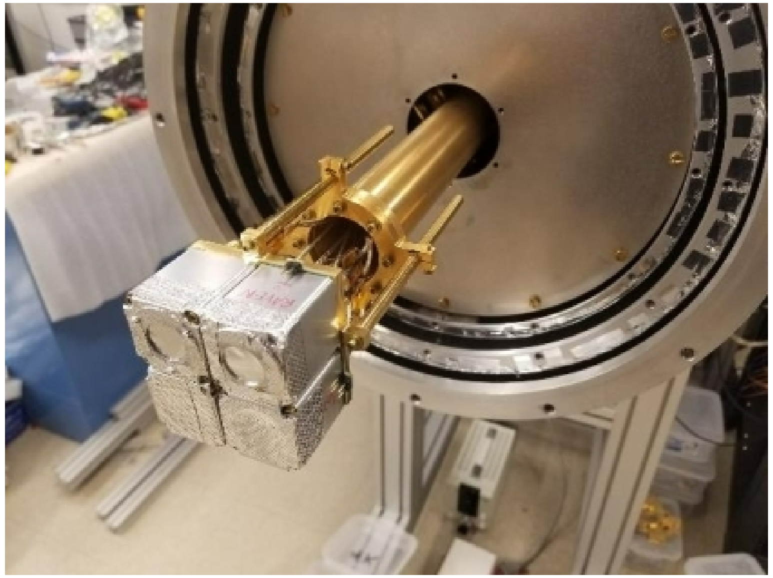
We note that the detector speed has been increased to accept even higher x-ray rates, so additional gains can still be achieved through an electron source strength increase of ~3 or more

Efficiency comparison including filters and absorber

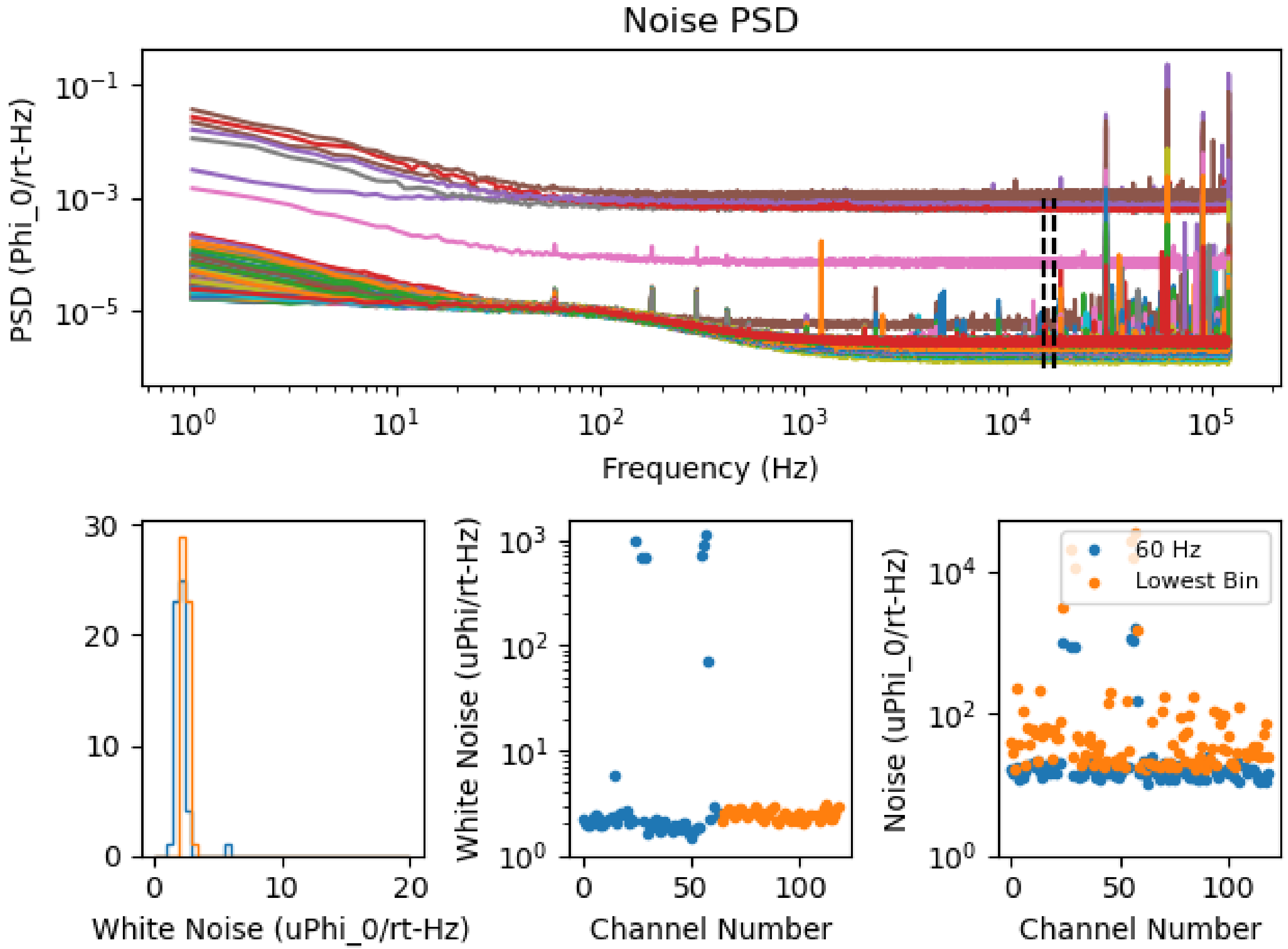


Current status

- Cryostat mechanical design and buildout has been completed! Began integration with SEM.
- Finished building out 4 microsnout subarray (1000 pixels).
- Performing tomography demo with 1000-pixel system. Preliminary results expected for ASC 2022.

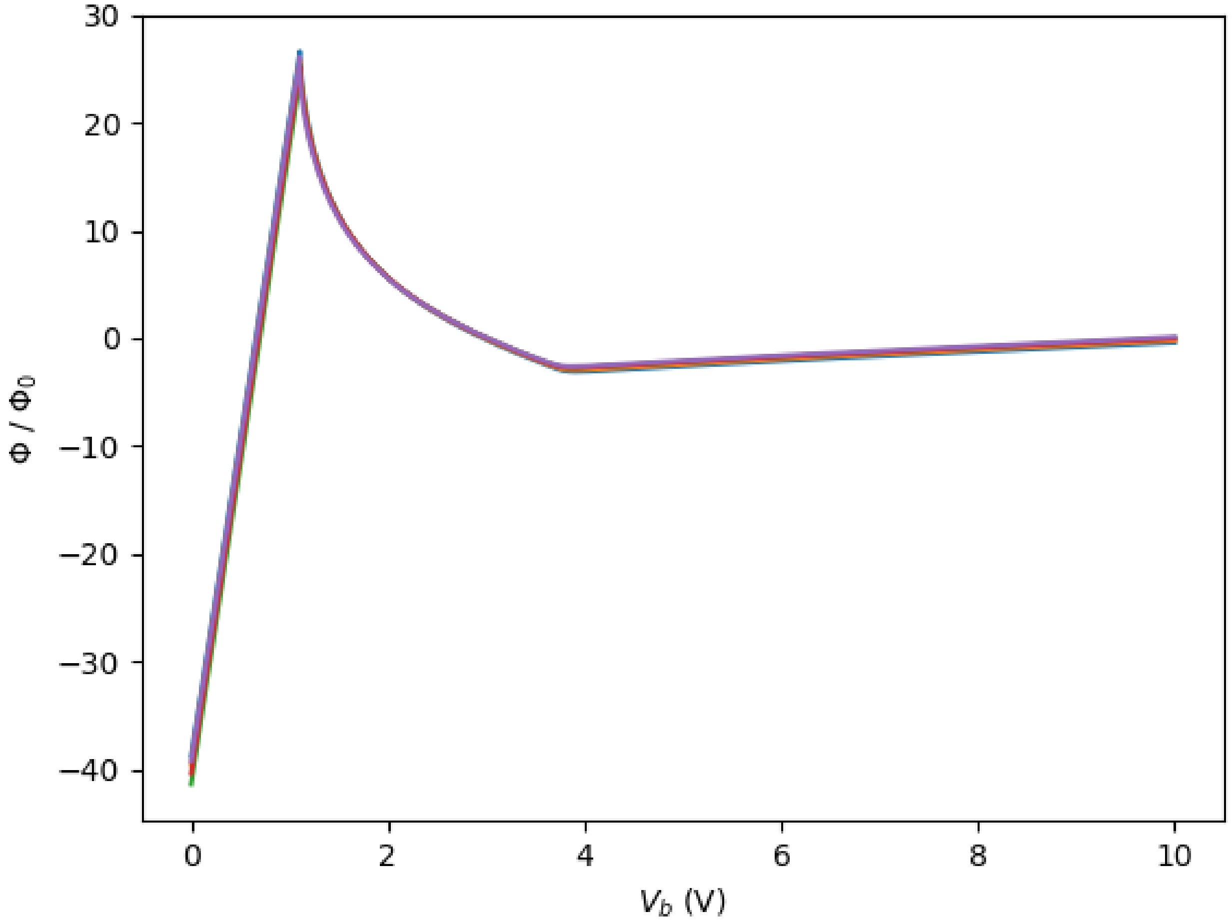


Noise measurements



- Measuring readout white noise of about 2-3 $\mu\Phi_0/\sqrt{\text{Hz}}$, devices designed to about 10 μA per Φ_0.
- Seeing slightly better readout noise performance from the MUX chips with higher critical currents than designed, working on understanding this behavior.
- Considerable effort has been taken to isolate cryostat ground from electronics/earth ground. This can be seen in the relatively low 60 Hz noise levels.

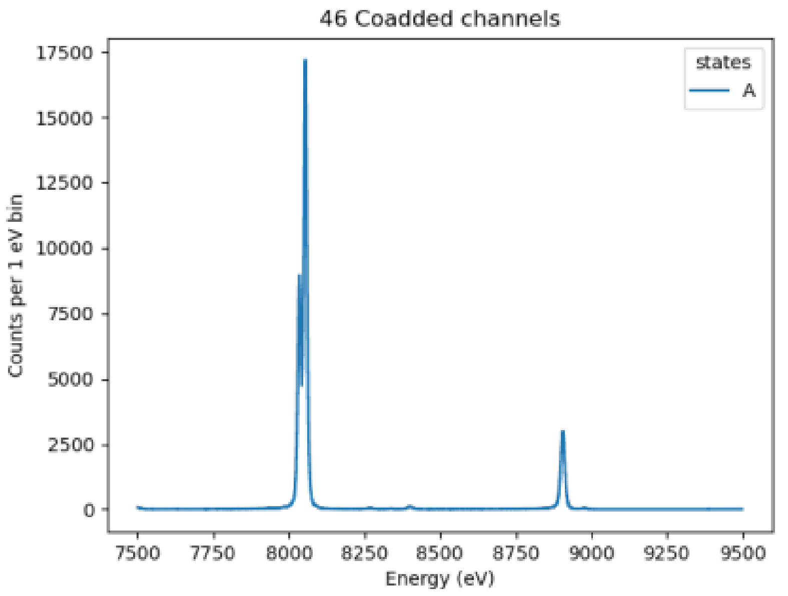
IV Curves

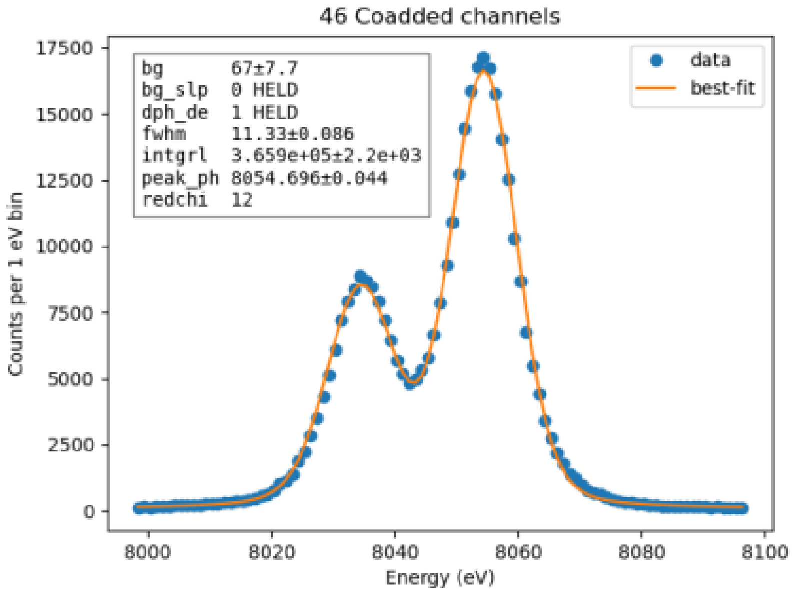


IV curves prior to any sort of normalization (data coming directly out of the DAQ). Good indicator of whether a detector will is behaving properly and able to be read out. First sweep of half a microsnout showed working IV curves on 111 out of 124 possible channels, or around <u>90% yield</u>.

X-ray detection

- Began x-ray testing on first microsnout with external tube source containing copper foil.
- Data acquisition tools use the same framework as the current 240-pixel system, but will need to be scaled up for 3,000 detectors and expected x-ray data rates.
- First tests showed a resolution of ~11 eV at Cu Kα (8 keV).
  - Some work remaining to optimize phase correction for detector speed.
  - Devices coupled to w4 µMUX chips displayed better resolution (9 eV).

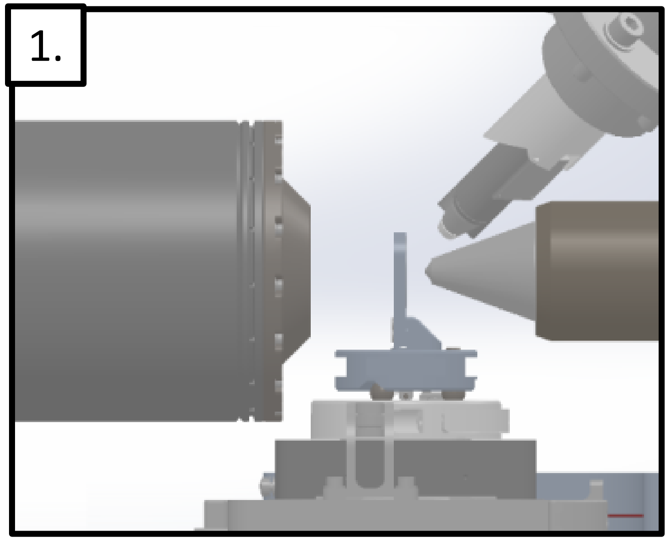




Summary

1. Developed system that utilizes TES resolving power to perform x-ray tomography on microcircuits.
2. Used prototype system to generate first 3d image of ~160 nm scale features, using voxel sizes of 40 nm x 40 nm x 80 nm.
3. Building 3000 TES spectrometer upgrade primarily aimed to reduce collection time.

1.



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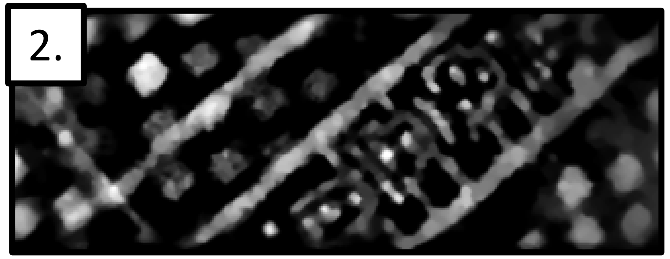

3.

Acknowledgements / Disclaimers

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