IEEE/CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), October 2017.
Contributed presentation We-C-DET-08 given at ISEC 2017, Sorrento, Italy.

ADVANCEMENTS IN HIGH-EFFICIENCY, FAST TRANSITION EDGE SENSORS SPECTROMETER FOR X-RAY SCIENCE

ORLANDO QUARANTA
Detector Group
Advanced Photon Source

ISEC 2017 – Sorrento (NA) - Italy

COLLABORATORS

Argonne NATIONAL LABORATORY

Jonathan Baldwin
Ralu Divan
Lisa Gades
Tim Madden
Antonino Miceli
Umesh Patel
Orlando Quaranta
Daikang Yan

NIST

Brad Alpert
Luis Miaja Avila
Dan Becker
Doug Bennett
Ed Denison
Randy Doriese
Joe Fowler
John Gard
Jim Hays-Wehle
Gene Hilton

Young Il Joe
Ben Mates
Kelsey Morgan
Christine Pappas
Galen O’Neil
Carl Reintsema
Dan Schmidt
Dan Swetz
Joel Ullom
Leila Vale

SLAC NATIONAL ACCELERATOR LABORATORY

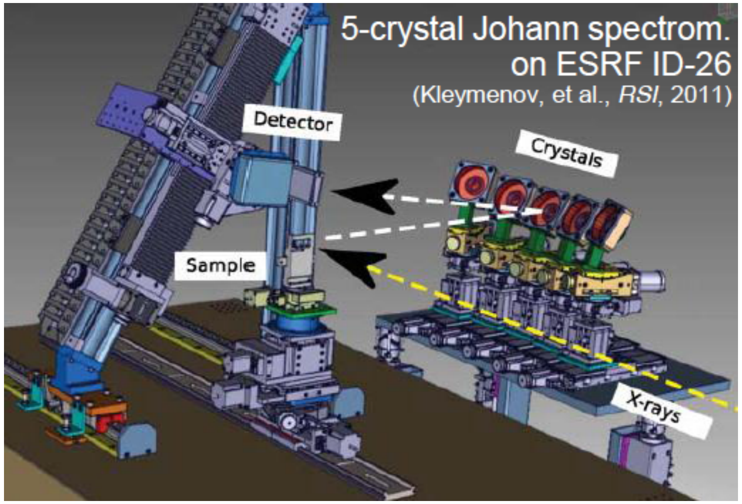
Hsiao-Mei “Sherry” Cho
Joseph Frisch
Kent Irwin
Sang-Jun Lee
Dale Li
Dennis Nordlund
Charles “Jamie” Titus
Paul Welander

SXS

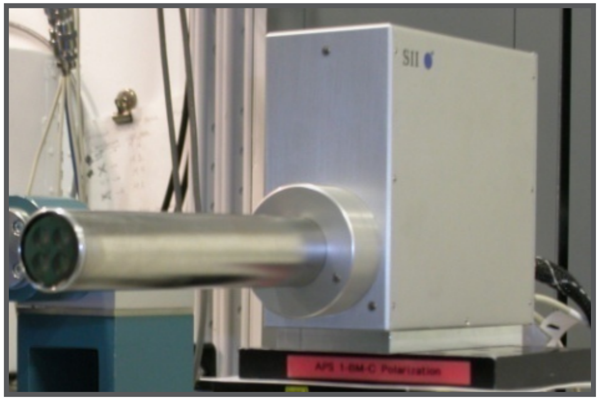
WHY ?

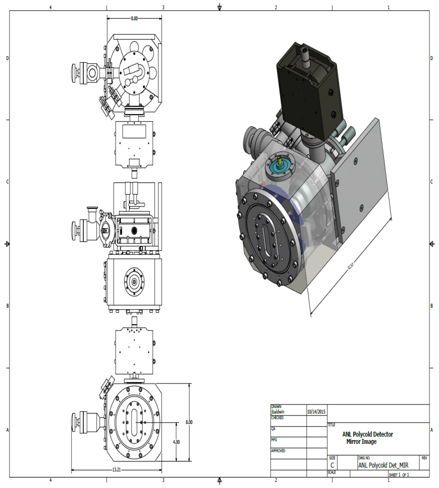
The best of two worlds

- Wavelength-dispersive spectrometers (crystals, gratings)
  - Excellent energy resolution
  - Excellent background rejection


5-crystal Johann spectrom. on ESRF ID-26
(Kleymenov, et al., *RSI*, 2011)

- Energy-dispersive detectors (SDD, Ge)
  - Wide energy range
  - Large solid angle



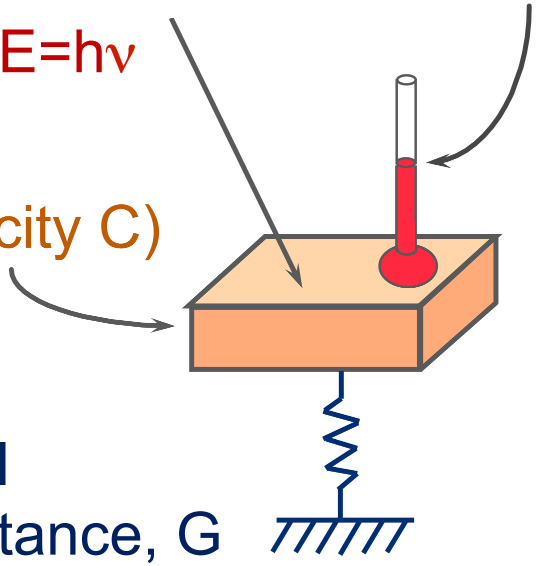


- “Ultimate” Superconducting Detectors
  - Wide energy span
  - ΔE ~ 1 eV
  - Soft to hard x-ray ranges
  - Count rate > 100 kcps

- Transition Edge Sensors are the closest option

THERMAL DETECTORS (I.E., MICRO-CALORIMETERS)

Low temperature is required



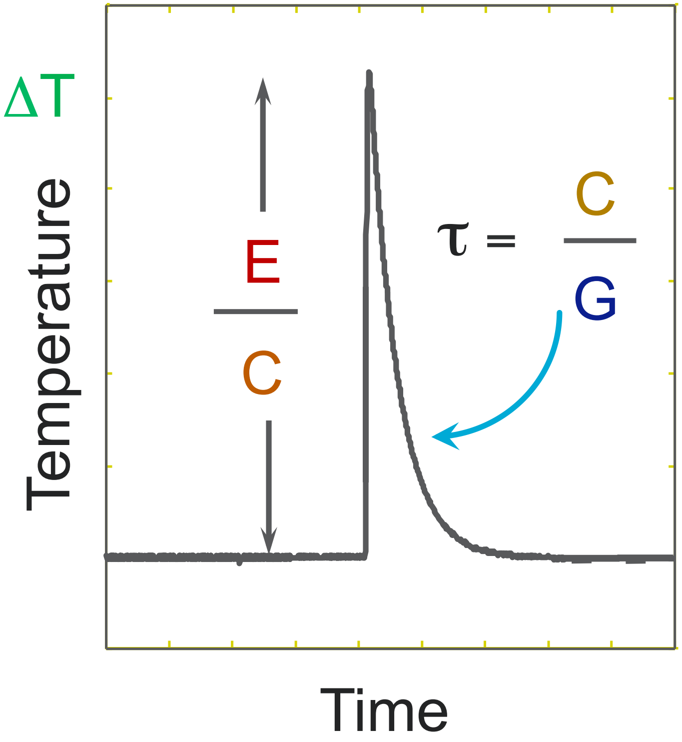
X-ray

$E=h\nu$

Thermometer, ΔT

Absorber
(Heat Capacity C)

Thermal
Conductance, G



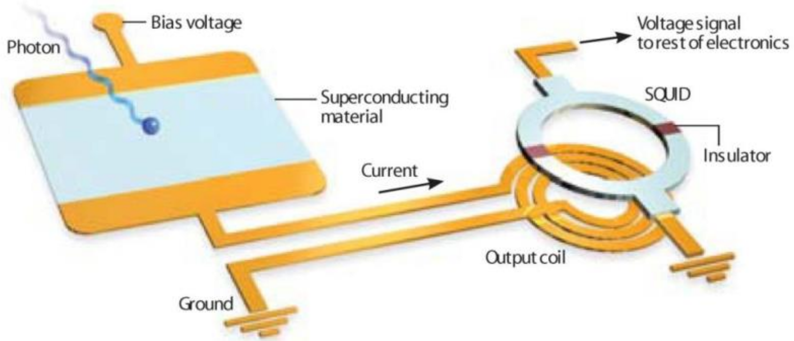
$$E=C\times\Delta T \qquad \Delta E=(k_B\times T^2\times C)^{1/2}$$

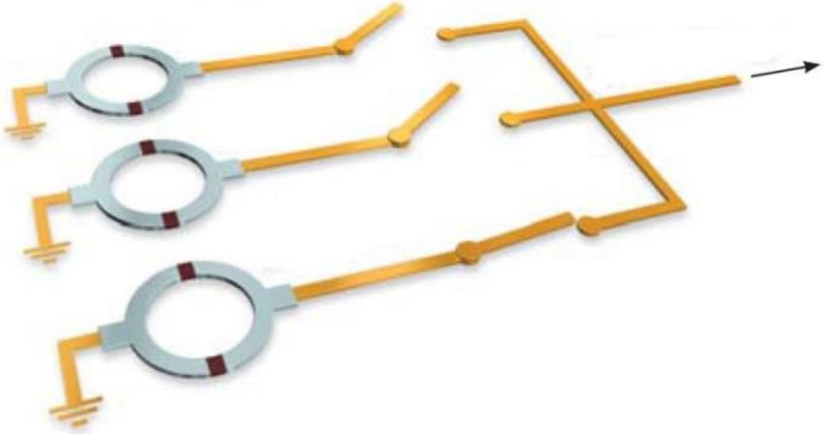
Operate at low temperatures (T~ 0.1K) where C, G and thermodynamic fluctuations are small.

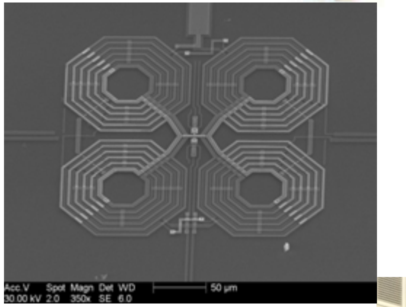
SUPERCONDUCTING TRANSITION EDGE SENSORS

SQUIDs and Time Division Multiplexing

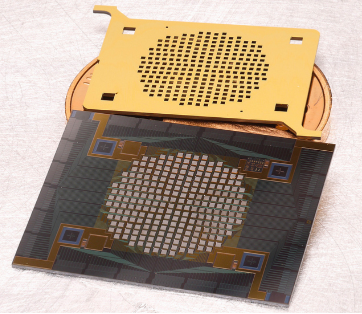
- Each TES in a column is connected to a single SQUID
- SQUIDs in the column are turned on and off in a sequential order
- The entire column is connected to a second stage SQUID
- Very mature technology
- Used at APS and SLAC (soft x-ray detectors)





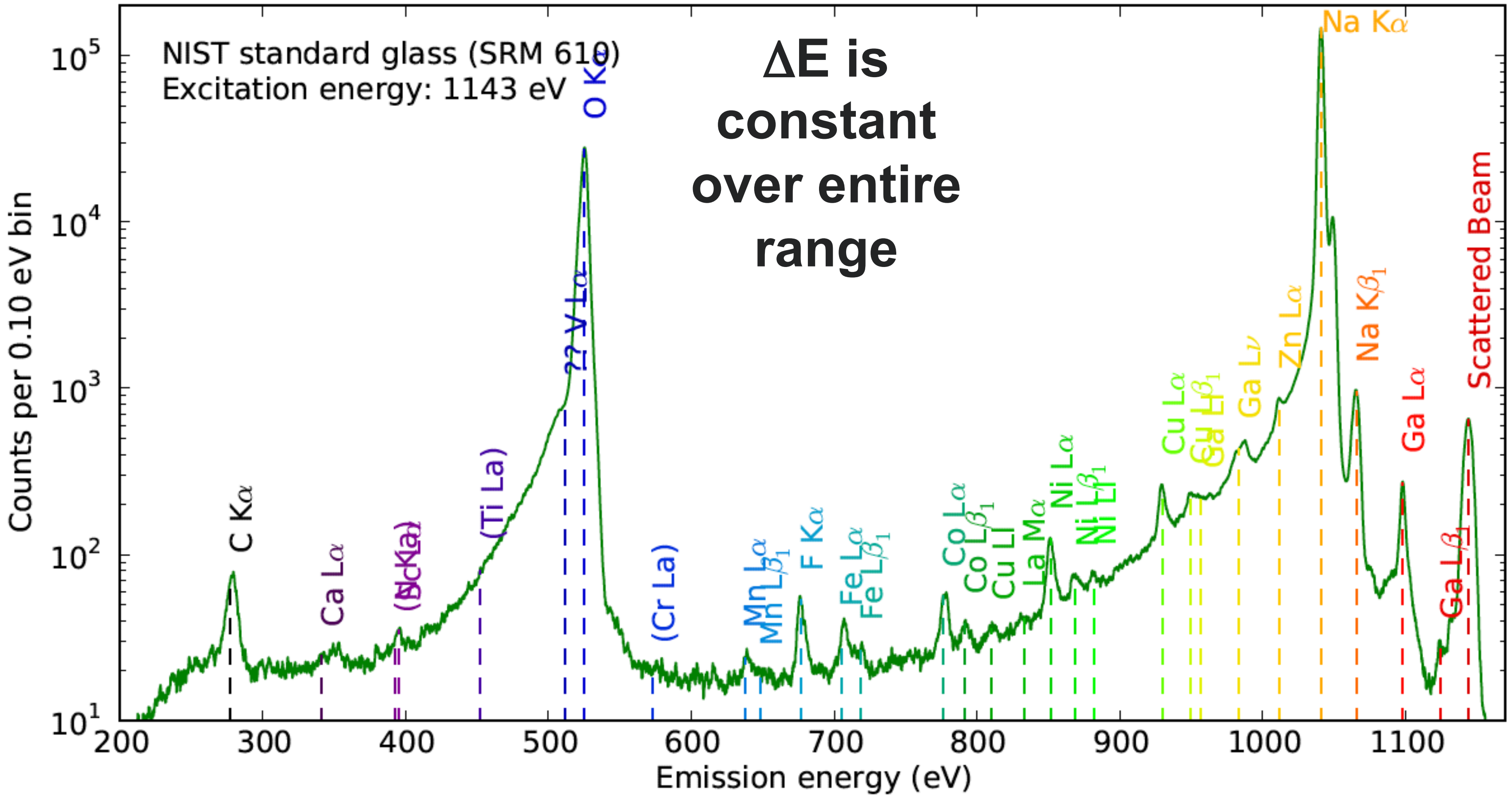


NIST 240-pixel array



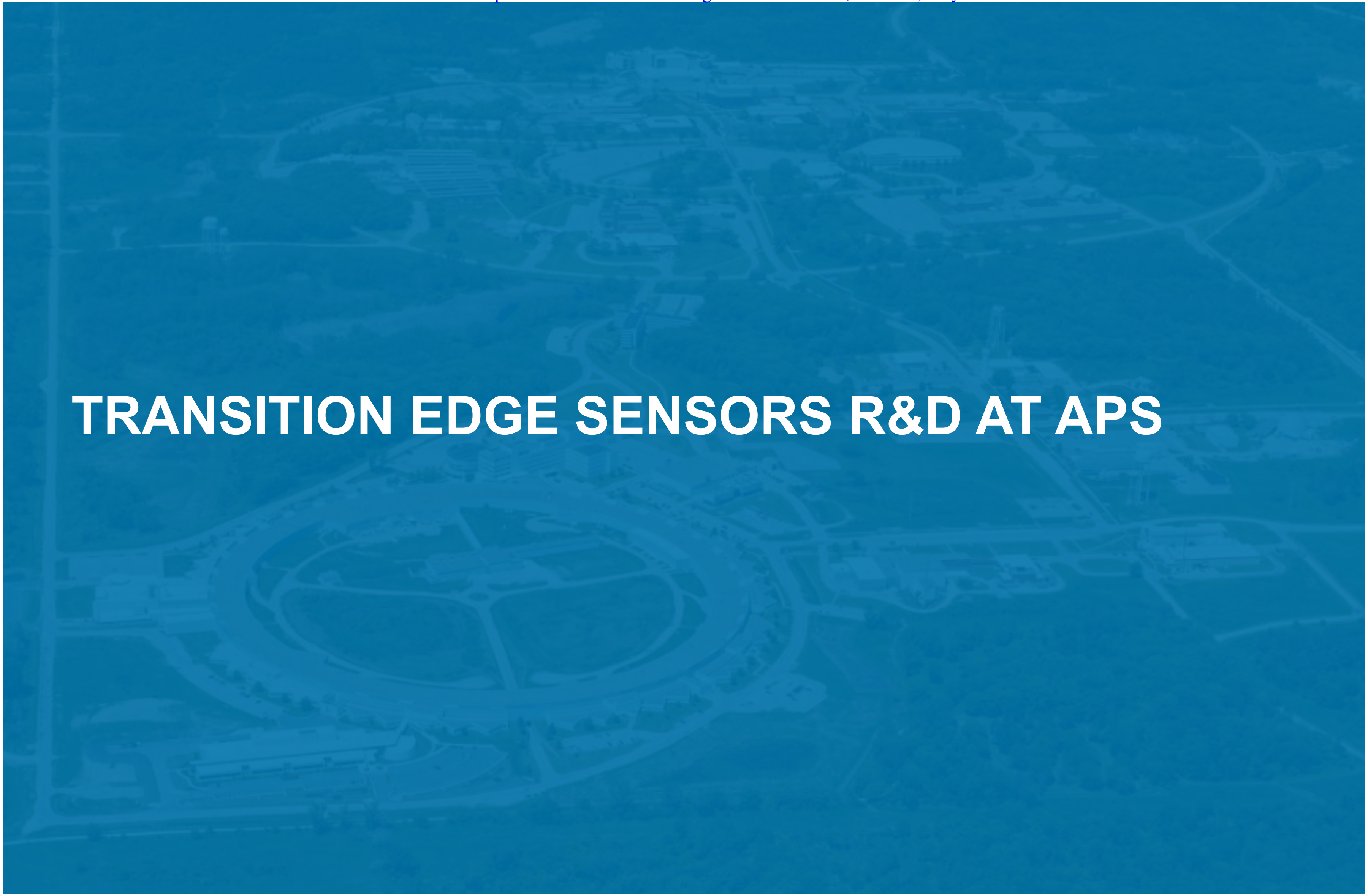
SUPERCONDUCTING TRANSITION EDGE SENSORS

Time Division Multiplexing



ΔE is constant over entire range

Ullom *et al* (NIST)

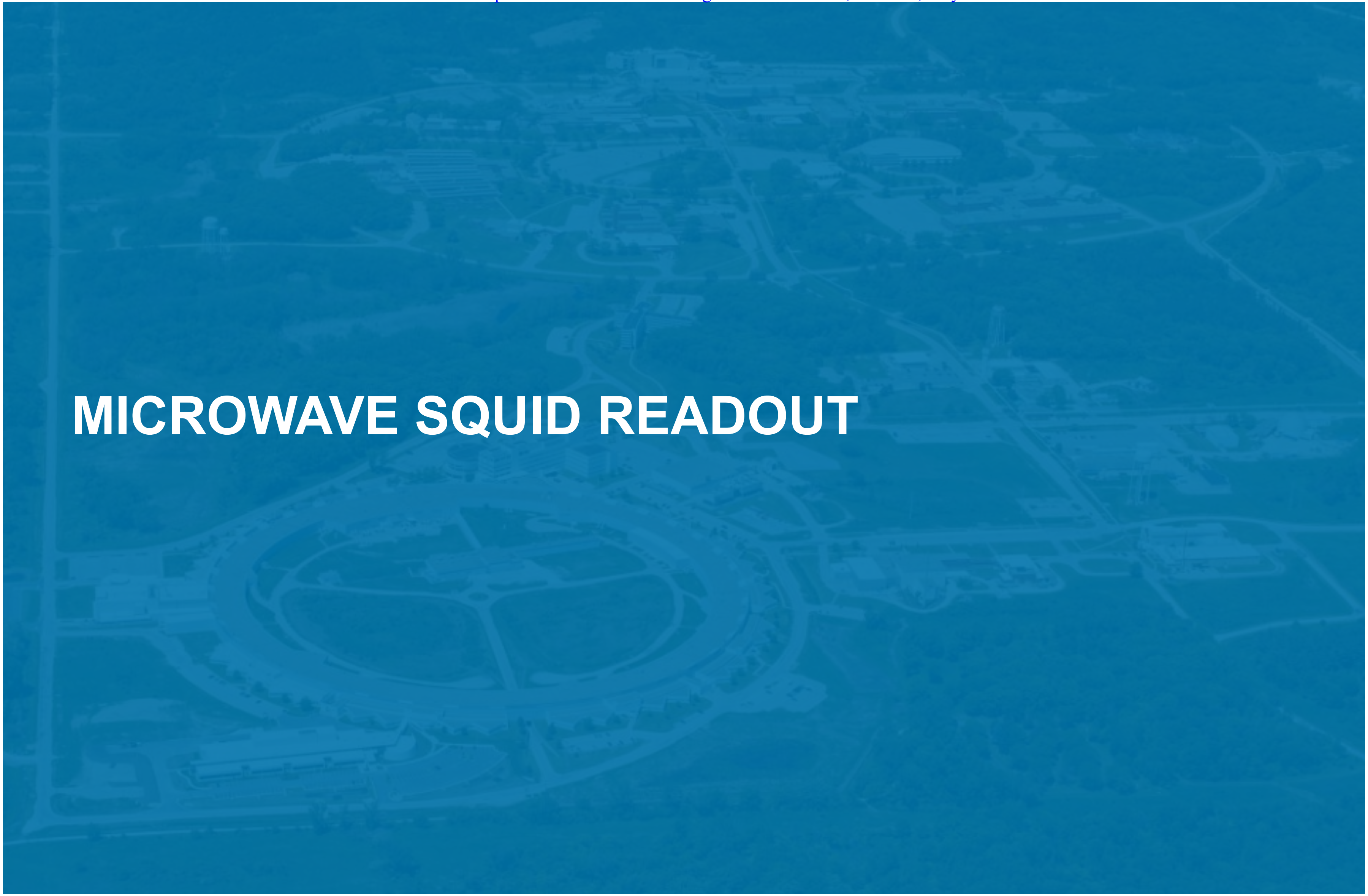


TRANSITION EDGE SENSORS R&D AT APS

CURRENT SYSTEMS LIMITATIONS…

… and the needs of APS

- “State of the art” systems:
  - Array size ~ 250 pixels, challenging to increase it due to the increased heat load
  - √N noise penalty (TDM)
  - Count rate is limited by cross-talk in the SQUIDs to ~ 10 cps/pixel (TDM)
  - Only for “low energy” < 1 keV
- APS needs:
  - Current array sizes are ok but a path toward much bigger arrays (~ 1000 pixels) is needed
  - Much higher count rates: ~ 100 cps/pixel
  - Strong interest in higher energies: 6 to 20 keV
  - Moderate interest in very high energies: 20 to 100 keV
- APS research approach:
  - Alternative readout technique – Microwave SQUID readout from NIST
  - Stopping power without loosing energy resolution – Electroplated Bi

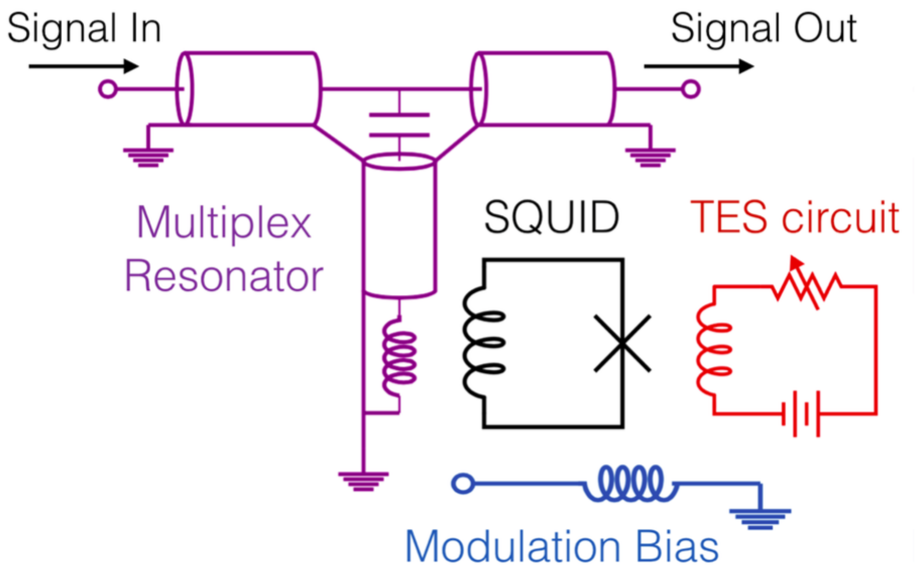


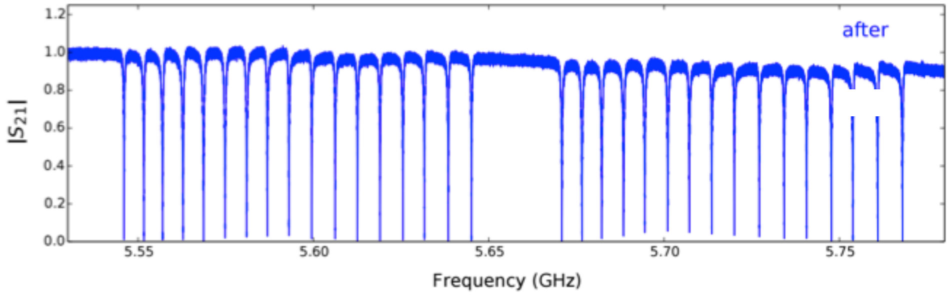
MICROWAVE SQUID READOUT

Argonne
NATIONAL LABORATORY

MICROWAVE MUX READOUT FROM NIST

Frequency Division Multiplexing (i.e., microwave mux) – each sensor is simultaneously sampled





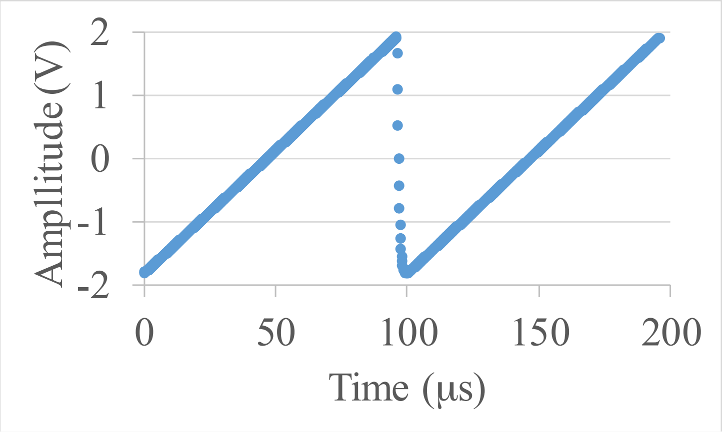
B. Mates, et al, *Appl. Phys. Lett.* ***92***, 023514 (2008)

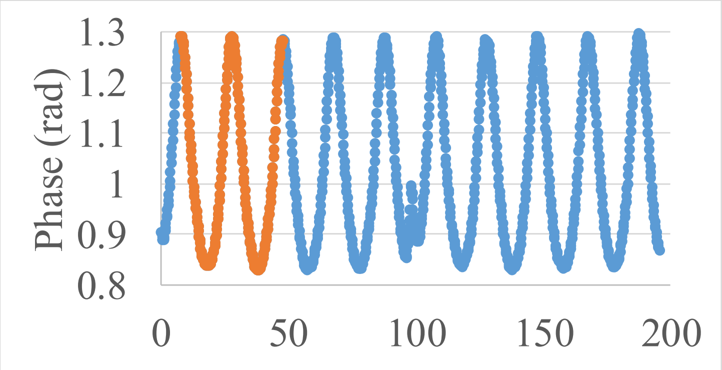
- Each TES detector is coupled to a SQUID amplifier and a microwave resonator.
- The photon absorption in a TES causes a temporary variation in the TES current. This is coupled to the SQUID via the coupling inductance, which amplifies this variation. This then induce a measurable shift in the superconducting resonator frequency, via the inductive coupling between the SQUID and the resonator.
- The TESs are multiplexed in frequency via the corresponding resonator frequency.
- Possible to multiplex ~ 500 TESs with single pair of coax and 4 DC lines.

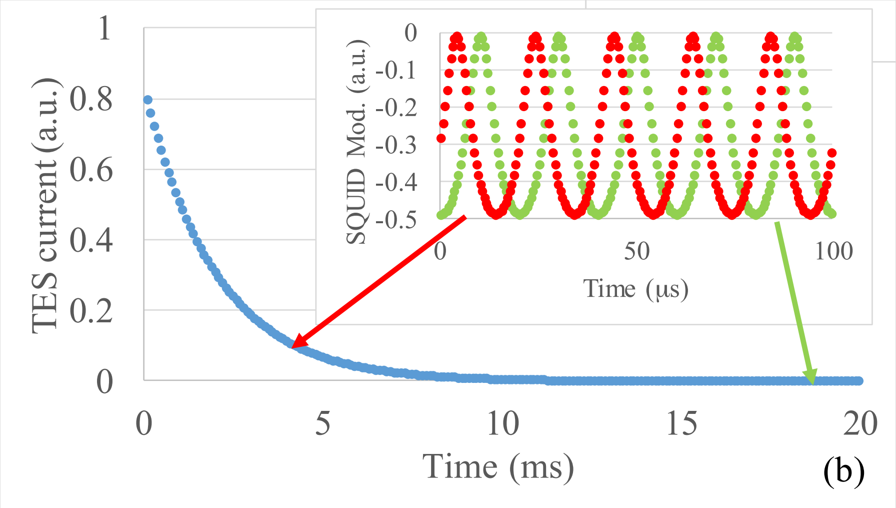
FLUX RAMP MODULATION

Definition

- A periodic ramp that sweeps through the multiple quanta in the SQUID is applied.
- If the ramp rate is much higher than the TES current pulse time constant, then these will look like a phase shift in the SQUID response to the ramp.
- The TES current is directly proportional to the induced phase shift in the modulation: ~ 9 µA/phase period in the SQUID.



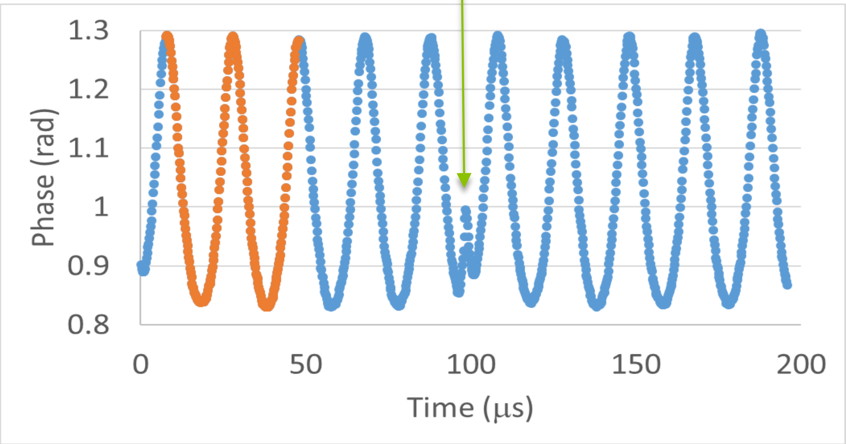




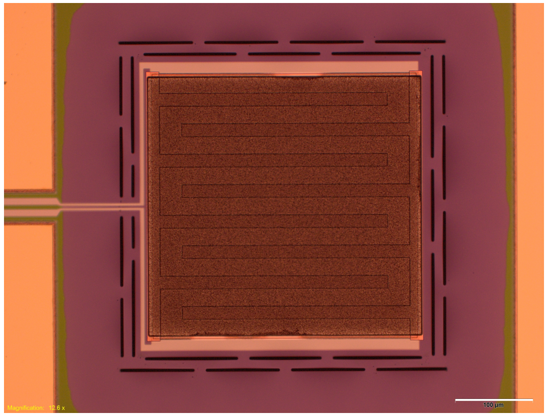
FLUX RAMP MODULATION

Parameters

- Tunable Parameters:
  - Number of oscillations in one flux ramp - N_{OSC}
  - Ramp frequency - F_{RAMP}
  - Number of oscillations used in one modulation - N_{USED}
- Benchmarks:
  - System Noise Level (*SNL*) - Noise at 1 kHz (i.e. above the cut-off frequency from the TES/shunt resistor and the coupling inductance
  - System Linearity (*SL*) - Residual to a linear fit of the TES normal state branch



The reset at the end of each ramp cause a glitch



6 keV x-ray TES from NIST:

- Mo/Cu, T_C = 105 mK, R_{TES} = 8.8 mΩ and evaporated Bi absorber.
- R_{SHUNT} = 300 mΩ and L = 690 nH.

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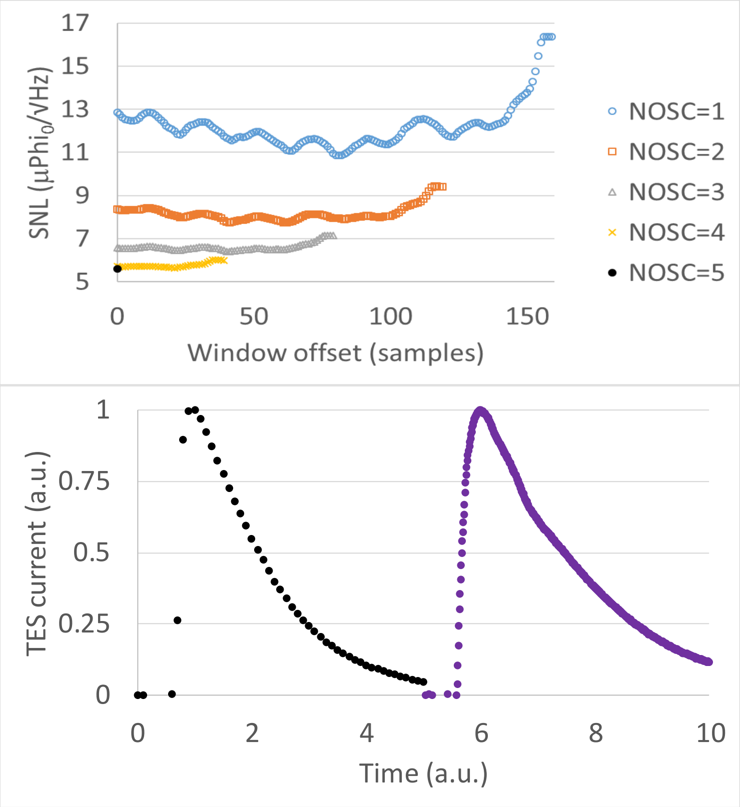
FLUX RAMP MODULATION

Optimization

- Parameters optimization at F_{RAMP}=10 kHz and N_{OSC} = 5:
  - Best *SNL* is achieved with $N_{USED} \geq 4$ - *SNL* ~ 5 - 6 µPhi$_0$/√Hz.
  - Similar results for *SL*, with a slight advantage in the case N_{USED} = 4 - SL ~ 0.024 Phi$_0$.
  - A better grounding of the mux chip lower *SNL* to 3 - 4 µPhi$_0$/√Hz.
- High sampling rate help the pulse reconstruction
- The limited bandwidth of the resonators (~ 300 kHz) limits the achievable modulation rate: $F_{RAMP} \times N_{OSC}$.
- To obtain good sampling rate of the TES current (high F_{RAMP}) N_{OSC} must be kept low
- Parameters optimization at F_{RAMP}=100 kHz and N_{OSC} = 1:
  - N_{USED} = 1 - *SNL* ~ 6 - 7 µPhi$_0$/√Hz and SL ~ 0.039 Phi$_0$.



- F_{RAMP}=10 kHz and N_{OSC} = 5
- F_{RAMP}=100 kHz and N_{OSC} = 1

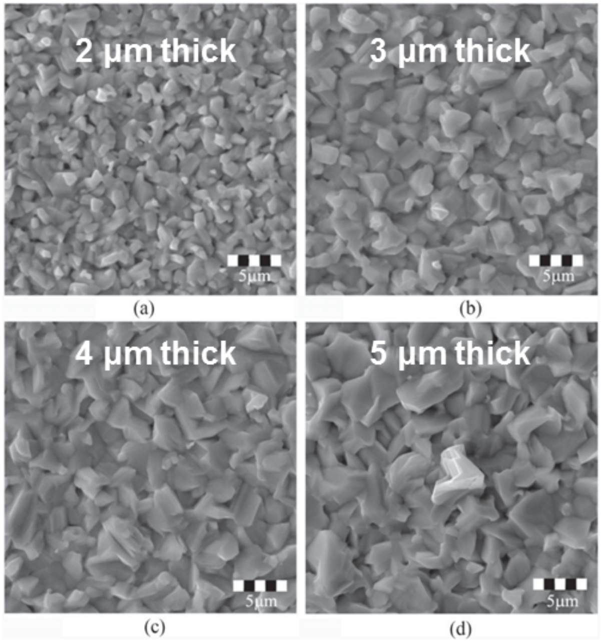
ELECTROPLATED BI ABSORBER

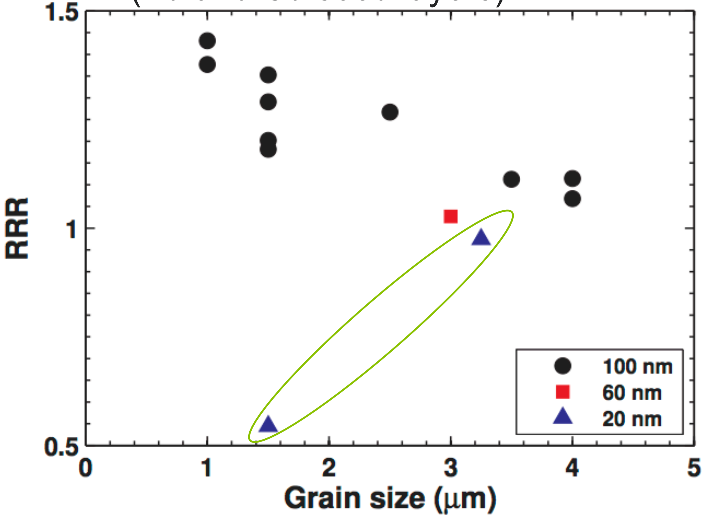
BISMUTH ABSORBERS

Why and How

- Why Bismuth?
  - Low heat capacity.
  - High stopping power.
- Why Electroplating?
  - Some evaporated Bi films show a low energy tail that affect the ultimate energy resolution.
  - Electroplated films can grow bigger grains which might help with the tail problem,
  - Relatively easy to grow thick absorber for increased stopping power at high energies.
  - Compatible with pre-existing TES designs and processing (Au and Cu seed layers).

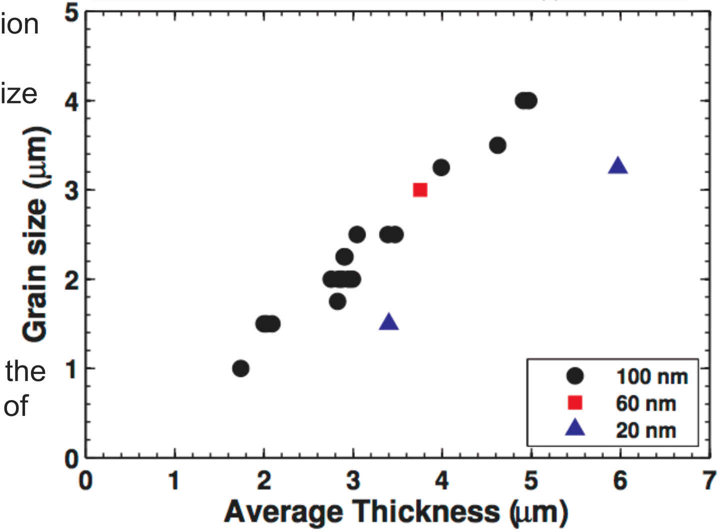
Bismuth grain size varied with thickness. (a) 2 μm thickness showing ~1-2 μm grains (b) ~2-2.5 μm grains. (c) ~2.5-4 μm grains. (d) ~3-5 μm grains.





When the Au contribution is minimized the RRR scales with the grain size as expected.

Grain size grows with the film thickness (typical of electroplating)

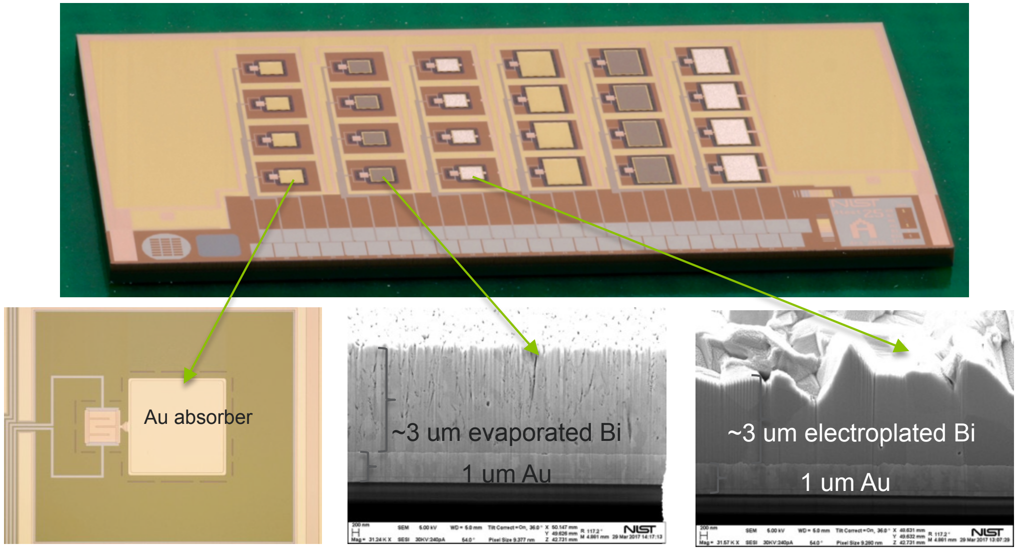


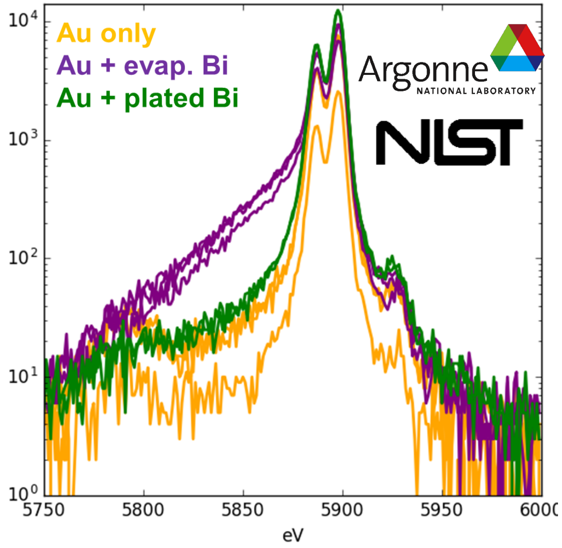
L. M. Gades, et. al., *IEEE Trans. Appl. Supercond.*, (2017)

BISMUTH ABSORBERS

Application to TES

- Devices with Au, evaporated Bi, and electroplated Bi on the same chip have been fabricated and characterized under different energy photons.
- Spectra from Au and electroplated Bi are similar, with no low-energy tail.



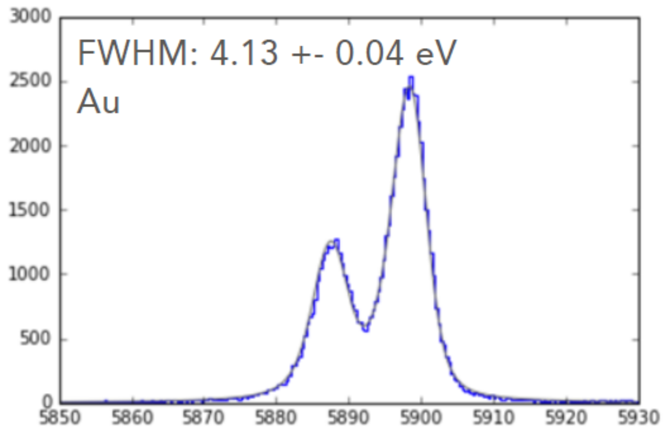


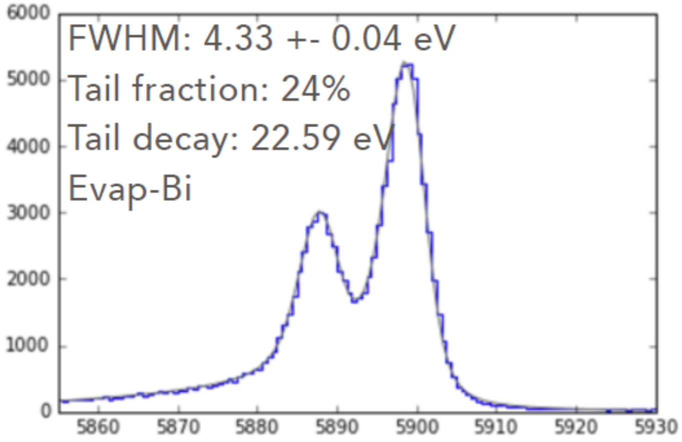
Mn Kα: FWHM ~4 eV @ 6 keV

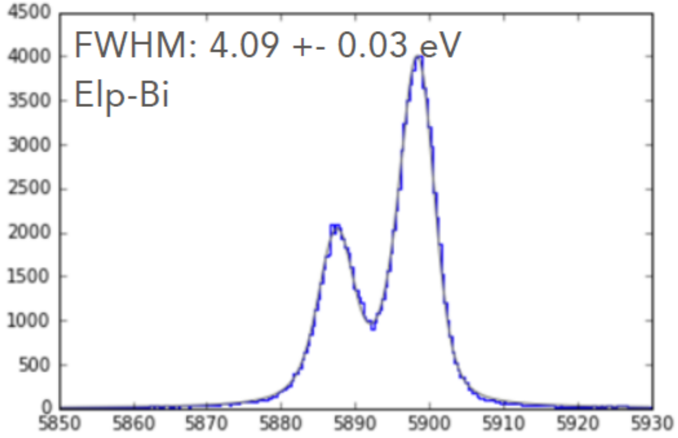
- The energy resolution is not affected by the Bi.
- The physical mechanism is still unclear but probably due to the much larger grains.

BISMUTH ABSORBERS

Energy resolution







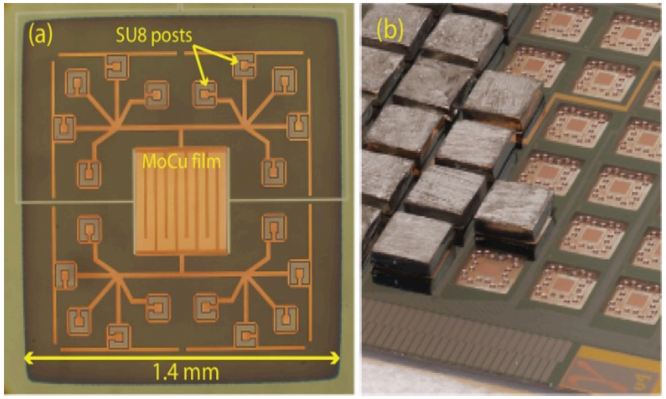
- Energy resolution not affected by the presence of the Electroplated Bi
- Contribution to *C* negligible (also confirmed by the analysis on the pulses).

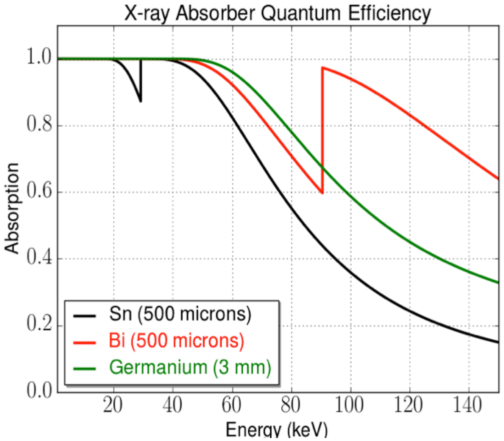
BISMUTH ABSORBERS

Open questions and future steps

- Better understanding of the physics behind the effect:
  - Physical analysis on representative samples in progress.
  - The pulses from the three different devices seem identical.
  - Possible variation of the tail shape with the energy of the incident photons may shed some light on the physical mechanism (Tatsuno *et al.* J.Low Temp Phys."Absolute energy calibration of x-ray TES …" 2016).
  - Electroplated sample with different grain sizes may lead to different results, i.e. nature of the deposition technique vs morphology of the film.
- Limits of the technique: how thick absorbers can be fabricated? (Already achieved 20 μm structures with standard lithography)

NIST gamma-ray spectrometer

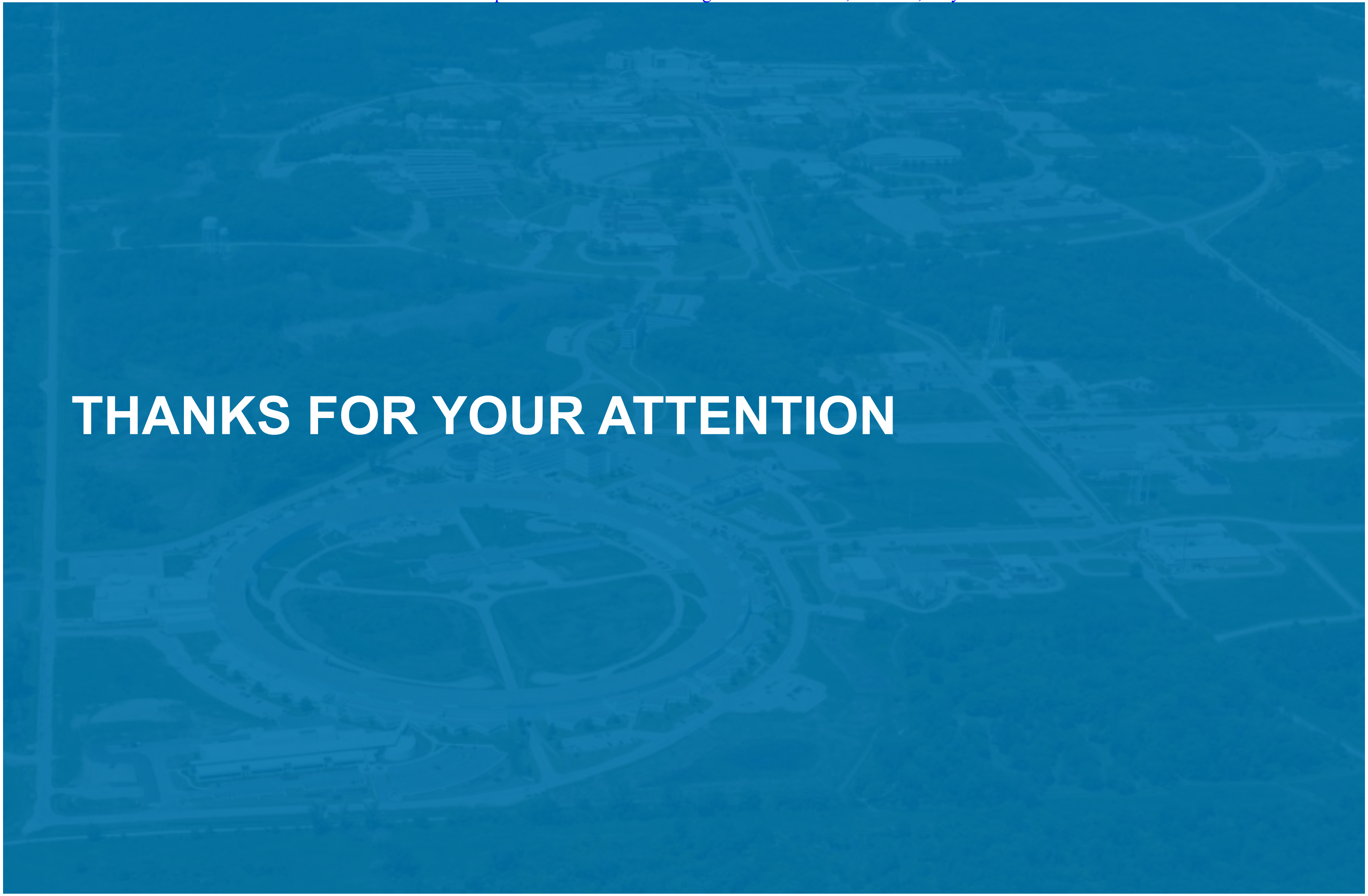




CONCLUSIONS

And possible evolutions

- Microwave SQUID multiplexing technology successfully used for the testing and characterization of 6 keV X-ray TESs.
- Noise levels comparable to the standard TDM technology have been achieved.
- Reasonable speeds have been archived with the current mux chip (300 kHz resonators) at a small price in noise, but some synchrotron applications (100 – 1000 cps/pixel) may require a new generation of broadband mux chips (1 MHz resonators).
- Electroplated Bi absorbers characterized by μm size grains have been developed.
- TES testing devices with electroplated Bi absorbers show no sign of low energy tails, unlike the usual evaporated Bi.
- TES testing devices with electroplated Bi absorbers have shown performance comparable to those of the TESs of reference (Au only).
- Very thick absorbers for high energy applications (6 to 20 keV) have been deposited.
- Study of the applicability to very high energies (20 keV to 100 keV) are under way.



THANKS FOR YOUR ATTENTION