NASA

Stanford University

NIST National Institute of Standards and Technology

X-IFU

ATHENA X-ray Integral Field Unit

NASA contributions to the X-IFU

Supported through PCOS SAT program: "**Providing enabling & enhancing technologies for a demonstration model of the Athena X-IFU**"

Presented by: Simon Bandler, (NASA/GSFC)

X-IFU Project Manager for U.S. contribution to the Athena X-IFU

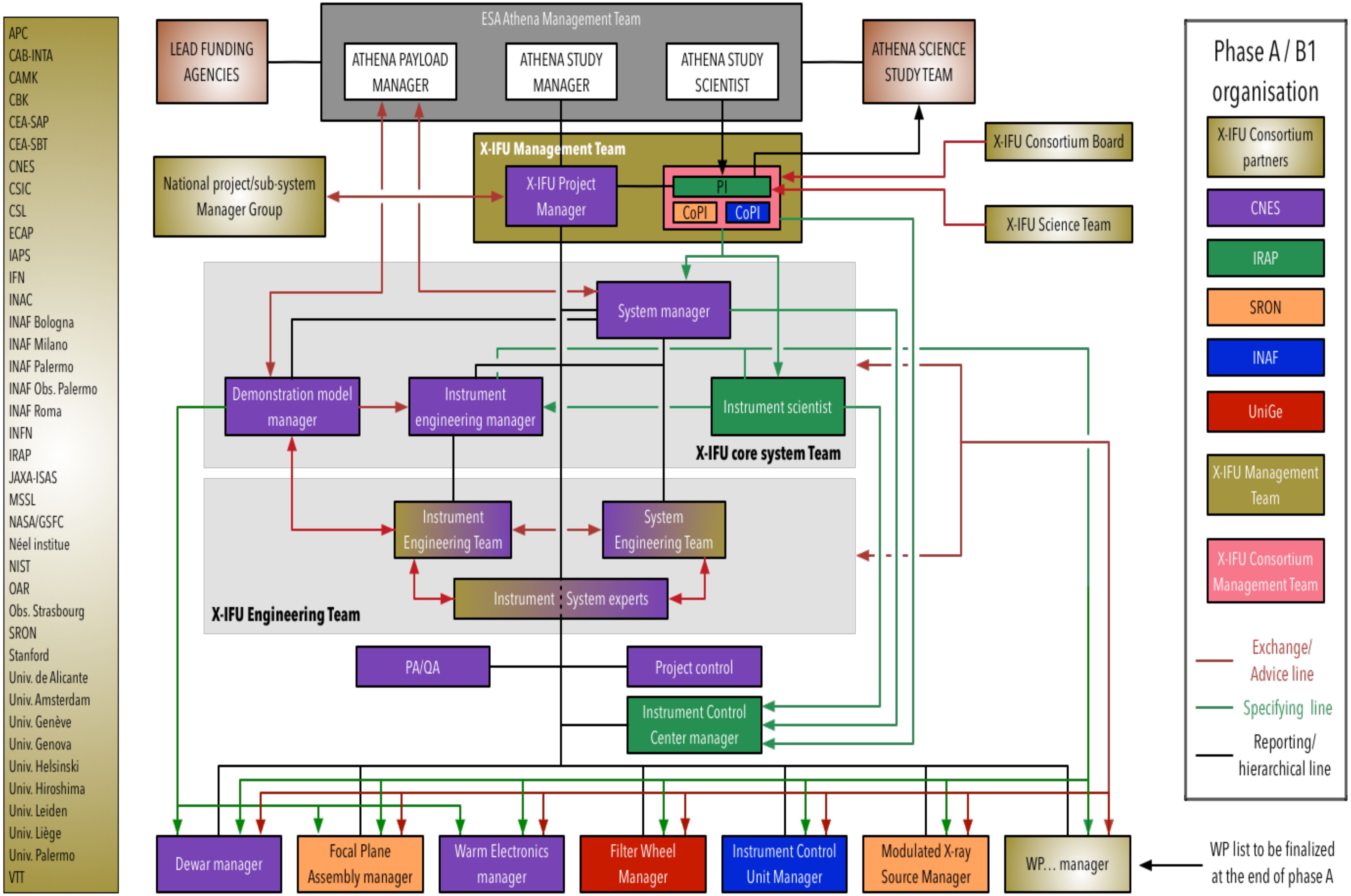
X-IFU Detector Scientist: Caroline Kilbourne (NASA/GSFC)

Member of the X-IFU consortium board: Richard Kelley (NASA/GSFC)

Major collaborators: NIST, Stanford University

January 5th, 2017

X-IFU Organization overview:



Detector development program overview

ATHENA X-IFU X-ray Integral Field Unit

- Ongoing array fabrication & testing
    - DM Array development
    - Developed fabrication capability to make hybrid arrays
    - Designing large (Athena) scale array fabrication
- Studies of physics and performance of TESs under AC bias
    - Collaborative study of GSFC TESs at SRON
    - FDM read-out electronics now being used at GSFC
    - Microwave read-out of TES under AC bias without feedback (NIST)
- Continued studies of small and large TES designs for optimal performance
- Large-scale X-IFU scale array test platform build-up – with DC-biased TESs
- Continued TDM/CDM multiplexing development (back-up read-out)
- Development of flight-compatible electronics for the TDM/CDM option.
- Development of *"around-the-corner"* flex
- Investigation of bump-bonded connections to TES wafer
- Radiation hardness testing

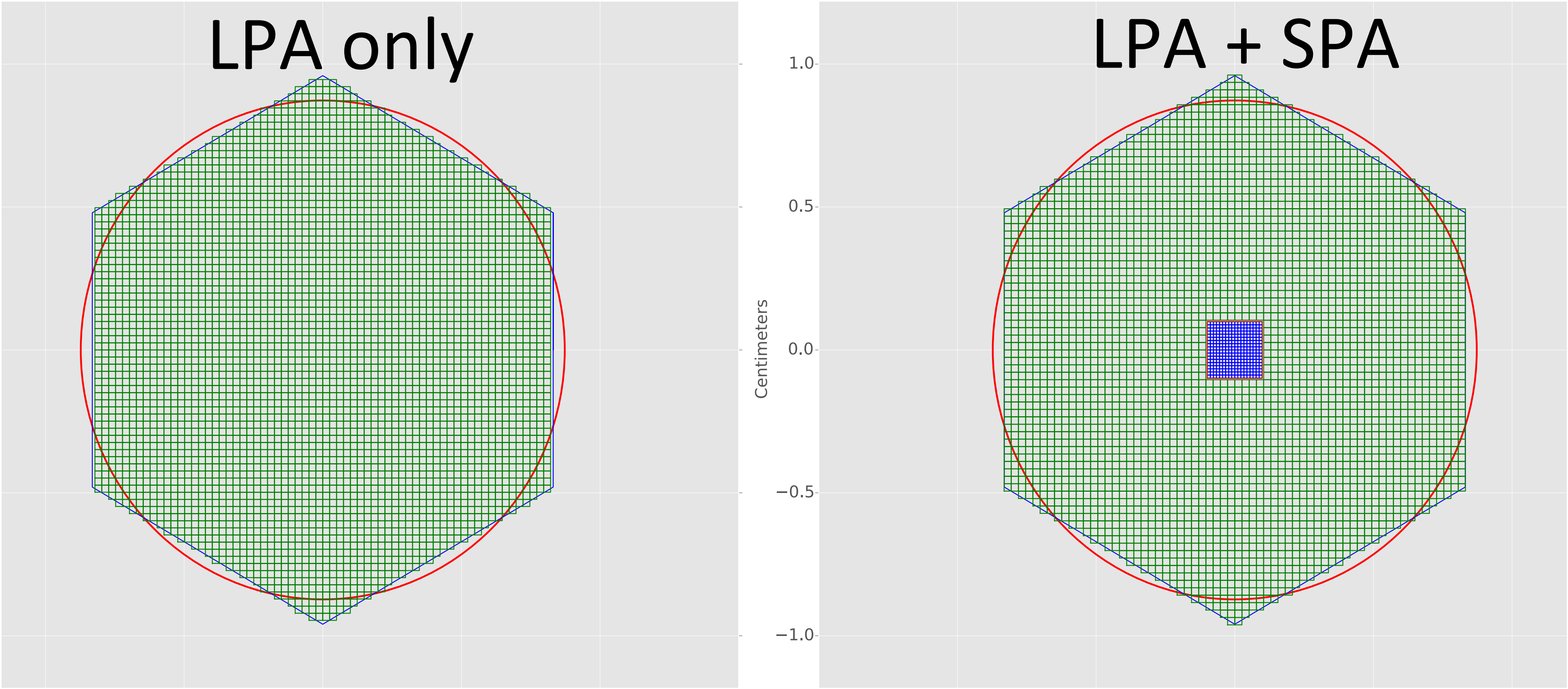
Technical Targets

ATHENA IFU X-ray Integral Field Unit

Parameter	DM Requirement	Athena requirements
Energy Range	0.3-12 keV	0.3 (0.2) – 12 keV
Energy Resolution	< 3 eV (FWHM)	2.5 eV (E < 7 keV) E/ΔE=2800 (E > 7 keV)
Number of Pixels	~ 1000	FOV = 5’ diameter/hexagon (~3840 pixels)
Pixel Size	0.25 – 0.3 mm	Pitch = 265 μm Size > 250 μm
Event throughput at required resolution	2 cps/pixel	1 mCrab (50 cps/pixel > 80% high-res events) 1 Crab (> 30% low-res events)

Technical implementation options – start of year

- **Optimizations targeted at different proposed Large Pixel Array (LPA) and Small Pixel Array (SPA) detector configurations.**
  - Uniform array of same pixel size (LPA1)
    - 250 µm pixels, 1 mCrab point source count-rate requirement (~50 cps/pixel)
  - Hybrid arrays (LPA2/3 + SPA)
    - 115 µm SPA pixels, 10 mCrab point source count-rate requirement (~100 cps/pixel)
    - 260 µm LPA pixels, with reduced count-rate (a few cps/pixel)

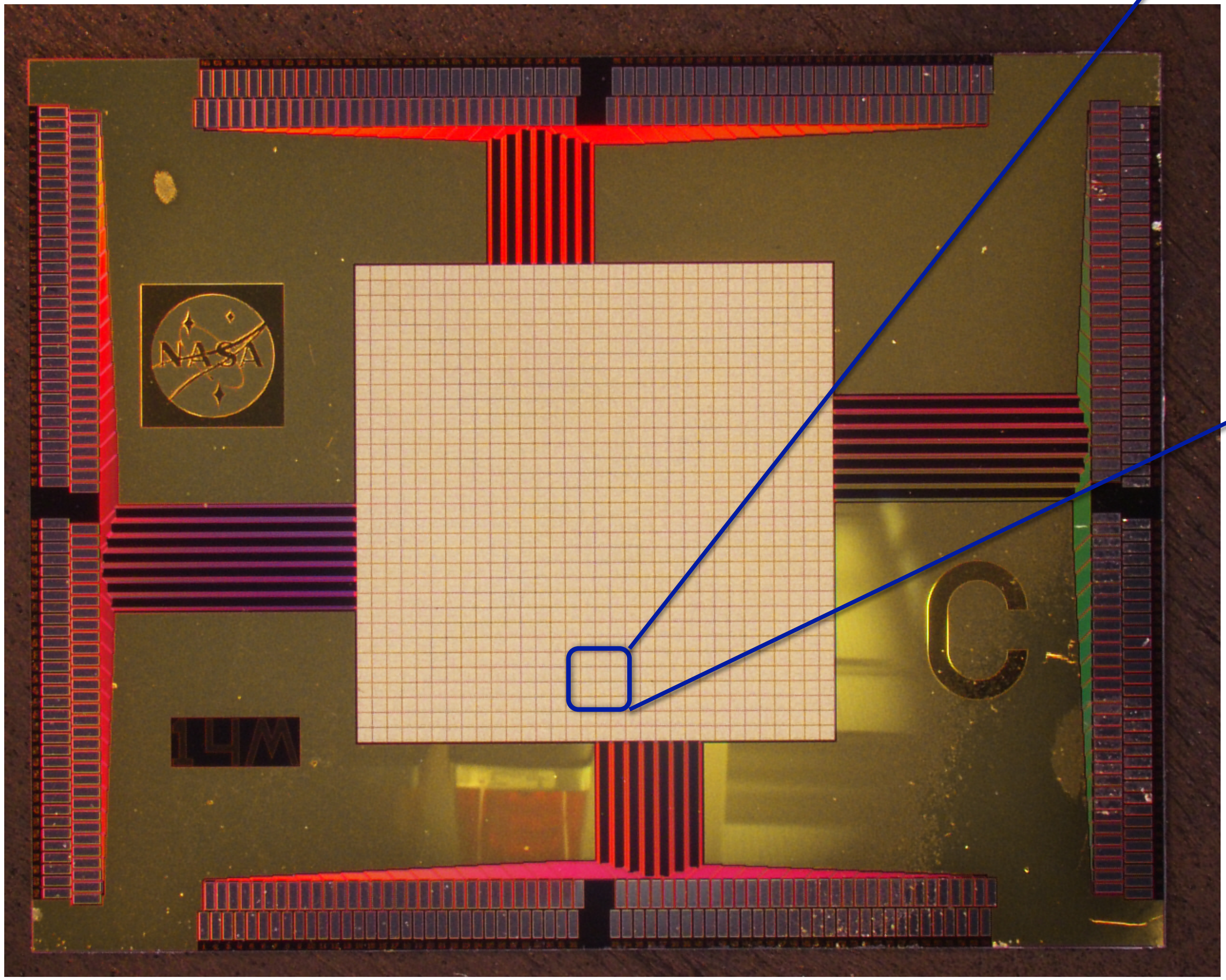


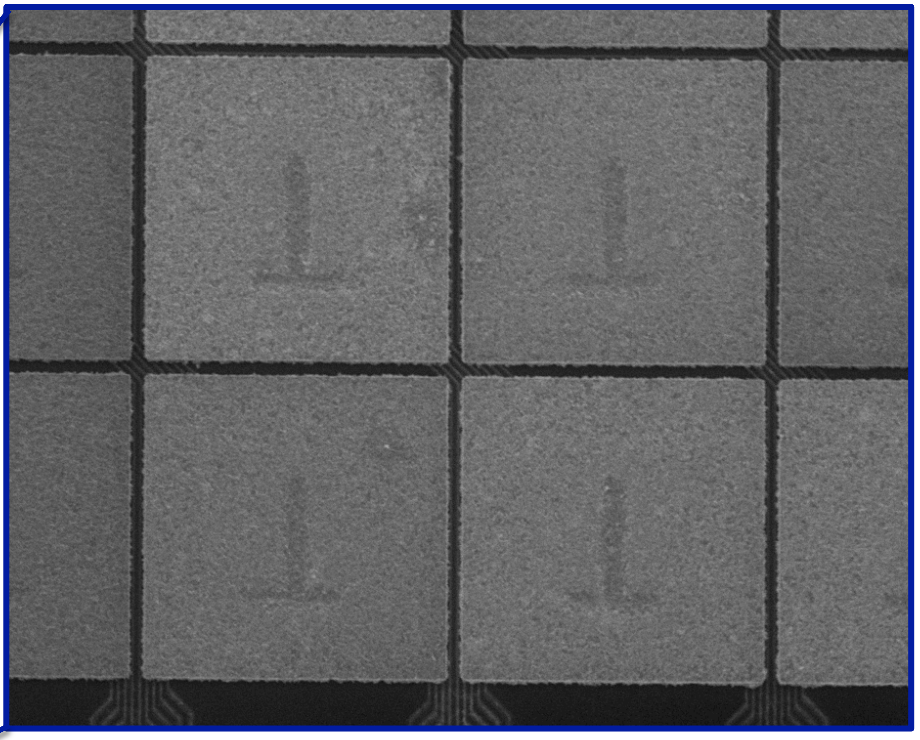
Detector performance design parameters

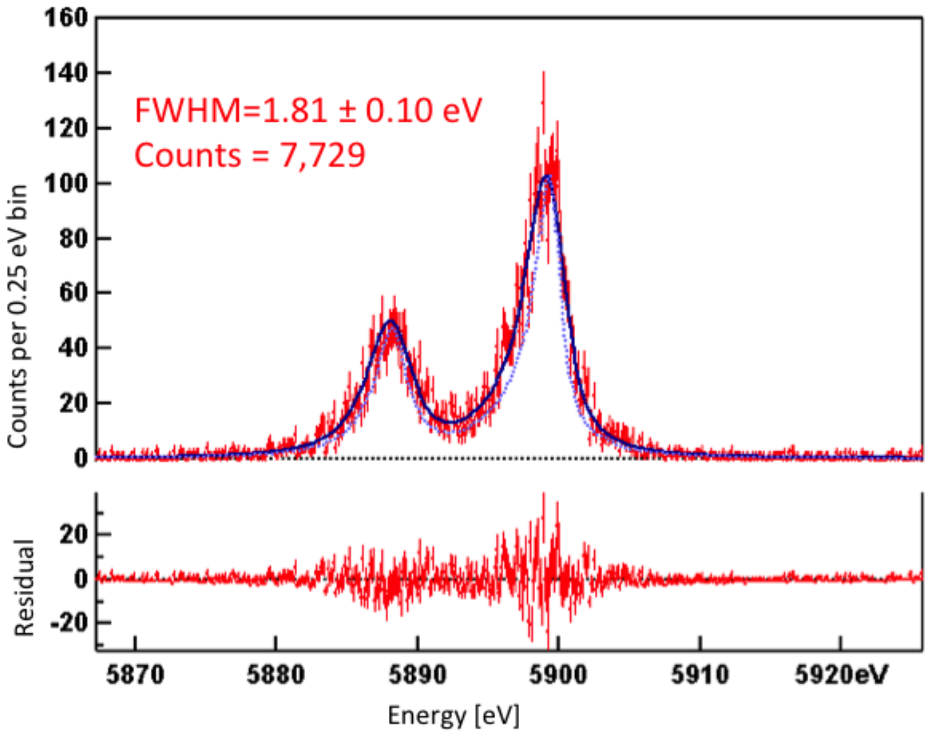
Parameter	LPA 1	LPA 2	LPA 3	SPA 1	SPA 2
Pixel size	249 μm	249 μm	300 μm	110 μm	100 μm
Temperature, T_0	90 mK	90 mK	90 mK	90 mK	90 mK
Heat capacity, C @ T_0	0.8 pJ/K	0.8 pJ/K	0.8 pJ/K	0.26 pJ/K	0.26 pJ/K
Bath conductance, G_b @ T_0	200 pW/K	114.7 pW/K	57.3 pW/K	300 pW/K	300 pW/K
Temperature exponent, n	3.0	3.0	3.0	4.0	4.0
α	75	75	75	100	100
β	1.25	1.25	1.25	10	10
Unexplained noise factor, M	0	0	0	0.8	0.8
Resistance, R_0	1 mΩ	1 mΩ	1 mΩ	1.1 mΩ	1.1 mΩ
Current, I_0	68.06 μA	51.5 μA	36.4 μA	72.62 μA	72.62 μA
Bath temperature, T_{bath}	55 mK	55 mK	55 mK	55 mK	55 mK
Power, $P_0 = I_0^2 R_0$	*4.63 pW*	*2.65 pW*	*1.33 pW*	*5.8 pW*	*5.8 pW*
R_{shunt} (for DC circuit)	0 mΩ	0 mΩ	0 mΩ	0 mΩ	0 mΩ
$R_{parasitic}$ (Parasitic in LC filter)	1 mΩ	1 mΩ	1 mΩ	1 mΩ	1 mΩ
R_{eff} (effective shunt from $R_{parasitic}$)	33.4 μΩ	60.1 μΩ	131 μΩ	62.1 μΩ	62.1 μΩ
Transformer Turns Ratio, TTR	5.47	4.08	2.76	4.01	4.01
L_{in} (for DC circuit)	0 nH	0 nH	0 nH	0 nH	0 nH
L_{filter} (LC filter inductance)	2 μH	2 μH	2 μH	2 μH	2 μH
L_{eff} (L_{filter}/TTR^2)	*67 nH*	*121 nH*	*262 nH*	*124 nH*	*124 nH*
Electro-thermal time const, τ_{etf}	*436 μs*	*788 μs*	*1.736 ms*	*306 μs*	*306 μs*
Critically damped time const, τ_{crit}	*160 μs*	*286 μs*	*617 μs*	*79 μs*	*79 μs*
Time constraint for 80% high res	*8.6 ms*	*112 ms*	*112 ms*	*4.2 ms*	*4.2 ms*
ΔE_{FWHM} (∞ rec length, small signal)	*1.74 eV*	*1.74 eV*	*1.75 eV*	*1.58 eV*	*1.58 eV*
ΔE_{FWHM} (high res, small signal)	*1.82 eV*	*1.75 eV*	*1.76 eV*	*1.65 eV*	*1.65 eV*
Max slew rate / keV	*85 mA/s/keV*	*36 mA/s/keV*	*12 mA/s/keV*	*220 mA/s/keV*	*220 mA/s/keV*
f_{eff} – effective bandwidth	*963 Hz*	*553 Hz*	*277 Hz*	*1714 Hz*	*1714 Hz*

Demonstration model (DM) kilo-pixel arrays
- being fabricated and tested

- 32 x 32 array – close-packed microstrip wiring
- Absorbers: Au: 1.75 μm, Bi: 4 μm, on 250 μm pitch

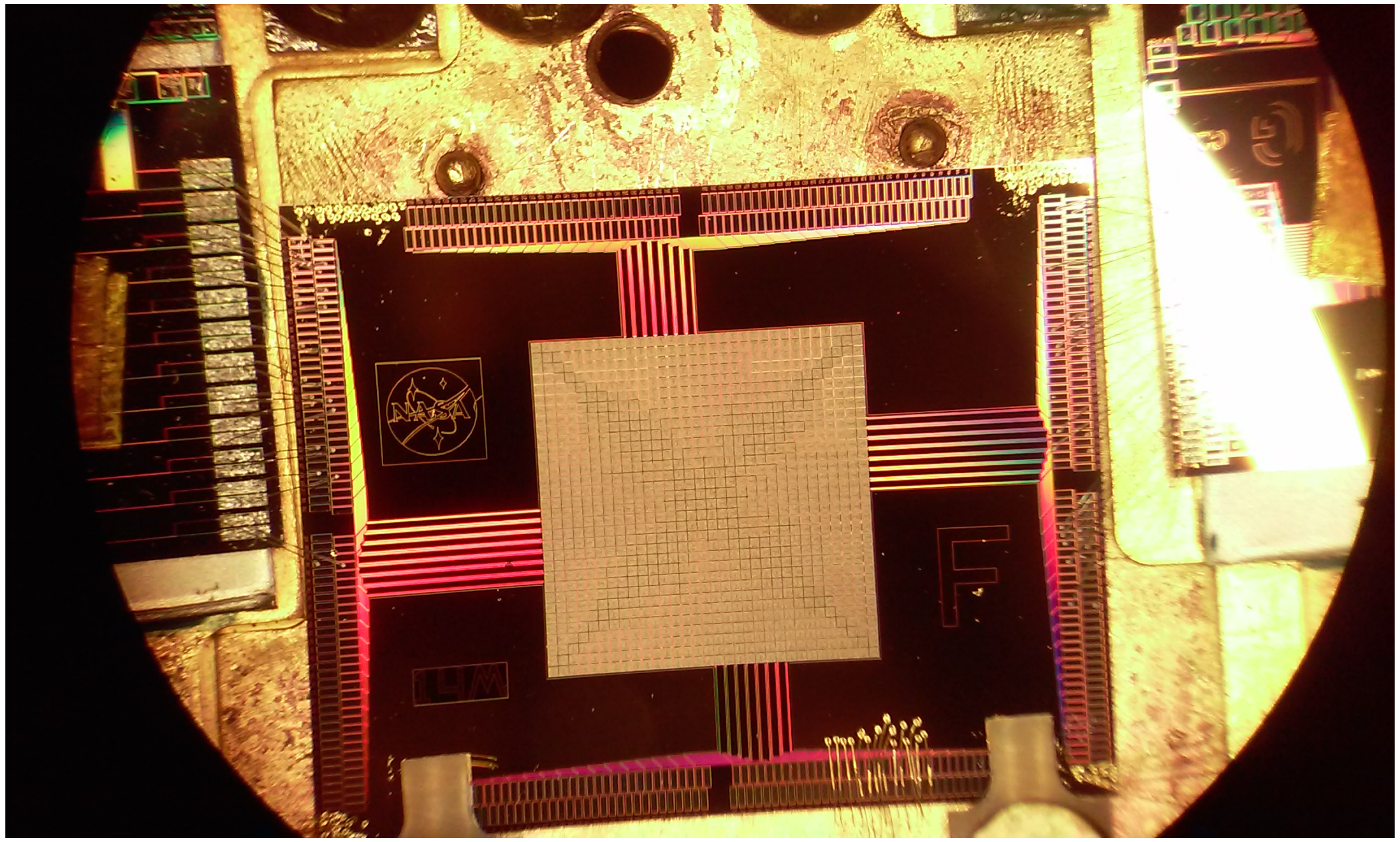


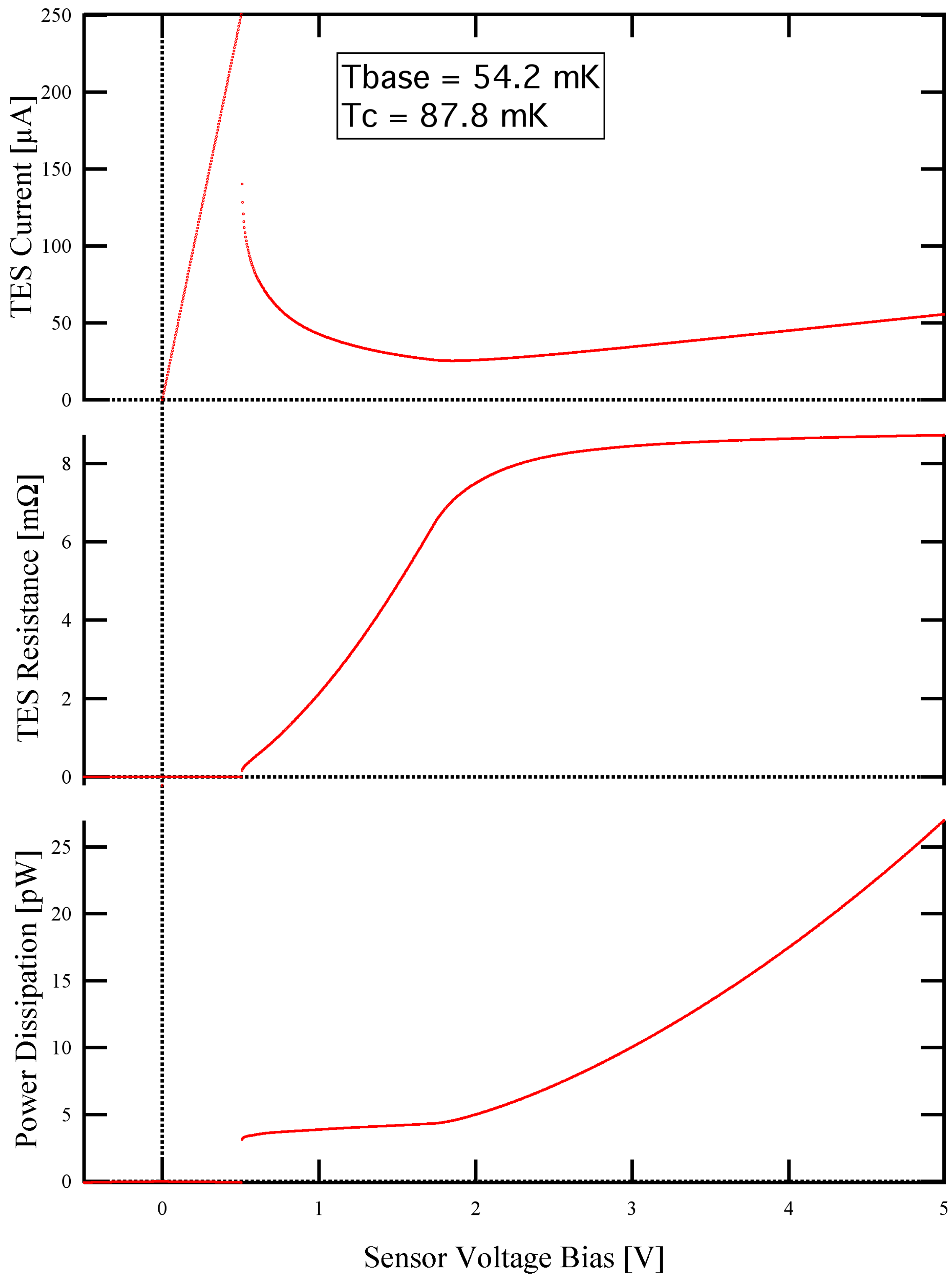




Technical Progress

- Problem encountered with some recent arrays, eventually found to be due to heat-sinking layers going superconducting, due to Ti sticking layer under gold.
- Problem now fixed and heat-sink layers (& NASA logo!) no longer superconducting.
- New arrays have yielded with more uniform transition temperature (and hence performance) than previously.
- Smoother I-V curves under DC-bias, leading to reliably better performance.

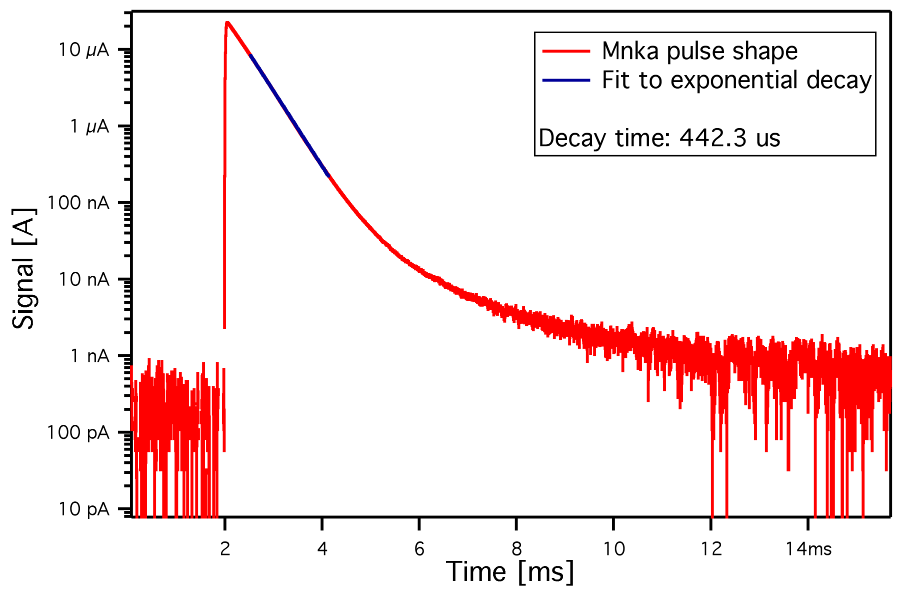




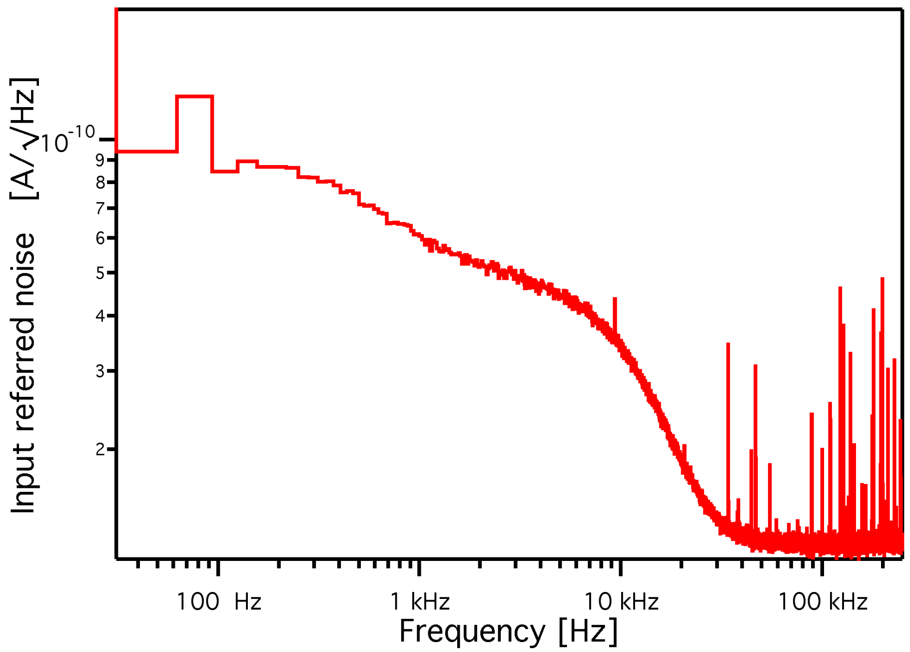
Properties of DM "LPA1"-like pixels (140 um TES)

- Pixel properties agree well with those expected from modeling:

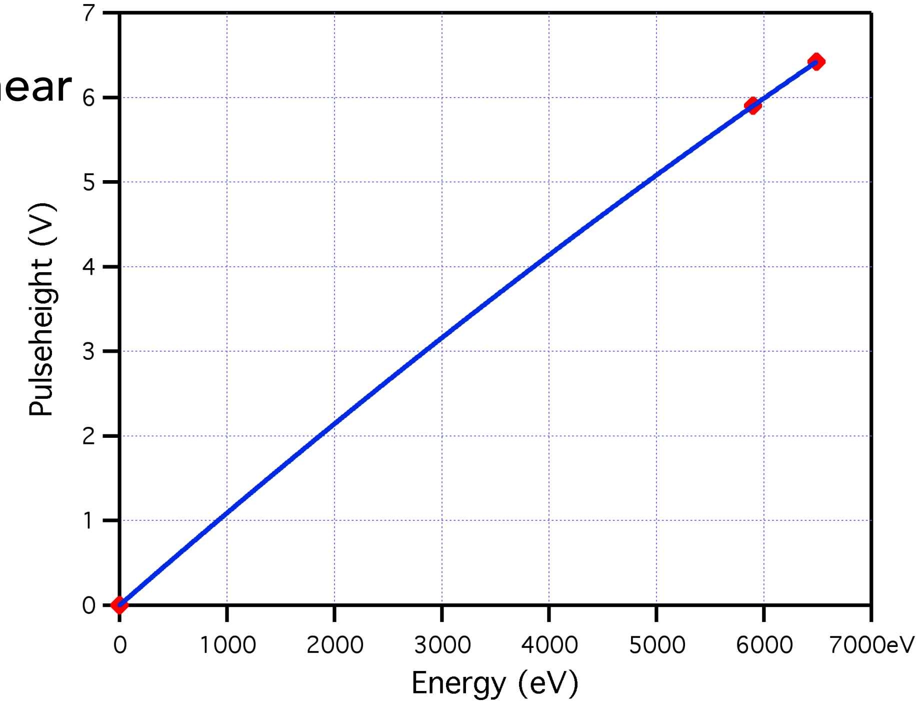
Decay time for LPA1: from modeling: 436 us, measured: 442 us



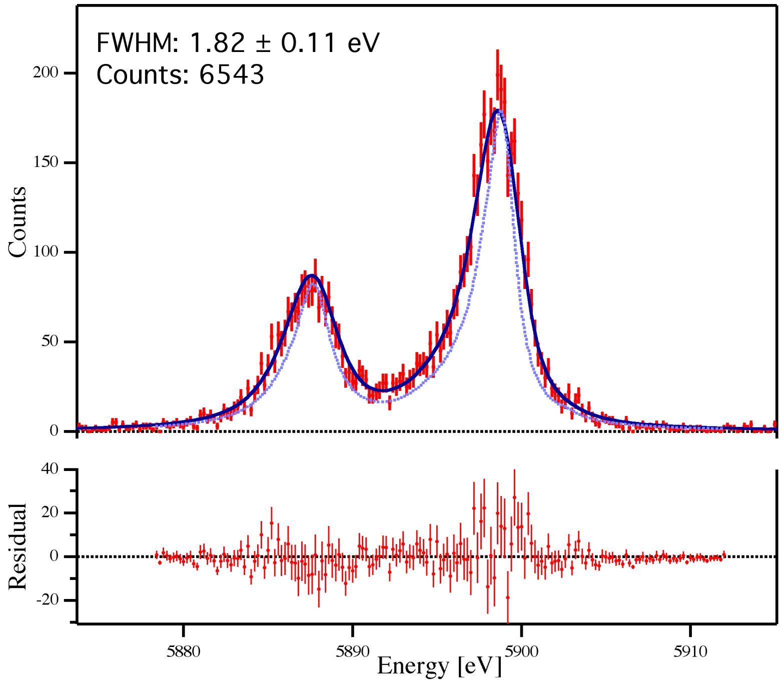
Measured noise levels – as expected



Gain close to linear – as expected



Best spectrum:



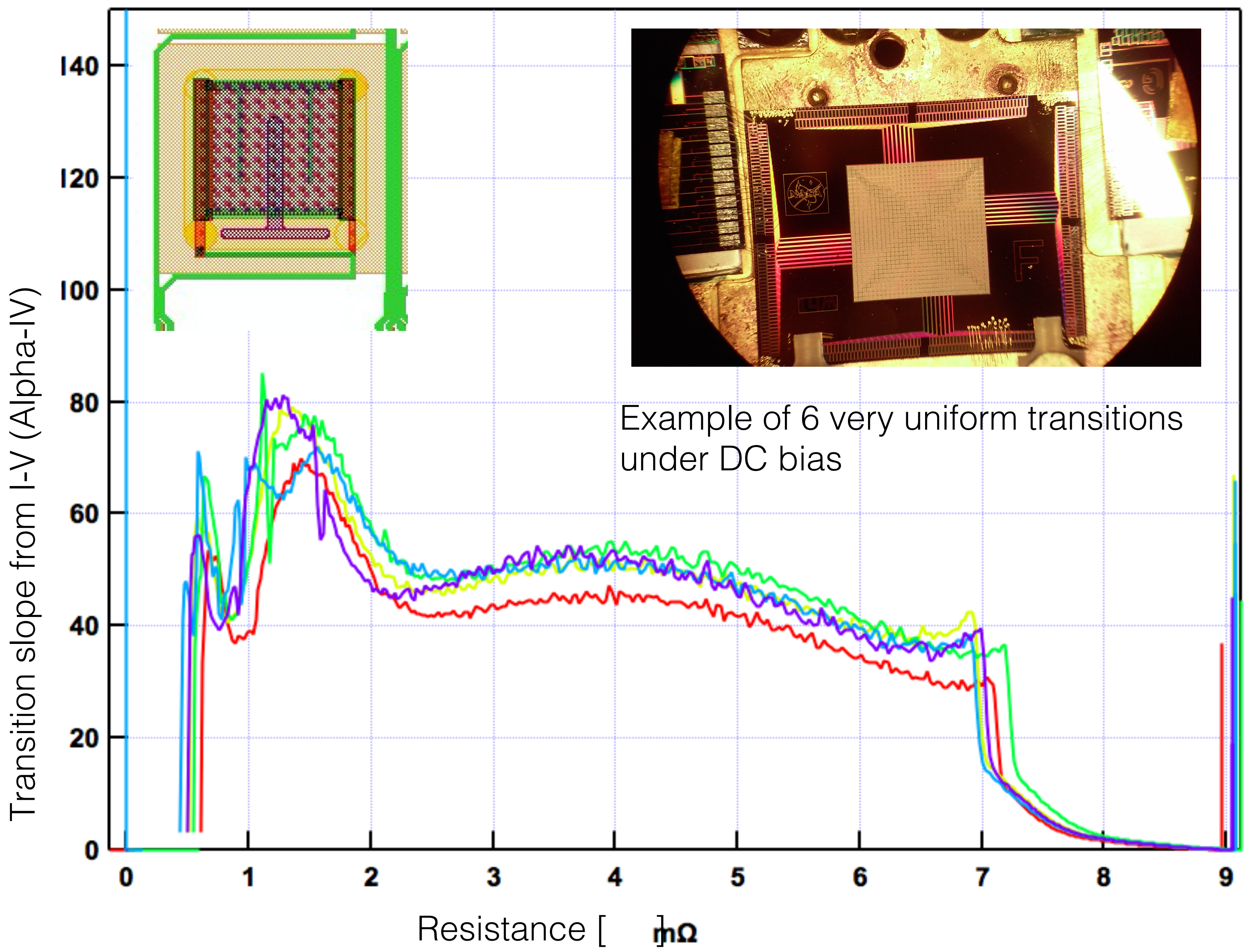
LPA1-arrays: Key transition properties now very uniform

- 140 um TES
- Measured variation of Tc across chip: ~0.5mK
- Average Tc ~ 89.4mK (Target 90.0 mK)

- G(Tc) ~ 200 pW /K
- - close to target 200 pW/K
- - now using thinner SiN that reduced G
- to target value.

- Tested spectral resolution of 6 pixels pixels at R/Rn ~ 20%
- Typical values:
- Int. nep without x-ray ~ 2.05eV
- Int. nep with x-ray ~2.25 eV
- Resolution for 6 KeV x-ray ~ 2.3– 2.4eV

- Generally good uniformity of the transition shape. Some minor subtle variations.



Technical Progress: LPA-2/3 style arrays

Several approaches under study for adjusting G_{bath} for different configurations.

1) Pixel size.

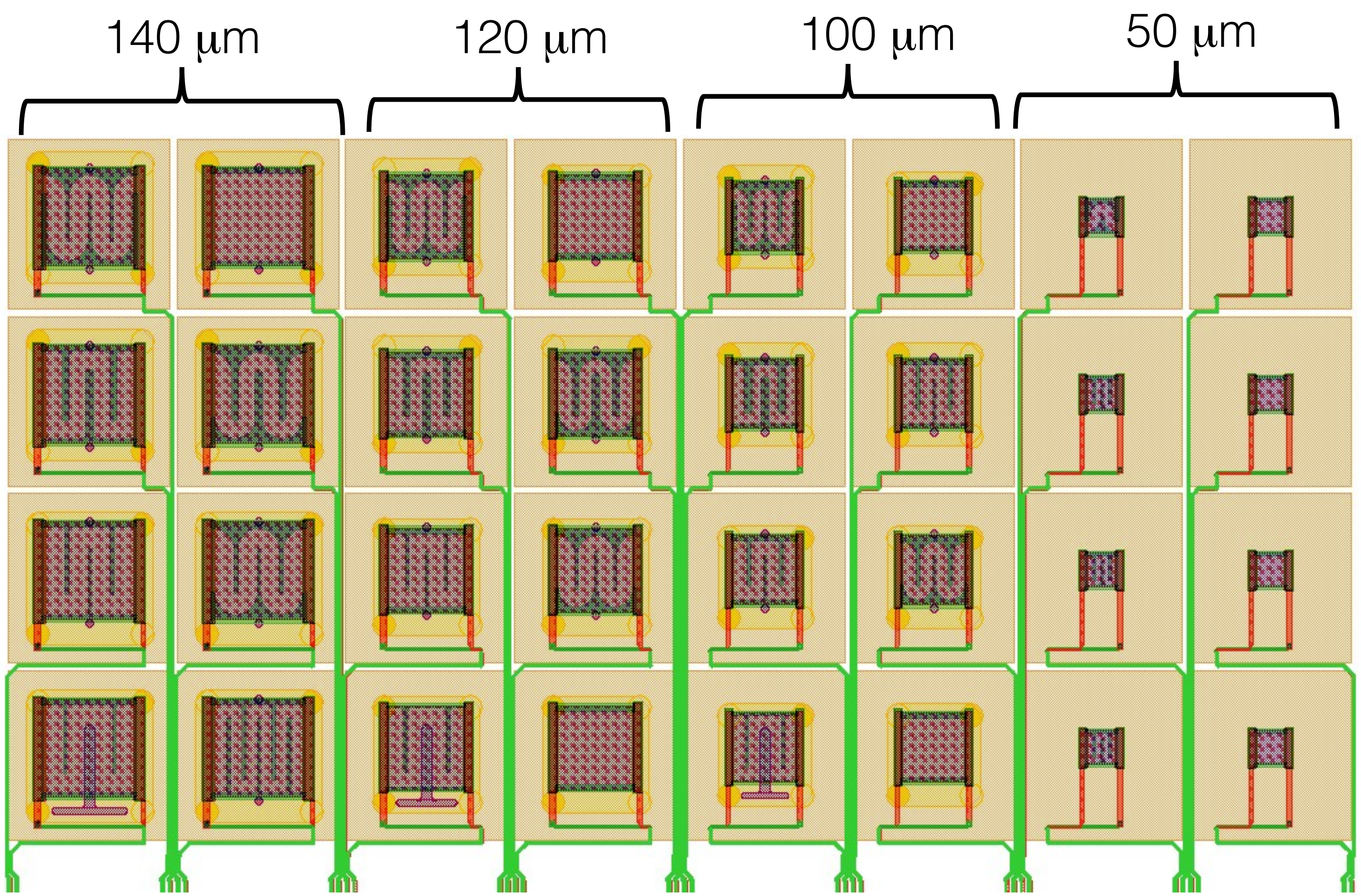
- G scales with TES perimeter.
- 140->100 μm => 30% reduction in Gb.
- Recent arrays yielded agrees with this expected scaling.
- Alone not enough to make LPA2 with 0.5 μm SiN
- New 50 μm TES – good for LPA3

2) Perforate/slot membrane.

- G scales with slot fraction.

3) Reduce SiN membrane thickness.

- Thickness range: 0.25, 0.5, 1 μm.
- Latest arrays use 0.5 μm, future prototypes will use 0.25 μm

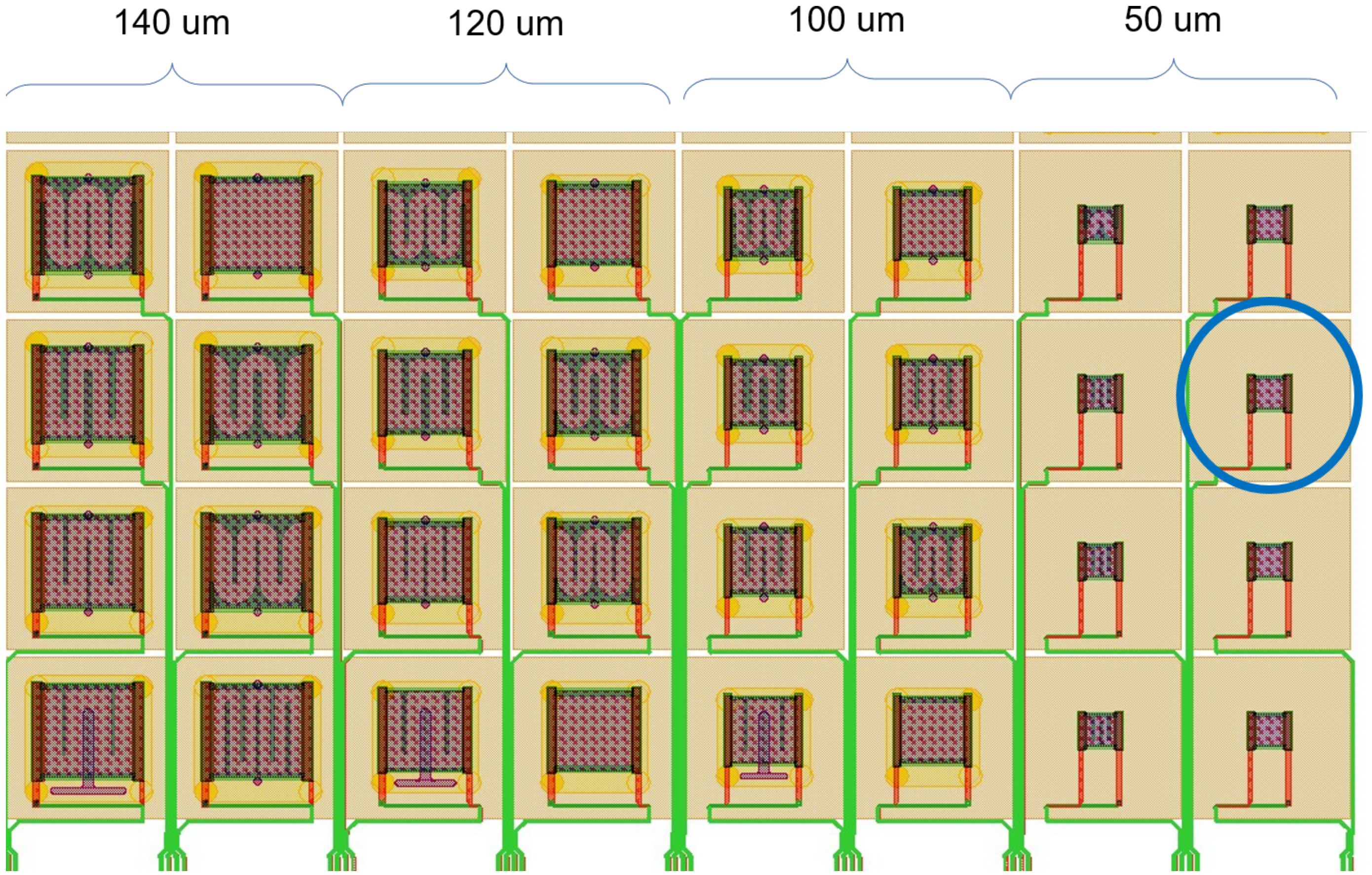


"Mixed chip" with TESs of different sizes (different G's) as well as different normal metal and absorber "stem" designs

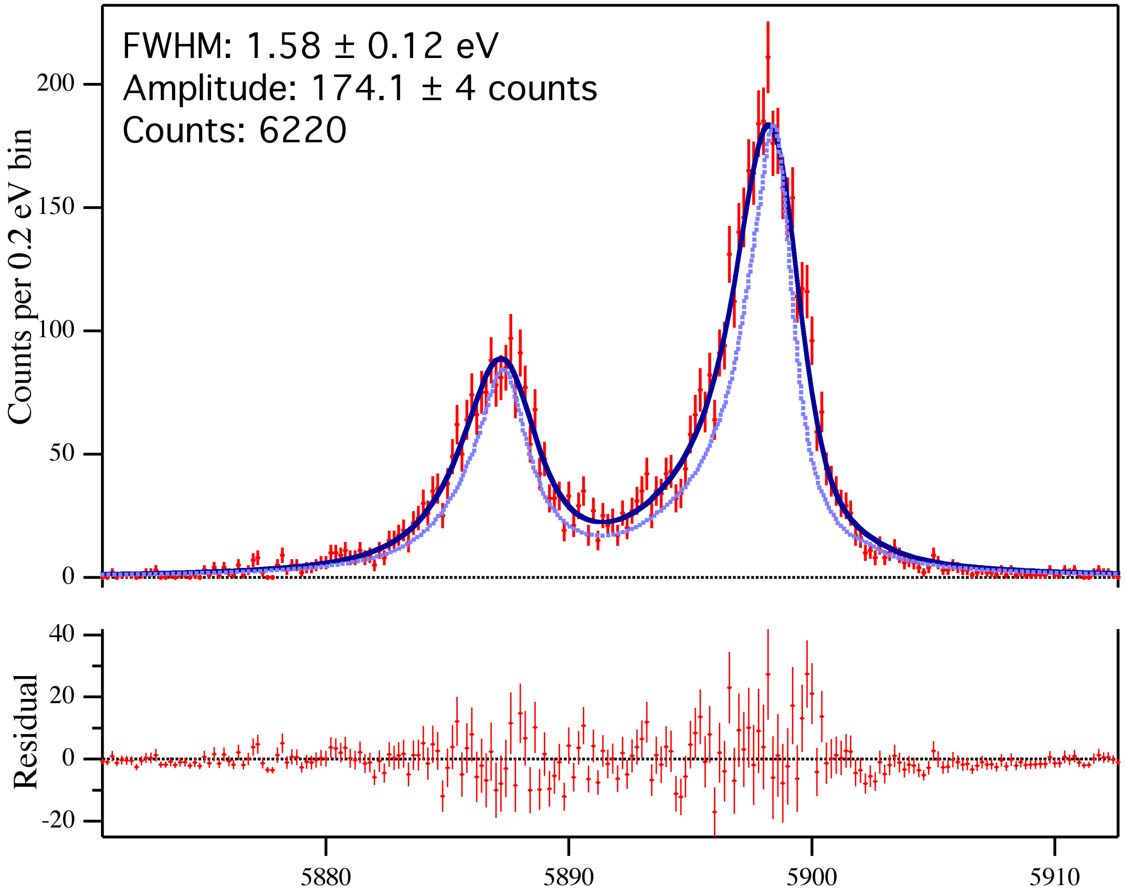
Simon Bandler

Technical Progress: Development of "LPA3" style pixels

- Smaller "low-G" 50-micron TESs on membrane, "LPA-3"-like.
- Usual "LPA" absorber size (~240 microns)
- X-ray pulse decay time (t_{etf}) = 2.2 ms - ideal for lower expected count-rates and larger multiplexing factor!
- No stripes, T_c at low bias = 107 mK,
- Operated at 5% Rn, transition temperature under bias (5% Rn): 86 mK
- With smaller TES size, optimistic about performance under AC bias
- Shipping chip of this type to SRON.



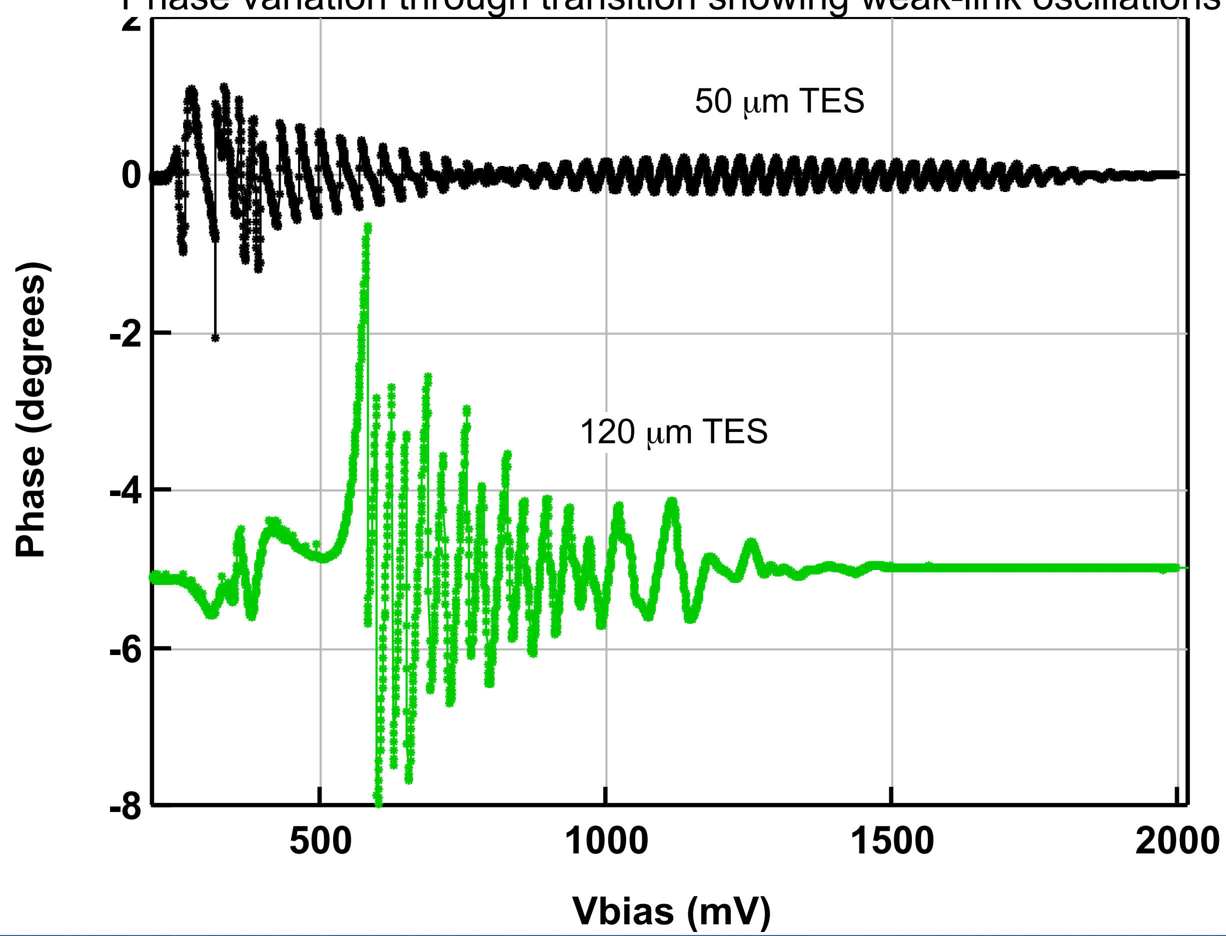
Best ever spectrum at 6 keV for pixel of this size!

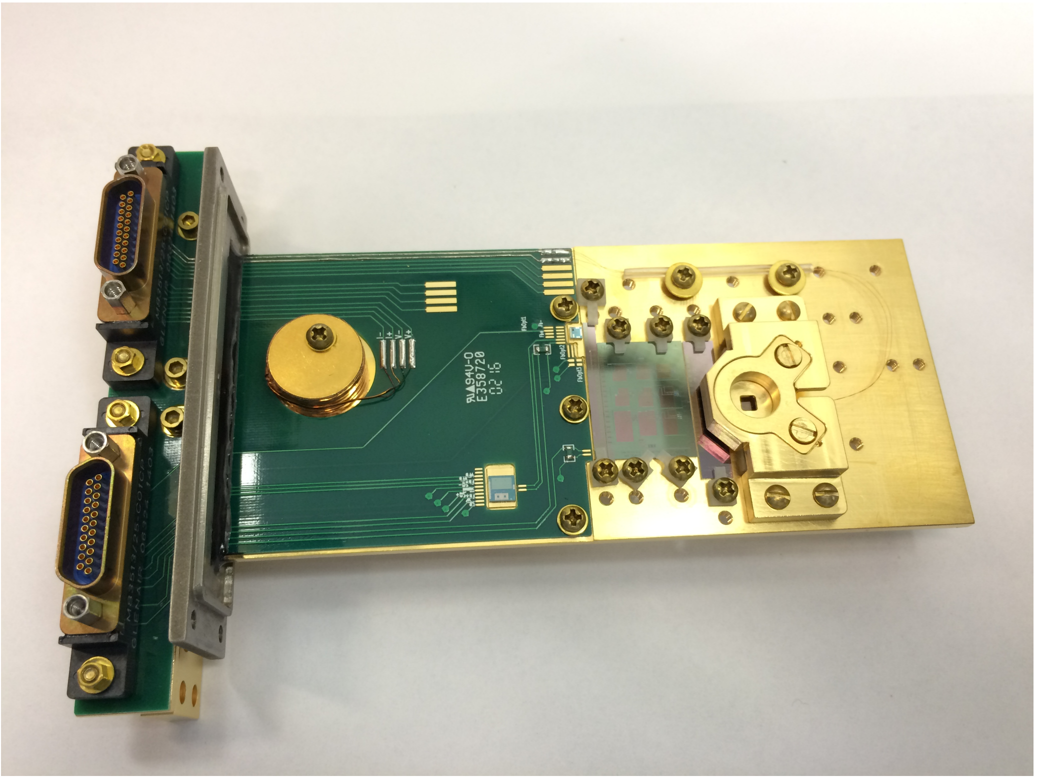


Technical Progress: TESs under AC bias

- Partly in Ullom's AC bias SAT, more extensive studies covered in this program. This work now merging into this single Athena SAT program.
- Sent test detector array chips to SRON and participated in tests of these devices at SRON – ongoing.
- Began AC-bias tests at GSFC.
- Purchased/installed SRON-style FDM electronics for testing at GSFC.

Phase variation through transition showing weak-link oscillations





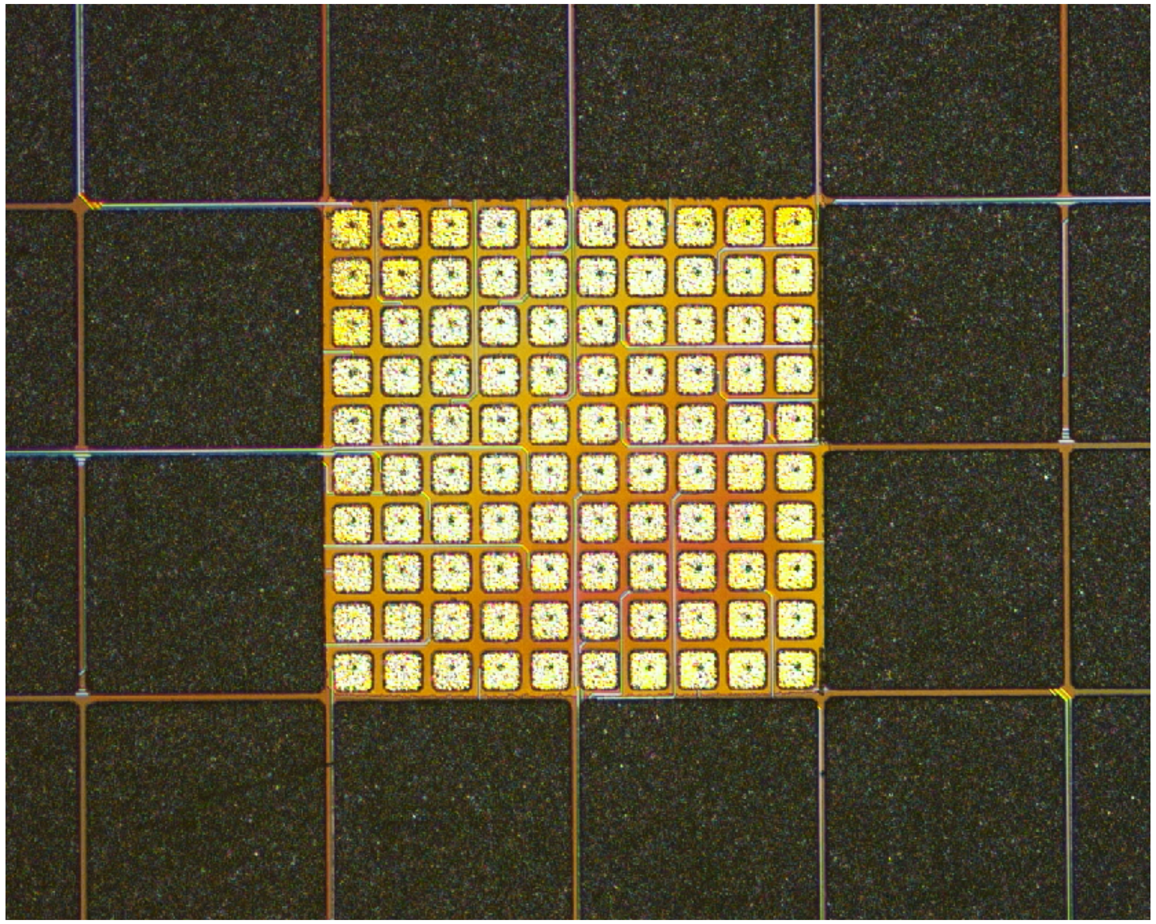
Technical Progress: Hybrid Arrays

Fabrication techniques being developed for producing *"hybrid"* arrays ("Athena-2").

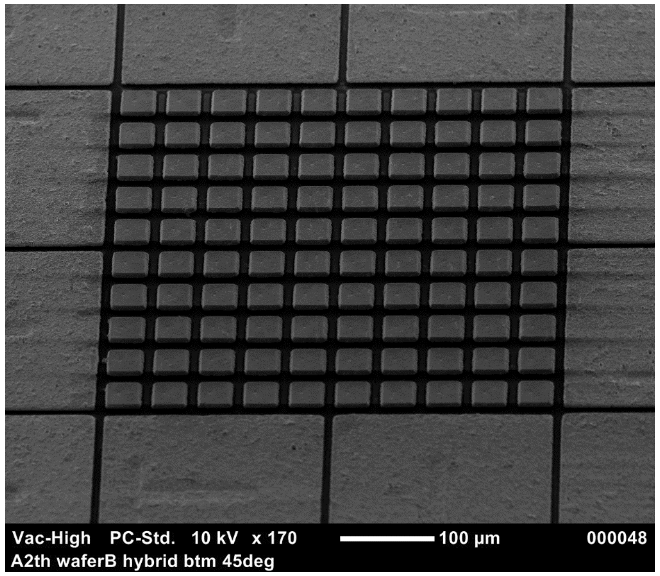
- General process to fabricate hybrid arrays demonstrated by last consortium meeting

- Ion-milling process development
  - needed for minimum gaps between pixels with different pixel types
  - significant progress made.

- Heatsinking integration with demonstration parts
  - progress made & continued development



Hybrid array with two absorbers



Technical Progress: Design of first "Athena-3" full-scale arrays, fully wired

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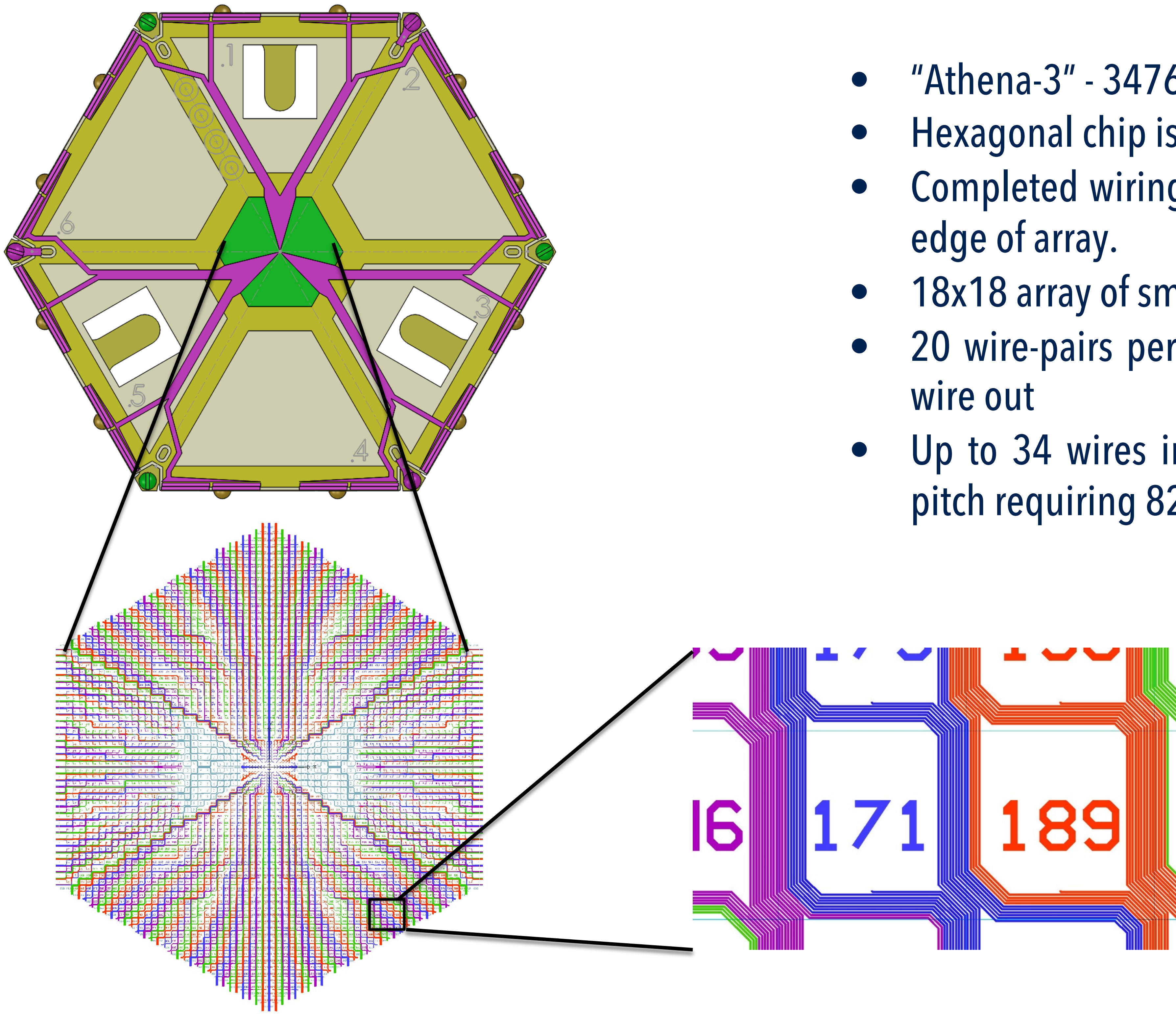
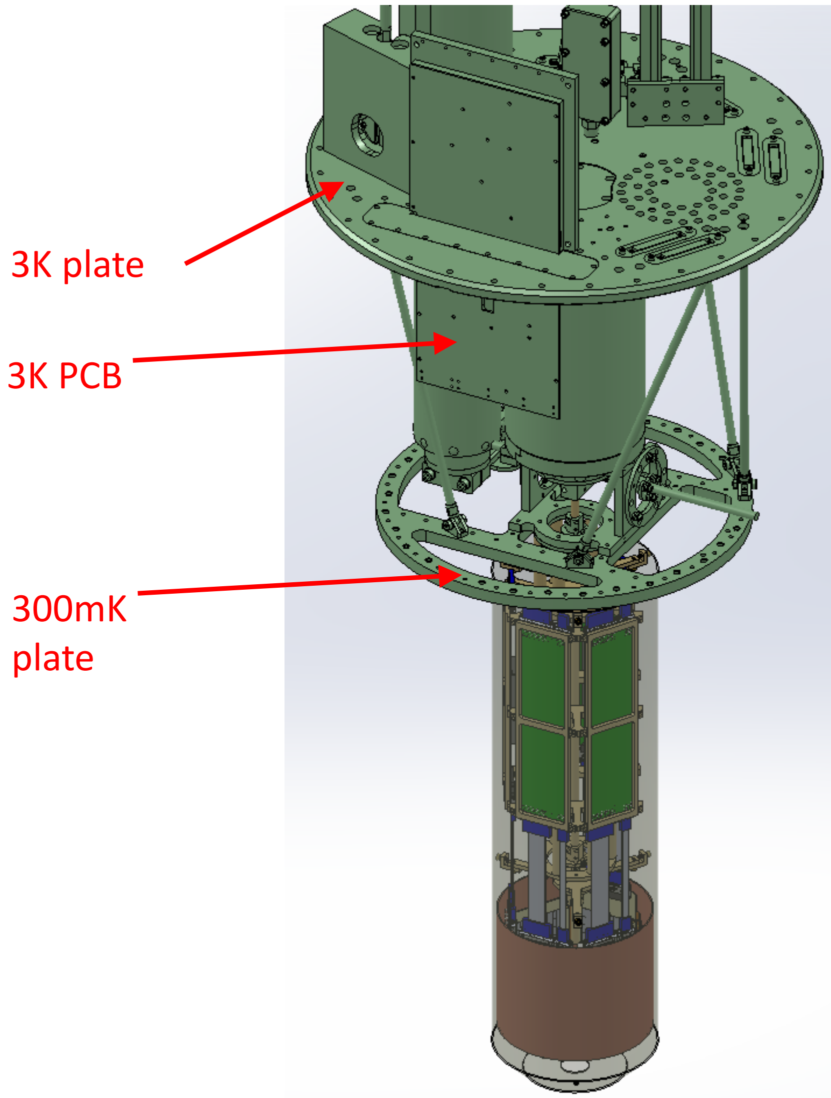


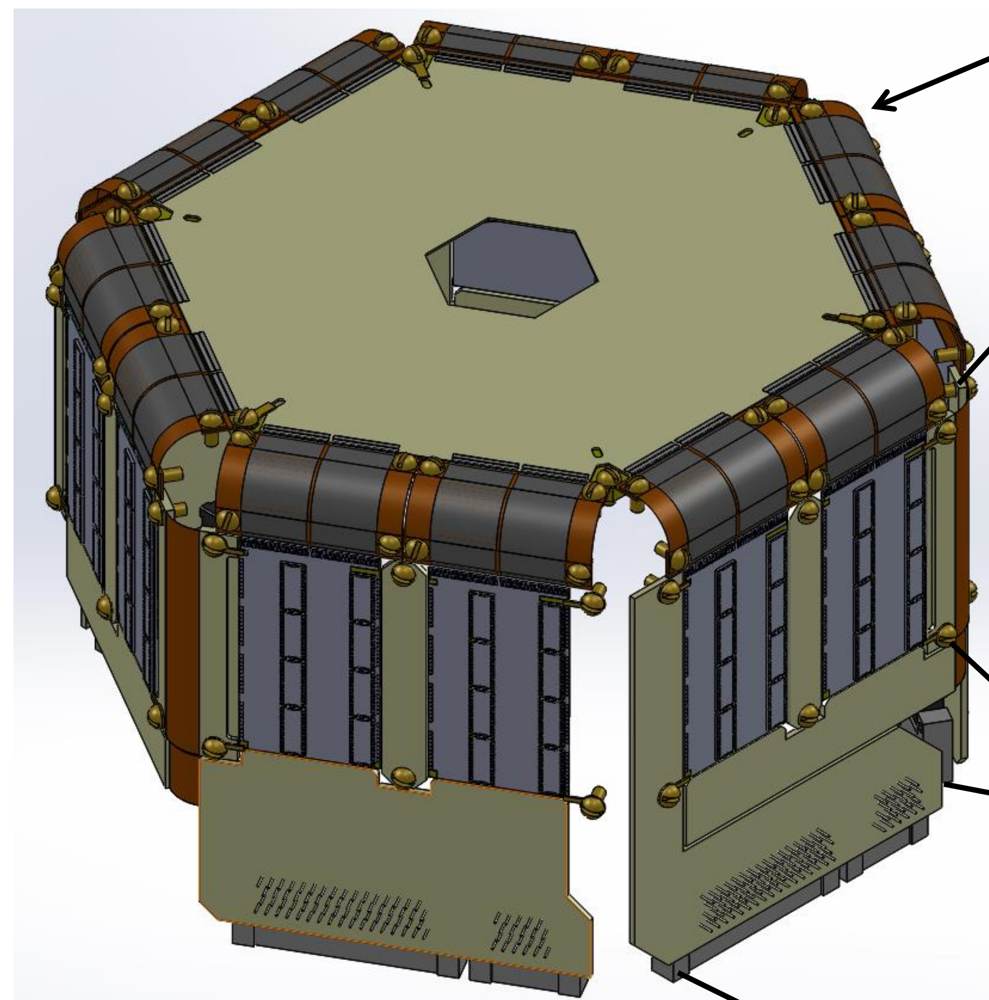
- "Athena-3" - 3476 large pixels on 260 μm pitch.
- Hexagonal chip is 91mm on diagonal
- Completed wiring of hybrid array for each pixel to edge of array.
- 18x18 array of small pixels - 115.5 μm pitch)
- 20 wire-pairs per muntin maximum is needed to wire out
- Up to 34 wires in corners. (Wiring on 4 micron pitch requiring 82 micron wide muntin).

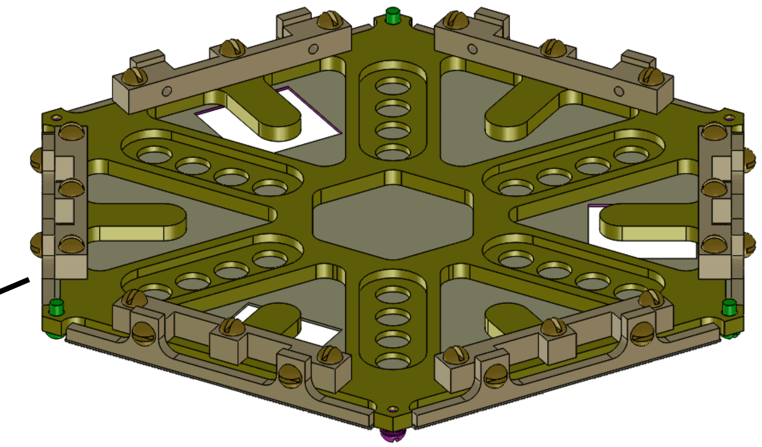
Details of array where in-muntin wiring count is 20 but corners exceed 20.

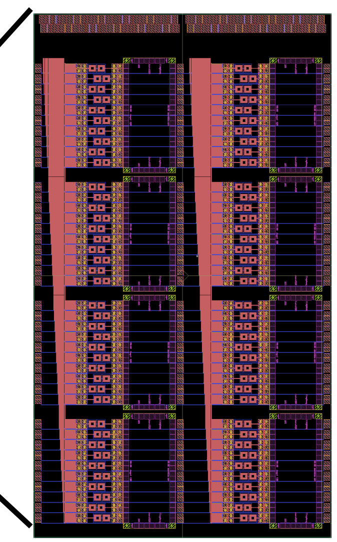
Technical Progress: Architecture for kilo-pixel scale characterization of arrays with 3840 TESs

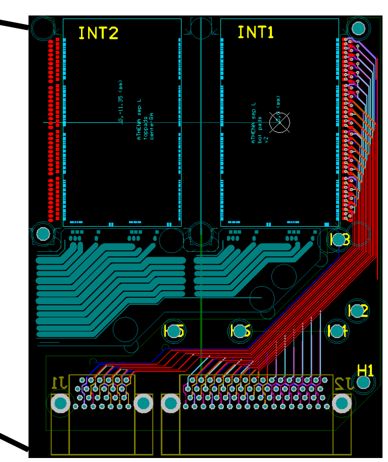
- **Large-scale characterization under DC bias:**
- 40-row, 24 column architecture => 960 pixel characterization







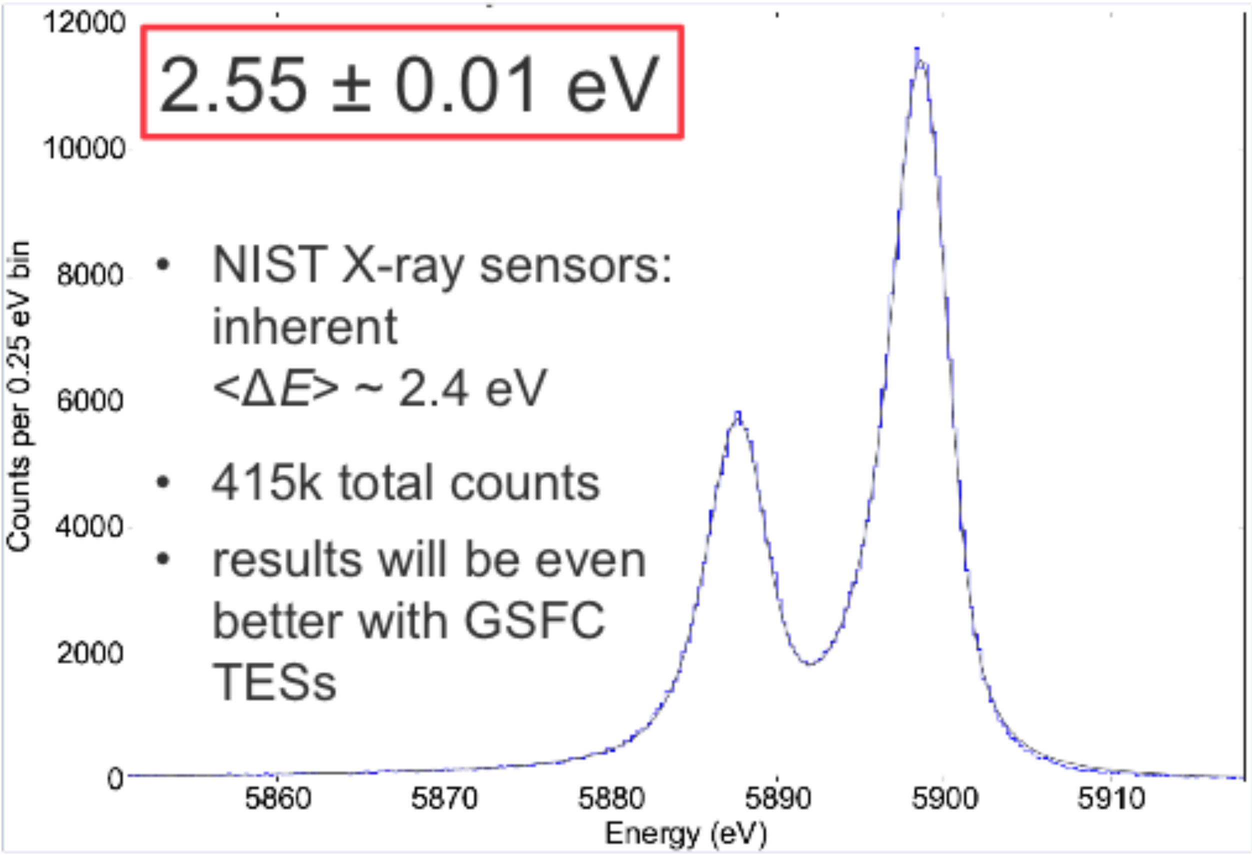


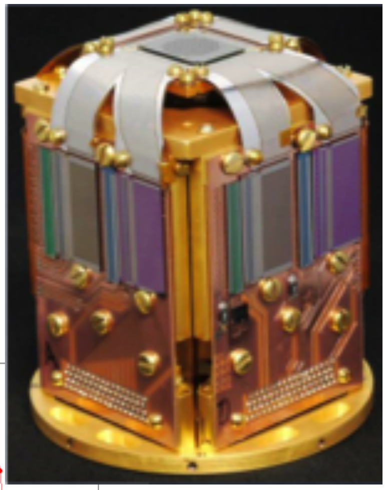


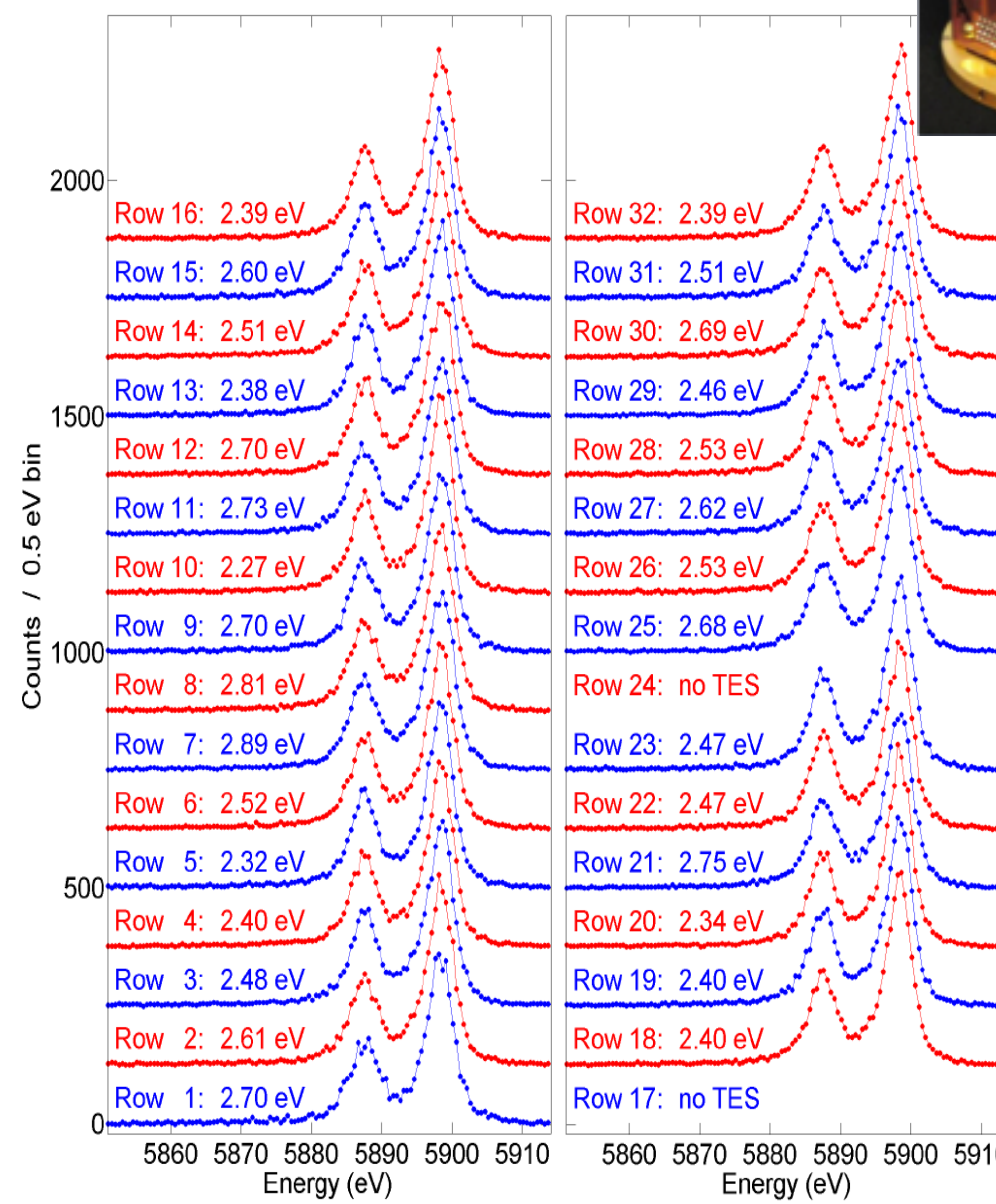
- Installing one at NIST, one at GSFC
- Delivered to NIST, delivering to GSFC Jan. 2016

- Heat-sinking to rear side of array
- Kinematic mounting of wafers

Time-division multiplexing



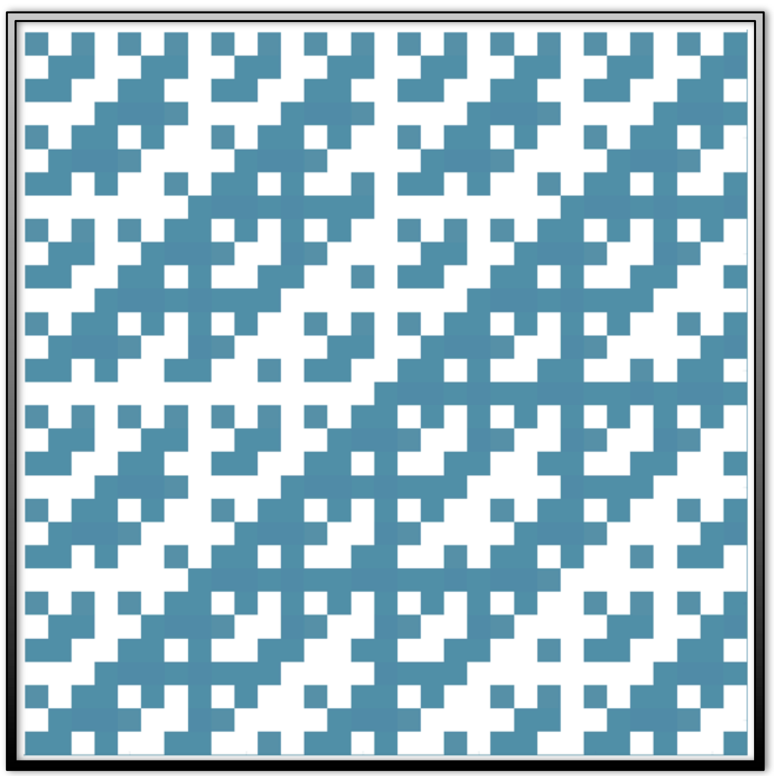




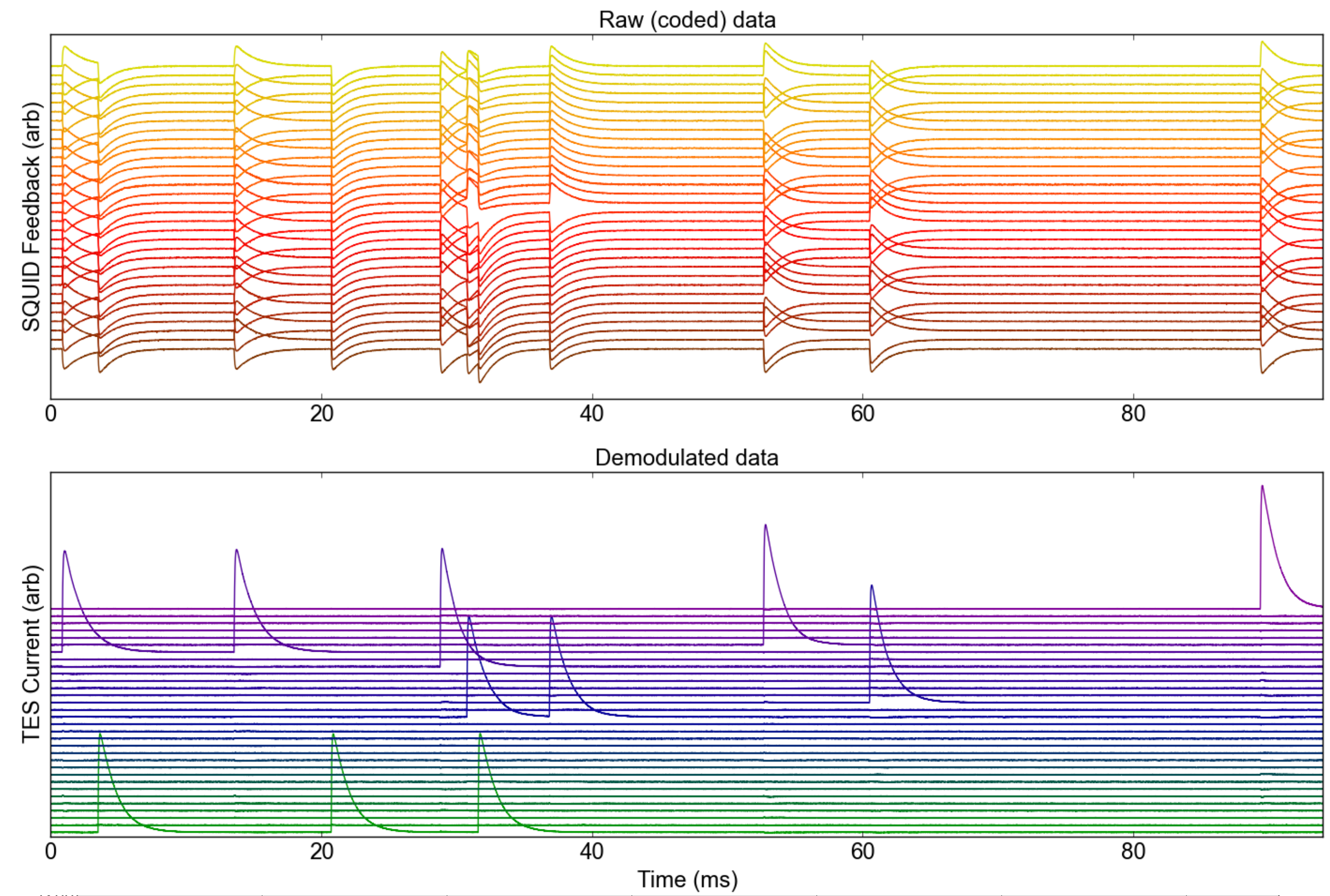
- Combined spectrum: 32-row TDM
- T_{row} = 160 ns
- Almost no energy resolution degradation from multiplexing

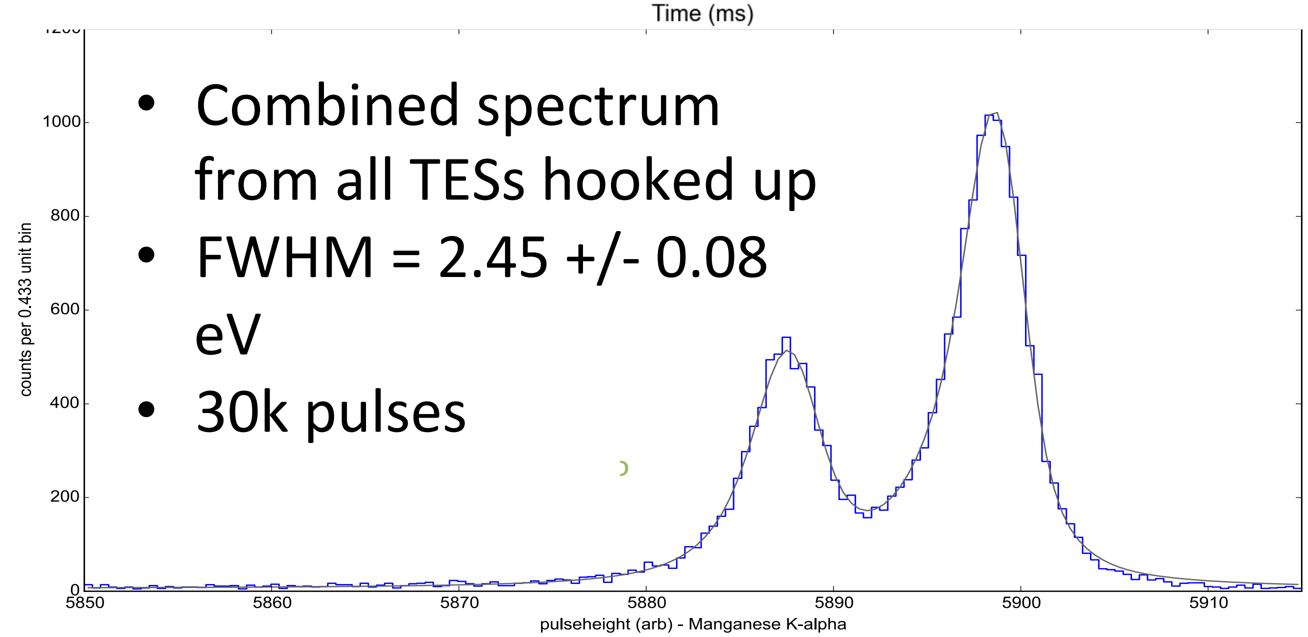
CDM 32-row feasibility demonstration

- FWHM = 2.45 +/- 0.08 eV
- 30k pulses
- from read-out
- No energy resolution degradation from read-out
- Now also 2.77 eV in 30 sensors (excluding unmodulated channel)

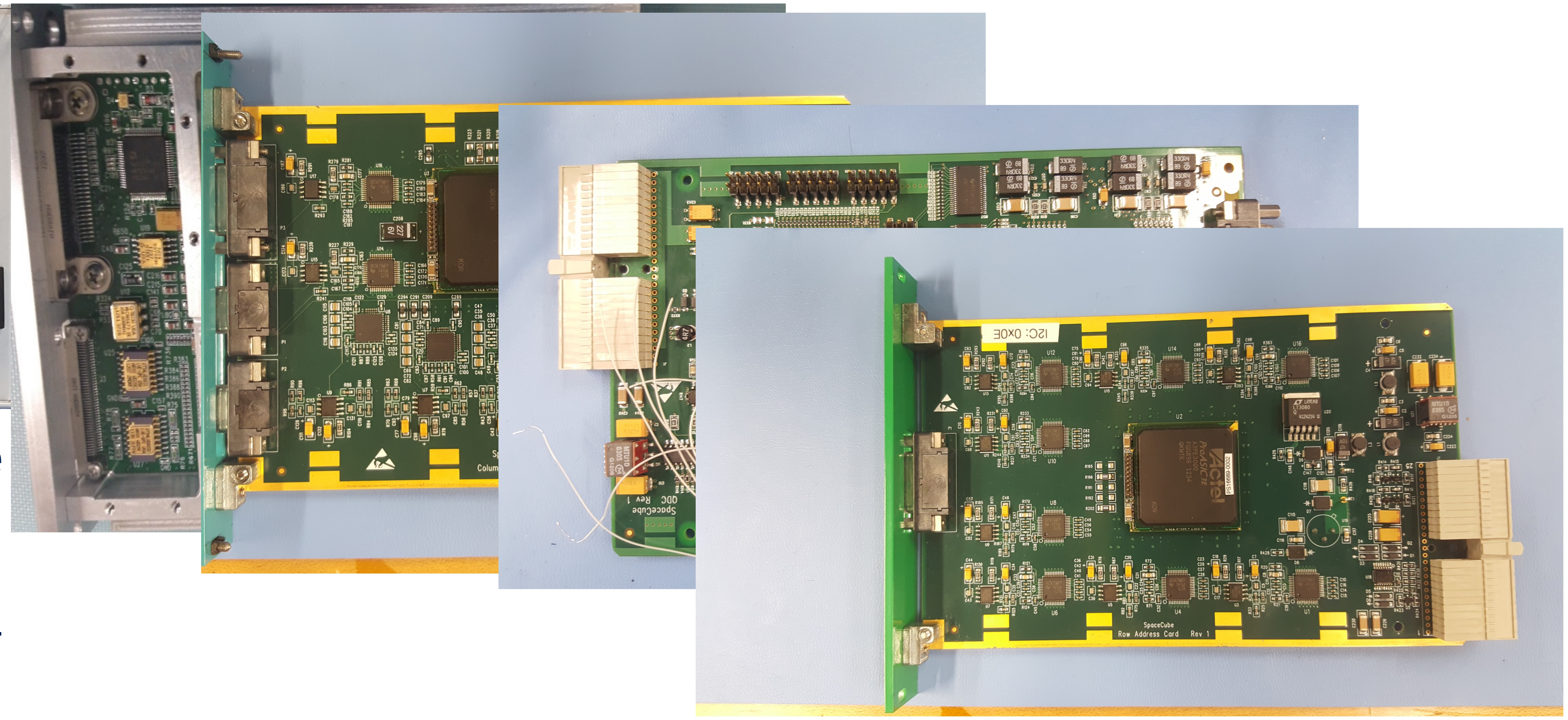


Modulation matrix

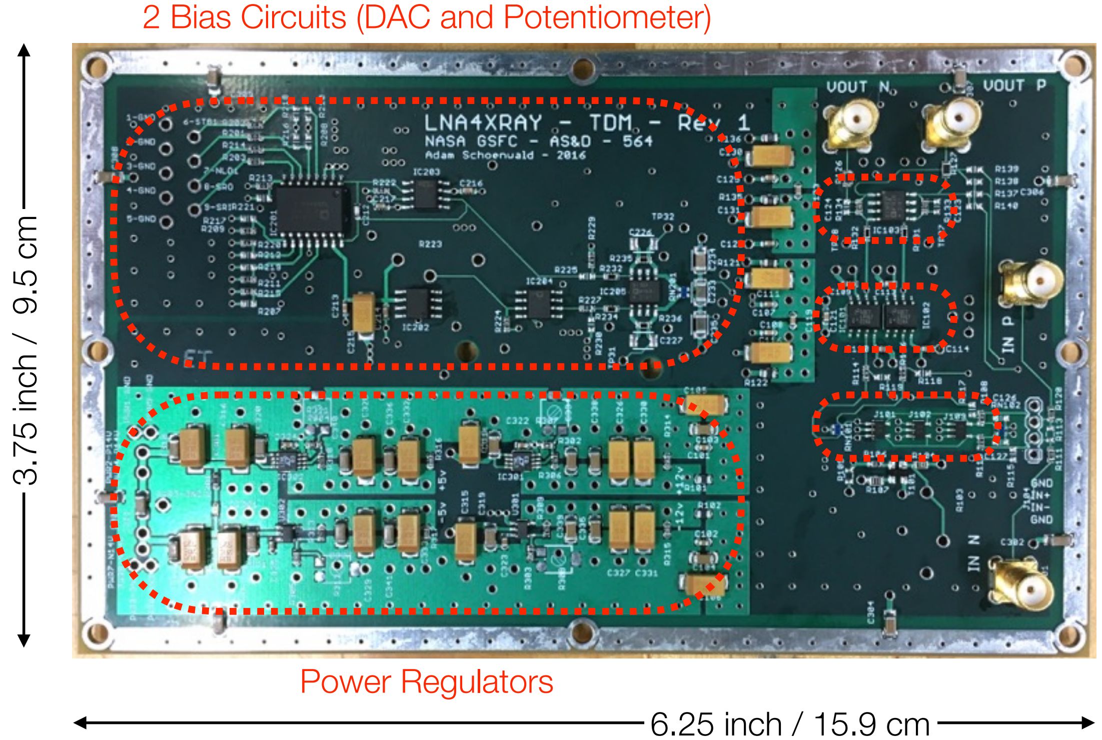


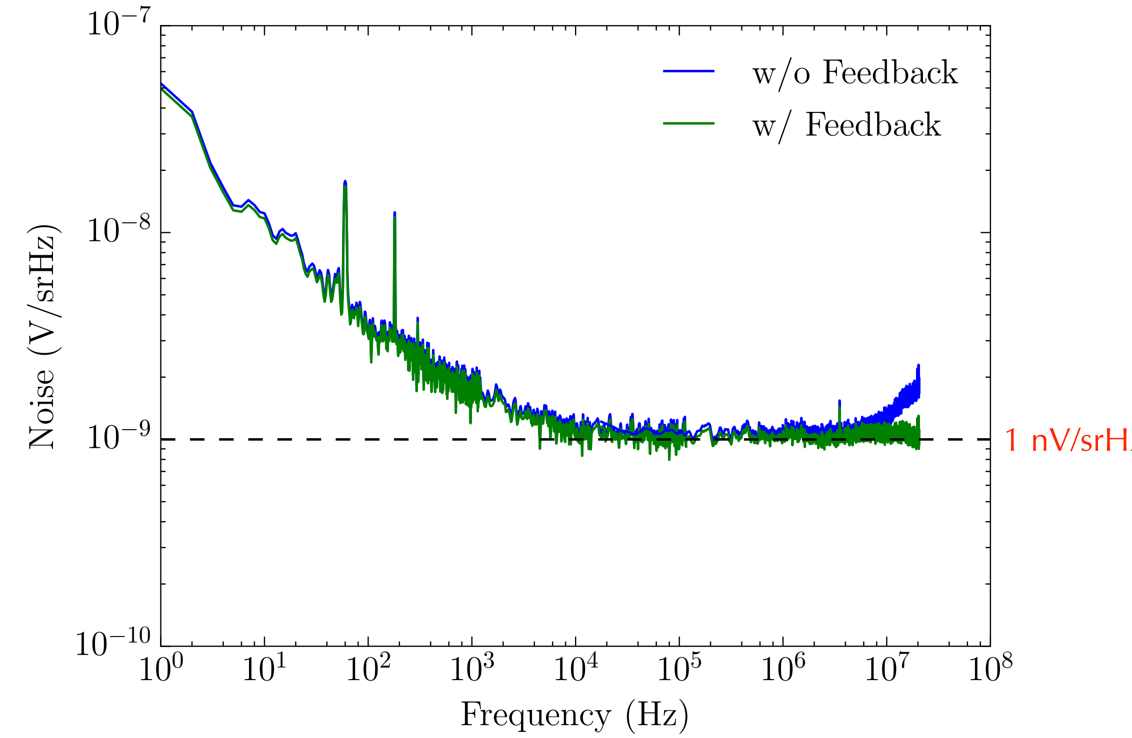


Technical Progress: Flight-compatible electronics for the TDM/CDM option – utilizing GSFC "Spacecube"

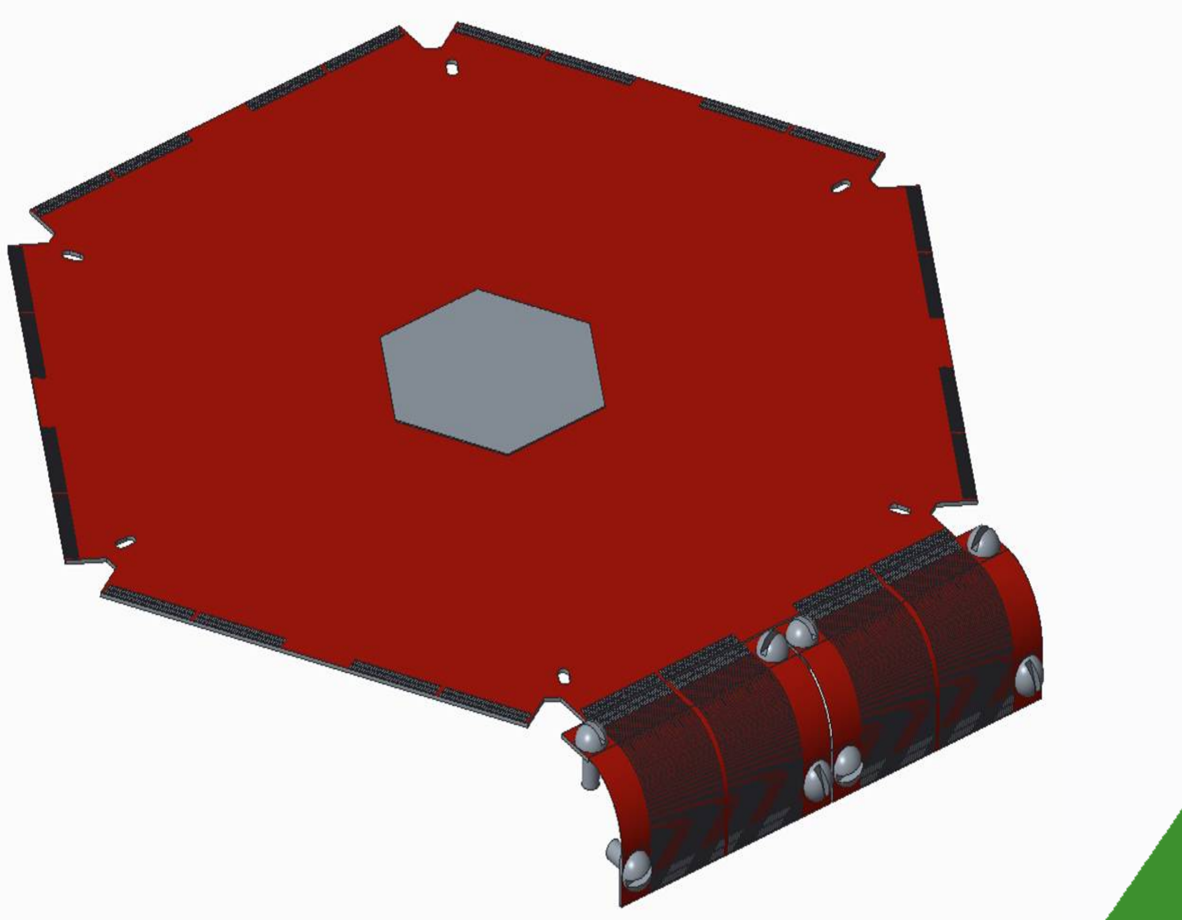


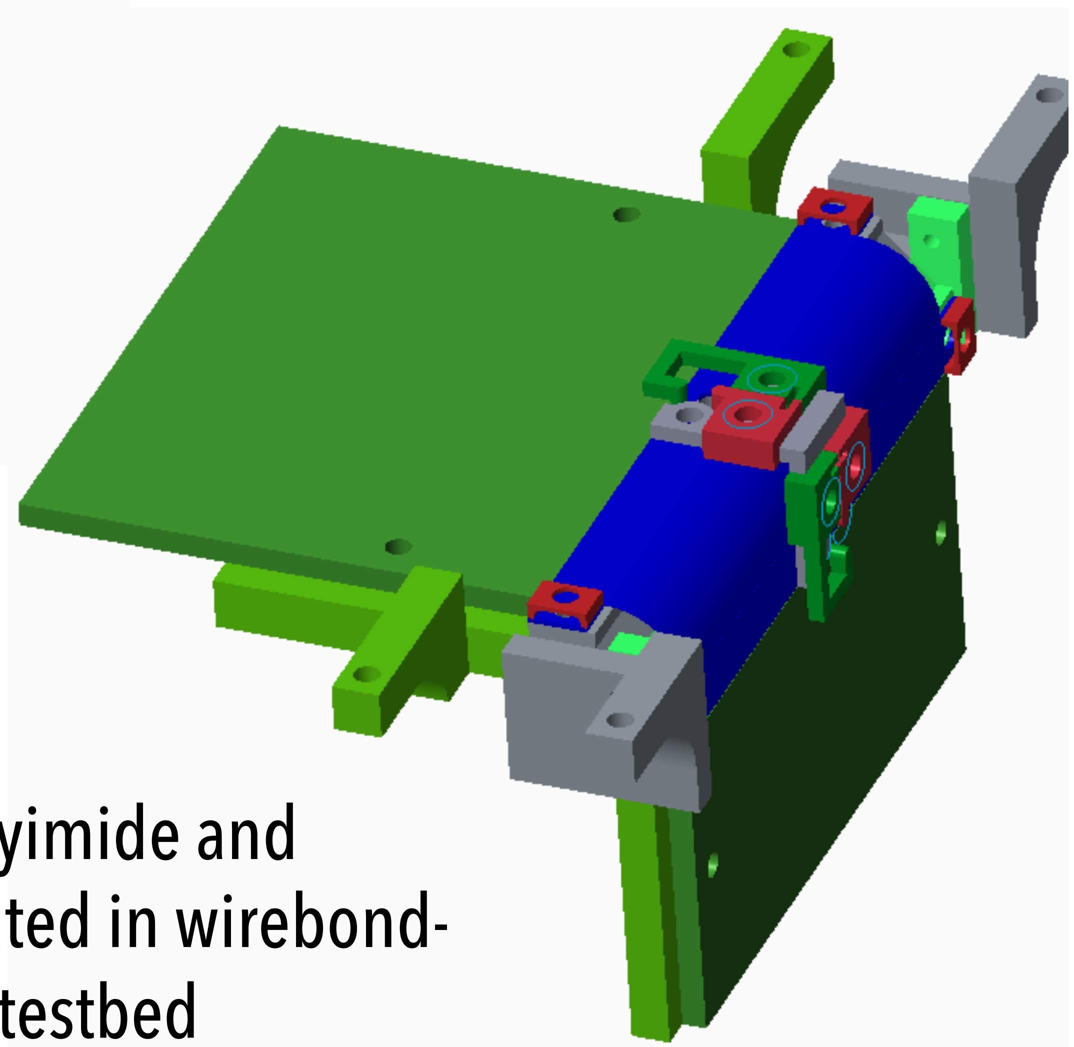
- Further Development of flight-compatible digital feedback electronics - following on from GSFC IRAD program.
- Designed, fabricated and tested new flight-compatible low-noise amplifier.

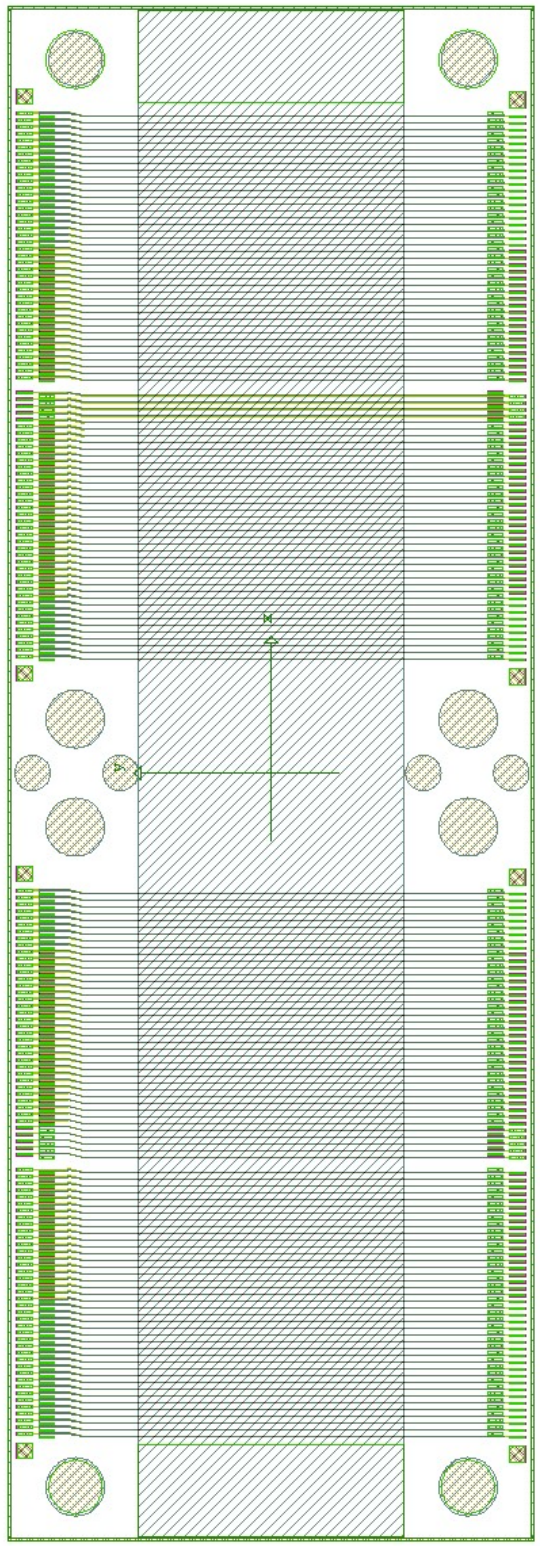




Development of "around-the-corner" flex, with microstrip wiring, to be integrated with bump bonding connections







Flex cable consisting of 12 micron polyimide and microstrip Nb leads will be demonstrated in wirebond-wirebond configuration on TDM/FDM testbed

Technical Progress: Bumpbonded version of assembly with 72 mm hex chip

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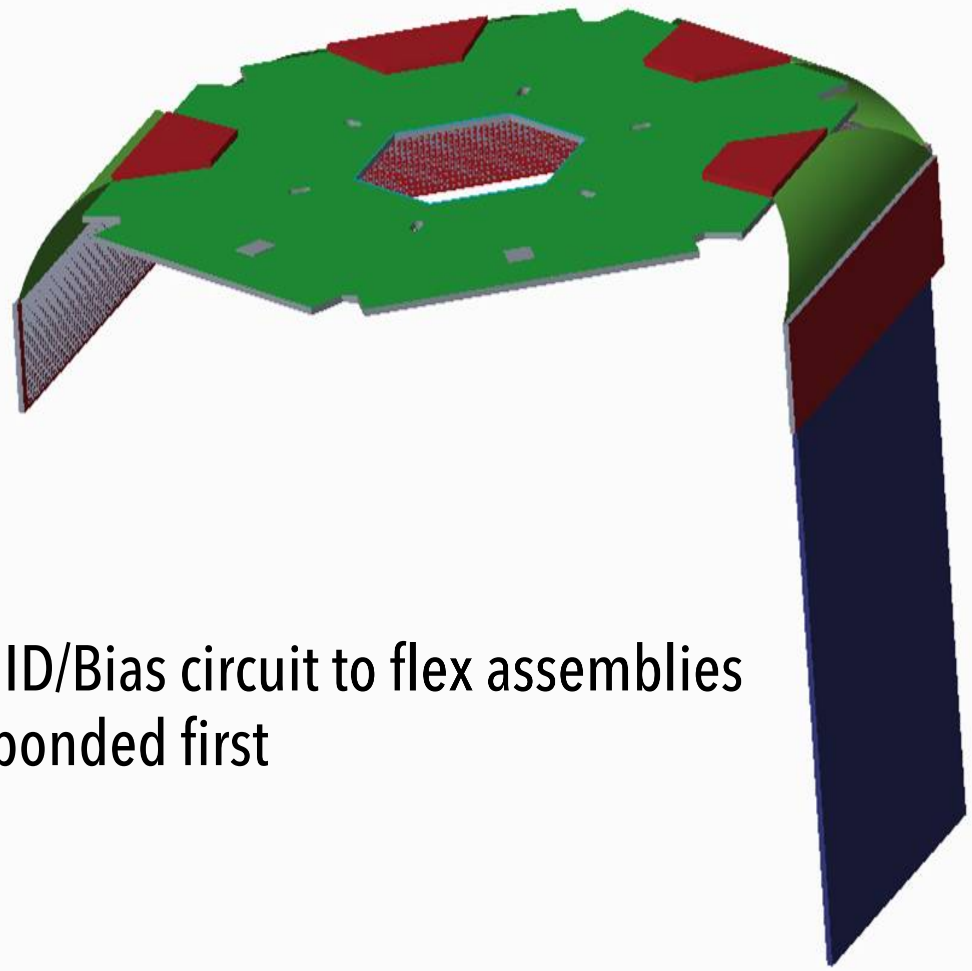
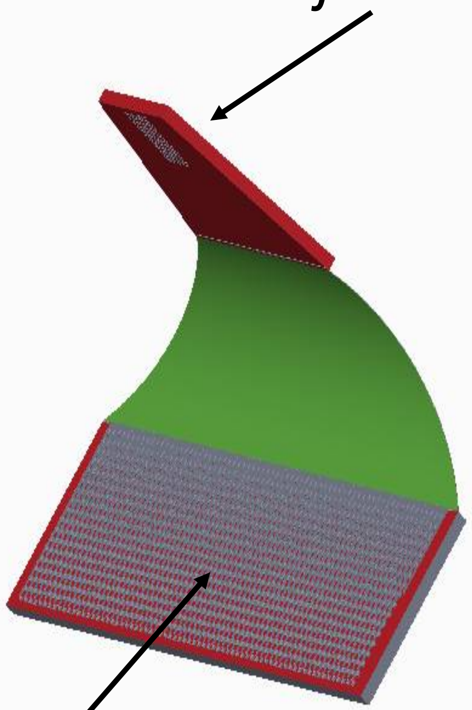


SQUID/Bias circuit to flex assemblies are bonded first

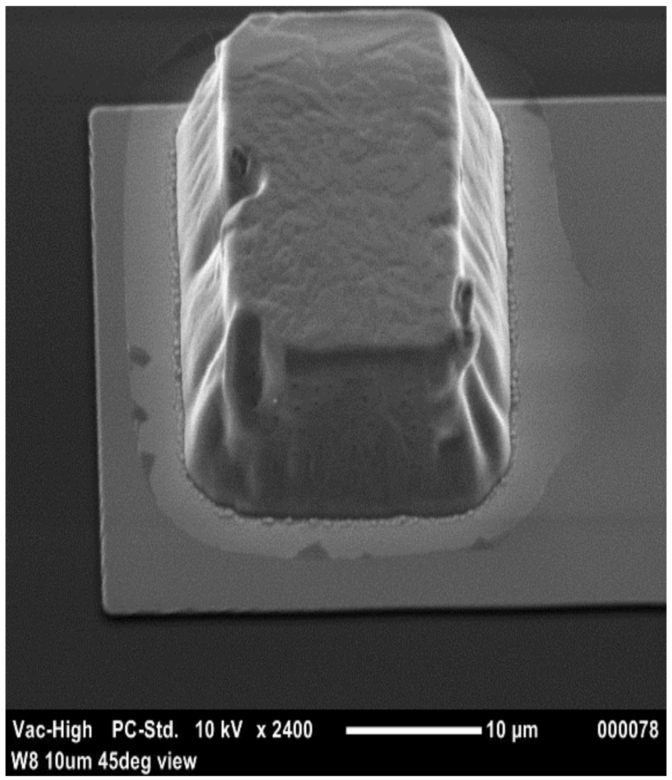


Panel with 10 micron In bumps is silicon only

Mating panel to readout board shown with solder bump option (larger area)

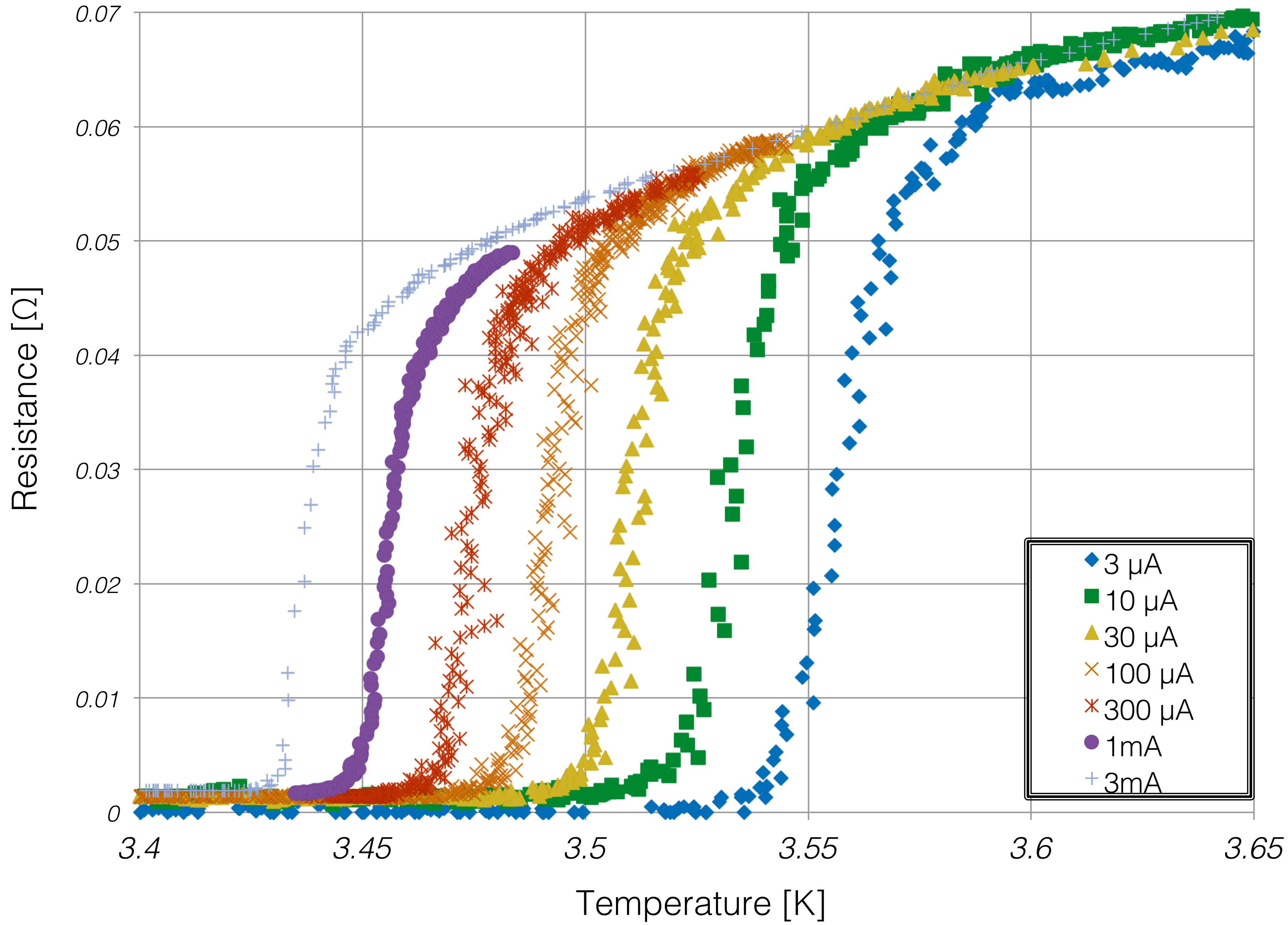
- Fields of indium bumps can be added to hex chip and flex connector.
- Designed to carry 640 pairs of leads for 3840 pixel bias/readout on six sides.
- 72 mm hex chosen to match current iteration of SQUID board (with 35 mm edge)

Technical Progress: Indium bump process development



Indium bump shape – aggressive clean

R v T for 512 In bumps in series at different excitations



10 micron to 10 micron indium bump – Ic above 3 mA at 3 K

Single strings of bumps showed 100% yield at kilopixel scale (512x2)

Important baseline detector change: Uniform LPA1 => LPA2

- Baselining of use of defocussing of X-ray optic allows the spreading of X-rays from point sources across large number of pixels, making the point source count rate requirement (1 mCrab) and goal (10 mCrab) easier to achieve.
- It was also determined that for some read-out options (TDM, possibly also FDM), that by careful design, detector count rate requirement could be met by LPA2 pixels without defocussing.
- 11/28/2016 – Change on the detector baseline configuration from LPA1 to LPA1 pixels - approved by Consortium Management Team.
- Should now focus development activities on LPA2 pixels.
  - To be discussed: availability of LPA2-like arrays for the DM
- Reserve margin in readout engineering challenge for now.
  - TBD if this will be used to relax requirements / increase margins in readout design and/or reduce #'s of channels.
  - It will likely add read-out margin as read-out requirement for LPA1 was very demanding for TDM, CDM and FDM, and affected power dissipated by SQUID read-out at 50 mK.
- Uniform array of LPA2 (not hybrid) now is very clearly the baseline
  - However, SPA/hybrid array remains an option in order to meet energy resolution goals (1.5 eV), but likely with new central array pixel designs.

Potential requirement of observations of ~1 Crab sources by X-IFU under study

- Long-standing 1 Crab capability (> 30% low-res events, ~ 30 eV)
- When using defocussing optic, the scientific justification for observing ~ 0.1 – 1 Crab sources is under study by X-IFU science team.
  - Perhaps with use of Be filter to reduce counts under ~ 1 keV.
  - If 10 times fewer counts with filter, after throughput considerations, may be OK.
  - But use of filter increases proportion of high energy X-rays, potentially more problematic for cross-talk.
  - Modeling of effects of cross-talk on these measurements now under investigation assuming FDM, using end-to-end simulations.
  - Simulations suggest 10 eV resolution may be achievable, but simulations not yet verified by measurements. (Suggest caution).

Key meetings in 2016

- February 2016, Utrecht: FPA Review meeting.
- May 2016, Utrecht: X-IFU Consortium meeting
- September 2016, Toulouse: X-IFU Read-out Workshop
- November 2016, Toulouse: X-IFU progress meeting
- Several system team meetings throughout year.
  - Evolution of several documents: Error budget, calibration plan, e2e simulations etc.

Conclusions of read-out workshop:

- FDM: no show stoppers have been identified during the discussions but there are various open issues and closure is expected in about 6-8 months (new SQUIDs, DAC studies, multiple pixel tests).
  - However, required performance of pixels under AC still needs to be verified.
  - New suggestions that problematic dissipation in TESs at high frequencies may be unavoidable.
  - Steps in transition low in transition make pixels harder to operate lower in the transition than under DC bias.
- TDM is **mature** and could be used as backup but CDM would be desirable (significantly more margin) but still needs some additional confirmation.
  - We will begin to develop 64-row and 80-row CDM capability, in addition to baseline 40-row.

Technical targets: Upcoming development, key challenges and milestones

ATHENA X-ray Integral Field Unit

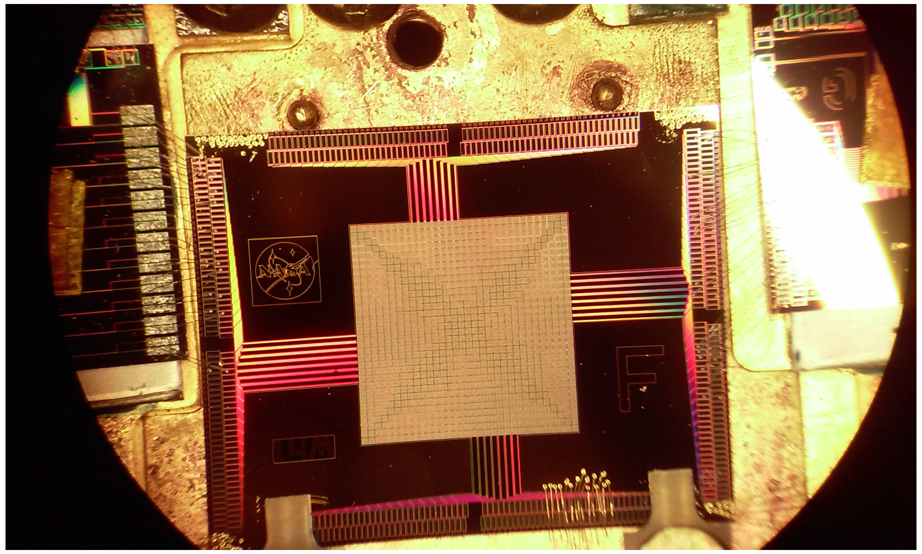
- Evolution of process and quality control for improved yield in DM-arrays.
- Development of LPA2-style arrays for DM.
- Delivery of candidate and spare DM arrays (June. 2016 – Dec. 2017).
- Further studies of pixel types with different TES sizes designs under DC bias.
- Further studies of all pixel types under AC-bias, and delivery of arrays to SRON for this testing.
- Start fabricating first full-scale hexagonal arrays with 3840-pixels.
- Demonstration of latest TDM multiplexing capability (up to 8 channels x 32 rows) – Feb. 2017.
- Fabrication and testing of electrical cross-talk in CDM+ arrays
- Development of 64 and 80-row CDM multiplexer.
- New cryostat for testing of 960 pixels of full-scale arrays being delivered Jan. 2017.
- Installation of new focal-plane assembly for large-scale testing of full-scale arrays (24 channels x 40 rows).
- New infra-structure investments. Purchase of:
  - New fast-turnaround cryogenic system, down to 250 mK.
  - Additional new cryostat for testing full-scale arrays at 50 mK.
  - Very uniform silicon oxide deposition system.
  - New e-beam evaporator specifically for Athena.
  - New photoresist spinner.

Team

- GSFC
  - Adams, Bandler, Chervenak, Chang, Chiao, Costen, Datesman, DeNigris, Eckart, Ewin, Finkbeiner, Kilbourne, Kelley, Manos, Meyer, Miniussi, Moseley, Porter, Ripley, Sadleir, Sakai, Schoenwald, Smith, Wakeham, Wassell, Yoon
- NIST
  - Ullom (lead), Bennett, Doriese, Fowler, Gard, Hilton, Morgan, Reintsema, Schmidt, Swetz
- Stanford
  - Irwin, Chaudhuri

Conclusions

- Tremendous progress has been achieved over the past year, as a large number of activities have ramped up.
- Uniform and reproducible kilo-pixel arrays with desired properties for DM now yielded and tested under DC bias.
  - new TDM multiplexed demo scheduled for Feb. 2017.
  - need to study best options for producing LPA2-style arrays.
- CDM with 30 sensors successfully demonstrated with no energy resolution degradation from the read-out.
- Greater understanding of physics of TESs under AC bias.
- Further developed process to successfully produce hybrid arrays, incorporating different absorber compositions with high fill factor.
- Well established members of X-IFU consortium, working very well together in collaboration with colleagues at SRON to tackle large number of technical hurdles and in a joint study of TESs under AC bias.
- Some potentially fundamental restrictions of pixels under AC bias have been identified and are being studied further.
- Very important to maintain the TDM/CDM options.



Back-up

Schedule management

- New schedule for producing arrays for the Engineering Model (EM) have made the development program much more achievable, and has relaxed some of the urgency to move focus from developing DM arrays to EM arrays.

- Delays in definition of DM interface between FPA and cryostat has meant that delivery of components of the DM delayed, until at least June 2017.
  - However, prototype of DM still desired by SRON ~ Jan. 2017.
  - Provides opportunity to improve yield and uniformity of DM arrays.

- Overall schedule for Phase-A has not changed, in spite of delay in AO announcement, which was needed for the delta "Mission Configuration Review" (MCR) to take place.

- ESA-defined TRL-5/6 still required by ~Q2 2019

- FDM read-out still not proven. AC-biased TESs have performance ~ 20-40% worse than under DC bias at low frequencies, and worse at high frequencies.
  - TDM/CDM needs to continue to develop as a viable back-up, at least until 2018.

Thermal conductance to heat sink

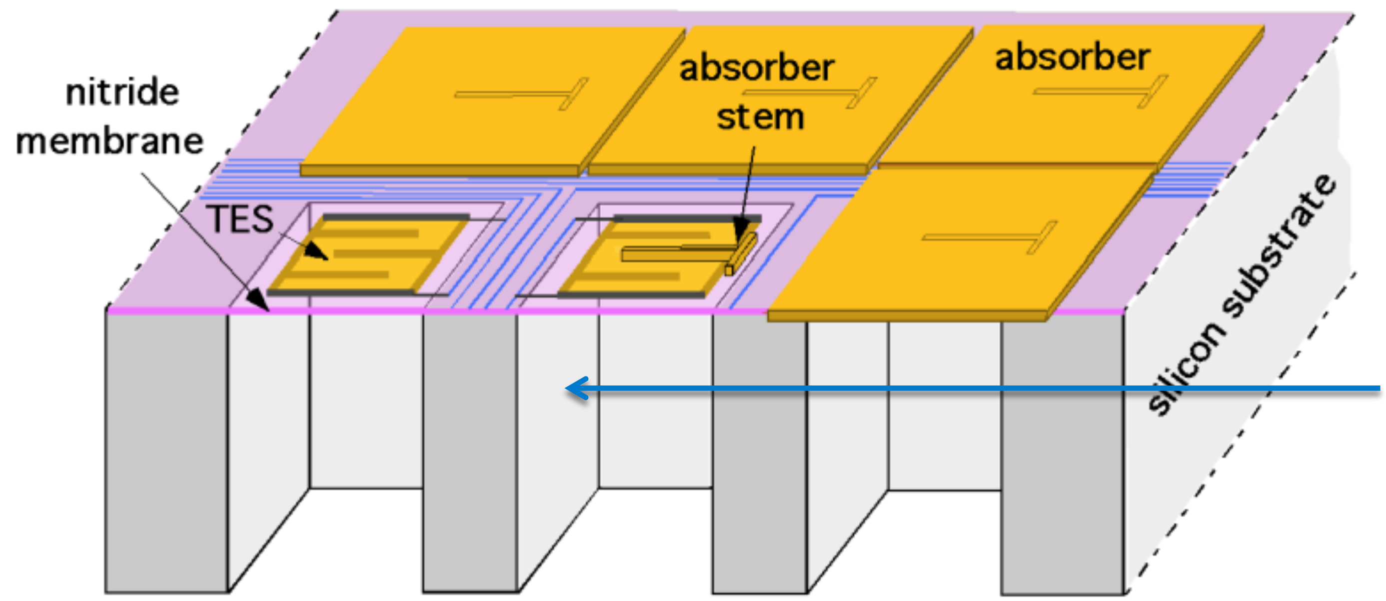
- Nominal Target G_b ~ 200 pW/K (4.63 pW)
- 'Standard' pixel design ~ 275 pW/K

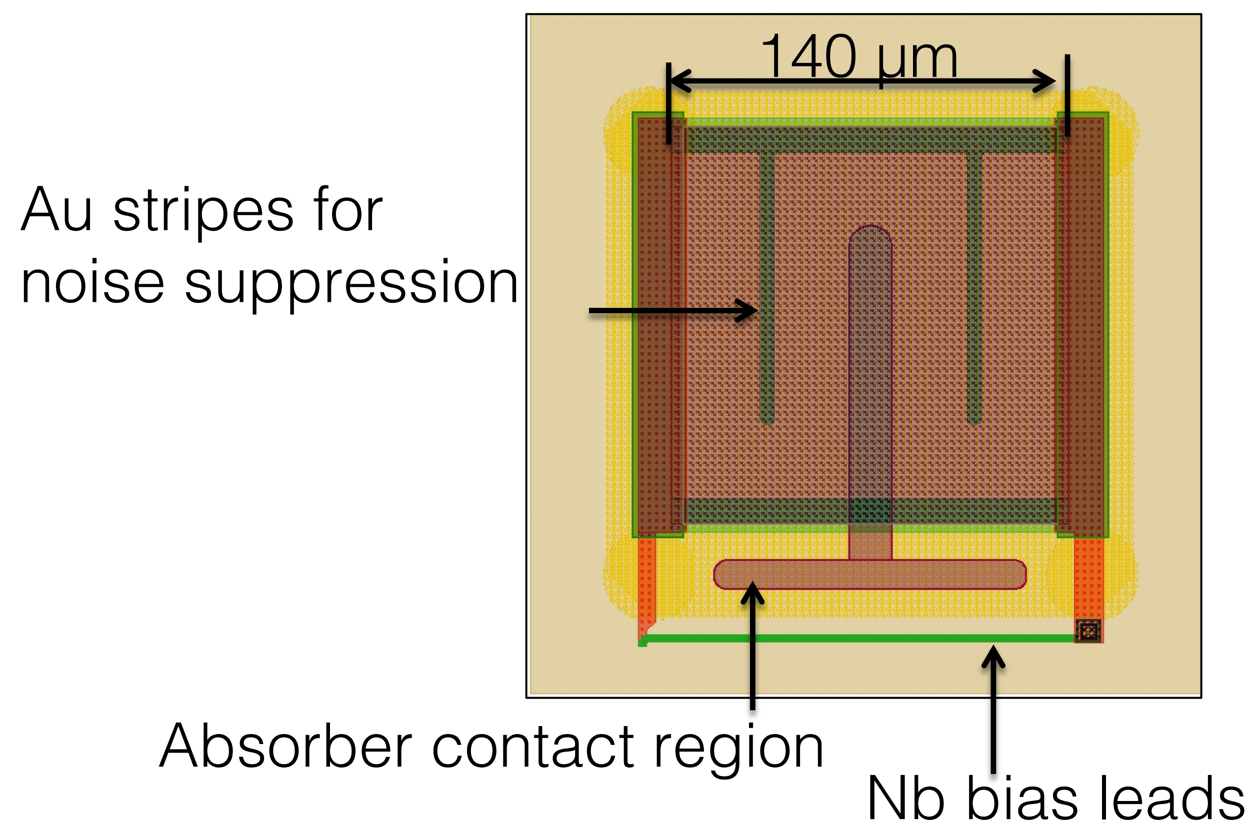
Several approaches under study for adjusting G_{bath}:

1) Pixel size.
   - G scales with TES perimeter.
   - Size range: L ~ 140-100 μm.

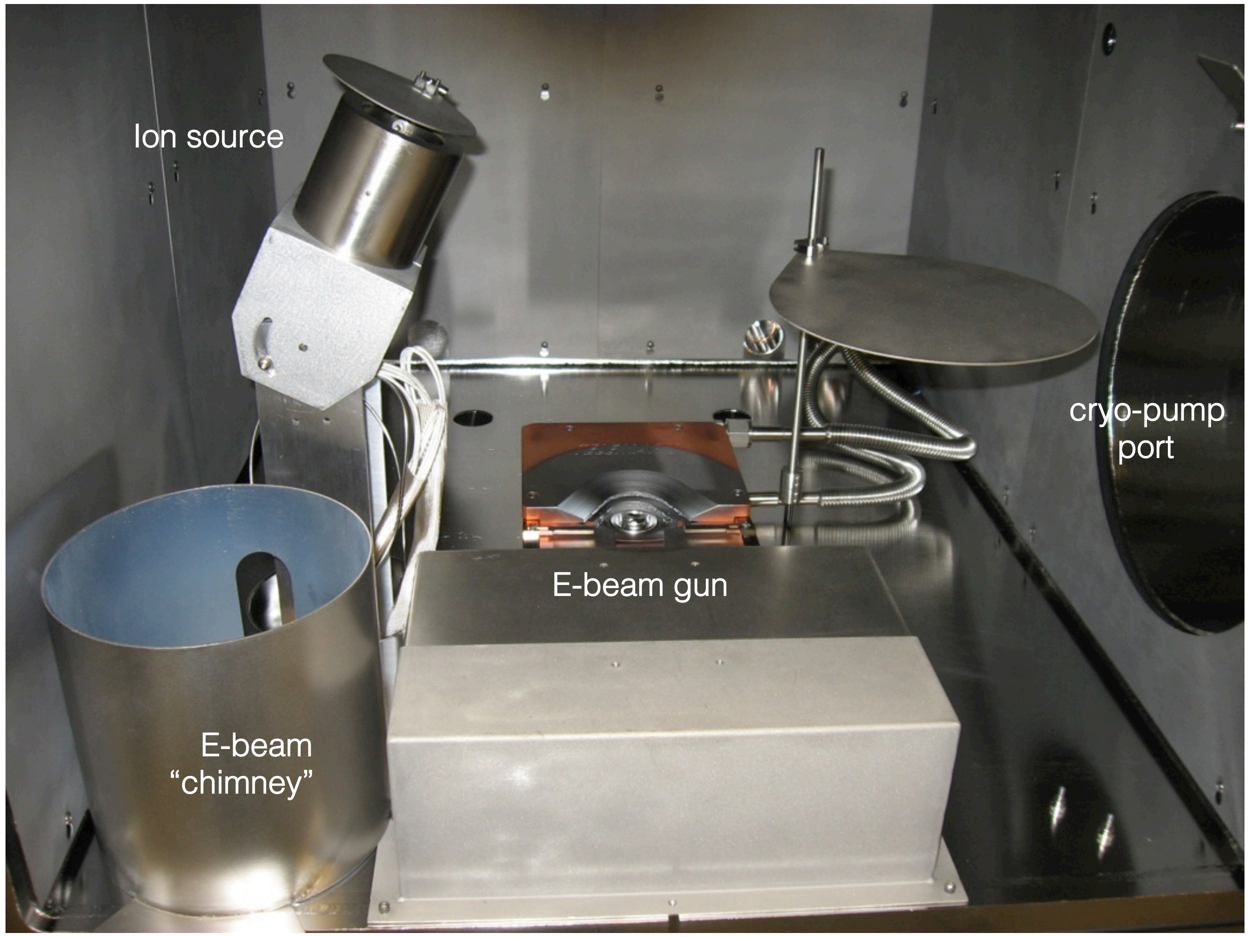
2) Perforate/slot membrane.
   - G scales with slot fraction.
   - Slot fraction range: 0.25 to 0.75.

3) Reduce SiN membrane thickness.
   - Thickness range: 0.25, 0.5, 1 μm.



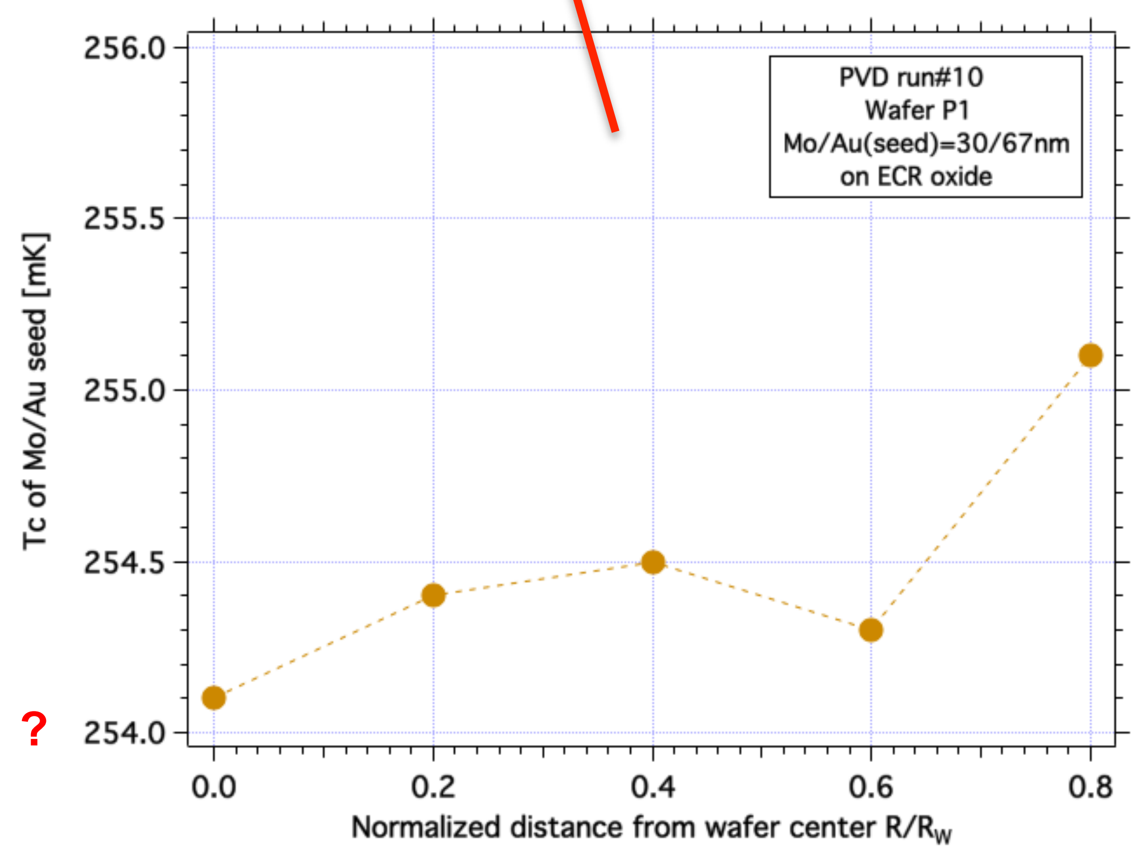


FY14 INVESTMENT: New TES bilayer (PVD) Evaporator System



Inside view of chamber with E-beam and ion source

Tc highly uniform across wafer ≤ 1mK



- New TES bilayer deposition system now functioning as desired producing very uniform MoAu bilayers.
- First developed recipe for uniform films on SiN, and then more recently on ECR silicon oxide.
- First arrays using these bilayers to be fabricated in early 2017.

Technical Progress: Radiation testing

"Piggy-backed" on radiation hardness testing for Litebird in Japan:

- Irradiation Test at HIMAC with a 160 MeV proton beam
- Total irradiation is 10 krad = 100 Gy
- The irradiation time was 50 minutes.
- Irradiated package contained TES arrays, including a previously tested *"Athena-1"* array, & TDM/CDM SQUIDs.
- Package placed at the center of proton beam.
- Package was highly activated
  - required waiting a few weeks.
- Will retest array soon