Toward large FOV high-resolution X-ray imaging spectrometer: microwave multiplexed readout of 32 TES microcalorimeters

PB-28

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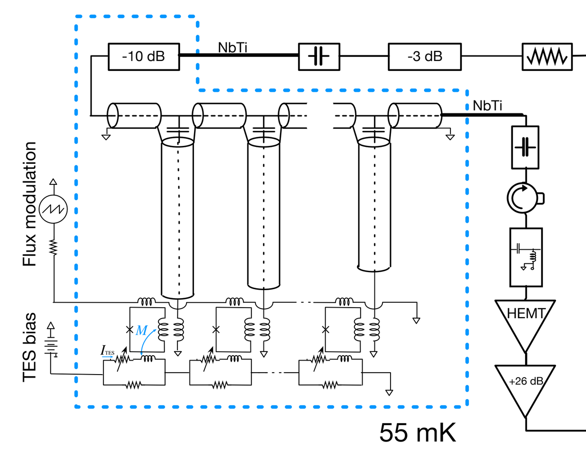
Abstract

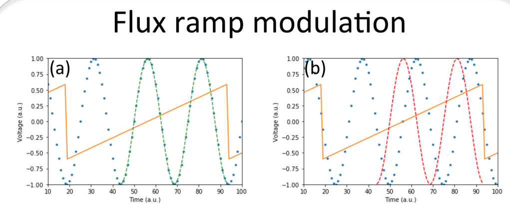
We performed a small-scale demonstration at GSFC of high-resolution x-ray TES microcalorimeters read out using a microwave SQUID multiplexer. This work is part of our effort to develop detector and readout technologies for future space based x-ray instruments such as the microcalorimeter spectrometer envisaged for *Lynx*, a large mission concept under development for the Astro 2020 Decadal Survey. In this paper we describe our experiment, including details of a recently designed, microwave-optimized low-temperature setup that is thermally anchored to the 50 mK stage of our laboratory ADR. Using a ROACH2 FPGA at room temperature, we simultaneously read out 32 pixels of a GSFC-built detector array via a NIST-built multiplexer chip with Nb coplanar waveguide resonators coupled to RF SQUIDs. The resonators are spaced 6 MHz apart (at ~5.9 GHz) and have quality factors of ~15,000. Using flux-ramp modulation frequencies of 160 kHz we have achieved spectral resolutions of 3-5 eV FWHM on each pixel at 6 keV. We will present the measured system-level noise and maximum slew rates, and briefly describe the implications for future detector and readout design.

Microwave SQUID multiplexing



- A few GHz of bandwidth per amplifier channel
- TESs couple to unique microwave resonator
- RF SQUIDs built into microwave resonator
- Inductance modulates resonance frequency
- Linearize output without feedback (common modulation)
- Single microwave feed-line can read out hundreds of pixels

Flux ramp modulation

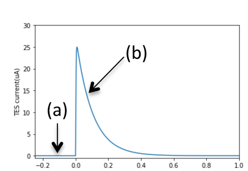


- Flux ramp much faster than input signal
→phase shift ϕ is almost constant during ramp and proportional to TES current

$$\phi = \frac{2\pi M}{\Phi_0} I_{TES}$$

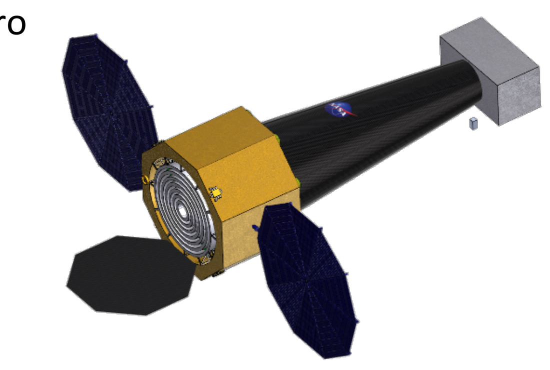
- For demodulation

$$\phi = \arctan\left(\frac{\sum V(t)\sin 2\pi f_r t}{\sum V(t)\cos 2\pi f_r t}\right)$$



Lynx

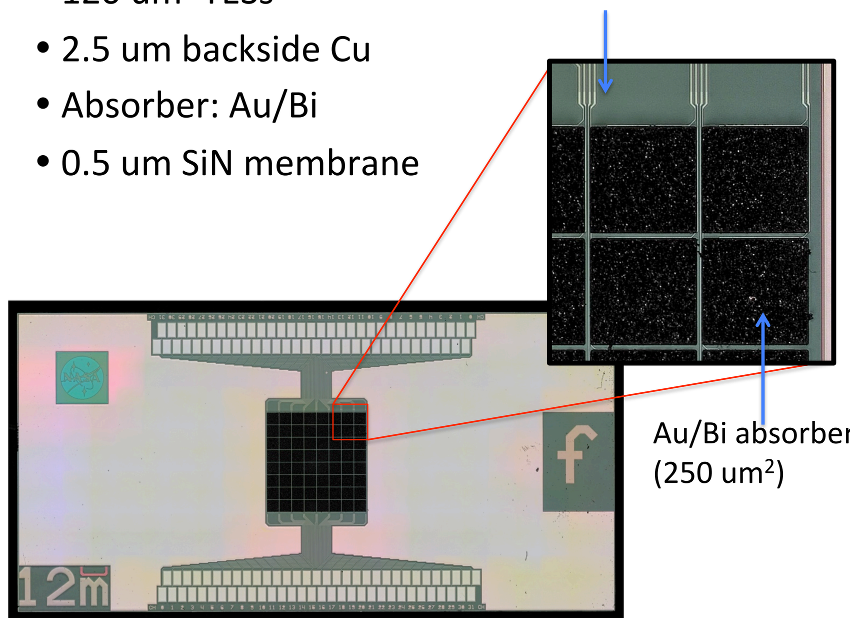
A large mission concept under development by NASA for the Astro 2020 Decadal Survey



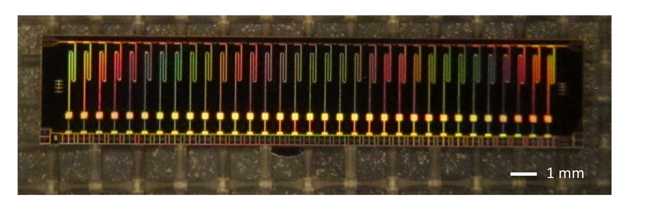
■ **Microcalorimeter detector array for *Lynx***
- **Energy resolution: better than 3 eV FWHM at 0.2 – 10 keV**
- **Number of readout channel > 56,000**
(number of pixel > 150,000 with hydra)
- Various angular resolution, energy resolution and count rates
- Sensor: Transition-edge sensor(TES) or magnetically coupled calorimeter (MCC)
- Initial approach: Use position-sensitive TES microcalorimeter, "Hydras". These have multiple absorbers attached to each sensor
- See also
  - PE-46, "The Design of the *Lynx* X-ray Microcalorimeter," Simon Bandler et al.
  - PE-59, "Design and optimization of multi-pixel transition-edge sensors for X-ray astronomy application," Stephen J. Smith et al.

8 X 8 TES microcalorimeter, NASA/GSFC

- T_c ~ 89 mK
- 120 um^2 TESs
- 2.5 um backside Cu
- Absorber: Au/Bi
- 0.5 um SiN membrane



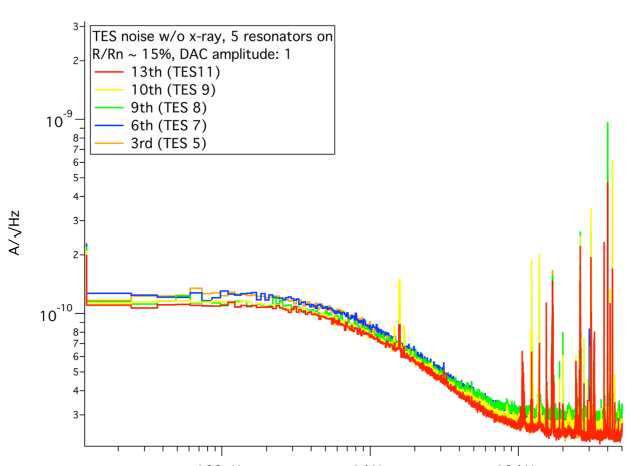
uMUX chip, NIST



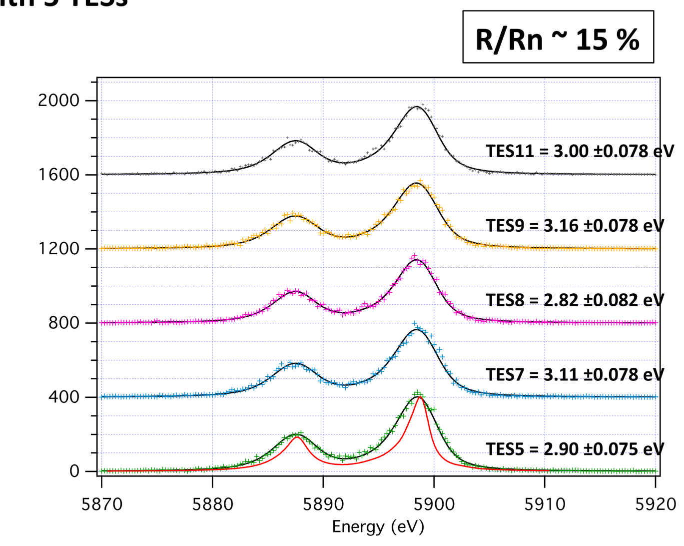
- Fabricated by NIST
- 33 Nb microwave resonators
- Resonance freq.: 5.7-6.0 GHz
- 300 kHz bandwidth
- Frequency spacing: ~6 MHz
- Quality factor ~ 15,000
- Coupling constant : 8.73
(SQUID input – flux ramp circuit)

Promising initial results: microwave multiplexing of 5 TESs

5 resonators with 5 TESs

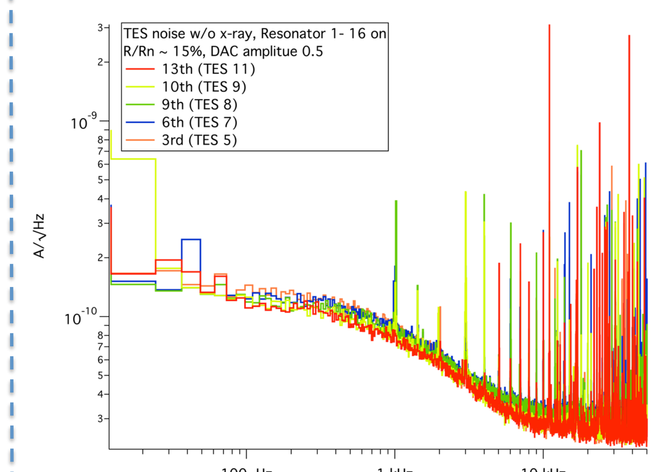


NEP with X-ray: 2.57– 2.77 eV@ ~ 5.9 keV



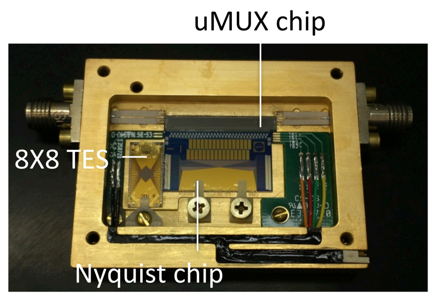
<ΔE>=3.00 eV FWHM @ MnKα 5.9 keV

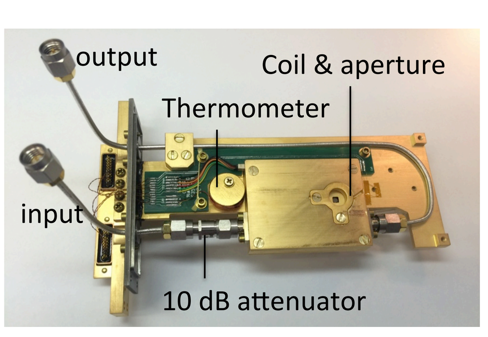
16 resonator multiplexing
(5 TESs, 11 without TES)

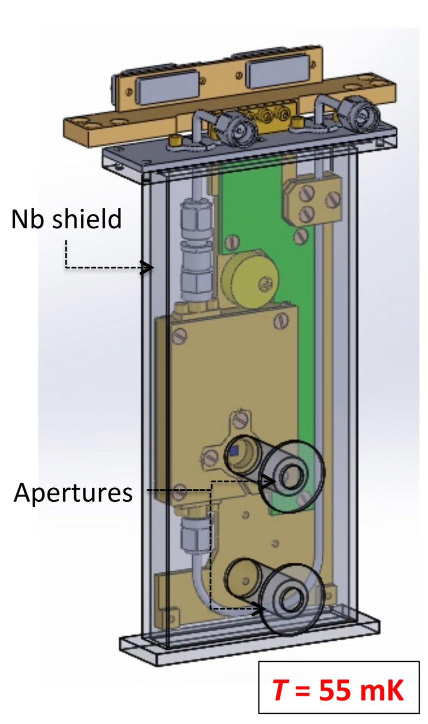


NEP with X-ray: 2.60 – 2.81 eV @ ~ 5.9 keV
No NEP degradation compared to five resonator multiplexing !

Low temperature uMUX setup

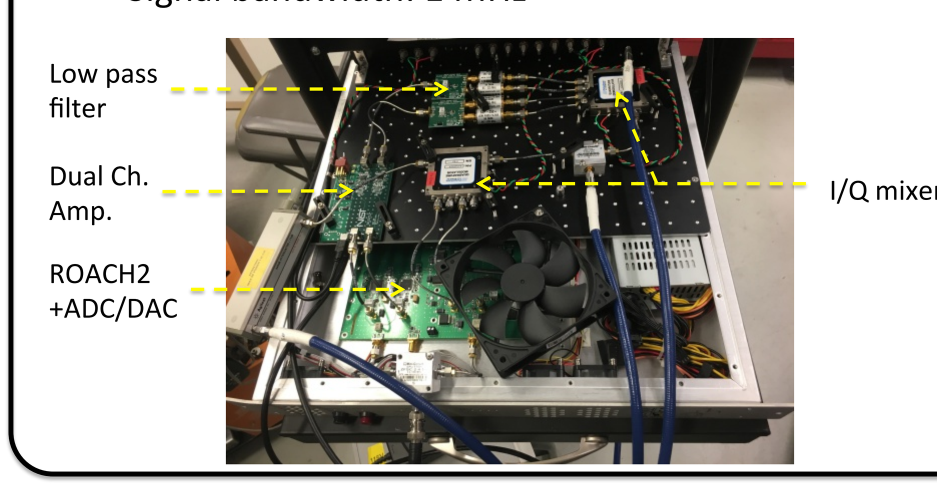




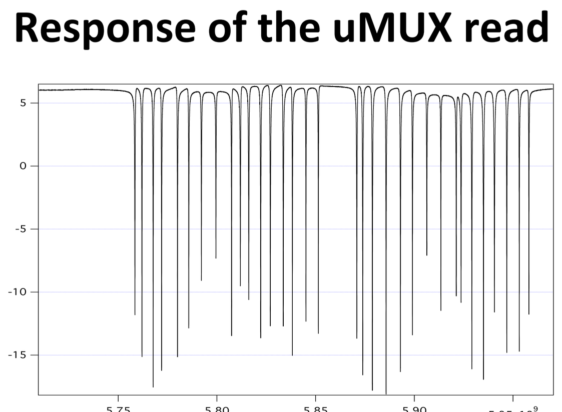


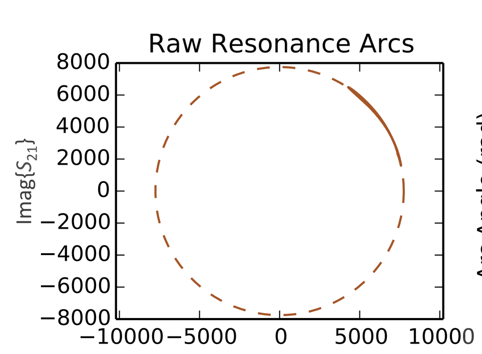
Room temperature electronics

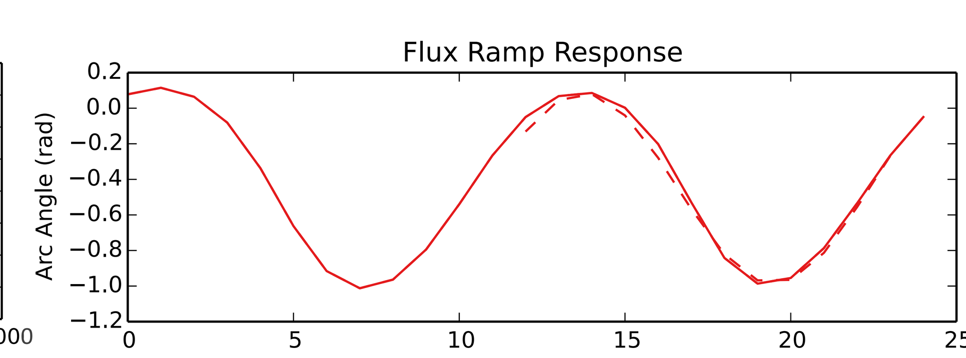
- ROACH 2 with MKID ADC/DAC board
- ADC/DAC sampling rate: 512 Msps
- Number of channels: 32
- Bin select: 8 MHz sampling per channel
- Signal bandwidth: 1 MHz



Response of the uMUX read out



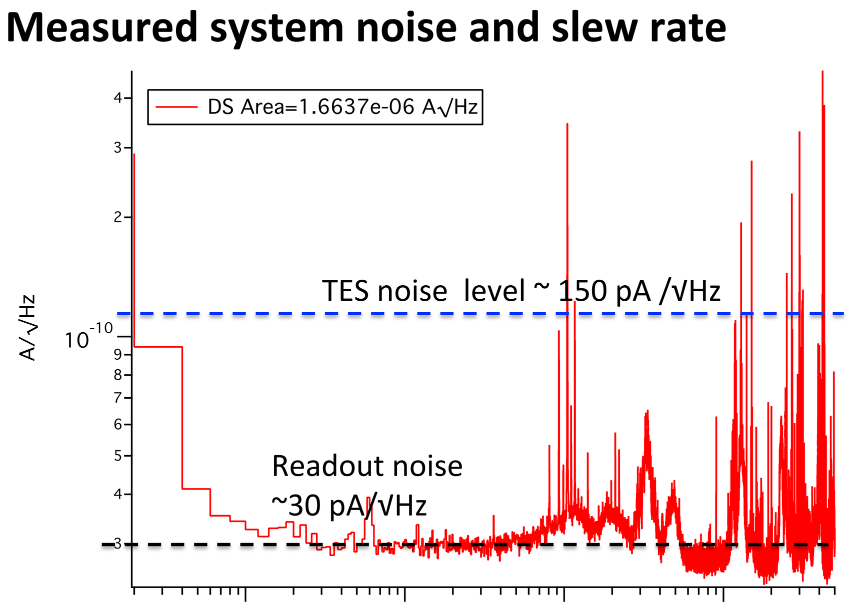


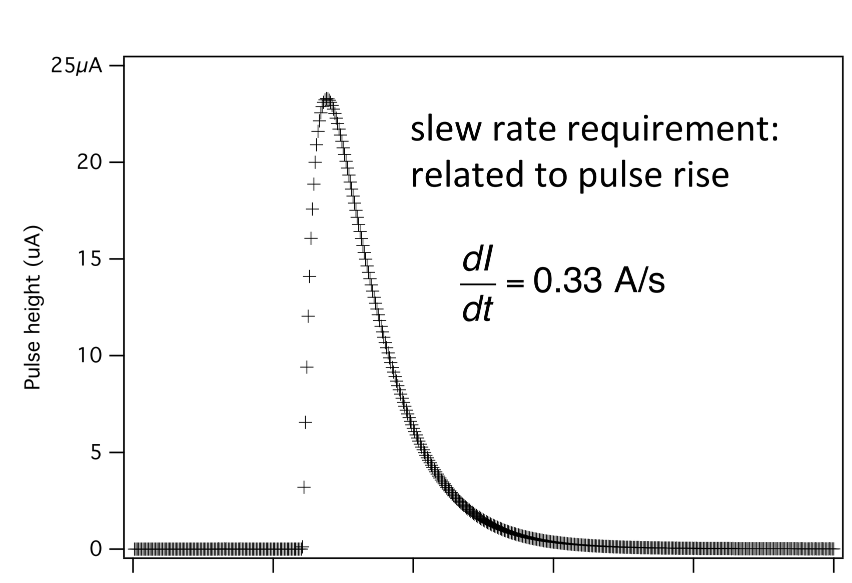


- 33 resonators
- Center frequency ~ 5.87 GHz, 6 MHz spacing
- Q ~ 13500
  – Q_c ~ 14500 → Q_i~1.5–2x10^5

- Solid line: measured rf-SQUID response to flux ramp signal
- Dashed line: fitted signal to find mixed frequency
- Flux ramp frequency: 160 kHz, mixed frequency ~ 330 kHz
- Throw away transient part, used only 1 Φ_0

Measured system noise and slew rate



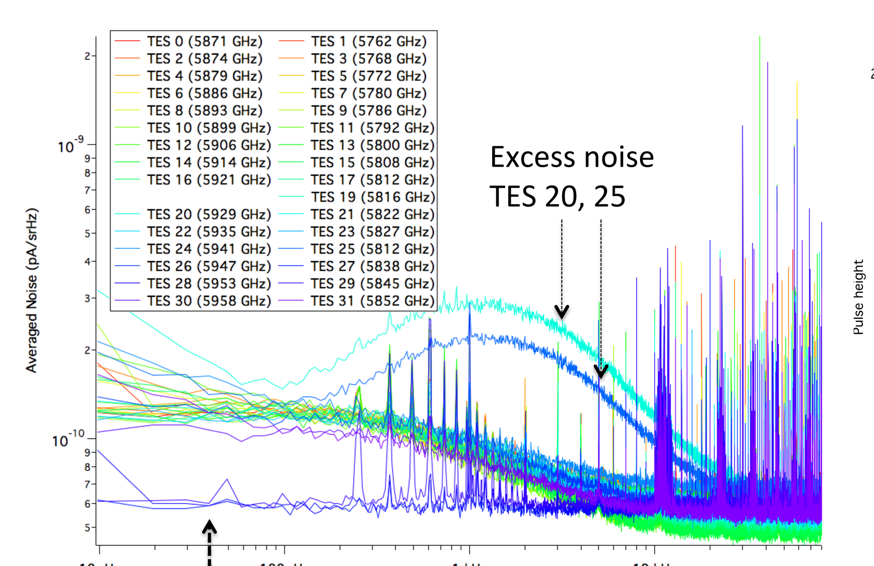


- Noise of readout circuit is the measured noise without TES connection
- microwave readout circuit: 30 pA/√Hz
- TES noise level: ~ 150 pA/√Hz
  → uMUX readout noise is a factor of ~5 below the TES noise level

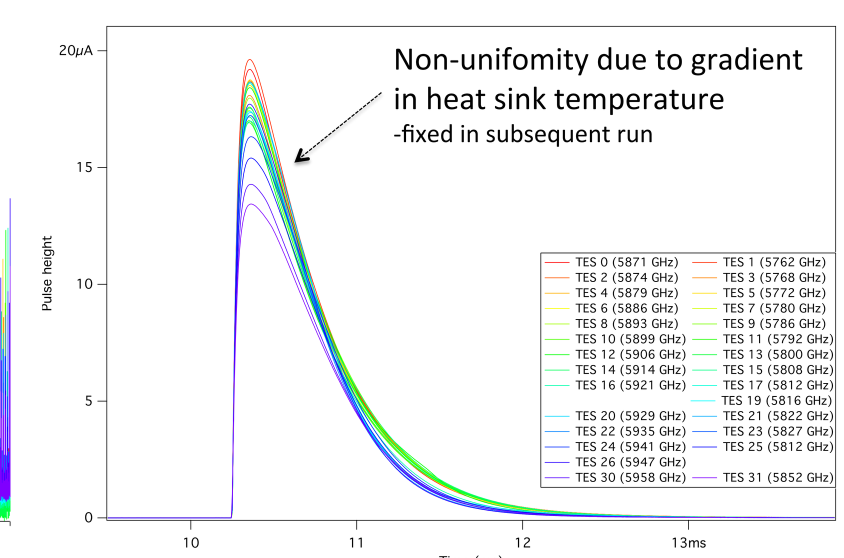
- Max slew rate depends on pulse rise, flux ramp frequency and resonator bandwidth
- Trade between slew rate capability and resonator packing density
- Approaches for *Lynx*:
- slow the rise of the hydra pixels, increase the resonator bandwidth

Ongoing work: microwave multiplexing of 32 TES microcalorimeters

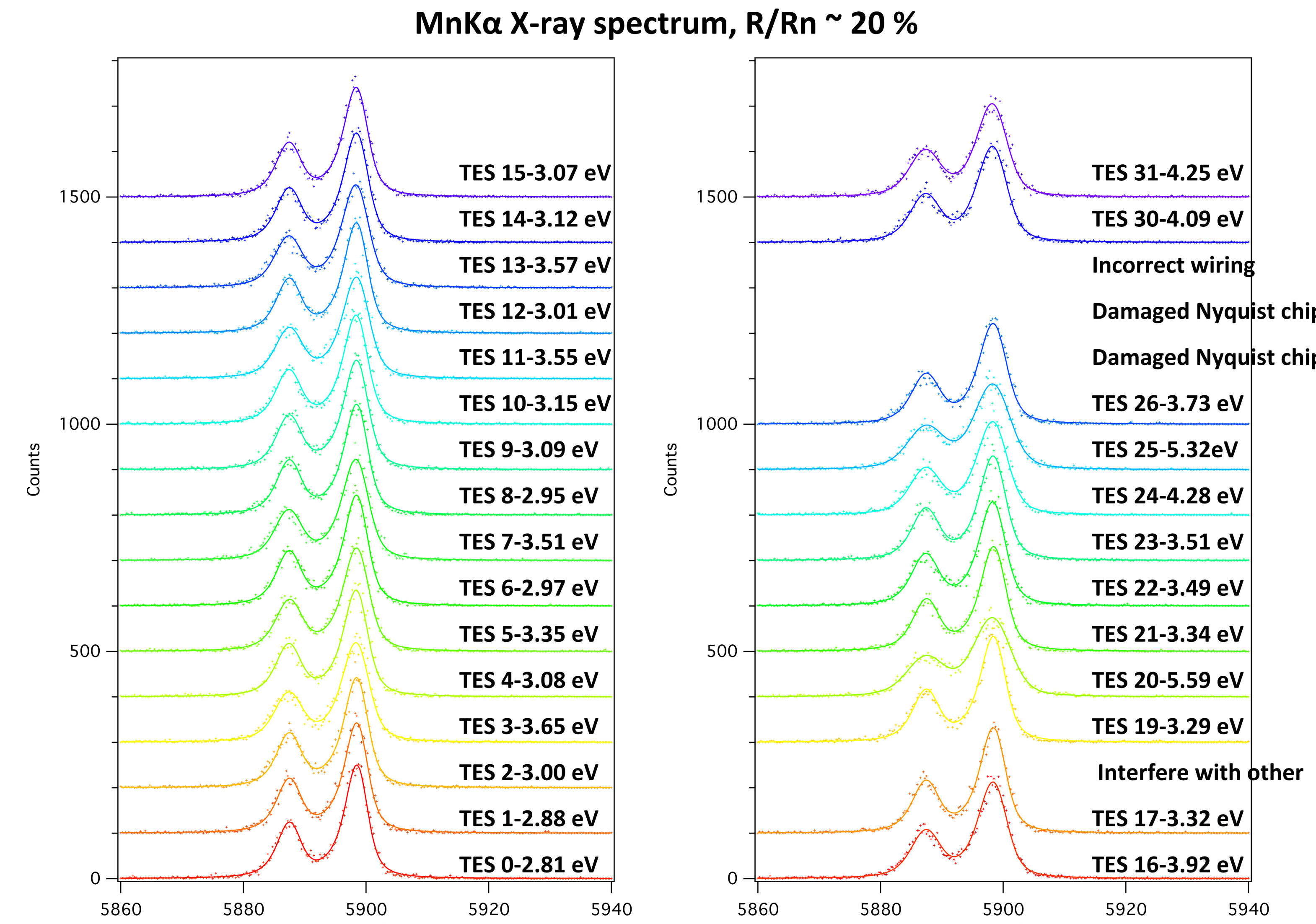
Changed TES detector chip with the goals of:
1. Improved energy resolution – expect non-multiplexed ΔE_{FWHM}=1.6 eV based on measurements of similar chip
2. 32-channel multiplexing – bond pad layout compatible with μMUX chip layout



Due to the damaged Nyquist inductor and incorrect wiring



MnKα X-ray spectrum, R/Rn ~ 20 %



- <ΔE> = 3.53 eV FWHM @ 5.9 keV including all measured pixels
- TES 18: Resonator intentionally turned off to avoid interference with other resonator
- TES 20 / 25: Relatively poor energy resolution due to excess detector noise

In progress: fixed wiring, replaced damaged Nyquist chip (4/2017), required new μMUX chip due to subsequent damage during handling, μMUX screening underway (4-7/2017)
Future work: microwave readout of 'Hydra' pixels for *Lynx* (see Bandler, Smith)