Advanced Time Division, Code Division, and Microwave SQUID Multiplexers

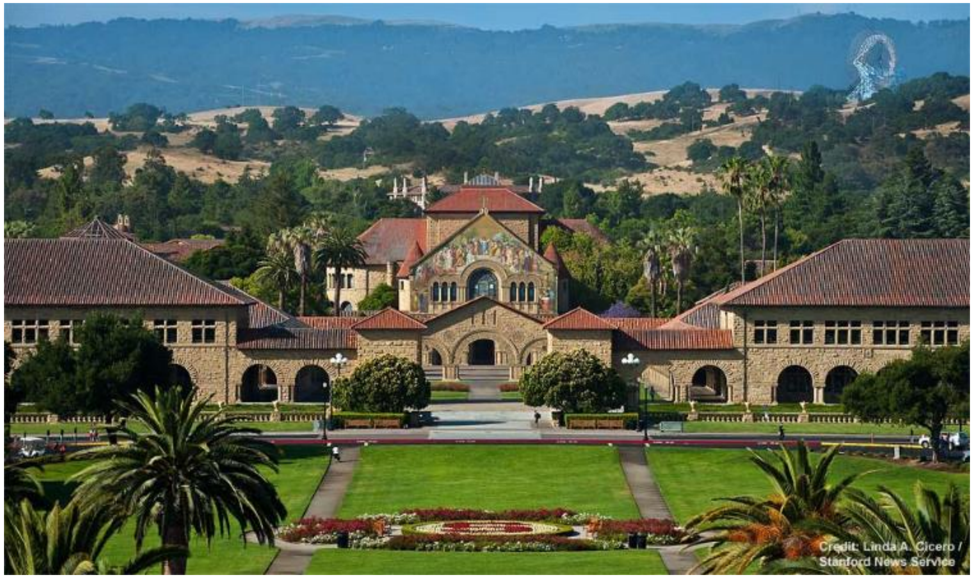
for X-ray Microcalorimeter Arrays

Kent Irwin
Stanford University

17th International Workshop on Low-Temperature Detectors

Kurume, Japan
July 20, 2017

Collaboration



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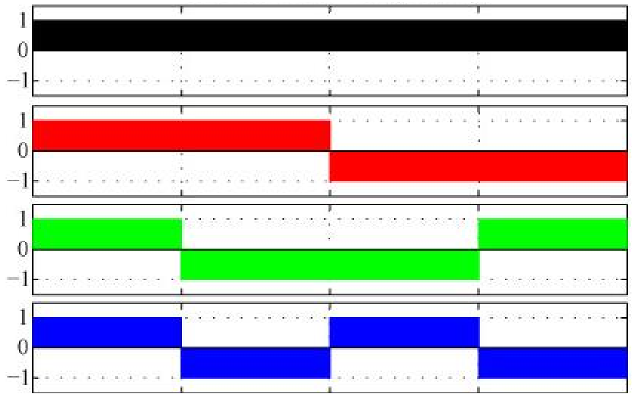
X-ray microcalorimeter mux: state of the art

Time-division MUX

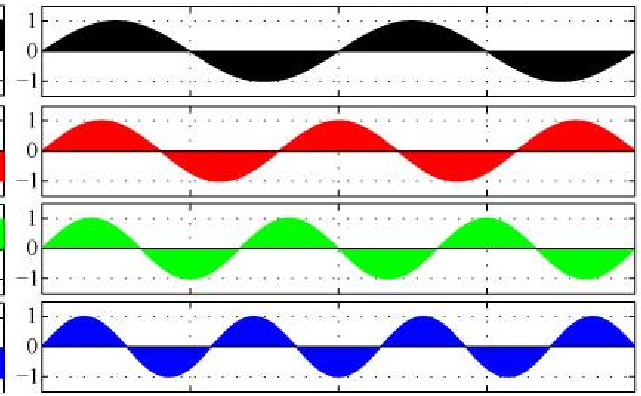
- dc bias TES
- Define time band by sampling SQUIDs sequentially
- Backup readout tech for Athena X-IFU

Code-Division MUX



- dc bias TES
- Define Walsh code by modulating polarity of coupling to SQUID
- Backup readout tech for Athena X-IFU

µwave SQUID MUX



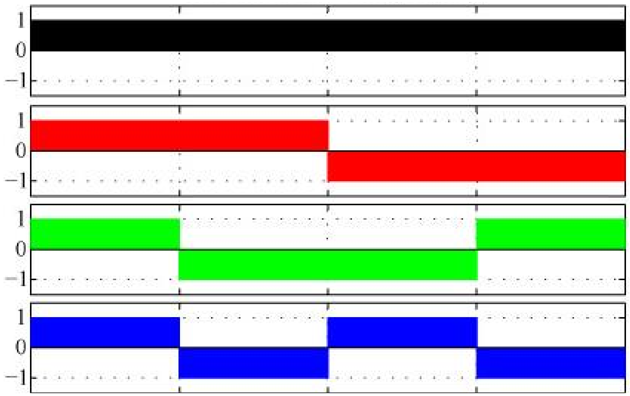
- dc bias TES
- Define frequency bands with SQUID in resonant circuits
- In development for Lynx (Bandler PE-46)

Most mature and highest performance x-ray MUX circuits

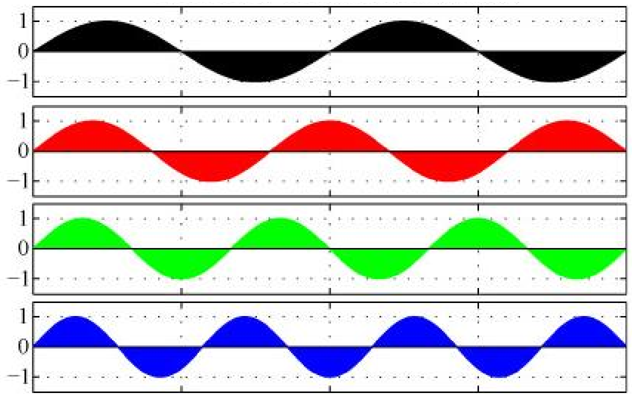
X-ray microcalorimeter mux: state of the art

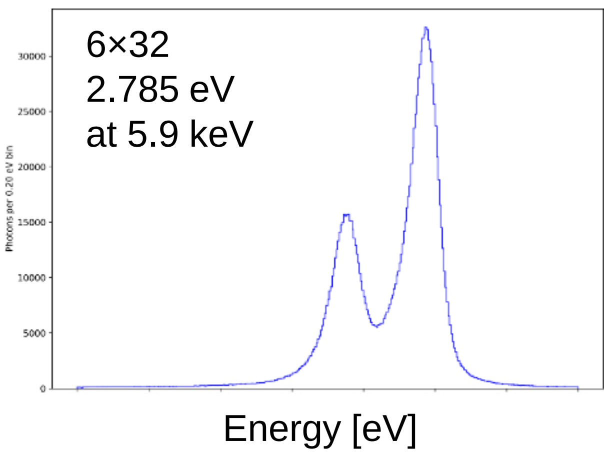
Time-division MUX

Code-Division MUX

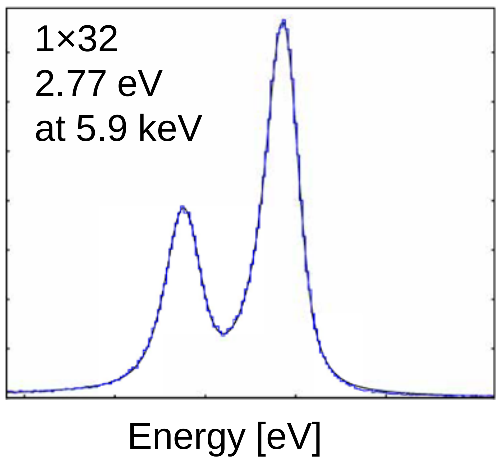


μwave SQUID MUX

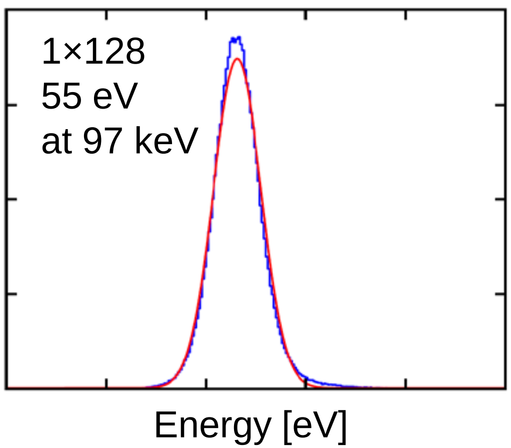




Joe Fowler, this session



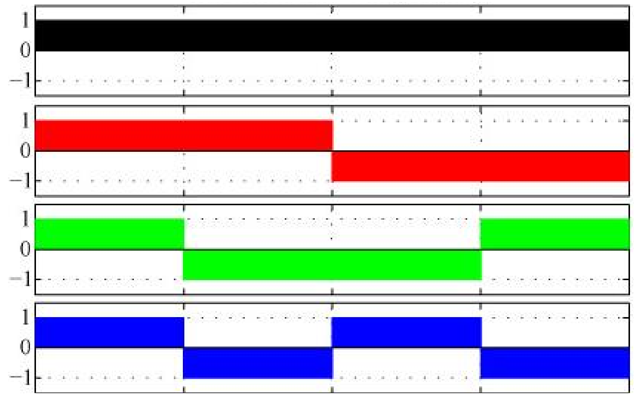
K. Morgan et al., Appl. Phys. Lett. 109, 112604 (2016);

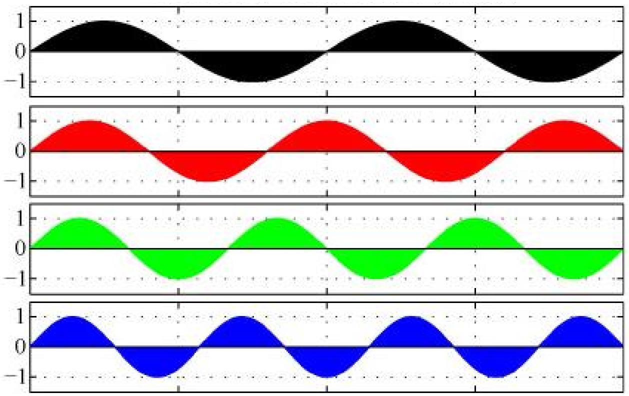


Ben Mates, this session

X-ray microcalorimeter mux: new architectures

Time-division MUX	Code-Division MUX	µwave SQUID MUX





Need: reduced crosstalk on feedback

This presentation:

Switched feedback

Need: robustness against single-point failure

This presentation:

Error-correction codes

Need: high mux factors with high slew-rate

This presentation:

Spread-spectrum mux

These architectures have not been presented previously

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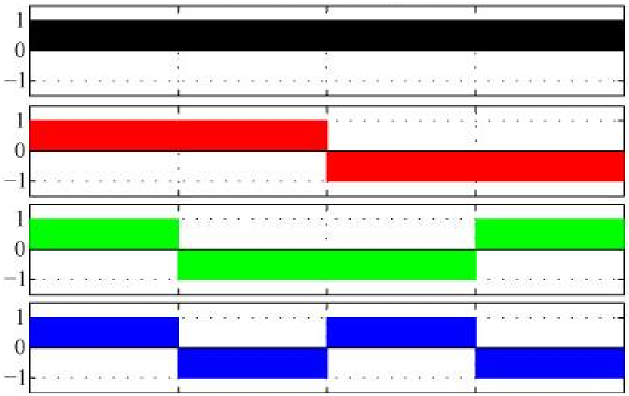

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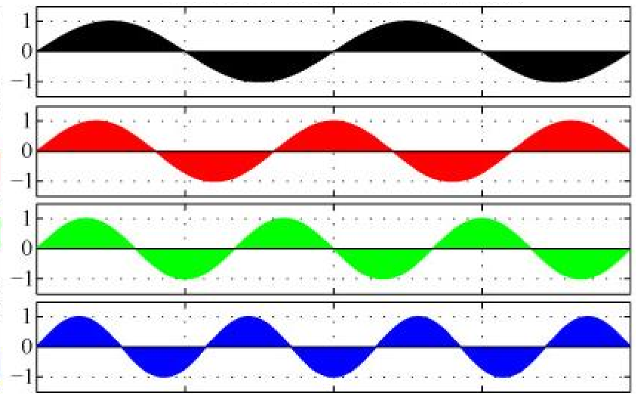
µwave SQUID MUX



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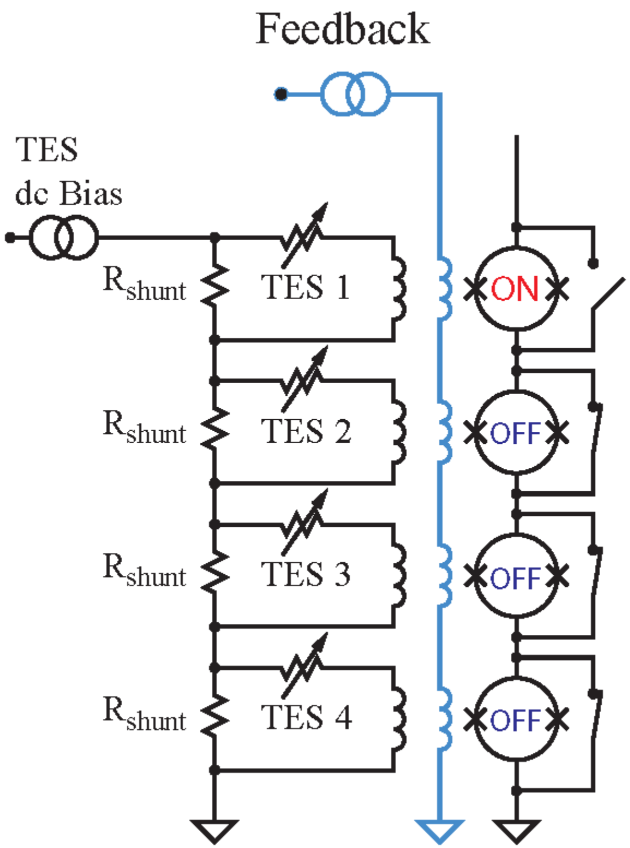
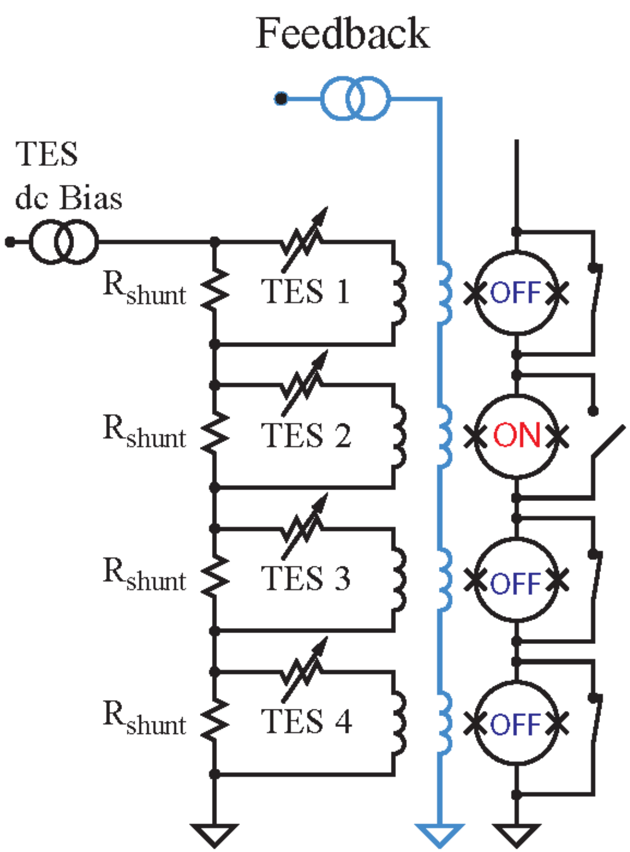
Time-division SQUID multiplexer



- All SQUIDs except one turned off by shunting the current with a superconducting switch.
- Feedback signal applied to 'ON' SQUID
- Signal from TES connected to that SQUID is measured
- Next SQUID switched on

Heritage
J. Chervenak, *Appl. Phys. Lett.* **74**, 4043 (1999).
H.H. Zappe, *IEEE Trans. on Magn.* **13**, 41, (1977).
J. Beyer, *Superc. Sci. Tech.* **21,** 105022 (2008).



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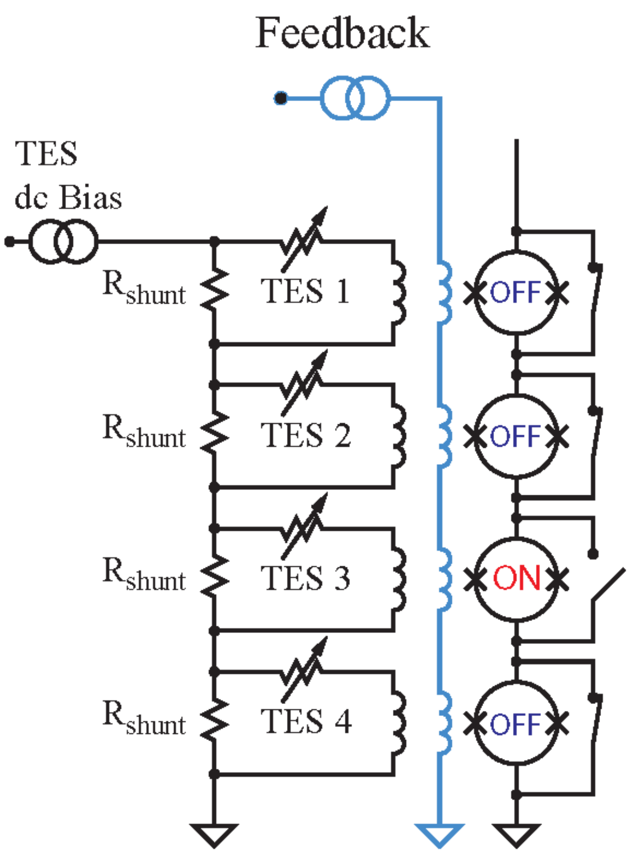

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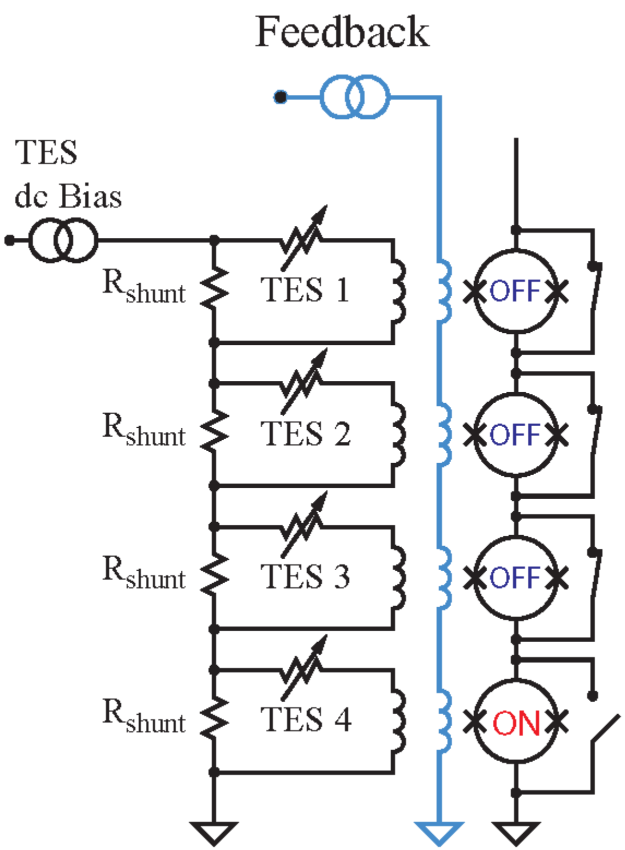

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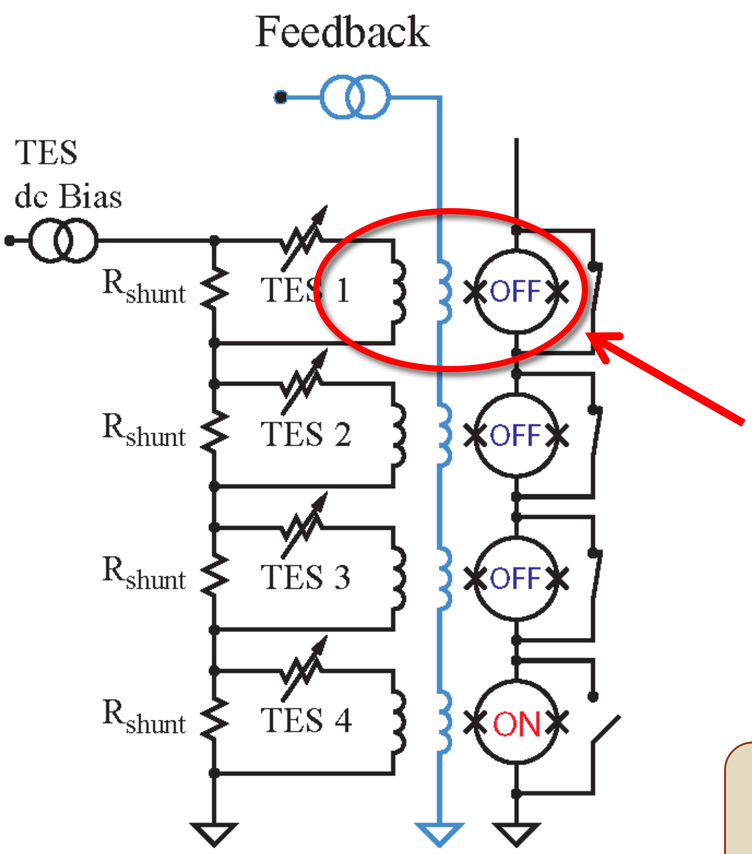
Problem: (small) feedback crosstalk in time-division MUX



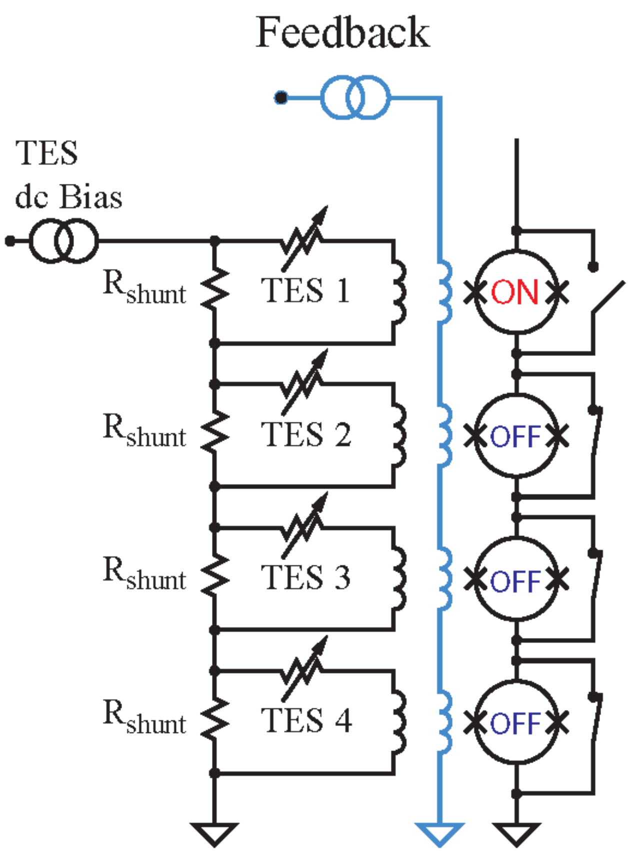
Feedback crosstalk in TDM

- The feedback (FB) signal passes through both ‘ON’ and ‘OFF’ SQUIDs
- The inductive coupling from the feedback to input is minimized by design.
- However, small residual FB-IN coupling drives a voltage across the TESs in the ‘OFF’ channels, leading to a small source of crosstalk (~ part per thousand)

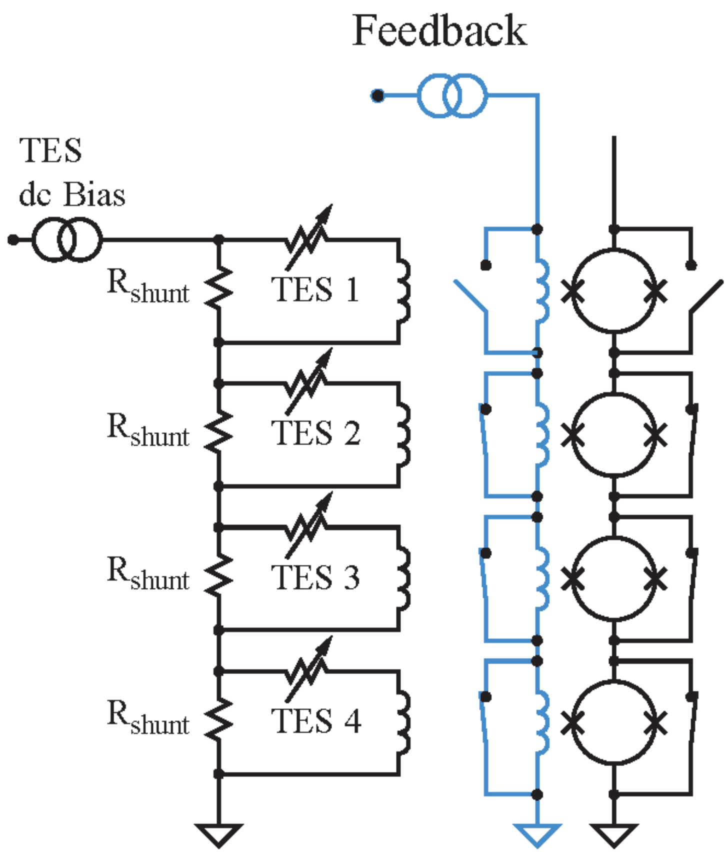
Solution: Divert the feedback signal away from ‘OFF’ SQUIDs with feedback switches

Implementation of feedback switch

Traditional TDM

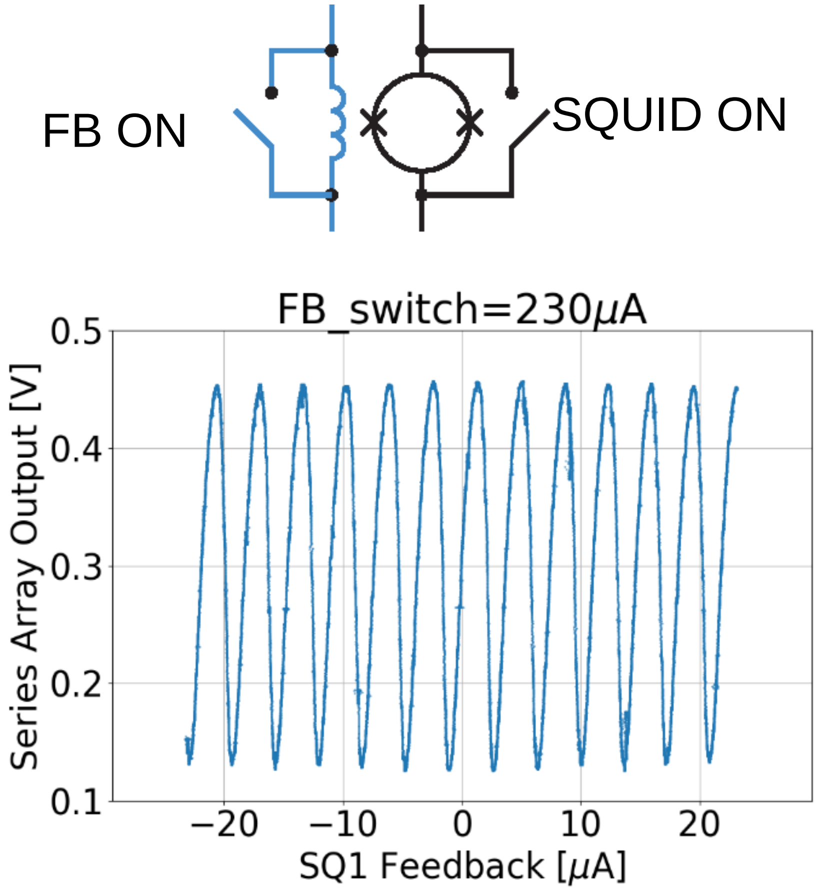


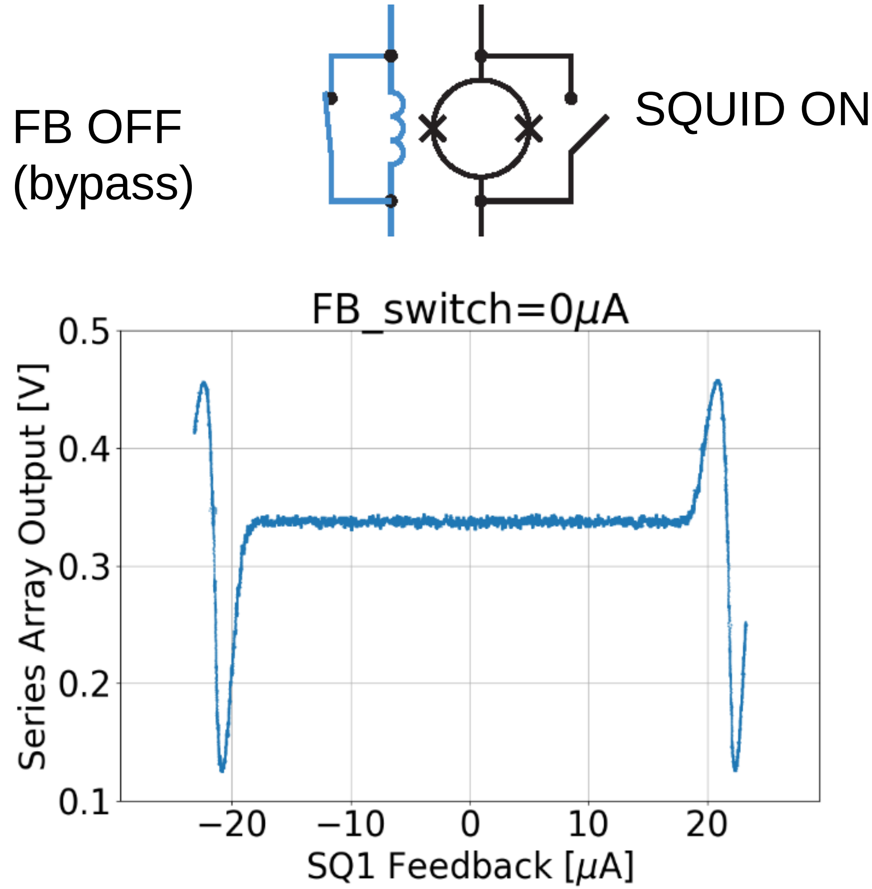
TDM with feedback bypass switch



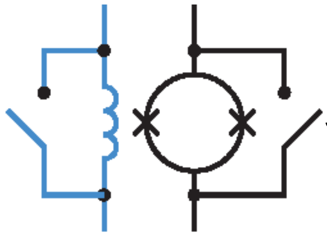
- Uses same switch design as SQUID bypass (Zappe interferometers)
- No extra wires: same address wires used for both SQUID and FB switch
- Has been designed, fabricated, and tested

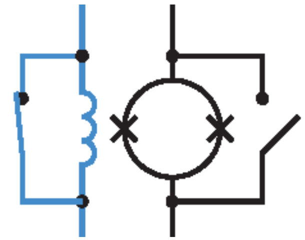
TDM feedback switches have been implemented

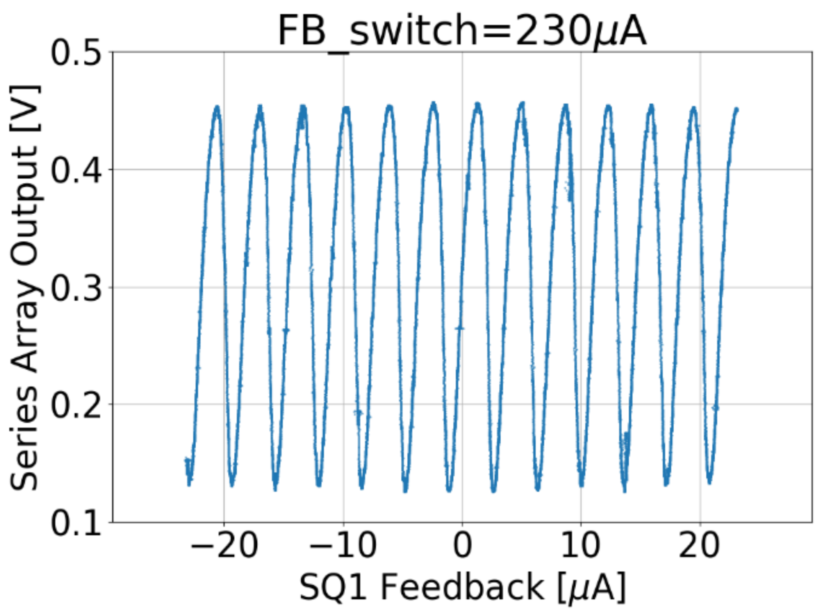


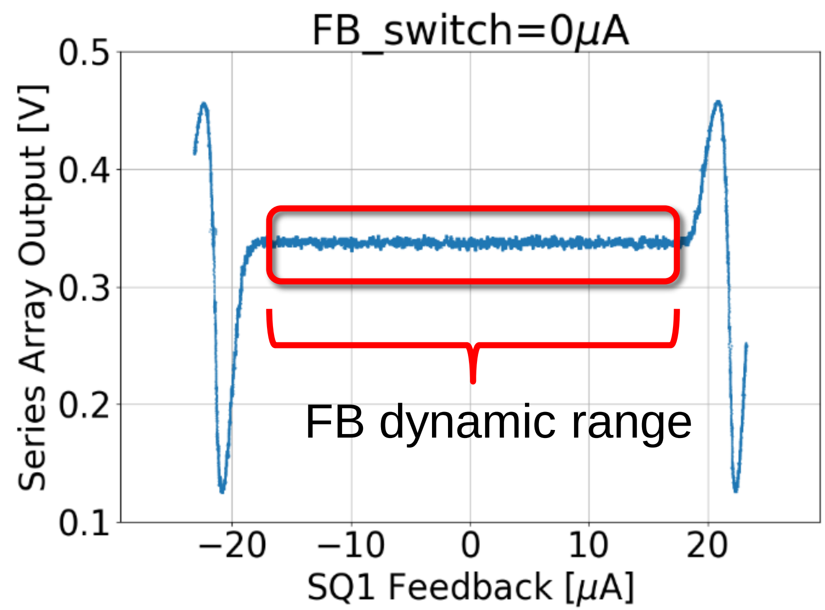


TDM feedback switches have been implemented

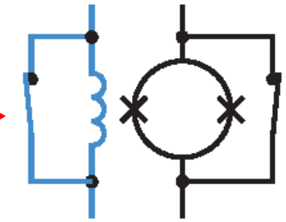
FB ON  SQUID ON

FB OFF (bypass)  SQUID ON





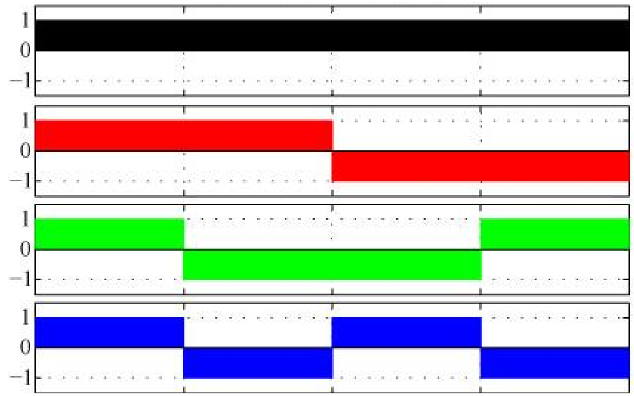
- FB switches work
- In operation, same address wires actuate SQUIDs + switches →
- See Carl Dawson's poster (PB-19) for details



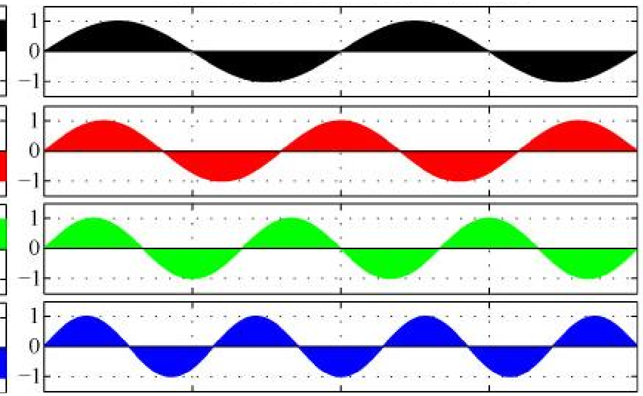
X-ray microcalorimeter mux: new architectures

Time-division MUX

Code-Division MUX



µwave SQUID MUX



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Spread-spectrum mux

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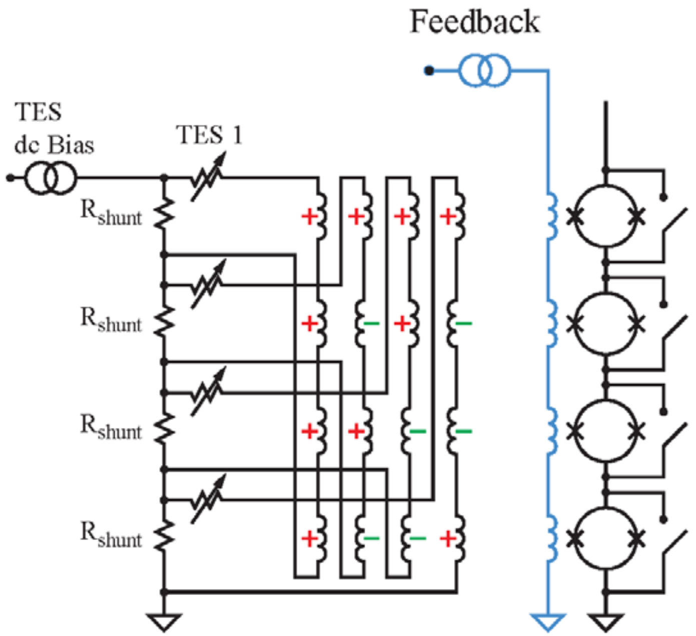
Code-division SQUID multiplexer



Flux-summed architecture (Φ-CDM)
KD Irwin et al., *SUST* 23, 034004 (2010).

- N TESs couple to N SQUIDs in Walsh pattern
- SQUIDs are turned on one at a time
- N TES signals reconstructed from N SQUID signals
- Drop-in compatible with TDM circuits
- Higher dynamic range than TDM

$$(SQ1 \quad SQ2 \quad SQ3 \quad SQ4) = \begin{bmatrix} 1 & 1 & 1 & 1 \\ 1 & -1 & 1 & -1 \\ 1 & 1 & -1 & -1 \\ 1 & -1 & -1 & 1 \end{bmatrix} \begin{pmatrix} TES\ 1 \\ TES\ 2 \\ TES\ 3 \\ TES\ 4 \end{pmatrix}$$

Multiplexed

$$(TES1 \quad TES2 \quad TES3 \quad TES4) = \frac{1}{4} \begin{bmatrix} 1 & 1 & 1 & 1 \\ 1 & -1 & 1 & -1 \\ 1 & 1 & -1 & -1 \\ 1 & -1 & -1 & 1 \end{bmatrix} \begin{pmatrix} SQ1 \\ SQ2 \\ SQ3 \\ SQ4 \end{pmatrix}$$

Demultiplexed

Single-point SQUID failure in CDM

- If one of the ‘N’ SQUIDs fails, the result is a rank-deficient matrix, which can’t be inverted

$$(SQ1 \quad SQ2 \quad SQ3) = \begin{bmatrix} 1 & 1 & 1 & 1 \\ 1 & -1 & 1 & -1 \\ 1 & 1 & -1 & -1 \end{bmatrix} \begin{pmatrix} TES\,1 \\ TES\,2 \\ TES\,3 \\ TES\,4 \end{pmatrix}$$

- Redundancy can be built in by under-populating the TESs, so that the system is over-constrained

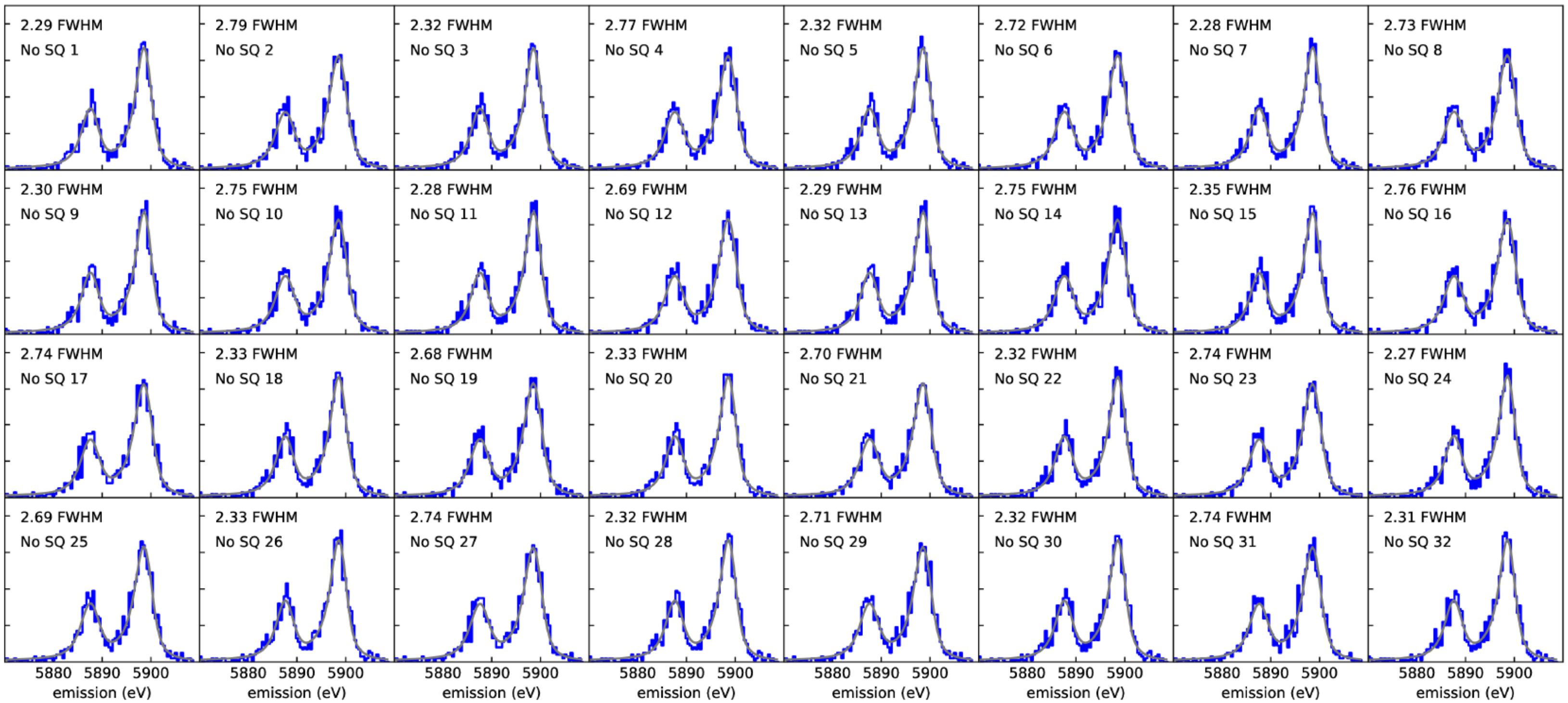
$$(SQ1 \quad SQ2 \quad SQ3 \quad SQ4) = \begin{bmatrix} 1 & 1 & 1 & 1 \\ 1 & -1 & 1 & -1 \\ 1 & 1 & -1 & -1 \\ 1 & -1 & -1 & 1 \end{bmatrix} \begin{pmatrix} TES\,1 \\ TES\,2 \\ TES\,3 \\ 0 \end{pmatrix}$$

- Upon SQUID failure, the disconnected TES can be struck from the matrix, leading to an invertible, full-rank matrix

$$(SQ1 \quad SQ2 \quad SQ3) = \begin{bmatrix} 1 & 1 & 1 \\ 1 & -1 & 1 \\ 1 & 1 & -1 \end{bmatrix} \begin{pmatrix} TES\,1 \\ TES\,2 \\ TES\,3 \end{pmatrix}$$

- No TES signals are lost!

Experimental demonstration: loss of one SQUID in N=32



- Loss of any one SQUID doesn’t significantly degrade the pixel resolution
- For details, see Jamie Titus, PB-22 “Error Correcting Codes for code-division multiplexed TES detectors

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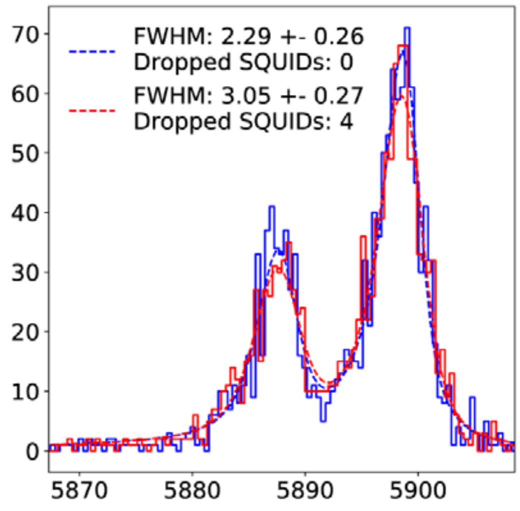
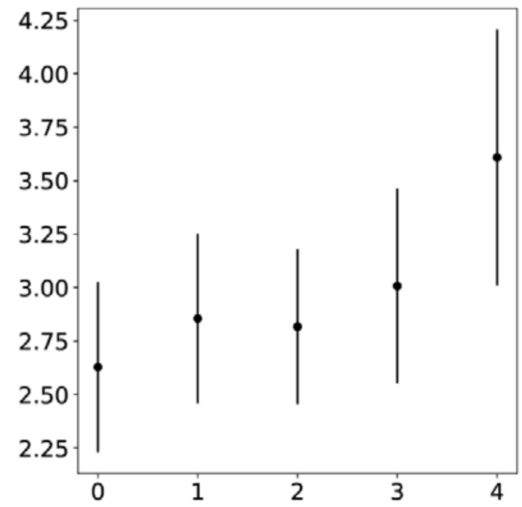
Experimental demonstration: loss of multiple SQUIDs



Experimental Mn K-α spectra from one pixel of a CDM system where SQUID failures have been simulated. With 4 SQUIDs "failed", the energy resolution of the pixel degrades slightly.

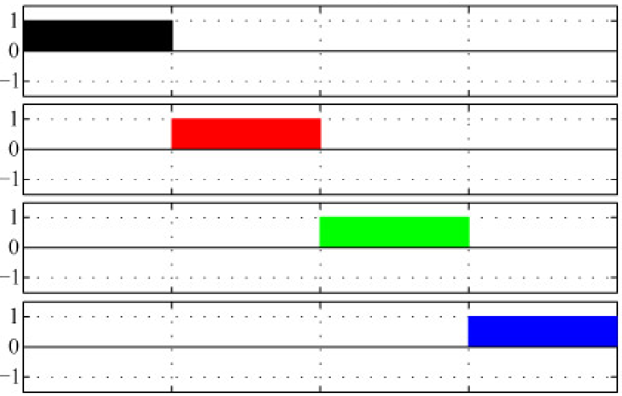


Average energy resolution of the TES array as a function of the number of simulated SQUID failures.

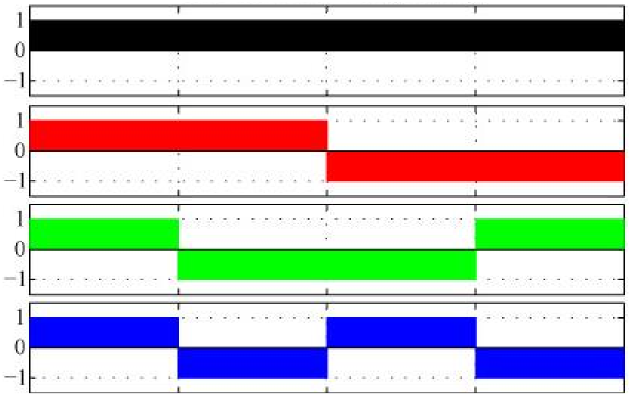
- Disconnection multiple TESs enables reconstruction of signal when multiple SQUIDs are lost. Degradation is small in this experiment for up to 3 lost SQUIDs
- For details, see Jamie Titus, PB-22 "Error Correcting Codes for code-division multiplexed TES detectors

X-ray microcalorimeter mux: new architectures

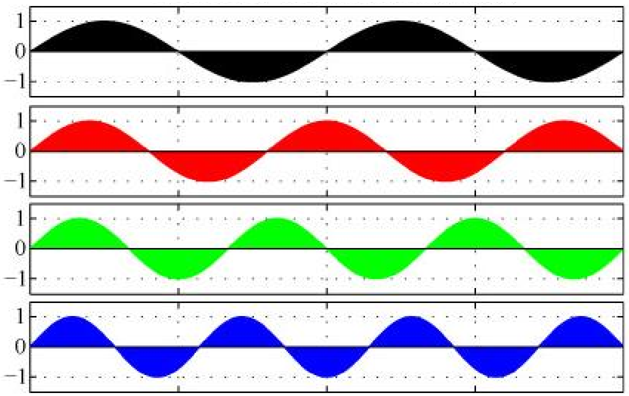
Time-division MUX



Code-Division MUX



μwave SQUID MUX



Need: reduced crosstalk on feedback

Need: robustness against single-point failure

Need: high mux factors with high slew-rate

This presentation:

Switched feedback

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Error-correction codes

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Spread-spectrum mux

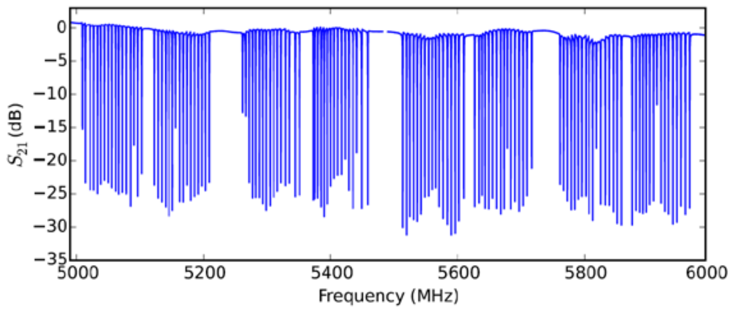
<u>μmux heritage</u>

- KD Irwin and KW Lehnert, "Microwave SQUID multiplexer," Appl. Phys. Lett. **85**, 2107 (2004).
- JAB Mates, GC Hilton, KD Irwin, LR Vale, and KW Lehnert, "Demonstration of a multiplexer of dissipationless superconducting quantum interference devices," Appl. Phys. Lett. **92**, 023514 (2008).

What limits the density of resonators in μmux?

1. Signal bandwidth. But this is almost always small.

2. Fab constraints on Q and accuracy of resonator placement.



See Ben Mates talk, this session

- Can probably be improved to ~1 MHz spacing with fab improvements and trimming
- Many TES per resonator: ***hybrid mux*** (μmux hybrid with TDM, CDM, FDM)

For discussion, see Irwin, "Shannon Limits for Low-Temperature Detector Readout," AIP 1185, 229 (2009)

3. Slew rate of x-ray pulse

← Hybrid mux doesn't help with this

The slew rate limits the mux factor in μmux

- Total bandwidth (e.g. of HEMT)

$$N_{pixels} = \frac{BW_{total}}{S \times 2 \times n_{\Phi_0} \times f_s}$$

- Normalized spacing (∼ 10)
- Double side-band
- Flux quanta in ramp (e.g. 2)
- Flux-ramp frequency (effective sampling frequency)

From Ben Mates' talk this morning:

$$BW/pix = 2Sn_{\Phi_0} \times f_s$$

Maximum flux slew rate

$$\left.\frac{d\Phi}{dt}\right|_{max} = f_s \times \varepsilon\Phi_0$$

$\varepsilon\Phi_0 \sim 0.5\ \Phi_0$ is the maximum allowed error signal

$$BW/pix = \frac{2Sn_{\Phi_0}}{\varepsilon} \frac{M}{\Phi_0} \left.\frac{dI}{dt}\right|_{max}$$

Some example numbers

M=230 pH, n_{Φ_0}=2, S=10, $\varepsilon = 0.5$

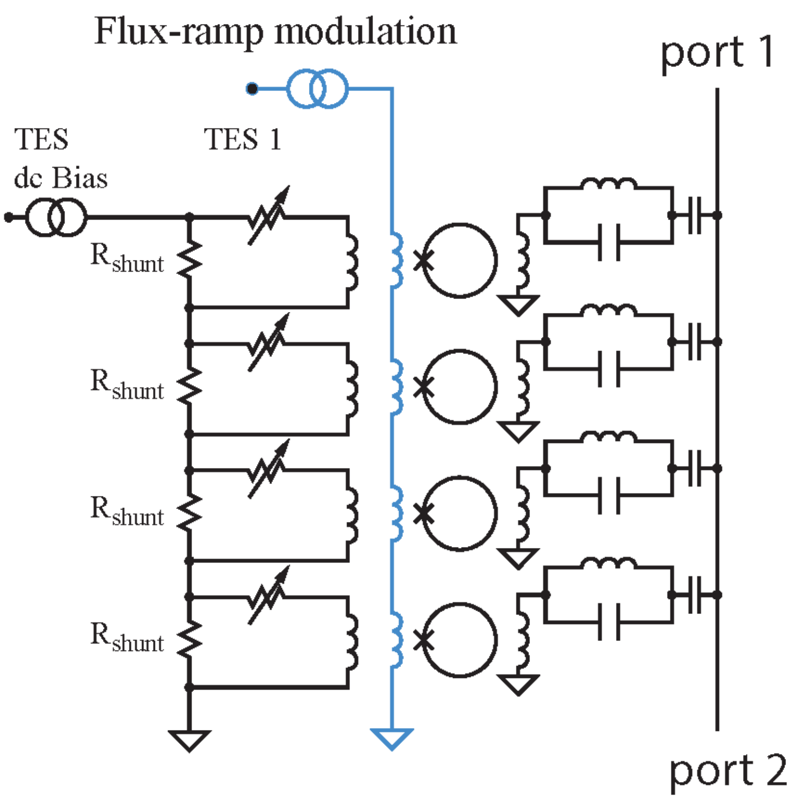
dI/dt=0.4 A/s (Athena LPA1)

BW/pix ~ 4 MHz

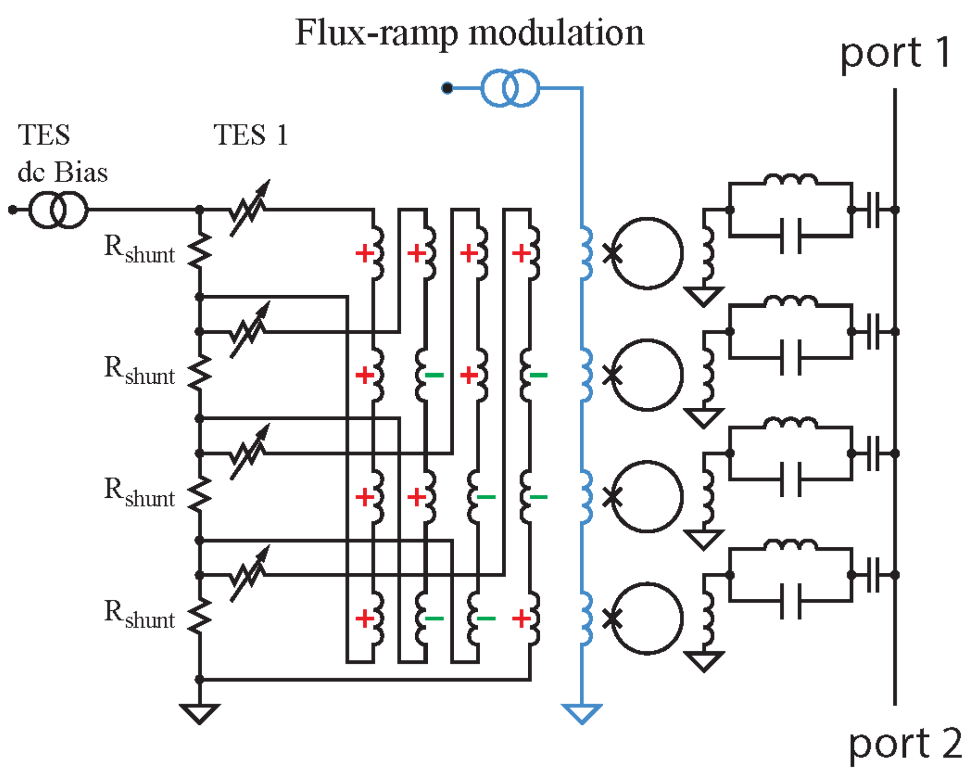
Conclusion: slew rate sometimes limits the MUX factor

The MUX factor can be increased by spreading the flux signal over multiple resonators in a Walsh code

Microwave SQUID MUX (FDM)

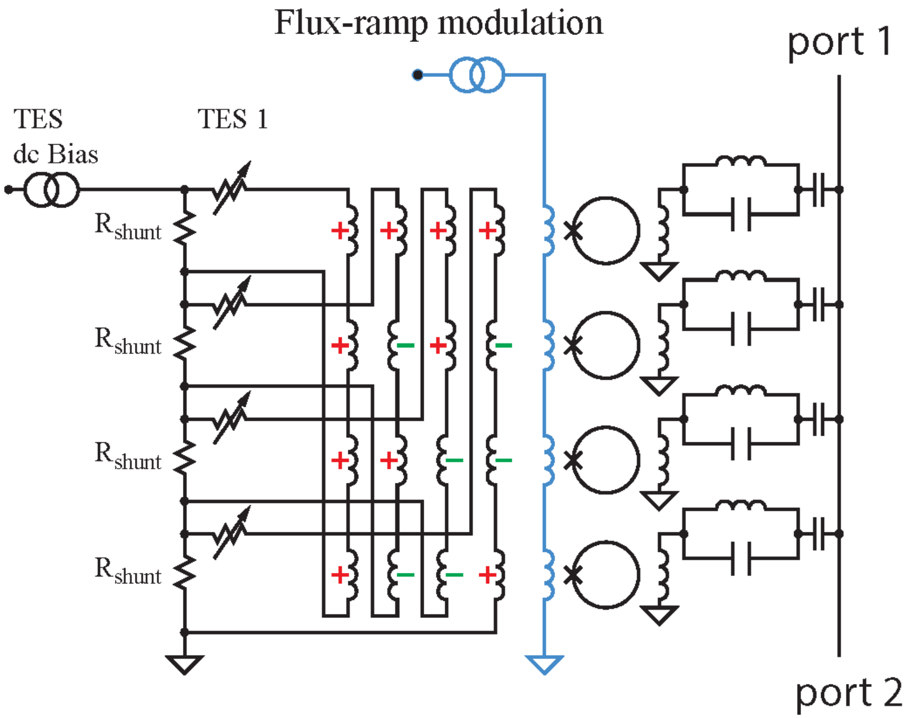


Spread-Spectrum MUX



Spread-spectrum multiplexer (SSmux)

N_{ss}=4



Bandwidth per pixel in SSmux

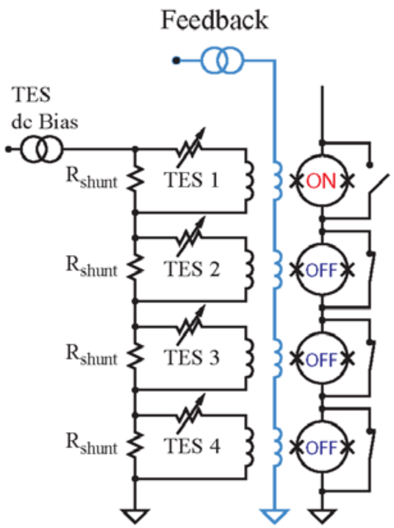
$$\frac{BW}{pix} = \frac{2Sn_{\Phi_0}}{\varepsilon} \frac{M_0}{\Phi_0} \frac{1}{\sqrt{N_{ss}}} \left.\frac{dI}{dt}\right|_{max}$$

The signal from each TES is spread over N_{ss} resonators in a Walsh code

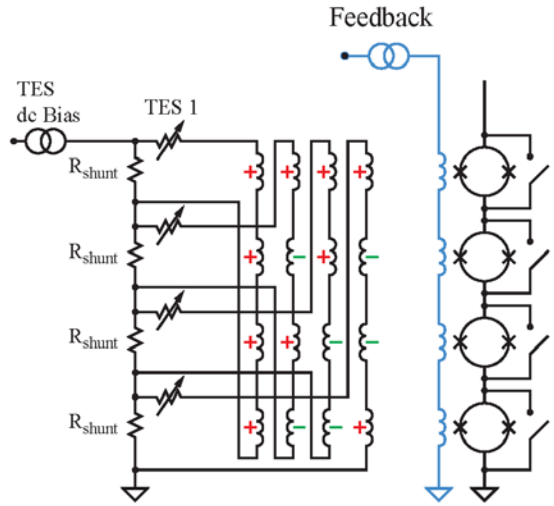
- Number of TESs still equals number of resonators (but SSmux can be combined with hydras & hybrid MUX)
- N_{ss} independent samples of the SQUID noise reduces the effective SQUID noise amplitude by $\sqrt{N_{ss}}$
- Signal-to-SQUID-noise ratio in SSmux can be made the same as µmux if M_0 is reduced to $M_0/\sqrt{N_{ss}}$
- Max slew rate required in each resonator is reduced by $\sqrt{N_{ss}}$ as long as the photon rate is low (only one photon rising at a time in N_{ss} pixels)
- MUX factor in SSmux increased by factor $\sqrt{N_{ss}}$ relative to µmux

Conclusion: next generation mux architectures

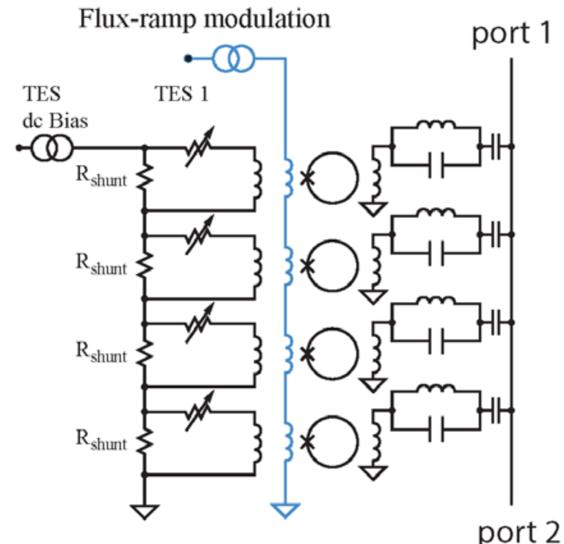
Time-division MUX



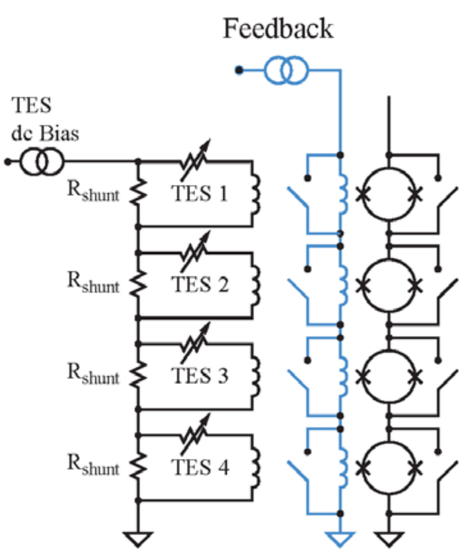
Code-Division MUX



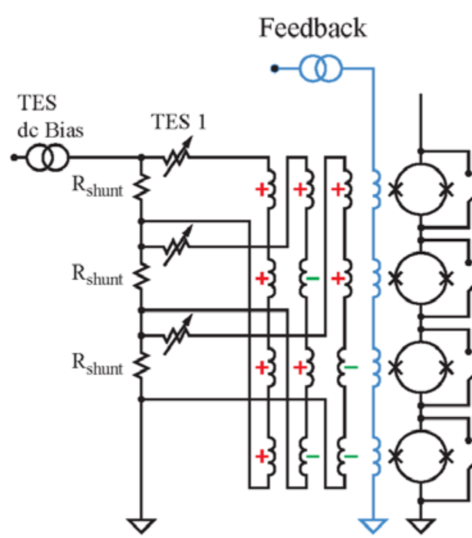
µwave SQUID mux



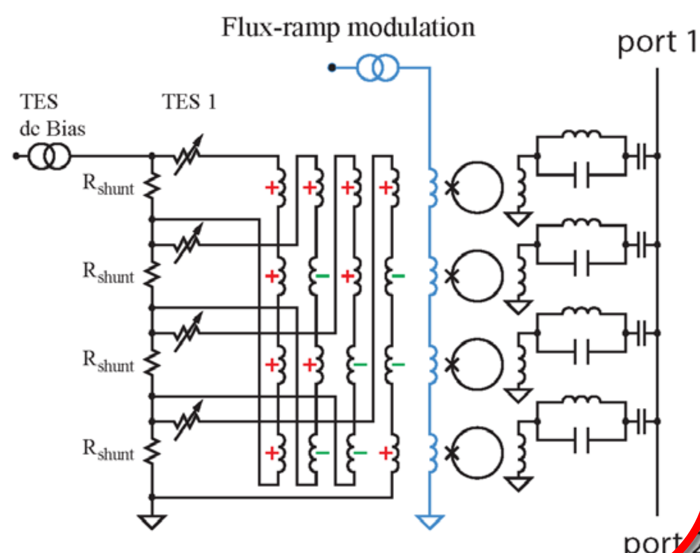
Feedback switches



Error correcting codes



SSmux



- We have implemented feedback switches in TDM to reduce crosstalk
- We have implemented error correction in CDM: experimental demo of correction of SQUID failures
- We propose Spread-Spectrum mux (SSmux). Drop-in compatible with μmux system, with increased multiplex factor for low count rate sources (e.g. astronomical).

The slew-rate-limited MUX factor in SSmux is increased by factor $\sqrt{N_{ss}}$ relative to μmux