SQUID-based Readout Schemes for Microcalorimeter Arrays

- Mikko Kiviranta
- Heikki Seppä
- Jari S. Penttilä
- Juha Hassel
- Jan van der Kuur
- Piet de Korte
- Martin Frericks
- Wouter van Kampen
- Piet de Groene

Motivated by the XEUS mission by the ESA

Single-pixel signal path

Absorber → Transition edge → SQUID amplifier → Room-temperature amplifier

Non-feedback bare parameters:

- **Power gain**: \( \frac{1}{2} \alpha \left( 1 - \frac{T_{\text{sw}}}{T} \right) \left( 8\pi \omega^2 L_{\text{sw}} C_j \right)^{1/2} \)  
  Can be very large

- **Bandwidth**: \( \frac{G_T}{C_T} \)  
  Input coil resonance  
  Can be up to GHz’s or more

- **Dynamic range**: \( \frac{\Delta T}{T} \left[ \frac{G_T}{\sqrt{4k_B}} \right] \) \( \Phi_0 \left( \frac{9.8 L_{\text{sw}}^{1/4} C_j^{1/4}}{L_{\text{sw}}^{1/4} C_j^{1/4}} \right) \sqrt{k_B T} \) \( \sim 10^9 \) with standard analog circuits

Use negative feedback to trade gain for bandwidth & dyn range
Use positive feedback to trade BW & dyn range for gain
The designer’s job

[Diagram showing various elements and noise sources]

- Take care of the bandwidths, too.
- FB modifies input & output impedances (noise matching)

Standard arrangement for the feedback paths ...

[Diagram showing standard arrangement for feedback paths]

“Electro-Thermal Feedback (ETF)”

“Flux Locked Loop”

… but there’s a number of other possibilities, eg.:

[Diagram showing other feedback arrangements]

“Temperature-locked loop”

Local FB for the SQUID
What if we have a large number of pixels?

**Direct readout:**
- Feasible (compare: MEG devices)
- Heat leak through the wires
- Complex and fragile

**Correlation-based schemes:**
- Noises are summed - *bad*
- Acceptable only when SNR can tolerate summation

**Multiplexing:**
- Fingerprint signals by multiplying by an orthogonal set of functions \( f_1(t), f_2(t) \ldots \) (sines & cosines; Hadamard functions; wavelets ...)
- Sum to a single wire
- Detect the signals by multiplying with the same set \( f_1(t), f_2(t) \ldots \) and integrate over all times
- Multiplier: (i) TES, (ii) SQUID, (iii) some extra device

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**Hadamard codes** (Karasik & McGrath)

**Sines & cosines** “frequency MUX”

**Timeslot functions** “time domain MUX”

**Modified timeslot functions** for enhanced duty cycle (4ch versions are symmetrically bipolar)

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**TESes as modulators**
- \( I(t) = G(t) \times U_b(t) \)
- Conductance \( G \) carries the signal
- Bias voltage carries the modulating function
- No direct thermal response: average RMS heating
- Magnetic nonlinearity?
- Only \( N \) wires from TES chip to SQUID chip for \( N \times M \) pixels
- Only \( N \) SQUIDs
**SQUID as modulator**

- Signal is multiplied by SQUID response function \( I = M I_{\text{TES}} \times \partial I / \partial \Phi \).
- \( \partial I / \partial \Phi \) is a non-linear function of \( U_b \).
- Works best with two-level mod-functions.
- \( m \times n \) wires from TES chip to SQUID chip, if cannot be integrated monolithically.

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**Noise folding**

- Wideband noise is added after the modulator.
- The noise from a given pixel aliases into frequency bands / timeslots / codes of other pixels.
- (i) Provide gain so that noise summing can be tolerated.
- (ii) Use frequency-preferring / timeslot-preferring / code-preferring noise blocker.
- In case of freq. MUX, the blocker is just an LC resonator.
- With other MUX schemes, active elements and external clock signal feeds are needed.
Filter implementation

- L is set by stability requirement
- 80 nH fits in ~ 0.2 × 0.2 mm
- C implementability sets lower limit to f ~ 25 MHz
- Magnetic cross-coupling demands ~ 1 mm filter-to-filter separation:
  (i) crosstalk between different columns
  (ii) limits total BW available to a column
- Band separation
  - Only to avoid noise folding
  - Channel confusion: taken care by post-detection filters

X-ray absorbers and TESes

Noise-blocking LC filters

\[ L \text{ is set by stability requirement} \]

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C implementability sets lower limit to f ~ 25 MHz

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Band separation

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Common inductance in a column

- Magnetic cross-coupling (example) appears as common series inductance, like \( L_p \)
- Parasitic inductance \( L_p \) in wiring: reactive part tuned out with \( C_p \), \( L_p \) limits the bandwidth.
- Transformers ramp up the impedance level, to help with parasitic L
- SQUID input inductance \( L_{in} \) can be screened away with negative feedback
- Feedback by flux injection or current injection

Quantum-limited bandwidth:

\[ \epsilon = \frac{1}{2} L_{in} I_0^2 = \frac{R I_0^2}{4 \pi \Delta} \]

XEUS: \( R = 10 \, \text{mQ} \)

24 hbar for 32 chans separated by 200 kHz
Dynamic range

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TES current:  \[ \frac{I_{pp}}{I_n} = \frac{2\sqrt{2} \times 2.36 \times E_{\text{max}}}{\Delta E_{\text{FWHM}} \sqrt{\tau_i}} \]
\[ \sim 5 \times 10^6 \text{ for XEUS} \]

SQUID:  \[ \frac{\Phi_0 / 2}{\Phi_n} = \frac{\Phi_0}{9.8L_{SQ}^{3/4}C_j^{1/4}k_B T} \]
\[ \sim 2.4 \times 10^7 \text{ for } T = 1 \text{ K}, \]
\[ C_j = 0.5 \text{ pF}, L_{SQ} = 4 \text{ pH} \]
\[ (\epsilon \sim 2.2 \text{ hbar}) \]

SQUID:  \[ \frac{\Phi_0 / 2}{\Phi_n} = \frac{\Phi_0}{5.3L_{SQ}^{3/4}C_j^{1/4}k_B T_n} \]
\[ \sim 8 \times 10^6 \text{, when } T_n = 10 \text{ K} + 20 \text{ K} \]
\[ \text{for 30MHz RT amp + cables} \]
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Need some more dynamic range for linearity?

- Harmonic production by an event? (No, falls above the signal band)
- Mixing between an event & imperfect idle current balancing? (Probably not)
- Mixing between two coincident events? (Not likely if pixels are scattered)
- Gain stability? (Probably yes)

Dynamic range - how to improve?

- Alleviate DR requirement?
  Increase integration time (= filter settling time), still retaining thermal stability condition.

- Array SQUID for sqrt(n) -fold DR improvement?

- Long negative feedback at carrier freq. through RT not feasible, but...
  … (i) FB through low-dissipation MOS amplifier at 20 K?
  … (ii) FB through RT at baseband rather than carrier frequency?

Filters against noise folding … replaced by duplex filters

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Signal from TES

FB signal carries information

Baseband signal

Carrier is deterministic

Filter for loop stability (mixed-up version of a PI-controller)
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\[ \text{LO} \]
Total system: a scenario

Adaptive idle current
cancellation: grayed out