# SQUID-based Readout Schemes for Microcalorimeter Arrays


- Mikko Kiviranta
- Heikki Seppä
- Jari S. Penttilä
- Juha Hassel

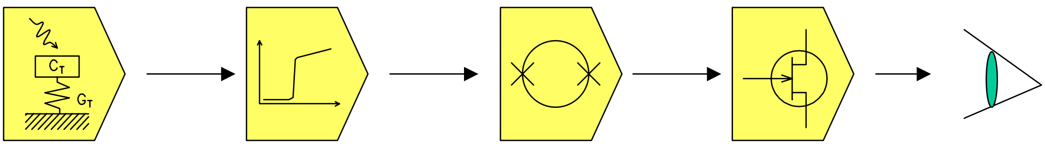
**The Technical Research Center of Finland**

- Jan van der Kuur
- Piet de Korte
- Martin Frericks
- Wouter van Kampen
- Piet de Groene

**The Space Research Organization of the Netherlands**


Motivated by the **XEUS** mission by the **ESA**

## Single-pixel signal path

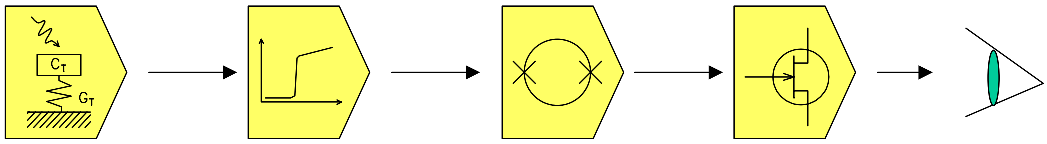


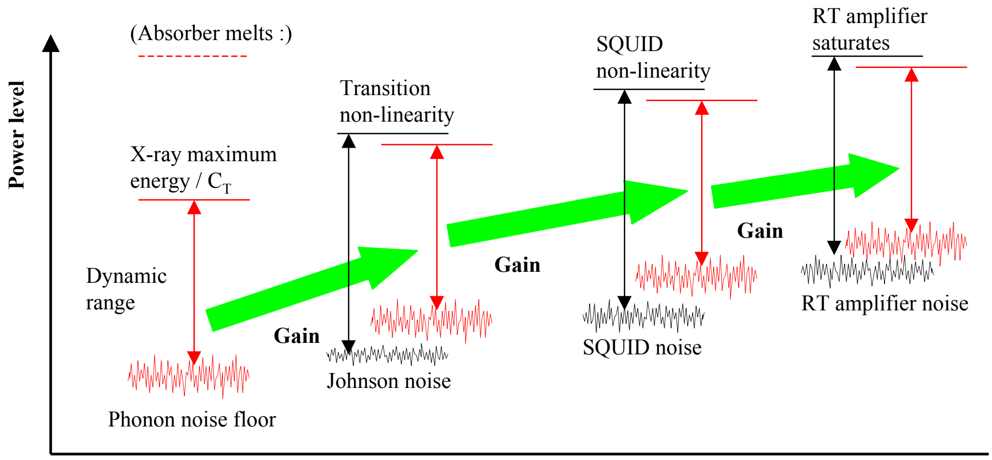

Non-fedback bare parameters:

| | | | |
|---|---|---|---|
| **Power gain** | $\frac{1}{2}\alpha\left(1-\frac{T_{bath}}{T}\right)$ | $\left(8\pi\omega^2 L_{SQ}C_j\right)^{-1}$ | Can be very large |
| **Bandwidth** | $\frac{G_T}{C_T}$ | Input coil resonance | Can be up to GHz's or more |
| **Dynamic range** | $\frac{\Delta T}{T}\sqrt{\frac{G_T}{4k_B}}$ | $\frac{\Phi_0}{9.8L_{SQ}^{3/4}C_j^{1/4}\sqrt{k_B T}}$ | ~ $10^9$ with standard analog circuits |

Use negative feedback to trade gain for bandwidth & dyn range
Use positive feedback to trade BW & dyn range for gain

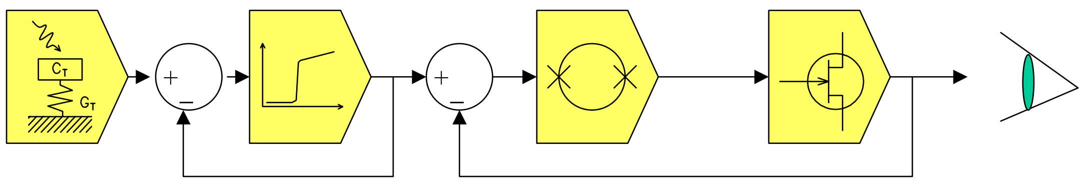
# The designer's job




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

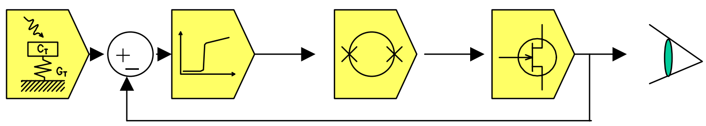
# Standard arrangement for the feedback paths ...



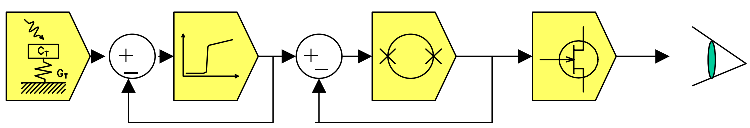

"Electro-Thermal Feedback (ETF)"

"Flux Locked Loop"

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



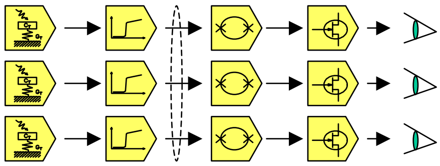
"Temperature-locked loop"



Local FB for the SQUID

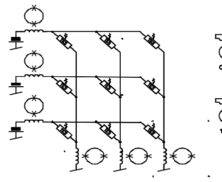
# What if we have a large number of pixels?

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

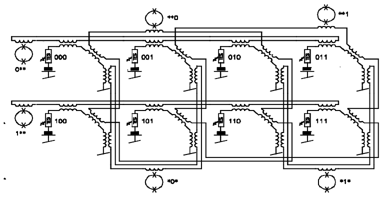


Wiring to 20 mK stage
(2.8 μWh cooling capacity [XEUS])

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

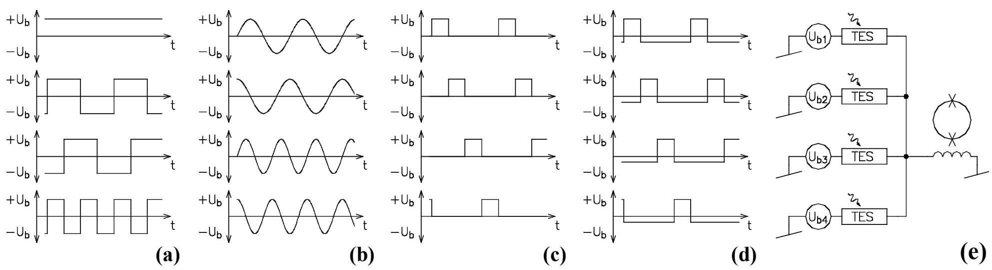


2D-array: 3 x 3 pixels



3D-array: 2 x 2 x 2 pixels

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

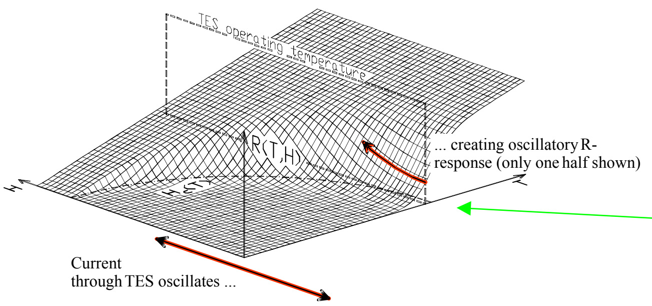



Hadamard codes (Karasik & McGrath)

Sines & cosines "frequency MUX"

Timeslot functions "time domain MUX"

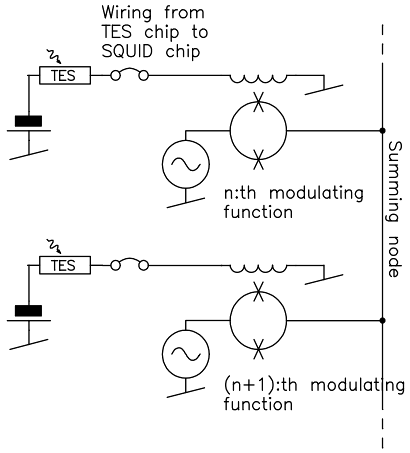
Modified timeslot functions for enhanced duty cycle (4ch versions are symmetrically bipolar)




## 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

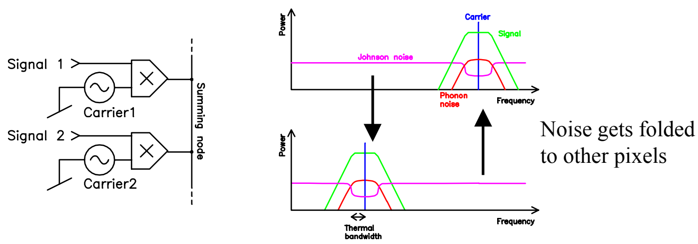
- Signal is multiplied by SQUID response function $I = MI_{TES} \times \partial I / \partial \Phi$.
- $\partial I / \partial \Phi$ is a non-linear function of $U_b$
- Works best with two-level mod-functions
- $m \times n$ wires from TES chip to SQUID chip, if cannot be integrated monolithically



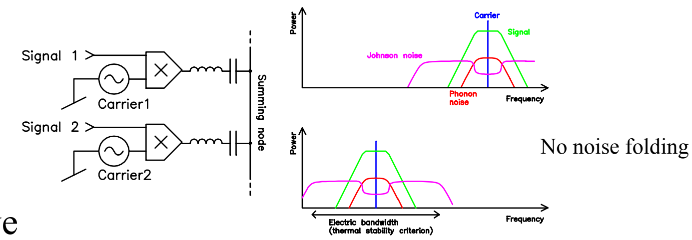

# Noise folding

- 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

**Without noise blockers**

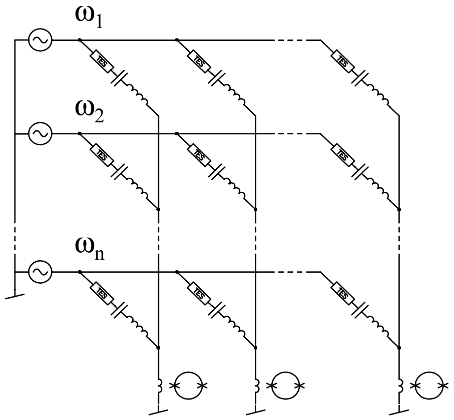


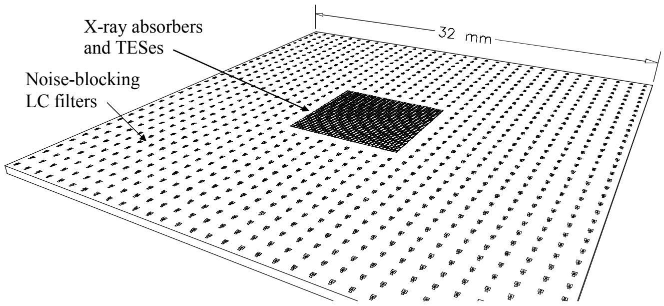

**With noise blockers**



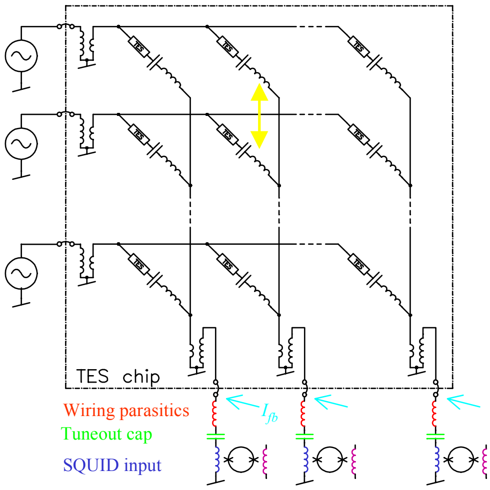
# Filter implementation

- 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




# Common inductance in a column

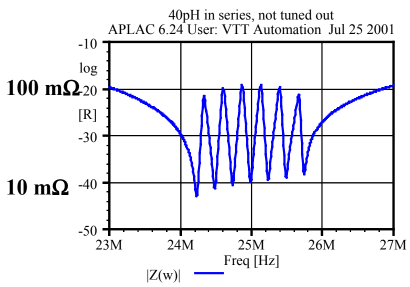


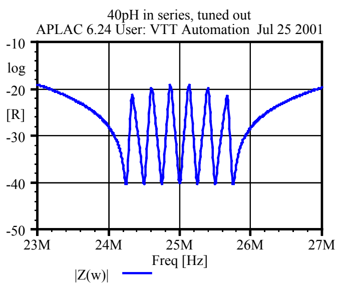

- **Magnetic cross-coupling (example) appears as common series inductance, like $L_p$**
- **Parasitic inductance $L_p$ in wiring: reactive part tuned out with $C_e$, $L_p$ limits the bandwidth.**
- **Transformers ramp up the impedance level, to help with parasitic L**
- **SQUID input inductance $L_{in}$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

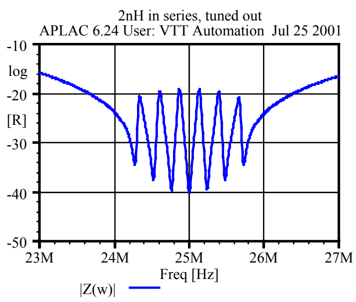
**Quantum-limited bandwidth:**

$$\varepsilon = \frac{1}{2} L_{in} I_n^2 = \frac{R I_n^2}{4\pi \Delta f}$$

**XEUS:** $R = 10$ mΩ
24 hbar for 32 chans
separated by 200 kHz



# Dynamic range

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

SQUID:
Limited by self-noise

$$\frac{\Phi_0/2}{\Phi_n} = \frac{\Phi_0}{9.8 L_{SQ}^{3/4} C_j^{1/4} \sqrt{k_B T}}$$

~ $2.4 \times 10^7$ for $T = 1$ K,
$C_j = 0.5$ pF, $L_{SQ} = 4$ pH
($\varepsilon$ ~ 2.2 hbar)

SQUID:
Limited by cable
noise & RT amplifier

$$\frac{\Phi_0/2}{\Phi_n} = \frac{\Phi_0}{5.3 L_{SQ}^{3/4} C_j^{1/4} \sqrt{k_B T_n}}$$

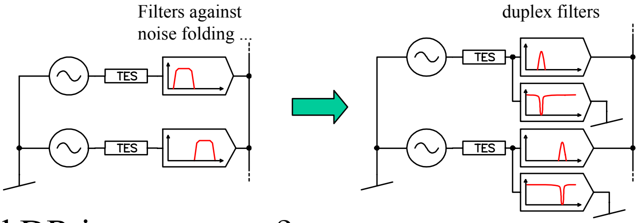
~ $8 \times 10^6$, when
Tn = 10 K + 20 K
(for 30MHz RT amp + cables)

**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)

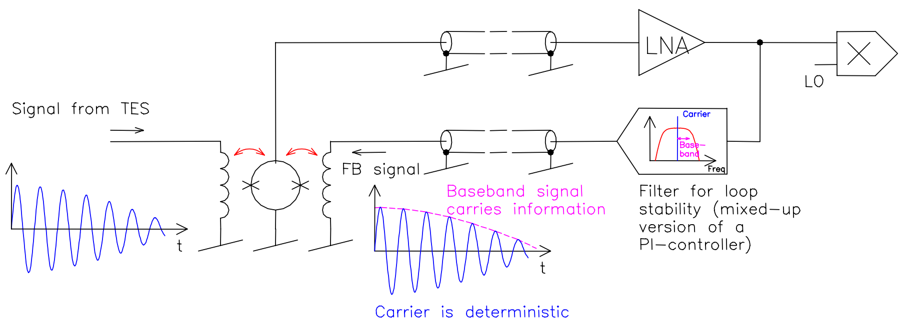
# Dynamic range - how to improve ?

- 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?



# Total system: a scenario