Multiplexed microwave readout of cryogenic TES microcalorimeters

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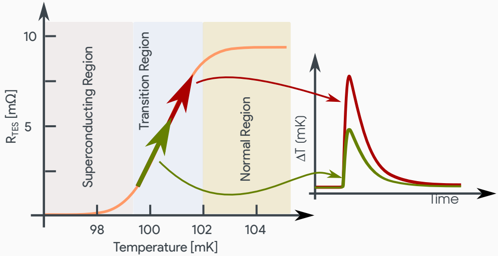
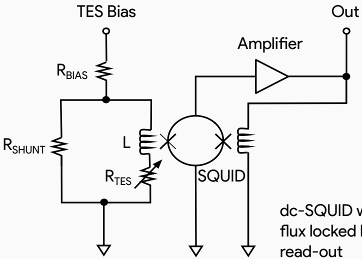
on behalf of Milano-Bicocca group

TES-based microcalorimeters

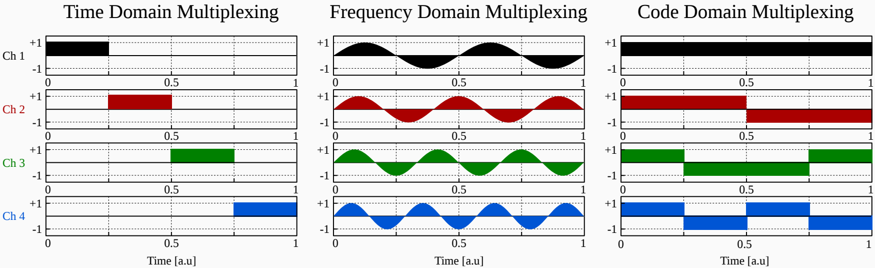




dc-SQUID with flux locked loop read-out

- Superconductor biased in its transition ⇒ strongly temperature-dependent resistance;
- "Self-biased region" ⇒ the power dissipated in the device is constant with the applied bias;
    - Electrothermal feedback: if $R_{TES} \uparrow \;\Rightarrow\; I_{TES} \downarrow \;\Rightarrow\; P_J \downarrow \;\Rightarrow$ cooling the device back to its equilibrium state in the self-biased region;
- Low resistance: read out with SQUIDs (Superconducting Quantum Interference Devices);
    - TES operates in series with the input coil *L* which is inductively coupled to the SQUID:
    - Change in TES current ⇒ change in the input flux to the SQUID;
- SQUIDs enable multiplexing ⇒ read out of many sensors using a smaller number of amplifier channels

Multiplexing of TES Arrays



- **Time Domain Multiplexing (TDM)**
  - TES outputs are switched by applying the bias current to one SQUID amplifier at a time;
  - The outputs of many SQUIDs are added into one output channel;
- **Frequency Domain Multiplexing (FDM)**
  - TESs are voltage biased with a sinusoidal bias voltage;
  - The output signal is modulated in amplitude following the TES resistance transient;
  - The output of the TESs is connected to a single SQUID;
  - The signal from each detector can be retrieved by using standard demodulation technique;
- **Code Domain Multiplexing (CDM)**
  - The signals from all the SQUID amplifiers are summed with different Walsh-matrix polarity patterns;
  - The original signals can be reconstructed from the reverse process;

The need for speed

- Many current and future applications for TESs require:
  - significantly faster pulse response
  - large arrays ($N_{\text{pixels}} > 1000$)

- Detectors at free-electron laser facilities

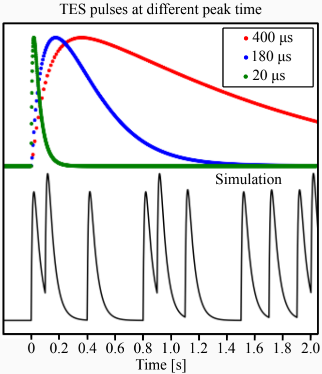
  $\Rightarrow$ pulse response fast enough
  to match repetition rates of the source;

- Neutrino endpoint (HOLMES) need enormous statistics:

  $\Rightarrow$ large number of pixel (>1000);

  $\Rightarrow$ high activity per pixel ($\sim$ 300 event/sec/pixel);

  $\Rightarrow$ faster response to avoid pile-up effects
  (that can distort spectra)



- These applications need pulse times below 200 μs;

- A rapid pulse rise can facilitate the pile-up rejection but an adequate read out bandwidth is a fundamental requirement;

- The classical multiplexing schemas (TDM, CDM and FDM) provides a limited multiplexing factor (< 40) and limited bandwidth (few megahertz) on single detector.

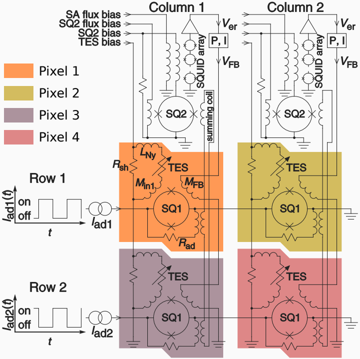
Important constraints on bandwidth

- A multiplexing technology needs to offer all of:
    - Low noise;
    - High sample rate;
    - High slew rate;
    - Low crosstalk;

- Together, these requirements dictate the bandwidth per channel;

- For the global system: $f_{\mathrm{BW}}^{(\mathrm{total})} >> \Delta f_{\mathrm{BW}}^{(\mathrm{ch})} \cdot N_{\mathrm{ch}}$

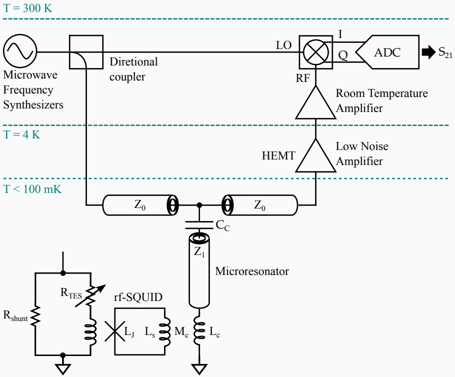
- The most mature multiplexing technology at present is Time-Division Multiplexing (TDM);

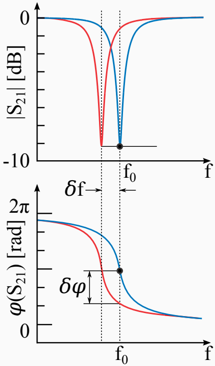


- Due to bandwidth limits and noise scaling, TDM is limited to a maximum multiplexing factor of approximately 32-40 sensors on one readout line;

- Increasing the size of microcalorimeter arrays ($N_{\mathrm{ch}} > 1000$) with high fast pulse response requires the development of a new read out technology;

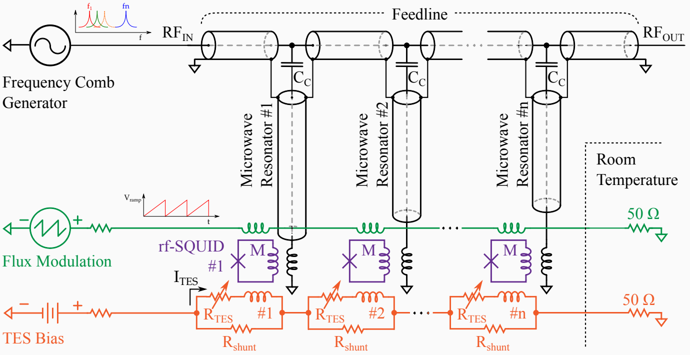
Microwave rf-SQUID multiplexing





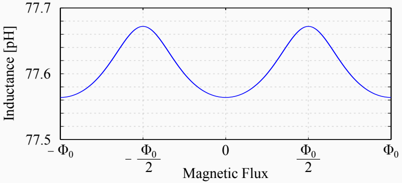
- dc-biased TES inductively coupled to a dissipationless rf-SQUID;
- rf-SQUID inductively coupled to a high-Q superconducting $\lambda/4$ resonator;
- Change in TES current $\Rightarrow$ change in the input flux to the SQUID;
- Change in the input flux to the SQUID $\Rightarrow$ change of resonance frequency and phase;
- Each micro-resonator can be continuously monitored by a probe tone;

Microwave rf-SQUID multiplexing (cont.)

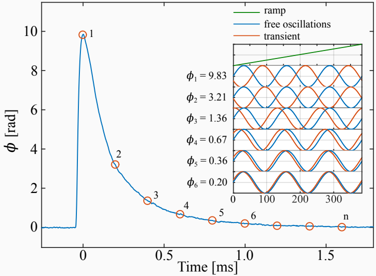


- By coupling many resonators to a single microwave feedline it is possible to perform the readout of multiple detectors
- Sensors are monitored by a set of sinusoidal probe tones (frequency comb);
- At equilibrium, the resonator frequencies are matched to the probe tone frequencies, and so each resonator acts as a short to ground;
- Large multiplexing factor ($>$ 100) and bandwidth, currently limited by the digitizer bandwidth.

Microwave rf-SQUID multiplexing: flux-ramp modulation



$$\Phi = \Phi_{TES} + \Phi_{ramp}$$

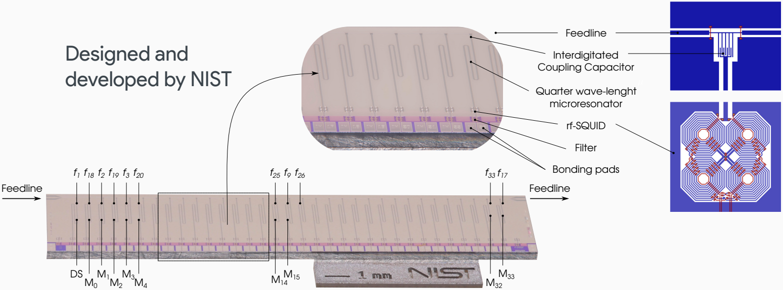


- A flux-ramp modulation is applied by a common line inductively coupled to all SQUIDs
- The signal is reconstructed by comparing the phase shift caused by the interaction of the radiation in the TES, with the free oscillation of the SQUID, when the TES is not biased;
- Each ramp acquisition represents a sample in the reconscruted phase signal: $f_{\text{sample}} = f_{\text{ramp}}$
- Necessary resonator bandwidth per flux ramp: $\Delta f_{\text{BW}} \geq 2\, n_{\Phi_0}\, f_{\text{ramp}}$
- To avoid cross talk $\Rightarrow$ spacing between resonances $S > \Delta f_{\text{BW}}$
- To avoid distortions $\Rightarrow f_{\text{ramp}} > 10/\tau_{\text{rise}}$ (potentially reduced by a factor 2);
- Minimum number of flux cycles per ramp: $n_{\Phi_0} = 2$ (possibly 1.1 with different ramp shape).

The Multiplexing chip

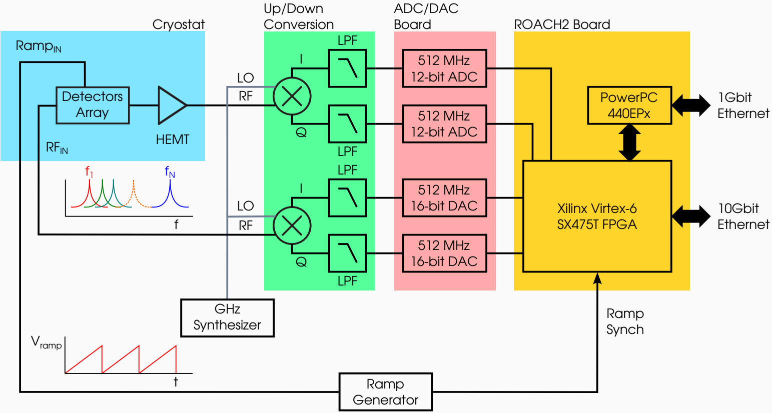
The core of the microwave multiplexing is the multiplexer chip

Designed and developed by NIST



- Superconducting 33 quarter-wave coplanar waveguide (CPW) microwave resonators;
- 200 nm thick Nb film deposited on high-resistivity silicon ($\rho > 10$ kΩ·cm);
- Each resonator has a trombone-like shape with slightly different length;
- The SQUID loop is a second order gradiometer consisting of four parallel lobes;
- Wiring in series different 33-channel chips with different frequency band allows to increase the multiplexing factor (daisy chain)

Microwave readout hardware implementation



- A key enabling technology for large-scale microwave multiplexing is the digital approach;
- This allows to exploit standard software-defined radio (SDR) used in microwave-frequency communication.

Bandwidth Budget and multiplexing factor

The number of multiplexable TES per ADC board is

$$n_{\mathrm{TES}} = \frac{f_{\mathrm{ADC}} \cdot \tau_r}{2 \cdot n_{\Phi_0} \cdot g_f \cdot R_d} \quad \text{with} \quad \Delta f_{\mathrm{BW}} \geq 2\, f_r\, n_{\Phi_0} \quad , \quad S \geq g_f\, \Delta f_{\mathrm{BW}} \quad , \quad f_s = f_{\mathrm{ramp}} \geq \frac{R_d}{\tau_r}$$

f_s = sampling rate

f_{ramp} = flux ramp frequency

Δf_{BW} = resonator bandwidth

n_{Φ_0} = number of flux quantum per ramp

S = frequency spacing between tones

g_f = guard factor between tones

τ_r = rise time

R_d = distortion suppression factor (2 is Nyquist limit)

f_{ADC} = ADC bandwidth

n_{TES} = number of TES per board

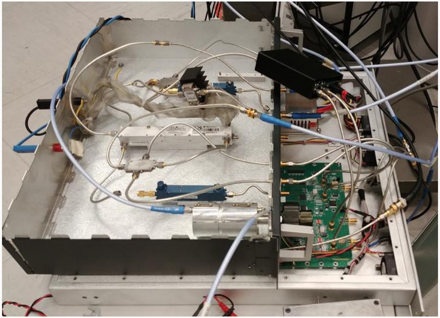
The target rise time for HOLMES is $\tau_r = 10\ \mu s$

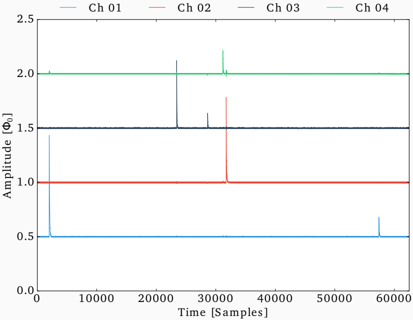
τ_r [μs]	f_r [kHz]	f_{ADC} [MHz]	n_{Φ_0}	Δf_{BW} [MHz]
10	500	500	2	2
g_f	S [MHz]	R_d	n_{TES}	
7	14	5	~36	

- The HOLMES multiplexing factor is around 32 pixels per ADC board;
- In order to cover the total 1024 pixels, 1024/32=32 ADC boards are needed;
- The typical RF bandwidth for a HEMT amplifier is from 4 to 8 GHz;

  ⇒ a single HEMT can amplify 4000 MHz/500 MHz=8 ADC boards;
- 4 HEMT amplifiers are needed for a total of 32 ADC boards;

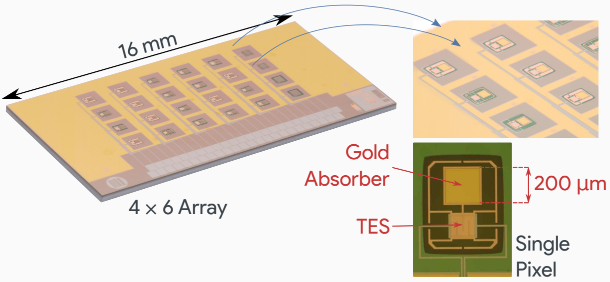
HOLMES multiplexing readout: current status

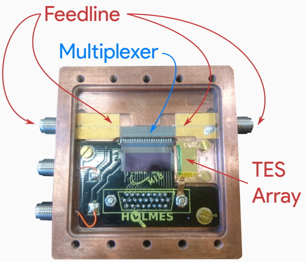




- ROACH2 board for tones generation/acquisition and for digital processing;
- Custom intermediate frequency (IF) circuitry for up/down conversion;
- Working with: $n_{\Phi_0} = 2$, $f_{\text{ramp}} = 500\,\text{kHz}$, $f_{\text{ADC}} = 512, \text{MHz}$
- 16-channel firmware from NIST (uses only half of available ADC bandwidth);
- 4 pixels measurements ⇒ limited by available tone power;

HOLMES detectors: 1stgeneration



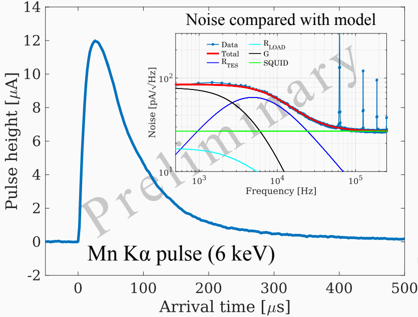


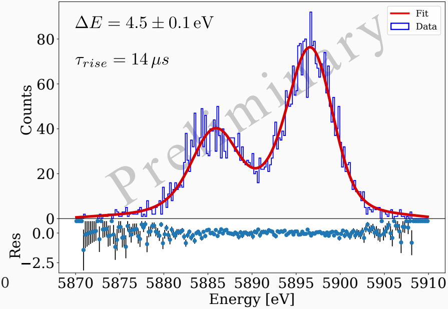
Detector Holder

- Sensor: TES Mo/Au bilayers, critical temperature $T_c = 100$ mK;
- Absorber: Gold, 2 μm thick for full e^-/γ absorption (sidecar design);
- First 4 $\times$ 6 array prototype produced at NIST at test in Milano with μwave-readout;
- Different Perimeter/Absorber configurations in order to study the detector response;

HOLMES detectors: characterization results

Fluorescence source used to test the detectors response

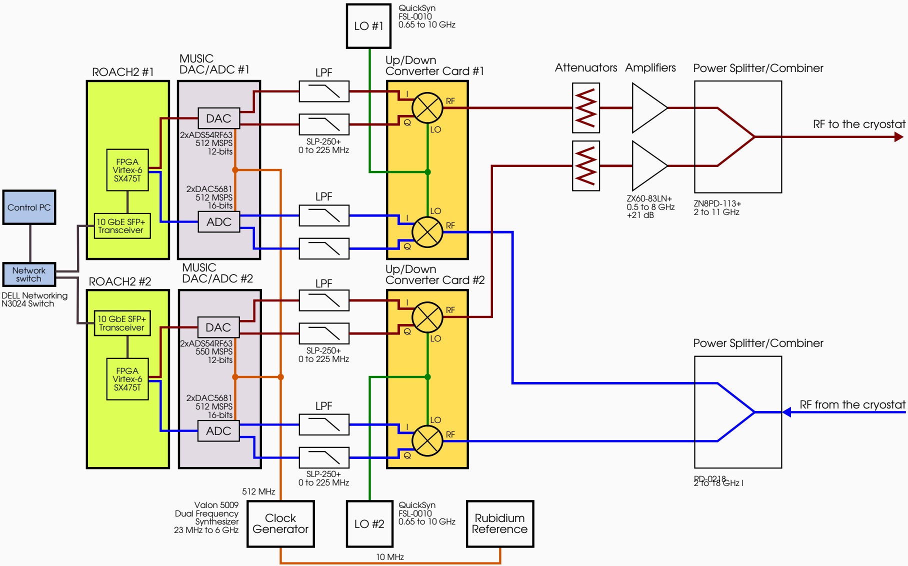




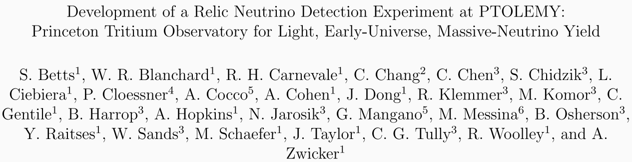
4 detector satisfied the HOLMES requirements

TES #	ΔE_{Al}	ΔE_{Cl}	ΔE_{Ca}	ΔE_{Mn}	τ_{rise} [μs]	τ_{short} [μs]	τ_{long} [μs]
2	8.6 ± 0.3	8.8 ± 0.7	7.8 ± 0.2	8.3 ± 0.3	11	56	220
6	6 ± 1	6.0 ± 0.4	6.4 ± 0.4	6.2 ± 0.4	12	34	170
8	4.5 ± 0.3	5.0 ± 0.5	5.0 ± 0.2	4.5 ± 0.1	13	54	220
11	4.3 ± 0.3	4.5 ± 0.3	4.6 ± 0.3		14	32	180

HOLMES multiplexing readout: 64 channel readout



Multiplexing readout and PTOLEMY

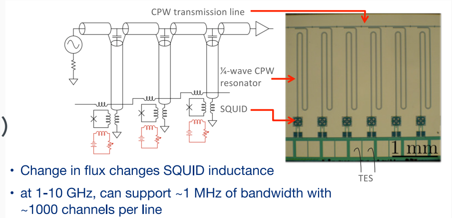


Development of a Relic Neutrino Detection Experiment at PTOLEMY:
Princeton Tritium Observatory for Light, Early-Universe, Massive-Neutrino Yield

S. Betts[1], W. R. Blanchard[1], R. H. Carnevale[1], C. Chang[2], C. Chen[3], S. Chidzik[3], L. Ciebiera[1], P. Cloessner[4], A. Cocco[5], A. Cohen[1], J. Dong[1], R. Klemmer[3], M. Komor[3], C. Gentile[1], B. Harrop[3], A. Hopkins[1], N. Jarosik[3], G. Mangano[5], M. Messina[6], B. Osherson[3], Y. Raitses[1], W. Sands[3], M. Schaefer[1], J. Taylor[1], C. G. Tully[3], R. Woolley[1], and A. Zwicker[1]

arXiv:1307.4738
26 Aug 2013

(from the PTOLEMY proposal)



- Change in flux changes SQUID inductance
- at 1-10 GHz, can support ~1 MHz of bandwidth with ~1000 channels per line

Figure 17: Microwave-readout Massive SQUID Multiplexer concept for approximately 1000 channels per coplanar waveguide(CPW) transmission line operating at 1-10 GHz with a bandwidth of 1 MHz per channel. Multiplexers based on this principle have been developed by the NIST/University of Colorado TES X-ray microcalorimeter readout.

- The PTOLEMY collaboration proposed the microwave-readout from the beginning;
- Is the current status of development compatible with the PTOLEMY requirements?

The read out noise in microwave multiplexing

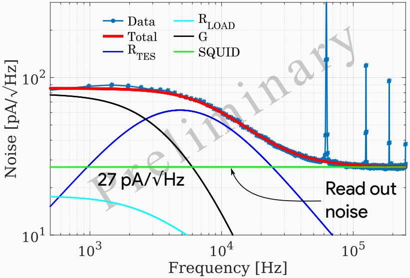
- There are four main sources of noise:
  - Johnson noise in the flux input circuit;
  - intrinsic flux noise in the SQUID;
  - HEMT noise (dominant);
  - Two-Level System (TLS) noise in the resonator;
- The HOLMES read out noise is around

$$n_s = 30\,\mathrm{pA}/\sqrt{\mathrm{Hz}}$$

- The INRiM TESs showed a 0.113 eV @ 0.8 eV energy resolution with a read-out noise of

$$n_s = 6 - 7\,\mathrm{pA}/\sqrt{\mathrm{Hz}}$$

Noise compared with model



- Probably this reasult is not achievable with the current microwave multiplexing read out noise;
- What is the maximum read out noise acceptable for the PTOLEMY TESs?
- Is the microwave multiplexing noise compatible with the PTOLEMY requirements?
- (Maybe) too early to answer these questions but it is a technical aspect to take into account.

Conclusion

- TES x-ray microcalorimeters have already demonstrated high resolution and fast response $\Rightarrow$ Large array of these detectors are suitable for several applications;
- Standard multiplexing technologies are reaching their full potential;
- For much faster and/or more numerous sensors, a wider system bandwidth is needed;
- Microwave multiplexing reached the needed maturity for reading out large array of TESs;
  - Next generation of ADCs/DACs (6-8 GS/s) and of programmable logics could increase the multiplexing factor by at least 1 order of magnitude;
- The Microwave multiplexing read out noise is dominated by the HEMT noise;
  - The current noise level guarantees a good resolution in case of X-ray spectroscopy: $\Delta E = (4.5 \pm 0.1)$ eV @ 5.9 keV;
  - ... but it may represents a limitation in low energy threshold applications (Dark Matter, CEνNS, etc)
- The current HEMT noise temperature is around $T_N \simeq 2$ K (it could be improved in the future);
- The development of a parametric amplifier (with quantum-limited noise) could guarantee a noise level $\sim 1/50$ times better;