Cryogenics microwave rf-SQUID multiplexing read-out for the calorimetric measurement of the neutrino mass

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WOLTE 13

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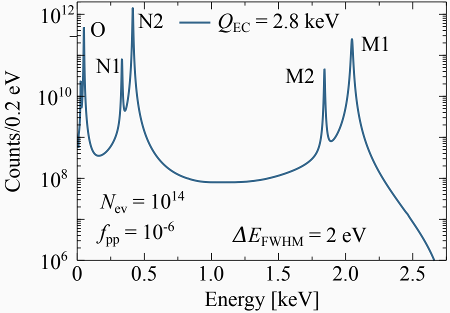

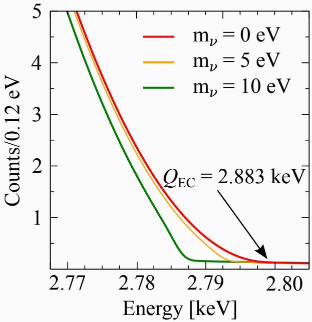

- Electron capture from shell $\geq$ M1: $^{163}\text{Ho} + e^- \rightarrow {}^{163}\text{Dy}^* + \nu_e(E_c)$;
- End-point shaped by $\sqrt{(Q - E_e)^2 - m_\nu^2}$ (the same of the β-decay);
- Searching for a tiny deformation caused by a non-zero neutrino mass to the spectrum near its end point;
- Calorimetric measurement of Dy atomic de-excitations (mostly non-radiative) $\Rightarrow$ measurement of the entire energy released except the ν energy;

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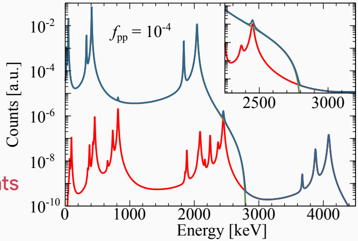
The statistical sensitivity $\Sigma(m_\nu)$ has:

- Strong dependence on statistic: $\Sigma(m_\nu) \propto N_{events}^{1/4}$
- Strong dependence on rise time pile-up: $f_{pp} \simeq A_{EC} \cdot \tau_r$ (A_{EC}: pixel activity, τ_r: time resolution)
- Weak dependence on energy resolution ΔE;

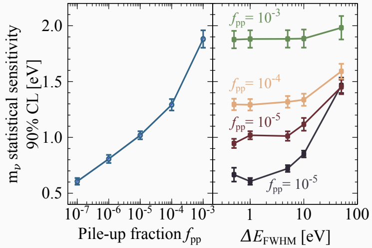
Large arrays of fast detectors are a fundamental requirements

Pile-up Spectrum

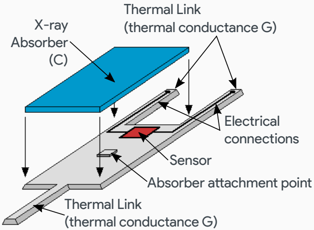


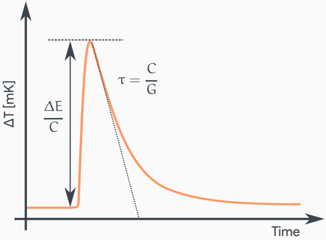
HOLMES target

- Microcalorimeters base on Transition Edge Sensors with ^{163}Ho implanted Au absorber;
- Pixel activity of $A_{EC} \sim 300$ Bq/det;
- Energy resolution: O(eV)
- Time resolution: $\tau_{res} \sim 3\,\mu$s ($\tau_{rise} \sim 10\,\mu$s);
- 1000 channels for $3 \cdot 10^{13}$ events collected in $T_M = 3$ years;
- Expected Sensitivity: $m_\nu \leq 2$ eV



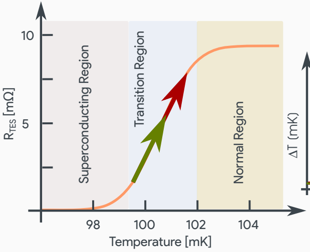
Low Temperature Microcalorimeters

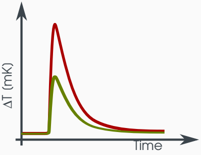


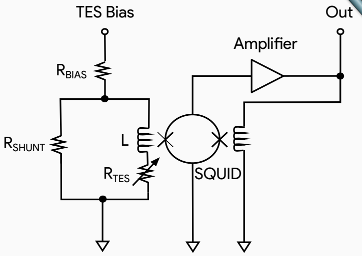


- The X-ray microcalorimeter $\Rightarrow$ senses the heat generated by X-ray photons absorbed and thermalized in a very low heat capacity element
- Complete energy thermalization: ionization, excitation $\Rightarrow$ heat $\Rightarrow$ calorimetry;
- $\Delta T = \Delta E/C$ where ΔE is the released energy and C the total thermal capacity;
  - Absorber with very low thermal capacity: $C \downarrow \quad \Rightarrow \quad \Delta T \uparrow$;
  - Debye low for superconductors below T_C and dielectric: $C \propto (T/\Theta_D)^3$;
  - A very low temperature is needed: $T \downarrow \Rightarrow C \downarrow \Rightarrow \Delta T \uparrow \Rightarrow (T = 10 \div 100$ mK);
- Limit to energy resolution $\Rightarrow$ statistical fluctuation of internal energy $\Delta E_{rms} = \sqrt{k_B T^2 C}$;

TES-based microcalorimeters







- 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;

Arrays of TES detectors

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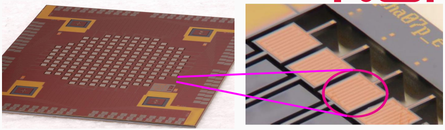
NIST



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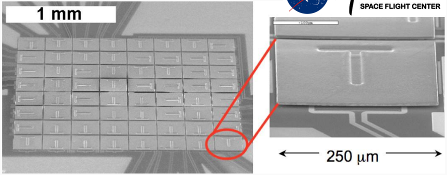

- Development strongly supported by the X-ray astrophysics community for the past couple of decades (but also Dark Matter and rare events research);
- Small size $\Rightarrow$ low thermal capacity C $\Rightarrow$ excellent energy resolution:

$$\Delta E_{\mathrm{FWHM}} = 1.6\ \mathrm{keV}\ @\ 5.9\ \mathrm{keV} \quad \text{and} \quad \Delta E_{\mathrm{FWHM}} = 0.9\ \mathrm{keV}\ @\ 1.48\ \mathrm{keV}$$

- Arrays can be easly fabricated using standard thin film deposition and optical lithography techniques;
- Suitable for any application that simultaneously requires high spectral resolving power and high collection efficiency:
  - X-ray astrophysics
  - Direct measurements of the neutrino mass
  - X-ray and γ-ray spectroscopy for nuclear materials analysis;
  - Microbeam analysis
  - Beamline science

- SQUIDs enable multiplexed readout

  $\Rightarrow$ readout of many sensors using a smaller number of amplifier channels.

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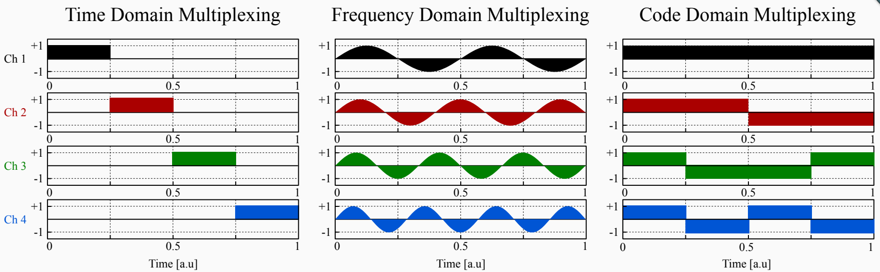

- **TDM**: Time Domain Multiplexing
  - TES outputs are switched by applying the bias current to one SQUID amplifier at a time;
  - The outputs of many SQUIDs are added into one output channel;
- **FDM**: Frequency Domain Multiplexing
  - TESs are voltage biased with a sinusoidal bias voltage;
  - The 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;
- **CDM**: Code Domain Multiplexing
  - 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

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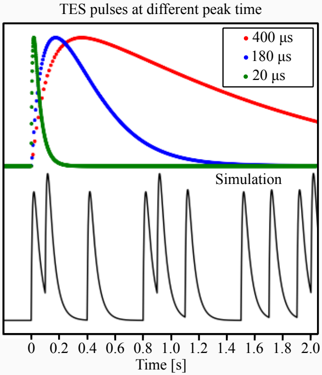
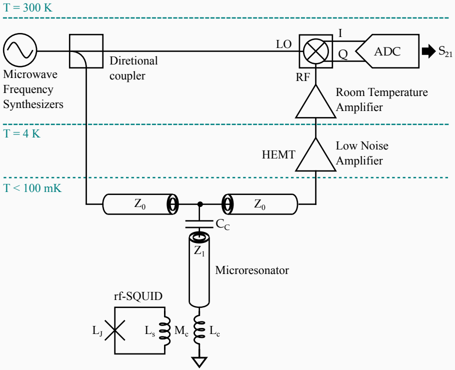
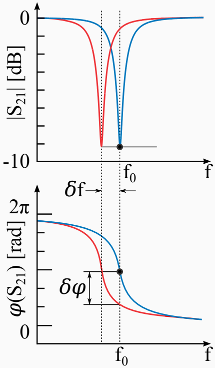
- Many current and future applications for TESs require:
  - significantly faster pulse response
  - large arrays ($N_{\text{pixels}} > 1000$)
- Detectors at free-electron laser facilities
  ⇒ pulse response fast enough
  to match repetition rates of the source;
- Neutrino endpoint (HOLMES) need enormous statistics:
  ⇒ large number of pixel (>1000);
  ⇒ high activity per pixel ($\sim$ 300 event/sec/pixel);
  ⇒ 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 adeguate 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.

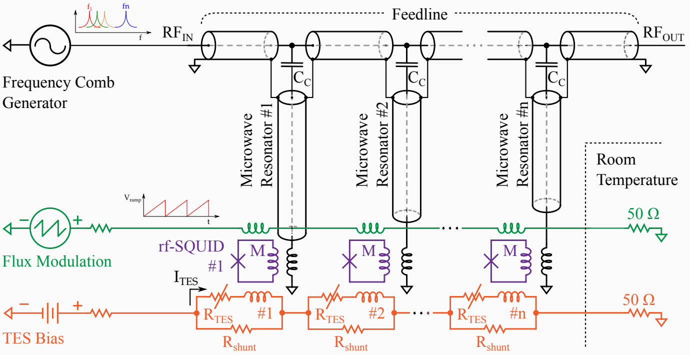
Microwave rf-SQUID multiplexing





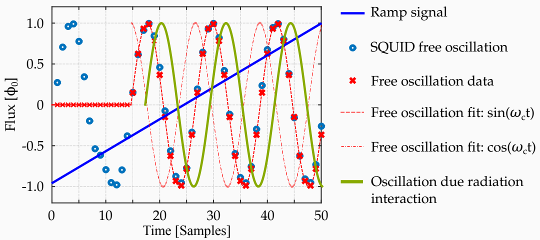
- dc-biased TES inductively coupled to a dissipationless rf-SQUID;
- rf-SQUID inductively coupled to a high-Q superconducting $\lambda/4$ resonator;
- Change in TES current $\Rightarrow$ change in the input flux to the SQUID;
- Change in the input flux to the SQUID $\Rightarrow$ change of resonance frequency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

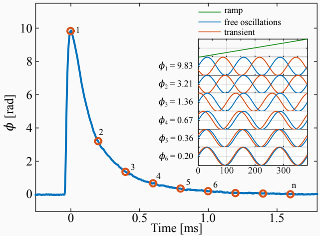
Microwave rf-SQUID multiplexing (cont.)



- 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





- 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);
- Minumum number of flux cycles per ramp: $n_{\Phi_0} = 2$ (possibly 1.1 with different ramp shape).

The Multiplexing chip

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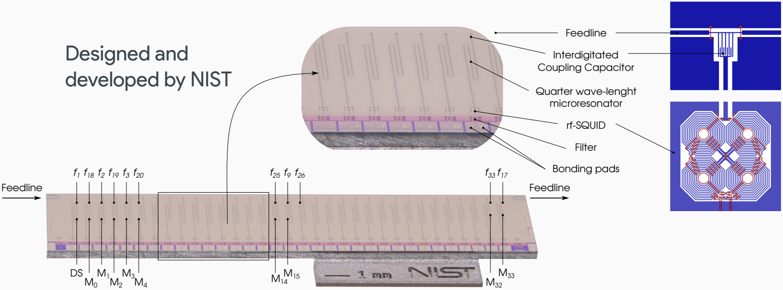
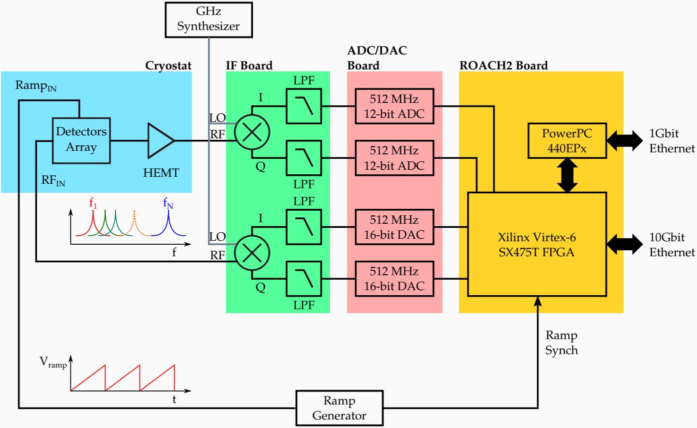
The core of the microwave multiplexing is the multiplexer chip

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)

Microware 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

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The number of multiplexable TES per ADC board is

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

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	$\sim$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;

  $\Rightarrow$ 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: the multiplexer chips (μmux17a)

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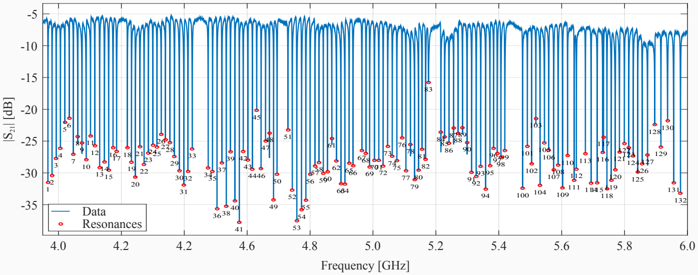
Forward transmissiom S_{21} of 4 different band chips wired in series



- Chips specifically designed for the HOLMES requirements:

  Resonators bandwidth: $\Delta f_{BW} = 2$ MHz;

  Resonators spacing : $\Delta f = 14$ MHz;

  Resonators depth : $\Delta S > 10$ dB;

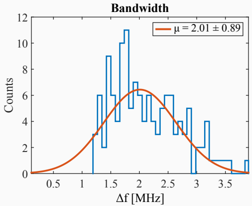
- From experimental characterization of 132 resonators (4 chips):

  Resonators bandwidth: $\Delta f_{BW} = (2 \pm 0.89)$ MHz;

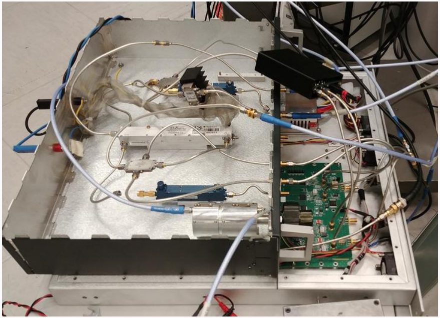
  Resonators spacing : $\Delta f = (13.78 \pm 0.95)$ MHz;

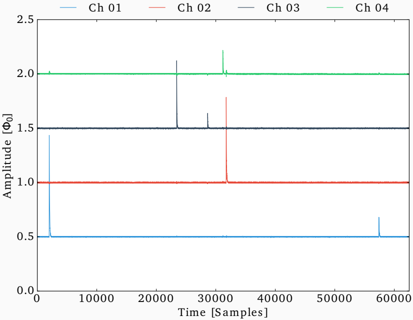
  Resonators depth : $\Delta S = (28.6 \pm 5.9)$ dB;

  SQUID noise : $n_{SQUID} = (2 - 3)\ \mu\Phi_0/\sqrt{\text{Hz}} \sim (23 - 35)\ \text{pA}/\sqrt{\text{Hz}}$



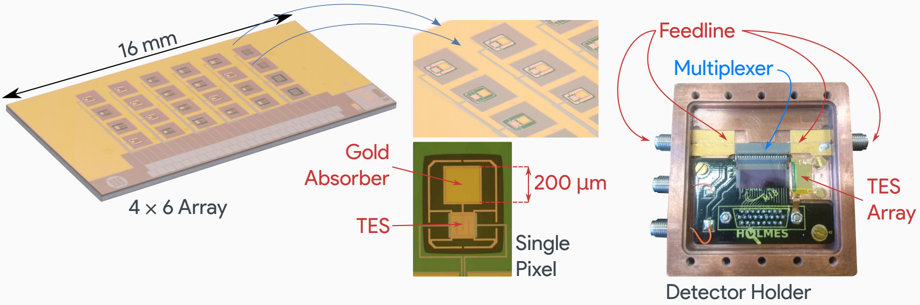
HOLMES multiplexing readout: current status





- 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 $\Rightarrow$ limited by available tone power;

HOLMES detectors: 1^{st}generation



- 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;

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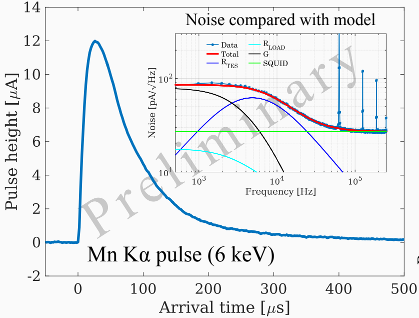
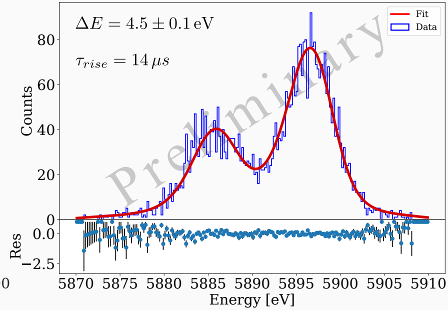
Fluorescence source used to test the detectors response

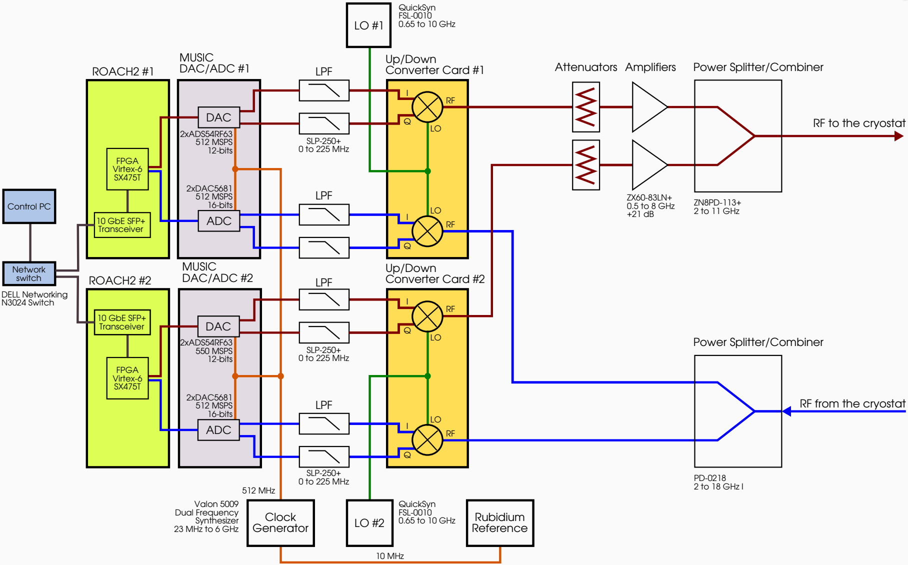




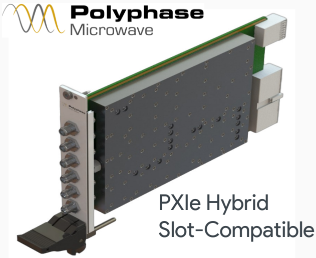
4 detector satisfied the HOLMES requirements

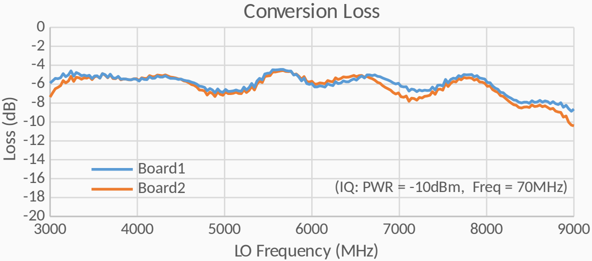
TES #	ΔE_{Al}	ΔE_{Cl}	ΔE_{Ca}	ΔE_{Mn}	τ_{rise} [μs]	τ_{short} [μs]	τ_{long} [μs]
2	8.6 ± 0.3	8.8 ± 0.7	7.8 ± 0.2	8.3 ± 0.3	11	56	220
6	6 ± 1	6.0 ± 0.4	6.4 ± 0.4	6.2 ± 0.4	12	34	170
8	4.5 ± 0.3	5.0 ± 0.5	5.0 ± 0.2	4.5 ± 0.1	13	54	220
11	4.3 ± 0.3	4.5 ± 0.3	4.6 ± 0.3		14	32	180

HOLMES multiplexing readout: 64 channel readout



HOLMES multiplexing readout: up/down conversion boards





- Commercial design but customized to match the HOLMES requirements;
- Working in C-Band (4.0 to 8.0) GHz ⇒ fully compatible with the HEMT bandwidth;
- Internal or External LO Synthesizers;
- 30 dB/ 1dB step programmable RF Attenuation;
- Total loss around -7 dBm ⇒ compatible with the power needed to drive 32 microresonators.
- Two boards delivered in Milano in August 2018;

HOLMES detectors: 2nd generation

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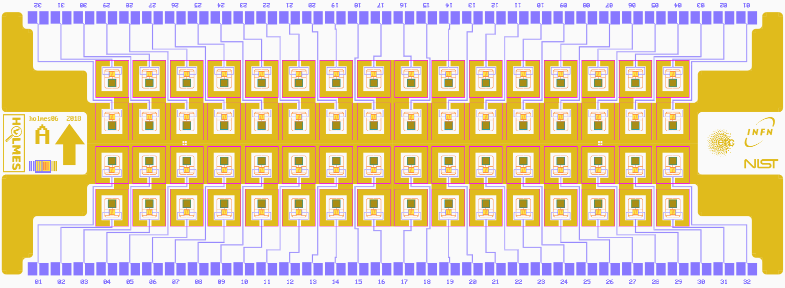

- 4 $\times$ 16 linear sub-array designed for high implant efficiency;
- First production with sensor/absorber for determining the better pixel baseline;
- Second production with pixel baseline implemented and with ^{163}Ho-implanted absorber;
- Read-out with the 64-channel system currently in development;
- Physics data from the first two microcalorimeter sub-arrays starting from 2019;

Conclusion

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- TES x-ray microcalorimeters have already demonstrated high resolution and fast response $\Rightarrow$ Large array of these detectors are suitable for the direct measurement of neutrino mass;
- 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 matury for reading out large array of TESs;
- Microwave multiplexing is appropriate for HOLMES experiment;
  - Well-matched bandwidth and peak-to-peak frequency shift;
  - Low readout noise;
  - 500 kHz readout demonstrated for 4 pixels;
- The development of a 64-channel multiplexing and read out system is in progress;
- First physics measurement from the first two sub-array starting from 2019;
- Final 1024-pixel configuration will follow;