Detectors and microwave multiplexing for the HOLMES experiment

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HOLMES

erc

Determination of the absolute electron (anti-)neutrino mass
26-20 March 2018, ECT*, Trento, Italy

Outline

- ^{163}HO EC spectrum experiment
- ^{163}HO pile-up spectrum
- HOLMES
    - HOLMES sensitivity
    - RF-SQUID read out with multiplexing microwave
    - Bandwidth budget
- Characterization of the HOLMES multiplexing readout
- TES characterization

HO Electron capture experiments

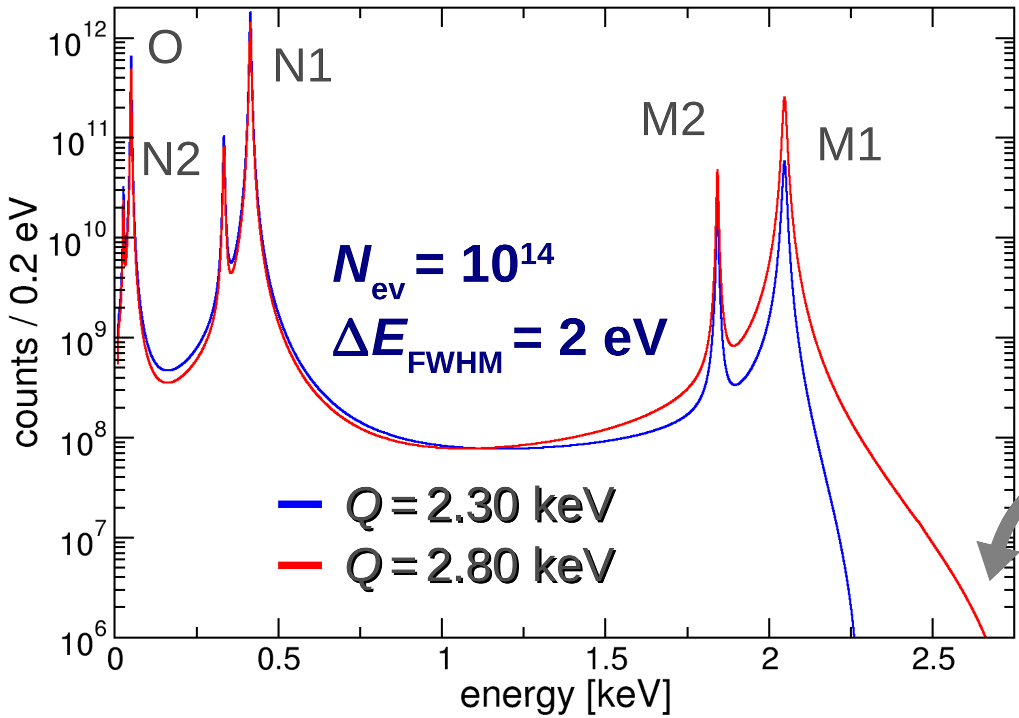
$$^{163}\mathrm{Ho} + e^- \rightarrow {}^{163}\mathrm{Dy}^* + \nu_e$$

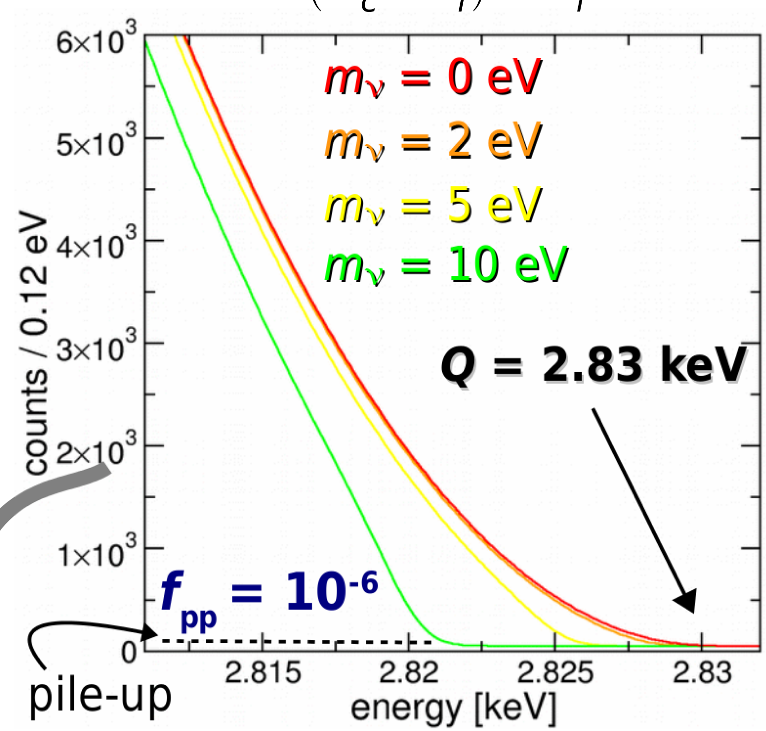
electron capture from shell ⩾ M1

A. De Rujula and M. Lusignoli, Phys. Lett. B 118 (1982) 429

- calorimetric measurement of Dy atomic de-excitations (mostly non-radiative)
- rate at end-point and ν mass sensitivity depend on Q
  - Past measurements: Q= 2.3-2.8 keV. Recently measured $\boldsymbol{Q}$ **= 2.83±0.04 keV**
- $\tau_{1/2} \approx$ 4570 years → few active nuclei are needed

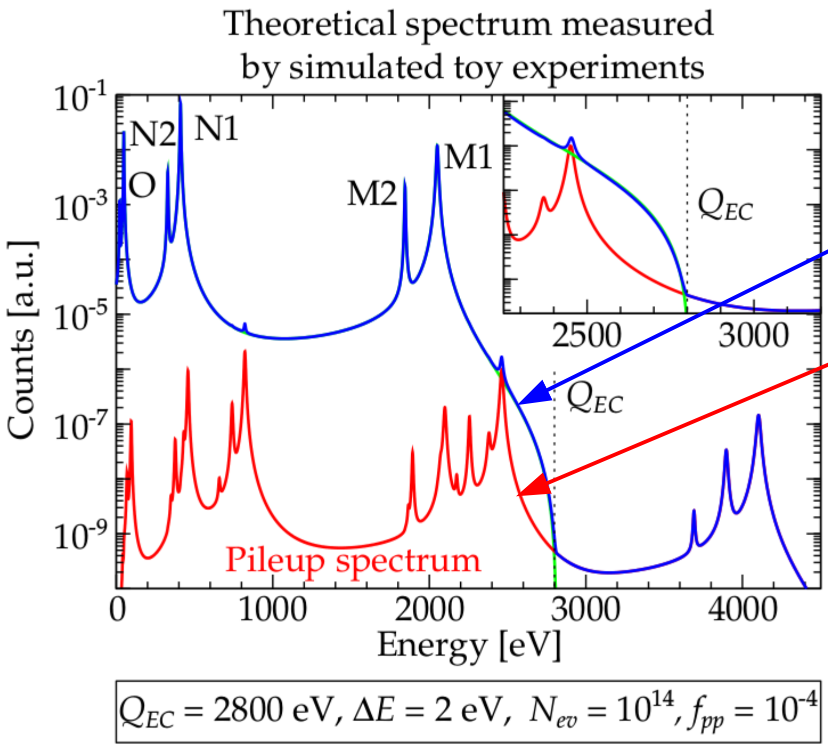
$$\frac{d\lambda_{EC}}{dE_c} = \frac{G_\beta^2}{4\pi^2}(Q-E_c)\sqrt{(Q-E_c)^2-m_\nu^2} \times \sum_i n_i C_i \beta_i^2 B_i \frac{\Gamma_i}{2\pi}\frac{1}{(E_c-E_i)^2+\Gamma_i^2/4}$$





Ho Pile-up spectrum

HOLMES

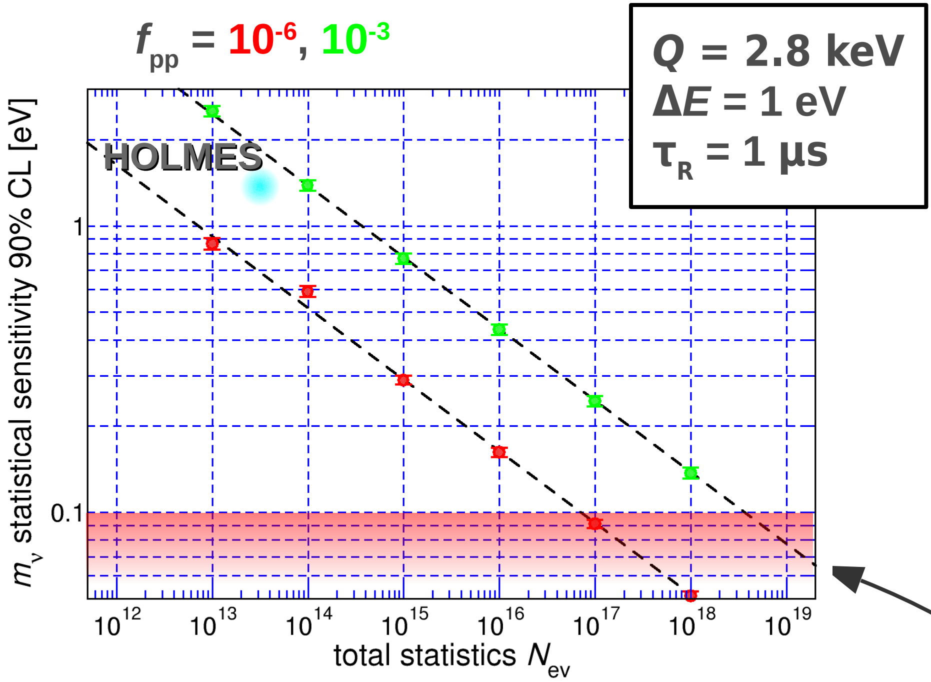


$$S(E_c) = [N_{ev}(N_{EC}(E_c, m_\nu) + f_{pp} \times N_{EC}(E_c, 0) \otimes N_{EC}(E_c, 0)) + B(E_c)] \otimes R_{\Delta E}(E_c)$$

N_{ev}	: total number of events
$N_{EC}(E_c, m_\nu)$	: ^{163}Ho spectrum
$B(E)$	: background energy spectrum
$R_{\Delta E}(E_c)$	: detector energy response function
f_{pp}	: fraction of pile-up events
$R_{\Delta E}(E_c)$	: detector energy response function
ΔE	intervall of energy

- Pile-up pulse occurs when multiple events arrive within the temporal resolving time of the detector;
- Unresolved pile-up produces background close to the end-point;
- The 163 Ho pile-up events spectrum is quite complex and presents a number of peaks right at the end-point of the decay spectrum;
- To resolve pile-up:
  - Detector with fast signal rise-time τ_{rise} ;
  - Pulse pile-up recovery algorithms;

^{163}Ho statistical sensitivity - Montecarlo simulations



$$\propto \sqrt[4]{1/N_{ev}}$$

Requirements:

- high energy resolution ≈1eV
- fast response ≈1μs
- large multiplexable array ≈1000

M. Galeazzi et al., arXiv:1202.4763v2
A. Nucciotti, Eur. Phys. J. C, (2014) 74:3161

HOLMES (ERC-Advanced Grant n. 340321)

HOLMES

Goals

- neutrino mass measurement: m_ν statistical sensitivity around 1 eV
- prove technique potential and scalability:
  - assess EC Q-value
  - assess systematic errors

Detectors: Transition Edge Sensor
with ^{163}Ho implanted in Au absorbers

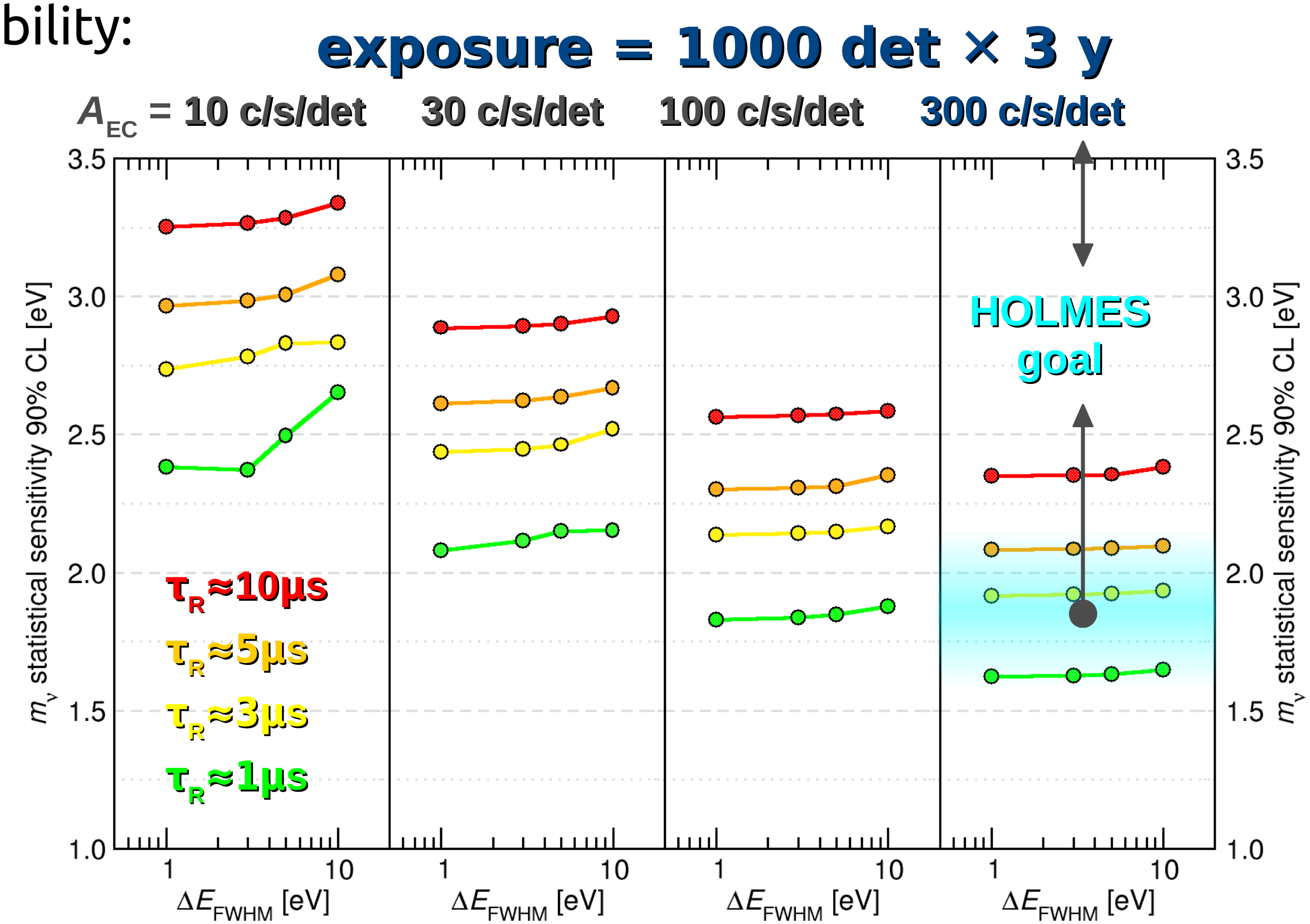
Activity: 6.5x10^{13} nuclei per detector
→ 300 dec/s

Performances: $\Delta E \approx$ 1 eV, $\tau_R \approx$ 1 µs

64 channel demonstrator

Final configuration: 1000 channel array
- 6.5×10^{16} ^{163}Ho nuclei
- 3×10^{13} events in 3 y

→ Project Started on February 1st 2014



B. Alpert et al., Eur. Phys. J. C, (2015) 75:112
http://artico.mib.infn.it/holmes

RF-Squid read out with multiplexing microwave

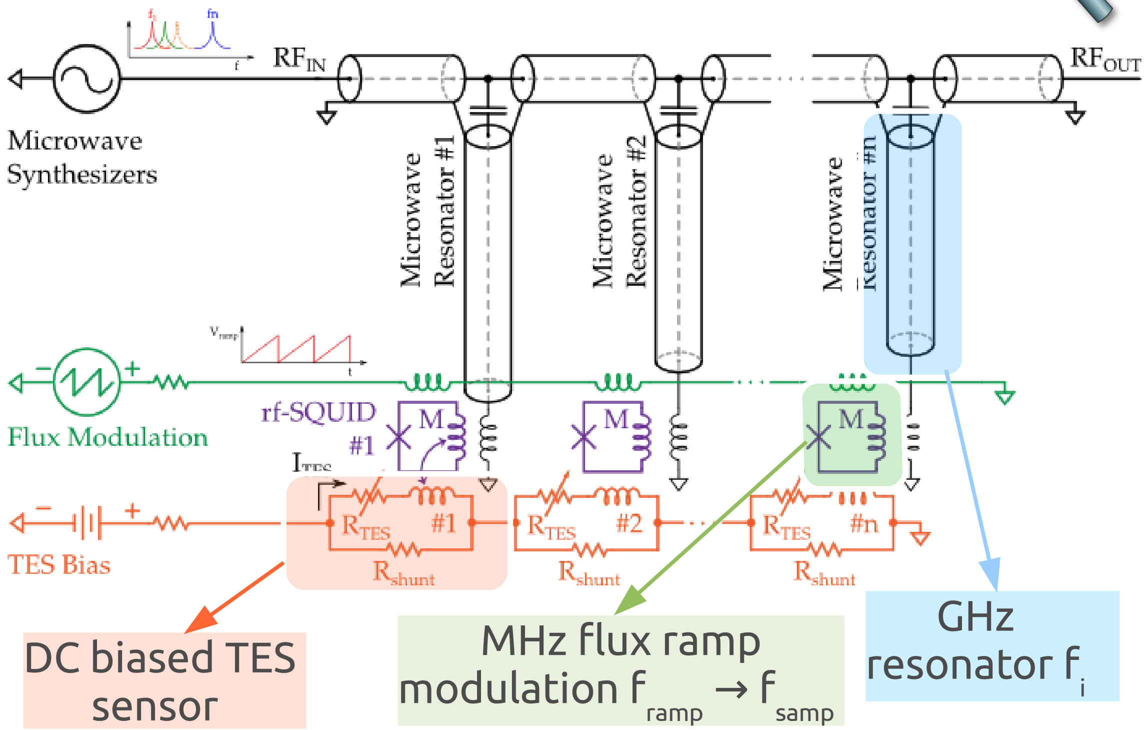
- RF- SQUID coupled with DC biased TES and a λ/4-wave resonant circuit
- RF-SQUID read out with flux ramp demodulation (common flux line inductively coupled to all SQUIDs)
- Signal reconstructed by Software Defined Radio Technique (ROACH 2, ADC bandwidth 550 MHz)

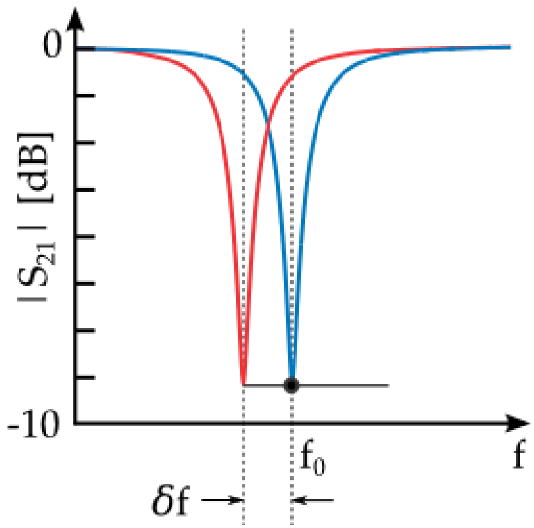
1. An event in the absorber increases the temperature and therefore the resistance of the TES;

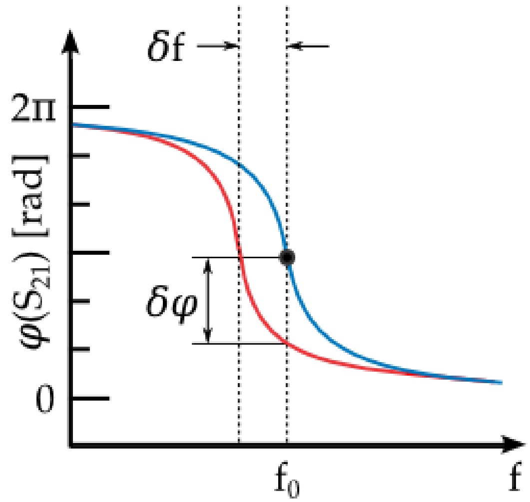
2. Change in TES current ⇒ change in the input flux to the SQUID;

3. The RF-SQUID transduces a change in input flux into a variation of resonant frequency;

4. The ramp induces a controlled flux variation in the rf-SQUID, which is crucial for linearizing the response.



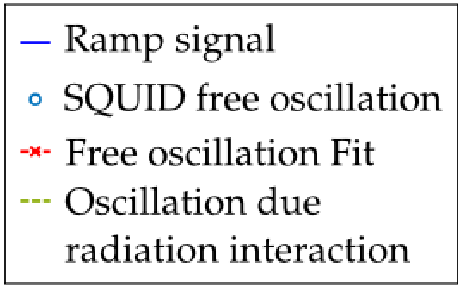


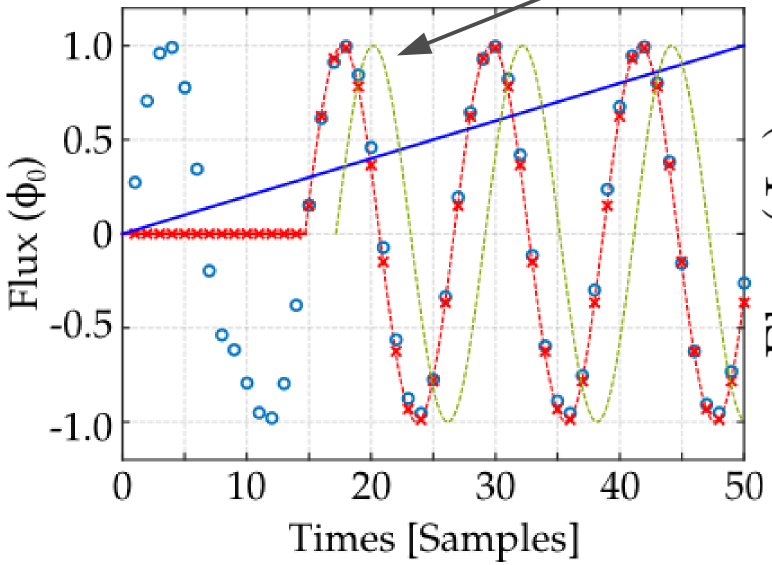


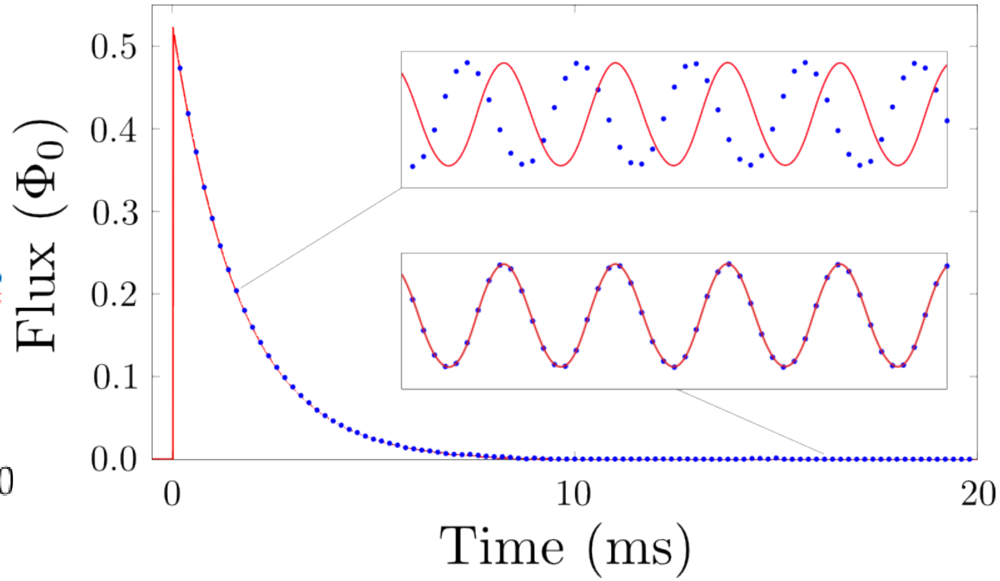
Signal reconstruction

$n_{\Phi_0}=3$ ($n_{\Phi_0}\geq 2$)

$f_{mod}=n_{\Phi_0} f_{ramp}$







Each ramp acquisition represents a sample in the reconstructed phase signal

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.

TES microwave multiplexing with RF-SQUID ramp modulation + ROACH2-based Software Defined Radio (SDR)

DAQ Bandwidth budget

The detector design is mostly driven by the read-out bandwidth requirements.

- Effective sampling rate is set by the ramp: $f_{ramp} = f_{samp}$
- Necessary resonator bandwidth per flux ramp: $f_{res} \geq 2 n_{\Phi_0} f_{samp}$
- To avoid cross talk spacing between resonances: $f_n \geq g_f f_{res} \quad [g_f = 7]$
- To avoid distortions (signal BW): $f_{samp} \geq \dfrac{R_d}{\boldsymbol{\tau}_{rise}} \approx \dfrac{5}{\boldsymbol{\tau}_{rise}}$ [τ_{rise} exponential]
- Available ADC bandwidth f_{ADC} with ROACH2 system 550 MHz
- Multiplexing factor:

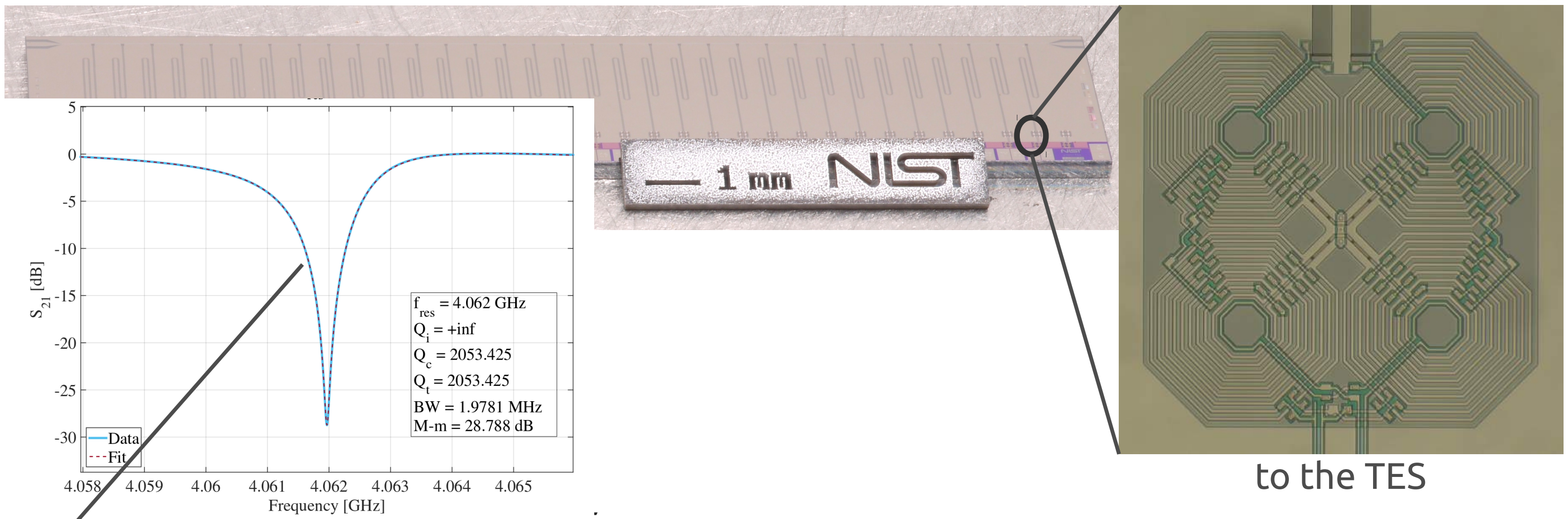
$$\boxed{n_{TES} = \frac{f_{ADC}}{f_n} \leq \frac{f_{ADC}\,\tau_{rise}}{2 R_d g_f n_{\Phi_0}} \approx \frac{f_{ADC}\,\boldsymbol{\tau}_{rise}}{140}}$$

for fixed $\boldsymbol{f_{ADC}}$**=500MHz** and $\boldsymbol{n_{TES}}$**≈35 ↔ $\boldsymbol{\tau_{rise}}$≈10μs** with $\boldsymbol{f_{samp}}$**=0.5MHz**

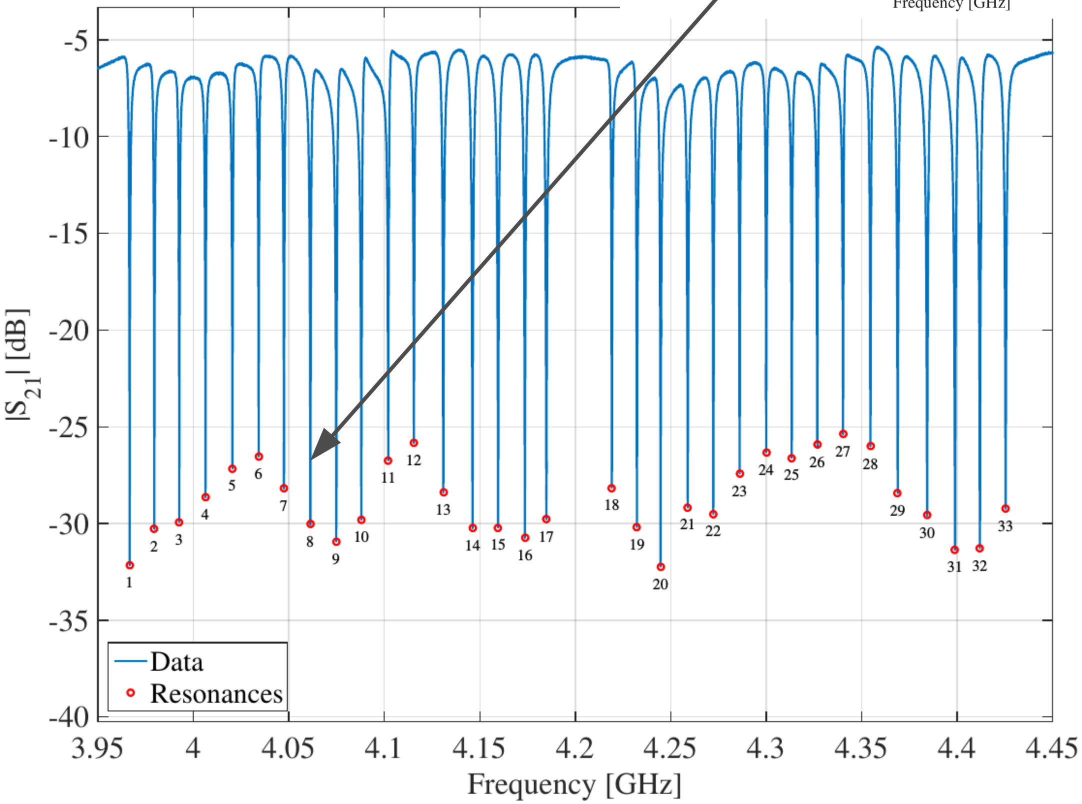
μmux characterization @ MIB

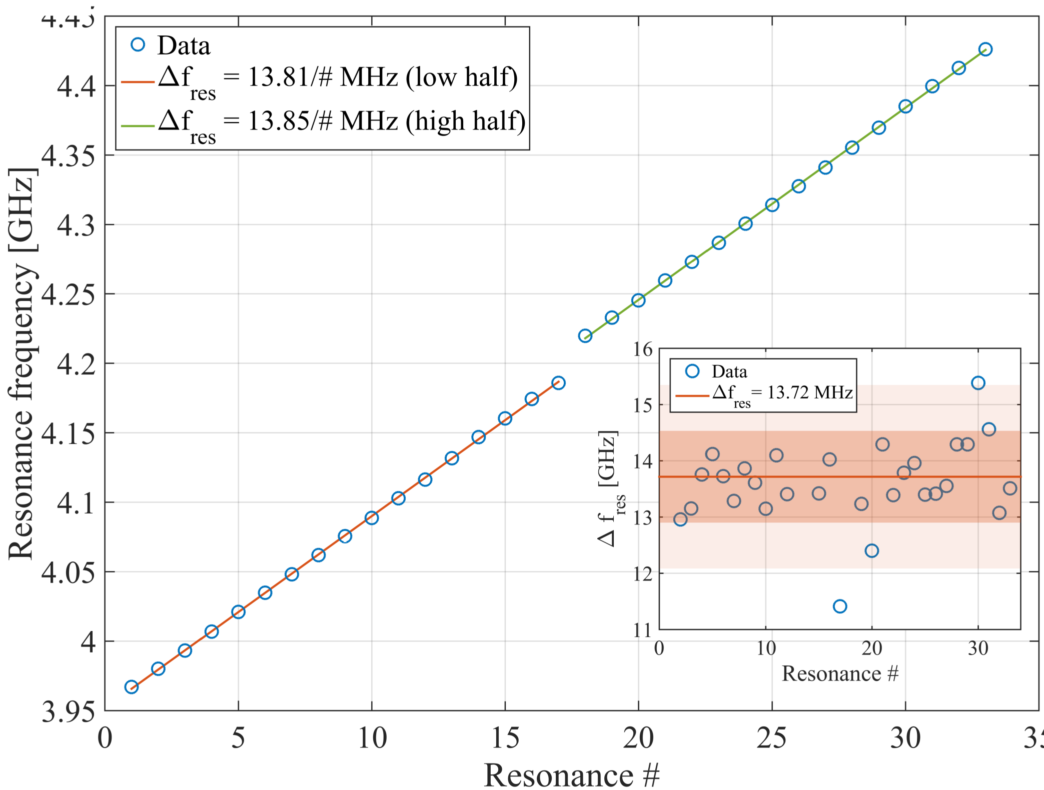
→ chip μMUX17A
→ 33 resonances in 500 MHz
  - width 2 MHz
  - separation 14 MHz
→ squid noise <≈2 $\mu\Phi_0/\sqrt{Hz}$

to the RF-coupling



to the TES

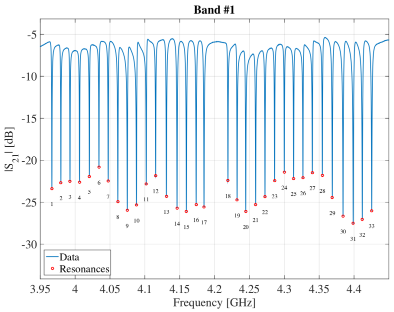




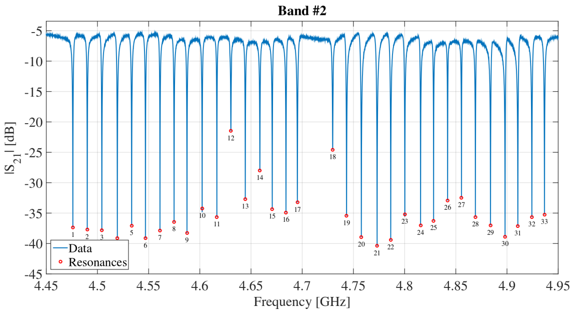
Cold Amplifier Bandwidth budget

The S21 is amplified with a HEMT Cold Amplfier

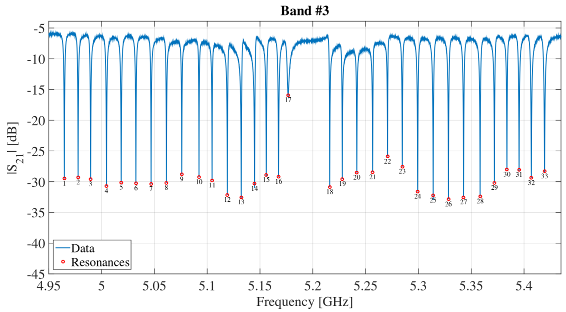
→ HEMT bandwidth 4-8 GHz
→ Gain ~ 45 dB
→ T_N ~ 2 K



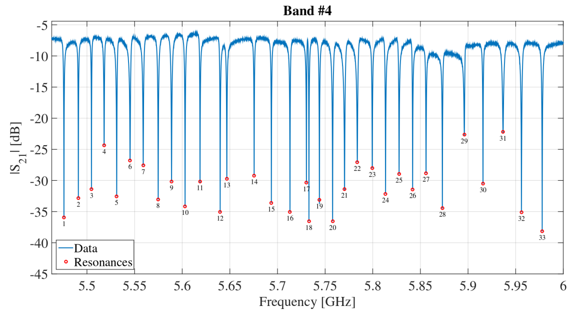
ROACH2 - 1



ROACH2 - 2



ROACH2 - 3

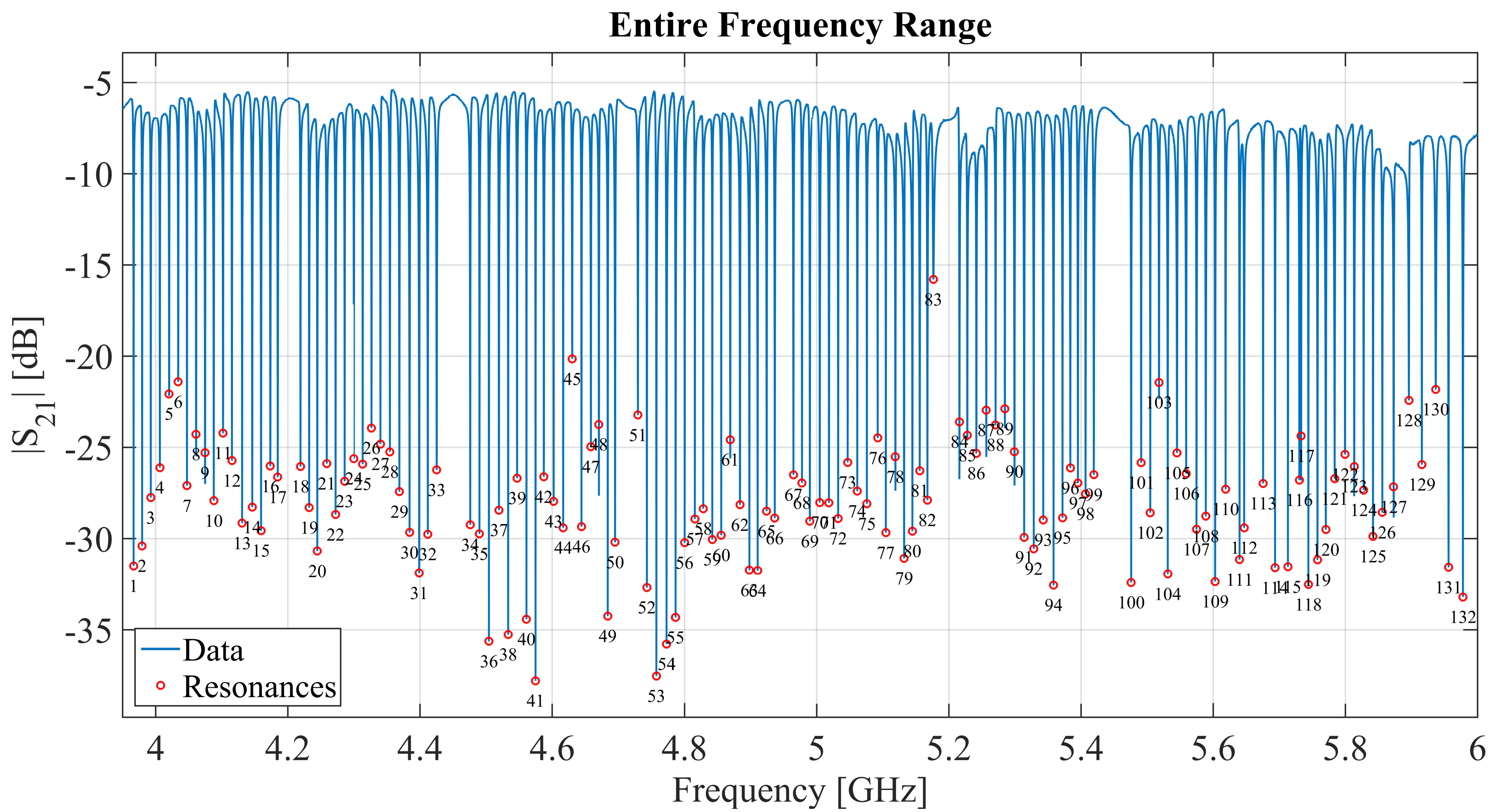


ROACH2 - 4

4 ROACH cover half HEMT amplifier bandwidth

From 4 to 6 GHz

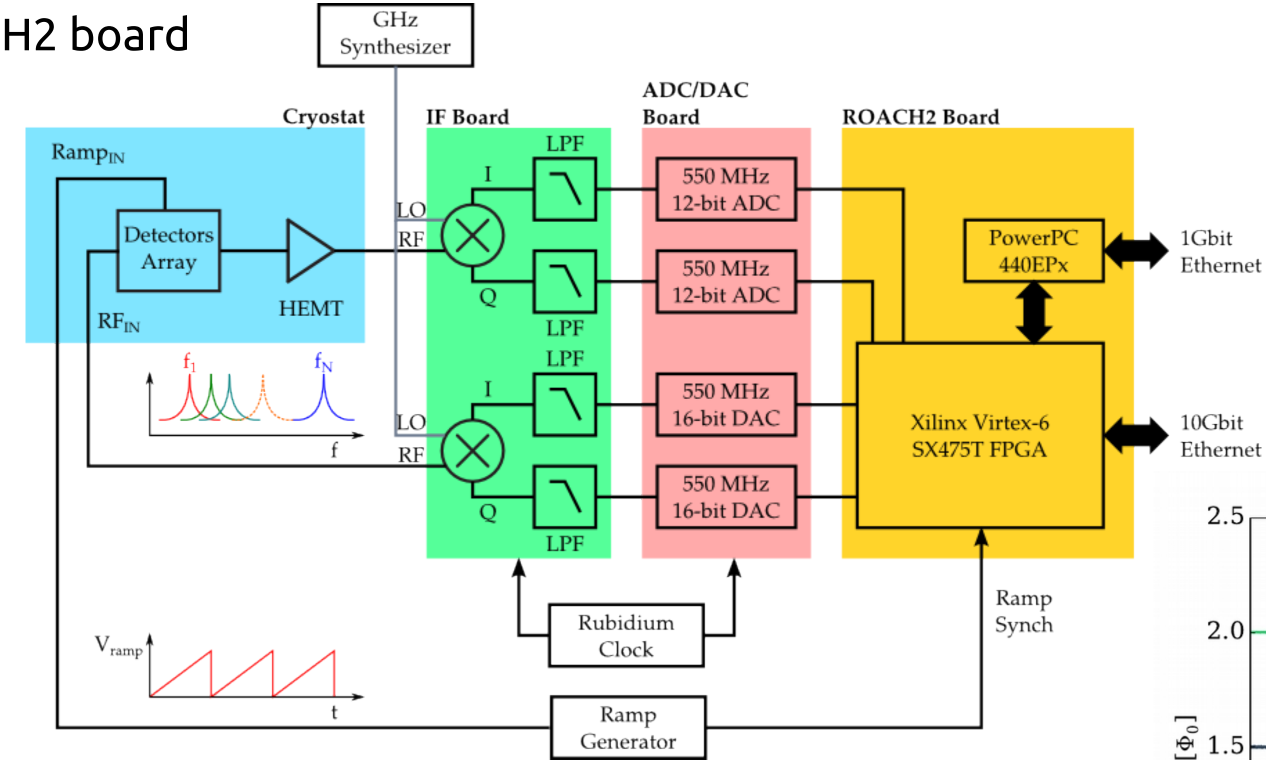
Four μmux in series are able to cover a wide frequency range (from 4 to 6 GHz)



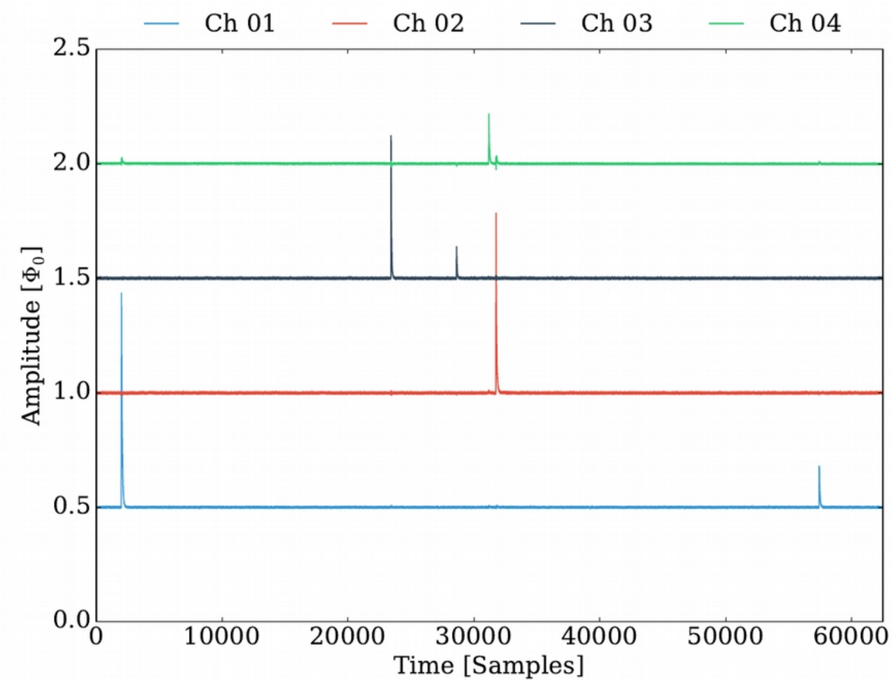
TES read out with ROACH2

HOLMES

With the 550 MHz ADC BW of the ROACH2, 500 kHz effective pulse sampling, 14 MHz resonance spacing, 2 MHz resonance width and $2\Phi_0$ SQUID oscillation/ramp → 33 multiplexable channels per ROACH2 board



- Acquisition with ROACH2 board of 4 pixels limited by tone power (temporary discrete IF components)
- 16 ch firmware from NIST (only half of the BW)
- checks on algorithms, noise, ΔE, τ_R, slew rate
- fluorescence source: ^{55}Fe (primary) + Al,Cl,Ca



Holmes detectors

TES detectors:

- Mo/Cu TES coupled to Gold absorbers where 163 Ho will be ion-implanted

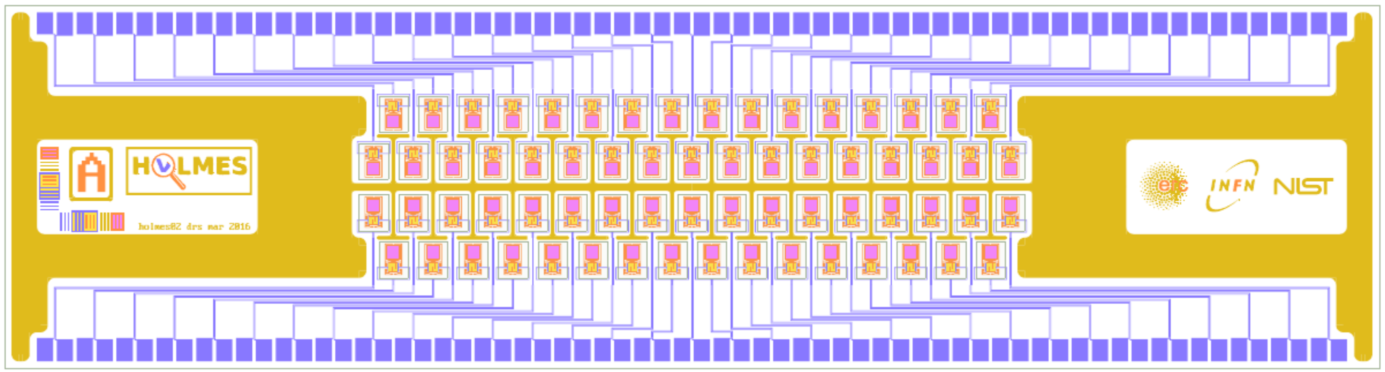
  Specs @ 2.8 keV: $\Delta E_{FWHM} \sim 3$ eV, $\tau_{rise} \approx 10\ \mu s$, $\tau_{decay} \approx 100\ \mu s$

- Optimize design for speed and resolution

- 2 mm Au thickness for full electron and photon absorption

  (99.99998% / 99.927% full stopping for 2 keV electrons / photons)

- Side-car design to avoid TES proximization effect and G engineering for τ_{decay} control



- Production and R&D for detectors optimization: NIST, Boulder Co, USA

- Implantation: Genova, Italia

- Etching: Milano-Bicocca

- Measurement: Milano-Bicocca

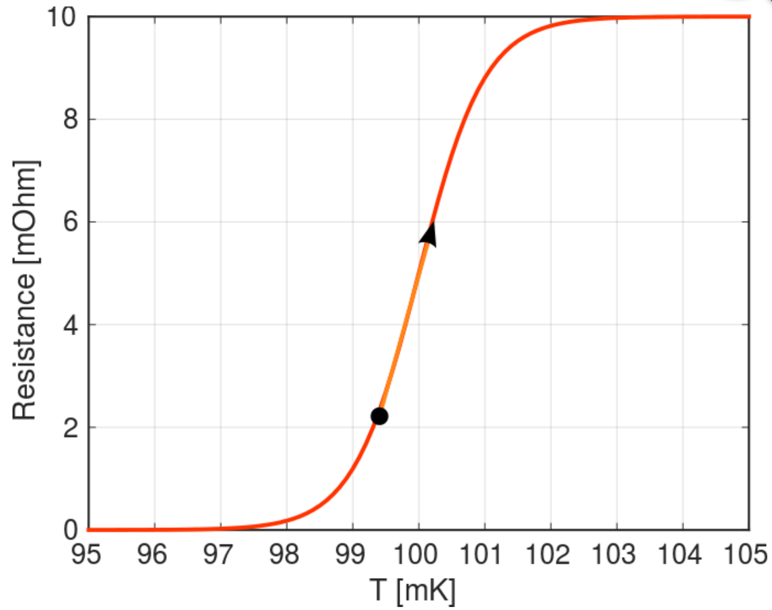
TES

Transition Edge sensors: exploit the strong dependence of R vs T of a superconductor kept in its transition

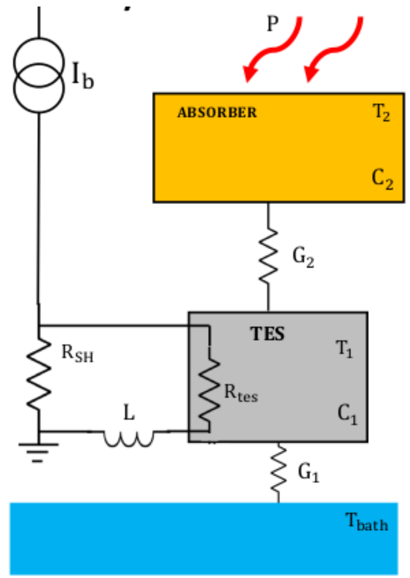
fast detector response for high counting rate

➢ signal rise time determined by electrical cut-off (L/R)

➢ signal decay time (at the first order) set by C/G: large G to reduce dead time



Two- body model (2 heat capacities)



$$C_{TES}\frac{dT_{TES}}{dt}=P_j-A(T_{TES}^n-T_1^n)-B(T_{TES}^m-T_{bath}^m)+\delta(t-t_0)E$$

$$C_1\frac{dT_1}{dt}=A(T_{TES}^n-T_1^n)$$

$$L\frac{dI}{dt}=V-IR_L-IR(T,I)$$

The analytic solution is the sum of three exponentials. One time constant represents the rise time while the other two the decay times.

TES single pixel design

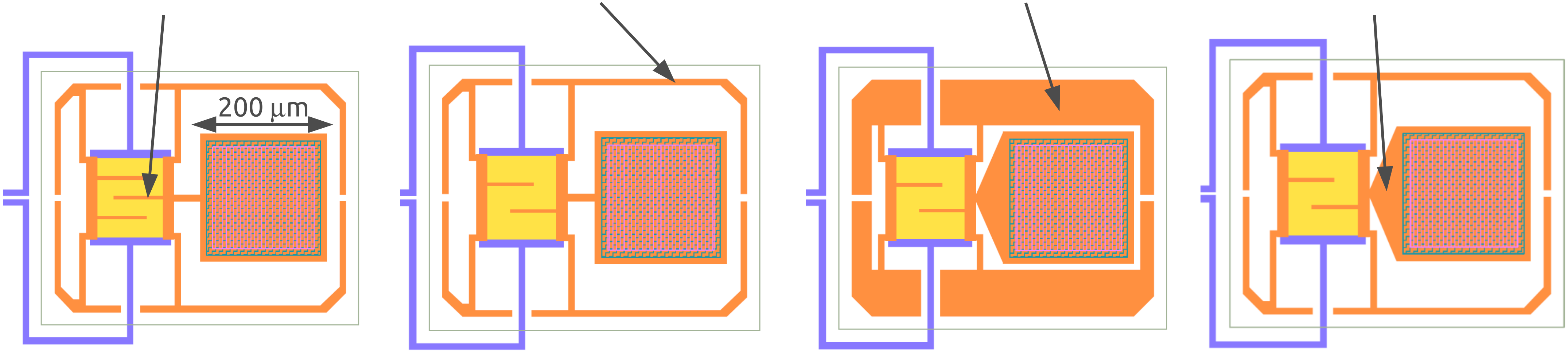
Different geometries understudy:
- different absorber/TES coupling
- different sensors (3 or 2 normal metal bars)
- different heat capacities

3 Cu bars for steering the current in a meandering pattern

The perimeter increases G without raising the heat capacity C

Bigger copper perimeter in order to increase C without increasing G

Stronger coupling between absorber and TES

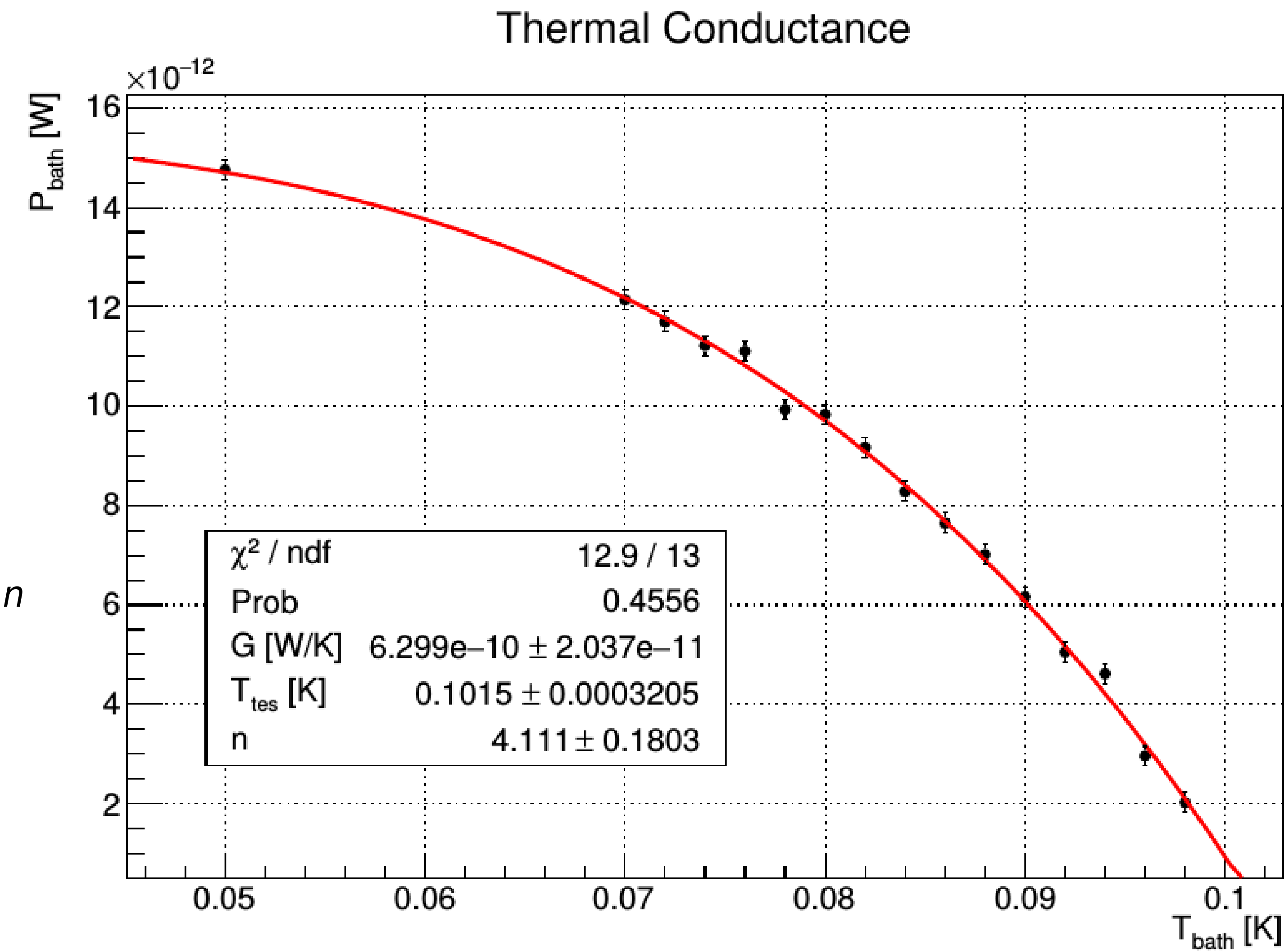


G measurement

at the equilibrium

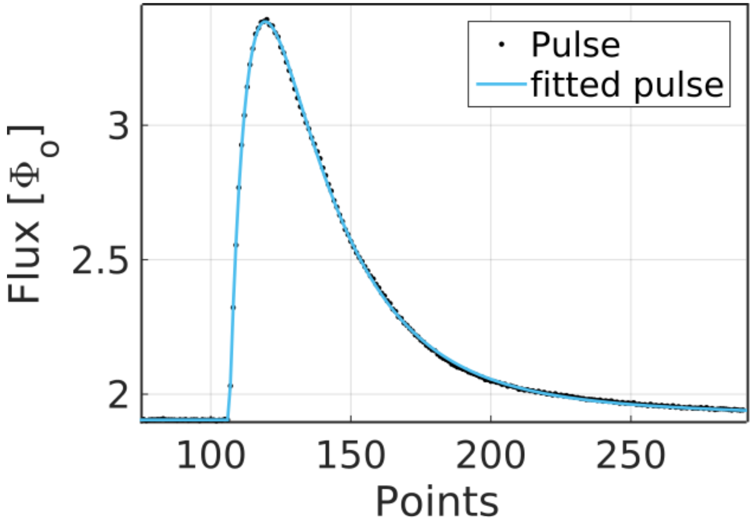
$$P_{bath} = P_j = I^2_{TES} R_{TES}$$

$$P_{bath} = \frac{G T_{TES}}{n} \left[1 - \frac{T_{bath}}{T_{TES}} \right]^n$$



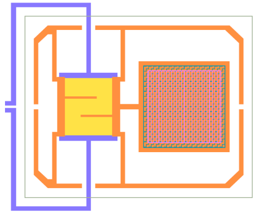
Rise and decay time

Pulses fitted with the sum of three exponential (two body model)



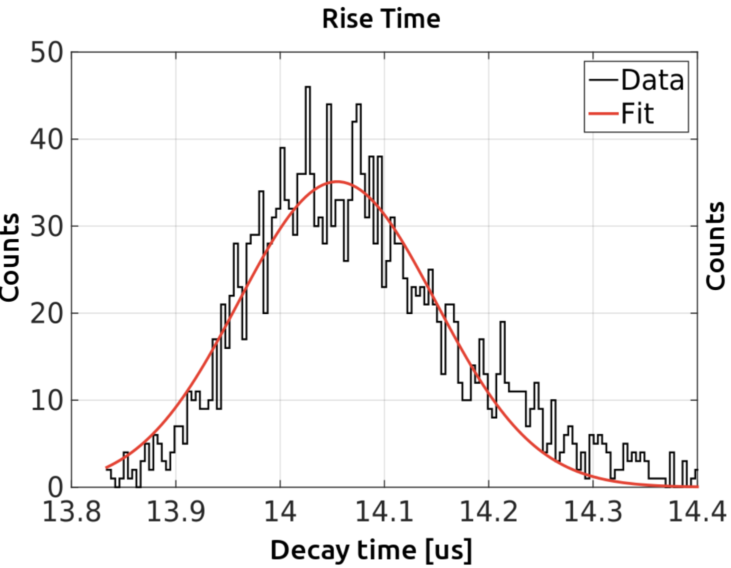
Line	τ_{rise}	$\tau_{decay\ short}$	$\tau_{decay\ long}$
Al	19 μs	37 μs	179 μs
Cl	16 μs	46 μs	220 μs
Ca	14 μs	51 μs	243 μs
Mn	12 μs	57 μs	260 μs

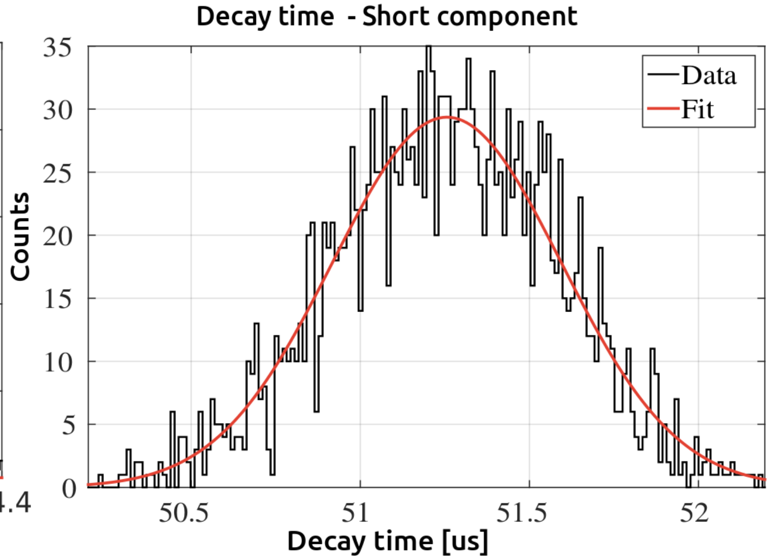
Working point
~ 20 % R_n

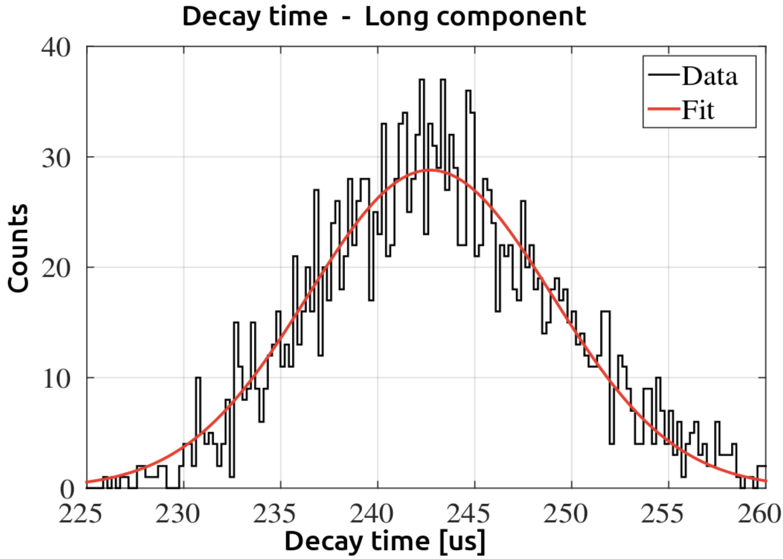


L = 55 nH

Ca line:

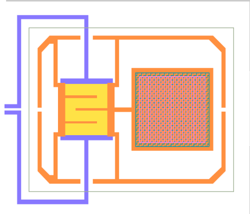
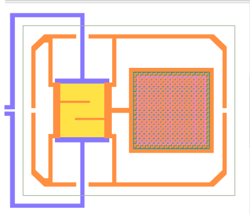
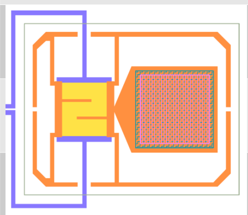


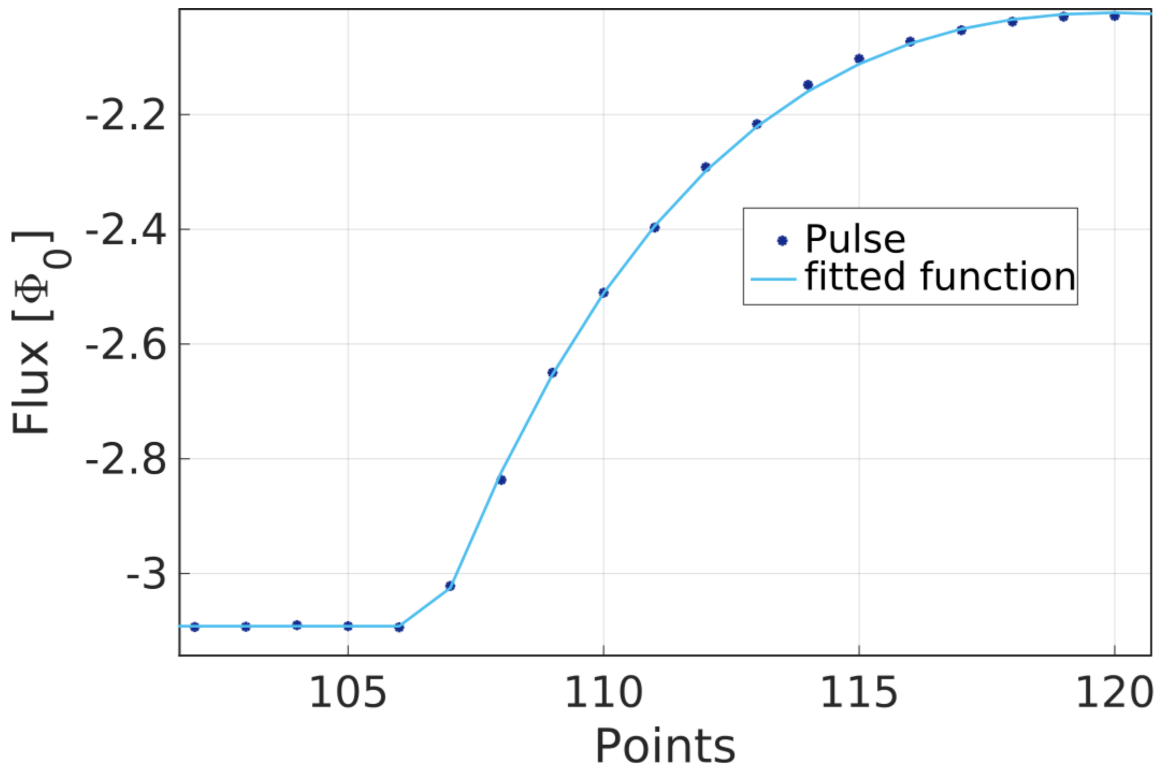




Rise time at different working point

Cl line

TES geometry	τ rise µs	R0 mΩ
	8,9	1,18
	8,5	1,42
	7,7	1,66
	14,2	1,08
	12,6	1,32
	10,2	1,54
	12,3	1,16
	11,6	1,4
	10,5	1,65



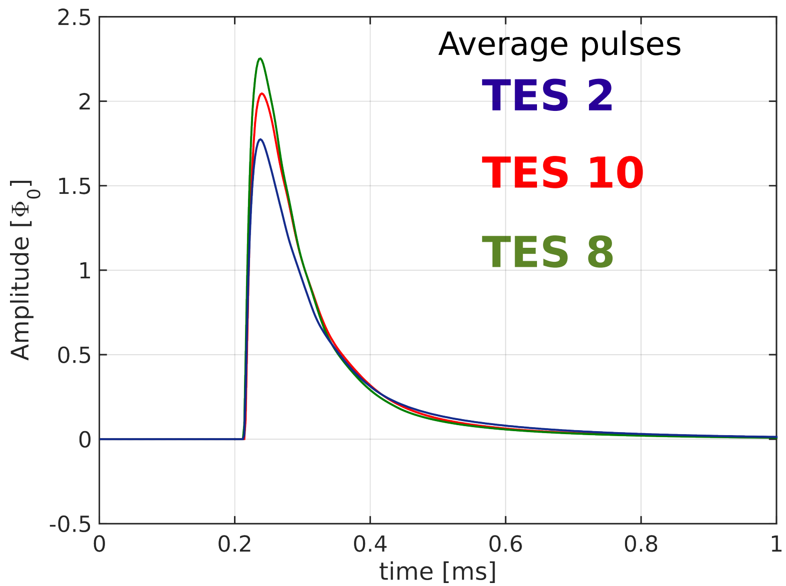
Data Analysis 1

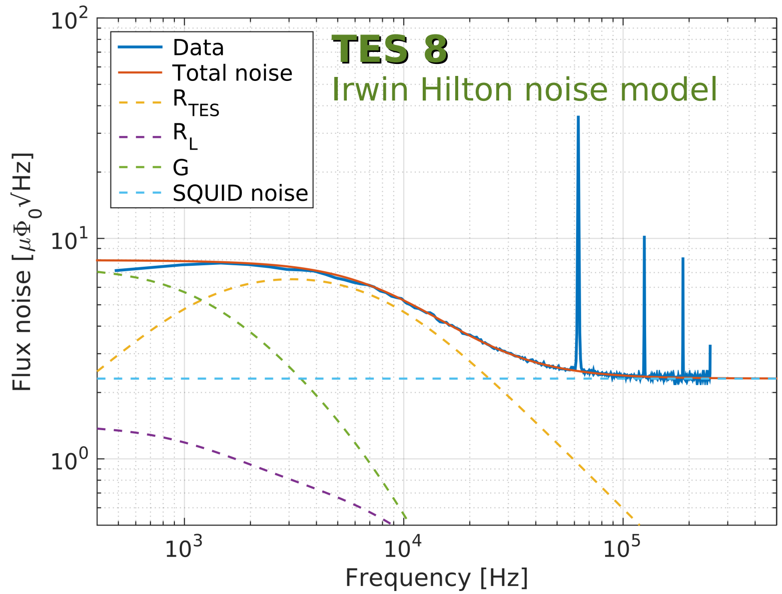
- Analysis with the Optimum filter (TD and FD)
- Stabilization Amplitude vs Baseline and Amplitude vs time
- Calibration of the energy spectra with a E= f(x) = ax^2 +bx

signal $S(\omega)$

noise $N(\omega)$

$$H_{OF}(\omega) \propto \frac{S^*(\omega)}{N(\omega)}$$

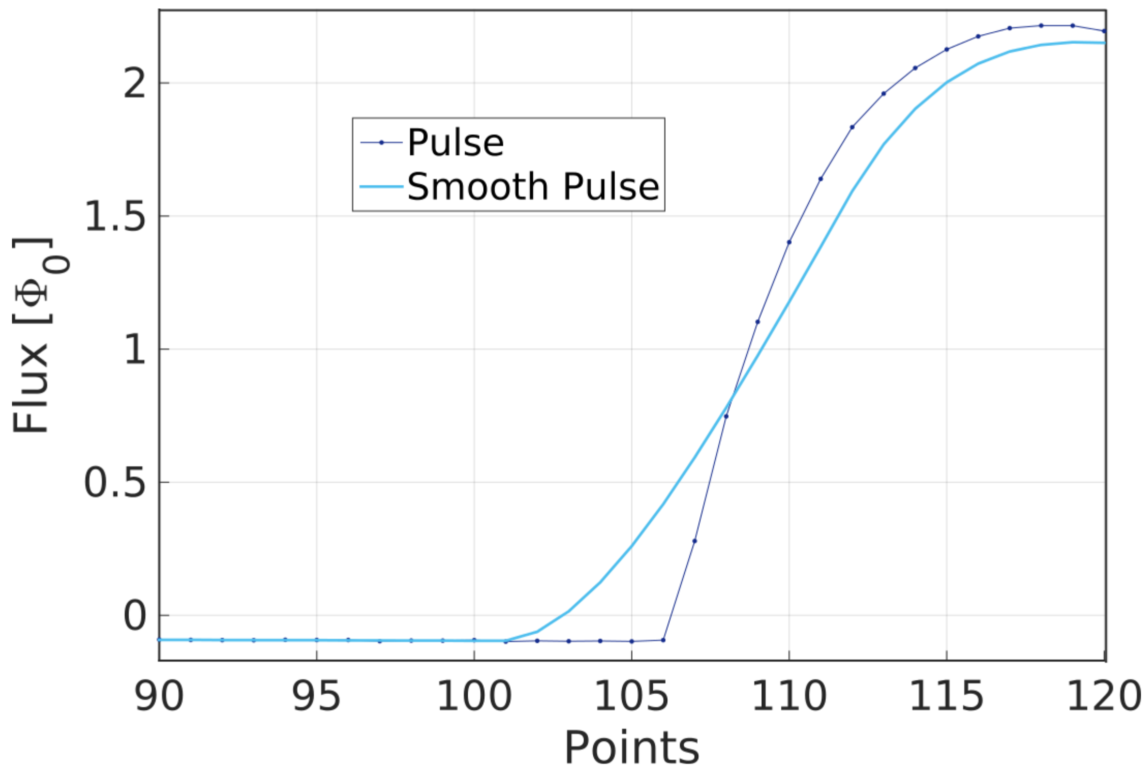




Data Analysis 2

- The pulse heights obtained by optimal filtering are subjected to an unwelcome dependence on the arrival time

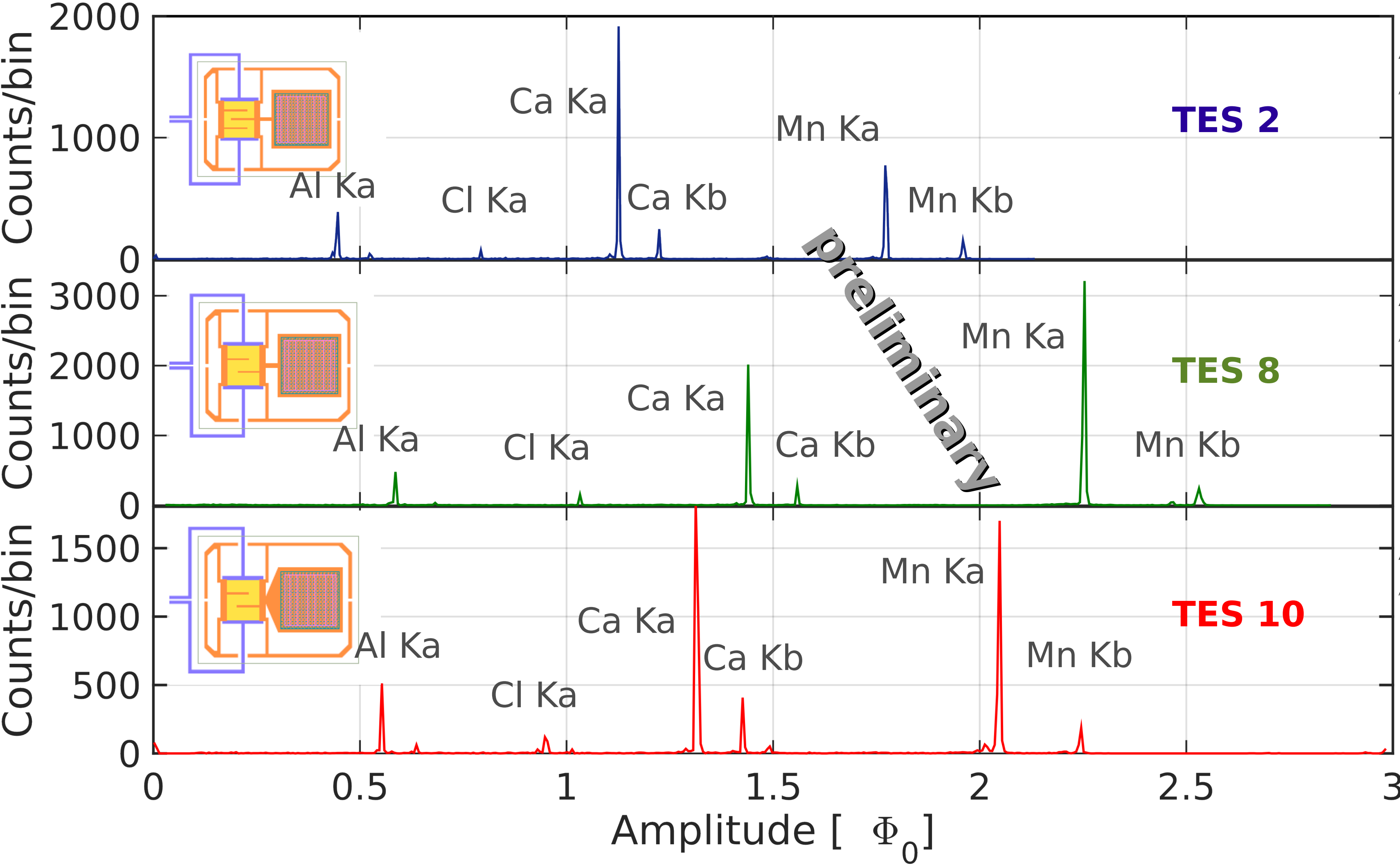
→ Smooth of the signal with a moving average



TES spectra

200×200 μm² absorber
C = 0.8 pJ/K
G ~ 600 pW/K
^{55}Fe + Fluorescence source

- f samp = 500 kHz
- Tbath= 32 mK, Working point ~ 20%Rn
- collimated source (i.e. lower activity per pixel)
- low statistics on the Cl Kα line



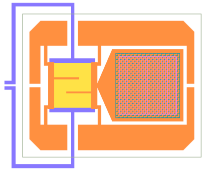
ΔE_0= 4eV
τ_{rise}= 12μs, τ_{decay}= 95μs
Slew rate = 0.4Φ_0/S @ 5.9 keV
S/N=1420 @ 5.9 keV

ΔE_0= 4eV
τ_{rise}= 13μs, τ_{decay}=77μs
Slew rate = 0.4 Φ_0/S @ 5.9 keV
S/N=1490 @ 5.9 keV

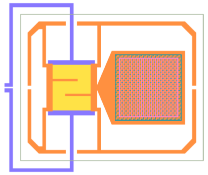
ΔE_0= 4eV
τ_{rise}= 13μs, τ_{decay}=83μs
Slew rate = 0.4Φ_0/S @ 5.9 keV
S/N=1334 @ 5.9 keV

Energy resolution

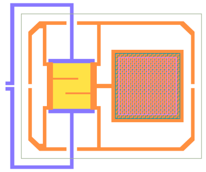
Working point ~ 20 % R_n



$\Delta E_0 = 6.5$ eV

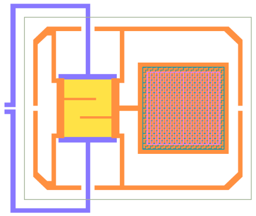


$\Delta E_0 = 4.5$ eV



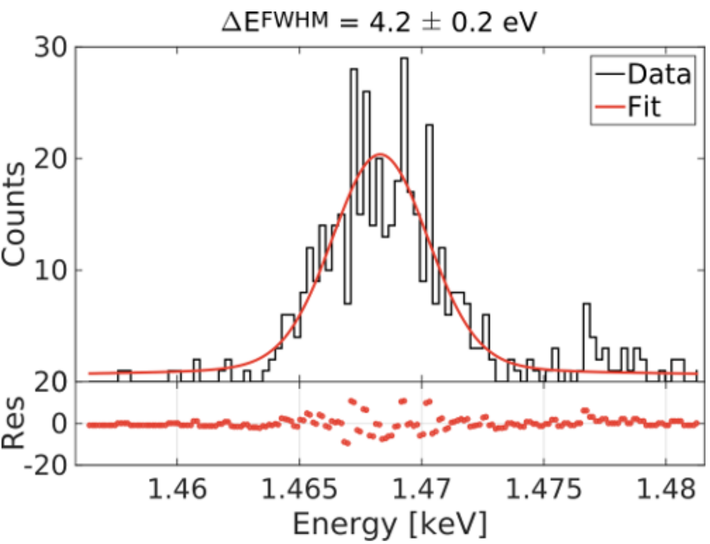
$\Delta E_0 = 4.2$ eV

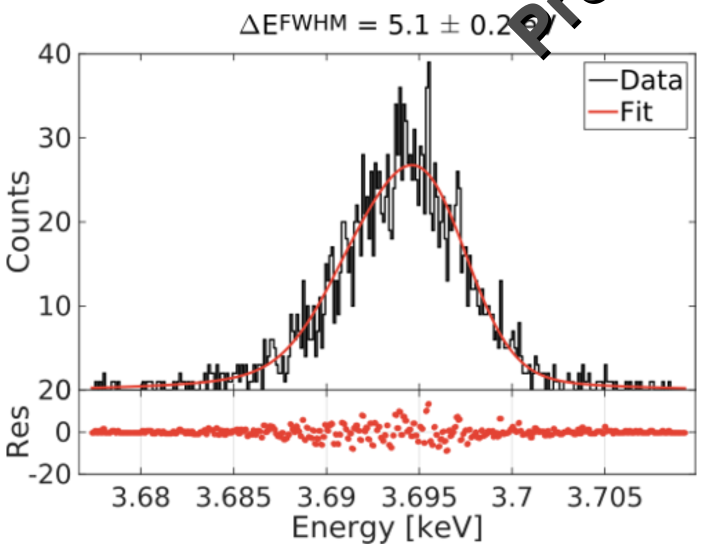
	Ka1 [eV]	E [eV]	ΔE [eV]	E [eV]	ΔE [eV]	E [eV]	ΔE [eV]
Mn	5898,75	5890,5 ±0,5	6,2 ± 0,4	-	-	5897,12± 0,06	4,7 ± 0,1
Ca	3691,68	3720,5 ± 0,2	6,4 ± 0,4	3685,8 ± 0,1	4,6 ± 0,3	3702,96 ± 0,07	5,5 ± 0,2
Cl	2622,39	2608,7 ± 0,2	6,0 ± 0,4	2635,2 ± 0,2	4,5 ± 0,3	2628,03 ± 0,2	5,3 ± 0,5
Al	1486,7	1469,4 ± 0,4	6 ± 1	1474,9 ±0,2	4,26 ± 0,3	1474,9 ± 0,1	4,6 ± 0,3

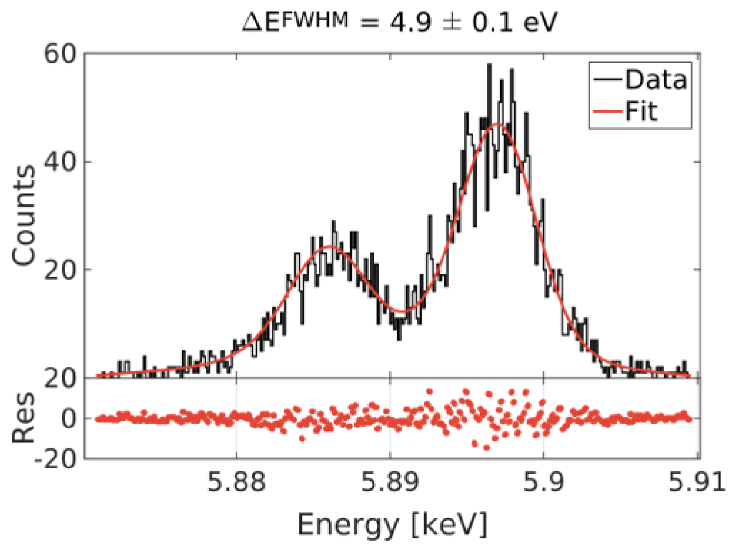


- Working point ~ 20 % R_n
- Measuring time ~ 44 h

Preliminary







Conclusion

- With the 550 MHz ADC BW of the ROACH2, 500 kHz effective pulse sampling, 14 MHz resonance spacing, 2 MHz resonance width and $2F_0$ SQUID oscillation/ramp → 33 multiplexable channels per ROACH2 board

- A multiplexing factor of 33 preserves the performances of each detectors in term of energy and time resolutions.

- Tuning the stray inductance L the rise time of the detectors is ~ 10 μs which is compatible with a time resolution of 3 μs obtained applying pile-up rejection algorithms

→ An energy resolution of ~ 4 eV @ 5.9 keV is achieved with these fast detectors (two geometries are possible).

- The performances (energy and time resolution) required by HOLMES are achieved