Development of the rf-SQUID based multiplexing system for the HOLMES experiment

Andrei Puiu

Dipartimento di Fisica "G. Occhialini", Università di Milano-Bicocca, Milano, Italia

INFN - Sezione di Milano Bicocca, Milano, Italia

A. Puiu[1], B. Becker[2], D. Bennett[2], M. Faverzani[1], E. Ferri[1], J. Fowler[2], J. Gard[2], J. Hays-Wehle[2], G. Hilton[2], A. Giachero[1], M. Maino[1], J. Mates[2], A. Nucciotti[1], C. Reintsema[2], D. Schmidt[2], D. Swetz[2], J. Ullom[2], L. Vale[2].

[1]University of Milano-Bicocca & INFN Milano-Bicocca, Milano, Italy

[2]NIST, Boulder, CO, USA

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PI: S. Ragazzi, HI: INFN

Measuring the neutrino mass is one the most compelling issues in particle physics.
The European Research Council has recently founded HOLMES, a new experiment for a direct measurement of neutrino mass. HOLMES will perform a precise measurement of the end point of the Electron Capture decay spectrum of ^{163}Ho in order to extract information on neutrino mass with a sensitivity as low as 0.4 eV.
HOLMES, in its final configuration will deploy a 1000 pixel array of low temperature microcalorimeters: each calorimeter consists of an absorber, where the Ho atoms will be implanted, coupled to a Transition Edge Sensor thermometer. The detectors will be kept at the working temperature of ~90 mK using a dilution refrigerator. To read out 1000 or more detectors inside a cryostat is no trivial matter: at the moment, the most appealing read out technique applicable to large arrays of Transition Edge Sensors is rf-SQUID multiplexing. It is based on the use of rf-SQUIDs as input devices with flux ramp modulation for linearisation purposes; the rf-SQUID is then coupled to a super-conductive LC resonator in the GHz range, and the modulated signal is finally read out using the homodyne technique.In our contribution we outline the performance and special features of the multiplexing system and readout methods chosen for HOLMES.

HOLMES baseline

GOALS

- neutrino mass measurement with a m_ν statistical sensitivity as low as 0.4 eV
- demonstrate technique potential and scalability

Detectors: Transition Edge Sensors (TES) with ^{163}Ho implanted in Bi/Au absorbers

Activity: 6.5*10^{13} nuclei per detector → 300 dec/sec

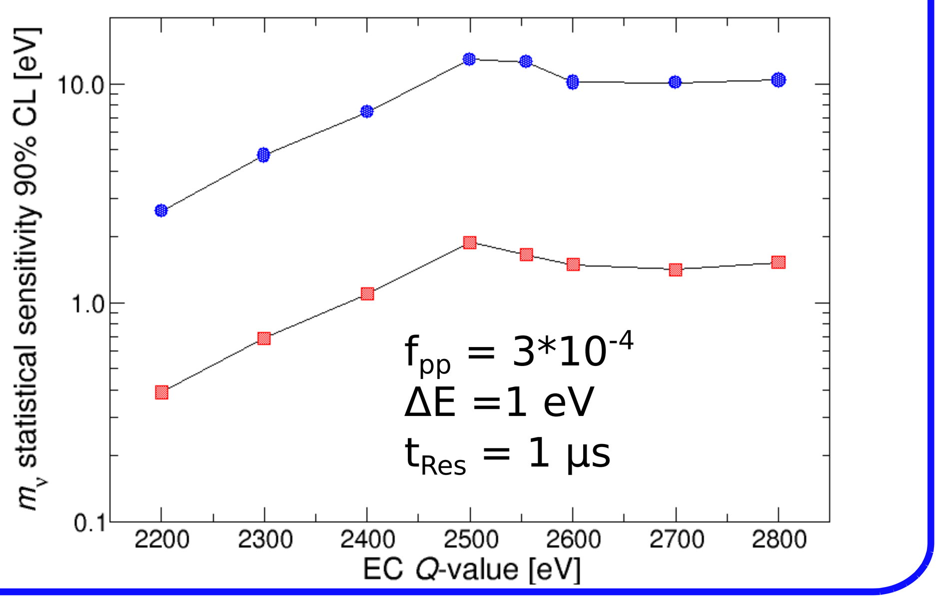
Performance: ΔE≈1eV and t_{Res}≈1μs

Final configuration:
1000 channel array
6.5*10^{16} ^{163}Ho nuclei → ≈18μg
3*10^{13} events in 3 year

Project Start: 1 Feb 2014

B. Alpert et al, EPJ C, March 2015, 75:112
http://artico.mib.infn.it/nucriomib/experiments/holmes
A. Nucciotti, Eur. Phys. J. C (2014) 74:3161

mid-term prototype	full scale HOLMES
16 channels	1000 channels
t_M=1 month	t_M=3 years
A=300 Bq/ch	A=300 Bq/ch
statistics:	statistics:
10^{10} events	3*10^{13} events

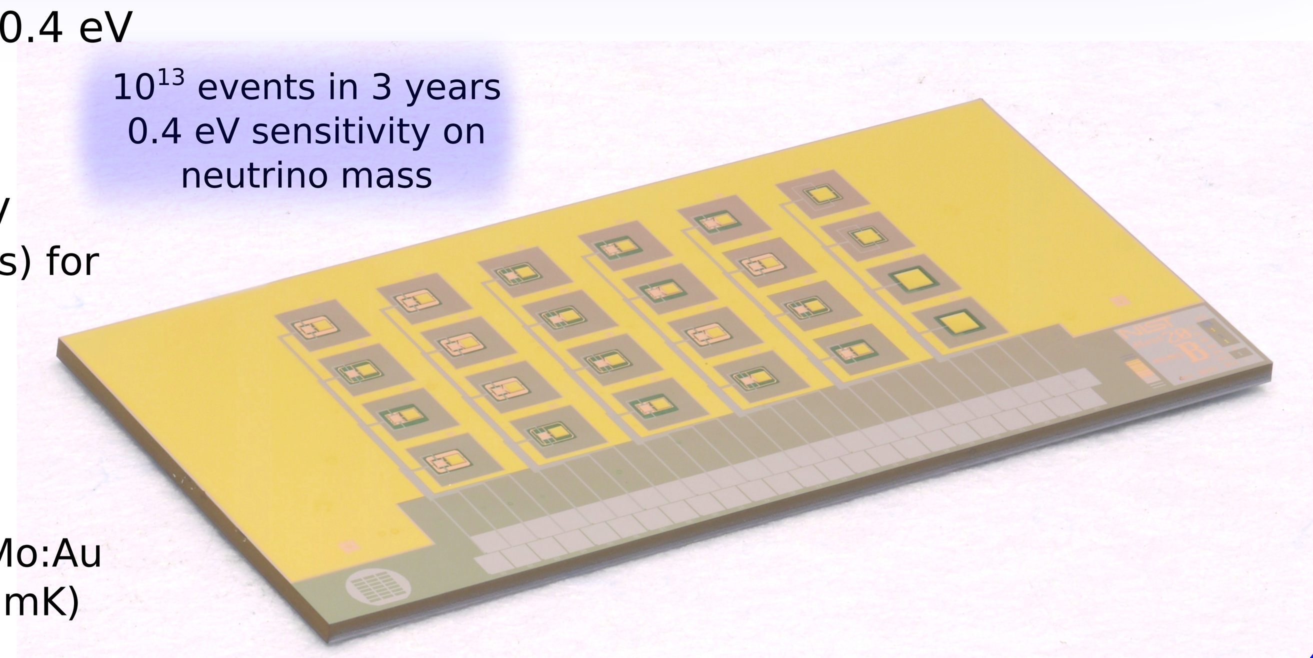


TES for HOLMES

Experimental requirements for 0.4 eV
Low temperature calorimeters with

- Energy resolution ~1 eV @ 2 keV
- Fast response detectors (t_{Res} ~1 μs) for a better pile-up discrimination
- Very large detector array (1000 detectors) -> multiplexing
- Low impedance for faster pules
- Tunable critical temperature Tc exploiting the proximity effect → Mo:Au or Mo:Cu proximity TES (Tc ~ 100 mK)

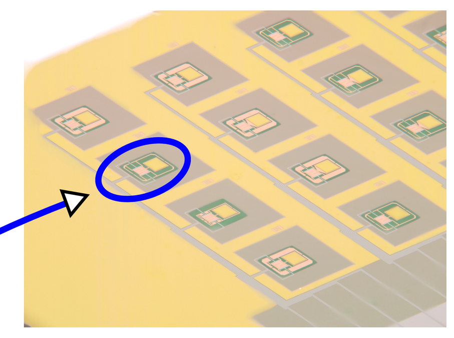
10^{13} events in 3 years
0.4 eV sensitivity on neutrino mass



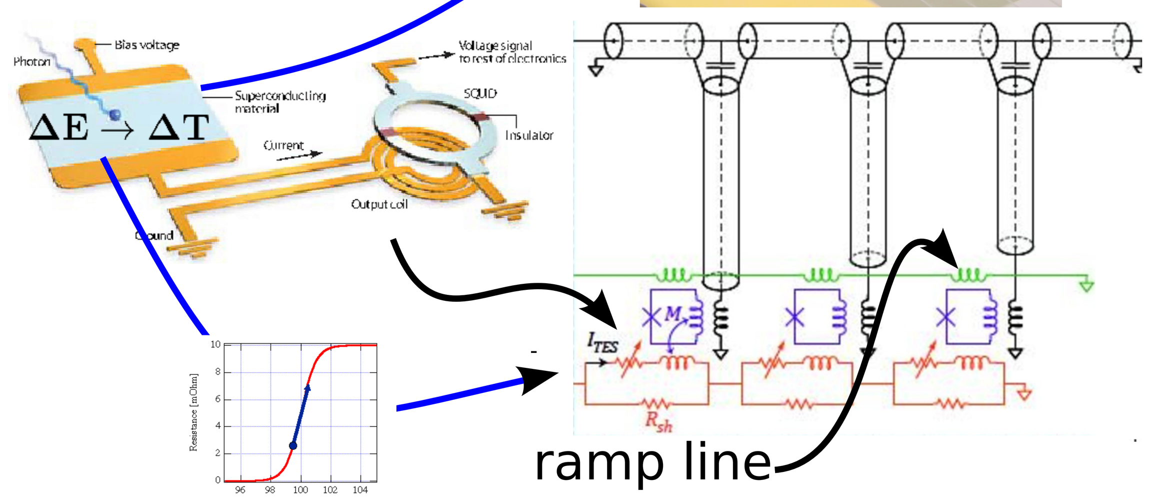
Principle of operation

- Superconductor kept at the bottom of the transition region
- Incoming radiation breaks cooper pairs in the superconductor
- Pair braking causes resistivity increase in the TES circuit.

- DC biased TES
- each TES is coupled to a rf-SQUID
- each SQUID is coupled to the inductive component of resonating LC circuit in the GHz range.

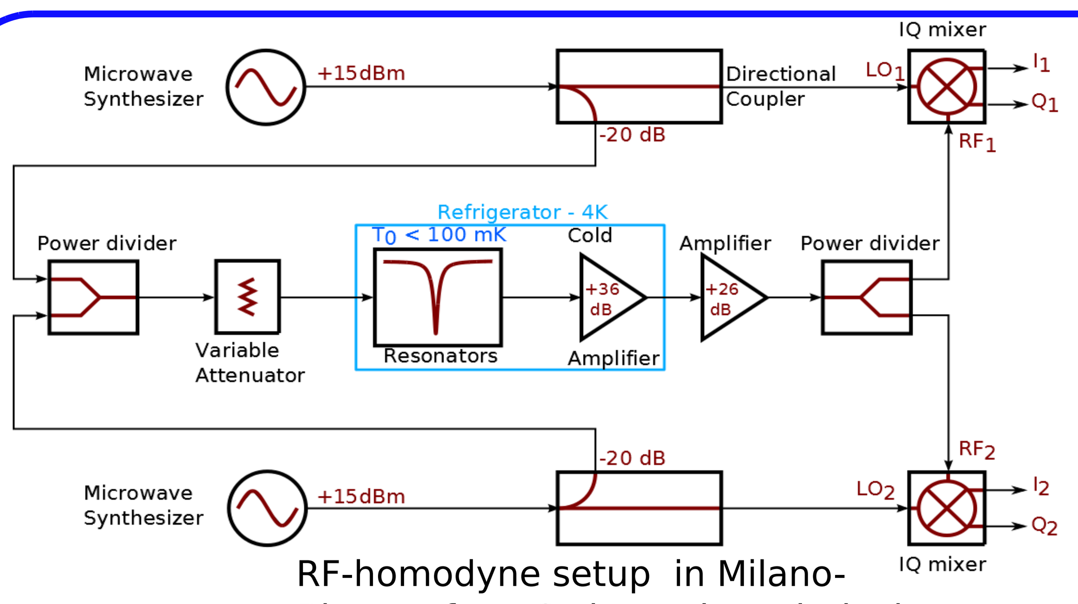


In order to linearize the periodic response of the rf-SQUID another inductor si coupled to each one of the rf-SQUIDs.
A periodic ramp is sent to each inductor along a common line; the ramp induces a controlled flux variation in the rf-SQUID, which is crucial for linearizing the response.



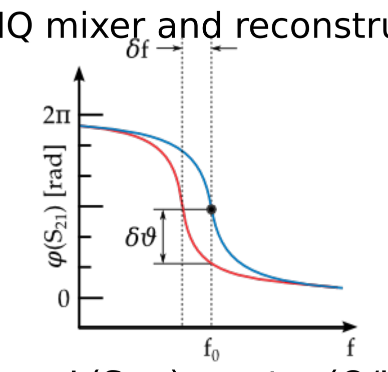
An increase in the TES temperature causes an extra variation in the magnetic flux linked to the rf-SQUID which can be then precisely measured.

TES operation



RF-homodyne setup in Milano-Bicocca for a 2 channels multplexing

The use of RF-SQUID provides a natural environment for RF-multiplexing. Signal from each detector is downconverted with a IQ mixer and reconstructed offline

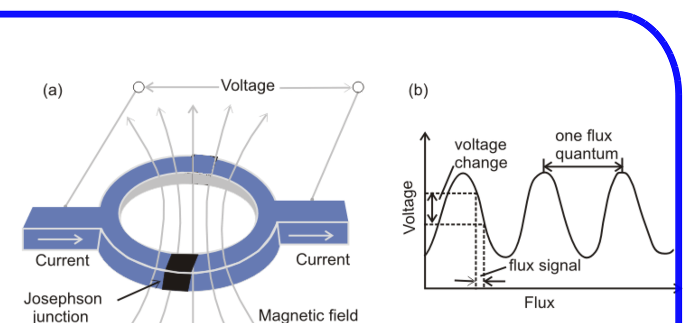


Φ(S$_{21}$)=arctan(Q/I)

Homodyne detection

RF multiplexing

The signal is reconstructed by comparing the output of the squid caused by the interaction of the radiation in the TES with the free oscillation of the squid caused by the ramp modulation when the TES is not biased (local oscillator).



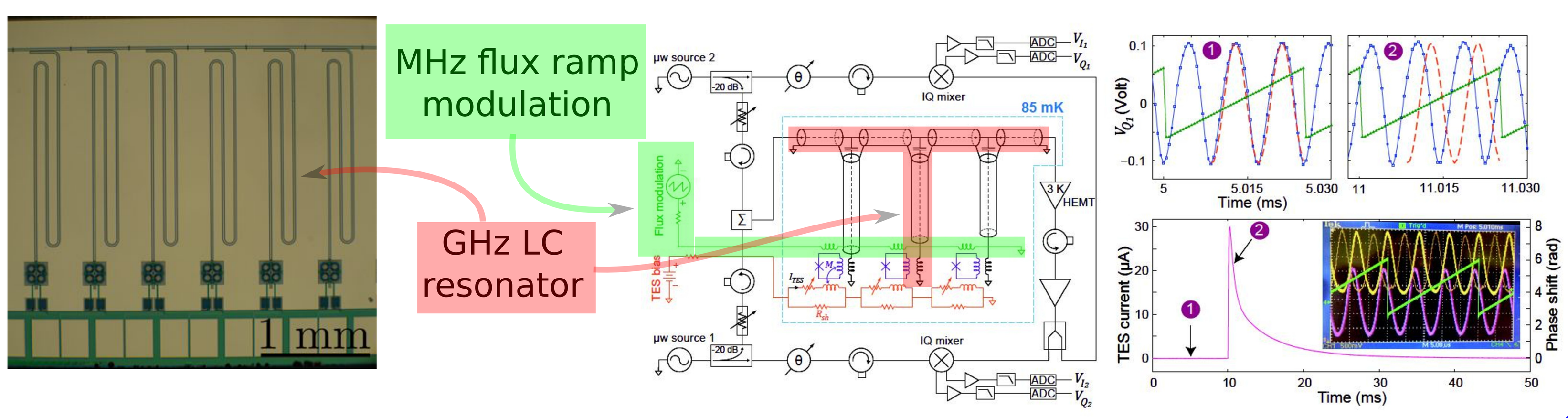
Bandwidth Budget:

- Effective sampling rate is set by the ramp – f_r
- Necessary resonator bandwidth per flux ramp: $\Delta f \gtrsim 2n_{\Phi 0} f_r$
- To avoid cross talk spacing between resonances $f_n \gtrsim \Delta f$ [potentially reduced by a factor 2]
- To avoid distortions $f_r \geq 10/\tau_r$ [potentially reduced by a factor 2]
- Available ADC bandwidth f_{ADC} with ROACH2 system 550 MHz
- Mux factor:

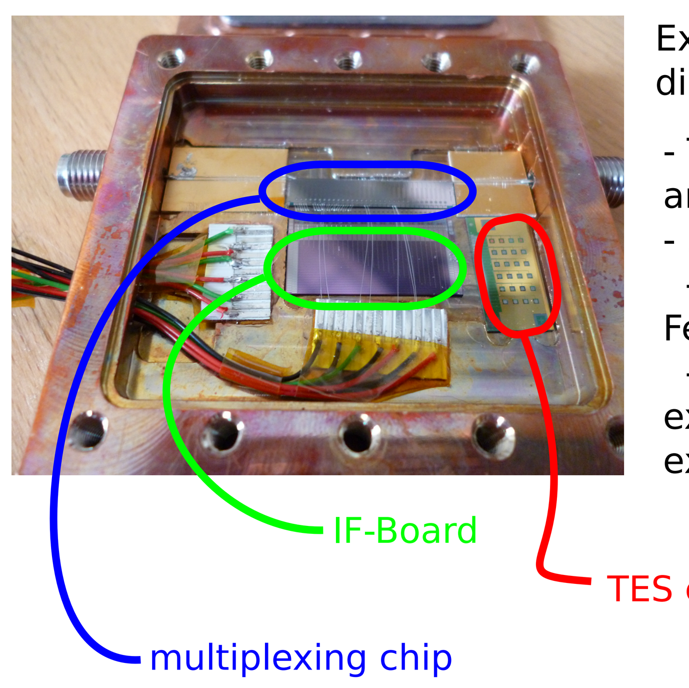
$$n_{mux} = \frac{f_{ADC}}{f_n} = \frac{f_{ADC}\tau_r}{25 \cdot 2n_{\Phi 0}}$$

- Number of flux per ramp $n_{\Phi 0}$
  - currently 3, easily scalable to 2, feasible 1.1

$$\tau_{rise} = 5\ \mu s,\ n_{\Phi 0} = 2 \rightarrow n_{mux} \approx 50$$



Experimental setup



Expimental setup in new Oxford Instruments cryo-free dilution refrigerator fully equipped for rf-SQUID readout

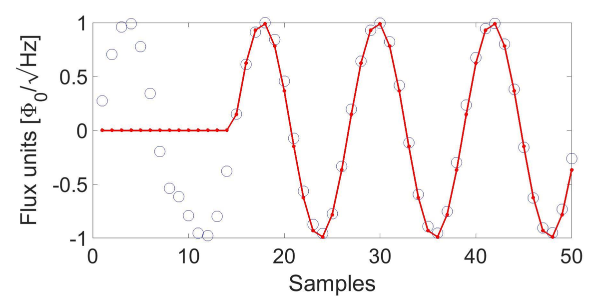
- TES connected to Interface (IF) board with bias circuit and R_{shunt} (NIST)
- 22 available multiplexed channels:
  - -> 4 channels connected to TES chips illuminated with Fe-55 source (few Bq)
  - -> 3 channels with the rf-SQUID input coil connected to external lines for studying the rf-SQUID response to an external stimulus

- G squid = 0.075 (V/Φ_0)
- M squid-ramp = 25 pH
- M TES-squid = 210 pH
- μA per flux unit in Φ_0 = 8.87
- f_{ramp} = 62.5 kHz
- f_{ADC} = 2.5 MHz

First test and results

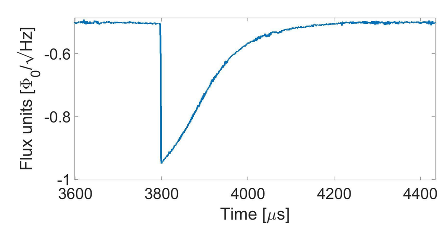
We have set up a new and fully operational multiplexed system for reading out TES detectors coupled to SQUID amplifiers relying on the rf-technique

local oscillator with fit (red line)

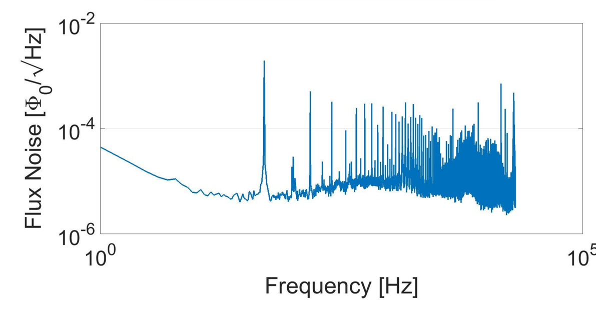


From the demodulated signal pulses are reconstructed and noise can be evaluated in terms of flux unit Φ_0, using a dedicated sofware

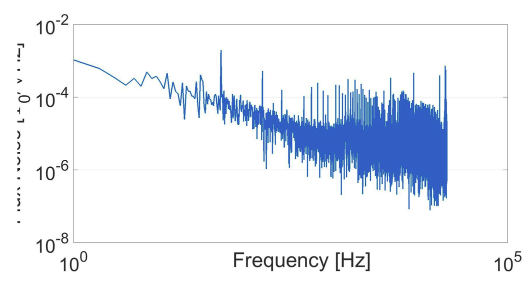
An example of a 6 keV reconstructed pulse (acquired not @ optimal point)



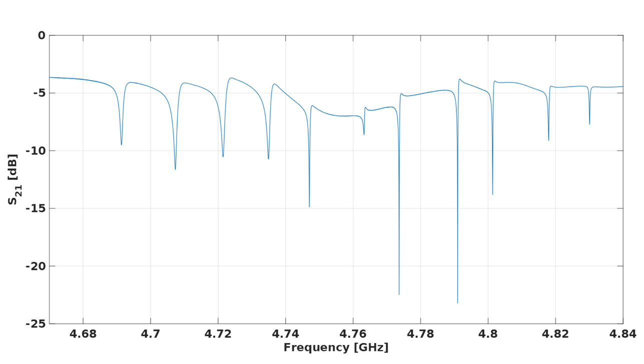
An example of a load curve
- T_{bath}=51mK; the optimal working point is shown



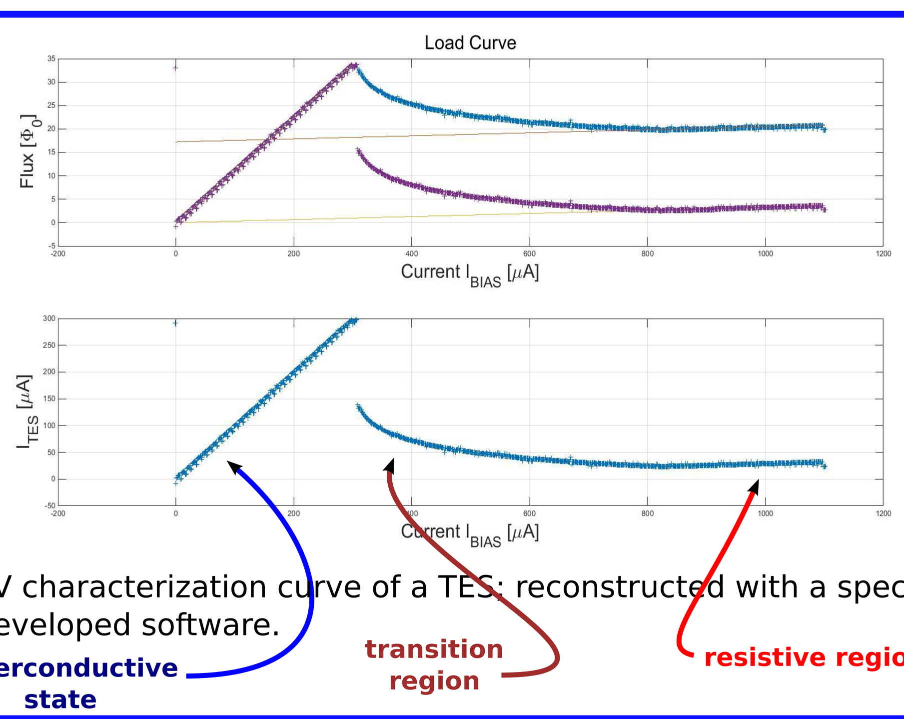
SQUID noise



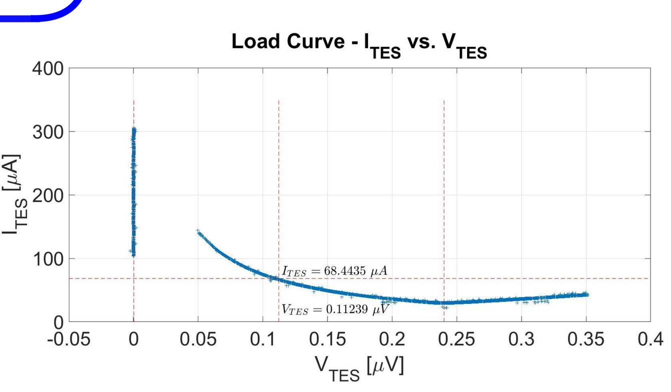
TES noise



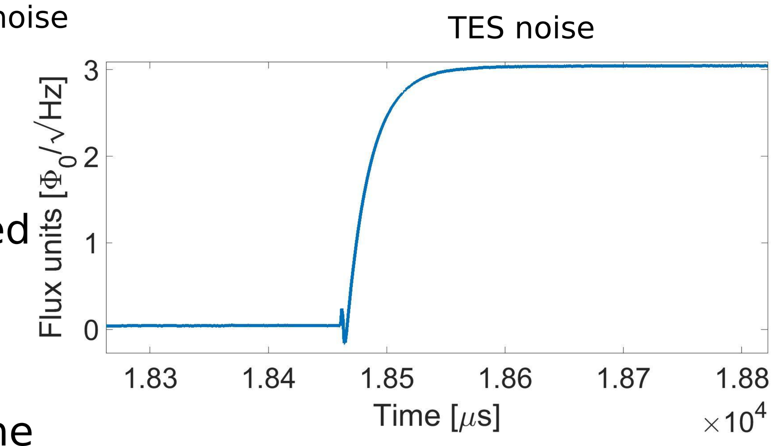
Transmission function of the resonances on the multiplexing chip. Each LC circuit is coupled to a rf-SQUID and TES.



I-V characterization curve of a TES: reconstructed with a specially developed software.



An example of a 6 keV reconstructed pulse acquired @ optimal working point.
The ramp frequency (signal sampling) is currently limited at 62,5 kHz by the ADC sampling rate.
At the optimal working poing signals are fast and the SQUID slew rate is higher than the available sampling.



Newer and faster DAQ to be delivered before September 2015