100 $\hbar$ SQUID AMPLIFIERS FOR THE ULTRACRYOGENIC GRAVITATIONAL WAVE DETECTORS

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Resonant Detector Sensitivity

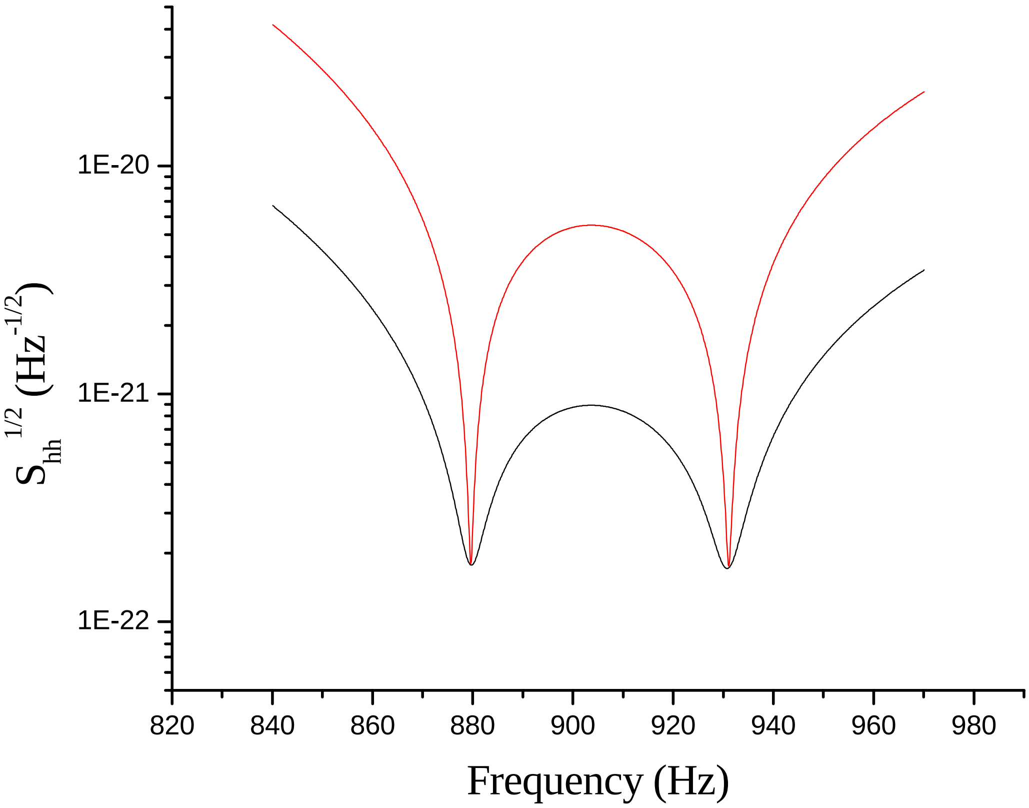
Important Factors

- Temperature and Q of bar and transducer
- <u>Amplifier noise</u>
- <u>Matching network</u>

Effect of the Amplifier Sensitivity

T_n=15 μK ——> ε=350 $\hbar$

T_n=0.35 μK ——> ε=8 $\hbar$



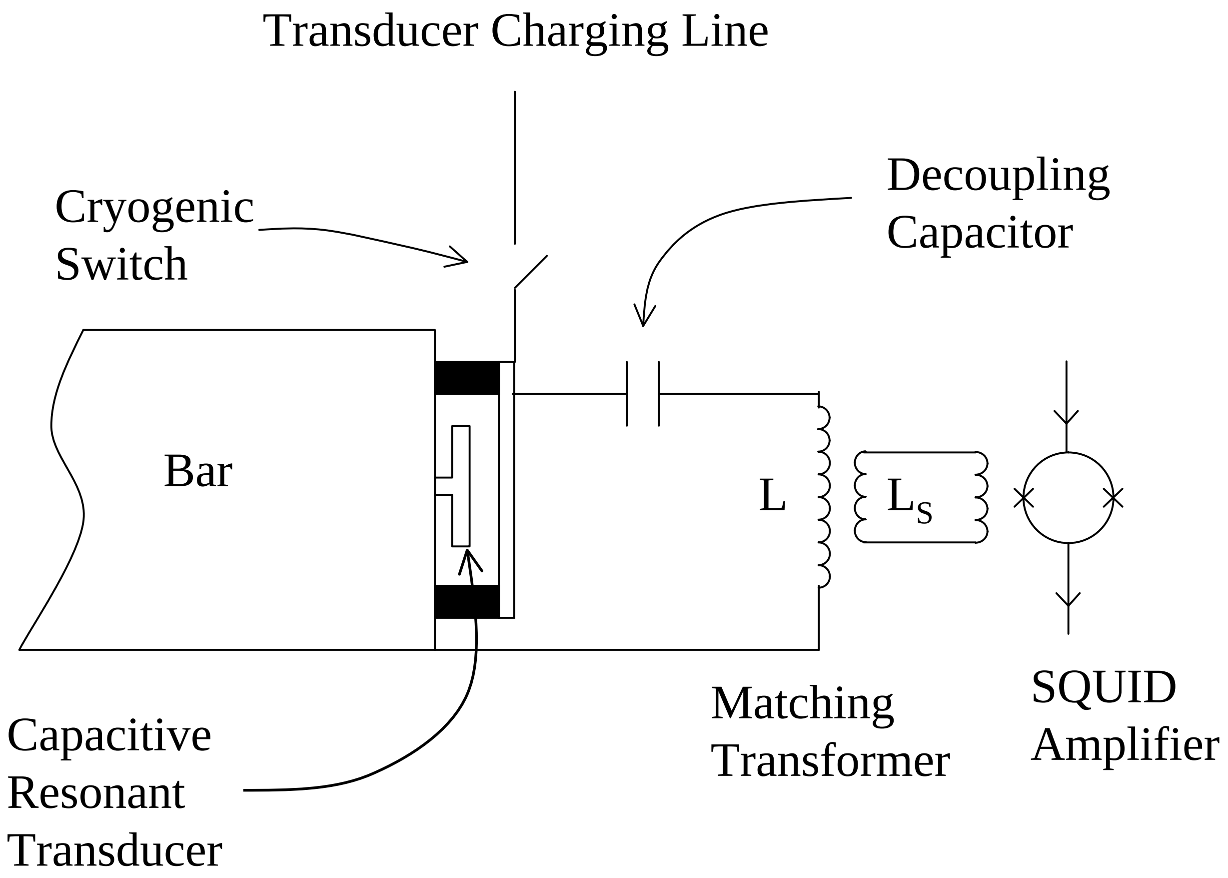
Two tuned modes (bar and transducer)

T_{bar}=100 mK

Q_+, Q_- = 3×10^6

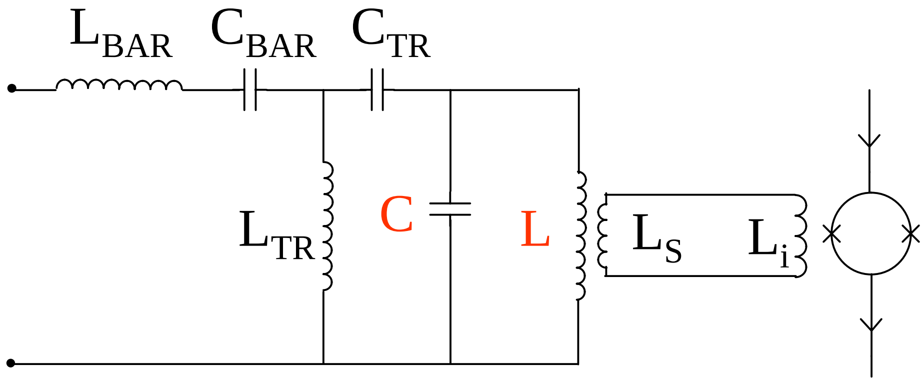
! Low noise SQUIDs are needed

Schematic electromechanical circuit of the g. w. detector AURIGA



Besides bar and transducer there is a third electrical mode.

Equivalent Electrical Scheme of the AURIGA Detector



From the point of view of the SQUID the detector is constituted by 3 coupled electrical resonators

1) Bar
2) Transducer
3) resonator given by the transducer capacitance C and the inductance L of the matching transformer primary coil

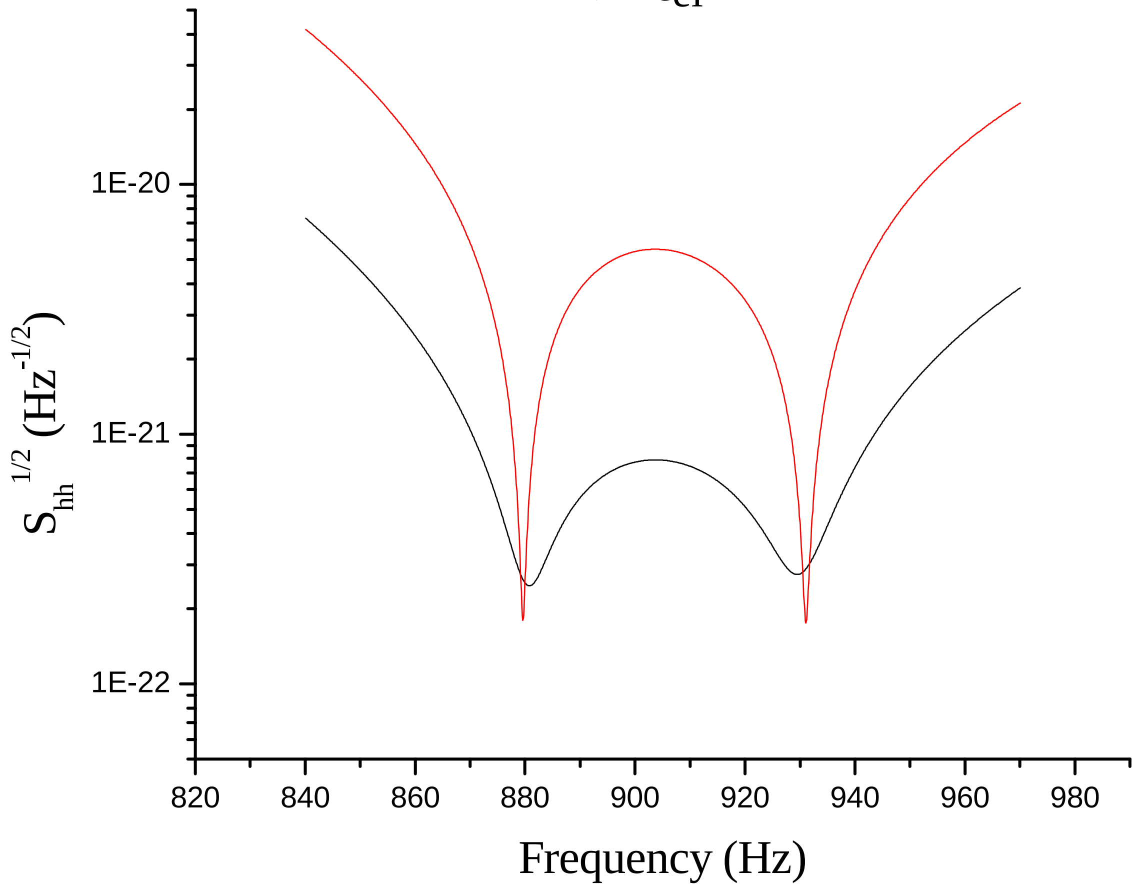
The tuning of the third mode is convenient if
1) its Q is high ($\sim 10^6$)
2) its noise is thermal

High Q resonators with thermal noise are needed

Effect of the Tuning of the Third Mode

2 tuned modes

3 tuned modes, Q_{el}=400000



Common characteristics

- SQUID T_n= 15 μK
- T_{bar}=100 mK
- Q_+, Q_- = 3×10^6

! A full SQUID noise characterization is needed

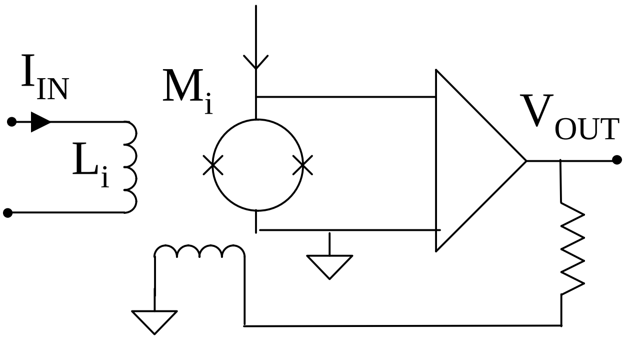
Summary

The reasons for the development of a low noise SQUID able to operate strongly coupled to a high Q LC resonator are

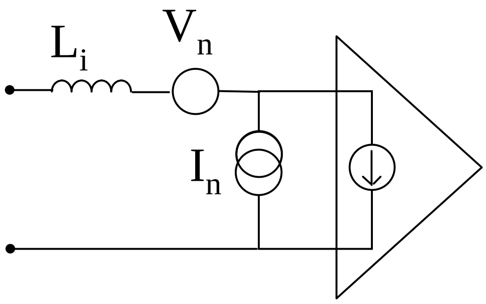
- In a noise matched g.w. detector the minimum detectable energy is determined by the SQUID T_n
- The tuning of the third electrical mode is convenient only if its Q is very high
- The LC resonator is a good simulator of the detector
- With the high Q LC resonator we can give a full noise characterization of the SQUID amplifier

The SQUID Amplifier

SQUID operated in flux locked loop



SQUID current amplifier noise model



Expected noise

Typical values

$$S_i \cong 16 \frac{k_B T L_{SQ}^2}{R M_i^2} \approx 10^{-25} \; A^2/Hz$$

$$S_v \cong 11 \omega^2 M_i^2 \frac{k_B T}{R} \approx 10^{-37}/\omega^2 \; V^2/Hz^3$$

$$S_{iv} \cong 12 \frac{i \omega L_{SQ} k_B T}{R}$$

Noise Temperature

$$T_n = \sqrt{S_i S_v - \mathrm{Im}^2\{S_{iv}\}} \Big/ 2k_B \leq \sqrt{S_i S_v} \Big/ 2k_B$$

True Energy Resolution

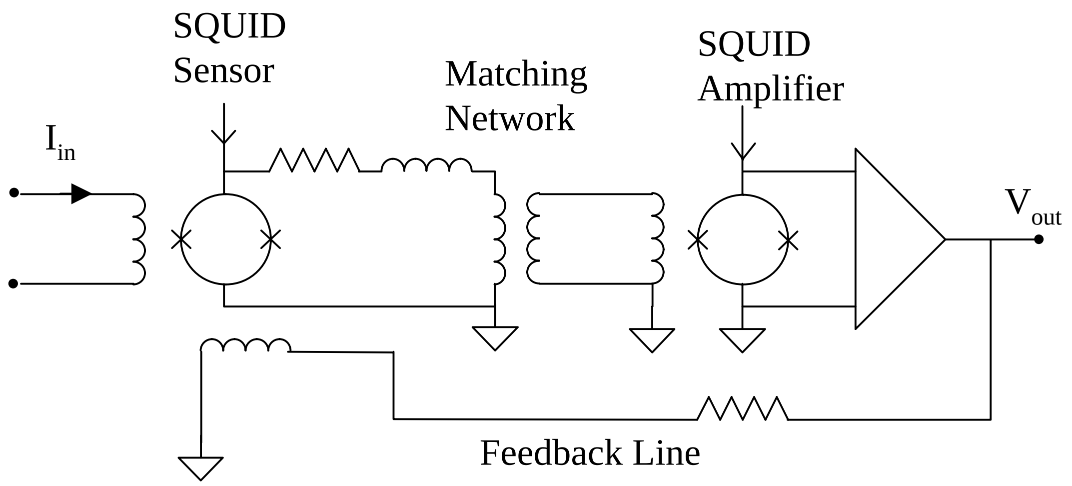
$$\varepsilon = k_B T_n / \omega_0$$

Energy Resolution from additive noise

(incomplete expression)

$$\varepsilon' = \frac{1}{2} L_i S_i = \frac{L_i S_\phi}{2M_i^2}$$

Two-stage SQUID amplifier



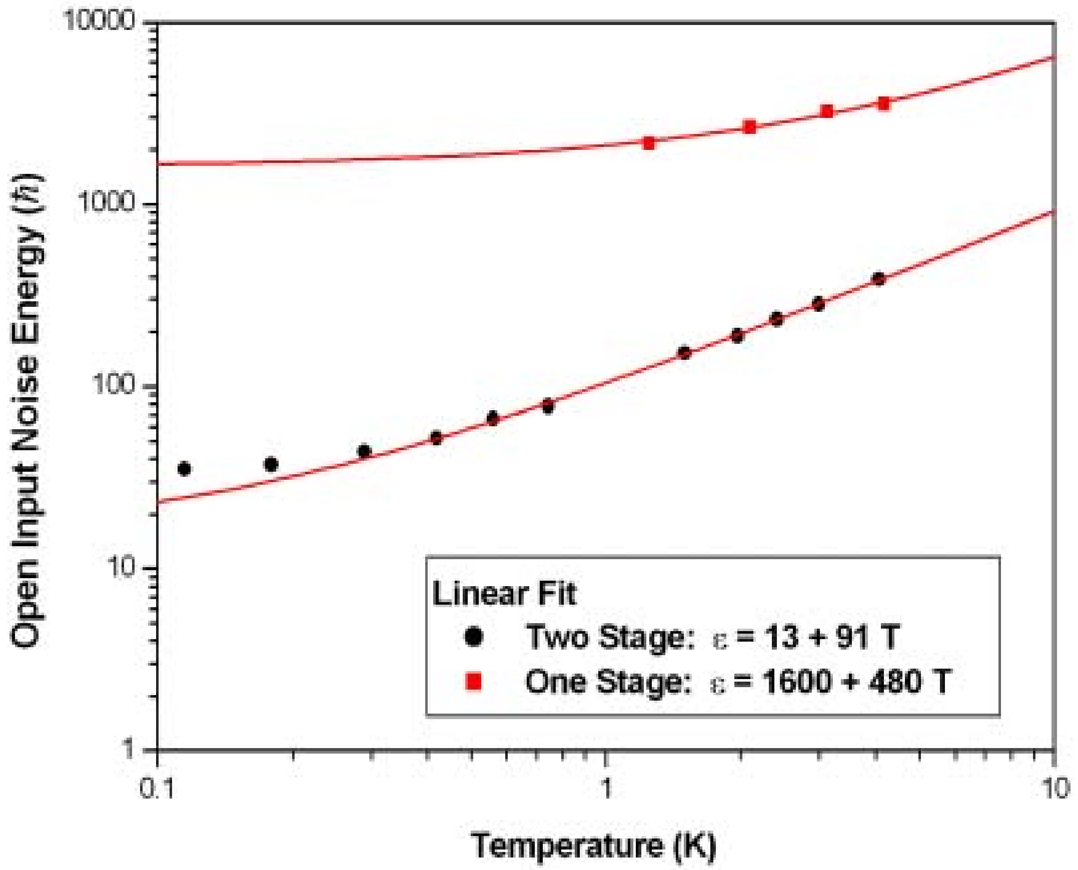
Advantages

• the noise contribution of the electronics at T_{AMB} can be made negligible

• the effect of EM interference is reduced

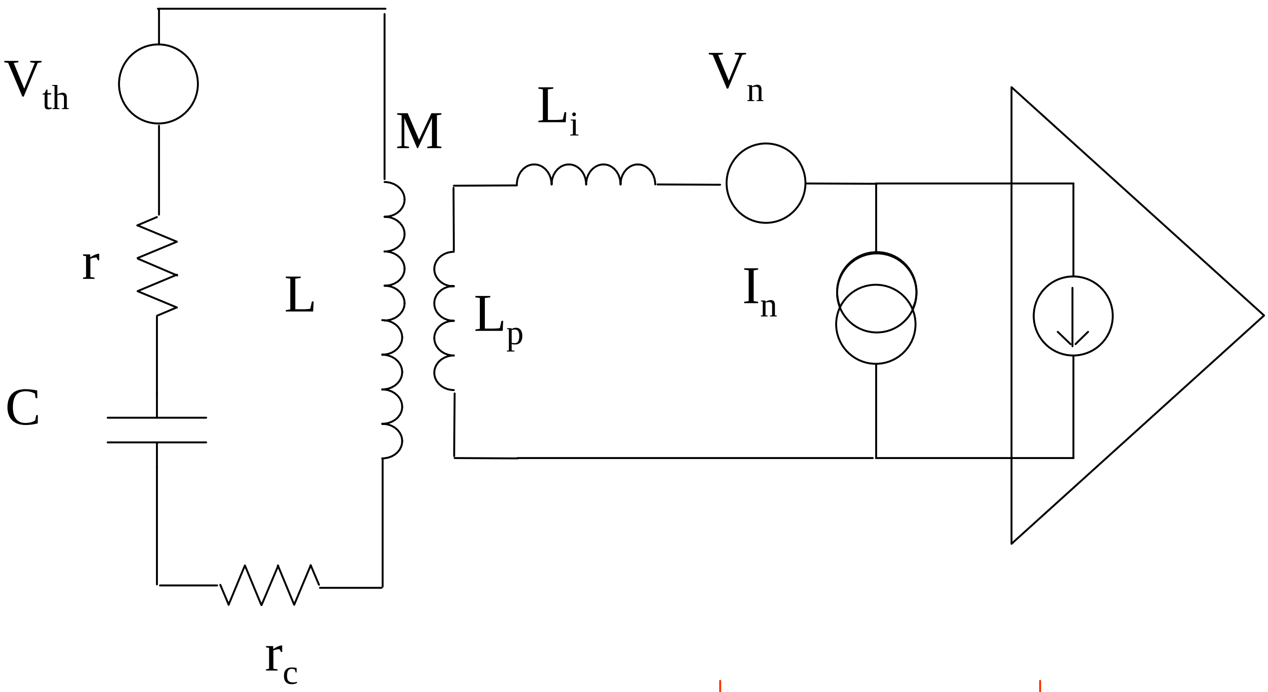
• the noise is, in principle, thermal

Energy Resolution from additive noise



$$\varepsilon' = \frac{L_i S_i}{2} = \frac{L_i S_\Phi}{2M_i}$$

Back Action Noise Measurement



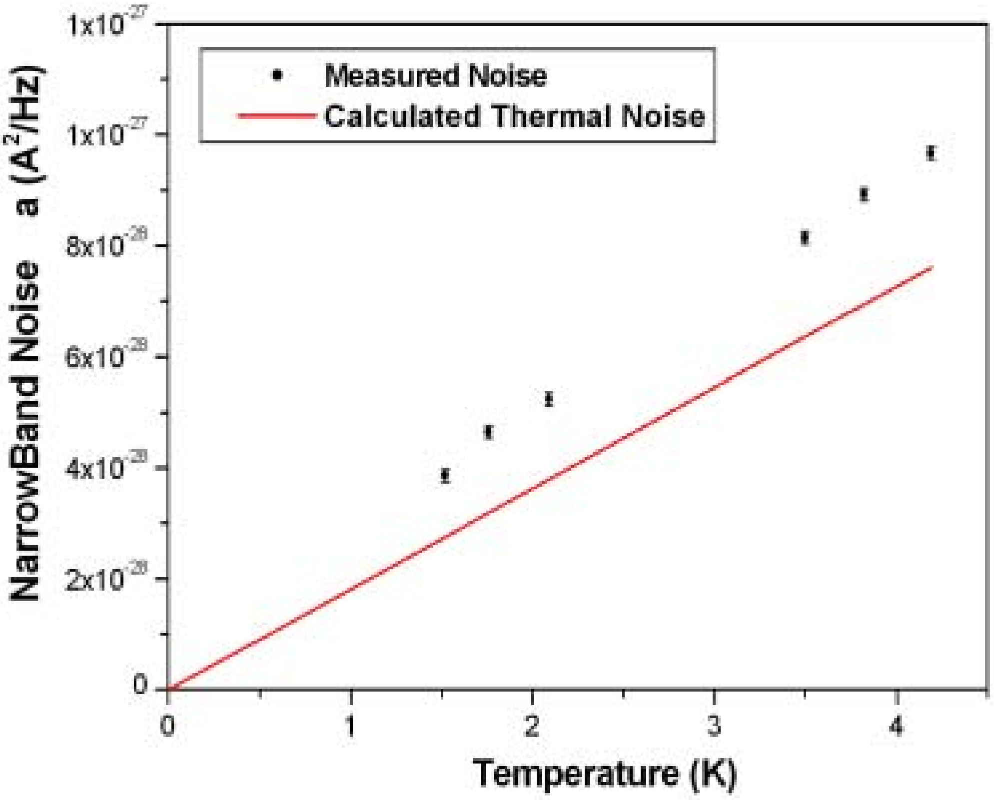
$$\sigma_{out}^2 = \left(\frac{Q_a}{Q_i}\right)(MT_RG)^2\left[\frac{k_BT}{L_{eq}} + Q_i\,\frac{S_v(\omega)}{2\omega_0}\left(\frac{M}{L_tL_{eq}}\right)^2\right]$$

Resonator thermal noise

SQUID back action noise

Characteristics of the resonators

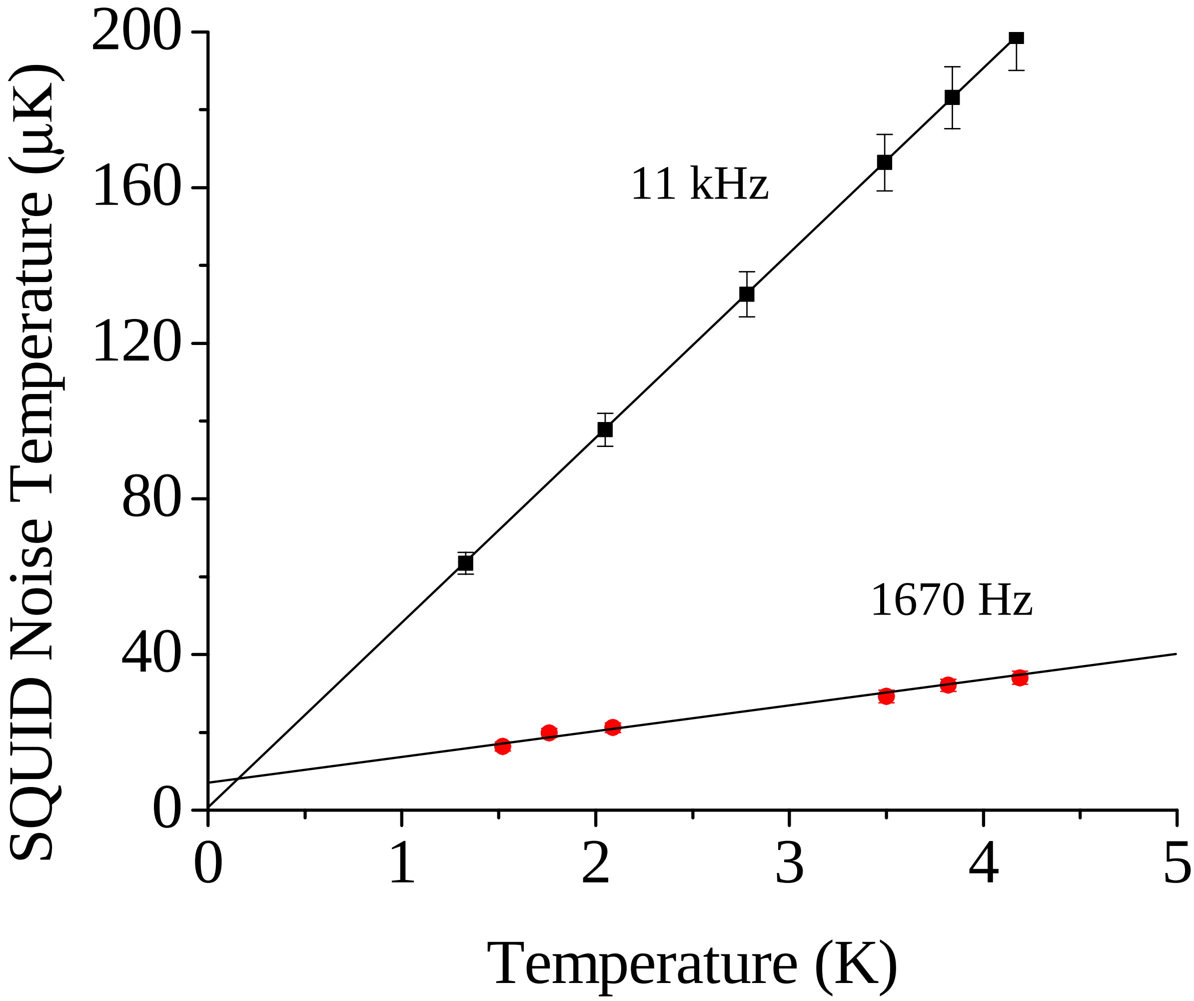
- Resonance frequency = 200 Hz-20 kHz
- $Q = (2 - 0.5)\times 10^6$
- L = 20 mH - 7 H
- C = 1 - 600 nF



Two-stage SQUID

Resonance Frequency = 1670 Hz
Quality Factor = 1.1 × 10^6
L = 0.55 H   C = 19 nF

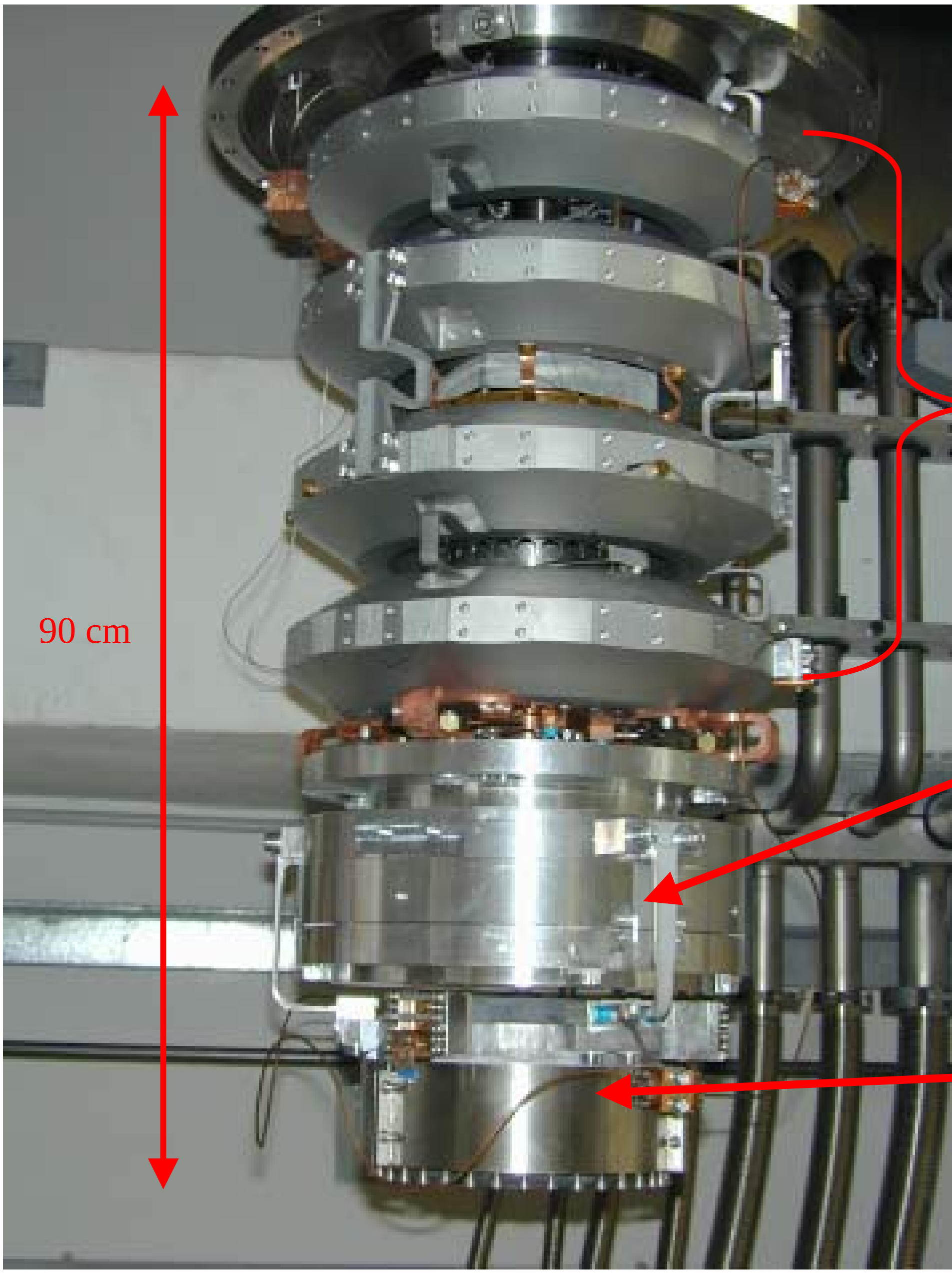
Two-stage SQUID Noise Temperature

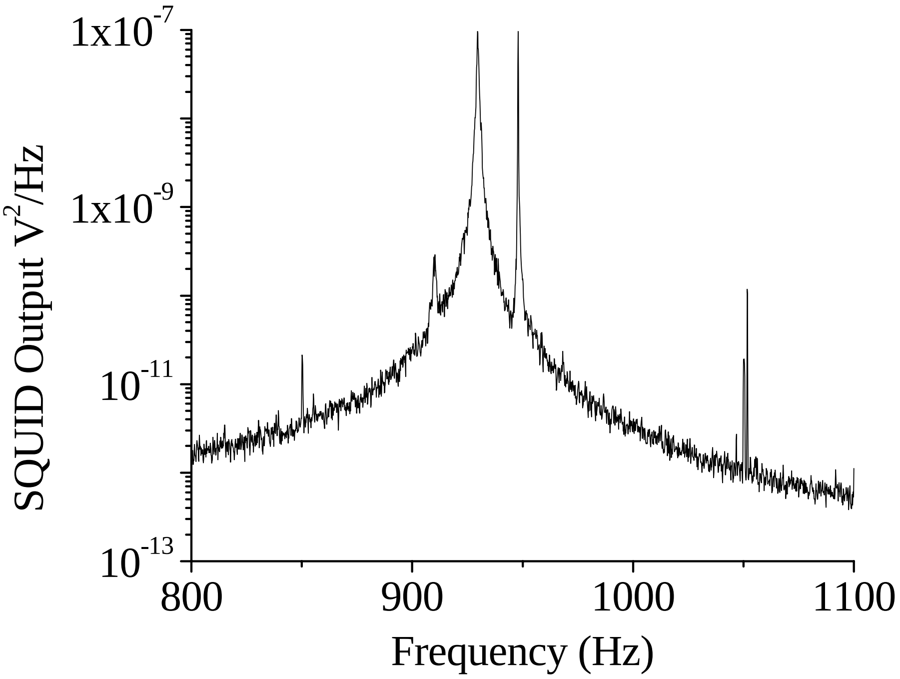


- Intercept different from zero in the 1/f noise region
- Slope in agreement with the theory within a factor two

TEST FACILITY at Legnaro Labs

Ultracryogenic site for the development of transduction systems





TRANSDUCER + MATCHING STAGE + SQUID

- The system is stable
- Few spurious peaks in the spectrum

TRANSDUCER

- Q=1.1 × 10^6
- thermal noise at 4.2 K
- El. Field 8 × 10^6 V/m

ELECTRICAL MODE

- Q=450000
- thermal noise at 2 - 4.2 K

TWO-STAGE SQUID

- Additive and back action noise as expected
- Sufficient dynamic range