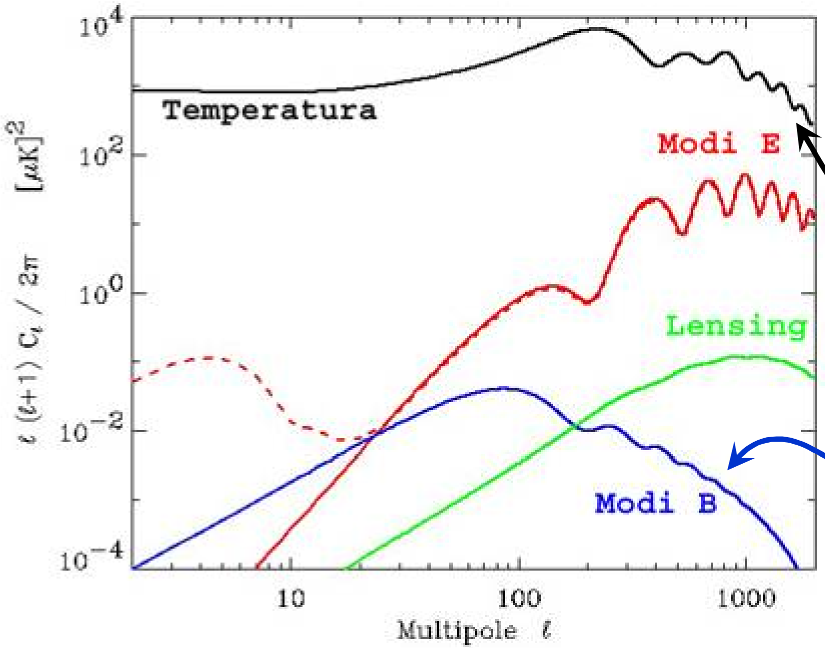
Development of Kinetic Inductance Detectors for the study of the Cosmic Microwave Background Polarization

M. Calvo, Dep. of Physics, University of Rome ‘La Sapienza’

Why are new detectors necessary?



The study of CMB radiation and its temperature fluctuations has given us a much deeper knowledge of our Universe

The greatest challenge right now is the measurement of the CMB polarization, and in particular of the B modes.

The expected signal is very small ($\approx 0.1\mu K$)

Detectors have already reached the point where measurements of CMB radiation are dominated by the intrinsic fluctuations of the CMB emission itself (*BLIP*)

The only way to increase the S/N ratio is therefore to increase the number of pixels: $S/N \propto \sqrt{n_{riv}}$

Present status for ultrasensitive detectors

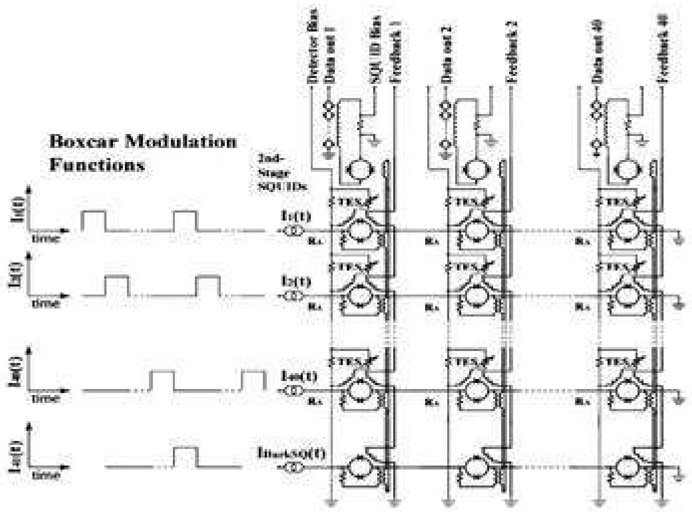
For satellite and balloon borne missions, large and *multiplexed* arrays are essential.

Scaling up the pixel count with current detectors is extremely complex

Transition Edge Sensors:

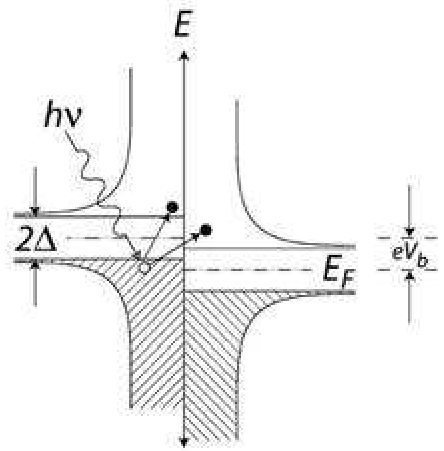
TDM: many SQUIDs, high cost
FDM: many high Q filters

} + high temperature stability needed!



Superconducting Tunneling Junctions:

One FET amplifier per sensor
Hard to get uniform properties



A possible solution:

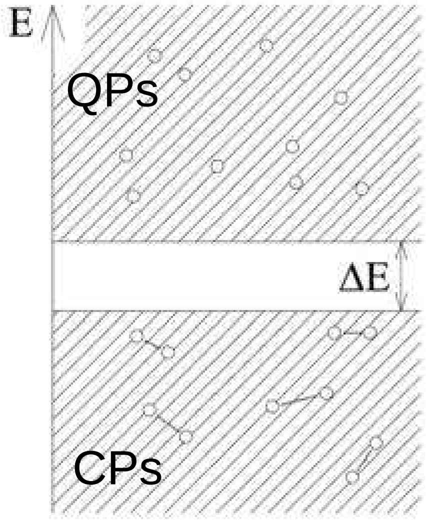
Kinetic Inductance Detectors

Main characteristics:

- order of 10^3-10^4 pixels read with a single coax
- *Extremely simple cold electronics:* one single LNA can be used for 10^3-10^4 pixels. The rest of the readout is warm.
- *Ease of fabrication:* one single layer of material is needed.
- *Very flexible:* different materials and geometries can be chosen to tune detectors to specific needs.
- *Very resistant:* materials are all suitable for satellite and space missions.

KIDs working principle:

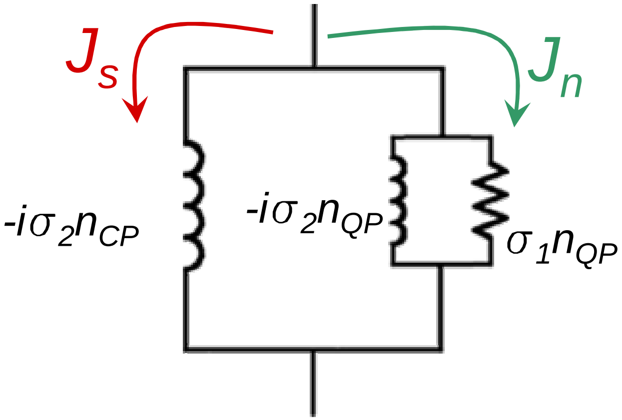
In a superconductor below T_c , electrons can bind to form CPs with binding energy $E=2\Delta=3.5*k_bT_c$.

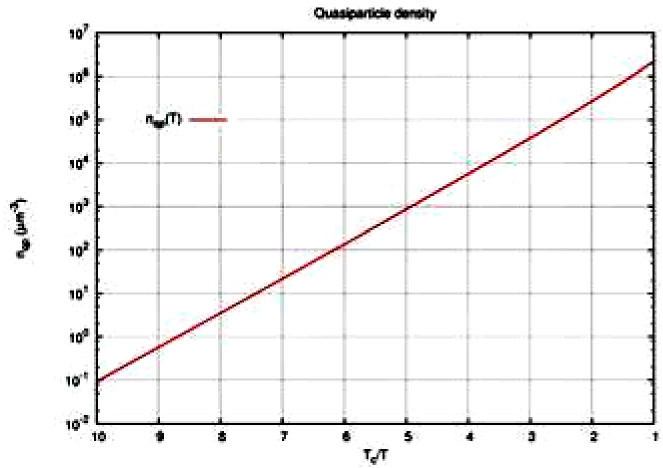


The CPs have zero DC resistance, but the reactance is non-zero and has two distinct contribution → *kinetic* and *magnetic L*.

The total conductivity of the material can be estimated using the *two-fluid model*

The values of σ_s and σ_n depend on the densities of QPs and CPs. By measuring them, we can get information on n_{qp} .



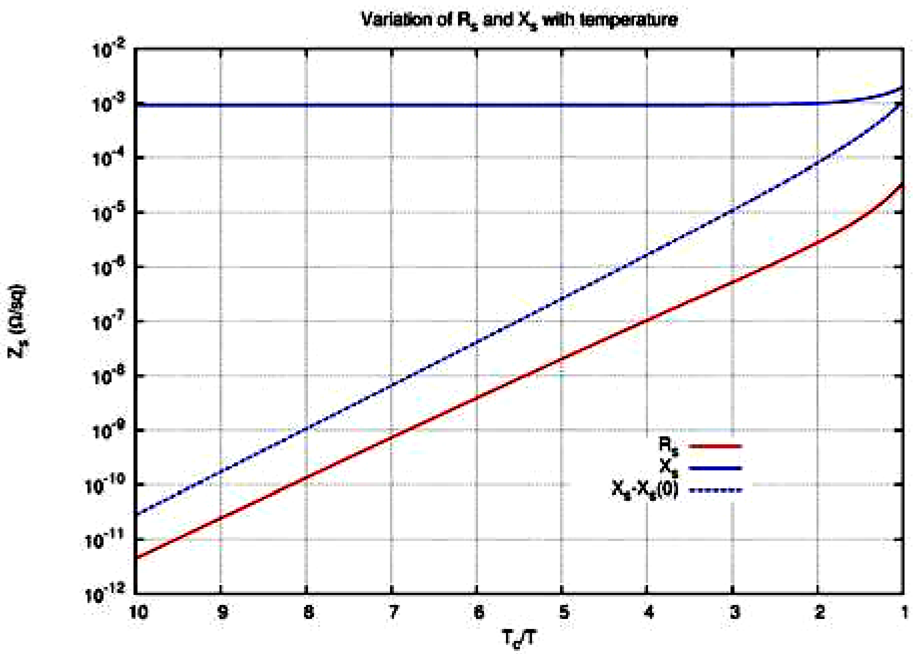


A better theory...

A better estimate of σ_s and σ_n is obtained using the Mattis Bardeen integrals:

$$\frac{\sigma_2}{\sigma_n} = \frac{1}{\hbar\omega}\int_{\Delta-\hbar\omega}^{\Delta} d\epsilon \frac{[1-2f(\epsilon+\hbar\omega)]\left(\epsilon^2+\Delta^2+\hbar\omega\epsilon\right)}{\sqrt{\Delta^2-\epsilon^2}\sqrt{(\epsilon+\hbar\omega)^2-\Delta^2}}$$

$$\frac{\sigma_1}{\sigma_n} = \frac{2}{\hbar\omega}\int_{\Delta}^{\infty} d\epsilon \frac{[f(\epsilon)-f(\epsilon+\hbar\omega)]\left(\epsilon^2+\Delta^2+\hbar\omega\epsilon\right)}{\sqrt{\epsilon^2-\Delta^2}\sqrt{(\epsilon+\hbar\omega)^2-\Delta^2}}$$



Note that:

- R_s decreases exponentially
- X_s becomes constant
- X_s/ R_s grows exponentially

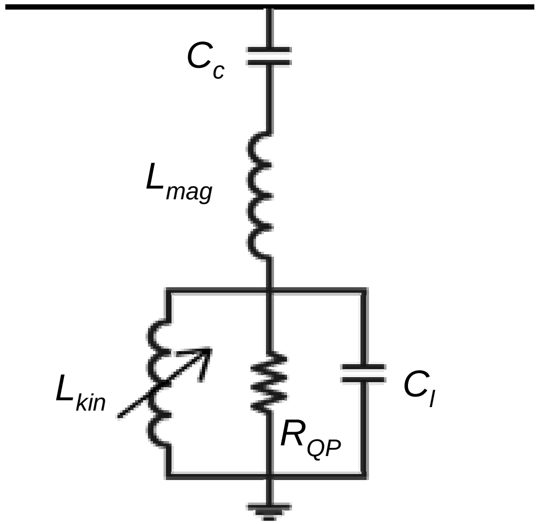
D. C. Mattis and J. Bardeen, in Phys Rev 111 (1958)

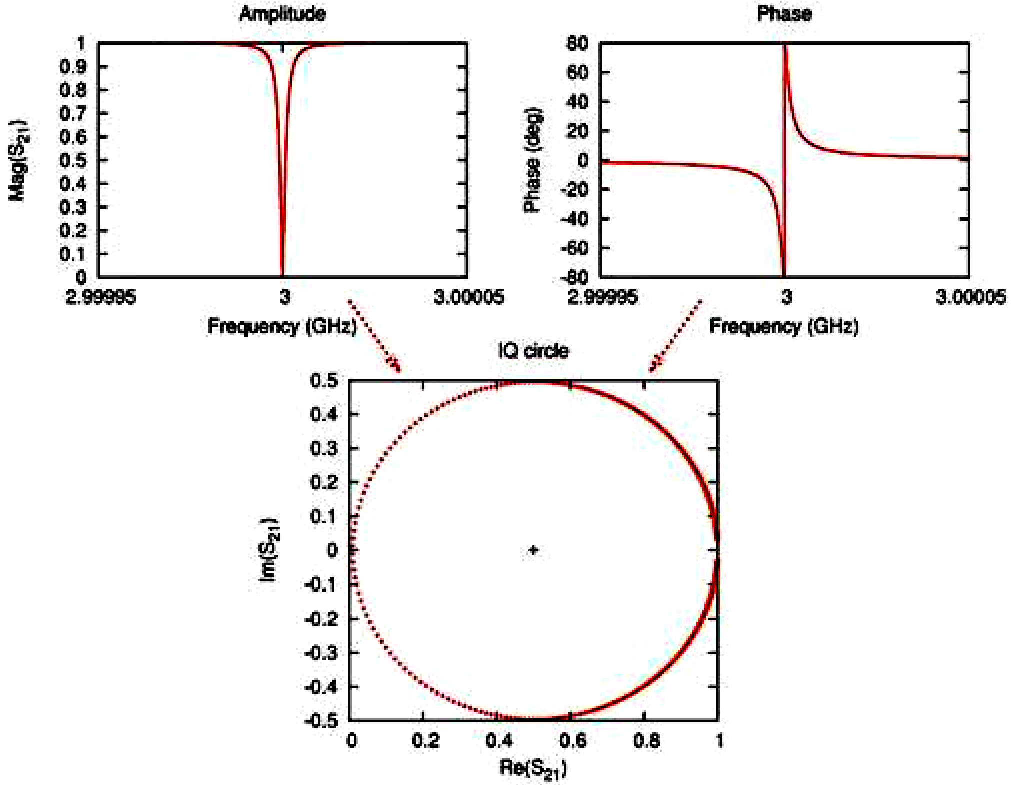
How can we measure the small variations of L_{k}?

The superconductor can be inserted in a resonating circuit with extremely high *Q*, since:

$$Q \propto X_s / R_s$$

The resonator is extremely simple to do, and consists of a shorted length of superconducting line capacitevely coupled to the feedline ⟶ *$\lambda/4$ resonator*



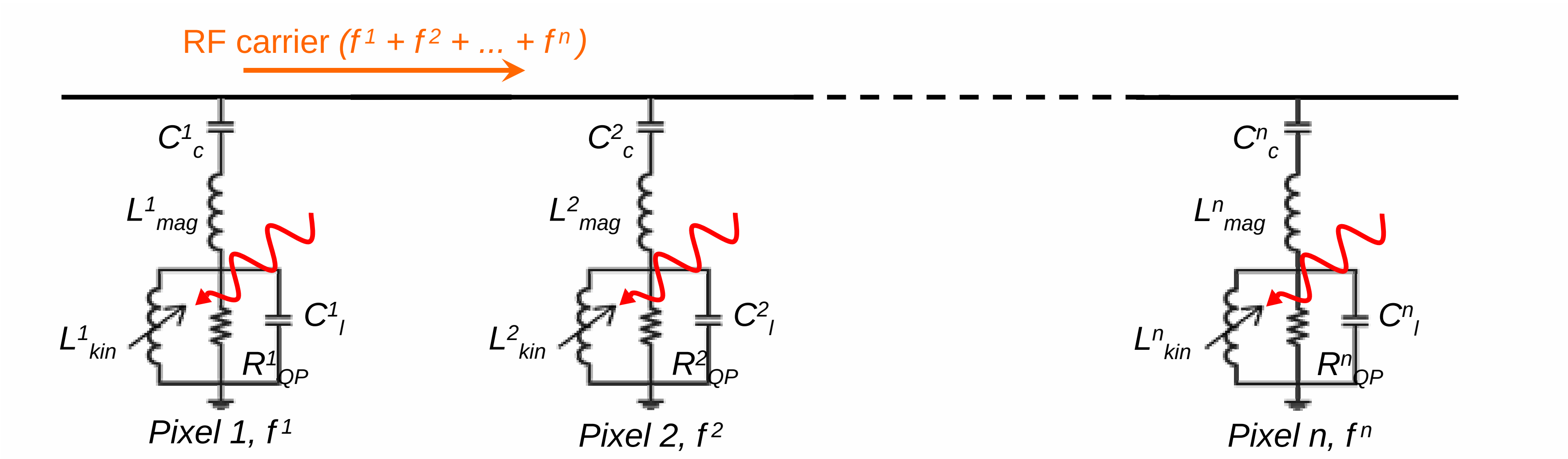


Multiplexing

KIDs are *intrinsically* multiplexable:

- Unitary transmission off resonance
- Q values very large (~10^6)

Each resonator acts at the same time as *detector* and *filter*



One single amplifier needed!

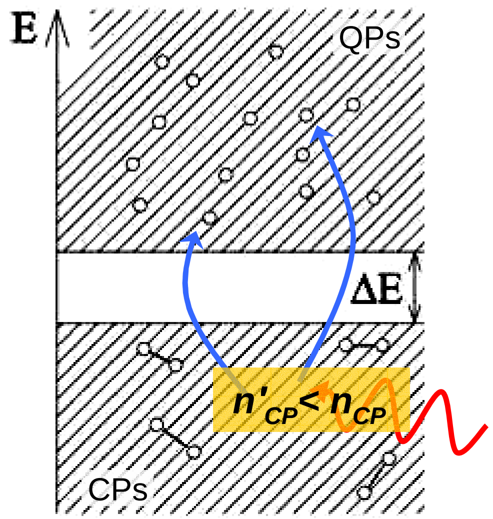
Many potential applications

M. Calvo et al. in Conf. Proc. of 1st International LDB Workshop (2008)

E.Andreotti et al. in NIMR A 572 (2008)

How do we actually measure the incoming radiation?

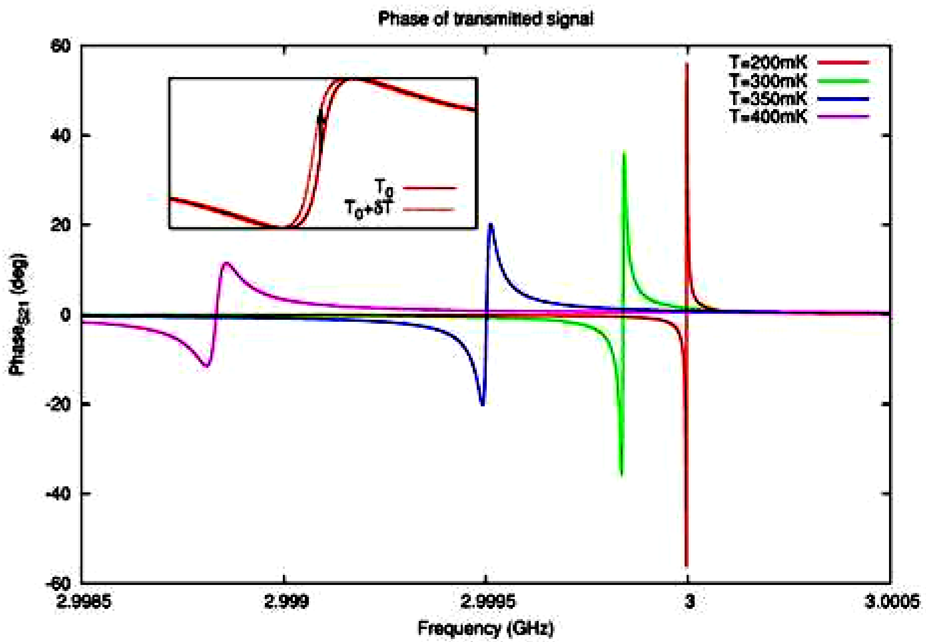
- *Suppose a photon hits the detector*
- *If its energy is high enough ($h\nu > 2\Delta E$) it can break CPs*
- *The density of CPs therefore changes*
- *This leads to a variation of L_{kin}*



The same effect can be accomplished by increasing the temperature of the superconductor

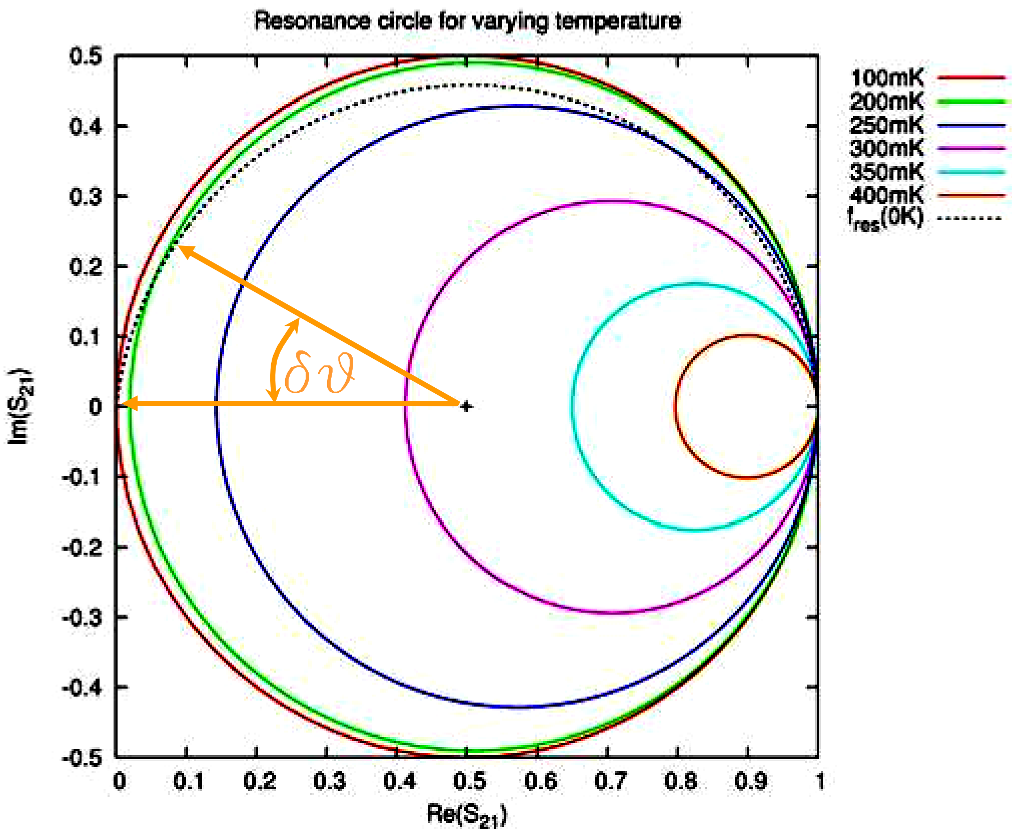
The readout is accomplished by monitoring the phase of the transmitted signal

$$f_0 \propto 1/\sqrt{L}$$



Readout technique

Usually the phase is redefined and referred to the center of the resonant circle:



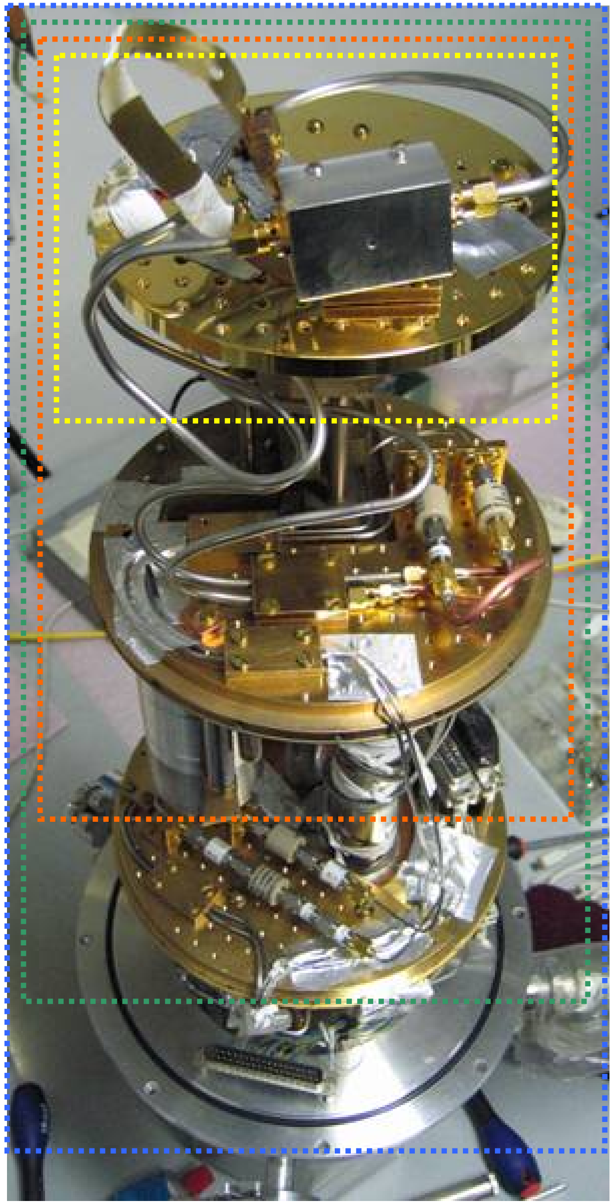
This kind of plots can give all the information regarding resonator parameters

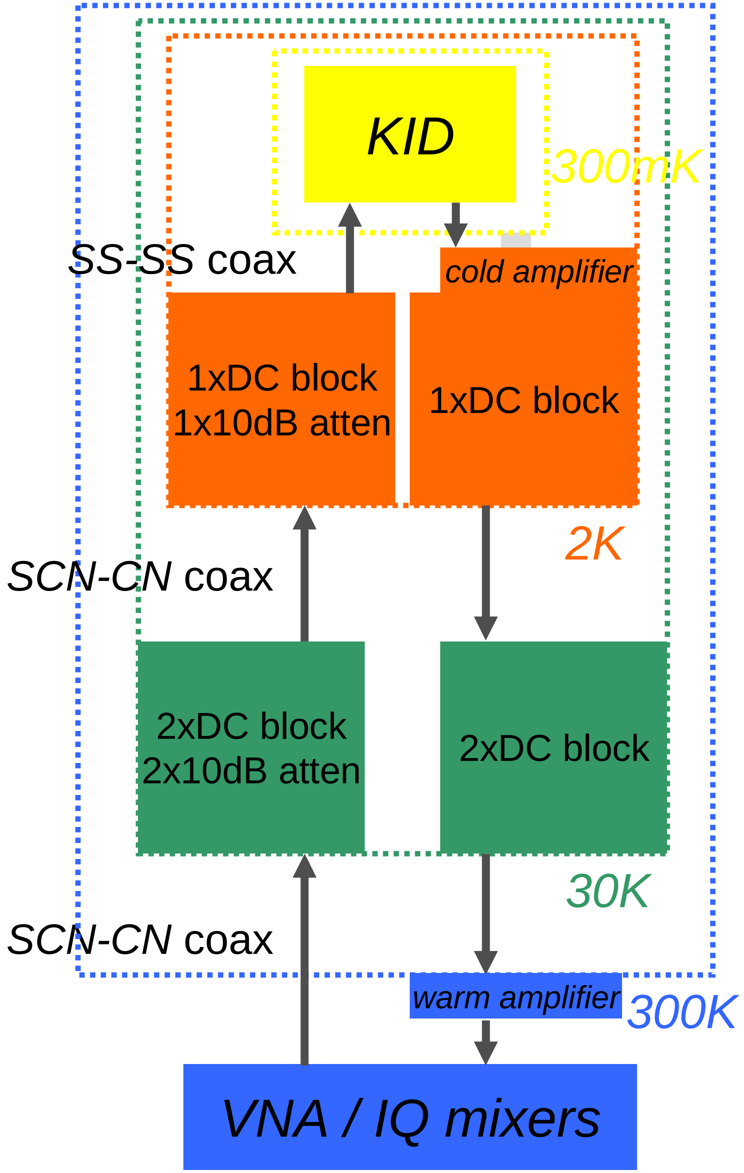
It is also the basis for actual measurements of radiation

Remember that:

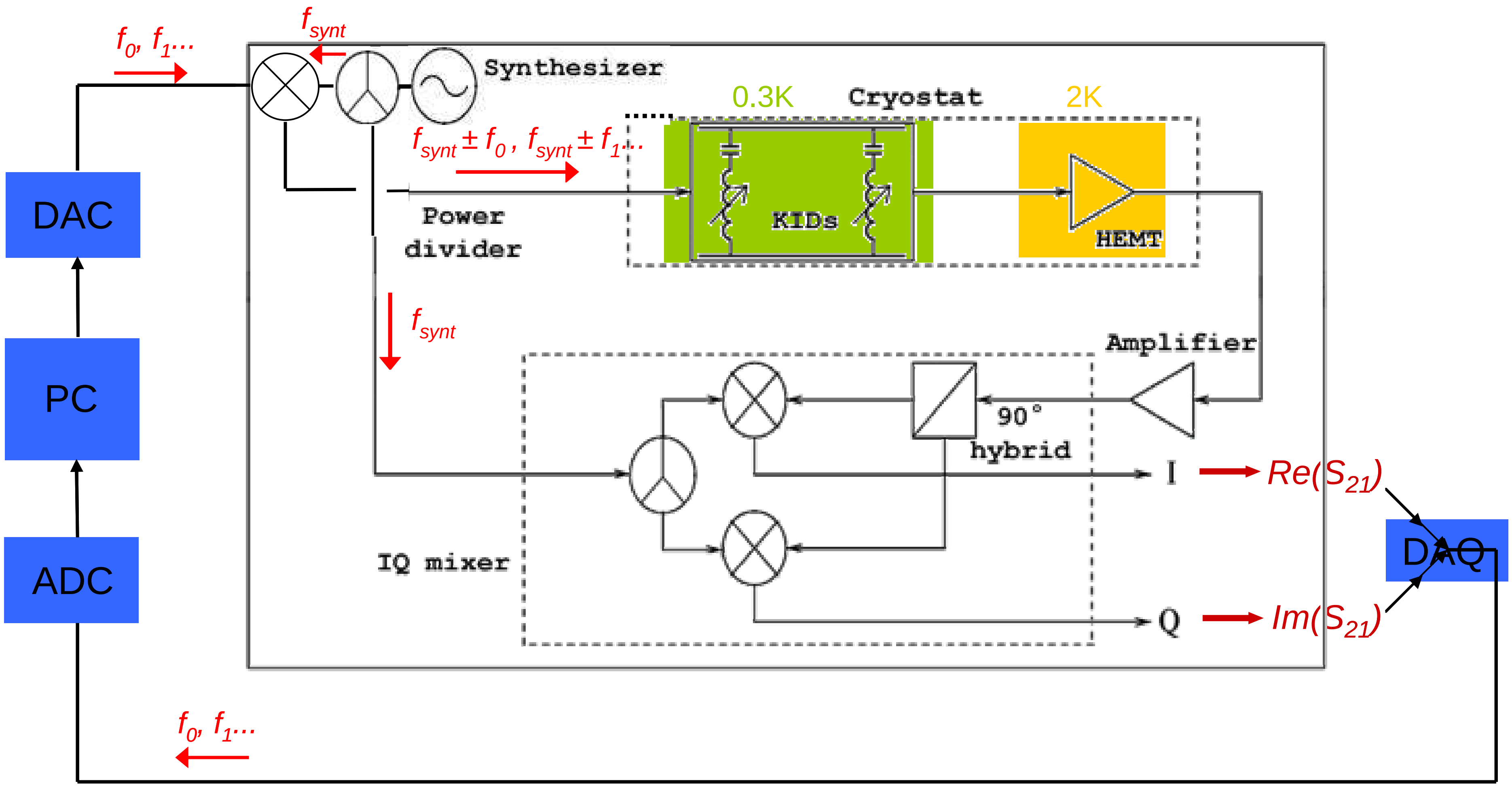
$$\frac{\delta\vartheta}{\delta T} \xleftrightarrow{n_{QP}(T)} \frac{\delta\vartheta}{\delta n_{QP}}$$

Cryogenic system overview





KIDs readout system

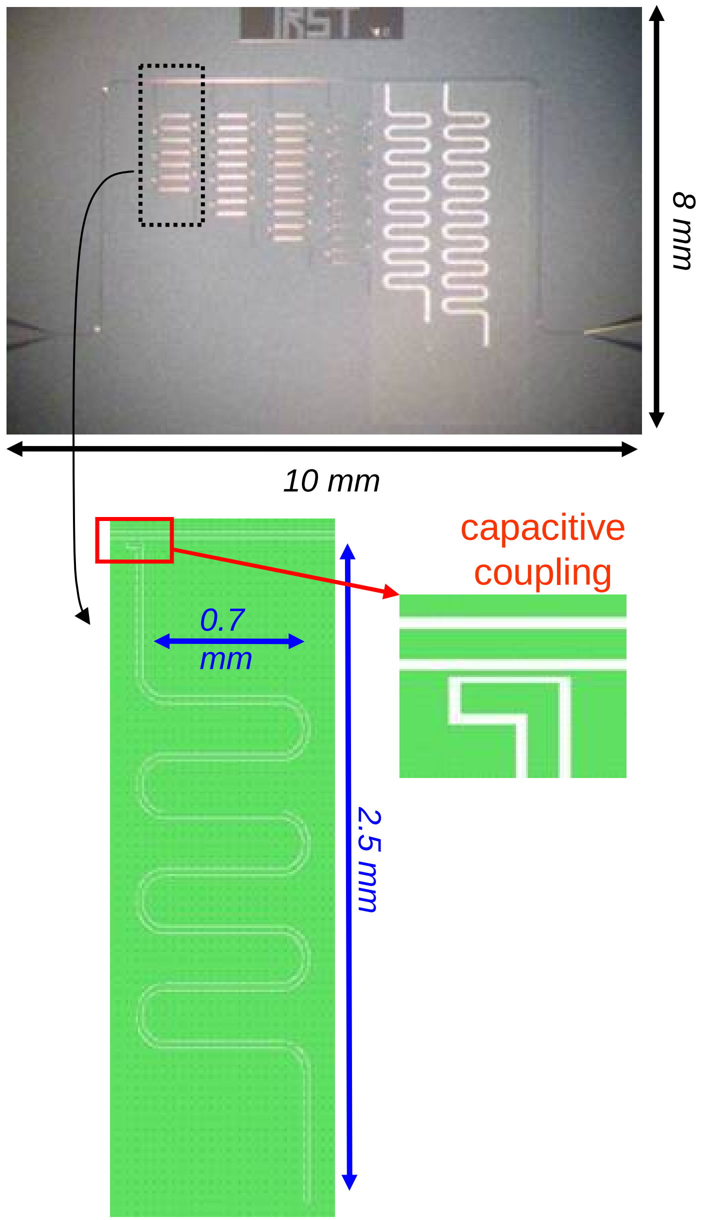


Single pixel readout system

Multipixel readout system

Both systems share the core components!

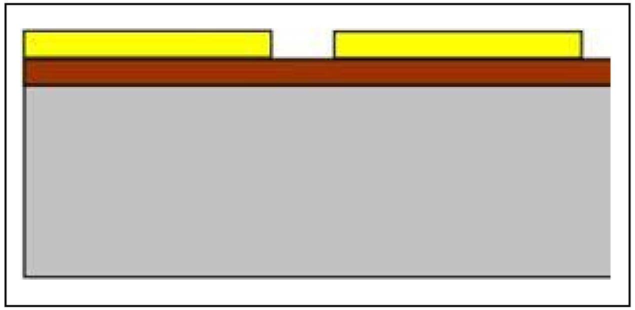
KID chip description



Material: Aluminium

6 resonators of varying length

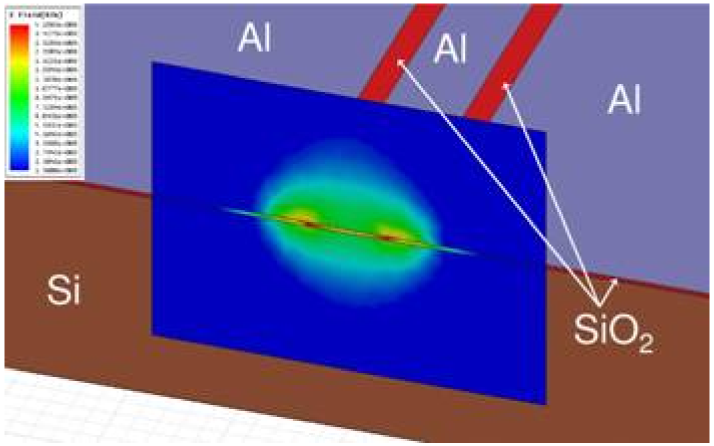
Substrate:



Al CPW (200nm)

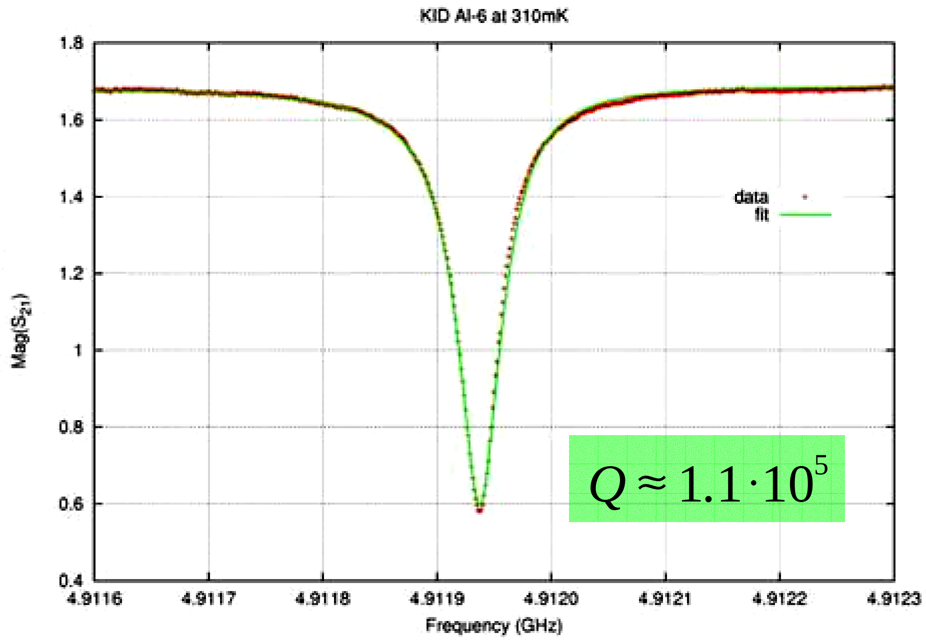
SiO_2 (1μm)

Silicon Substrate (0.5mm)



The dielectric constant is not exactly determined!

Base temperature characterization

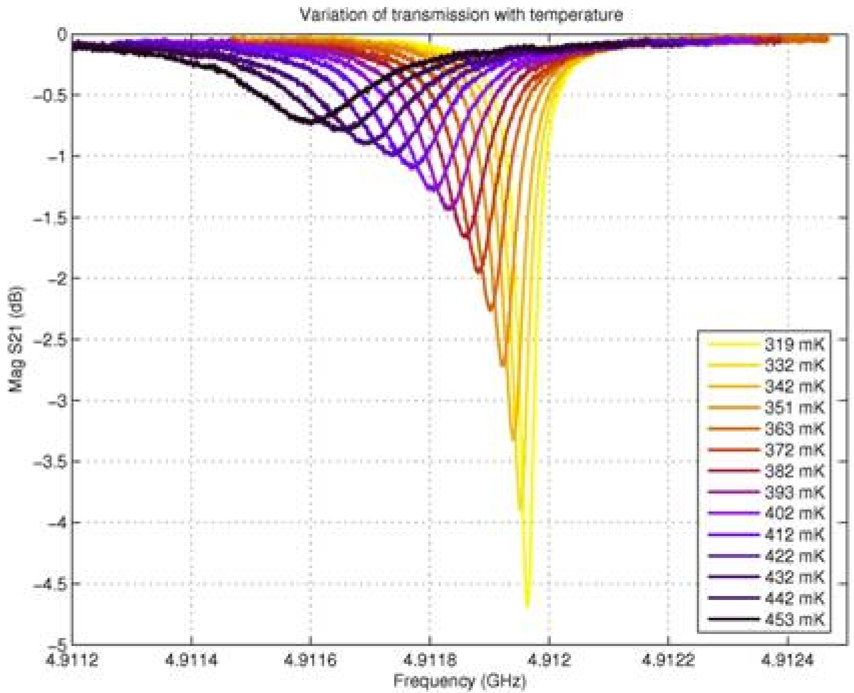


Typical resonance amplitude curve

All 6 resonances observed!

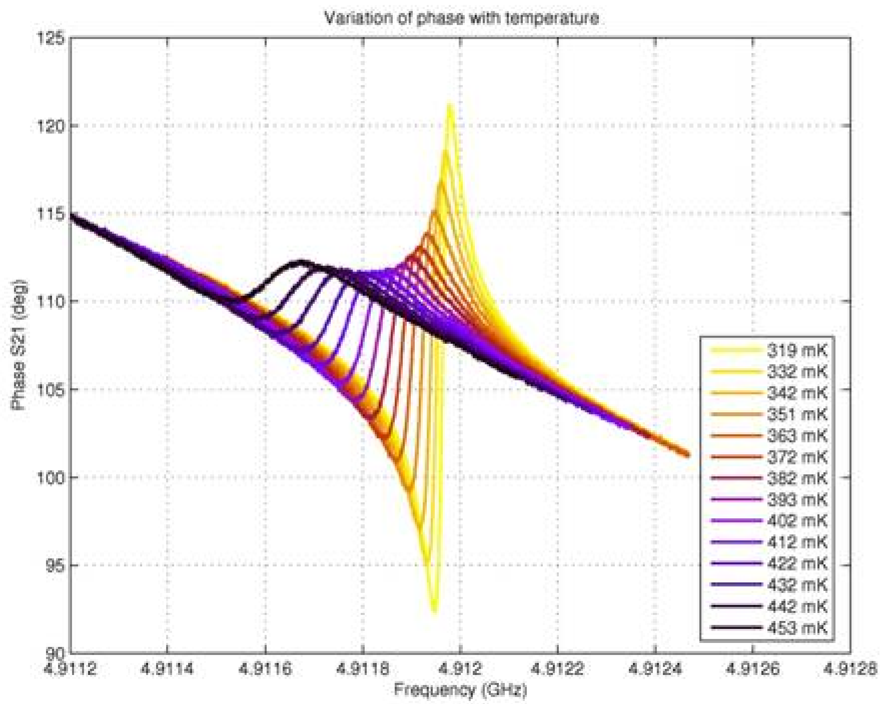
Kid # on chip	Kid #	Length (μm)	f_0^{obs} (GHz)	σ_{f_0} (kHz)	Q_L^{obs}	σ_{Q_L}	ϵ_{eff}
1	6	6960	4.911962736	9	110350	200	8.65
2	5	8670	3.944695790	5	74120	80	8.65
3	4	10380	3.298130134	10	16620	50	8.65
4	2	12080	2.835951816	6	81010	130	8.65
5	3	13790	2.890248677	3	137490	110	$\simeq 5.6$
6	1	15500	2.765257669	5	69810	80	$\simeq 5.6$

Effect of temperature variation - 1



Amplitude

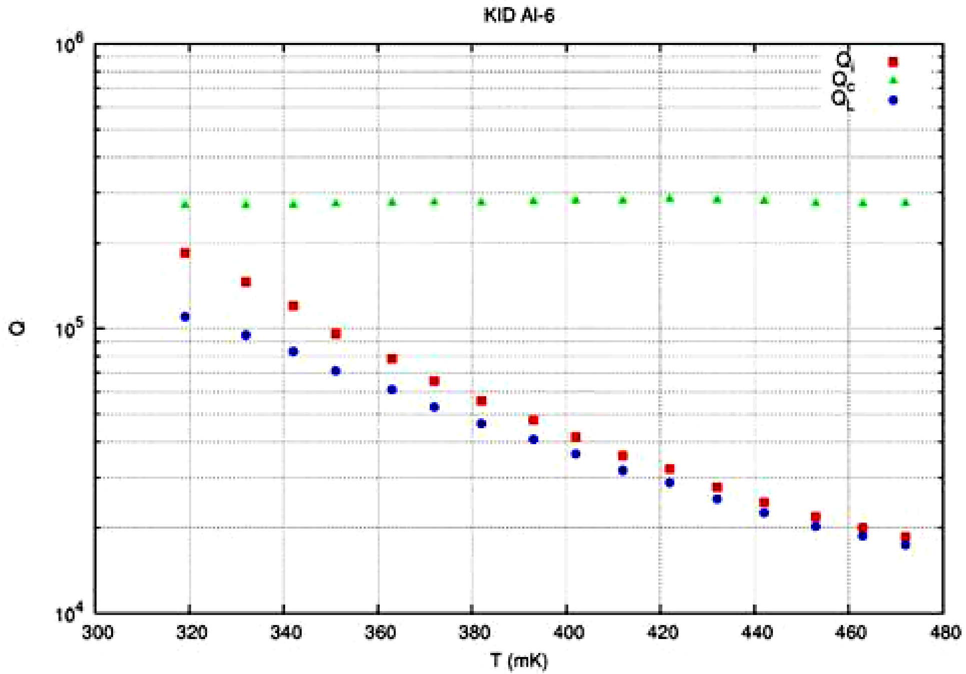
Phase



Higher T ➡ Higher n_{qp} ➡ Higher losses

Higher T ➡ Lower n_{qp} ➡ Lower f_0

Effect of temperature variation - 2

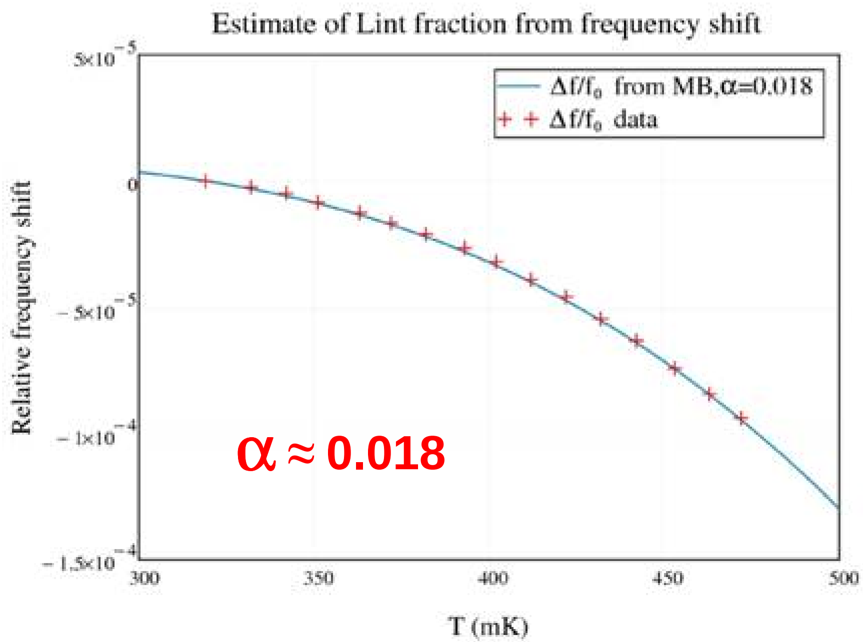


Quality factor increase

Estimate of kinetic inductance fraction

$$f_0 \propto \frac{1}{\sqrt{L_{TOT}(T)}}$$

$$\alpha = \frac{L_{kin}}{L_{TOT}} \qquad \frac{\delta f_0(T)}{f_0(0)} = -\frac{1}{2}\frac{\alpha \delta L_{kin}(T)}{L_{kin}(0)}$$

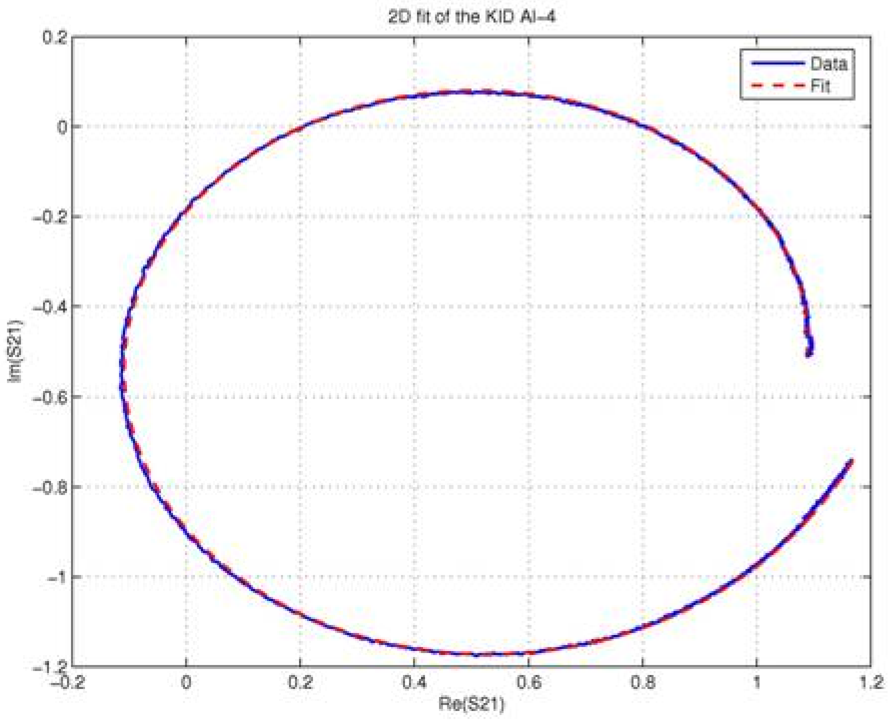


$\alpha \approx 0.018$

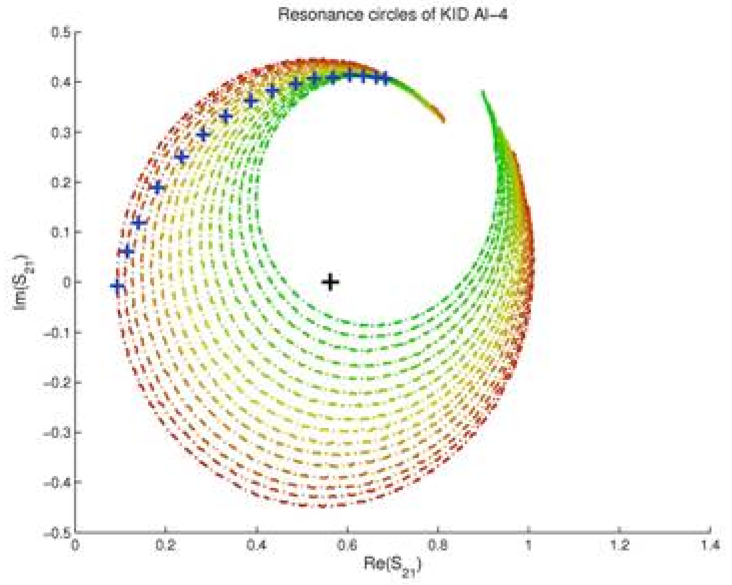
2D data analysis

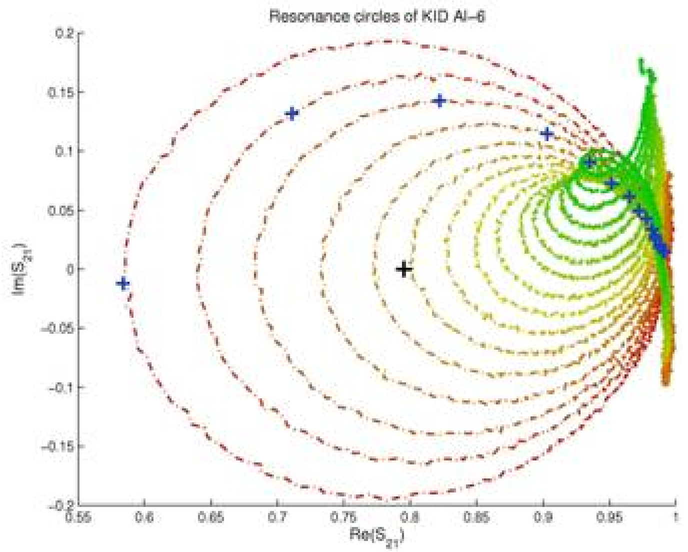
A fitting procedure has been developed to estimate the parameters of the resonators and the effect of the IQ mixers

The results are in very good agreement with the data:

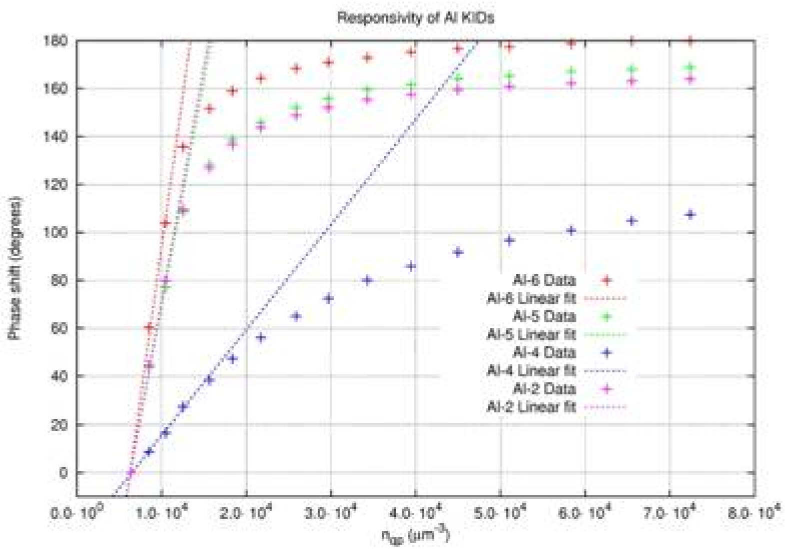


Temperature variation - 3





The blue points correspond to the base temperature resonant frequency

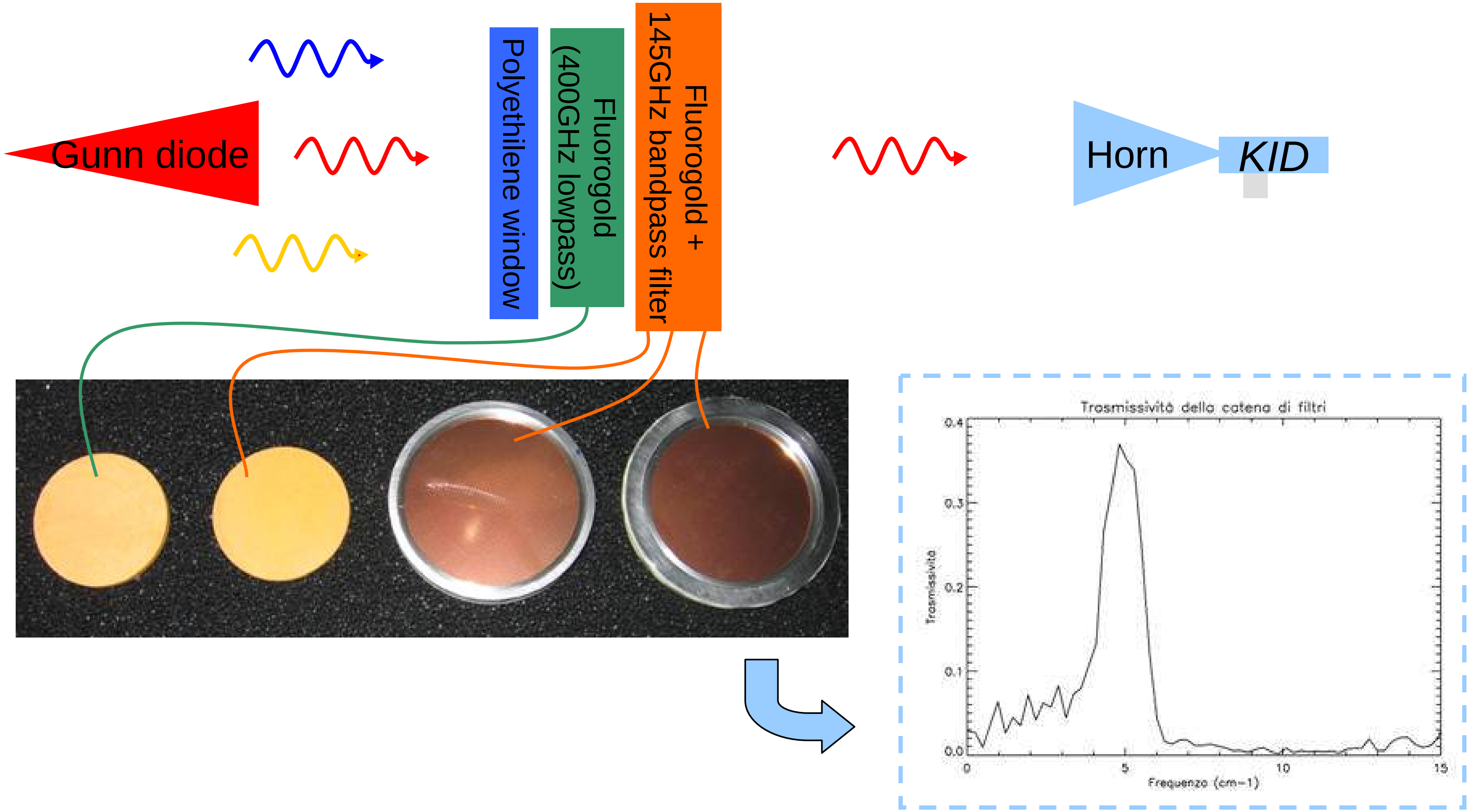


We obtain sensitivities of 10^{-3}-10^{-2} deg/n_{qp}

equivalent to 10^{-9}-10^{-8} deg/N_{qp}

Optical measurements

System modified by adding a filter chain



We have seen light!

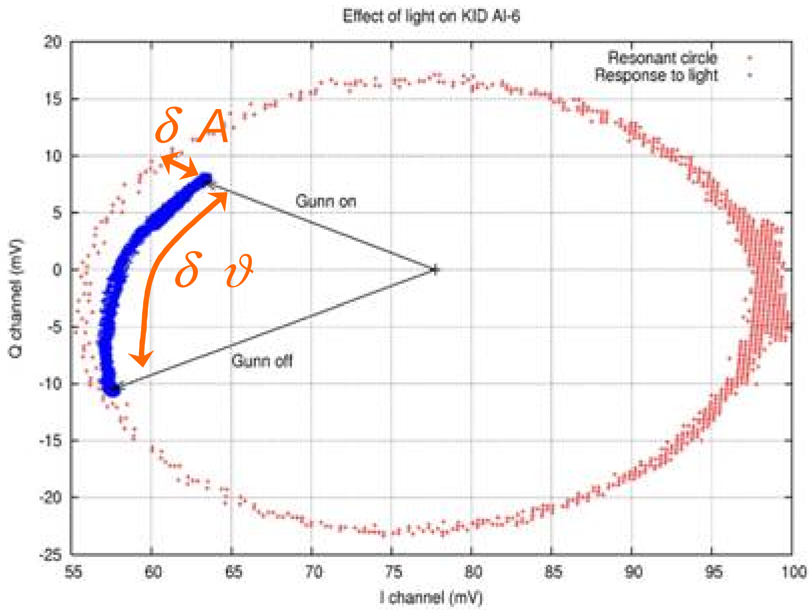
Typical IQ resonant circle, T=314mK.
The blue line represents the response to radiation.

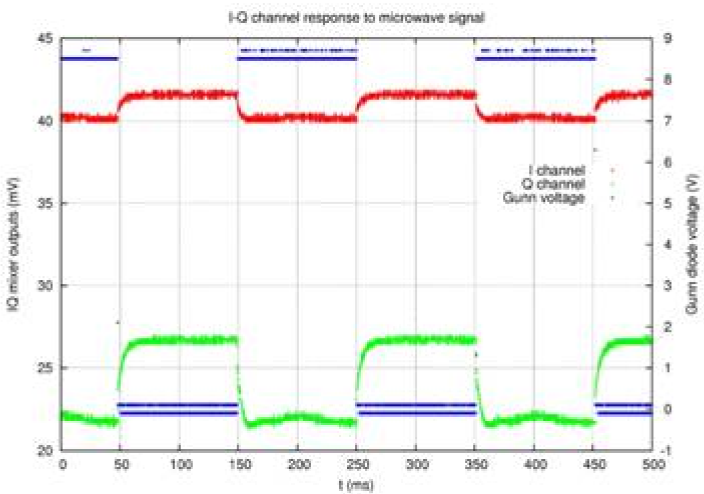
We get

$$\delta\vartheta = 57^\circ$$

$$\to \delta n_{QP} = 2300 \mu m^{-3}$$

$$\to \delta N_{QP} \approx 6 \cdot 10^{7}$$

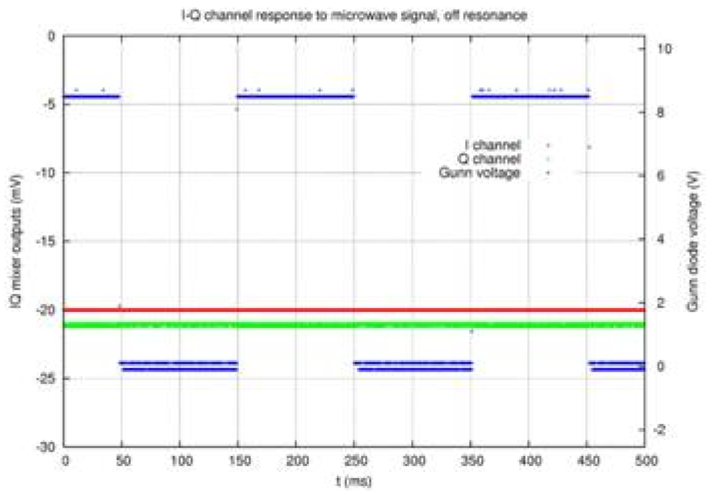




Just a check...

On reso ←

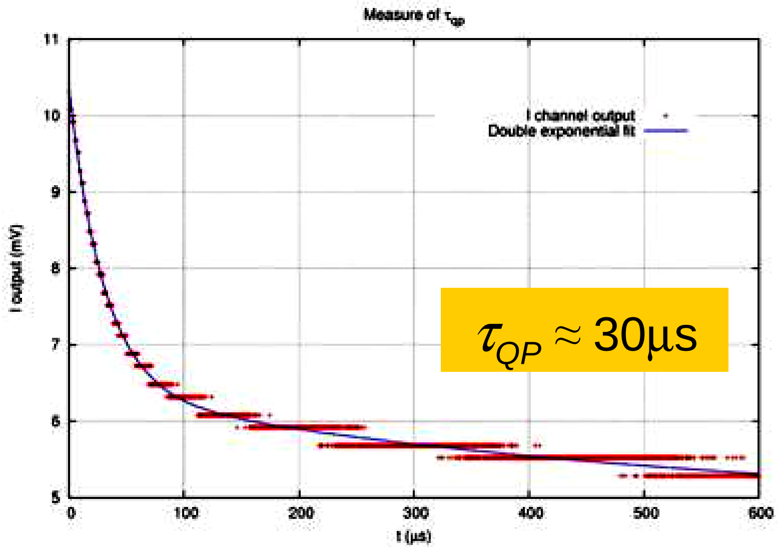
Off reso →



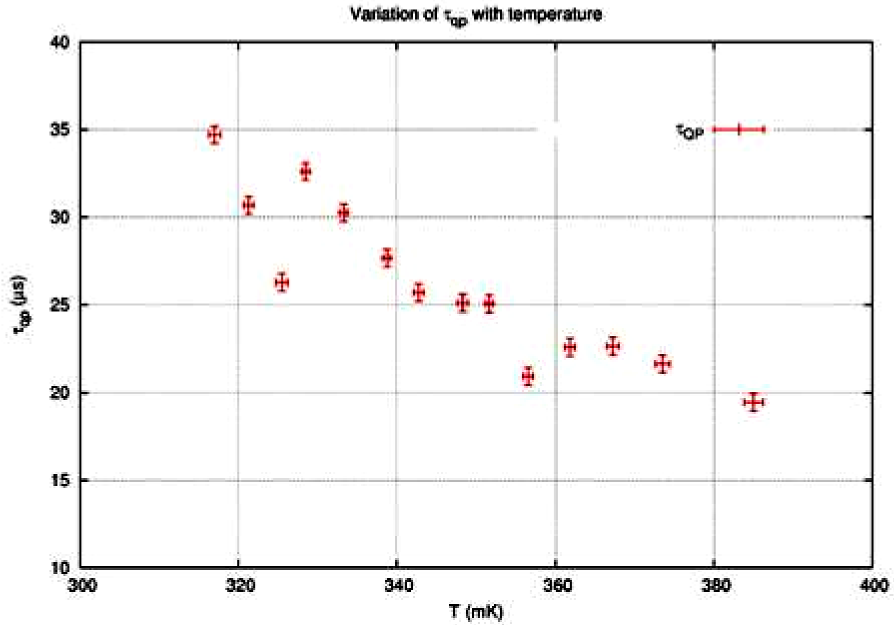
Quasiparticle lifetime

To estimate the absorbed power that induces the signal we still need one piece of information:

$$P_{abs} = \frac{n_{qp}\Delta}{\eta\tau_{QP}}$$



When *T* decreases, the quasiparticle lifetime increases (n_{QP} smaller!)



Estimating absorption efficency

We now have all the data to evaluate P_{abs} which is:

$$P_{abs} = 0.094 nW$$

A precise determination of the power reaching the sensor cannot be done due to the configuration of our system (reflections, alignement of components..)

Still it is possible to get an idea of the numbers assuming uniform distribution of the power emitted by the Gunn in its beam, and considering the area subtended by the $\lambda/4$ line. We find

$$P_{in} = 4.9 nW$$

Though this is a lower limit for a series of assumptions made in the calculations

The upper limit on the absorption therefore is

$$a \leq 2\%$$

Very low, but it was expected...

A possible solution: LEKID

Our chip was not optimized for coupling to radiation

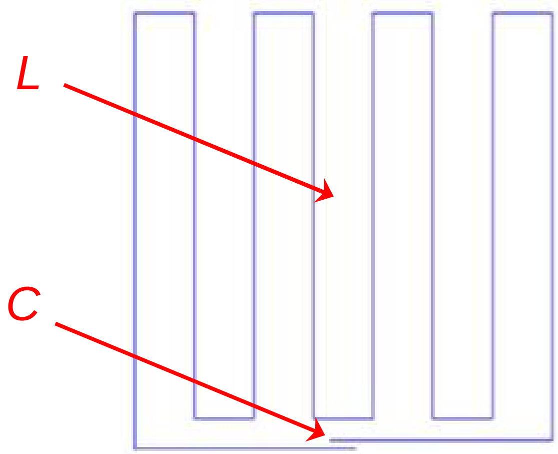
- *Distributed element KIDs*

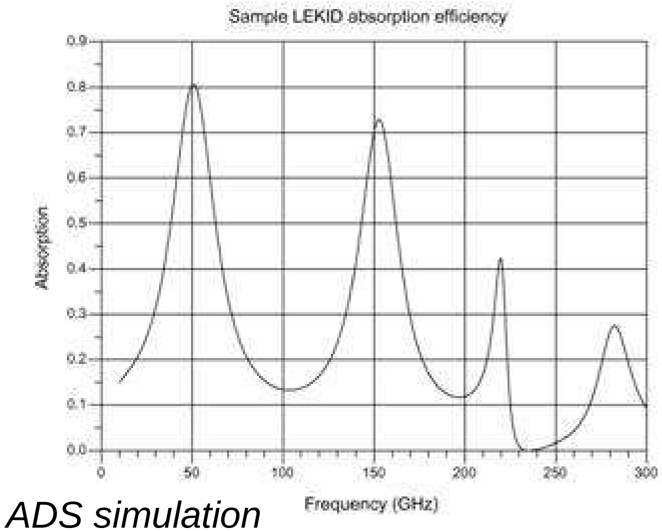
  Response depends on where the photon hits the sensor

  Needs some sort of antenna

- *Lumped element KIDs*

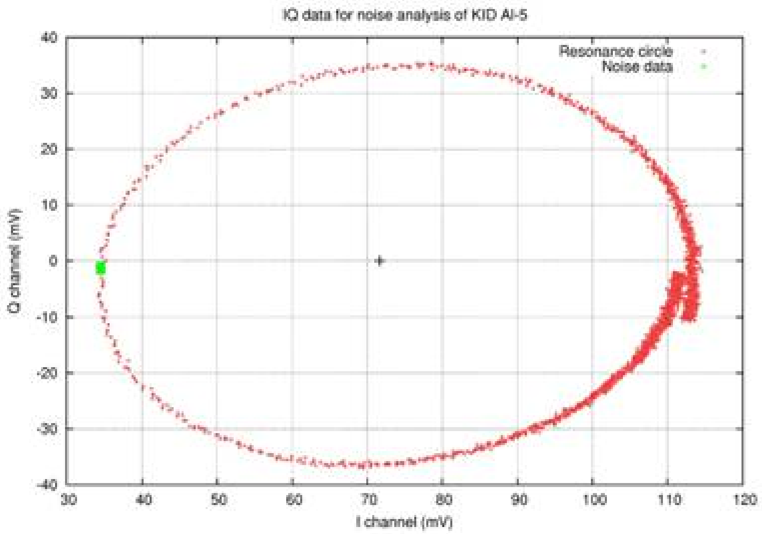
It is possible to tune the meanders to match free space impedance!





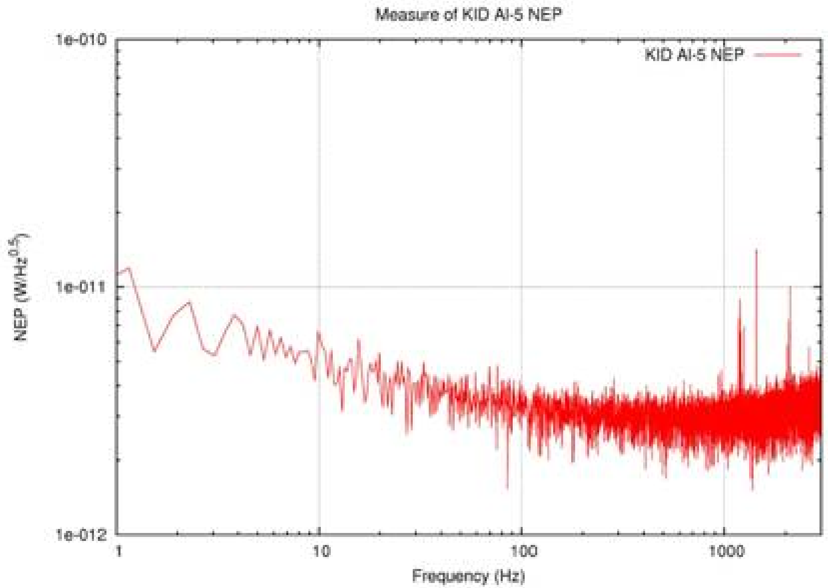
ADS simulation

Electrical NEP measurement



High sample rate data acquired

$$NEP^2 = S_\vartheta \left[\frac{\eta \tau_{QP}}{\Delta} \frac{\delta \vartheta}{\delta N_{QP}} \right]^{-2} \left(1 + \omega^2 \tau_{QP}^2\right)$$



Still too high for real applications, but:

Dominant contribution given by the warm readout components!

Theoretical limit given by GR noise is as low as $10^{-20} W/Hz^{0.5}$ at *100mK*

P. K. Day et al. Lett. Nature 425 (2003)

Conclusions

- The KIDs concept has been studied and theoretical models have been developed to analyze their reponse

- The experimental testbench has been completed and characterized

- The first chip has been made and thouroughly tested

- The first results are very promising
  - High Q factors even at *300mK* ---> *multiplexing!*
  - Good agreement with theoretical predictions
  - First light already seen

- Yet still some open issues
  - Develop a system to reach lower T (*dilution fridge?*)
  - Optimize optical coupling ---> *LEKID*

Thanks for your attention!