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# Microwave Kinetic Inductance Detectors for Long Duration Balloon experiments

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**Abstract.** Long Duration Balloon experiments have played a key role in the study of the Cosmic Microwave Background. The measurement of its temperature anisotropies has been the first step towards a deeper understanding of the structure of the Universe. Yet to date many questions regarding its birth and evolution remain open. The polarization signal of the CMB can help us answer most of them. In particular, the so called *B modes* would be a direct test of the Inflation and could give information on the scale of energies at which it took place. The amplitude of the B modes is expected to be less then $1\mu K$. In order to measure this kind of signal one needs either a very long integration time, or a very fast mapping speed. In the case of LDB and satellite missions the second is the only viable solution. This poses a serious technological challenge as large arrays of detectors are usually very hard to implement.
In this paper we present the working principle of the Microwave Kinetic Inductance Detectors and their status of development in Italy, focusing on the key aspects that make them ideal for application in LDBs experiments and in particular for a high purity, ultra-sensitive, polarization mapper.

**Key words.** Microwave Kinetic Inductance Detectors – Cosmic Microwave Background – CMB polarization – Long Duration Balloons experiments

## 1. Introduction

Over the last decades there has been a huge development in the detectors for millimetric and sub-millimetric radiation. Spider web bolometers with germanium and transition edge sensors have already reached a noise level that is comparable or less than the intrinsic noise of the CMB radiation itself. The increase in sensitivity that is mandatory for the measurement of the B modes of CMB polarization cannot therefore be attained by means of more sensitive detectors, but rather using large arrays

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of sensors in the focal plane, including from hundreds to thousands of pixels. To reduce the thermal load on the cold stage of the experiment one has to develop a multiplexing strategy for the readout, to be able to read more pixels via a single cable. Such a system is very complex to implement for the detectors commonly used today.

In this context we have started studying the Microwave Kinetic Inductance Detectors (Day et al. 2003; Mazin 2003). MKIDs working principle is based on the dependance of the surface impedance of a superconductor from the density $n_{cp}$ of Cooper Pairs. When a photon of energy $h\nu > 2\Delta$ is absorbed by the superconductor it causes a decrease in $n_{cp}$ and a consequent increase in the kinetic inductane $L_{kin}$. The very small variation of $L_{kin}$ can be monitored by designing a resonating superconducting component shunting a feedline. Since the losses in the superconductor are extremely low, $Q$ factors of up to $10^6$ can be obtained. Therefore, even a small shift of the resonance due to the variation of $L_{kin}$ produces a significant effect both on the amplitude and the phase of a fixed bias signal sent through the feedline at the unperturbed resonant frequency.

The high $Q$ value is of primary importance also because it ensures that each resonator produces an effect only in a very narrow range of frequencies around the resonant one. The ideal bias frequency for MKID resonators is in the few GHz range: such a high frequency allows very high Q factors, and thus the multiplexing of thousands of pixels with a single feedline. Using one single coax cable all the pixels can then be read out simultaneously, by means of frequency domain multiplexing. These detectors therefore provide a solution that offers a high mapping speed, combined with a low thermal input on the cold stage.

## 2. Experimental setup

The experimental setup needed to work with MKIDs consists of two main components, the cryogenic system and the RF readout.

### 2.1. Cryogenic system

For the MKIDs to work properly, they are to be kept at temperatures well below their critical temperature, $T_c$. In our laboratory setup this is accomplished by a closed cycle $^3He - ^4He$ refrigerator mounted on the Cold Head of a Pulse Tube cooler. In a typical balloon application, a simple liquid He dewar can be used in place of the pulse tube. Using the low ambient pressure as a very high efficiency pump, the baseline temperature will be well below the superfluid transition, and its stability will depend quite weakly on the float altitude stability. A vapor cooled shield (see the contribution of L. Nati et al. in these proceedings) will provide the intermediate temperature necessary for thermalization of the bias and readout cables.

To send the RF signal to the MKID, minimizing the thermal load, a series of 3 low thermal conductivity coax cables has been used, thermalized at the 2 intermediate temperature stages that are available ($30K$ and $3K$). Furthermore, DC blocks have been added on every stage. A DC block consists of a very small break in the center pin of the coax cable. This strongly reduces the thermal conductivity through it, still allowing high frequency signals to travel through.

Thanks to all these precautions the base working temperature reached in our setup is approximately $310mK$. This is reasonably low for Aluminum ($T_c = 1.25K$) resonators, and ideal for Niobium Nitride ($T_c \simeq 13K$) ones.

### 2.2. RF system

The basic idea to readout the MKIDs is to combine the signal sent into the cryostat with the one getting out of it, in order to measure the effect of the detector on its amplitude and phase. This can be accomplished in two ways. The first one is using a Vector Network Analyzer: this option is very good for characterizing the devices in terms of resonant frequency and $Q$ factor, but it is too slow for many applications.

If one wants to study fast signals, the solution is based on a RF synthesizer and an IQ mixer. The synthesizer produces a constant tone, which is split in two branches, one used

**Table 1.** Resonant frequency and $Q$ factors of the resonators on the Al chip at $T = 310mK$.

| Resonator # | $f_{res}$ $[GHz]$ | $\sigma_{f_{res}}$ $[GHz]$ | $Q$ $[\cdot 10^4]$ | $\sigma_Q$ $[\cdot 10^4]$ |
|---|---|---|---|---|
| 1 | 2.765257 | 0.000007 | 7.0 | 0.1 |
| 2 | 2.83595 | 0.00001 | 8.0 | 1.8 |
| 3 | 2.89025 | 0.00002 | 14.0 | 1.1 |
| 4 | 3.298130 | 0.000007 | 1.44 | 0.04 |
| 5 | 3.944696 | 0.000009 | 7.2 | 1.3 |
| 6 | 4.91196 | 0.00002 | 11 | 3 |

as a reference and the second sent into the cryostat. The signal coming out of the cryostat and the reference one are then mixed together via an IQ mixer, which produces two output signals, proportional to the phase and quadrature components of the inputs product. If the two inputs are at the same frequency, the outputs are DC signals.

The advantage of this scheme is that it can be upgraded with relative ease to a multipixel system, if a comb of frequencies is generated via a fast DAC that is then up-converted to RF frequencies and sent into the cryostat; an IQ mixer is then used to recover the signals of all the pixels.

To control the power which is used to readout the MKIDs, a variable warm attenuator has been added to the fixed value ones which are inside the cryostat. The output signal is then boosted by a cold amplifier and a by a warm amplifier, for a total gain of $60dB$.

## 3. First measurements

The first chip that we have used is made of Aluminum on a Silicon substrate, produced at the IRST-ITC in Trento. The resonator is a distributed one, in which the resonant frequency is determined by the length of the superconducting strip coupled to the feedline. The chosen geometry is that of a coplanar waveguide.

The first fridge cycle has been devoted to the determination the main properties of the resonator. Even though, given the limitations of our cryogenic system, the temperature was slightly higher then the ideal one, the obtained $Q$ values were nonetheless very high, and the resonant frequency has been determined with high accuracy, as it is shown in table 1. Already at this temperature, 1000 pixels could easily fit into a $1GHz$ bandwidth, a good proof of the feasibility of this multiplexing scheme.

We then moved to study the effect of increasing temperature on our resonators. As $T$ is raised, more and more Cooper Pairs will break due to thermal excitations and become unbound electrons or, as they are usually called in this context, *Quasi Particles*. The consequent increase of $L_{kin}$ and of the residual resisitivity of the QPs, $R_{qp}$, should affect the resonance figure by shifting it towards lower frequencies (since $F_{res} \propto 1/\sqrt{L_{kin}}$) and making it broader and shallower. One of the temperature sweeps is presented in figure 1.

The variation of the surface impedance of a superconductor can be evaluated using the Mattis-Bardeen theory (Mattis and Bardeen 1958), which gives the real and complex components of the surface conductivity. The kinetic inductance represents only a fraction $\alpha$ of the total inductance, which has also a component due to the magnetic field energy, $L_{mag}$, which doesn't vary with the value of $n_{cp}$. Starting from

$$f_{res} \propto 1/\sqrt{L_{tot}}$$

and variating it, one therefore finds

$$\frac{\delta f_{res}(T)}{f_{res}(0)} = -\frac{1}{2}\alpha\frac{\delta L_{kin}(T)}{L_{kin}(0)}$$

Thus an estimate of the fraction $\alpha$ of the kinetic inductance can be obtained easily by fitting the data to the theoretical prediction of Mattis-Bardeen theory. The value of $\alpha$ we get is $\alpha = 0.024 \pm 0.001$. The graph is shown is figure 2. This parameter has to be maximized

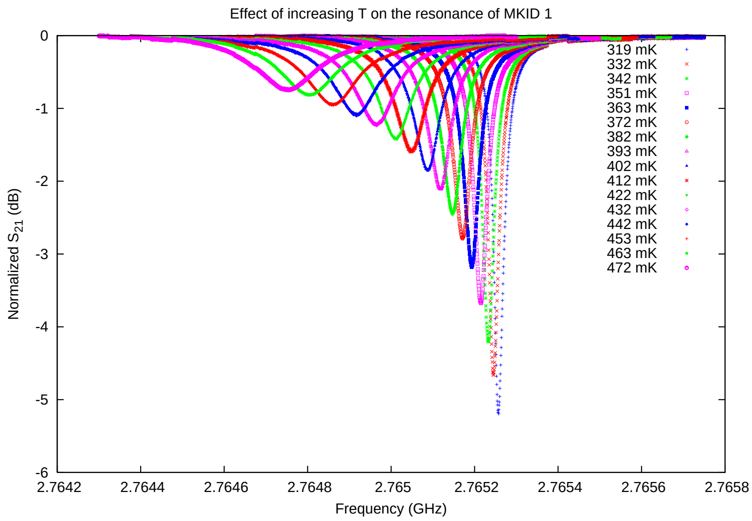


**Fig. 1.** Variation of the resonance peak as the temperature is increased from $320mK$ to $470mK$. Both the frequency shift and the degradation of the $Q$ factor are clearly visible. Notice how such a large increase of $T$ shifts the resonance center by less then $1MHz$.

to get more sensitive devices, as the larger the fraction of inductance which is of kinetic origin, the larger the effect its variation will have.

As a last step we illuminated the chip with a $145GHz$ light source, namely a Gunn diode, to check that the detectors were actually sensitive to photons of high enough energy (for

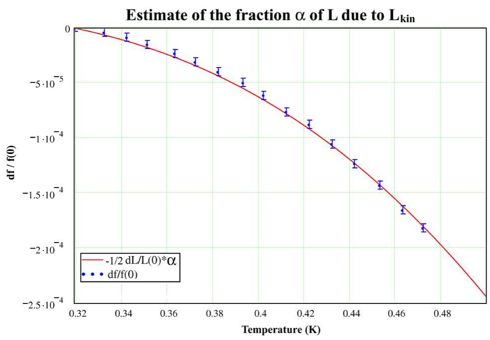


**Fig. 2.** Evaluation of the kinetic inductance fraction $\alpha$ obtained relating the data to the theoretical predictions of Mattis-Bardeen integrals.

Aluminum, $\nu_{gap} \simeq 90GHz$). To take the data in this case we used the system based on IQ mixers. The relevant variables in this case are the inphase and quadrature output of the mixers, which are plotted in the complex plane and are related to the complex value of the $S_{21}$ parameter commonly used to describe RF devices. Sweeping the frequency across the resonance one gets a circle in this plane, whose radius is proportional to the depth of the resonance itself.

To readout the MKIDs we used a constant frequency signal at $f_{res,dark}$ and measured the output variation due to the Gunn. Since this was the first run of chips we made, they were not optimized for coupling to radiation, and the throughput of our optical system was not well defined. Nevertheless we clearly saw a signal synchronous to the on/off frequency of the Gunn diode. We expect the effect of light to be analogous to that of an increase in temperature, as in both cases there is a decrease of $n_{cp}$. In particular we should see the signal coming out of the cryostat less attenuated when the Gunn is on, and with a different phase, as the resonance has shifted. Both these effects are

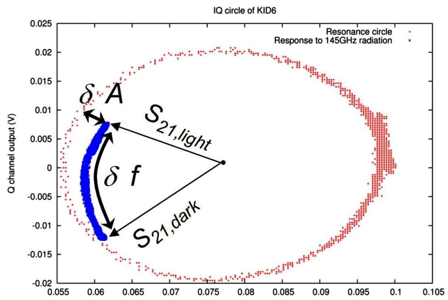


**Fig. 3.** Effect of $145GHz$ radiation shone on the detectors. Even though the optical coupling is not at all optimized, the signal is clearly visible showing that the sensors can be used for radiation of this wavelength, particularly interesting for many fields of Cosmology.

evident in the measured data plotted in figure 3.

## 4. Future prospects

The test-bench we have setup will be modified in the near future to reach lower temperatures (below $100mK$), by means of a dilution refrigerator. This will allow better measurements on the Aluminum KIDs , on which we would like to concentrate, as they are the best ones to use at the "CMB" frequencies around $150GHz$. In the meantime we have begun the optimization of the chips, in particular as far as the optical coupling is concerned: we are designing a new mask with *Lumped Element KIDs* (Doyle et al. 2008), a kind of KID detectors whose geometry can be tuned to match the impedance of free space. This improve enormously the coupling to the incoming radiation.

Until now all the resonators have been studied one at a time. The multiplex RF electronics is under development at the University of Perugia, and as soon as the readout system is ready we will include it in the Rome test facility.

## 5. Use of MKIDs in LDB experiments

Several balloon and space missions have been recently proposed in the mm/sub-mm range. All need a cryogenic system optimized for extremely long hold-time. The issue of the heat load from the readout is especially important for a space mission with consumable liquid He, where the duration of the mission is limited by the hold time of the cryogen. For this reason MKIDs could be the detectors of choice for the future B-Pol mission (see http://www.b-pol.org). This mission is aimed at the detection of B-modes in CMB polarization, and a set of several thousand detectors will be needed. In view of this mission, a balloon-borne survey (B-B-Pol) is needed to validate all the involved technologies (see the paper by P. de Bernardis in these proceedings). MKIDs could represent the detectors of choice for the high-frequency instrument of B-B-Pol (140 and 220 GHz bands).

## 6. Conclusions

The first MKIDs chip that we have used is working as expected, and though we are still at the beginning of the development process the results obtained make us optimistic: the $Q$ values are of order $10^5$ even at relatively high temperatures, and we have managed to see light without yet having optimized the coupling. We are therefore confident that the optimization process that is ongoing will lead us to the development of sensors that could play a key role in future LDB and satellite missions.

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