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Superconducting Kinetic Inductance Detectors for astronomy and particle physics

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ABSTRACT

Kinetic Inductance Detectors (KID) represent a novel detector technology based on superconducting resonators. Since their first demonstration in 2003, they have been rapidly developed and are today a strong candidate for present and future experiments in the different bands of the electromagnetic spectrum. This has been possible thanks to the unique features of such devices: in particular, they couple a very high sensitivity to their intrinsic suitability for frequency domain multiplexed readout, making the fabrication of large arrays of ultrasensitive detectors possible. There are many fields of application that can profit of such detectors. Here, we will briefly review the principle of operation of a KID, and give two sample applications, to mm-wave astronomy and to particle physics.

1. Kinetic Inductance Detectors

Kinetic Inductance Detectors (KID) represent a superconducting detector technology that has been rapidly spreading since its first proposal in 2003 [1]. Superconducting detectors can provide extremely high sensitivities and a negligible thermal noise, and can therefore open the path to new applications and devices. In a superconductor, the current is carried primarily by Cooper Pairs (CP), electrons paired via a phonon-mediated interaction with a binding energy 2Δ given by $2\Delta = 3.5 k_b T_c$, where k_b is the Boltzmann constant and T_c is the critical temperature of the considered superconductor. A minor contribution to the conductivity is nonetheless also given by the electrons that remain unbound, referred to as quasi-particles (qp). While the latter are dissipative and give raise to a resistive term, the Cooper Pairs are bosons, and can therefore move through the lattice in a dissipation-less way. Yet, CPs accumulate energy of magnetic and kinetic origin due to their motion, and will show an inertia if an external field is applied to change such energy content. From a circuital point of view this results in an inductance associated to CPs, so that if an AC field is applied to the superconductor this will show a non-zero reactance. The part of this reactance of kinetic origin is what is referred to as kinetic inductance, L_k, and depends on the density of Cooper Pairs, n_{cp}. Thus, the absorption of a photon of energy above 2Δ in the superconductor will lead to a variation of n_{cp}, and therefore to a change of L_k. To measure δL_k, the KID uses the superconductor as a variable component of a superconducting resonator. The change of L_k results in a variation of the resonant frequency, f^0. It can be shown that the relationship between the absorbed power, P, and the frequency shift is linear for small variations of power : $\delta f^0 \propto \delta P$ [2].

Different geometries can be adopted to make a resonator. The first type of KID to be proposed were *distributed resonators*, in which a strip of superconductor is capacitively coupled to a readout feedline at one end and shorted to ground at the other. In this case, a standing wave can be excited giving raise to a resonance. This happens if the strip length is one fourth of the excitation wavelength, hence the name of $\lambda/4$ resonator. A different solution is the one provided by the Lumped Element KID [3]. In this case, the resonance is obtained by using two separate components, a capacitor and an inductor, whose dimensions must be much smaller than the excitation wavelength. The resonance in this case is given by $f^0 = 1/2\pi\sqrt{(LC)}$.

To readout the signal, a bias tone is sent on the feedline coupled to the resonator. By monitoring the changes in the amplitude and phase of the transmitted tone it is possible to reconstruct the corresponding variation of the KID resonance frequency, δf^0. One of the main advantages of KIDs is that the resonator only affects a very small frequency band around f^0, and does not load the readout line outside this band. It is therefore possible to couple many detectors to one single feedline, simply by slightly changing the design of each pixel in order for them to have different

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resonating frequencies. Multiplexing factors of order 10^3 can be achieved. Reading out thousands of pixels using just one input and one output coaxial cable decreases the thermal load on the cold stages of an experiment drastically, making kilopixel arrays of cryogenic detectors a reality.

2. KID for astronomy: the NIKA2 camera

One of the field that can more directly benefit from the use of KIDs is millimeter and sub-millimeter astronomy. The energy of photons in this band of the electromagnetic spectrum is very low: $E_\gamma = h\nu = hc/\lambda = 1.2$ eV/mm. As a consequence, the detection of light at these wavelengths has been one of the most difficult challenges for astronomers. Until recently, the main solution has been that of using bolometric detectors, in which the cumulative effect of many photons leads to the heating of a sensor, whose resistivity is strongly temperature dependant. The latest and most effective implementation of bolometers are the Transition Edge Sensors [4]. Although single-pixel performances of TES are remarkable, they are not well suited for multiplexed readout, needing a complex cold electronic system for addressing each detector of one array. KIDs are a valid alternative, provided that the T_c of the superconductor chosen is sufficiently low for the photons in the band of interest to be able to break CPs. This is true if their energy $h\nu$ is larger than the binding energy $3.5k_bT_c$ of the CPs. Therefore, the minimum observable frequency is given by $\nu_{gap} = 3.5k_bT_c/h$. In the case of Aluminium, a material commonly used for KIDs, the critical temperature is $T_c \sim 1.3$ K. Thus, Aluminium based KIDs are well adapted to sense all photons of frequency above $\nu_{gap} \sim 100$ GHz, corresponding to wavelengths lower than ~ 3 mm.

NIKA2 (New IRAM KID Arrays 2) is a mm-wave camera based on KID that will be installed at the IRAM 30 m telescope in Sierra Nevada (Spain) in September 2015. This camera builds upon the experience gained during the development and deployment of its pathfinder instrument, NIKA [5,6], but goes a step further in terms of overall performances. The IRAM telescope is located in a dry area at 2850 m altitude, and is thus ideally suited for operation in the two atmospheric windows centered at 1.25 and 2 mm. It has a correct Field of View of 6.5 arcmin, and the 30 m primary mirror gives a resolution as low as 10.5 arcsec at 1.25 mm. This makes it one of the best tools for astronomers working at millimeter wavelengths. NIKA2 aims at taking full advantage of the potential of such a telescope by providing simultaneous data taking in both bands and fully sampling the whole FoV without degrading the resolution. This implies using arrays of up to 1000 detectors at 2 mm and 2000 detectors at 1.25 mm. In the latter band the instrument will be polarization sensitive, by using two separate arrays, one for each polarization. The total KIDs count will thus be of up to 5000 (Fig. 1).

The detectors used for NIKA2 are based on Lumped Element KID (LEKID), with the inductance having the shape of an Hilbert 3rd order fractal [7] (Fig. 2). The arrays are made of thin Aluminium (between 18 and 25 nm) on a Silicon substrate. The pixel design is therefore similar to what had been used in NIKA, obtaining very good performances. The total number of pixels is on the other hand increased by a factor 10, passing from 300 in NIKA to almost 5000: a full 4 in. wafer is now needed to fill the focal plane surface. The readout of the KID is based on the NIKELv1 electronics board [8]. Each board can readout up to 400 pixels over a 500 MHz bandwidth. The arrays have therefore multiple feedlines (4 for the 2 mm band, 8 for the 1.25 mm one), each used to excite around 250 pixels. The arrays are cooled down to 100 mK using a dilution refrigerator coupled to two Pulse Tube coolers for continuous operation. The whole system (cryogenics, detectors and readout chain) is already operational and undergoing the final improvements before its installation on site at the end of September 2015.

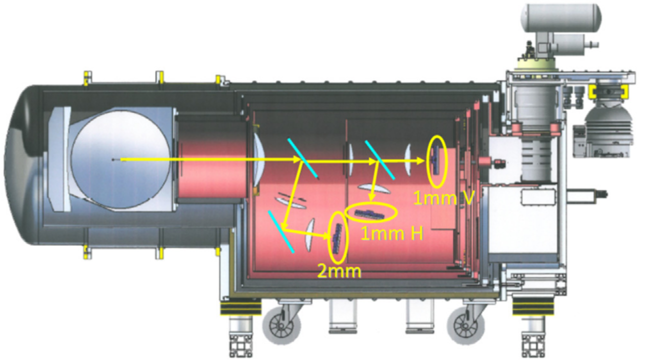

Fig. 1. Drawing of the NIKA2 cryostat. The overall length of the instrument is 2.3 m. The arrows (yellow online) show the approximate path of the light depending on the wavelength and polarization. The 1 mm light is split according to its polarization (H for horizontal, V for vertical) using a wire-grid polarizer. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

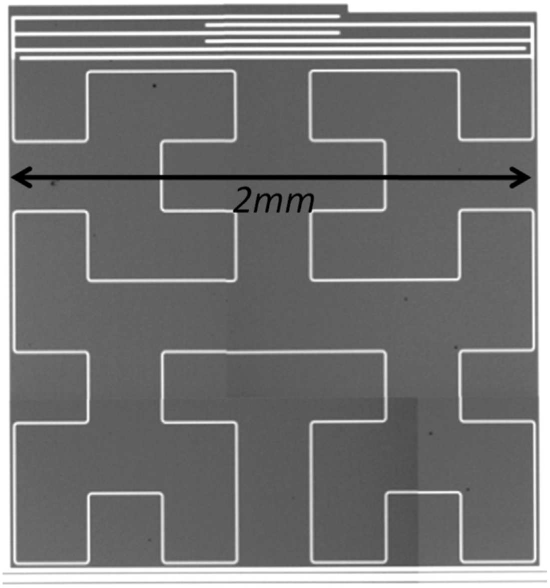

Fig. 2. Image of a Hilbert LEKID used for NIKA2. The Aluminium film is white, the Silicon of the underlying wafer is grey. The capacitance is given by the interdigitated parallel fingers at the top, while the inductance is the meandering line. The size of this pixel was 2 mm^2. The feedline to which it is coupled is seen at the bottom of the image.

3. KIDs for high energy particles

The KIDs intrinsic advantages make them appealing even outside the limits of millimeter astronomy, and different groups are now working to develop devices adapted for use at shorter wavelengths, such as visible light or X-rays. When the energy associated to the impinging photon, or particle, increases, it becomes more and more difficult to efficiently absorb it in the superconducting film. For instance the α particles produced by radioactive sources can in general pass through the few nanometers of the superconducting film without releasing a significant energy fraction. If photons are considered, as the wavelength of the radiation to be absorbed decreases, the optical coupling between the photons and the detectors becomes more complex, and the lithographic structures